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**SUMMARY REPORT ON FUEL DEVELOPMENT AND
MINIPLATE FABRICATION FOR THE RERTR PROGRAM,
1978 TO 1990**

by

T. C. Wiencek

**Argonne National Laboratory
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August 1995

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SUMMARY REPORT ON FUEL DEVELOPMENT AND MINIPLATE FABRICATION FOR THE RERTR PROGRAM, 1978 TO 1990

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ABSTRACT

This report summarizes the efforts of the Fabrication Technology Section at Argonne National Laboratory in the program of Reduced Enrichment Research and Test Reactors (RERTR). The main objective of this program was to reduce the amount of high enriched ($\approx 93\%$ ^{235}U) uranium (HEU) used in nonpower reactors. Conversion from low-density ($0.8\text{--}1.6\text{ g U/cm}^3$) HEU fuel elements to highly loaded (up to 7 g U/cm^3) low-enrichment ($<20\%$ ^{235}U) uranium (LEU) fuel elements allows the same reactor power levels, core designs and sizes to be retained while greatly reducing the possibility of illicit diversion of HEU nuclear fuel.

This document is intended as an overview of the period 1978–1990, during which the Section supported this project by fabricating mainly powder metallurgy uranium–silicide dispersion fuel plates. Most of the subjects covered in detail are fabrication-related studies of uranium silicide fuels and fuel plate properties. Some data are included for out-of-pile experiments such as corrosion and compatibility tests. Also briefly covered are most other aspects of the RERTR program such as irradiation tests, full-core demonstrations, and technology transfer. References included are for further information on most aspects of the entire program. A significant portion of the report is devoted to data that were never published in their entirety. The appendices contain a list of previous RERTR reports, ANL fabrication procedures, calculations for phases present in two-phase fuels, chemical analysis of fuels, miniplate characteristics, and a summary of bonding runs made by hot isostatic pressing.

1 INTRODUCTION

The Reduced Enrichment Research and Test Reactor (RERTR) program was initiated by the U.S. Department of Energy in 1978. The main objective of this program was to provide the technical means to reduce the amount of high-enriched ($\approx 93\%$ ^{235}U) uranium (HEU) used in nonpower reactors. Conversion from low-density ($0.8\text{--}1.6\text{ g U/cm}^3$) HEU fuel elements to highly loaded (up to 7 g U/cm^3) low-enrichment ($<20\%$ ^{235}U) uranium (LEU) fuel elements allows the same reactor power levels, core designs and sizes to be retained while greatly reducing the possibility of illicit diversion of HEU nuclear fuel. The study began with a technical and economic assessment of the use of HEU in research and test reactors.¹ A proposal by D. D. Lanning, R. A. Lewis, and D. Stahl² in 1977 initiated the funding for this effort. The primary focus of this report is on delineation of the fuel-production experiences of the Fabrication Technology Section at Argonne National Laboratory (ANL). An outline overview of the areas of the RERTR program where the Fabrication Technology Section made major contributions is given in Fig. 1. The report also covers areas where the Section's input was minor; these are briefly reviewed and references are cited. Although the yearly status of the program has been covered in previous reports,³⁻⁴ this report also briefly discusses other parts of the overall program and serves as a compendium of various RERTR references. A complete list of RERTR reports published to date or in progress under the ANL-RERTR-TM series is given in Appendix A.

A screening list of potential fuels considered for this program is provided in Table 1, while a uranium loading comparison of the major fuels of interest is given in Fig. 2. The figure compares fuels of increasing densities and illustrates the decreasing volume-fraction of fuel required to achieve a specific uranium loading (g U/cm^3). Two major types of fuel technology were available at the beginning of this program; cast-type fuels, the original technology for reactor element construction; and dispersion-type fuels, the second generation of reactor fuels. The cast-type fuels are single- or multiple-phase cast alloys of uranium plus the alloying element(s); Al is usually the alloying element. Cast fuels are limited by the increasing formation of intermetallic phases in the metal system, which occurs at $\approx 30\text{ wt.\% U}$ for the U-Al system. The major negative consequence of this limit is that the fabrication properties of cast fuel deteriorate severely with increased intermetallic phases in the alloy fuel. Dispersion-type fuels overcome this limit because they contain a powdered fuel that is

Fig. 1. Flow chart of ANL activity areas in RERTR program

Table 1. Fissile dispersants for potential fuel development

Compound	Melting Point, °C	Density (g/cm ³)	Uranium Loading (g/cm ³)	Relative Uranium Loading
U	1133	19.1	19.1	1.00
U-10% Mo Alloy	1150	18.2	16.4	0.86
UAl ₂	1590	8.1	6.6	0.35
UAl ₃	1350	6.7	5.0	0.26
UAl ₄	730	6.0	4.1	0.21
UBe ₁₃	2000	4.37	2.9	0.15
UC	2500	13.6	13.0	0.68
UC ₂	≈2500	11.7	10.6	0.56
UO ₂	2875	10.96	9.7	0.51
U ₃ O ₈	a	8.40	7.1	0.37
UN	2630	14.3	13.5	0.71
U ₆ Mn	726	17.8	17.1	0.90
U ₆ Fe	815	17.7	17.0	0.89
UFe ₂	1235	13.2	9.0	0.47
U ₃ Si	930 ^a	15.6	15.0	0.79
U ₃ Si ₂	1665	12.2	11.3	0.59
USi	1570	10.4	9.3	0.49

^aDecomposes. Source: Ref. 5

mechanically mixed with a powdered ductile metal matrix by powder-metallurgy techniques. Because the dispersion-plate fuel zones are not limited by the formation of intermetallic phases, they can be fabricated with higher loadings than an equivalent cast-type fuel. The upper limit of dispersion fuels is ≈80–85 wt.% fuel, depending on the fuel and the matrix system. Three dispersion fuels were considered for study: uranium oxide, uranium aluminide, and uranium silicide. If the dispersion fuels were not successful, U-Mo cast fuels were considered to be a backup. Experience had shown the first two fuels to exhibit excellent irradiation performance up to loadings of ≈40–45 wt.% fuel.

A data base was developed for low-volume-percentage HEU oxide (U₃O₈) and aluminide fuels. The fuel properties at higher fuel loadings needed to be established, and maximization of fuel loadings and determination of irradiation properties at high loadings were the main

Fig. 2. Comparison of uranium loadings ($g\ U/cm^3$) for uranium and various uranium compounds

objectives of the studies of these first two fuels. Three different research programs were initiated. Oak Ridge National Laboratory (ORNL) was chosen to investigate the oxide fuels,⁶ EG&G at the Idaho National Engineering Laboratory was selected to examine the aluminide,⁷ and ANL focused on the uranium silicide fuels. The decision to investigate uranium silicide was based on previous encouraging irradiation results with aluminum-modified, aluminum-clad, extruded uranium silicide fuel tubes.⁸ Also, a very small number of irradiations of U_3Si_2 dispersions indicated acceptable irradiation properties.⁹

Figure 3 is the phase diagram for the U-Si system. Three fuels were of interest: U_3Si , which forms by a peritectoid reaction at 925°C ; and U_3Si_2 and USi , which form directly from the liquid. Mixed-phase uranium silicides with compositions between U_3Si and U_3Si_2 were studied in the hope that they would retain the best properties of each compound. A list of these and other fuels studies at ANL is given in Table 2.

Fig. 3. U-Si phase diagram

Table 2. Fuels fabricated at ANL

Fuel Formula ^a	ANL Target Composition (wt.% U)	Alloying Elements (wt.%)
U ₃ Si	96.0	4.0 Si
U ₃ Si _{1.5}	94.5	5.5 Si
U ₃ Si _{1.6}	94.0	6.0 Si
U ₃ Si ₂	92.5	7.5 Si
USi	89.4	10.6 Si
U ₃ SiAl	95.0	3.5 Si + 1.5 Al
U ₃ SiCu	95.8	4.0 Si + 0.17 Cu
UAl ₂	80.0	20.0 Al
U ₆ Fe	96.0	4.0 Fe
U ₆ Mn _{1.3}	93.7	6.3 Mn
U ₇₅ Ga ₁₀ Si ₁₅	94.1	3.7 Ga + 2.2 Si
U ₇₅ Ga ₁₅ Ge ₁₀	91.0	5.3 Ga + 3.6 Ge

^aFormulas should not be taken literally. Although some target compositions may be nearly single phase and may be very close to the formula composition, the notation is simply a convenient way to describe a particular alloy.

Irradiation was conducted in the Oak Ridge Research Reactor (ORR) at Oak Ridge National Laboratory (ORNL). Figure 4 details the miniature fuel plate (miniplate) design used for the irradiation studies.

After the initial irradiation results, U₃Si₂ emerged as the fuel of choice for most research and test reactors. However, a few very highly loaded reactors could still not be converted to LEU. In an effort to convert these reactors, other higher-density fuels were studied. These studies included dispersions of U₆Fe, and of U₃Si+Cu in aluminum and novel fuel-fabrication techniques to increase the fuel loading beyond conventional levels. U₆Mn was also studied from a scientific point of view to compare its stability with U₆Fe. U₆Mn was never considered a viable reactor fuel because of its high neutron absorption due to the Mn.

Full-size fuel elements were irradiated in the ORR with U₃Si₂ elements manufactured by three commercial fabricators:¹⁰ Babcock & Wilcox (USA),

Fig. 4. Design of miniplate for irradiation experiments

Compagnie pour l'Etude et la Realisation de Combustibles Atomiques (CERCA, France), and NUKEM (Federal Republic of Germany). The study showed that LEU U_3Si_2 -Al dispersion fuel elements will perform at least as well in research and test reactors with power densities up to that of the ORR. In 1988, the U.S. Nuclear Regulatory Commission granted approval for the use of U_3Si_2 -Al as an acceptable replacement for the standard highly

enriched $\text{UAl}_x\text{-Al}$ and $\text{U}_3\text{O}_8\text{-Al}$ dispersion fuels currently being used in licensed nonpower reactors.¹¹

Conversion to LEU U_3Si_2 is now progressing throughout the world, including the USA,¹² Germany,¹³ and Japan.¹⁴

2 FUEL DEVELOPMENT AND MINIPLATE FABRICATION

2.1 Synthesis of Fuels

All alloys were made by arc melting together appropriate quantities of high-purity uranium and the specific alloying element(s) to yield an ingot of the required composition. Ingots were arc melted on a water-cooled copper hearth plate with a water-cooled, nonconsumable, tungsten electrode in an atmosphere of $\approx 80\%$ He + 20% Ar maintained at a slight positive pressure to inhibit ingress of air. Ingots were cooled, inverted, and remelted at least four times to ensure homogeneity. Ingot weights ranged from ≈ 50 g to a maximum of 1,000 g.

After melting, some alloys required heat treating. U_3Si , for example, forms by a peritectoid reaction ($\text{U}_3\text{Si}_2 + \text{U}_{\text{ss}}^* \rightarrow \text{U}_3\text{Si}$) at and below 925°C . Annealing in a protective inert (argon) atmosphere for 72 h at 800°C was necessary to complete the reaction in the arc-melted ingots.

The ingots (after heat treating if required) were then broken into pieces suitable for further comminution. Ingot fracturing was usually done in a normal laboratory environment with a 50-ton (4.45×10^5 N) press and a punch-and-die set that would contain the pieces as they were generated. Because all the uranium alloys used in this program tend to be pyrophoric — some more than others — powder-production procedures were varied according to the nature of each alloy.

The brittle compounds, U_3Si_2 , USi , UAl_2 , and U_6Fe , were comminuted in a once-through nitrogen glovebox with a hardened steel mortar and pestle operated manually. A few alloys were ground to appropriate-size powder in a motorized mortar and pestle within the glovebox. In this case, the mortar and pestle were made of mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$). However,

* U_{ss} = uranium solid solution.

chemical analysis showed that the abrasiveness of the particles ground in this manner yielded powders that were "surface-contaminated" with Al_2O_3 and SiO_2 . Once this was confirmed, the use of mullite as a grinding device ceased.

U_3Si , $\text{U}_3\text{Si}_{1.5}$, and U_3SiCu , which are tough or contain a tough phase, were ground most effectively in a "Shatterbox," a unit commercially available from Spex Industries, Inc., of Edison, NJ. A Model 8500-115/60 Shatterbox Laboratory Mill was employed at ANL. Broken ingot pieces are placed within a tungsten-carbide-lined dish with external dimensions of ≈ 19 cm diameter by ≈ 6 cm height. A ring and a puck, also made of tungsten carbide, are contained within the dish, and a tungsten-carbide-lined cover is placed over the top and rigidly clamped in place with an O-ring seal that prevents loss of powder or admission of appreciable quantities of air. The unit then spins the assembly in an oscillatory planar motion at ≈ 900 rpm, pulverizing the sample between the dish wall, the ring, and the puck. Operation times varied with particle size and amount of charge, but individual runs were normally 1-3 min for charges of 20-40 g. Heat generated by the grinding was allowed to dissipate before the dish was opened and/or rerun. The unit was operated in a normal laboratory environment.

The grinding product, whatever the procedure, was sieved in 3-in. (76 mm)-diameter stainless steel sieves, pans, and covers. In general, three particle sizes were separated: +100 mesh ($>150 \mu\text{m}$), -100+325 mesh ($<150 \mu\text{m}$ and $>45 \mu\text{m}$), and -325 mesh ($<45 \mu\text{m}$). The fuel powders utilized in the fabrication of miniplates for ORR irradiation were typically 85% -100 +325 mesh and 15% -325 mesh. For some experiments, the ratio of these two fractions was changed. In no case were +100 mesh particles knowingly used for fuel-plate fabrication. As will be discussed later, a large needle-shaped particle can have one dimension greater than 100 mesh and pass through the sieve. Such a particle, if not removed during the sieving process, could cause a miniplate to be rejected.

2.2 Fabrication of Fuel Plates

After the fuel was comminuted, it was weighed and then mixed in individual bottles with aluminum powder in a V-blender. To avoid blisters during rolling, it was essential to vacuum-degas the as-received aluminum powder and not store it for extended periods in air. Standard powder

metallurgy methods were used to form a compact from the fuel and aluminum powder. The compact was placed in a 6061 aluminum frame and then cover plates were placed on the top and bottom of the frame. Prior to assembly, the plate and covers were chemically cleaned to remove the aluminum oxide film. The assembly was then welded and hot rolled to approximate size. After the appropriate testing, the plates were cold rolled and machined to miniplate specifications. Details of difficult and/or modified fabrication procedures and a process flow chart are presented in the next section. A complete set of fabrication procedures is given in Appendix B.

2.3 Notes on Fabrication Procedures

Figure 5 is a flow chart of the RERTR miniplate fabrication plan, as produced in 1983; many changes have been made in procedures since then. This section highlights the important changes, in numerical order. The fabrication procedures discussed below are marked with a wide vertical bar in the figure.

2.3.1 Rolling and Machining of Stock for Plate Assemblies (Frames and Covers; Procedure 2)

As the percentage of fuel was increased to 50 vol.%, the frame openings were increased in size. Two sizes were used: 1.676 x 0.541 in. (42.57 x 13.74 mm) for ≤ 30 vol.% and 1.678 x 0.542 in. (42.62 x 13.77 mm) for > 30 vol.%.

2.3.2 Arc Melting of Fuel Alloys (Procedure 3): Supplementary General Arc-Casting Procedures

A preweighed alloy charge was loaded in the water-cooled copper hearth; the standard ingot weighed ≈ 350 g. This value was chosen because it was the maximum capacity of the furnace. All U-Si alloys were made at higher Si levels than stoichiometric composition. Small Si losses were caused by the "high" vapor pressure of Si. These losses can be better estimated by examining Appendix D (Chemical Analyses). The furnace was closed and the chamber was evacuated to ≈ 10 $\mu\text{m Hg}$ (1.33 Pa) and then backfilled with argon. This procedure was repeated. The system was evacuated again and backfilled with a gas mixture of 70 vol.% He and 30 vol.% Ar to 1 psig (7 kPa). Power was applied to the electrode and an arc

Fig. 5. Flow chart of RERTR miniplate fabrication plan

was initiated. By adjusting the electrode-to-work-piece gap, a 20-V optimum was obtained. The current was gradually increased to 400–600 A. These values apply only to the specific equipment used at ANL for arc melting. The current used for other melts was controlled mainly by the size of the melt to be made. Melt time was normally 2–3 min. Power was then reduced and the arc extinguished. The melted charge was furnace-cooled to room temperature (which normally takes 10–40 min, depending on the mass size). The furnace was then opened and the melted charge removed, weighed, and returned to the furnace (in an inverted position, i.e., the original back or bottom side of the melt was now on top). The furnace was closed, evacuated, purged, reevacuated and backfilled with the He/Ar mix and the charge was remelted. The process was repeated four times. Normally, the charge was totally alloyed after the second melting. The two additional meltings were done to ensure homogeneity. The intermediate weight checks served as indicators of melt condition. Small losses are to be expected under normal melting, where a weight increase can indicate melt contamination, or a large weight loss can indicate a possible loss of an alloying element.

This process is a general procedure and has been used to prepare a large number of melts.

2.3.3 Modifications of Process

- Preparation of U–Si Series
 - Bury Si under U.
 - On remelting, slowly increase power (preheat the casting before melting to reduce spalling of the melt out of the mold due to thermal shock; spalling tendency increases with increase in Si content).
 - After final melting, employ slow cooldown by reducing power to prevent catastrophic cracking.
- Preparation of Alloy Containing High-Vapor-Pressure (HVP) Elements
 - Bury HVP element.
 - Back fill to ≈ 5 psig.
 - Melt power kept as low as possible.
 - Charge kept in molten state for minimum time.

Note that high-purity He and Ar are required to produce clean melts. Weld grade gases are not of acceptable purity.

2.3.4 Power Supply for Arc Furnaces

The power supply is a heavy-duty solid-state DC rectifier type. It is rated at 1000 A at 100% duty cycle. The unit has a continuously variable amperage control and a soft-start control. It is also equipped with a remote foot-controlled contactor and amperage control, plus a high-frequency arc starter and arc stabilizer.

2.3.5 Heat Treatment of Fuel Alloys (Procedure 3)

During the heat treatment of the Al, Si, Fe, and Mn uranium compounds, extra precautions were required to prevent ignition of the fuel ingots. The heavy-wall, 4-in.-diameter (102 mm) by 12-in. (305 mm)-long stainless steel retorts were allowed to cool overnight and then opened under a flowing argon system. After gradual exposure to air, the samples could be handled the same as other powders.

2.3.6 Comminuting Ingots to Powder (Procedure 4)

The ease of comminution cannot be based on hardness values alone. In an effort to increase the friability of U_3Si , extra silicon was added to the basic alloy during one series of experiments. This increased the amount of U_3Si_2 present. Table 3 shows the results of powder production after 30 and 60 min. It should be noted that there is only a small increase in powder production until the Si level reaches 6.0 wt.%.

Other alloys were ranked as follows relative to U_3Si_2 :

- U_3Si_2 - Easily comminuted into -100 mesh powder.
- $U_3Si_{1.6}$ - Slightly more difficult.
- U_3Si - Much more difficult.
- USi - Comparable to, if not easier.
- U_6Fe - Comparable down to 200 mesh. Very difficult to reduce to -100 mesh.
- $U_6Mn_{1.3}$ - Very similar.
- U-Ga-Ge Alloys - Much more difficult, very ductile.
- U-Ga-Si Alloys - Much more difficult, very ductile.

Table 3. Comminution of U_3Si + U_3Si_2 alloys

Percent Silicon (Balance Uranium)	Powder Produced (g), 30 min	Powder Produced (g) 60 min	Total (g)
4.8	0.3	4.5	4.8
5.6	1.1	4.5	4.8
6.5	10.3	Not Measured	>>10.3

2.3.7 Pressing Compacts (Procedure 9)

Most of the additions to this procedure are small details that are sometimes overlooked when making a compact. The platen plates should be ground flat. After grinding, the platens should be adjusted for parallelism with a dial indicator (± 0.002 in., ± 0.05 mm). If these tolerances are not maintained, the result is uneven gage compacts. Cleanliness of the die and punches is an absolute must. Smeared material in the die clearance will cause ejection to be difficult and produce compacts with cracked edges. Although most of the compacts were made by raising the lower punch and leveling (as described in the procedure), a few compacts were leveled in the die with the bottom punch in its compacting position. This was done by using a finely adjustable leveling tool, which is shown in Fig. 6. By adjusting the height level and making multiple passes across the powder in the die, a compact that was very uniform in thickness could be produced in the center of the die. The advantage of this method was that very uniform compacts could be made and there were fewer problems with smearing because the leveled powder was never lowered through the tapered section of the die.

Compacting forces versus volume loading for various fuels, and the resulting porosity, are given in Table 4. These values can be converted to pressures by using the 1.670 in. (42.42 mm) x 0.540 in. (13.72 mm) die area. The differences in the fuels are most likely due to the powder shape. The highly cold-worked U_3Si was more flakelike and did not flow as easily as the more equiaxed U_3Si_2 . Another general trend was that as the percent of fuel was increased, the required compacting pressures also increased.

Fig. 6. Adjustable compact-powder-leveling tool

2.3.8 Clean and Assemble (Procedure 10)

An additional step was added to the cleaning procedure after the oakite etch. After being rinsed in water, the plates were wiped with a lint-free cloth to remove as much of the "smut" as possible. If the plate and cloth were kept moist, removal was much more thorough. This method produced noticeably cleaner frames and covers and also increased the life of the nitric etch solution.

Before assembly, the compacts were gently wiped with a clean lint-free cloth to remove loose particles and excess lubricant. A magnifying glass was used to check for stray particles before the top cover plate was installed. Any remaining particles were removed with a lint-free cloth. As a result of this careful cleaning and inspection of the assembled compacts, the number of plates with fuel out-of-zone was reduced and blisters were rarely ever observed over the fuel zone during the entire course of the program.

Table 4. Compacting forces and resulting porosity for various fuels

Fuel; Force ^a		Porosity	
10 ³ lb	10 ³ N	Vol.% ^b	(%)
U₃Si₂			
15	(66.7)	13	11.6
20	(88.9)	13	9.7
18	(80)	30	14.0
19.5	(86.7)	30	13.4
22	(97.8)	30	11.8
26	(115.6)	30	9.1
43	(191.1)	44	7.3
25	(111.1)	44	14.0
45	(200.0)	50	7.9
35	(155.6)	50	10.6
30	(133.3)	50	12.8
29	(128.9)	50	13.7
65	(288.9)	45 (Thin)	14.0
50	(222.2)	50 (Thin)	14.0
45	(200.0)	44 (Thick)	14.0
55	(244.4)	44 (Thick)	12.0
U₃SiAl			
32	(142.2)	30	14.0
45	(200.0)	40	15.0
47	(208.9)	40	14.3
50	(222.2)	50	13.7
47.5	(211.1)	50	14.0
55	(244.4)	55	15.2
U₃Si			
20	(88.9)	12	11.6
30	(133.3)	28	10.3
25	(111.1)	30	14.0
44	(195.6)	41	14.0
45.5	(202.2)	41	13.4
45	(200.0)	41	13.6
52	(231.1)	42	10.3
58	(257.8)	42	7.9
47.5	(211.1)	50	15.2
55	(244.4)	50	12.8
52.5	(233.3)	50	13.4
60	(266.7)	50	11.6
58	(257.8)	42 (Thin)	15.4

^a0.540 x 1.670 in. = area of punch = 0.902 in.² (5.82 cm²).

^bThick = 0.030 in. (0.76 mm). meat (i.e., fuel); Thin = 0.0126 in. (0.032 mm) meat. Nominal = 0.020 in. (0.51 mm).
Average compact thickness = 0.164 in. (4.17 mm).

2.3.9 Assembly Hot Rolling (Procedure 12)

A few minor changes were made to the rolling procedures. No wipers were used on the rolls, and the amount of oil was controlled much better by hand-wiping the rolls on the exit side before every pass. The effect of the heat lamps was insignificant and their use was discontinued early in the program. After the fourth or fifth pass, the tandem assemblies were reidentified (by numbers stamped at the top-surface right-hand corner of the trailing edge) and sheared in half. The reason for the stamping was that after a few passes, the identification numbers became difficult to read. The plates were sheared in half because they would have become too long to fit in the furnace.

2.3.10 Cold Rolling and Leveling (Procedure 13)

The oil used for cold rolling was changed to Cindol #4641, (E. F. Houghton & Co.), which gave a better surface finish than the previously used kerosene. Great care should be taken to keep oil use to a minimum, or the surface finish will deteriorate. Waviness is caused by too much oil on the roll or insufficient (<10%) reductions. The application of back tension to the exit side of the mill can help reduce this problem.

2.3.11 Radiography of Plates (Procedure 14)

The fuels studied required different exposures to produce radiographs with an acceptable density. Table 5 is a summary of all the fuels X-rayed in this program. As for most other materials, the exposure is a complex relationship and not governed merely by the fuel density.

A second important point is the uniformity of the X-ray source. As the target wears in the X-ray tube, the uniformity of the X-ray beam is decreased. Regular maintenance of the tube should be followed, including tube replacement when required.

2.3.12 Metallography (Procedure 15)

These procedures were modified during the course of the entire program. As new fuels and better procedures were developed, they were recorded in the section's log books but were not formalized until 9/89. A complete updated metallography procedure is included in Appendix B.

Table 5. Exposure times and parameters^a

Fuel; Thickness of Meat		Vol. %	Exposure Time (min)
in.	mm		
U ₃ Si ₂			
0.020	0.51	13	0.33
0.020	0.51	32	1.0
0.020	0.51	40	1.75
0.020	0.51	50	2.75
0.0126	0.32	45 Thin	1.25
0.0126	0.32	50 Thin	1.50
0.030	0.76	44 Thick	4.5
U ₃ Si, U ₃ SiCu			
0.020	0.51	12	0.5
0.020	0.51	28	1.5
0.020	0.51	40	3.0
0.020	0.51	42	3.75
0.020	0.51	45	4.0
0.020	0.51	47	4.25
0.020	0.51	50	4.75
0.0126	0.32	42 Thin	1.75
UAl ₂			
0.020	0.51	50	1.0
U ₆ Fe			
0.020	0.51	42	4.75
0.020	0.51	48	6.75
USi			
0.020	0.51	40	0.75
U ₃ Si _{1.5}			
0.020	0.51	31	1.5
0.020	0.51	41	3.25
0.020	0.51	48	4.0

^aAll at 100 kV, 5 mA. 1/4 in. lead backing and developed by ANL Nondestructive Testing Section. Film type- Kodak M-8 lead pack 2.00 Film Density, Distance = 30 in.

2.3.13 Cutting and Machining Miniplates to Final Dimensions (Procedure 16)

As a quick method to check the alignment of the fuel zone after the first machine cut, an X-ray was taken on Type 52 Polaroid film. The typical exposure was 90 kV, 3 mA, for 6 s.

2.4 Phases Present in Silicide Fuels

Discussions of silicide fuels often involve considerations of the relative amounts of the various phases (distinguishable crystalline entities) present in U-Si alloys at different Si levels. This topic is being reexamined more carefully as the requirements for certain reactors exceed the U loading levels possible with "pure" U_3Si_2 . This section is a supplement to Ref. 15.

Table 6 is a list of the calculated and experimentally measured compositions of U_3Si , U_3Si_2 and USi , the three most U-rich phases in the U-Si system, which is shown in Fig. 3. In all calculations and plots that follow, the 3.9 wt.% Si figure for the composition of U_3Si , the rounded value of 7.3 wt.% Si for U_3Si_2 , and the 10.6 wt.% Si value for USi were used. The densities of these phases recorded in Table 6 have been used as necessary. The ANL-determined density of 15.2 g/cm^3 at 4.0 wt.% Si, not 3.9 wt.% Si, was used for all calculations and introduces a slight error. The density figures and the microstructural condition they represent require some amplification. The three compounds (the terms *phases*, *intermetallic compounds*, or *intermediate phases* may be used interchangeably) of interest here are often described as *line compounds*. In the language of phase diagrams, this means that within the experimental ability to define composition, a single formula and composition is assigned to each compound. Each is represented, therefore, as a vertical line in a phase diagram. From a practical standpoint — even in terms of research activity it may be considered essentially impossible to produce an alloy at the exact stoichiometry of the compound and of such atomistic homogeneity that only the "pure" phase is present. A small but finite amount of the phase to the left or the right of the compound of interest is expected in the microstructure. It is even possible that with minor perturbations in the distribution of the two components (U and Si in this case), there may be regions where the phase to the left of the compound of interest is present,

Table 6. Calculated and measured values for U_3Si , U_3Si_2 , and USi

Phase	Calculated wt. %			Density Determined at ANL	
	Si ^a	Si ^b	Si ^c	g/cm ³	wt. % Si in Alloy
U_3Si	3.78	3.79	3.9 ^f	15.2 ^d	4.0
U_3Si_2	7.29	7.31	7.3	12.2 ^e	7.3
USi	10.55	10.58	10.6	10.9 ^e	10.6

^aCalculated for natural U; atomic weight of 238.03 used.

^bCalculated for 20% enriched U; atomic weight of 237.45 used.

^cExperimentally determined value; depleted U used.

^dFor alloy heat treated at 800°C; presumed to be at equilibrium.

^eFor as-arc-cast alloy.

^fU-Si (ϵ) phase has been shown to form between 3.9 and 4.0 wt. % Si, giving atom concentrations consistent with $U_3Si_{1.03}$ to $U_3Si_{1.06}$ (Ref. 16).

as well as other regions in the same piece of material where the phase to the right of the compound is present.

To potentially complicate the situation somewhat, the presence of impurities (and they are inevitably present) can lead to the existence of other phases that may or may not be distinguishable under the microscope, depending on their size and the magnification employed. Impurities must also be expected to be in "solid solution" (i.e., within the crystalline lattice) in each of the phases present. The presence of such impurities in solid solution is discernible only with analytical procedures capable of accurately detecting very small quantities of a foreign species. The required equipment and techniques often are not available or simply do not exist.

The density figures recorded and used for the compounds of interest here may not necessarily represent the most accurate values possible. Experimental errors, analytical variability, the presence of impurities, and the question of knowing when equilibrium is reached all conspire against

the question of knowing when equilibrium is reached all conspire against the quest for an absolute value. The value of 10.9 g/cm^3 for USi is probably accurate to $\pm 0.1 \text{ g/cm}^3$. Values determined for U_3Si_2 have ranged from ≈ 11.9 to 12.2 g/cm^3 ; the 12.2 value has been arbitrarily used. The value of 15.2 g/cm^3 for U_3Si represents the best measured value for an equilibrated alloy at $4.0 \text{ wt.}\%$ Si. There is a finite amount of U_3Si_2 in the equilibrated alloy at $4.0 \text{ wt.}\%$ Si, but the density figure was not adjusted accordingly.

Figure 7 is a plot of weight percent and volume percent of U_3Si_2 as a function of Si content, based on application of the tie line and lever principles for alloys at equilibrium. Likewise, Fig. 8 is a similar plot for USi as a function of Si content at Si levels between U_3Si_2 and USi , also for equilibrium conditions. Equilibrium is emphasized because neither of the principles may be quantitatively applied to a nonequilibrium state. Nevertheless, for arc-cast alloys in the range of 7.3 to $10.6 \text{ wt.}\%$ Si and for properly heat treated (e.g., 800°C – 72 h air cooled) alloys in the range of 3.9 to $7.3 \text{ wt.}\%$ Si, it is reasonable to presume that a macroscopically homogeneous melt (alloy) will approach the equilibrium condition.

To determine the weight percent or volume percent of a phase present in two-phase fields under consideration at smaller incremental Si contents than can be conveniently read from the plots, the formulas for such calculations are presented in Appendix C.

For equilibrated (properly heat treated) compositions between U_3Si and U_3Si_2 , at $5.41 \text{ wt.}\%$ Si there is exactly $50 \text{ vol.}\%$ of each phase. In simplest terms, compositions greater than $5.41 \text{ wt.}\%$ Si will have microstructures with U_3Si_2 as the dominant phase. Nevertheless, U_3Si may be a continuous phase even though it is a minor constituent. Because of the way U_3Si_2 crystallizes from the liquid state and because of the morphology of the annealed microstructures, there is evidence that the U_3Si phase is continuous (interconnecting) up to $\approx 6 \text{ wt.}\%$ Si.

Under nonequilibrium conditions, alloys of 3.9 and $7.3 \text{ wt.}\%$ Si may be expected to contain ($\text{U}_{\text{ss}} + \text{U}_3\text{Si}_2 + \text{U}_3\text{Si}$) in percentages that cannot be calculated quantitatively. It is possible to say, however, that the amounts of U_{ss} (uranium solid solution) and U_3Si_2 will diminish with heat treatment (below 925°C) and the amount of U_3Si will increase, ultimately reaching the equilibrium value.

Fig. 7. Percentages of U_3Si_2 at various Si levels

It is important to remember that U_3Si is formed by a peritectoid reaction (the horizontal line at 925°C in Fig. 3) and that any as-cast alloy in the range 0 to 7.3 wt.% Si will have some U_{ss} present in the microstructure. This is true even though the molten alloy is perfectly homogeneous and irrespective of the melting or casting techniques used. The amount of U_{ss} in an as-cast alloy may be calculated by the same procedures used to produce Figs. 7 and 8, and a plot of such data is shown in Fig. 9. In generating Fig. 9, the presentation was simplified by assuming no solid solubility of Si in U. Formulas for calculating weight percent and volume percent of U_{ss} in this composition range are shown in Appendix C.

Fig. 8. Percentages of USi at various Si levels

For alloys heat treated below 925°C, the peritectoid reaction $U_{ss} + U_3Si_2 \rightarrow U_3Si$ occurs at equilibrium and no U_{ss} remains in alloys with >3.9 wt.% Si. All heat-treated alloys in the composition range 0–3.9 wt.% Si will have no U_3Si_2 remaining. The weight percent of U_{ss} will be a linear function of the Si content in the stated range, with 100% U_{ss} at 0% Si and 0% U_{ss} at 3.9 wt.% Si.

Concern has been expressed periodically about the possible existence of Si-rich compounds (e.g., USi_3) in U–Si alloys with ≈ 7.5 wt.% Si. Such a circumstance violates the rules of phase equilibria unless the molten alloy was grossly heterogeneous before freezing. Considering the melting practices used by ANL and commercial vendors, it is unlikely that such a condition would exist. During irradiation or prolonged heat treatment of

Fig. 9. Percentages of U_{ss} at various Si levels

fuel powders dispersed in Al, however, $U(AlSi)_3$ will form. This is, in fact, the phase that is predicted in Ref. 15. $U(AlSi)_3$ is a shorthand notation for UAl_3 that has some of the Al positions occupied by Si atoms.

In some fuel alloy specifications, the fabricator may be required to identify the amount of each phase present in a fuel alloy as determined, for example, by X-ray diffraction analysis. It is important to recognize that under the best of conditions, at least 5 vol.% of a phase must be present for the phase to appear in a diffraction pattern. More likely, 10 vol.% is required before lines from that phase will be evident. Also, the pattern is generated by diffraction from approximately the top 20-Å layer of each particle. Thus, depending on particle size, the diffraction pattern may represent the phases present in only a small percentage of the bulk of the

sample. In other words, X-ray diffraction of powders is not a good analytical tool for identifying the amount of each phase present in a multiple-phase alloy.

A key ingredient of the preceding discussion as it applies to RERTR fuel alloy development and fabrication is described in the following three paragraphs.

Whenever a U-Si fuel is described, a notation such as U_3Si , U_3Si_2 , or USi may be recorded. For other fuels, equivalent notations might be $U_3Si_{1.5}$, U_6Fe or U_6Mn , or U_3SiAl , for example. The descriptive formulas must not be taken literally. In all cases, at least one other phase is present; the amount of the second phase is quantitatively related to the deliberate addition (and impurity) content of the alloy.

In all of the development and fabrication work with U-Si alloys, compositions have always been selected to be on the Si-rich side of the stoichiometric compound. This choice was deliberately made to preclude the presence of uranium solid solution in the alloy and therefore in the fuel particles. The absence of U_{ss} will be the case only if the molten alloy is homogeneous before freezing and, in the case of alloys ranging from 3.9 to 7.3 wt.% Si, after proper heat treatment.

Because perfect homogeneity and equilibrium are goals that can be approached but not achieved, more than one phase in a fuel alloy must always be expected.

2.5 Crystal Structures of Uranium Silicides and Other Uranium Compounds

As indicated previously, compounds in the U-Si system that were the focus of this study were U_3Si , U_3Si_2 , and USi . Figures 10–12 illustrate the atom locations and interatomic distances in three dimensions. Other uranium compounds were studied by X-ray diffraction. The powder composition, previous heat treatment, crystal structure type, and crystal lattice constants (where measurable) are summarized in Table 7.

Fig. 10. Crystal structure of U_3Si

2.6 Chemical Analysis of Fuels

The fuel alloy powders in this program required the most accurate possible characterization before irradiation in the Oak Ridge Research Reactor (ORR). One of the more obvious requirements was an accurate determination of the chemical composition of the alloys to provide, among other things, isotopic values for the uranium contained in these fuels. The pure Al powder, as well as the 6061 Al frame and cover stock, were also analyzed and the results are described. This section summarizes the results obtained at ANL's Analytical Chemistry Laboratory (ACL) with these materials.

Fig. 11. Crystal structure of U_3Si_2

Fig. 12. Crystal structure of USi

Table 7. Characteristics of uranium compounds in U-Si, Fe, Mn systems

Fuel	Melt No.	Powder Condition	Interatomic Distances		Type	Product	Elements ^a (wt.%)		
			a ₀	c ₀			U	Si	Other
U ₆ Fe	D157	As-cast	—	—	Tetragonal	U ₆ Fe	96.0	—	4.0 Fe
U ₆ Fe	D157	168 hr at 700°C	—	—	Tetragonal	U ₆ Fe	96.0	—	4.0 Fe
U ₃ Si	D-218	Splat quenched	—	—	Tetragonal	αU + U ₃ Si ₂	96.0	4.0	—
U ₃ Si ₂	D-219	Splat quenched	—	—	Tetragonal	U ₃ Si ₂	92.5	7.5	—
USi	D-203	As-cast	—	—	Orthorhombic	USi	89.4	10.6	—
U ₆ Mn _{1.3}	D-235	As-cast	—	—	Cubic	U ₆ Mn, UO _{2.5} , broad lines	93.7	—	6.3 Mn
U ₆ Mn _{1.3}	D-235	48 hr at 700°C	5.47	—	Cubic	U ₆ Mn, UO _{2.5} , UMn ₂	93.7	—	6.3 Mn
U ₃ Si ₂	D220-224	As-cast	7.328	3.900	Tetragonal	U ₃ Si ₂	92.5	7.5	—
U ₇₅ Ga ₁₀ Si ₁₅	E230	Cold worked	—	—	Tetragonal	Distorted U ₃ Si structure	93.7	2.2	3.7 Ga
U ₇₅ Ga ₁₅ Ge ₁₀	E229	Cold worked	—	—	Tetragonal	Distorted U ₃ Si structure	90.8	—	5.4 Ga 3.8 Ge
U ₇₅ Ga ₁₀ Si ₁₅	E230	4 hr at 600°C+ 5 hr at 700°C	6.037	8.785	Tetragonal	U ₃ Si type	90.8	—	5.4 Ga 3.8 Ge
U ₇₅ Ga ₁₅ Ge ₁₀	E229	4 hr at 600°C+ 5 hr at 700°C	6.061	8.926	Tetragonal	U ₃ Si type	90.8	—	5.4 Ga 3.8 Ge
U ₃ Si ₂	D259A	As-cast	7.345	3.885	Tetragonal	U ₃ Si ₂	92.7	7.3	—
U ₃ Si	D193-194	72 hr at 800°C & Cold Worked	—	—	Tetragonal	Blurred U ₃ Si	96.0	4.0	—
U ₃ Si ₂	D187-192	As-cast	7.327	3.900	Tetragonal	U ₃ Si ₂	92.5	7.5	—

^aSee Appendix D (Chemical Analyses) for balance of elements not listed.

To have the analytical data represent the powder actually used in the fuel plates, nearly all samples submitted to the ACL were of the 85% -100+325 mesh (-149 μ m + 44 μ m), 15% -325 mesh (-44 μ m) ratio. In a very few instances, a portion of an as-arc-cast ingot was submitted for analysis. This was sometimes done when a new fuel alloy (e.g., UAl₂) was being made for the first time and a corroboration of the intended composition was desired.

For the Al powder analyses, samples were submitted in as-received condition, as well as after vacuum degassing at $\approx$ 500°C. In all cases, the powder was sieved -100 mesh (<150 μ m), although the supplier's data indicate that at least 85% of the powder is -325 mesh (<45 μ m).

The 6061 Al was analyzed in as-received condition after appropriate cleaning to remove oxide and oil.

The target compositions are listed in Table 2. The target silicon weight percent for U₃Si was 4.0. This is slightly higher than the stoichiometric composition (3.78 wt.%);* The average of nine analyses was 3.93 wt.% Si. Thus, there was a Si loss of $\approx$ 2% and charges should be adjusted upward to compensate for this loss. The target wt.% silicon for the U₃Si₂ was 7.5; this is also slightly higher than the stoichiometric composition of 7.29 wt.% silicon. The average of five analyses gave a value of 7.50 wt.% silicon. Thus, no corrections are necessary for silicon losses in U₃Si₂.

To simplify examination of the data for the interstitials (H-O-N), Table 8 has been generated from Appendix D, which lists the complete chemical analysis data. The values for oxygen show that all the listed compounds, except for U₃Si₂ and USi, absorb appreciable amount of oxygen. This result was confirmed by our observation of the powdered materials. Table 9 gives the weight gains for U₃Si₂ powder exposed to air for times up to 406 h. U₃Si₂ powder was bright and shiny after the test, and previously made powder remained "metallic" even after years of storage in air. The other fuels were noticeably brown immediately after fabrication, and this supports the oxygen analysis results.

*At its experimentally determined composition, 3.9 wt.% Si, U₃Si actually contains 1.03 atoms of Si for every three atoms of U.

Table 8. H-O-N analyses of ANL-generated RERTR fuel powders

Fuel Type	No. of Independent Analyses	How Comminuted	Average Range (ppm by weight)		
			Hydrogen	Oxygen	Nitrogen
U ₃ Si	6	Shatterbox-Lab environment	22(15-30)	4600(3400-5900)	341(240-605)
U ₃ SiCu	2	Shatterbox-Lab environment	20(8-40)	3800(3600-4000)	300(220-490)
	2	Motorized mullite mortar & pestle. N ₂ glovebox ^a	15(14-17)	12,800(12,200-13,400)	590(480-700)
U ₃ Si _{1.5}	2	Steel mortar & pestle N ₂ glovebox	10(8-12)	3100(2200-4000)	250(140-370)
U ₃ Si ₂	4	Steel mortar & pestle N ₂ glovebox	6(5-9)	430(315-560)	90(66-120)
USi	3	Steel mortar & pestle N ₂ glovebox	3(0-5)	407(350-470)	230(165-280)
UAl ₂	1	Steel mortar & pestle N ₂ glovebox	22	4500	5900
U ₆ Fe	2	Steel mortar & pestle N ₂ glovebox	20(15-26)	2300(2300)	138(120-160)
U ₆ Mn _{1.3}	3	Shatterbox-Lab environment	10(0-20)	3300(1400-4600)	330(107-495)

^aPowders demonstrated to have a surface coating of Al₂O₃ and SiO₂ picked up from mullite mortar and pestle.

Table 9. Mass of U_3Si_2 powder as a function of time of exposure to laboratory air^a (g)

Time in Air (h)	+100 Mesh ($>150\ \mu m$)	100 + 325 Mesh ($<150\ \mu m >45\ \mu m$)	-325 Mesh ($<45\ \mu m$)
0	619.34	243.08	181.076
24	619.34	243.07	181.069
48	619.33	243.07	181.067
72	619.33	243.07	181.067
144	619.31	243.05	181.056
168	619.31	243.05	181.051
216	619.30	243.04	181.042
240	619.30	243.04	181.044
336	619.31	243.04	181.046
406	619.29	243.02	181.044
Net Change (%)	-0.008	-0.02	-0.02

^a $U + 7.5\ wt.\% Si$ powder, produced in a once-through, high-purity nitrogen atmosphere glovebox.

2.7 Summary of Miniplate Data

During the RERTR Program, 328 miniplates (including 260 intended for irradiation in the ORR) and 12 full-size plates were fabricated at ANL. Table 10 gives a brief summary of some important characteristics of the 260 miniplates fabricated for irradiation. More-detailed information for each of these 260 miniplates is given in Appendix E.

Thirteen fuel types were studied. Seven of these were from the list of screening candidates given in Table 1. Fig. 13 gives the distribution of fuels for the first 70 miniplates, where one sees that the emphasis was on the highest-density U-Si compound and on a more-corrosion-resistant alloy

Table 10. Summary of miniplate characteristics for irradiation in ORR

Fuel Type	Enrichment	Uranium Density (g/cm ³)	Meat Porosity (Vol.%)	Number of Plates
U ₃ SiAl	LEU	4.50 - 4.68	5.9 - 9.4	16
	LEU	5.61 - 5.90	10.3 - 18.0	9
	LEU	6.11 - 6.33	11.7 - 20.0	8
	LEU	6.41 - 6.67	14.3 - 20.9	5
	LEU	6.88 - 7.07	16.9 - 19.5	12
U ₃ Si	DU	6.09 - 6.18	8.2 - 9.6	2
	LEU	2.92 - 2.92	2.1 - 2.4	4
	LEU	4.72 - 4.83	4.9 - 7.2	20
	LEU	5.65 - 5.73	16.3 - 17.6	6
	LEU	6.05 - 6.16	14.0 - 15.6	6
	LEU	6.23 - 6.42	10.3 - 12.1	10
	LEU	6.47 - 6.73	9.6 - 11.5	4
	LEU	6.92 - 7.26	12.0 - 15.8	10
	MEU	4.51 - 4.52	4.2 - 4.4	2
	MEU	5.79 - 5.91	13.7 - 15.3	2
	MEU	6.23 - 6.40	9.7 - 12.0	4
	HEU	1.98 - 1.99	1.7 - 1.8	2
U ₃ Si ₂	DU	4.75 - 4.77	7.6 - 8.1	2
	LEU	3.72 - 3.77	4.1 - 5.2	8
	LEU	4.92 - 5.22	8.2 - 13.5	20
	LEU	5.59 - 5.67	12.4 - 13.5	8
	MEU	3.94 - 3.95	4.2 - 4.3	2
	MEU	4.91 - 5.18	11.0 - 15.7	4
	HEU	1.66 - 1.66	0.8 - 0.8	2
USi	DU	3.71 - 3.82	9.2 - 11.8	6
	LEU	3.78 - 3.90	7.3 - 10.3	6
	MEU	3.81 - 3.91	7.3 - 9.4	6

Table 10. (Contd.)

Fuel Type	Enrichment	Uranium Density (g/cm ³)	Meat Porosity (Vol.%)	Number of Plates
U ₃ SiCu	LEU	5.31 - 5.41	11.7 - 13.3	4
(Mullite-Coated)	LEU	5.72 - 5.82	14.7 - 15.9	2
	MEU	3.78 - 3.80	5.7 - 6.1	2
U ₃ SiCu	LEU	5.94 - 6.13	9.9 - 13.0	4
(Uncoated)	LEU	6.73 - 7.03	15.0 - 16.7	6
	MEU	4.11 - 4.15	3.8 - 4.8	2
U ₃ Si _{1.5}	LEU	5.07 - 5.17	12.6 - 14.3	4
	LEU	5.83 - 5.96	18.3 - 20.2	2
	MEU	3.84 - 3.91	8.3 - 10.0	2
UAl ₂	MEU	2.95 - 2.99	17.8 - 18.8	4
U ₆ Fe	DU	6.91 - 7.10	8.5 - 10.9	2
	LEU	7.03 - 7.26	10.7 - 13.5	2
	LEU	7.76 - 8.02	13.7 - 16.5	6
U ₆ Mn _{1.3}	LEU	6.89 - 7.12	13.2 - 16.0	4
	MEU	6.19 - 6.35	13.0 - 15.2	4
U ₃ Si _{1.6}	LEU	3.59 - 3.67	9.0 - 10.0	4
(As-Cast)	LEU	4.70 - 4.77	14.2 - 16.8	4
U ₃ Si	LEU	4.63 - 4.73	11.6 - 12.8	4
(As-Cast)	LEU	5.21 - 5.28	15.0 - 17.0	4
U ₇₅ Ga ₁₅ Ge ₁₀	LEU	2.70 - 2.73	7.6 - 8.5	4
U ₇₅ Ga ₁₀ Si ₁₅	LEU	2.78 - 2.83	6.2 - 8.0	4

containing about 1.5 wt.% Al, designated U_3SiAl . After the first irradiation results showed that U_3SiAl was particularly prone to breakaway swelling and that U_3Si_2 was quite stable under irradiation, there was a shift in emphasis toward U_3Si and U_3Si_2 . As can be seen from Fig. 14, which plots the distribution of fuels for the second series of miniplates, the latter two fuels received the major portion of the effort. The other U_3Si variants listed were studied in an attempt to find a fuel which was both more stable than U_3Si and more dense than U_3Si_2 . The U-Ga-Ge and U-Ga-Si alloys were intended for use in the wire-concept plates discussed in Section 2.13. The miniplates discussed here, however, contained particles rather than wires and were intended to provide basic irradiation performance data for these fuels. Figure 15 shows the range of the fuel volume fraction in the fuel meat of the plates studied.

Fig. 13. Distribution of miniplates by fuel type: initial studies

Fig. 14. Distribution of miniplates by fuel type: later studies

Fig. 15. Range of fuel loadings (vol.%) fabricated; listed by fuel type

2.8 Physical Properties of Fuel, Cladding, and Matrix

2.8.1 Densities of Fuels in Ingot Form

Table 11 contains a list of the experimentally measured immersion densities for various fuels that were studied at ANL. These density determinations were made by the Archimedes Principle, i.e., the liquid-displacement method. The condition of the sample is also listed. All measurements were made on ingot-size samples. The main purpose in determining these values is to calculate the volume percent fuel for each plate. By knowing the density of the fuel, we could safely stay within the boundaries of the fabrication limits for powder-metallurgy fuel plates. No information on powder density is reported here.

2.8.2 Microhardness of Fuels in Ingot Form

Microhardness measurements were made on metallographically mounted specimens, and data (reported in Vickers diamond pyramid hardness) are recorded in Table 12. None of the fuels listed was "single" phase. The closest compounds to the given weight percents are used for convenience. Reference to Section 2.4 of this report on phases should be made to determine the amount of phase present for each ingot.

2.8.3 Microhardness of Fuel, Cladding, and Matrix in Unirradiated Plates

In the fuel alloy development work at ANL, the ingots were comminuted to $<150\text{-}\mu\text{m}$ powder for use as a dispersed phase. It was therefore of interest to measure the hardness of unirradiated fuel powders, as well as of the clad and matrix. This information served as a baseline for postirradiation examination (PIE) studies. Table 13 lists the microhardness data from a number of metallographically sectioned miniplates.

2.8.4 Porosities of Unirradiated Fuel Plates

The porosity content of dispersion fuel plates is of major importance to fuel fabricators. Two key variables of interest are fuel type and volume percent fuel. With the accumulation of data on the various fuels studied over the length of the RERTR program, some general trends for fuel-zone porosities of dispersion fuel plates can be observed. This section

Table 11. ANL fuel density data

Fuel Formula ^a	ANL Target Composition (wt.% U)	Other Elements (wt.%)	Experimentally Measured Immersion Density (g/cm ³)	Fuel U Density ^b (Total g U/cm ³)
U ₃ Si	96.0	4.0 Si	15.2 ^c 14.6 ^d	14.59 14.02
U ₃ Si _{1.5}	94.5	5.5 Si	13.7 ^c	12.95
U ₃ Si _{1.6}	94.0	6.0 Si	13.0 ^d	12.22
U ₃ Si ₂	92.5	7.5 Si	12.2 ^d	11.28
USi	89.4	10.6 Si	10.9 ^d	9.74
U ₃ SiAl	95.0	3.5 Si + 1.5 Al	14.2 ^c	13.49
U ₃ SiCu	95.8	4.0 Si + 0.17 Cu	15.2 ^c	14.57
UAl ₂	80.0	20.0 Al	7.9 ^d	6.32
U ₆ Fe	96.0	4.0 Fe	17.4 ^d	16.70
U ₆ Mn _{1.3}	93.7	6.3 Mn	16.8 ^d	15.70
U ₇₅ Ga ₁₀ Si ₁₅	94.1	3.7 Ga + 2.2 Si	15.6 ^e	14.68
U ₇₅ Ga ₁₅ Ge ₁₀	91.0	5.3 Ga + 3.6 Ge	15.8 ^e	14.38

^aFormulas should not be taken literally. Although some target compositions may be nearly single phase and may be very close to the formula composition, the notation is simply a convenient way to describe a particular alloy.

^bDensity x weight fraction U.

^cAfter heat treatment of 72 h at 800°C.

^dAs-arc-cast.

^eAfter heat treatment of 96 h at 800°C.

summarizes the porosity data of unirradiated fuel plates generated during the program at ANL. Preliminary trends of the data are included in Ref. 17.

In calculating porosities and fuel-zone volumes, no "corrections" have been applied to compensate for any reaction between the silicide and the matrix and clad. For unirradiated plates, there is no evidence for any

Table 12. Microhardness of fuels

Ingot No.	Designation Composition ^a	Ingot Condition	Load	Diamond Pyramid Hardness		No. of Indentations
				Avg.	Range	
D157	U ₆ Fe (DU) [4.13 wt.% Fe]	As-arc-cast piece	50	538	487-608	8
			100	552	530-579	7
			500	525	494-538	
D157	U ₆ Fe (DU) [4.13 wt.% Fe]	Arc-cast piece annealed 650°C-168 h, w.q. ^b	50	519	498-575	7
			100	543	508-572	7
			500	506	485-522	7
D157	U ₆ Fe (DU) [4.13 wt.% Fe]	Arc-cast ingot piece annealed 700°C-168 h, w.q. ^b	50	498	441-570	7
			100	484	468-503	7
			500	516	504-533	7
D166	U ₃ Si (DU) [4.0 wt.% Si]	As-arc-cast annealed 72 h-at 800°C, air cooled)	500	541	516-591	5
			500	265	249-271	5
D168	U ₃ Si _{1.5} (DU) [5.6 wt.% Si]	As-arc-cast annealed 72h-at 800°C, air cooled	500	658	646-677	5
			500	438	330-524	5
D171	U ₃ Si ₂ (DU) [7.5 wt.% Si]	As-arc-cast annealed 72 h-at 800°C, air cooled	500	699	673-719	5
			500	694	638-723	5
E201	U ₃ SiCu (LEU) [3.99 wt.% Si + 0.18 wt.% Cu]	Arc-cast piece annealed 800°C, 72 h-air cooled	500	306	283-365	8

Table 12. (Contd.)

Ingot No.	Designation Composition ^a	Ingot Condition	Load	Diamond Pyramid Hardness		No. of Indentations
				Avg.	Range	
E202	U ₃ SiCu (LEU) [3.99 wt.% Si + 0.17 wt.% Cu]	Arc-cast piece annealed 800°C 72 h-air cooled	500	288	269-334	8
D203	USi (DU) [10.40 wt.% Si]	As-arc-cast	100	1021	980-1048	4
			500	704	654-750	5
E204	USi (LEU) [10.48 wt.% Si]	As-arc-cast	100	968	868-1070	4
			500	739	720-765	5
E205	USi (MEU) [10.48 wt.% Si]	As-arc-cast	100	918	842-980	4
			500	786	732-840	5
D228	U ₆ Mn (DU) [4 wt.% Mn]	As-arc-cast	500	469	464-475	5
D228	U ₆ Mn (DU) [4 wt.% Mn]	Annealed 675°C 168 h- air cooled	500	482	460-506	7
E229	U ₇₅ Ga ₁₅ Ge ₁₀ (LEU) [5.3 wt.% Ga + 3.7 wt.% Ge]	Annealed 800°C 96 h- air cooled	500	190	177-197	7
E230	U ₇₅ Ga ₁₀ Si ₁₅ (LEU) [3.7 wt.% Ga + 2.2 wt.% Si]	Annealed 800°C 96 h- air cooled	500	213	207-216	7

Table 12. (Contd.)

Ingot No.	Designation Composition ^a	Ingot Condition	Load	Diamond Pyramid Hardness		No. of Indentations
				Avg.	Range	
D235	U ₆ Mn _{1.3} (DU) [6.18 wt.% Mn]	As-arc-cast	50	628	613-644	4
			500	560	544-585	5
E236	U ₆ Mn _{1.3} (LEU) [6.08 wt.% Mn]	As-arc-cast	50	562	509-593	5
			500	519	511-528	5
E237	U ₆ Mn _{1.3} (MEU) [6.11 wt.% Mn]	As-arc-cast	50	552	540-575	5
			500	501	497-509	5

^aDU = depleted uranium; LEU = low enrichment uranium; MEU = medium-enriched uranium.

^bw.q. = water quenched

Table 13. Summary of hardness data for unirradiated plates

Material ^a	Plate Condition	Diamond Pyramid Hardness, 50-g load ^b		No. of Indentations
		Avg.	Range	
6061 Clad	O-Temper	48	42-56	21 ^c
6061 Clad	≈15-20% cold work	94	87-102	21 ^c
MD101 Al Matrix	O-Temper	38	32-47	22 ^c
MD101 Al Matrix	≈15-20% cold work	53	49-56	7
U ₃ SiAl				
(large particles)	O-Temper	400	362-453	7
(small particles)		530	381-655	5
U ₃ SiAl				
(large particles)	≈15-20% cold work	475	425-522	7
(small particles)		489	400-500	7
U ₃ Si				
(large particles)	O-Temper	458	340-584	8
(small particles)		640	441-810	7
(large particles)	≈19% cold work	404	321-453	18 ^c
U ₃ Si ₂				
(large particles)	O-Temper	728	666-841	8
(large particles)	≈19% cold work	782	644-874	6

^aThe difference between large and small was arbitrarily set at large particle size ≈150 μm + 100 μm, small particle size ≈100 μm

^bLeitz Miniload microhardness tester, 50-g load.

^cMeasurements made on several samples from different plates.

significant reaction of this type. Early in the work, the fuel-zone growth observed to occur during 0-tempering was ascribed to the formation of less-dense phases during such a reaction. This may not be true. Fuel-zone growth during the prolonged 0-temper anneal may be the result of gases being released and of clad creeping (see Section 2.11, Compatibility Tests).

The results are shown in Fig. 16. Each data point is an average of 2 to 18 individual plate measurements. All of the data plotted are for 0.020 in. (0.51 mm) aluminum matrix fuel plates only. A complete listing of the data used to generate Fig. 16 is given in Table 14. The trend of increasing voids with increasing volume percent of fuel is completely consistent with the results of a definitive study of U_3O_8 and UAl_x dispersed-phase fuel plates conducted at ORNL by Martin and Martin.¹⁸ The work described in that reference was confined to fuel contents of up to ≈ 35 vol.%; all porosity values were $<10\%$. The trends shown in Fig. 16 are likewise consistent with those reported by Copeland and Martin.¹⁹ The Copeland and Martin data are for U_3O_8 plates at loadings up to ≈ 50 vol.%; none of the porosity values exceed 12%.

Fig. 16. Percent porosity versus volume percent for various fuels

Table 14. Summary of porosity data by fuel

Fuel	Nominal Vol.% Fuel	U Loading (g/cm ³)	No. of Plates	Percent Porosity in Fuel Zone (as fabricated)			
				Avg.	High	Low	
<u>Miniplates</u>							
U ₃ Si _{1.5}	30	3.8	2	9.1	9.9	8.3	
	40	5.1	4	13.4	14.3	12.6	
	46	5.9	2	19.3	20.2	18.3	
USi	39	3.8	18	9.3	11.8	7.3	
U ₃ SiCu	27	3.8	2	9.5	9.6	9.3	
Mullite	38	5.4	4	18.5	19.4	17.9	
Coated	41	5.7	2	21.9	22.6	21.2	
U ₃ SiCu	28	4.1	2	4.3	4.8	3.8	
	42	6.0	4	10.9	12.9	9.9	
	48	6.9	6	15.5	16.7	14.4	
U ₃ SiAl	34	4.5	4	6.6	7.6	5.6	
	0-Temper	34	4.5	10	6.5	9.4	5.9
	0-Temper	44	5.7	4	11.8	14.5	10.3
		46	6.0	10	12.4	13.9	11.7
		49	6.3	6	14.9	15.9	14.3
		51	6.4	4	16.0	16.3	15.1
		53	6.9	4	17.1	17.6	16.9
		54	7.0	6	18.3	19.5	17.4
U ₃ Si	14	2.0	2	1.7	1.8	1.6	
	20	2.9	4	2.3	2.4	2.1	
	31	4.5	2	4.4	4.4	4.3	
	34	4.8	8	5.0	5.6	4.5	
	40	5.7	2	12.8	13.0	12.5	
	41	5.8	6	12.7	13.0	12.5	
	42	6.1	2	8.9	9.6	8.2	
	43	6.2	6	11.3	12.1	10.5	
	(Thin) ^a	43	6.3	4	10.8	12.0	9.7
		44	6.4	6	10.8	12.1	9.6
		46	6.7	2	10.9	11.5	10.2
		48	6.9	2	12.3	12.7	11.9
		49	7.2	10	15.0	16.1	12.7
U ₃ Si ₂	13	1.7	2	0.8	0.8	0.8	
	33	3.8	8	4.4	5.0	4.0	
	35	4.0	2	4.3	4.3	4.2	
	40	4.5	16	8.4	11.5	6.6	
	42	4.8	2	7.9	8.1	7.6	
	45	5.1	10	10.0	10.5	9.5	
	(Thin) ^a	46	5.2	2	11.4	11.8	11.0
	(Thick) ^a	46	5.2	4	8.7	9.1	8.2
		50	5.6	8	13.0	13.5	12.4

Table 14. (Contd.)

Fuel	Nominal Vol.% Fuel	U Loading (g/cm ³)	No. of Plates	Percent Porosity in Fuel Zone (as fabricated)		
				Avg.	High	Low
U ₆ Fe	42	7.0	2	9.8	11.0	8.5
	43	7.1	2	12.1	13.5	10.7
	47	7.9	7	15.5	16.8	13.7
UAl ₂	48	3.0	4	18.4	18.9	17.8
U ₆ Mn (Thin) ^a	40	6.3	4	14.3	15.2	13.0
	45	7.1	4	14.7	16.0	13.2
U ₃ Si (As-cast)	34	4.8	4	11.9	12.7	11.5
	(As-cast) 38	5.3	4	15.9	16.6	14.9
U ₃ Si _{1.6}	30	3.7	4	9.5	10.0	9.0
	39	4.8	4	15.4	14.2	16.8
	40	4.9	8	16.2	20.6	13.9
6061 Matrix U ₃ Si (Thin) ^a	40	5.8	2	14.6	15.4	13.7
	42	6.1	4	14.9	15.6	14.0
6061 Matrix U ₃ Si (Thin) ^a	44	5.0	5	12.8	13.5	12.2
	44	5.0	2	15.3	15.7	14.8
<u>Full-Size Plates</u>						
Tungsten	39	—	2	4.3	4.3	4.3
U ₃ Si	36	5.1	1	6.7	6.7	6.7
U ₃ SiAl	20	2.7	2	2.6	2.8	2.4
	38	5.0	3	8.3	8.7	7.9
	46	6.1	2	12.7	12.7	12.6

^aThin = 0.030 in. (0.76 mm); Thick = 0.013 (0.32 mm).

It appears that there is one curve (or envelope) for U_3Si_2 , a second (higher) curve for U_3Si , and a third higher curve for $U_3Si_{1.5}$. While plate porosities cannot be read to fractions of a percent from the plot, it certainly is possible to be semiquantitative in assessing the porosity of any plate for any given fuel and volume fraction.

Another point worth noting concerns the volume percent of fuel. Many of the ANL tables list the volume of fuel as a percent of the total volume of the compact. The volume percent of fuel in a finished plate may be larger or smaller than this number, depending on the porosity present in the finished plate. However, when grams U per cm^3 in a fuel zone are recorded, the actual volume of the fuel zone — as calculated from immersion density measurements — was used and divided into the grams U weighed out as fuel for that particular plate. These points are raised because, for example, the individual plate data sheet will indicate a volume percent of fuel in the plate when in fact the volume percent of fuel figure listed is for the compact used to produce the plate. In a few instances, actual volume percent of fuel in the fuel zone of a finished plate have been back-calculated. The data for these have been identified.

Density values for the fuels are necessary to calculate the porosity values for the finished unirradiated plates. The values (in g/cm^3) used to generate the information in Table 14 are:

U_3Si	-	15.2	$U_3Si_{1.5}$	-	13.7
U_3Si_2	-	12.2	U_6Fe	-	17.4
U_3SiAl	-	14.2	UAl_2	-	7.9
U_3SiCu	-	15.2	USi	-	10.9

2.9 Metallography Results and Interpretation

2.9.1 Fuels in Ingot, Powder, and Plate Form

The metallography of uranium silicides has been documented in previous references: the fuels U_3Si , U_3Si_2 , and U_3SiAl were covered in Ref. 20, while microstructures of a series of fuels from U_3Si through U_3Si_2 were presented in Ref. 15. For a general description, Figs. 17-19 show the microstructure of U_3Si , $U_3Si_{1.5}$, and U_3Si_2 . The " U_3Si " in Fig. 17 is two-phase. The major phase is U_3Si and the second, lesser phase is U_3Si_2 . The reason for this two-phase structure is that this fuel contains more than the

calculated stoichiometric amount of Si (3.78 wt.%). All the "U₃Si" made at ANL was actually two-phase. As the Si is increased to 5.6 wt.%, the amount of U₃Si₂ in the microstructure increased, as shown in Fig. 18. The microstructure for 7.5 wt.% Si (Fig. 19) is almost 100% U₃Si₂ with a small amount of USi. The indicated weight percents of Si are for the arc-melt-charge weights. These alloys were not analyzed after melting and are probably slightly lower in Si.

2.9.2 General Defects of Rejected Fuel Plates

During the miniplate production for the RERTR program, a small number of defective plates were produced. Many of the defects are common to any type of roll-bonded fuel plate. A general description of each defect is given below, along with a photographic example of the described defect. It should also be noted that many of the defects are related and are caused by one another or by a common factor.

Blisters. Blisters are a common problem experienced when fabricating powder-metallurgy fuel plates. They usually appear as round (but sometimes elliptical or irregular) raised areas on the fuel plate surface. They can occur during rolling but are seen more often after the blister test and are caused by gas. One source is adsorbed gas on the powder, which is driven off during hot rolling. A second source could be excess lubricant on the compact, which would also volatilize at the hot rolling temperatures used. Fig. 20 shows a typical large blister. Most blisters detected were less than 0.1 in. (2.5 mm) in diameter. Degassing the powder usually eliminates the problem. The powder can be degassed at 500°C for 2 hr at 10⁻⁵ torr or less (1.3 mPa), the compact can be degassed at 300°C for 4 hr at 10⁻² torr or less (1.3 Pa), or both compact and powder can be degassed.

Fuel Plate Specifications Deviations: Dogboning, Clad Thinning, and Fuel Particles Out-of-Zone. Certain specifications had to be met for insertion of miniplates into the ORR. A minimum clad thickness was specified, along with a fuel zone area. Dogboning, clad thinning and fuel-out-of-zone are deviations from these specifications. These three defects are related in that clad thinning and fuel-out-of-zone usually occur with dogboning. Dogboning results when a soft clad is rolled over a hard core. The cladding tends to deform and the core tends to resist deformation. The end result is a core

Fig. 17. U + 4.0 wt.% Si. Annealed for 72 h
at 800°C

Fig. 18. U + 5.6 wt.% Si. Annealed for 72 h
at 800°C

Fig. 19. U + 7.5 wt.% Si. As-arc-cast

Fig. 20. Rollbonded fuel plate with typical blister

with a thick area at each end, which resembles a bone, and a thinned cladding. As the volume percent fuel is increased, the core becomes harder and the cladding begins to deform more than the core. This effect is greatest at the ends of the core and becomes an appreciable quality concern somewhere between 35–40 vol.% fuel. On a macro scale, severe clad thinning can be detected as a wrinkling on the surface of the fuel plate. An example of this effect is shown in Fig. 21. After microscopic examination, the dogbone and clad thinning are much more visible (Fig. 22).

Increased rolling stresses generated by the increased resistance to deformation cause fuel to be forced between the frame and the covers. This is a common source and location of fuel-out-of-zone. An example of dogboning and fuel-out-of-zone is seen in the two "tails" at the end of the fuel zone in Fig. 23. Fig. 24 is a higher magnification of the interface zone. It can be seen that particles are forced well beyond their normal location. Another common name for fuel-out-of-zone is "white spots," because the relatively few individual particles or "spots" can be seen on a radiograph of the fuel plate.

The solution to this problem was to accept the limitations of the fuel/matrix system. For conventional rolling processes, volume percent fuel loading is usually limited to 45. In the European community, stronger cladding/frame materials are used and the effect of dogboning is slightly lessened. A comparison of the differences in the fabricator's alloys to see if there is any correlation between alloy hardness and uniformity of fuel loading would be an interesting study.

Here is one final comment on fuel-out-of-zone. An accepted practice is to have the compact thicker than the frame. This could lead to increased fuel-out-of-zone due to the gap between the cover plate and the frame. Why is it necessary to have the compact thicker than the frame before making the first rolling pass? If both were the same thickness, then would the amount of fuel-out-of-zone be reduced without any change in the plate's quality? This too would be an interesting study.

Fig. 21. Example of cladding thinning at high loading

Fig. 22. Rupture of cladding caused by excessive dogboning; $\approx 50 X$

Fig. 23. Example of dogboning and fuel out-of-zone in highly loaded miniplate

Fig. 24. Higher magnification of fuel out-of-zone

Raised Areas. These defects appear as random irregular small shapes that are slightly higher (thicker) than the rest of the plate. They are caused by the occasional larger-maximum-mesh-size particle that passes through the sieving screen. These particles are usually needlelike in shape. The result after rolling is an area where the percent fuel is very high and most of the deformation is accommodated by the cladding. This defect could be also described as localized dogboning. The result is a raised area and clad thinning above this area. An example of a cross section of a raised area showing the large particle is given in Fig. 25. This problem was minimized by double-sieving all fuel powder before use.

Oxidation of Fuel Particles. Because all of the uranium-silicides studied are pyrophoric, oxidation of fuel is a common problem. The source of this oxide is contact of the powder at a elevated temperature with oxygen. Common conditions for this are (1) improper welding of assemblies by not using chill blocks; (2) compacts that are too thick for tight fit of covers and frame, thus allowing excess oxygen to reach the fuel during preheating for rolling; and (3) exposure to oxygen during powder fabrication. Under metallographic examination, an oxidized particle has a gray appearance and the oxidation is usually limited to the outer surface of the particle, although severe exposure to oxygen can oxidize the entire particle. Fig. 26 illustrates typical oxidized fuel in the core.

Fig. 25. Cross section of raised area showing large particle that caused the defect

Fig. 26. Oxidized fuel particles in miniplate; $\approx 1000 \times$

This problem was solved by fabricating the powders in an inert-atmosphere glovebox and by careful processing to minimize the exposure of the fuel plate assembly to air during welding and hot rolling.

2.10 Aqueous Corrosion Tests

2.10.1 Introduction

To provide aqueous corrosion data for fuels used in ANL-fabricated miniplates, tests were run with deliberately defected plates. The procedures in the first several experiments were, to the best of our ability to duplicate them, identical to those used at ORNL on plates made with fuels other than those described here. The data recorded here were accumulated over a seven-year span. During this time, personnel and — to some extent — procedures changed. Experience tended to improve the setup and more information was collected for the most recent tests. All aqueous corrosion data generated at ANL during the RERTR program are recorded in this section.

2.10.2 Materials and Experimental Procedures

All experiments were conducted by suspending one plate with Al or 6061 Al wire in boiling distilled water in either a large (2-L) beaker or a wide-mouth (2-L) Erlenmeyer flask. The beakers, flasks, and glass boiling beads were either new for each test or were thoroughly cleaned between tests. Provisions were made to automatically replenish water lost by boiling and evaporation. Each plate was totally submerged for the life of the test except for brief withdrawals for weighing and inspection.

Plates were either "minis," fabricated to standard ORNL-RERTR specifications (procedures and plate dimensions are recorded in Ref. 21), or "compatibility study" plates fabricated with a round compact that resulted in an elliptical fuel zone after rolling (procedures and plate dimensions are recorded in Ref. 22). Plate thicknesses were nominally either 0.050 or 0.060 in., (1.27 or 1.52 mm) depending on the choice of plate for the test. The clad for all plates was 6061 Al; the fuel zone matrix Al powder was degassed ALCAN 101. Fuel zone thickness for all tested plates was nominally 0.020 in. (0.51 mm). Most plates were made with fuels based on depleted U, but some were LEU fuel plates. The choice was based on availability and willingness to sacrifice the plate. All plates were made with

85% of the fuel in the -100 +325 mesh size ($<150\text{ }\mu\text{m}$, $>45\text{ }\mu\text{m}$) and 15% of the fuel as -325 mesh ($<45\text{ }\mu\text{m}$) powder.

With one exception, the plates used for these experiments had a No. 30 drill hole (0.1285 in. diameter, 3.264 mm) penetrating the thickness of the plate at approximately the midpoint of the fuel zone. The exception was one plate containing U_6Fe . We only had one such miniplate to use for this test and it had been longitudinally sectioned for metallographic studies. This was the most severe test because the full length of the fuel zone was exposed to the boiling water. For plates with the drilled hole, $\approx 0.008\text{ in.}^2$ (5.2 mm^2) of fuel zone area was exposed to the boiling water. For the U_6Fe plate, the exposed fuel zone area was $\approx 0.08\text{ in.}^2$ (52 mm^2), or 10 times the area exposed in the drilled plates.

All plates, again with the exception of that containing U_6Fe , were given a light Oakite-160 dip, followed by a nitric acid + water dip, followed in turn by a rinsing in boiling distilled water. This chemical cleaning was done before the hole was drilled and was conducted so that all tests would be run with plates of uniform surface condition.

The water container was heated with an electric hot plate controlled by the input from a variable transformer. Settings were maintained to provide constant nucleate boiling in the glass beads at the bottom of the container. Temperatures were measured by either a conventional thermometer (early tests) or by a digital-readout thermistor thermometer. Because boiling was initiated at the bottom of the beaker or flask and the temperature was measured adjacent to the fuel plate, which was about halfway up the container, the measured temperatures were always $\approx 98^\circ\text{C}$.

Each plate was weighed to the nearest milligram before the test began and was withdrawn periodically (usually twice) and weighed during the 168-h duration of the exposure. Only the time in the boiling water was counted toward the 168-h total. Plate thickness measurements were likewise made before, during, and at the conclusion of the test.

In one case after a test was completed, the plate was placed in an air-environment laboratory oven at $\approx 180^\circ\text{C}$ for a short time. In other instances, the plates were placed in a vacuum desiccator at room temperature for times up to 66 h. This was done to see if water was absorbed (or adsorbed)

into the fuel zone and, if so, whether it could be driven out by either procedure.

2.10.3 Results and Discussion

Table 15 is a summary of the most important data for the nine plates tested, including "DM-86," a miniplate-sized piece of as-cold-rolled 6061 Al cut from the excess material of a miniplate assembly. This plate served as a reference control and also had a hole drilled through its approximate center.

To maintain readability, specific data for the fuels used in the test plates are recorded separately in Table 16. There is no reason to believe that the use of LEU or DU would have any effect on the test results. However, the use or absence of a heat treatment of the fuel before comminution might have an effect on fuel dissolution during the test. In particular, uranium solid solution (U_{SS} , or "free" uranium) would be expected to react with boiling water more readily than any of the uranium compounds. It is known that by design, U_{SS} exists in the plates containing as-cast " U_3Si " and " $U_3Si_{1.6}$." Likewise, it might be expected that an O-tempered plate might not behave exactly like a similar plate in the as-cold-rolled condition.

Table 17 summarizes measurements — some qualitative, some quantitative — of the level of activity either on the plate or in the water after the test was completed. In the earliest tests, loose activity on a plate or dissolved uranium in the water was "detected" by smearing a plate with a paper tissue or dipping a cotton swab in the water, allowing the tissue or swab to dry, and determining the presence of any activity by holding the tissue or swab to a hand-and-foot monitor. Such determinations were crude and the results might be questionable. In later tests, quantitative data were generated by direct measurements on water sent to ANL's Analytical Chemistry Laboratory (ACL). In the case of the U_6Fe plate (DUMF-48-84R), the 2 L of water remaining in the Erlenmeyer flask after the test was concluded was filtered twice through laboratory filter paper, and both filter papers, as well as the filtered water, were analyzed for U. The data recorded in Table 17 for this plate represent the level of dissolved U in the twice-filtered water. The first filter paper was found to contain 757 μg of U, while the second filter paper contained 238 μg of U. It is presumed that these values represent very small particles of fuel that had been suspended in the water.

Table 15. Summary of boiling water tests of defected plates

Plate I.D.	Plate Condition	Nominal Plate Thickness (in.)	Fuel Type ^a	Vol.% Fuel in Fuel Zone	Total U in Fuel Zone (g/cm ³)	Initial Plate Weight (g)	Final Plate Weight (g)	Weight Change (g)	Plate Thickness Change (in.)
DMT-1	O-Temper	0.050	U ₃ SiAl (HT)	33.2	4.7	32.232	32.220 32.219 ^b	-0.012	None
DUMB-2A	O-Temper	0.050	U ₃ Si (HT)	30.8	4.5	32.487	32.487 ^c	None	None
MEAX-30-19R (A37)	O-Temper	0.060	U ₃ Si ₂ (HT)	33.2	3.7	30.451 ^c	30.468 ^c	+0.017	+0.0002
DUMT-52.5-30F	O-Temper	0.050	U ₃ SiAl (HT)	≈50	≈7.1	43.675 ^d	43.860 ^d	+0.185	None
DUMF-48-84R	Cold-rolled	0.060	U ₆ Fe (AC)	≈47	≈7.8	25.604	25.620 25.617 ^e	+0.016	See text
CS-160	Cold-rolled	0.060	U ₆ Mn _{1.3} (AC)	44.2	6.9	38.306	38.329 ^c	+0.023	+0.0007
CS-165	Cold-rolled	0.060	U ₃ Si (AC)	38.5	5.4	39.654	39.811 39.799 ^f	+0.157 +0.145	+0.0007
CS-167	Cold-rolled	0.060	U ₃ Si _{1.6} (AC)	40.1	4.9	38.056	38.111 ^h	+0.055	+0.0003
DM-86	Cold-rolled	0.050	None	0	0	27.439	27.439 ^h	None	+0.0003

^aHT indicates fuel heat treated before comminution; AC indicates fuel comminuted and used in as-arc-cast condition.

^bAfter 2.5 h at 180°C.

^cUnchanged after 16 to 24 h in vacuum desiccator.

^dUnchanged after ≈60 h in vacuum desiccator.

^eAfter 2 h in vacuum desiccator.

^fAfter 66 h in vacuum desiccator.

^hUnchanged after 66 h in vacuum desiccator.

Table 16. Fuels used in defected plate tests

Plate I.D.	Treatment of Fuel Type	Fuel before Comminution	Uranium Enrichment	Analysis (wt.%) ^a	Phases Present in Fuel Microstructure ^b
DMT-1	U ₃ SiAl	800°C-72 h	DU	U + 3.49 Si + 1.46 Al	U ₃ Si + U ₃ Si ₂ + UAl ₂
DUMB-2A	U ₃ Si	800°C-72 h	DU	U + 3.95 Si	U ₃ Si + U ₃ Si ₂
A37	U ₃ Si ₂	800°C-72 h	LEU	92.27 U + 7.49 Si	U ₃ Si ₂ + USi
DUMT-52.5-30F	U ₃ SiAl	800°C-72 h	DU	U + 3.5 Si + 1.5 Al (nominal)	U ₃ Si + U ₃ Si ₂ + UAl ₂
DUMF-48-84R	U ₆ Fe	As-arc-cast	DU	U + 4.13 Fe	U ₆ Fe + UFe ₂
CS-160	U ₆ Mn _{1.3}	As-arc-cast	DU	93.21 U + 6.18 Mn	U ₆ Mn + UMn ₂
CS-165	U ₃ Si	As-arc-cast	LEU	95.80 U + 3.96 Si	U _{ss} + U ₃ Si ₂
CS-167	U ₃ Si _{1.6}	As-arc-cast	LEU	93.81 U + 6.02 Si	U ₃ Si ₂ + U _{ss}

^aAnalyzed compositions except as noted. Where no values for U are recorded, no analysis for U was conducted.

^bThe first phase listed is the dominant one.

Table 17. Other data for boiling water tests

Plate I.D.	Water before Test			Water after Test			Activity on Plate ^a	Activity in Water ^a
	Conductivity (μ mho/cm)	pH	U Content (ng/mL)	Conductivity (μ mho/cm)	pH	U Content (ng/mL)		
DMT-1	NM ^b	NM	NM	NM	NM	NM	None	None
DUMB-2A	NM	NM	NM	NM	NM	NM	None	None
A-37	NM	NM	NM	NM	NM	NM	None	None
DUMT-52.5	NM	NM	NM	NM	NM	NM	None	None
DUMF-48-84R	NM	NM	NM	NM	NM	11	See text	Yes
CS-160	NM	NM	NM	NM	NM	NM	NM	NM
CS-165	NM	NM	NM	33	7.2	24	Slight	Yes
CS-167	NM	NM	NM	42	8.55	5.9	None	Yes
DM-86	1.6	6.58	<1	42.4	8.41	NM	None	None

^aSee text.

^bNot measured

After a test, the water shows a modest increase in pH, indicating a very slightly basic condition. The electrical conductivity of the water rises as a result of the presence of new ions. These property changes are not considered significant. The U concentrations, at levels measured in nanograms per milliliter, seem very low but reactor operators or safety committees would have to make the final decision on the significance of such values.

As pointed out earlier, the U_6Fe plate was sectioned longitudinally before being used in the boiling water test. It was observed that particles from the fuel zone were deposited in the flask. A metallographic examination of a section of the boiled plate showed that corrosion of the aluminum (the corrosion path appeared to be along the matrix, not through the fuel particles) proceeded to a depth of ≈ 0.6 in. (15 mm) into the fuel zone. Nevertheless, the plate still gained 16 mg (or $\approx 0.06\%$).

For all tests conducted — including that of the piece of 6061 Al containing no fuel — plates darkened with increasing exposure to the boiling distilled water. At the conclusion of the test, each plate was quite black. The black material was adherent and could not be rubbed off except with an abrasive. No attempt was made to identify the nature of the blackened surface. The general appearance did resemble the "smut" remaining on a plate after dipping in the Oakite-160 solution (our standard chemical cleaning agent). However, the smut remaining after an Oakite dip can be removed by wiping with a tissue.

The weight changes of individual plates were generally quite small. The weight gain for the U_6Fe plate was significant when we recognize that particles had clearly been dislodged from the fuel zone. Note also that the as-cast U_3Si fuel plate had a substantial weight gain that may be associated with the presence and corrosion of U_{ss} in the fuel particles.²³

Dimensional (thickness) changes were likewise small except for the U_6Fe plate, which "opened up" to create a maximum thickness of 0.143 in. (3.63 mm) at one point. The comments regarding no thickness changes for several plates is almost certainly a reflection of the location, number, and accuracy of the micrometer readings taken on the plate after the test. That is, all plates must have shown some growth, no matter how small, as a result of the formation of hydrated Al_2O_3 .

2.10.4 Failure of Cladding during Irradiation for Uranium Silicide Fuels

Two occurrences of a breach of cladding during irradiation of a uranium silicide fuel plate are documented in the literature. ANL plate No. A211, which contained ≈ 42 vol.% of U_3Si in a 6061 Al alloy matrix, failed by a cladding rupture after a burnup of approximately 50%.²⁴ Cladding thinning, which was caused by the stronger 6061 Al matrix, was probably the starting point of the failure. A crack developed, water reacted with the fuel, a darker phase was formed, and fission products were released. No increase in ORR primary coolant activity level was measured during this time. This implies that the release rate was below the detection rate of the monitor. After reaction, breakaway swelling occurred in the fuel and caused pillowing of the plate.

The second mention of a failed uranium-silicide plate is given in Ref. 25. This $U_3Si_{1.3}$ plate was irradiated under the German AF Program. Again, failure was also initiated by cladding thinning at a point where a thermocouple was attached to the plate. It is also interesting, but perhaps not significant, to note that U_3Si was the dominant fuel in both failed plates.

Considerable corrosion of the fuel occurred during the in-reactor failures, contrary to what might have been expected from the results of the aqueous corrosion tests. Because out-of-pile corrosion tests cannot duplicate irradiation conditions such as radiolysis of the cooling water, it is obvious, therefore, that such tests are not reliable indicators of whether corrosion might occur during irradiation. In other words, passing the aqueous corrosion test only indicates possibly acceptable breach-of-cladding corrosion resistance in the pile; failing the aqueous corrosion test indicates that a fuel will have unacceptable breach-of-cladding corrosion resistance in the pile.

2.11 Compatibility Tests

Two major issues of concern were compatibility of the fuel with the aluminum matrix material and the dimensional stability of the fuel plate. The preferred response of any fuel under irradiation would be no change in volume or only a small, steady, predictable change. To develop a data base for the thermally induced expansion of U-Si dispersed in Al, smaller so-called compatibility plates (unirradiated) were heated to 400°C and their

volumetric changes were measured. A detailed report examined the volumetric changes of U_3Si , U_3SiAl , and U_3Si_2 in an aluminum matrix after heating for extended periods at $400^\circ C$.²⁶ It was found that there is a reaction between the fuel and the matrix and that its intensity varies with the fuel type and increases with the volume-percent of fuel. The cause of the growth of the silicide fuel plates was determined to be a two-step process: (1) the reaction of the uranium silicide with aluminum to form a less-dense product, $U(Al,Si)_3$; and (2) the release of hydrogen as a result of the reaction and the subsequent creep and pillowing of the fuel plate when the internal pressure within the fuel zone exceeds atmospheric pressure. Since the publication of that report, additional fuels have been tested. The results of these tests are given in Tables 18 and 19 and graphed in Fig. 27.

As a matter of interest, if an average particle size of $100\ \mu m$ is assumed, there are $\approx 1.8 \times 10^6$ fuel particles within the $2.36\ cm^3$ fuel zone of a miniplate at $\approx 40\ vol.\%$ fuel. The total surface area of these particles is $\approx 570\ cm^2$. This is a large surface area over which reactions can take place.

A later study proposed a definite relationship between the thermal response of a fuel and its response under irradiation.²⁷ Annealing studies were suggested for use as a screening test for new fuels for which no thermo-dynamic properties have been measured and/or no irradiation data are available. Based on the above concept, it appears that as-cast U_3Si and $U_3Si_{1.6}$ should have slightly poorer irradiation properties than their heat-treated counterparts. The gallinide alloys at $20\ vol.\%$ had changes in volume similar to those of U_6Fe at $41\ vol.\%$. These fuels do not appear to be very promising and would probably have demonstrated poor irradiation performance had the irradiation program not been prematurely terminated when the ORR was shut down.

2.12 X-Ray Analysis of the U-X-Al System

Because the U-Si-Al system forms an important base for much of the ANL work, a definitive study of this system was conducted and is presented in Ref. 28. Many other fuels have been tested since this 1982 reference; current data are given in Table 20. All of the studied compounds form a $U(SiAl)_3$ compound upon reaction with Al. Only the ratio of Al to Si varies with each compound.

Table 18. Thermal compatibility tests on unirradiated plates

Plate No.	Fuel Type	Vol.% Fuel	g U/cm ³ in Fuel Zone	Matrix	Fuel Zone Porosity, As-Fabricated ^a (%)	Fuel Zone Volume As-Fabricated ^a (cm ³)
CS-17 ^b	None	0	0	None	0	2.708 ^b
CS-150	U ₆ Fe ^c	40.6	7.1	MD101	11.2	0.9681
CS-157	U ₃ Si ^d	42.5	6.1	6061	15.9	0.9675
CS-159	U ₃ Si ₂ ^c	44.0	5.0	6061	14.8	0.9764
CS-161	U ₆ Mn _{1.3} ^c	44.4	7.0	MD101	14.1	0.9459
CS-162	U ₆ Mn _{1.3} ^c	43.8	6.9	MD101	15.3	0.9591
CS-163	None	0	0	6061	1.6	0.9302
CS-164	U ₃ Si ^c	38.7	5.4	MD101	13.0	0.9811
CS-166	U ₃ Si _{1.6} ^c	40.3	4.9	MD101	13.4	0.9418
CS-168	U ₇₅ Ga ₁₀ Si ₁₅ ^d	19.2	2.8	MD101	6.4	0.9924
CS-170	U ₇₅ Ga ₁₅ Ge ₁₀ ^d	18.7	2.7	MD101	8.5	1.0162

^aAssumes no fuel + Al reaction during fabrication.^bControl sample of "pure 6061" figures cited as FZ volumes are density in g/cm³.^cAs cast.^dHeat treated.Note: CS plates not fabricated with UAl₂ (as cast); U₃SiCu (heat treated); U₃Si_{1.5} (heat treated); USi (as cast).

Table 19. Percent fuel zone volume increase after time at 400°C (h), unirradiated plates

Plate No.	24	96	192	264	432	600	693	909	1053
CS17 ^a	2.708 ^a	-	2.708 ^a	-	2.708 ^a	-	2.708 ^a	2.708 ^a	2.708 ^a
CS-150	8.0	17.8	-	31.9	-	65.6	-	≈100.0	-
CS-157	6.3	-	20.8	-	33.8	-	45.5	51.7	55.3
CS-159	1.4	-	5.0	-	9.4	-	14.2	16.8	18.8
CS-161	2.7	-	10.1	-	51.5	-	90.3	111.3	123.0
CS-162	1.6	-	12.2	-	38.6	-	70.7	89.9	100.0
CS-163	0.3	-	0.4	-	0.3	-	0.3	0.3	0.3
CS-164	5.4	12.1	-	26.2	38.7	48.7	-	-	-
CS-166	7.1	14.0	-	24.8	33.3	39.1	-	-	-
CS-168	10.4	19.2	-	23.8	25.8	26.7	-	-	-
CS-170	8.5	15.8	-	19.8	21.6	22.1	-	-	-

^aControl sample of "pure 6061" figures cited as FZ volumes are density in g/cm³.

Fig. 27. Change in fuel zone volume versus time at 400°C for various fuels

2.13 High-U-Density Plates

2.13.1 Summary of HIP Runs for Development of Highly Loaded Fuel Plates

Other innovative techniques were examined to meet the low-enrichment needs of the high-performance (6–9.0 gU/cm³) reactors. Two concepts have been proposed to address this issue. The first effort involved the generation of wires of U₃Si and/or U₇₅Ga₁₀Si₁₅. These wires would be used as filaments bonded into Al in such a geometry as to generate plates with loadings approaching 9.0 gU/cm³ in the fuel zone. The second effort involved a dispersion concept in which a highly loaded (>50 vol.% U₃Si₂), uniformly clad fuel plate is produced with areal loadings equivalent to 9.0 gU/cm³. In both concepts, hot isostatic pressing (HIP) is a key processing technique. Since 1975, this process equipment has become more readily available and HIPing has gone from being a specialized laboratory technique to a commercially used process. In this fabrication method, the workpiece is hermetically sealed in a deformation container, placed in a high-pressure

Table 20. Reaction of uranium-based fuel alloys with aluminum matrix

Fuel	Wt.%	Melt No. or Plate No.	Condition	Interatomic Distance	Type	Reaction Product	Other Identified Constituents
U ₃ Si ₂	30	CS5	1000 h at 450°C	4.23	Cubic	U ₂₅ Al ₅₈ Si ₁₇	--
U ₃ Si	30	B18	1000 h at 450°C	4.259	Cubic	U ₂₅ Al ₇₁ Si ₄	Al
U ₃ SiAl	30	T20	1000 h at 450°C	4.259	Cubic	U ₂₅ Al ₇₁ Si ₄	Al
U ₃ Si ₂	40	--	72 h at 500°C	4.233	Face-Centered Tetragonal	U ₂₅ Al ₆₀ Si ₁₅	U ₃ Si ₂
USi	40	A177	As-fabricated	4.21	--	U(Al ₂ Si) ₃	Al
U ₃ Si ^a	40	CS164	600 h at 400°C	4.26	--	UAl ₃	U ₃ Si ₂ + Al
U ₃ Si _{1.6} ^a	40	CS166	600 h at 400°C	4.255	--	U ₂₅ Al ₇₀ Si ₅	U ₃ Si ₂ + Al
U ₇₅ Ga ₁₀ Si ₁₅	19	CS168	600 h at 400°C	4.257	--	U ₂₅ Al ₇₀ Si	U ₃ Si + Al
U ₇₅ Ga ₁₀ Ge ₁₀	19	CS170	600 h at 400°C	--	--	U(AlSi) ₃	Al
U ₇₅ Ga ₁₀ Si ₁₅	--	D263	As-HIPed ^c	4.268	--	U(Al,Si,Ga) ₃	Al

^aAs-cast^bBalance aluminum^cHIP = hot isostatic pressing

environment (approximately 30 ksi [207 MPa]) and heated to an appropriate temperature in the range of 200–1500°C. The combination of heat and pressure densifies, sinters and bonds the workpiece.

The potential advantages of a HIPed fuel plate are uniform cladding and fuel zone thickness, as well as control of the fabrication atmosphere, temperature, and pressure. With the appropriate HIP, plates can be batch processed. However, a complete installation capable of batch processing full-size plates could easily cost more than \$0.5 million.

Preliminary results of this effort are covered in Ref. 29. Appendix F is a complete summary of all the hot isostatic press (HIP) runs conducted in the development of a process for fabricating a highly loaded fuel plate. The first HIP bonding run was on 3 x 3 x 0.125 in. (76 x 76 x 3.2 mm) plates of 6061

Al. These plates were Oakite-etched and wire brushed on their bonding faces before being TIG edge-welded in air with 4043 filler rod. The pieces were pressurized and then heated to 500°C. After HIPing, the welds were removed from the samples; no bonding was observed. It was thought that the absence of bonding was due to the welds not being pressure-tight. For the next run, two more weldable materials were HIPed. These were 99.99 pure Al and 1100 Al. After cleaning, welding in air without a filler rod, and HIPing, both test pieces were found to be bonded. Metallographic samples were taken and showed a continuous layer at the interface. This layer was subsequently shown to be an aluminum oxide compound.³⁰ In an attempt to reduce this layer, the welding operation was moved to an Ar glovebox. All of these runs produced nonbonds. It is now believed that the total exposure time to oxygen is the critical factor for achieving a bond. To prevent Al oxidation, the thermodynamic data state that a partial pressure of oxygen $<10^{-20}$ atmosphere is necessary. The partial pressure of oxygen in the glovebox was orders of magnitude greater than this, so there was little advantage over welding in air. In fact, use of the glovebox at least doubled the time to weld the piece, allowing more time for oxide growth.

After three unsuccessful HIP runs with samples welded in the Ar glovebox, it was decided to return to welding in air and to heat the piece first before pressurizing in the HIP. This should allow the small amount of deformation that occurs during HIPing to take place when the sample is more plastic, promoting a better bond. Also, on run "F," two methods of cleaning were used: first, wire brushing of the bonding faces alone and, second, Oakite cleaning followed by wire brushing. The results were a nonbond on the first sample and a bond on the second sample. This suggests that wire brushing alone of Al is not sufficient to clean the surface of the sample for an acceptable HIP bond.

Based on this information, the next run (G) was a HIP run of two 6061 Al plates and two edge-welded 1100 Al plates. Both were prepared by Oakite cleaning, followed by wire brushing, welding, and preheating before pressurizing. Only the 1100 Al bonded, and it was decided to concentrate on proving the concept with 1100 Al as the cladding material and to return to 6061 Al at a later date.

To test the reproducibility of bonding, two 1100 Al rods were HIPed (Run H) and machined to tensile samples. The results were excellent

bonds, with failure occurring outside the bond interface after tension testing.

2.13.2 HIPing of Standard Miniplates

Tables 21 and 22 summarize the results of the next series of runs. Table 21 shows the results of HIPing 40 vol.% U_3Si_2 miniplates produced by the standard roll-bonding process. As-fabricated porosity appears to have been reduced to <1% (assuming no fuel/Al reaction) after HIPing at 500°C. It may be interesting to irradiate such low-porosity plates to determine how the added integrity of the plate due to the decreased porosity affects the irradiation results.

Table 21. Summary of HIPed 40 vol.% U_3Si_2 miniplates

Miniplate	HIP Run	Time (h)	Temperature (°C)	Pressure K/in. ² (MPa)	Void %
162F	As-fabricated	-	-	-	8.7
162R	As-fabricated	-	-	-	8.9
162F	1	2	300	17.1 (118)	5.7
162R	1	2	300	17.1 (118)	5.2
162F	2	2	300	15.0 (103)	5.2
162R	2	2	300	15.0 (103)	4.7
162F	3	2	400	10.7 (73.8)	3.2
162R	3	2	400	10.7 (73.8)	2.9
162F	4	2	500	10.7 (73.8)	0.2
162R	4	2	500	10.7 (73.8)	0.5
163F	As-fabricated	-	-	-	9.7
163R	As-fabricated	-	-	-	10.1
163F	1	2	500	10.8 (74.5)	0.8
163R	1	2	500	10.8 (74.5)	1.2

Table 22. Summary of HIPed 55 and 60 vol.% tungsten plates

HIP Run I.D.	No. of Times HIPed	Fabrication Variables			Void %	Notes
		Time (h)	Temperature (°C)	Pressure K/in. ² (MPa)		
I	1	2	500	10.7 (73.8)	9.4	55 vol.%; sectioned
M ^a	1	2	500	10.6 (73.1)	8.8	60 vol.%
R	2	4	500	11.2 (77.3)	5.3	60 vol.%
S	3	4	500	11.1 (76.6)	4.9	60 vol.%
V	4	1.5	500	25.8 (178.0)	2.1	60 vol.%

^aAfter the first HIPing, the plate was cold rolled 14.7%, and porosity increased to 21.1%.

2.13.3 HIPing of Thin Compact Plates

Data on the concept of HIPing a plate with a very-uniform fuel zone thickness are given in Table 22. (runs I, M, R, S, and V). The original compact height before HIPing for run "I" was approximately 0.042 in. (1.07 mm), and porosity was 15%. It was believed that after HIPing, there would be a reduction in thickness of the "fuel zone." This was not found to be true. There was a reduction in the percentage of porosity to 8.8% during HIPing, but after metallographic sectioning the final fuel zone thickness was the same as that of the original compact. A possible explanation for this result is that the Al clad is being extruded into the porosity. To correct for this effect, thinner compacts 0.030 in. (0.76 mm) or less must be made. Also, there was very little distortion in the plate. The second interesting result of these tests was that porosity was much greater than the 1% seen after the miniplate HIP tests. This could be due to the effect of bridging of the fuel or perhaps U_3Si_2 creeps more than W under the HIPing conditions. Finally, a substantial increase was discovered in the amount of porosity in the fuel zone after cold rolling a HIPed plate. Moreover, after cold rolling and re-HIPing, there was much plate distortion. The necessity of cold rolling and the sequence of fabrication will have to be refined for this concept to be

2.13.4 Wire-Concept Plates

Runs "Q" and "T" were the first runs with the wire concept; both were successful and resulted in bonds. It was difficult to determine if any reaction had occurred between the U-Ga-Si and the Al during HIPing.

2.13.5 HIPing of Tensile-Strength Specimens

Run "U" was an attempt to measure the tensile strength of the fuel/clad interface by using a rod-shaped test sample with a fuel/Al matrix core. Because of welding difficulties, only one rod bonded; when this rod was machined into a tensile specimen, it fractured through the fuel zone. Fuel bonded to both mating surfaces. This indicated that bonding had taken place but that the strength of the plate was limited by the strength of the meat. This strength is directly related to the porosity of the fuel zone and to the bonding or lack of it between matrix and fuel particles. If the void can be reduced to <1% for the plate concept by the use of higher pressures or longer times, this type of rod experiment may yield successful results.

2.13.6 HIPing of Bonding Plates

Runs W, X, and Y were used to study the bonding of 6061 Al to itself. Electron beam welding was employed to seal the samples in runs W and X. No bonding was observed for either of these runs. The electron beam welder was later found to have a problem that caused insufficient penetration, poor welds, and therefore no bonding. The samples for run Y were sealed by TIG welding. This run produced the most interesting and successful results to date. Specimen Y (X2) demonstrated that for a high probability of a good bond, the plates should be HIPed as soon as possible. Sample Y1 was sealed correctly and densification was known to occur due to the depression measured over the "fuel" zone. Some bonding was observed upon sectioning. For the next two specimens, 6061 Al plates were TIG-welded using 4043 filler rod. After HIPing and sectioning, two of the samples bonded.

2.13.7 HIPing of Electron Beam Welded Plates

Seven of the following runs (Z, AA, DD, EE, FF, HH, & II) used electron beam welding as the sealing method. Consistent gas-tight welds could not be made. However, when a good weld was made, bonding did occur.

Run GG was made using TIG welding. One of the two samples was gas-tight and formed a bond; it was machined into a tensile specimen and tested to failure. The sample failed outside the bond area, indicating a good bond.

2.13.8 Final HIPing of Wire-Concept Plates

HIP runs JJ and KK were the last HIP tests performed at ANL for the RERTR project. These plates were 1100AL with U-Ga-Si wires as the fuel and bonded quite readily. Metallographic results showed that a severe reaction had taken place during or after bonding (Fig. 28). It is possible that the reaction was not seen in earlier plates (Run T) due to separation of the fuel and matrix by a protective oxide film. It is proposed that this film was removed when the cleaning method was changed between these two runs from etching to abrasive cleaning. A compatibility annealing was also done on a wire-concept plate. The fuel for this experiment was $U_{75}Ga_{10}Si_{15}$. The results of these further annealings are given in Table 23. The reaction was confirmed, and metallography after 200 h at 400°C shows almost a complete reaction (Fig. 29). No further runs were made.

Fig. 28. Cross section of U-Ga-Si wire in aluminum matrix after HIPing

Fig. 29. Cross section of U-Ga-Si wire in aluminum matrix after HIPing and 200 h at 400°C

Table 23. Results of compatibility annealings of $U_{75}Ga_{10}Si_{15}$ wire-concept plate

Condition ^a		Density (g/cm ³)	Thickness over Aluminum Only		Thickness over Fuel Wires	
			in.	mm	in.	mm
As-HIPed and Chemically Cleaned		2.798	0.2443	6.205	0.2440	6.198
400°C	8 h	2.797	0.2439	6.195	0.2439	6.195
400°C	66.5 h	2.795	0.2440	6.198	0.2440	6.198
400°C	140 h	2.791	0.2440	6.198	0.2444	6.208
400°C	200 h	2.784	0.2440	6.198	0.2448	6.218

^aRecorded annealing times are cumulative times of "pulse-anneals."

2.13.9 Possibilities for Further Developments

Because the RERTR program lasted 12 years, many items that are worth recording were never investigated. Some of these ideas may have a very low probability of being successful, but they may spark some useful thoughts in other researchers. This section presents some ideas of the author for further development work on ultra-high-density fuel plates. It focuses on one of the last unresolved problems for the RERTR program: the conversion to LEU of a few highly loaded reactors. These reactors could not be fueled with conventional NRC-approved LEU U_3Si_2 plates without sacrificing their power levels or fuel cycle length. The four proposed solutions listed below attempt to increase the total loading of fuel per plate and assume that the finished plates will meet current quality requirements.

1. HIP a uniform full-size plate at 0.030 in. (0.076 mm) thick meat and very uniform cladding (± 0.002 in., 0.051 mm). Use only a light ($\approx 15\%$) finishing pass or etch to size.
2. Use the above process, but start with a thicker compact — 0.060 in. — (1.52 mm) followed by hot rolling to 0.030-in. (0.076 mm)-thick fuel zone.
3. Start with a longer and thinner compact and reduce the total hot reduction to 30–50% from its current $\approx 88\%$ level. Use conventional rolling techniques (no HIP).
4. Use standard methods and double-encapsulate the rolling assembly.

Method 1 was studied at ANL during 1988–1989. It has been successfully demonstrated that HIP bonding of 6061 Al is possible. The only other hurdle is making a large, thin compact (24 x 2.5 x 0.030 in. [610 x 64 x 0.76 mm]). All thin compacts must be leveled in the center of the die, and a loading funnel should be used in a standard repeatable pattern. Because of seam problems, use of multiple compacts is not recommended. If the compact was to be made by cold pressing, a large press would be required, i.e., ≈ 900 tons (8.0 MN). There are two possible ways to overcome this problem. The compact could be made by cold isostatic pressing (CIP), or if conventional pressing methods are to be used, a large compact could be given a low-compaction load and then compacted to higher densities with a smaller punch (at higher pressure). By multiple compacting, the compact

could be subjected to higher pressures with the same press due to the pressing of a smaller area. This method has a high probability of success but may not be economical or compatible with current fabrication equipment.

The second method uses a smaller compact. With a 50% increase in thickness, the compact could be made with 50% less surface area (12 x 2.5 x 0.060 in. [305 x 64 x 0.765 mm]). With one-half the original area, a 50% smaller press would be needed for compacting. The final 50% reduction would be done by rolling after HIPing. This could give an acceptable bond. It is believed that dogboning occurs when the compact is very thick and has very little restraint. As the fuel zone is enlarged, the ratio of volume of the fuel zone to the surface area of the cladding/fuel matrix increases. The frictional effects become greater as "individual" particles are constrained by the cladding. If the process is started with a much thinner (0.060 vs. 0.164 in. [1.52 vs. 4.17 mm]) compact, due to the increased constraint, there may be little or no dogboning.

The above theory that dogboning occurs when the compact is least dense and least constrained leads to Method 3, i.e., elimination of the HIP step in Method 2. This also assumes that the bond between the frame and the covers is established after the first or second hot pass. From the HIPing results, it appears that an assembly welded 100% around will roll and bond just as well as the standard open assembly. The reason is that bonding has been achieved with a 100% sealed HIP assembly. An added benefit to this method would be the reduction or elimination of the fuel oxidation problem. After assembly and welding, standard rolling techniques could be used. This would be by far the most cost-effective method, although it has a very low probability of success due to the possibility of blisters from the entrapped gas. There may be differences due to using rolling versus HIPing which account for the lack of blisters. This experiment may have been tried in the past but I have found no references to such a test.

Method 4 involves the addition of a second jacket around the standard assembly. With a strong, stiff, plain carbon steel jacket around the assembly, the meat could be uniformly constrained during rolling. If this is true, the meat has no driving force that can lead to dogboning. On a production scale, the extra cost of the second can would be minimal and could perhaps save money by reducing the number of rejected plates.

One additional possible solution has been mentioned many times. If the fuel particles could be coated with Al, then the frictional effects would be reduced and they would roll more like Al than fuel. If the thickness of the clad and core could then be uniformly reduced, there would be no dogboning. The problem with this solution is the loss of fuel loading due to the coating. If we assume 0.001 in. (25 μm) total coating per particle, this would mean the fuel particle has 0.0005 in. (13 μm) Al per side. The problem becomes more clear when we do a volume-percent fuel calculation. For example, the fraction of fuel in a 0.003 in. (76 μm) spherical fuel particle coated with 0.0005 in. (13 μm) layer of aluminum is only 0.42. This is much too low and is the major reason for not pursuing this option. Also, this does not take into account any reductions in loading due to packing-factor problems.

For comparison, these ideas are summarized in Table 24.

Table 24. Comparison of compact sizes and processes for proposed fabrication methods

Method	Press Size Required (tons)	Compact Size (in.) Length x Width x Thickness	HIP Required	Rolling Reduction (%)
1	900	24 x 2.5 x 0.030	Yes	0 Hot 0-15 Cold
2	450	12 x 2.5 x 0.060	Yes	35 Hot 15 Cold
3	450	12 x 2.5 x 0.060	No	35 Hot 15 Cold
4	300	2.5 x 2.5 x 0.64	No	86 Hot 15 Cold

2.14 Miniplate and Test Element Irradiation and Post-Irradiation Examination

Irradiation testing of the various fuels began with small plates (miniplates) to determine basic irradiation behaviors. All miniplate irradiations were performed in the Oak Ridge Research Reactor (ORR) at Oak Ridge National Laboratory (ORNL). The irradiation testing procedures are summarized in Ref. 31 and the results of postirradiation examinations are summarized in Ref. 32. Fuels with acceptable irradiation performance were then tested in full-sized fuel elements to confirm their behavior under typical reactor conditions. Early irradiation results indicated that the uranium silicide dispersion fuels had acceptable performance. This led to a decision in 1981 to proceed with the fabrication and irradiation of full-sized, low-enriched uranium silicide fuel elements in the ORR. At that time, U_3Si_2 was chosen because it could be more easily comminuted than U_3Si due to its brittle nature. This proved to be a fortuitous choice because U_3Si_2 was subsequently shown to be much more stable under irradiation than U_3Si .

Two U_3Si_2 fuel elements each were fabricated by NUKEM,* CERCA,** and B&W*** (six elements total) for testing in the ORR under cooperative arrangements. The RERTR program provided low-enrichment uranium and the testing. The fabricators supplied the fuel elements. There was no cost to either party for the other's services. Fabrication of the elements was completed in January 1982 by NUKEM, in March 1983 by CERCA, and in October 1983 by B&W. Irradiation of the first element began in May 1982, the final element was removed from the core in December 1984, and the examinations were completed in September 1986. Based on the excellent performance of these elements (Ref. 32), a whole-core demonstration was successfully performed in the ORR.³³

2.15 Technology Transfer

Working in this international effort, ANL has developed and demonstrated U_3Si_2 to be a fuel that satisfies many of the goals of the

*NUKEM GmbH, Hanau, Germany

**Compagnie pour l'Etude et la Realisation de Combustibles Atomiques, Romans-sur-Isere, France.

***Babcock & Wilcox Co., Lynchburg, VA, USA.

Reduced Enrichment Research and Test Reactor (RERTR) program. The technology of U-Si alloys and their use as nuclear fuel is being transferred to the international community in several ways. Annual meetings have been held from 1978 through 1994. At these meetings, all information generated at ANL has been freely disseminated. Separate special training programs have been conducted at ANL for U.S.³⁴, Danish,³⁵ and Republic of Korea³⁶ personnel. A similar training program in silicide fuel technology with Indonesian personnel was begun in 1988 in Indonesia.³⁷ A close cooperative liaison is still being maintained with Babcock & Wilcox as it moves forward with silicide fuels on a commercial basis.

3 SUMMARY

Uranium-silicide fuels have been successfully fabricated, developed, and irradiated. It has been shown that low-enriched U_3Si_2 -Al dispersion fuel elements will perform at least as well in research and test reactors with power densities up to that of the ORR as will the highly enriched UAl_x -Al and U_3O_8 -Al dispersion fuels currently being used. Currently, conversion to LEU U_3Si_2 is progressing throughout the world.

ACKNOWLEDGMENTS

Many people have contributed to this project over its 12-year span. The author would like to acknowledge and thank everyone who was involved in management of the program, especially R. F. Domagala, J. L. Snelgrove, H. R. Thresh, those who were responsible for the fabrication of hardware, including A. E. Dwight, H. C. Glienke, F. J. Karasek, C. F. Konicek, W. A. Kremsner, G. G. Mapalo, D. R. Perkins, D. L. Rink, D. R. Schmitt, K. E. Stair, C. Steves, J. R. Summers, G. J. Talaber, and J. A. Zic. Special thanks go to P. J. Peterson, who typed and assembled this report.

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APPENDIX A: LIST OF PREVIOUS TM REPORTS

1

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APPENDIX A

- ANL/RERTR/TM-1 Proceedings of 1978 RERTR International Conference.
- ANL/RERTR/TM-2 A Study of UO₂ Wafer Fuel for Very High-Power Research Reactors, by T. C. Hsieh, V. Z. Jankus, J. Rest, and M. C. Billone.
- ANL/RERTR/TM-3 Proceedings of 1980 RERTR International Conference.
- ANL/RERTR/TM-4 Proceedings of 1982 RERTR International Conference.
- ANL/RERTR/TM-5 Blackness Coefficients, Effective Diffusion Parameters, and Control Rod Worths for Thermal Reactors, by M. M. Bretscher.
- ANL/RERTR/TM-6 Proceedings of 1984 RERTR International Conference.
- ANL/RERTR/TM-7 A Differential Thermal Analysis Study of U₃Si-Al and U₃Si₂-Al Reactions, by R. F. Domagala, T. C. Wiencek, J. L. Snelgrove, M. I. Homa, and R. R. Heinrich.
- ANL/RERTR/TM-8 Requalification of Spert Pins for Use in University Reactors, by J. L. Snelgrove, R. F. Domagala, and L. R. Dates.
- ANL/RERTR/TM-9 Proceedings of 1986 RERTR International Conference.
- ANL/RERTR/TM-10 Performance of Low-Enriched U₃Si₂-Aluminum Dispersion Fuel Elements in the Oak Ridge Research Reactor, by G. L. Copeland and R. W. Hobbs (ORNL) and G. L. Hofman and J. L. Snelgrove (ANL).
- ANL/RERTR/TM-11 The Use of U₃Si₂ Dispersed in Aluminum in Plate-Type Fuel Elements for Research and Test Reactors, by J. L. Snelgrove, R. F. Domagala, G. L. Hofman, T. C. Wiencek, G. L. Copeland, R. W. Hobbs, and R. L. Senn.
- ANL/RERTR/TM-12 A Computer Code, NATCON, for the Analyses of Steady-State Thermal-Hydraulics and Safety Margin in Plate-Type Research Reactors Cooled by Natural Convection, by R. S. Smith and W. L. Woodruff.
- ANL/RERTR/TM-13 Proceedings of 1988 RERTR International Conference.

APPENDIX B: FABRICATION PROCEDURES

RERTR MINIPLATE FABRICATION PLAN (1983)

Revision No.: 0
Revision Date: April 15, 1980
Written By: R. F. Domagala
Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 1

MATERIALS & CHEMICAL ANALYSIS

I. Purpose

Materials used in the production of fuel plates must conform to certain requirements. While all materials are ordered to specifications satisfying these requirements, it is mandatory that check analyses be conducted on incoming materials as well as on alloys produced by arc melting or powder-produced by comminution. This procedure summarizes all these chemical analyses.

II. Materials & Equipment

Equipment for generating (e.g., cutting) stock for chemical analysis

III. Procedure

A. 6061 Sheet Stock and 4043 Wire for Welding

The 6061 stock shall be ordered to ASTM B209-77 "Standard Specification for Aluminum-Alloy Sheet & Plate." Any thickness plate in excess of required thickness for plate production and any heat treated condition is acceptable. Typical or lot analysis shall be required of vendor.

For each plate or portion of plate of 6061 received, a piece shall be cut and sent for chemical analysis. The analytical data must lie within the range specified for 6061. If it does not, that material may not be used for fuel plate production.

The 4043 welding rod (wire) may be ordered in any diameter. A portion of each batch received shall be sent for chemical analysis the results of which must conform to the ASTM-B285 standards for such wire. If it does not, the wire may not be used for welding assemblies for fuel plate production.

125"

B. Aluminum Powder

Any of three aluminum powders may be used:

Alcan-MD101

Reynolds - No. 120 atomized Powder

Alcoa - Atomized Powder No. 101

A typical analysis of any of these powders is 99.3% Al (excluding Al present as Al_2O_3) plus small amounts of impurities normally present in nominally pure Al powder. Of these contaminants, Fe & Si may be present to as much as 0.25%.

A chemical analysis shall be run on a sample of the as-received powder as well as on a sample of powder subject to the vacuum degassing step. The analyses must be within the manufacturers specification for the powder in both cases or it may not be used for fuel plate production.

C. Aluminum for Alloying

For ~~fuel~~ alloys containing Al (e.g., U + 3 1/2 w/o Si + 1 1/2 w/o Al) the Al used must be 99.99 per cent pure confirmed by chemical analysis.

D. Silicon for Alloying

The silicon used for alloying shall be Dow Corning Polycrystalline "Nuggets". The purity of this material is so high that impurities are reported by Dow Corning in parts per billion. Routine chemical analyses are not sensitive enough to confirm such purity levels and therefore no analysis shall be required.

E. Uranium

High purity uranium of the proper enrichment should be used for all fuel alloys. Inasmuch as an analysis of the resultant alloys prepared using this uranium is required, it is not necessary to conduct a separate analysis unless there is reason to be suspicious of the lot or typical analysis provided with the uranium.

F. Uranium-Base Fuel Alloys

Uranium base fuel alloys of required composition shall be made by arc melting in a non-consumable (tungsten) electrode water-cooled copper

hearth furnace. Charges shall be weighed and recorded to the nearest miligram. A sufficient number of melting cycles shall be conducted to ensure homogeneity. The weights of arc melted ingots shall be measured and recorded. Ingots showing a weight gain shall not be used for the production of any fuel plates, but may be used for practice plates or similar experiments. Weight losses shall be such that the true and intended compositions must be very close even if all the loss on melting was considered to be from the volatilization of one of the components of the alloy.

Chemical analyses of a portion of an arc melted alloy before or after heat treatment may be conducted. In the interest of economy, however, an analysis of the powder produced from such ingots in the size range employed for the fuel meat compacts may be the only analysis conducted. Analyses for total U, isotopic U, Si, and (Al ^{expanded} must be conducted. Analyses for other elements, either qualitative or quantitative, shall be run according to the requirements of any documents pertaining to the application of fuel plates made from such alloys. ←

IV. General

Superimposed on the above requirements there may be limits set on the presence of one or more contaminant elements in any of the materials used for plate production. Whenever such requirements exist, the analyses shall be run and the amount of contaminant must be within the specified limits.

Revision No: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 2

ROLLING & MACHINING OF STOCK FOR PLATE ASSEMBLIES (FRAMES & COVERS)

I. Purpose

Aluminum alloy 6061 is used for the frames and covers in fuel plate assemblies. The alloy is purchased commercially to ANSI/ASTM B209-77 standards in any thickness (in excess of required thickness) and in any heat treated condition available. Although some 6061 is available as Al-clad sheet or plate the work on this program involves only the unclad 6061.

The 6061 is usually available as plate 1/4 in. to 1/2 in. thick in sheets 4 ft. x 12 ft. with the 12 ft. length in the rolling direction. This material is sheared into pieces suitable for rolling and is then rolled to thicknesses appropriate for the assemblies. This procedure describes those steps which must be taken to produce the required stock.

II. Material and Equipment

6061 aluminum plate 1/4" to 1/2" thick x 4' x 12'

Cincinnati shear 1/2" mild steel capacity

9" x 16" rolling mill with flat rolls

2 sets of tongs

Resistance furnace with heat range capabilities to at least 550°C

Texaco Pinnacle-680 oil-1 part diluted by 3 parts Wet Edge (by volume)

Roll-wipers-wide enough to cover width of roll surfaces top and bottom using 1/2" thick felt No. F-10 white (Continental Felt Co., New York, N.Y.)

Remov

Heat lamps 2-(250 Watt) one focused on the top roll and one on the bottom roll.

III. Procedure

1. The 6061 material is sheared into pieces 4 ft. x 4 ft. sections. Each section is then sheared into pieces 4" x 12". The original (mill) rolling direction is maintained along the 12" length.
2. Sections are placed in the furnace set at 500°C (±15°C). Pre-heat time is 1/2 hour. Re-heat time between each pass is 5 min. No particular

10 or 5 min.

rolling schedule is required but 20% reductions per pass work very well at this temperature. When approaching the final thickness roll screwdown adjustments must be made.

3. For the picture frame stock the final rolled thickness is $\sim .168''$.
For the cover stock $\sim 0.128''$ for 0.050" plates, $\sim 0.155''$ for 0.060" plates
4. After cooling, the plates are straightened on a sheet leveler.
After straightening, $3'' \times 6''$ sections are cut from the rolled plates by shearing. To preclude, scratch or marring the material, paper is used on the shear table and/or plastic in the catch-tray. Paper is also placed between the hold-down pads and the plate surfaces when shearing.
5. The sheared sections are cleaned with acetone, wrapped with paper and stacked in plastic bags which are then identified as to material project, type, and size. *Machined to 3" x 6"*
6. For frames, the $3'' \times 6''$ pieces are sent to the shop to have cavities machined in them for accepting the pressed compacts. The cavities may be created by whatever shop practices are available. To date, the best results have been obtained by milling followed by a finishing operation involving electrical discharge machining with a graphite electrode such as POCO-EDM-C-1.
7. Specifications for frames and covers are shown on the attached figures, ANL drawings MY-A-4201-1 & MY-A-4201-2.

IV. General

The original rolling direction of the as-received plate is always maintained as the rolling direction in this and any other succeeding operation. Any portion of the as-received plate or any piece produced from it which has obvious or potential defects should be discarded.

Material should be ordered to ANSI/ASTM B209-77 standards and as a further check specimens should be cut from one or more sections of each as-received plate and sent for chemical analysis.

The thickness dimensions indicated in III-3 above are typical for 0.050 in. thick finished plates. These dimensions will vary according to the needs for the specific final plates. Likewise, the dimensions of 3" x 6" noted in III-4 may be changed to suit the particular fuel plate being produced.

DWG. NO.

NOTE

1. ALL CAVITIES TO BE SQ TO FRAME WITHIN $\pm .001$
2. DO NOT SCRATCH OR DENT SURFACE OF FRAME

RERTR Fabrication Procedure No. 2, Page 3

REF. NO.	NEXT ASSEMBLY	REQ'D
<p>THIS DRAWING IS THE PROPERTY OF</p> <p>ARGONNE</p> <p>NATIONAL LABORATORY</p>		
TITLE		
<p><i>RERTR MINIPLATE</i></p> <p><i>FRAME</i></p>		
SCALE	SHEET	DRAWING NUMBER
<p>1/2"</p> <p>5/8"</p> <p>1"</p>	1	<p>MY-A-4201-1</p>

SYM	ZONE	CHANGE	BY	CHK'D	DATE
<p>UNLESS OTHERWISE NOTED</p> <p>ALL DIMENSIONS ARE INCHES</p> <p>FRACTIONAL TOL. : 1/64</p> <p>DECIMAL TOL. : .005</p> <p>ANGULAR TOL. : 1/4</p> <p>REMOVE ALL BURRS AND SHARP EDGES</p> <p>SURFACES TO BE IN ACCORDANCE WITH ANSI B46.1 - 1962</p> <p>DIMENSIONS & TOLERANCES IN ACCORDANCE WITH ANSI Y14.5 - 1966</p>					
DRAWN BY		DATE	GP. LEADER		DATE
M. RUSSELL		12/14/77			
CHECKED		DATE	PROJECT MGR.		
1. J. I.		12/18/77			
REQ. ENGINEER		DATE	APPR'D/RELEASED		
L. J. Hernandez		12/18/79			
MATERIAL					
<p>6061 ALUM ALLOY</p> <p>THICKNESS AS PROVIDED</p>					

18450
UNING
MICRO-FILMED DATE

DWG. NO.

NOTE
1. DO NOT SCRATCH OR DENT
SURFACE OF COVER PLATE

REF. NO.	NEXT ASSEMBLY	REQ'D
<p>THIS DRAWING IS THE PROPERTY OF ARGONNE NATIONAL LABORATORY</p>		
<p>TITLE RERTR MINIPLATE COVER PLATES</p>		
SCALE 1/2" = 1"	SHEET 1	REV MY-A-4201-2

DATE 12/14/79	DATE 12/14/79	DATE 12/14/79
DRAWN BY H. RUSSELL	GP. LEADER	PROJECT MGR.
CHECKED P.J.	APPR'D/RELEASED	
RESP. ENGINEER P.J. Thompson		
MATERIAL 6061 ALUM. ALLOY		
THICKNESS AS PROVIDED		

SYN	ZONE	CHANGE	UNLESS OTHERWISE NOTED
			<p>ALL DIMENSIONS ARE INCHES</p> <p>FRACTIONAL TOL. : 1/64</p> <p>DECIMAL TOL. : .005</p> <p>ANGULAR TOL. : 1/4</p> <p>REMOVE ALL BURRS AND SHARP EDGES</p> <p>SURFACES TO BE IN ACCORDANCE WITH ANSI B46.1 - 1962</p> <p>DIMENSIONS & TOLERANCES IN ACCORDANCE WITH ANSI Y14.5 1986</p>

18450

RUNNING

Revision Date: April 15, 1980Written By: R. F. DomagalaApproved By: H. R. Thresh

RERTR Fabrication Procedure No. 3
ARC MELTING AND HEAT TREATING FUEL ALLOYS

I. PURPOSE

The alloys for the fuel portion of plates are typically uranium plus silicon binary or uranium plus silicon, ~~plus aluminum ternary compositions.~~ These can be most easily produced by melting in a non-consumable electrode (W) water-cooled copper hearth arc melting furnace. This procedure outlines the steps for weighing the charges, melting and subsequently heat treating the ingots before comminution.

Experience, supported by chemical analyses, has demonstrated that homogeneous alloys of the appropriate compositions can be produced by following the procedures below.

The 72-hour treatment at 800°C is specifically included in the procedure to complete the peritectoid formation of U_3Si in the binary system and, in general, to eliminate any uranium solid solution from the microstructure of either alloy.

II. MATERIALS AND EQUIPMENT:

Arc melting furnace

High purity uranium, aluminum and silicon (See RERTR Fab. Procedure No. 1)

304 Stainless steel retorts

Heat treating furnace

III. PROCEDURE

1. The Enr.U plates or pieces are acid etched in a solution of 50% HNO_3 (reagent grade) and H_2O (distilled or deionized) at room temperature long enough to remove the surface oxide.
2. The plates are rinsed in distilled or deionized water and then immersed in a container of acetone and air dried.
3. The U pieces are weighed individually.
4. Using the weights of the U as a basis, the various alloy charges are calculated. Ingot weights should be ~150 to ²⁰⁰₃₅₀ grams.
5. One charge at a time is placed in the mold of the arc furnace.
6. The furnace is evacuated and back-filled three times with argon gas.
7. The furnace is back-filled with 80% helium gas first and then topped with 20% argon gas. The arc furnace is operated at a slight positive pressure.
8. The arc is initiated with a high frequency starter.
9. The arc current is increased slowly to a ⁶⁰⁰300-400 amp level. This is to avoid blowing material out of the mold. The voltage is ~20 volts.

120

10. Using a controlled circular motion, the arc is held 40 to 50 seconds so as to attain the greatest amount of penetration.

*clean chamber**weighed*

11. After each melt, *the* ingot is cooled, flipped over in the mold, *and* remelted to facilitate greater homogeneity.

12. A total of five to six melts are made for each charge to assure total homogeneity.

13. The ingots are individually wrapped in tantalum foil. *for heat treatment*

14. The tantalum foil wrappers are identified with a stamp and placed in a stainless steel (304) retort which is identified.

15. Retorts are placed on a vacuum system for 20 hours.

16. The retorts are back-filled with a slight positive pressure argon gas.

17. Plugs are placed in the evacuation tubes of the retorts and then welded shut.

(for V_3Si)

18. The retorts are placed in a furnace at 800°C for 72 hours, *removed*, and air cooled. (Hevi-duty res. fce 18 KW).

19. The bottoms of the retorts are sawed off to enable removal of the ingots.

IV. GENERAL

1. No extra amounts of U, Al or Si need to be added to the charges to compensate for losses during arc melting.
2. Ingots showing a weight gain after arc melting may not be used for fuel plates. These are scrap and must be disposed of according to proper procedures. Alternately, they may be used for experimental work
3. The procedures described above apply to enriched or depleted uranium alloys without change.
4. Ingot weights are to be measured and recorded before and after each and every treatment.

Add Form

Ingot No. _____ Weighed by _____ Date _____

Other Identification _____

<u>Alloy Composition</u>	<u>Target Weight (grams)</u>	<u>Actual Weight (grams)</u>
_____ w/o	_____	_____
_____ w/o	_____	_____
_____ w/o	_____	_____
_____ w/o	_____	_____
_____ w/o	_____	_____
_____ w/o	_____	_____
Totals 100%	_____	_____

<u>Weight After</u>	<u>Date</u>
Melt #1 _____	_____
Melt #2 _____	_____
Melt #3 _____	_____
Melt #4 _____	_____

If ingot contains U fill in the following:

U Batch No. _____

Enrichment _____

Total Loss _____ g

Final Weight Loss (%) _____

Melted by _____ Date _____

Furnace _____ Volts _____ Amps _____ Min per melt _____

Weight _____ (After conditioning for hardness reading)

As Cast Hardness: Reading 1 _____ 2 _____ 3 _____ 4 _____
(Scale _____)

<u>Date</u>	<u>Time</u>	<u>Temperature (°C)</u>
-------------	-------------	-------------------------

Heat Treatment - In	_____	_____	_____
Out	_____	_____	_____
Cool	_____	_____	_____

Hardness - Heat Treated
(Scale _____) Reading 1 _____ 2 _____ 3 _____ 4 _____

Heat Treatment by _____ Date _____

Weight After Heat Treatment _____

Other Information _____

*Identify the nature, source and purity of alloying elements used on the back of this sheet.

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. .4

COMMUNUTING INGOTS TO POWDER

Delete "Ternary" alloy
Add U_3Si_2

I: Purpose

In order to produce fuel alloy compacts for fabrication of plates, it is necessary to convert the arc-cast and heat treated ingots into powder of the appropriate sieve sizes. This procedure describes the steps in such a conversion.

II. Materials and Equipment

Aetna 50-ton Press

Steel Container and

Spex Shatterbox

Standard Tungsten Carbide-lined Dish for Shatterbox

Tyler Portable Sieve Shaker

Three-inch diameter Sieves, Pans and Covers -- Stainless Steel

Identified and tared jars with screw lids for
containing alloy particles.

III. Procedure

1. Each arc melted and heat treated ingot is individually crushed. The ingot is placed in a hardened steel container with a 3-1/4" dia. cavity. A close-fitting pin is put into the cavity. This assembly is then placed on the platen of the Aetna standard 50-ton press. The press is activated and the ram brought down on the assembly. The gauge is allowed to go to the 50-ton limit and the ram retracted.
2. The assembly is opened. All material 1/4" in size or under is removed and placed into an identified and tared jar.
3. The remaining material is returned to the assembly for further crushing.
4. The binary (U + Si) alloy requires an average of four crushings per ingot while the ternary (U + Si + Al) requires six.

5. The binary alloy is ground in the Spex Shatterbox, 1/3 of a crushed ingot at a time. Each third is ground for 9 minutes total with a 5 minute stop every 3 minutes for cooling. This varies according to the amount of heat that developed. This is done in the tungsten-carbide "Shatterbox dish".
6. After grinding, the powder is sieved through +100 and -325 sieves for 5 minutes.
7. The -100 +325 mesh and the -325 mesh material are placed in respectively identified and tared jars.
8. The +100 mesh is returned to the dish along with the next third of the crushed ingot for further grinding.
9. The grinding is again done for 9 minutes, with 5 minute cooling periods every 3 minutes of grinding.
10. The powder is again sieved as before and the (-100 +325) and -325 mesh is added to the powder in the respective jars.
11. The +100 mesh is returned to the dish along with the final third of crushed material for further grinding.
12. Again, a total of 9 minutes grinding with a 5 minute cool every 3 minutes is performed.
13. The powder is sieved as before with the -100 +325 and -325 mesh added to the powder in the respective jars.
14. The remaining +100 powder is placed in a jar so designated and tared.
15. All other binary alloy ingots are processed the same way.
16. The ternary material requires a 15-minute (total time) grinding period with a 5-minute cool every 3 minutes. This is done after the binary is completed and the dish components cleaned with acetone.
17. A different set of sieves are used for the ternary. The same sifting procedure is used as with the binary.

18. The material for each ingot is divided into thirds, therefore resulting in three 15-minute grinding periods per ingot.
19. The powder is sieved into -100 +325, -325 and +100 batches and placed into respectively identified jars.
20. All jars are weighed and recorded.

IV. General

1. All the procedures described above must be carried out under controlled conditions so that no fuel alloy material will be lost or spread into a lab area.
2. Identical procedures are to be followed whether the alloy is made with depleted or enriched uranium.
3. A different set of sieves should be used for each different alloy composition. Sieves, covers and pans are to be thoroughly cleaned and degreased before using.

Crush 7
Mortar & Pestal • Add

Magnetic Separation

Revision No: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 5

VACUUM DEGASSING ALUMINUM POWDER

I. Purpose

In preparing charges for compacts to be used in minipla^{te} production, the uranium alloy powder is mixed with commercially available aluminum powder. Typically, Alcan MD101 is used, but alternatively, Reynolds Aluminum Grade 120 powder or Alcoa 101 powder have been found by others to be nominally identical in composition and performance. The as-received powder is normally sieved (-100 mesh) to be sure "clumps", if any, are removed and the sieved powder is vacuum degassed and stored. This procedure describes the steps in the degassing operation.

II. Equipment and Materials

Alcan MD 101 aluminum powder purchased commercially

Furnace (3-zone) with 304 SS vacuum retort

304 SS trays and grid assembly

Vacuum system capable of attaining and holding vacuum levels of 10^{-6} torr (clean, dry and outgassed)

III. Procedure

cleaned if necessary

1. Scoop powder from jar into previously degassed tray/grid assembly. Work area must be clean to prevent contaminating powder or the hardware involved.
2. Place tray onto extreme end of trough so that notches fit edges of trough.
3. Position trough/tray assembly in retort so that tray is located at back end of retort.
4. After closing retort, evacuate to 10^{-5} torr ($.01 \mu$ Hg) or less before turning furnace on. *slowly*
5. Powder is degassed at 500°C for two hours. This is accomplished by increasing controller settings from 200°C to 500°C in 100°C increments each 1/2 hour and then to 550°C on zone 3 for final setting.
6. Turn off furnace after two hours at final setting. Furnace is kept under dynamic vacuum while cooling.

7. When near room temperature (overnight) retort should be isolated from vacuum system and relieved to atmosphere.
8. Upon removal of powder from retort observe appearance for discoloration or clumps. Suspect powder should be rejected. (Disposed of).
9. Process powder through clean 100 mesh stainless steel sieve on sieve shaker for about 2 minutes.
10. Store powder in one-pint glass bottles with aluminum inserts in lids. Cap is to be sealed with a wrapping of plastic electrical tape.
11. Label bottle identifying it as degassed Al powder, lot number, degassing run number and data.
12. Keep hardware stored in plastic zip bags when not in use.

IV. General

Vacuum system retort assembly and trays must be kept clean at all times. The vacuum noted in III-4 (10^{-5} Torr) must be reached before heating is begun and must not exceed 1×10^{-4} torr during the degassing treatment. The leak rate of the clean dry and empty retort at room temperature should not exceed 2 torr per minute.

Airborne aluminum powder poses a potential explosive hazard. Good housekeeping and common sense will preclude any problem. Any spilled powder should be disposed of and never returned to containers where it might be recycled as useful material

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Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 6

CONDITIONING BOTTLES AND WEIGHING TRAYS

I. PURPOSE

In processing powders, it is always found that due to either electrostatic changes or mechanical trapping effects, very small amounts of the powders remain on or in the containers they have been placed in. That is, 100% emptying is realistically impossible. To minimize the amount of powder material left in such containers, "conditioning", (described herein), coats the surface with a small amount of powder and precludes additional losses to the container or weighing tray.

II. MATERIALS AND EQUIPMENT:

V-Blender (Patterson-Kelley Twin Shell Lab Blender, or equivalent)

Weighing Trays

4-Dram Bottles (1/2 oz. - Wide Mouth Vials w/screw cap
Kimble #60957-L)

Foam Rubber Holder

Plastic Zip Lock Bag

Rubber Cap Liners

6061 Al Cap Liners

MD 101 Al Powder (or equal)

Cleaned Bottles

III. PROCEDURE:

1. Remove cap liners from bottles (vials) and replace w/a rubber cap liner and an Al cap liner.

2. By modified glass-blowing procedures, round-out vial bottoms to eliminate corners which might tend to trap powders. Rinse with water and acetone, dry in oven at $\sim 140^{\circ}\text{C}$ for two hours.
3. Identify bottle and bottle cap.
4. Fill six bottles with approximately 5-grams Al powder. (Alcan MD 101).
5. Place six bottles in foam rubber holder and place in a plastic bag.
6. Insert package into V-blender.
7. Run V-blender for two hours.
8. Remove bottles from the blender and discard Al powder.
9. Remove and store bottles. Caps are to be on bottles.

IV. GENERAL:

1. Precondition weighing trays by manually "rolling" powder around in the tray for one minute.
2. Lightly tap bottles to remove excessive Al conditioning powder.
3. Al powder must be disposed of safely. Retain in a sealed container identified as "WASTE AL POWDER" until disposition is made through proper channels.

RERTR Fabrication Procedure No. 7WEIGHING COMPACT CHARGESI. Purpose

Compacts of Al powder plus uranium alloy fuel powder are used in the assemblies for rolling plates. Before the compact can be made, the appropriate quantities of the two ingredients must be accurately weighed and mixed. This procedure describes the steps to be taken in weighing the charges for the compact. The desired weights are determined by calculating the amount of each material required for the specific plate to be produced.

II. Materials and Equipment

Mettler Electronic balance PL 220 (or equal)

Conditioned weighing trays

Scoops

Degassed Al powder

Uranium fuel alloy powder

Conditioned bottles (glass with Al inserts in lids)

10-gram standard weight and 20-gram standard weight

III. Procedure

Explain.

1. Take an [Al conditioned weighing tray] place it on the balance and tare out its weight.
2. Transfer the appropriate weight of Al powder to the conditioned tray on the balance.
3. Record the weight of Al powder.
4. Weigh the preconditioned bottle to be used and record the weight and bottle number.
5. Transfer the weighed Al powder to the bottle by "folding" the weighing tray in half and slowly tapping the contents out. If there is any noticeable spillage, reweigh the powder.

6. Weigh and record the weight of the Al filled bottle.
7. Take a fuel alloy conditioned weighing tray, place it on the balance and tare out its weight.
8. Transfer the appropriate amount of uranium fuel alloy to the tray on the balance.
9. Record the weight of fuel alloy powder.
10. Transfer the weighed fuel alloy powder to the bottle containing the appropriate amount of Al powder. Cap the bottle. *→ If spillage, reject.*
11. Weigh and record the weight of the Al + fuel alloy containing bottle.
12. Remove and store charges to be mixed. *What about fines?*

IV. General

1. Always maintain "good housekeeping" with powders. Avoid any rapid movement of powders to minimize tendency to create airborne material.
2. Be sure balance is warmed up and clean.
3. Keep caps on bottles at all times except when filling them. Always weigh powders in capped bottles. Take care not to interchange caps.
4. At the beginning of each day the balance must be calibrated by using calibrated 10 gm. and 20 gm. weights. The balance should read within ± 2 milligrams of the indicated weight. If not, the balance must be serviced.
5. Generally, the fuel alloy powder will be U + 4 w/o Si or U + 3 1/2 w/o Si + 1 1/2 w/o Al. However, the same procedure applies if any other fuel alloy powder is used.
6. Record all weighings to the nearest milligram. It should be noted, however, that accuracies to the nearest 10 milligrams (0.01 gram) are adequate for this work.
7. The terms vial and bottle are used interchangeably in this procedure and in any other reference to the containers employed.

V. Sample Worksheets

1. Two worksheets are attached. One with sample data; one blank. The blank sheet is to be reproduced and used for recording all the powder compact weight data. One compact charge per sheet.
2. Spaces for additional information on mixing (RERTR Fab. Procedure #8) and compacting (RERTR Fab. Procedure #9) are included on this worksheet. The required data must be recorded in the appropriate spaces.

(SAMPLE)

RERTR Fab. Proc. No. 7 Page 3 of

RERTR POWDER COMPACT LOG

Date 4/14/81 Fuel Alloy V₃ Si Fuel Alloy Melt # RERTR-116
(nominal composition)
Target Composition 41 w/o Binary
Compact No. MEAB-41-35 F Wt., (Fines) 2.216 g
Wt., Ideal Aluminum 2.8745 g Total Fuel 14.753 g
(Coarse & Fines - Actual wt.)
Wt., Ideal Fuel (Coarse) 12.5327 g Wt., Vial + Fuel + Al 37.748 g
Wt., Ideal Fuel (Fines) 2.2116 g Press Force 44,000 lbs.
Vial # 5 Lubricant 1 w/o Stearic Acid
Wt., Empty Vial & cap (Initial) 20.129 g Blended By V-blender Time 3 hours
Wt., Aluminum 2.877 g Wt., Green Compact 17.614 g
Wt., Vial & Al 23.005 g Wt., Charge 17.623 g
Wt., Fuel (Coarse) 12.537 g Wt., Loss .009 g
Wt., Vial + Fuel (Coarse) + Al 35.535 g Dimensions, Green .1638 x .5413 x .16764
(inches)
Weighed by TCW Date 4/14/81
Blended & Compacted by TCW Date 4/15/81

Vacuum Degassed Al Powder from Lot #2455

Checked with standard before weighing. H.C.G.

RERTR POWDER COMPACT LOG

Date _____ Fuel Alloy _____ Fuel Alloy Melt # _____
(Nominal Composition)

Target Composition

Compact No. _____ Wt., (Fines) _____ g

Wt., Ideal Aluminum _____ g Total Fuel _____ g
(Coarse & Fines - Actual wt.)

Wt., Ideal Fuel (Coarse) _____ g Wt., Vial + Fuel + Al _____ g

Wt., Ideal Fuel (Fines) _____ g Press Force _____

Vial #	Lubricant
1	100% SAE 30
2	100% SAE 40
3	100% SAE 50
4	100% SAE 60
5	100% SAE 70
6	100% SAE 80
7	100% SAE 90
8	100% SAE 100
9	100% SAE 110
10	100% SAE 120
11	100% SAE 130
12	100% SAE 140
13	100% SAE 150
14	100% SAE 160
15	100% SAE 170
16	100% SAE 180
17	100% SAE 190
18	100% SAE 200
19	100% SAE 210
20	100% SAE 220
21	100% SAE 230
22	100% SAE 240
23	100% SAE 250
24	100% SAE 260
25	100% SAE 270
26	100% SAE 280
27	100% SAE 290
28	100% SAE 300
29	100% SAE 310
30	100% SAE 320
31	100% SAE 330
32	100% SAE 340
33	100% SAE 350
34	100% SAE 360
35	100% SAE 370
36	100% SAE 380
37	100% SAE 390
38	100% SAE 400
39	100% SAE 410
40	100% SAE 420
41	100% SAE 430
42	100% SAE 440
43	100% SAE 450
44	100% SAE 460
45	100% SAE 470
46	100% SAE 480
47	100% SAE 490
48	100% SAE 500
49	100% SAE 510
50	100% SAE 520
51	100% SAE 530
52	100% SAE 540
53	100% SAE 550
54	100% SAE 560
55	100% SAE 570
56	100% SAE 580
57	100% SAE 590
58	100% SAE 600
59	100% SAE 610
60	100% SAE 620
61	100% SAE 630
62	100% SAE 640
63	100% SAE 650
64	100% SAE 660
65	100% SAE 670
66	100% SAE 680
67	100% SAE 690
68	100% SAE 700
69	100% SAE 710
70	100% SAE 720
71	100% SAE 730
72	100% SAE 740
73	100% SAE 750
74	100% SAE 760
75	100% SAE 770
76	100% SAE 780
77	100% SAE 790
78	100% SAE 800
79	100% SAE 810
80	100% SAE 820
81	100% SAE 830
82	100% SAE 840
83	100% SAE 850
84	100% SAE 860
85	100% SAE 870
86	100% SAE 880
87	100% SAE 890
88	100% SAE 900
89	100% SAE 910
90	100% SAE 920
91	100% SAE 930
92	100% SAE 940
93	100% SAE 950
94	100% SAE 960
95	100% SAE 970
96	100% SAE 980
97	100% SAE 990
98	100% SAE 1000
99	100% SAE 1010
100	100% SAE 1020

Wt., Empty Vial & cap (Initial) _____ g Blended By _____ Time _____

Wt., Aluminum _____ g Wt., Green Compact _____ g

Wt., Vial & Al _____ g	Wt., Charge _____ g
------------------------	---------------------

Wt., Fuel (Coarse) _____ g Wt., Loss _____ g

Wt., Vial + Fuel
(Coarse) + Al _____ g Dimensions, Green _____
(inches)

Weighed by _____ Date _____

Blended & Compacted by _____ Date _____

[illegible]

Revision No: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTIR Fabrication Procedure No. 8

POWDER MIXING

I. Purpose

In order to generate a homogeneous compact, it is necessary to thoroughly mix powders of the appropriate materials. This procedure describes the steps involved in mixing such powders so as to ensure, as much as possible, the thorough intermingling of the powders from which a compact is to be made.

II. Equipment

V-blender (Patterson-Kelley Twin Shell Lab Blender, or equivalent)
"Conditioned" 4 dram bottles (glass, not plastic)
Foam rubber holder
Plastic zip-lock bag

III. Procedure

1. Place appropriate amount of materials (powder) into jars.
2. Secure caps on jars and record charge no. and jar no., seal caps with tape.
3. Place bottles into the slotted foam rubber. Place complete assembly into a plastic zip-lock bag and seal.
4. Place the plastic bags into the V-blender.
5. Mix charges for ~~two to~~ three hours. *minimum.*
6. Remove bags and inspect for leakage.
7. Remove and store charges to be compacted. Indicate date and hour mixing was completed on a label affixed to the jar.

IV. General

1. Charges should be compacted within 4 hours of mixing..
2. Blended charges are to have a minimum of agitation. Reblend any blended charge jar that is dropped. Hand carry all blended charges.
3. In the event of leakage from a jar retain all materials within the zip-lock bag and proceed with disposition of materials according to proper procedures for such disposition.

Revision No.: 0

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Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 9

PRESSING COMPACTS

I. PURPOSE

One step in the fabrication of a fuel element processed by powder metallurgy techniques is to surround the fuel with a protective clad. This is initiated by placing compacts into cavities milled into a "picture frame". These compacts are prepared by weighing, mixing and pressing in a die the appropriate quantities of powders of the specific materials at pressures calculated to produce the desired porosity. This Procedure describes the steps involved in producing the compact and applies, irrespective of the specific die size or the materials compacted.

II. MATERIALS AND EQUIPMENT:

Press

Die, Punches and Die Set

Stearic Acid and Methylene Chloride (Reagent Grade)

Artists' Brushes

Leveling Tool (Spatula)

Kimwipes (Kimberly Clark)

Alcohol (Ethanol)

Surgical Knife and Razor Blade

Zip Lock Bags

III. PROCEDURE:

1. Check die components; - to scrape any excess aluminum, use surgical

knife in corners and razor blade for flat surfaces. Remove smeared aluminum with alcohol solution. Rinse with alcohol and remove any evidence of galling.

2. Wipe all components with alcohol and Kimwipes. The edges and corners of the die are to be wiped clean.
 3. Lubricate die cavity with a solution of 1 wt. % stearic acid and methylene chloride (1 gram acid and 100 cc. methylene chloride). Shake solution before use. A fresh solution is to be used every day.
 4. Lubricate punch face with stearic acid solution using an artist's brush.
 5. Wipe off excess lubricant from the die cavity with a dry Kimwipe. Raise lower punch and wipe upper and lower punch.
 6. Raise the die so that the bottom punch is at about mid-die position.
 7. Hand mix charge by inverting bottle five times. Pour compact charge slowly and gently into the cavity. Fill the die cavity by starting in the center and moving left to right and back again.
- Tap empty jar with fingers to ensure complete emptying. Inspect jar to be sure it is empty.

8. Level fuel charge by lowering "floating" die until fuel (powder) level is just above the die surface. Strike off top with a spatula. Raise the floating die and repeat until striking the top yields no more powder.
9. Lower bottom punch smoothly to about mid-die position.
10. Place upper punch in die cavity and carefully slide die under the press.
11. Press compacts at pressures calculated to produce the desired porosity (density). This pressure will vary according to the nature of the charge and the size of the die. Typically, pressures in the range of 12 to 25 TSI required. Pressures are held for 10 seconds. Record pressing load and die size so that pressures (load/area) can be calculated and recorded.
12. Remove upper punch, insert "stripping block" and eject compact.
13. Handle compact carefully using surgical or PVC gloves. Place in plastic Zip Lock Bag and identify. Store finished compacts under a vacuum until ready to use.

IV. GENERAL:

Die and die set not to be vibrated during loading, leveling, and pressing. The artist brush used to apply the stearic acid solution is to be replaced if the brush shows signs of wear or damage as evidenced by loose bristles.

Bristles are not to be clipped or cut, but the brush replaced. A new brush is to be examined for loose bristles and these bristles removed by brushing the stearic acid solution on a clean steel surface until no loose bristles are found. The bottom platen of the press and the bottom surface of the die set are to be kept free of any oil film. The presence of a film will result in uneven gauge compacts. No shimming for the punch or die set is allowed. Keep brush in plastic bag and stearic acid solution covered when not in use.

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: _____

H. R. Thresh

RERTR Fabrication Procedure No. 10

CLEANING 6061 STOCK FOR ASSEMBLIES

I. Purpose

In rolling plate assemblies it is mandatory that the components be absolutely clean prior to assembly. Grease, dirt and surface oxides must be removed. This procedure describes the steps which must be taken to produce such stock.

The identical procedure may be employed to remove up to 0.003 in. from nominally finished miniplates to bring them within specified dimensions. Similarly, plates may be treated after final annealing to remove up to 0.002 in. of material, if necessary.

II. Equipment

Non-rotating spindle micrometer 0 - 1"

1 - 4000 ML SS beaker-for Oakite-160

1 - 4000 ML SS beaker-for hot preliminary rinse

1 - 4000 ML SS beaker-for hot final rinse

1 - 3000 ML Polyethylene or PVC container-for nitric acid solution

1 - 5 gal. Polyethylene or PVC container for rinse water

1 - 5 gal. Polyethylene or PVC container for rinse water

Baskets for cleaning covers and frames (polyethylene)

3 thermometers (0 to 150°C)

Acetone for degreasing

3 laboratory hot plates

Mixing Solutions

Add and dissolve 225 grams of Oakite-160 to 3000 ML of water (de-ionized).

The nitric acid solution consists of 55% nitric acid (60% reagent grade)

45% water (de-ionized) by volume. Always add acid to water.

III. Procedure

1. Remove from their protective wrapping the components of one assembly (2 cover plates and 1 picture frame).

2. Using a clean work area adjacent to the cleaning train, clean each part with acetone and Kimwipes. Wave each part to air dry and lay on clean tissues. Put on clean cotton or nylon gloves. Place one part at a time in the basket.
3. Etch part in Oakite solution by slowly agitating back and forth for approximately 1.5 minutes. Temperature should be 75-80°C and should remove .0018" to .0022". A laboratory hot plate is used for heating. *and never exceed 85°C*
4. Rinse in room temperature de-ionized water: Use 5 gal. container for this purpose. Agitate slowly up and down 10 to 15 times. *← Add wiping with Kimwipe*
5. Pickle in nitric acid solution for 2 minutes at room temperature. Agitate slowly.
6. Rinse in room temperature de-ionized water in 5 gal. container provided for this purpose. Agitate slowly up and down 15 to 20 times.
7. Again etch in Oakite for approximately 5 secs. at 75 to 80°C. Agitate slowly.
8. Rinse in room temperature de-ionized water in PVC 5 gal. container. Agitate slowly up and down 10 to 15 times. *→ Add wiping*
9. Pickle in nitric acid solution for 2 minutes at room temperature. Agitate slowly.
10. Rinse in room temperature de-ionized water in 5 gal. container. Agitate up and down 15 to 20 times.
11. Rinse in de-ionized hot water 75 - 80°C for 10 secs. Agitate slowly up and down. Use laboratory hot plate for heat.
12. Rinse second container of de-ionized hot water 75 - 80°C for 5 to 10 secs. Agitate up and down slowly.
13. Remove from hot water and air dry by gently waving basket back and forth. Examine for smut, stains or water spots. Surface should be bright and with a satin finish. Lay cleansed components on clean tissue. The aforementioned procedure should be followed for each frame and cover plate.

IV. General

The height of the solutions in containers must be more than 6". That is, plate must be completely submerged during each "dip". Add acid to water, never water to acid in mixing nitric acid solution.

If the components show any evidence of residual smut between steps III-5 and III-6, the components may (should) be wiped with Kimwipes until clean.

The procedures noted in this document are specific for 6061 Al Alloy. It is likely, however, that the same procedure may work equally well for any other Al alloy which may be used in this or similar assemblies.

Solutions should be changed after ~20 plates (3" x 6") have been processed or sooner if the steps noted above do not yield plates of the required cleanliness. Solutions and water are to be kept covered at all times when not in use.

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 11

ASSEMBLING & WELDING PLATE COMPONENTS

I. PURPOSE

In order to produce a properly bonded fuel plate, the frames, covers and compacts must be assembled for rolling. The generation of these components is described in other Fabrication Procedures; this document details the steps in assembling the items for hot rolling.

II. MATERIAL AND EQUIPMENT:

A well-lighted clean bench or table top covered with paper

Cotton gloves

Rubber gloves

2 Copper chill blocks ~2" X 5" X 3/16" thick

Helifarc welder (A.C.), 200-amp capacity min.

2 C-clamps

1 Vise for welding

Welding table

4043 Welding wire

6061 Cover plates (2)

6061 Picture frame (1)

Compacts (2).

III. PROCEDURE:

For handling of the assembly components, two people are required. One person to assemble the cover plates and picture frame; the other to place the

compacts into the picture frame. While the person assembling the aluminum plates can wear only cotton gloves, the person loading the fuel compact should wear latex gloves with cotton gloves over them. ~~The lower left hand corner of the cover plate and picture frames should be cut off at 45°.~~ This will serve to uniquely identify the front and rear position of the assembly and will reference the location of the fuel compacts in the assembly.

The plate is stamped with an ID # in the lower right side

1. Place the bottom cover on the table.
2. Place the picture frame on top of the cover, making sure it is aligned properly.
3. Place the compacts in each opening according to their designation.
4. Place the top cover on, maintaining the trimmed corner in relation to the compact designations.
5. With the assembly aligned, the chill blocks are placed on each side being centered with approximately the same amount of assembly being exposed around the perimeter.
6. A C-clamp is placed on each end directly on the chill blocks. The assembly is now ready for welding.

7. It is heliarc welded with, if necessary, 4043 welding wire. A bead is laid on the front and sides, stopping approximately 1/4" from each corner. The rear is the end ^{with the ID #} ~~from which one corner has been trimmed~~. On the rear, a 1/2" wide section in the center is left unwelded, still stopping 1/4" from each corner.
8. If it is impractical to begin the rolling pre-heat cycle at this point, the assembly plate can be placed in a pre-designated vacuum chamber and evacuated.

IV. GENERAL

1. The purpose of vacuum storing welded assemblies is to preclude moisture and gas pick-up on standing. Normally, the assemblies will be stored for several hours before rolling. However, it is acceptable to have them stored overnight or even over a weekend. The vacuum attainable with a good mechanical pump (5-10 Torr) is adequate.
2. In handling, clamping, and welding, it is imperative that no defects be generated in the surfaces of the frame and covers.
3. If a powder compact does not fit into the cavity, gentle heating (<100°C) of the frame with a hot plate is permissible. If a compact is damaged (e.g., corner or edge chipped) that compact should be removed and treated as a reject or, alternatively, left in place and the plate generated from that compact should be identified as a reject.

Revision Date: April 16, 1981Written By: R. F. DomagalaApproved By: H. R. ThreshRERTR Fabrication Procedure No. 12ASSEMBLY HOT ROLLINGI. PURPOSE

Fuel plates are produced by hot and cold rolling the assemblies consisting of 6061 frames and covers which contain, in cavities machined into the frames, powder metallurgically prepared compacts. This procedure describes the steps and precautions involved in hot rolling such assemblies.

II. MATERIALS AND EQUIPMENT

9" x 16" rolling mill with flat rolls (no camber, ~25 micro-inch finish)

2 sets of tongs w/stainless steel inserts fixed to the insides of the jaws

Resistance furnace capable of accepting assemblies (based on finished dimensions) w/heat range capability of at least 550°C.

Texaco Pinnacle-680 oil - 1 part diluted by 3 parts Wet Edge. (by volume)

Roll Wipers - brackets wide enough to cover roll surfaces top and bottom w/1/2" thick felt No. F-10 White (Continental Felt Co., New York, N.Y.).

Work gloves.

Heat Lamps - 2 (250 watt). One focused on the top roll and one focused on the bottom roll.

Welded Plate Assembly.

III. "REGULAR" PROCEDURE

Before each rolling operation, rolls are to be cleaned with a solvent (chloroethene, acetone). The felt wipers to be cleaned of debris or replaced and resoaked with Pinnacle oil solution. The heat lamps turned on and focused

on the rolls and heated (realistically to $\sim 115^{\circ}$ to 120°F). A stainless steel rack inside the furnace is used for supporting the assemblies while they are being heated. The resistance furnace temperature is set to control $500^{\circ} \pm 5^{\circ}\text{C}$. Temperature within the furnace must be confirmed with an independent thermocouple. Identities of assemblies are stamped or scribed on surface, well out of the area which will ultimately comprise the miniplate.

1. Load assemblies into furnace for pre-heat. Pre-heat for 45 minutes. [One, two, or three (maximum) assemblies may be placed in furnace].
2. Begin rolling. Make sure assemblies are lined up properly when feeding. There are a total of [~]eight (8) passes from start to finish.
3. The most important aspect of the rolling is related to the 1st three reductions. They are, respectively, $\sim 25\%$ of the original thickness, $\sim 25\%$ of the resulting thickness, and $\sim 20\%$ of that resulting thickness. The remaining reductions are divided into approximately 20% per pass down to final size. *The ID# is restamped after the*
4. Bonding is probably achieved with the first two or three reductions. *third pass.* There is a 10-minute re-heat time between the 1st and 2nd pass and the 2nd and 3rd pass. Subsequent re-heats are only 5 minutes per pass. Based on a fixed starting and finishing thickness, a set rolling schedule is established in regard to the above information. There is an allowance made for a predetermined percent cold reduction to the finished size.
5. Final hot-rolled thickness should be at least 10% over final plate thickness. While there is no maximum on the oversize thickness in hot-rolling, realistically, it should be kept in the 15-20% range.

IV. "SPECIAL" PROCEDURES

In some instances (e.g. at high vol. pct. fuel alloy in compact), it has been found advantageous to follow a modified hot-rolling schedule which is referred to here as "Special". In this instance all equipment, roll pre-heat, furnace temperatures, etc. are identical to the regular procedure but the rolling proceeds as follows:

1. Preheat assembly (or assemblies) at 500°C for 45 minutes.
2. The first pass is a 30% reduction in thickness. The assembly is returned to the furnace for a 10 minute reheat.
3. The second pass is a 50% reduction. (That is, 50% of the thickness remaining after the first pass.) The plate is allowed to air cool to room temperature after this pass.
4. Passes from this point on are done at room temperature with reductions at ~ 0.020 in. to 0.010 in. per pass entirely dependent on the judgement of the rolling personnel. Intermediate anneals (500°C, 5-10 min, air cool) may be conducted if, in the judgement of the rolling personnel, such anneals are desirable.
5. The tandem assembly may be sheared transversely into two pieces (as in the "regular" hot rolling procedure) at any point in the rolling schedule after the first two (500°C) passes. The reason for shearing is to create pieces that are more easily handled.
6. The room temperature reductions are carried out until the assembly (or the two pieces created by shearing the assembly) is of the proper thickness. For 0.060 in. plates this would be ~ 0.070 in. and for 0.050 in. plates this would be ~ 0.060 in. (the 0.010 in. oversize is, of course, to allow for the 10% or more cold work necessary in the final reduction to size).

7. After rolling to oversize is complete, the $485 \pm 15^\circ\text{C}$ anneal for 50 ± 10 min. must be conducted prior to any further work.

V. GENERAL

During the rolling process particular attention should be paid to the identification of the assembly plates, re-identifying when and if necessary. Initially, the plates are placed in the furnace with the end containing the 1/2" unwelded center facing the door. This is to allow gasses to escape when making the first rolling pass. [For each successive pass, the assembly is "flipped over" (i.e., the top surface becomes the bottom for pass two and once again is the top surface for pass three). However, the leading edge (front) of the assembly remains the front for all hot rolling passes.] It is essential to measure the thickness after each pass. Another important factor is to make passes as quickly as possible to reduce heat loss. After the fourth pass in the "regular" procedure, the plates are cooled to room temperature, sheared in half (transverse) to accommodate the furnace depth. The front section in this case should have the lower left-hand corner sheared off.

Not true
we flip
end to
end.

The "special" procedure was developed empirically with experience indicating that a more uniform fuel alloy distribution could be obtained with this modified practice.

Rolls, plates, tongs, etc. must be kept meticulously clean at all times.

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: _____

H. R. Thresh

RERTR Fabrication Procedure No. 13

COLD ROLLING AND LEVELING

I. Purpose

The specifications for miniplates require a minimum of ten percent cold work to be conducted after the blister anneal which follows the hot rolling. This procedure describes the steps for such rolling as well as any roller leveling which may be required to produce flat plates.

II. Materials & Equipment

Rolling Mill (may be the same mill used for hot rolling)

Roller Leveler

Tongs

III. Procedure

1. The hot-rolled and annealed plate will be in excess of ten percent thicker than the finished plate.
2. Clean rolls thoroughly (acetone and Kimwipes). Remove any roll tables or roll guides.
3. Practice rolling with 6061 stock to get the "feel" of the mill and to establish the settings of the mill required to produce a given thickness. The 6061 practice material should preferably be in a metallurgical condition simulating that of the miniplates (e.g., $485 \pm 20^{\circ}\text{C}$, 60 ± 10 minutes, air cool).
4. The generation of the final plate by cold rolling will be largely a matter of personal judgement of the personnel doing the rolling. Typically, reductions of ~ 0.002 to 0.003 in. per roll setting have been found effective. Multiple passes at a given setting are to be avoided, if possible, or kept minimal..
5. The rolling direction established throughout the fabrication procedures will be maintained. That is, the original (mill) rolling direction will be preserved and no cross-rolling is allowed.

6. It may, at the discretion of the rollers, be desirable to make what had been the leading edge during hot-rolling become the trailing edge during cold rolling. This is perfectly acceptable and no record need be made of such a variation. Similarly, it may be desirable to flip the plate such that the bottom surface may become the top surface on successive passes.
7. It is unlikely that the final thickness within ± 0.001 in. can be accomplished directly in all or even most cases. Therefore, it is best to stop cold rolling when the fuel plate is approximately 0.001 to 0.002 in. oversize and (later) remove this excess by chemical (Oakite solution) means.
8. Roller level plates as required. A minimum number of passes is best and no reduction in thickness should be accomplished in this step.

IV. General

Rolls, plates, tongs, etc., must be kept meticulously clean at all times.

Revision No: 1

Revision Date: July 11, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 14

RADIOGRAPHY OF PLATES

I. Purpose

During the course of producing fuel plates, x-ray photos of the assembly are necessary at various stages of production. This procedure describes the steps to be taken for any such radiographs.

II. Materials and Equipment

X-ray machine (Picker 110 KV "Hotshot" portable X-ray machine or equal)

X-ray Film (Kodak Type M lead pack, 8" x.10" or larger)

Film Developer (Kodak Model B Automatic Film processor, or equal)

Densitometer (Macbeth Model TD-502 Digital Densitometer with calibrating film density strip, or equal)

Step Wedge of appropriate composition and thickness

III. Procedures

A. General Fuel Location and Geometry (including x-ray of Finished Plate)

1. Place plate at any stage of the fabrication procedure on the X-ray film. Include alongside the plate, on the film cassette, enough lead markers so that the assembly or plate is uniquely identified. Be sure to include the date and a lead arrow indicating rolling direction as defined in the first rolling pass.
2. Expose film (70 KVP, 2 Ma, 5 seconds have been found to be useful x-ray parameters) KV? Small m?
3. Develop and dry film.

B. For Densitometric measurements of fuel concentration

1. Procedures are essentially the same as for A above except

that the x-ray tube parameters will have to be determined by trial and error to provide proper film exposure (what has worked well is ¹⁰⁰90 KVP, 3 ^{same component}Ma, 65 seconds). 30-120

2. In addition to the plate(s) and identification, an appropriate step-wedge will serve as a reference for measuring fuel concentration. Be sure to include under the step-wedge, shimstock of 6061 aluminum to a thickness equal to the calculated clad thickness (top & bottom) in the fuel zone area of the plate.

3. Expose and develop film. So as to minimize significant variation from one exposure to another, the same tube parameters should be used and the developing should, if possible, be conducted in an automated unit.

4. Using appropriate densitometer with 2 to 4 mm diameter spot size (a 3mm spot size has been used on all ANL work to date) measure and record a sufficient number of readings on each step of the wedge and on random positions of the plate to provide statistically satisfactory data. Because of the small size of the step-wedge, probably only four to six readings per step can be made. On the plate, however, 30 random readings are suggested.

5. To determine fuel concentration in a plate follow the procedure outlined below:

a. Plot densitometer intensity (avg.) vs. thickness for the step wedge. Use 8 1/2" x 11" linear graph paper and draw the best representative curve.

b. Take the arithmetic mean, the high and the low value of the densitometer data for the plate.

- c. Convert the densitometer values (e.g., the mean) to equivalent step-wedge thickness in inches.
- d. Depending on the composition of the step-wedge, convert the equivalent thickness to uranium content in grams/cm³ for the plate.
- e. Perform any other calculations required. For example, it may be necessary to convert to grams ²³⁵U per square meter of surface area. In this case the enrichment level of the uranium used in the fuel alloy must be factored into the calculations. (See sample calculation appended to this procedure.)

C. Inspection of X-rays

1. All X-rays will be inspected on an appropriate light box by at least two persons.
2. A flat-image measuring magnifier will be used for inspecting the geometry of the fuel zone and for determining if there are any fuel alloy particles out of the prescribed zone. The magnifier will have a magnification of between 5X and 10X. Commercial units usually can be purchased with various scales so that actual measurements can be made directly with the magnifier.
3. A record shall be made of plates which meet all requirements. Likewise, information on reject plates will be recorded identifying the nature and, if possible, the cause of the defect determined by X-ray.

IV. General

- A. Handling of the plates must be done carefully to preclude damaging any surfaces.

B. For plates processed to date, a 22 inch FFD (Focal spot-to film-distance) has worked satisfactorily.

C. The Picker unit identified under "Equipment" is now produced and sold by TFI Corporation (New Haven, Conn.). However, any X-ray unit of equal capability is quite acceptable.

V. Sample Calculations (Appendix)

This is intended to serve as a sample of the steps required and the calculations involved in the determination of Uranium (235) density for the fuel plates.

1. Following the steps outlined in RERTR Fabrication Procedure No. 14, X-rays for fuel density measurements are taken using the appropriate step wedge. For the work to date, the reference step wedge for the 30 v/o U_3Si or $U_3Si + Al$ plates was machined from a portion of a rapidly solidified cast alloy of Al + 30.07 wt. pct. U (by analysis). Seven steps were machined at 0.0986; 0.0942; 0.0892; 0.0844; 0.0793; 0.074 inches. New
wedge

The density of this alloy is known to be 3.568 grams per cm^3 , confirmed by density measurements at ANL.

2. Five density measurements are taken on the X-ray film of each step of the wedge using a 3mm spot size. An arithmetic mean is determined.
3. Thirty random readings are taken on the X-ray film of the fuel zone area of the miniplate. No values are discarded, an arithmetic mean is calculated; the minimum and maximum readings are noted. The spot size for these readings is also 3mm.

4. The average (mean) densitometer reading for each step of the wedge is plotted (ordinate) vs. the step wedge thickness (abscissa) on linear graph paper. The data points are connected by the best smooth line which can be constructed.
5. The mean, maximum and minimum densitometer readings for the fuel zone are noted on the plot and a horizontal line drawn to the curve and dropped down to the abscissa to determine an equivalent step-wedge thickness. The results are typically as sketched below:

6. For the step wedge alloy we have:

$$\frac{0.3007 \text{ g. U}}{1 \text{ g. Alloy}} \times \frac{3.568 \text{ g. Alloy}}{\text{cm}^3 \text{ Alloy}} = \underline{1.073 \text{ g. U/cm}^3 \text{ Alloy}}$$

If we further assume a portion of the wedge measuring 1 cm x 1 cm x t(in.) thickness we have:

$$U \text{ (total)} = 1 \times 1 \times t(\text{in.}) \times 2.54 \left(\frac{\text{cm}}{\text{in}} \right) \times 1.073 \left(\frac{\text{g. U}}{\text{cm}^3} \right)$$

U (total) = 2.719 x t(in.) Grams·U [for a 1 cm x 1 cm area]

$$\frac{\text{U total}}{\text{meter}^2} = \frac{2.719 \times t(\text{in.})}{\text{cm}^2} \times \frac{10^4 \text{ cm}^2}{\text{m}^2} = 2.719 \times t(\text{in.}) \times 10^4 \frac{\text{grams}}{\text{meter}^2}$$

For a miniplate at 19.88% enrichment and two surfaces to dissipate the heat:

$$\begin{aligned} \frac{\text{g } ^{235}\text{U}}{\text{meter}^2} &= \frac{2.719 \times t(\text{in.}) \times 10^4}{2} \times 0.1988 \\ &= 0.2703 \times 10^4 \times t(\text{in.}) \end{aligned}$$

"770" 11.8%
in. in. in.

Therefore, take the equivalent step wedge in inches, multiply it by

2703 and you have the ^{235}U density in grams/meter².

70.3 11.51%
enrich

e.g., for miniplate 30-4R(A-19)

Densitometer Reading	Equivalent t (inches)	$\frac{\text{g } ^{235}\text{U}}{\text{meter}^2}$	76.7% 11.24% enrich.
Avg. 1.53	0.0818	221	
Min. 1.25	0.0952	257	
Max. 1.88	0.0708	191	

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Revision Date: August, 1980
Written By: R. F. Domagala
Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 15

METALLOGRAPHY

I. Purpose

During the course of development work as well as the production of fuel plates, it is necessary to conduct metallographic studies of the products produced. This procedure outlines the steps required to conduct three different types of metallographic work necessary in the pursuit of this effort. The purposes of metallographic examinations are to determine the microstructure of the fuel alloy, the distribution of the powdered fuel alloy in the aluminum matrix, the bonding of the fuel zone to the cover plates, (clad) the bonding of the cover plates to the core frames and the thicknesses of core and cover plates as well as the existence of dog-bonding.

II. Materials & Equipment

Conventional metallographic equipment including a metallograph capable of magnification up to X1000 and with provision for polarized light observations and photography.

III. Procedures

A. Bonding of Cover Plates to Frame (6061/6061/6061 interfaces)

A specimen for examination may be cut from a rolled assembly at any point in the fabrication procedure. It is mandatory, however, that a section be taken after the assembly is reduced to final thickness and after it has been subjected to all the required annealing schedules. Specimens may be longitudinal or transverse, but will be sufficiently removed from the fuel zone (as determined by X-ray) so as to preclude cutting into or through any portion of the meat (fuel).

Specimens for determining interfacial bonding examination should be processed as follow:

1. Cut specimen on shear into sections small enough to fit into standard size (1 1/4" diameter) mount.

2. Segments should be set in Kold-Mount (acrylic) in a sequence respective of their relationship to one another.
 3. Acrylic is "cleared" in metallographic mounting press to make top and bottom surfaces parallel, and to produce a transparent mount.
 4. Rough grind through papers down to 600 grit.
 - 5a. Polish with 6μ , then 3μ diamond on nylon with Metadi fluid.
 - 6a. Polish with MgO on Gamal cloth and distilled H_2O .
 - 7a. Final polish with Leco "Finish-Pol" on Gamal cloth and distilled H_2O
 - 8a. Electroetch with a solution of 4% fluoroboric acid (HF_4) and H_2O for about 30 sec. at 30 V D.C. View under polarized light.
- Instead of steps 5a thru 8a, an alternative procedure which has proved effective is listed below as steps 5b thru 7b. If the b sequence is followed, start with a sample which has been carried through step 4 (600 grit).
- 5b. Polish with 6μ diamond, then 1μ diamond on Microcloth
 - 6b. Final polish first with MgO and distilled water on Microcloth and then with "Finish-Pol" (Leco) with distilled water on Microcloth
 - 7b. Electroetch in a 4% solution of HF_4 and water for two minutes at 1 amp (~ 30 volts). View under polarized light.

B. Cross-sectioned Studies of clad/fuel/clad

Procedures for this type of examination are the same as those recorded for A above with the exception of the etching step. In this instance the etchant should be 2 parts HF, 3 parts HCl , 5 parts HNO_3 , 190 parts H_2O . Immerse 10-20 sec. Wash in stream of warm water, rinse with alcohol and dry.

Viewing and photography is usually best done with conventional bright-field illumination.

C. Microstructure of U-Si and U-Si-Al Alloys

Examinations of the microstructure of the as-cast or heat treated alloys before comminution can also be conducted according to procedures outlines in Section 'A'. The etchant found effective for alloys in this system is a solution composed at 70 ml. H_2O , 72 ml. of reagent

grade HNO_3 , 1 ml of 48% HF and 3.4 grams of citric acid. The solution is prepared, the citric acid dissolved and the etchant applied by swabbing.

IV. General

1. Final polishing agents other than those noted herein may be used. The quality of the final microstructure may not be significantly different provided good metallographic practice is followed.
2. In lieu of acrylic mounts, Bakelite, Plastimet or other thermosetting polymers may be used for mounting samples. The obvious advantage of the acrylic is its transparency.
3. "Sampl-Klips" (AI Beuhler) may be used to support samples in mounting so that the section generated during processing will be perpendicular to the plate thickness.
4. Some of the items noted in Section III are Trade-Mark names - this is not always clearly identified. An equivalent material from another supplier is equally acceptable.

APPENDIX B

Revision No.:	<u>2</u>
Revision Date:	<u>September, 1989</u>
Written By:	<u>R. F. Domagala</u>
Approved By:	<u>H. R. Thresh</u>

RERTR Fabrication Procedure No. 15**Purpose**

During the course of development work, as well in the production of fuel plates, it is necessary to conduct metallographic studies of the products. This procedure outlines the steps required to conduct three different types of metallography necessary in the pursuit of this effort. The purposes of metallographic examinations are to determine the microstructure of the fuel alloy, the distribution of the powdered fuel alloy in the aluminum matrix, the bonding of the fuel zone to the cover plates (cladding), the bonding of the cover plates to the core frames, and the thicknesses of core and cover plates, as well as the existence of excessive fuel thickening commonly called "dog-boning." The procedures were developed for unirradiated miniplates and are intended primarily to serve the quality control needs of a fabricator.

Materials and Equipment

Conventional metallography equipment included a metallograph capable of magnification up to x1000 and with provision for polarized light observations and photography.

Procedures

Bonding of Cover Plates to Frame (6061/6061/6061 Interfaces). A specimen for examination may be cut from a rolled assembly at any point in the fabrication procedure. It is mandatory, however, that a section be taken after the assembly is reduced to final thickness and after it has been subjected to all the required annealing schedules. Specimens may be longitudinal or transverse, but must be sufficiently removed from the fuel zone (as determined by X-ray) to preclude cutting into or through any portion of the meat (fuel).

All of the metallographic supplies referred to by trade name were purchased from Buehler Ltd. of Lake Bluff, Illinois, and are identified with an asterisk.

Specimens for determining interfacial bonding examination should be processed as follows:

1. Cut specimen on shear into sections small enough to fit into standard-size (1.25-in. diameter) mount.
2. Segments should be mounted in an orderly sequence respective to one another. Diallyl phthelate is used most often for specimen mounting. In post-irradiation evaluation (PIE), metallographers use an epoxide (room-temperature cure) and may also use Bakelite and Cu powder if a conductive mount is required for microanalytical work later.
3. Rough-grind through papers down to 600 grit.
4. Polish with 1 μ m diamond on nylon with Metadi* fluid.
5. Polish with 0.05 μ m alumina on microcloth*.
6. Electroetch with solution of 4% fluoroboric acid (HBF₄) and H₂O for about 2 min at 30 VDC. (Al cathode, Pt probe). View under polarized light. In place of steps 4–6, an alternative procedure that has proved effective is listed below as steps 7–9. If the 7–9 sequence is followed, start with a sample that has been carried through step 3 (600 grit).
7. Polish with 1 μ m diamond paste on microcloth and choice of vehicle.
8. Final-polish with 0.05 μ m alumina and distilled water on microcloth.
9. Electroetch in 4% solution of HBF₄ H₂O for 2 min at 1 A (depends on sample size) and $\approx$ 30 VDC. View under polarized light.
10. A typical etched 6061 bonding structure is shown in Fig. B1. The grains and grain growth across the interface are clearly evident.

*Buehler Corp., Lake Bluff, IL, USA

Fig. B1. Typical etched 6061 Al grain structure ~50 X.

Cross-Sectioned Studies of Clad/Fuel/Clad. Procedures for this type of examination are the same as described above. In sectioning plates through the fuel zone, it has been found that shearing is an unacceptable procedure. There is enough mechanical stress imposed on the plate that deformation and damage to the fuel zone usually occurs. Cutting with a precision abrasive cutoff machine (such as an Isomet*) produces acceptable results. In this instance, the etchant should be 2 parts (by volume) HF, 3 parts HCl, 5 parts HNO₃, and 190 parts H₂O. Immerse for 10–20 s. Wash in stream of warm water, rinse with alcohol, and dry. Etching the fuel zone may be “tricky” due to porosity and pullouts. Thorough rinsing and drying is mandatory.

Viewing and photography is usually best done with conventional bright-field illumination. An optional etchant is identified below.

Microstructure of U-Si and U-Si-Al Alloys. The fuel etchants noted in the procedure are for U-Si and U-Si-Al alloys. For other fuel types (e.g., UAl₂, U₆Fe), different etchants and procedures were employed. Because the major interest is in silicides, information on the other fuel types was not recorded. Examinations of the microstructure of the as-cast or heat-treated alloys before comminution can also be conducted according to procedures

outlined above for bonding of cover plates. The etchant found effective for alloys in this system is a solution of 170 mL. H₂O, 72 mL. of reagent-grade HNO₃, 1 mL of 48% HF, and 3.4 g of citric acid. The solution is prepared, the citric acid dissolved, and the etchant applied by swabbing.

General

1. Final polishing agents other than those noted herein may be used. The quality of the final microstructure may not be significantly different provided good metallographic practice is followed.
2. In lieu of acrylic mounts, epoxides, Bakelite, Plastimet*, diallyl phthelate, or other thermosetting polymers may be used for mounting samples. The obvious advantage of acrylics and some epoxides are their transparency.
3. "Sampl-Klips*" (available from Buehler in stainless steel or plastic, we prefer plastic) may be used to support samples in mounting so that the section generated during processing will be perpendicular to the plate thickness.
4. Equivalent materials from metallographic suppliers other than Buehler are equally acceptable.

Note: Aluminum polishing wheels are the best choice in grinding and polishing. A slight electrolytic action may etch samples during polishing with brass (or bronze) wheels.

Revision No.: 0

Revision No.: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 16

CUTTING & MACHINING MINIPLATES TO FINAL DIMENSIONS

I. Purpose

Plates must be produced to accurately prescribed dimensions for insertion into the reactor vehicle. Miniplates are cut to final size after the rolling schedule is completed and after being roller leveled but before final annealing. The fuel zone in a plate is defined by x-raying. Notches cut into the sides of the plate are used to align the x-ray picture with the fuel zone in plate. The plate is marked for cutting with the x-ray picture taped to it.

II. Materials & Equipment

Plates for shearing

X-rays of plates

Tuck tape No. 5220 (Nuclear Grade)

D1 Acro Shear

Machine Shop equipment, e.g. milling machine

III. Procedure

1. After final rolling, excess material is trimmed off the lead and tail ends leaving the plate about 8" long.
2. Sharp V notches are filed ^{or cut} into all four sides of the plate so that the x-ray film can be aligned with its position after the film is developed. (Notches must not be placed symmetrically).
3. Plate is X-rayed; X-ray film is developed.
4. Write identity of plate in fuel zone of x-ray before cutting up x-ray. Use permanent ink Sharpie marker.
5. The x-ray has the view of the plate cut out of it on a paper shear. (It must be taken into account that the x-ray film image is slightly enlarged when developed).
6. The negative is taped onto the plate with the notches properly registered. The fuel zone of the plate is thus defined by its picture on the film.

7. The reverse side of plate is protected by covering it with nuclear grade Tuck tape. (No. 5220).
8. The width of the fuel zone is measured and this dimension is subtracted from 2" (the outside width of the finished mini-plate). Half of this difference, or at least 0.100", determines the border area around the fuel zone. A straightedge is placed on the plate longitudinally at the desired distance from the fuel zone and a line is scribed along this edge (through the film and into the plate) with a single edge razor blade.
9. A second mark perpendicular to the first line is made to indicate where one corner of the mini-plate shall be. This mark and the scribed line serve as a reference for shearing and machining.
10. Lines are next drawn on the X-ray film $\sim 1/16"$ (~ 0.060 in.) out from the final dimensions of the mini-plate as a guide for shearing.
11. The excess material is cut off on the shear (Di-Acro). All scrap pieces are collected and identified as to plate number and relationship to fuel zone. After shearing of each of the first three sides it is necessary to retape the negative to the fuel plate along the cut edge.
12. Remove negative from plate and cover bare surface with nuclear grade Tuck tape (No. 5220). Leave scribed line and corner mark visible for machinist.
13. Write identity of fuel plate on label and stick label onto taped surface of fuel plate.
14. Fuel plate is sent to machine shop (in accordance with criticality procedures) with instructions for machining to proper specifications. Dimensional specifications are shown in ORNL drawing No. X3E11821-105A.

IV. General

Precautions during handling must be such that no defects are introduced into the surfaces or edges of the plate. Identification of each plate must be unequivocally retained at all times.

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 17

BLISTER TESTING & ANNEALING

Remove O-temper
anneal steps

I. Purpose

Two annealing schedules are prescribed during the generation of fuel plates. The purposes of these anneals are to enhance bonding, to generate visible blisters in non-bond areas so that such (non-bond) plates may be rejected, and, finally, to reduce the plates to an O-temper conditions. This procedure describes such annealing steps.

II. Materials and Equipment

Furnace large enough to accept plates and able to be cooled at $\leq 28^{\circ}\text{C}$ per hour.

Rack to support plates.

6061 plates to serve as platens for the O-temper anneal.

These may be 1" to 2" thick. Tantalum plates (0.050 to 0.060 in. thick).

Tongs

III. Procedure:

A. After Hot-Rolling

1. Place plates on rack in furnace at $485 \pm 20^{\circ}\text{C}$. No more than six plates should be treated per run.
2. Hold at temperature for 60 minutes $\pm$ 10 minutes.
3. Remove plates from furnace and air cool.
4. Inspect for blisters. Both sides of each fuel plate shall be visually inspected. Detection of one or more blisters of any size that would remain in the finally sized fuel plate shall be cause for rejection.

B. After Cold Rolling

1. Have 6061 plates (platens) in furnace at $485 \pm 20^{\circ}\text{C}$. Tantalum plates can be between these platens.
2. Remove plates from furnace; place up to six fuel plates on tantalum sitting on bottom platen. Lay second tantalum

over fuel plates, place top platen over tantalum and return assembly to furnace. The entire operation should take five minutes or less.

3. Allow approximately five to ten minutes for assembly to reach $485 \pm 20^{\circ}\text{C}$. Hold at temperature for 60 ± 10 minutes and begin cooling.
4. Cool at $\leq 28^{\circ}\text{C}$ per hour down to $< 260^{\circ}\text{C}$. At this point the entire assembly may be removed from the furnace and the fuel plates removed.
5. Inspect the fuel plate as in Item III-A-4.

General

1. For Item III-B, the tantalum plates have been found to be effective in precluding having the fuel plates stick to the 6061 platens during this long anneal. Note that the entire procedure takes at least nine hours and is done most efficiently when at least part of the cool (the last part) is conducted overnight.
2. In the course of any anneal, fuel plate thicknesses should be measured and recorded before and after annealing.
3. Temperature measurements should be made with either a Chromel/Alumel or Pt/Pt + 10% Rh thermocouple. A temperature recorder should plot the slow cool of item III-B.
4. Care must be taken at all times to avoid getting particulate matter on the plates - particularly refractory particles from the furnace.

Revision No: 0

Revision Date: 8/80

Written By: R. F. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 18

FINAL INSPECTION

I. Purpose

Plates must be produced to accurately prescribed specifications with tight tolerances on dimensions, surface finish, flatness, and angularity of corners. An awareness of these rather severe requirements is mandatory in the entire fabrication process and is a recurring theme throughout the Fabrication Procedures.

There is, however, a Final Inspection which must be conducted to be sure the plates conform to the established requirements. This inspection must be made before plates are either shipped from ANL or used as "finished miniplates".

II. Equipment

Illuminated magnifier or 5x (Luxo LFM series or equal)

Granite Surface plate

Micrometers & Standards for checking them

Vernier Calipers & Standards for checking them

Ball-tipped dial indicator and supporting fixtures for measuring flatness

Small rubber or plastic mallet

Balance with readout to 0.001 gram (Metler PL 200 or equal)

Cleaning train as described in RERTR Fab. Procedure No. 10

Zeiss Optical Comparator (or equal)

Miscellaneous supplies such as lint-free tissues, acetone, etc.

III. Procedure

RERTR Fab. Procedures
No. 18

Page 2 of 8

1. To facilitate the final inspection, the first step usually is to go through the same procedure that is used for cleaning the assembly (RERTR Fab. Procedure No. 10). In most cases the final cold-rolled & O-temper anneal thickness exceeds that of the specified final thickness by ~ 0.001 in. The plates are etched in the Oakite Solution for a time calculated according to the amount of 6061 to be removed. For example, 45 seconds would remove approximately 0.001 inches total. The plates are dipped in the nitric and water solution and finally rinsed in hot water. (Dummy pieces of 6061 can be used to define the time necessary to remove the required amount of material.)

2. The plate thickness is determined by taking micro-meter readings in at least four locations over the fuel zone. This is done by dividing the fuel zone in four nominally equal imaginary parts and measuring the approximate center of each zone. All readings are recorded; an average is calculated. Dimensions are recorded to the nearest 0.0001 in.

Add
rail
thinner
measure

3. Both the width and the length of the plates are measured using a vernier caliper. Care must be taken to be certain that the plate is level within the caliper jaws. Both dimensions are recorded to the nearest ten-thousandth of an in: (The ten-thousandths is typically an estimated number.)

4. The fuel plates are individually weighed. This is done on a Mettler PL 200 digital-read-out balance (or equal) to three decimal places. The weights are recorded. [The balance must be checked with calibrated weights before and after weighing plates]. Two people should weigh the plates independently, both weights should be recorded.

5. Flatness is determined by laying the fuel plate on a granite surface plate and traversing the fuel plate surface from end to end with a calibrated, ball-tipped dial indicator gauge. A reading is taken along each edge and down the center. A thin piece of acetate is used between the ball tip and plate to prevent marring or scratching the fuel plate surface. Plates should be 0.004 in. T.I.R. or less. When they exceed this amount, a plastic or rubber lightweight mallet is employed. By gently tapping the fuel plate in those areas that are "high", the surface flatness can be brought into specification. This basically requires some experience through practice. In the fully annealed condition, the fuel plate is very soft and flattening may be accomplished without damage. This particular step may be performed elsewhere in the sequence. For example, if the fuel plates are noticeably distorted they must be flattened prior to measuring width, length, and thickness.

6. Perpendicularity or squareness is determined on a Zeiss comparator (or equal). The fuel plate is placed on a longitudinal edge and held between two parallel bars atop the traveling table. The vertical and horizontal edges are focused and aligned on the screen cross-hairs. The 0.0025 in. scale is used. By moving the table from one side to the other, the amount of variation of the longitudinal edge can be determined. Since the fuel plate is more than twice as long as it is wide, an

imaginary center of the length is determined and then related from that point to the width. The fuel plate is turned over and the same procedure repeated. The greatest deviation is recorded.

7. Visual inspection with illuminated magnifier such as Luxo LFM (5X). Although inspections for blisters and other surfaced effects have been made up to this point, another intense examination is now performed. Pits, scratches, or impressions are carefully scrutinized. If it is determined no blisters exist and other blemishes are well within the required specifications, the fuel plate is approved and general remarks are recorded. Regarding more noticeable blemishes adjudged acceptable by the inspection, an appropriate remark is recorded.

8. A completed miniplate is checked for loose contamination by gently but firmly wiping both sides and edges of each plate with an individual lint-free tissue moistened with either acetone or ethanol. The tissue is then subjected to an activity check. If no activity is present on the tissue the plate is acceptable. If activity is found, the process is repeated until the plate passes this inspection or until the plate is identified as a reject.

9. As part of the final inspection, the inspector should determine that all necessary X-rays have been taken and all fuel density calculations completed as described in RERTR Fab. Procedure No. 14.

IV. Inspection & Summary Sheets

A final inspection sheet (copy attached as p. 6) must be completed during the course of this inspection. All data should (must) be recorded and the dates and initials of the personnel conducting the inspection must be shown.

A single sheet summarizing the pertinent data concerning each miniplate (reject or acceptable, enriched or depleted must be generated. A sample copy of such a sheet is attached as p. 7.

V. General

1. All specifications recorded in ORNL Document No. Q-11821-ET-002-S-0 as well as ORNL drawing No. X3E11821-0105 must be met. If there are deviations from these specification which are judged not to merit rejection of the plate, a "Deviation Report" must be generated adequately describing the deviation and identifying how this deviation may be expected to affect performance.
2. The entire Final Inspection must be periodically reviewed by the MSD, QA representative (currently M. C. Parker). When plates are generated which are deemed satisfactory and are to be shipped or delivered outside the production facility (H-Wing), the QA representative must be requested to approve such disposition of plates.

CHARACTERISTIC (Dimensions in inches)	ACCEPT	REJECT	ACTUAL DATA &/OR REMARKS Dimensions in inches Weights in grams	DATE	INITIALS
• Visual @ ~5x for blisters, pits, scratches, inclusions, per notes 1,3,& 4 of X3E11821-0105					
• Visual for I.D. Marking & Location of 1/16" x 45° chamfer					
• Visual for Break Edges					

Measure &
Record

• Flatness 0.004" T.I.R.								
• 0.050 ± 0.001 or								
• 0.060 ± 0.001								
• 4.500 +0.000 -0.005								
• 2.000 ±0.002								
• <table border="1"><tr><td>1</td><td>A</td><td>.002</td></tr></table> 2 Places	1	A	.002					
1	A	.002						

FINAL INSPECTION OF REFTR MINIPLATEPLATE NO. A-

CHARACTERISTIC (Dimensions in inches)	ACCEPT	REJECT	ACTUAL DATA &/OR REMARKS Dimensions in inches Weights in grams	DATE	INITIALS

Review Final
X-rays for:

• 0.100" Min. (4 Places)					
• Lead & Trail Edge					
• Segregation of Fuel					
• Fuel Density per ORNL Q-11821-ET- 002					
• Measure & Record Final Fuel Plate Weight (Twice)					

Record Review:
Verify Record
Completeness
for:

• Complete Chem. Analysis of Fuel (in- cluding iso- topic)					
• Completion of all Fab. Steps per ANL Docu- ment M4030- 0002-SA-00

Page 8 of 8

Same
commentRERTR MINIPLATE DATA SUMMARY

Date: _____

Nominal Plate Thickness: _____ inches
Nominal Fuel Zone Thickness: _____ inches

ORNL Plate No.: _____ ANL Plate Code (used during fabrication): _____

Fuel Alloy Composition (Nominal): _____ U Batch No. _____

Fuel Alloy Composition (By Analysis): _____

Enrichment of U Employed in Fuel: _____ wt.% ^{235}U ☐ Nominal
☐ By Analysis

Cover and Frame Material: 6061 Al Thickness: Frame _____ Covers _____
(Inches, Avg. after Cleaning)

Weight of Fuel Alloy in Plate: _____ gms. Compact No: _____

Weight of Aluminum Powder in Plate: _____ gms.

Final Plate Weight: _____ gms. Calculated Volume of Fuel Zone: _____ cm^3
Plate Condition: _____

Volume Percent Fuel in Compact: _____

Volume Percent Fuel in Meat: _____ Calculated Volume Percent Porosity: _____
(In fuel zone) Plate condition: _____

Grams ^{235}U in Plate: _____ gms. Total U in Fuel Zone: _____ kg/m^3

Estimated (Measured) Minimum Clad Thickness of Plate _____ inches

Grams $^{235}\text{U}/\text{meter}^2$ of Surface Area (3 mm spot size): Avg. _____
(_____ Densitometer readings taken) Min. _____
Max. _____

Radiographs of Plate Taken: After Hot Rolling &
Short Blister Anneal: (Location) _____ (Density) _____

(IDENTIFY TYPE, DATE,
& HOW MANY) After Cold Rolling
& _____ Anneal: (Location) _____ (Density) _____

Final Miniplate (Location) _____ (Density) _____

Anneal After Hot Rolling _____ Blisters (?) _____
(Date) _____ (If yes, give location)

Anneal
After Cold Rolling: (_____ % Cold Work): _____ Blisters(?) _____
(Date of Anneal) _____ (If yes, give location)

Sample(s) taken for 6061/6061 Bonding Study: _____ Results: _____

Sample(s) taken for Clad/Core/Clad Study: _____

Final Plate Dimensions: Width: _____ inches (Range _____ in.)
Length: _____ inches (Range _____ in.)
Thickness: _____ inches (Range _____ in.)

Surface Finish of Plate: _____ Corners: _____

Flatness: _____

Disposition: ☐ OK; ☐ REJECT; PLATE LOCATION: _____

Other Data: _____

RFD/11/84

Revision No.: 0

Revision Date: April 15, 1980

Written By: R. F. Domagala

Approved By: _____

H. R. Thresh

RERTR Fabrication Procedure No. 19

FINAL ACID DIP

I. Purpose

The specifications for fuel plates require that they "...shall be free from all foreign matter including moisture, dirt, oil, organic compounds, scale, paint, ink, graphite, all solders, silver, lead, mercury, thorium, chlorine and flourine." (item 4.7 in ORNL Document Q-11821-RT-002-S-0). Further, "the exterior surfaces of the fuel plate shall be free from uranium after fabrication." A final pickling treatment which shall be performed before packaging to shipment to ORNL, of submerging the fuel plates in 45 volume percent HNO_3 - 55 volume percent H_2O solution for 2 to 4 minutes at room temperature followed by rinsing in either demineralized or distilled water meets the intent of this requirement" (item 4.8 in ORNL Document noted above).

The entire fabrication procedure is designed to satisfy item 4.7 above. This procedure addresses itself specifically to item 4.8.

II. Materials & Equipment

1. PVC or polyethylene container 3000 ml or larger for nitric acid solution
2. Two 5 gal. polyethylene or PVC containers for water
3. Polyethylene baskets for supporting fuel plates
4. Acetone
5. Nitric Acid, reagent grade
6. Distilled or demineralized water
7. Kimwipes or other suitable lint-free wipes.

Mixing Solution

Always add acid to water. Prepare enough solution of the 45 v/o HNO_3 - 55 v/o H_2O to totally cover plates

III. Procedure

1. Using acetone and a Kimwipe, carefully wash the surfaces and edges of each plate
2. Place plates one-at-a-time in basket

3. Immerse totally the plate in nitric acid solution and gently agitate in this manner for 2 to 4 minutes
4. Remove basket from acid solution
5. Gently agitate basket containing fuel plate in first five gallon container of water (✓1 minute)
6. Remove basket from first rinse water, allow to drip and transfer to second rinse water for another 1 minute gentle agitation in the second rinse water container
7. Remove basket, allow to drip. Remove plate by hand using lint-free gloves, transfer to Kimwipe and allow to air dry
8. Place dry plate in suitable packaging.

IV. General

At this stage the plates are extremely soft and must be handled with extreme care to avoid damage.

Revision No.: 1

Revision Date: May, 1981

Written By: R. F. Domagala/T.C. Wience

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 20

DENSITY MEASUREMENTS

I. Purpose

Density measurements may be required for alloys, finished plates or for materials in any stage of fabrication. This procedure outlines the steps for such determinations by the so-called "Archimedes Principle" - That is the liquid displacement method. It is not applicable as recorded here for the determination of density of powders or compacts made from powders.

II. Materials & Equipment

Balance with readout to 0.1 milligram equipped with a bottom hook for suspending samples

Fine Nichrome wire for suspending sample. Typically 0.008 in. diameter

Calibration weights for balance

Container for water (or other solution) large enough to adequately contain item being suspended

Distilled or deionized water

Invar or other standard of well documented density

III. Procedure

1. The density of a fuel plate is determined by measuring its buoyancy in a liquid of known density (in this case, water). The plate is first weighed in air, then suspended in water. The difference between these two weights equals the weight of the water displaced, and this, when divided by the density of water, gives the volume of the plate. This volume is then divided into the weight of the plate in air to give its density.
2. An allowance must be made for the apparatus used to suspend the plate when it is weighed in water. This apparatus consists of a length of 0.008 in. Nichrome wire with a loop on the end for holding the plate.

3. The balance is zeroed and checked with calibration weights.
4. The immersion solution used is ~~d~~ionized (or distilled) water to which a few drops of Foto-Flow are added as a wetting agent. The water is allowed to set for several hours to reach room temperature and to deaerate. When the specimen is immersed in the solution a soft artist brush is used to wipe off any air bubbles which may cling to the surfaces.
5. An Invar standard of known density is first measured to confirm the accuracy of the process and, in this case, a sample of fully annealed 6061 Aluminum is also measured along with each set of plate measurements for comparison.

The balance is re-zeroed before each separate specimen is measured.

6. Steps are as follows:
 - A = wt. of fuel plate in air
 - B = wt. of fuel plate + wire in H_2O
 - C = wt. of wire in H_2O
 - D = (B-C) wt. of fuel plate in H_2O
 - E = (A-D) wt. of H_2O displaced by fuel plate
 - F = density of H_2O at measured temp. (from ASTM Table)
 - G = (E/F) volume of fuel plate
 - H = (A/G) density of fuel plate

IV. General

1. All weight readings should be recorded to the nearest tenth of a milligram.
2. The balance must be checked for calibration for each batch of plates or at least twice per day.

(Continued on next page)

V. Sample Calculations (Appendix)

This is intended to serve as an example of the steps required for and the calculations involved in the determination of the percent porosity in the fuel zones of RERTR miniplates:

1. Reference Data:

$$\text{Density } (\rho) = \frac{\text{Mass}}{\text{Volume}}$$

$$\rho_{6061} = 2.71 \text{ g/cm}^3$$

$$\rho_{Al} = 2.70 \text{ g/cm}^3$$

$$\rho_{U_3SiAl} = 14.2 \text{ g/cm}^3$$

$$\rho_{U_3Si} = 15.2 \text{ g/cm}^3$$

$$\rho_{U_3Si_2} = \frac{12.2}{11.9} \text{ g/cm}^3$$

change + add other alloys?

2. Using the steps outlined in RERTR Fabrication Procedure No. 20, the following data are generated:

a. Weight of the fuel plate (g) = W_{fp}

b. Volume of the fuel plate (cm³) = V_{fp}

c. Density of the fuel plate (g/cm³) = ρ_{fp}

3. As a double check:

$$V_{cal.} = \frac{W_{fp}}{\rho_{fp}} = V_{fp}$$

$V_{cal.}$ & V_{fp} should agree to within $\pm 1\%$

4. Referring to the compact log sheets generated in RERTR Fab.

Procedure No. 7, record the following information on a data sheet (sample shown as p. 6)

a. Weight of fuel alloy in compact (g) W_f

b. Weight of Al powder in compact (g) W_{Al} .

5. To calculate the percent porosity in the fuel zone:

The volume of Al powder in the fuel zone:

$$V_{Al} = W_{Al} \div \rho_{Al}$$

The volume of fuel in the fuel zone:

$$V_f = W_f \div \rho_f \quad (\rho_f = \text{density of fuel})$$

This weight of solid Al₆₀₆₁:

$$W_{6061} = W_{fp} - (W_{Al} + W_f)$$

Volume of Al₆₀₆₁:

$$V_{6061} = W_{6061} \div \rho_{6061}$$

Volume of fuel zone:

$$V_{FZ} = V_{fp} - V_{6061}$$

Volume of voids:

$$V_v = V_{FZ} - [V_{Al} + V_f]$$

$$\text{Percent voids} = \frac{V_v}{V_{FZ}} \times 100$$

6. Two worksheets are included - one with sample calculations; one blank. The blank data sheet is to be reproduced and used for all data and calculations of porosity. One plate (& one condition) per sheet.

PERCENT POROSITY WORKSHEET

Given: Density = $\frac{\text{Mass}}{\text{Volume}}$ $\rho_{6061} = 2.71 \text{ g/cm}^3$ $\rho_{Al} = 2.70 \text{ g/cm}^3$
 $\rho_{U_3Si} = 15.2 \text{ g/cm}^3$ $\rho_{U_3SiAl} = 14.2 \text{ g/cm}^3$ $\rho_{U_3Si_2} = 12.2 \text{ g/cm}^3$

Type of fuel plate: _____
 (Fuel Alloy) (Thickness of Plate (in.)) (Condition of Plate)

Fuel plate ID Number: A- _____;
 A-No. (Fabrication Designation)

Weight of fuel plate: _____ g (W_{fp})

Volume of fuel plate: _____ cm^3 (V_{fp})

Density of fuel plate: _____ g/cm^3 (ρ_{fp})

Calculated volume of fuel plate: $\left(\frac{W_{fp}}{\rho_{fp}}\right)$ _____ cm^3 ($V_{cal.}$)

Weight of fuel in compact: _____ g (W_f)

Weight of Al powder in compact: _____ g (W_{Al})

Volume of Al powder: $\left(\frac{W_{Al}}{\rho_{Al}}\right)$ _____ cm^3 (V_{Al})

Volume of fuel in fuel zone: $\left(\frac{W_f}{\rho_f}\right)$ _____ cm^3 (V_f)

Weight of solid Al₆₀₆₁: $[W_{fp} - (W_{Al} + W_f)]$ _____ g (W_{6061})

Volume of Al₆₀₆₁: $\left(\frac{W_{6061}}{\rho_{6061}}\right)$ _____ cm^3 (V_{6061})

Volume of fuel zone: $(V_{fp} - V_{6061})$ _____ cm^3 (V_{FZ})

Volume of voids: $[V_{FZ} - (V_{Al} + V_f)]$ _____ cm^3 (V_v)

Percent voids: $\left(\frac{V_v}{V_{FZ}}\right) \times 100$ _____ % Voids

PERCENT POROSITY WORKSHEET

(Sample)

Given: Density = $\frac{\text{Mass}}{\text{Volume}}$ $\rho_{6061} = 2.71 \text{ g/cm}^3$ $\rho_{Al} = 2.70 \text{ g/cm}^3$
 $\rho_{U_3Si} = 15.2 \text{ g/cm}^3$ $\rho_{U_3SiAl} = 14.2 \text{ g/cm}^3$ $\rho_{U_3Si_2} = 12.2 \text{ g/cm}^3$

Type of fuel plate: $\frac{\text{Ternary}(U_3SiAl)}{(\text{Fuel Alloy})}$ $\frac{0.050}{(\text{Thickness of Plate (in.)})}$ $\frac{\text{FINISHED}}{(\text{Condition of Plate})}$

Fuel plate ID Number: $\frac{A-01}{A-No.}$; $\frac{MEAT-40-02F}{(\text{Fabrication Designation})}$

Weight of fuel plate: $\frac{31.0834}{\text{g}} (W_{fp})$

Volume of fuel plate: $\frac{7.297}{\text{cm}^3} (V_{fp})$

Density of fuel plate: $\frac{4.260}{\text{g/cm}^3} (\rho_{fp})$

Calculated volume of fuel plate: $\left(\frac{W_{fp}}{\rho_{fp}} \right) \frac{7.296}{\text{cm}^3} (V_{cal.})$

Weight of fuel in compact: $\frac{14.876}{\text{g}} (W_f)$

Weight of Al powder in compact: $\frac{2.940}{\text{g}} (W_{Al})$

Volume of Al powder: $\left(\frac{W_{Al}}{\rho_{Al}} \right) \frac{1.089}{\text{cm}^3} (V_{Al})$

Volume of fuel in fuel zone: $\left(\frac{W_f}{\rho_f} \right) \frac{1.048}{\text{cm}^3} (V_f)$

Weight of solid Al_{6061} : $\left[W_{fp} - (W_{Al} + W_f) \right] \frac{13.2674}{\text{g}} (W_{6061})$

Volume of Al_{6061} : $\left(\frac{W_{6061}}{\rho_{6061}} \right) \frac{4.896}{\text{cm}^3} (V_{6061})$

Volume of fuel zone: $(V_{fp} - V_{6061}) \frac{2.401}{\text{cm}^3} (V_{FZ})$

Volume of voids: $\left[V_{FZ} - (V_{Al} + V_f) \right] \frac{0.264}{\text{cm}^3} (V_v)$

Percent voids: $\left(\frac{V_v}{V_{FZ}} \right) \times 100 \frac{11.0}{\%} \text{ Voids}$

Revision Date: June 2, 1980Written By: R.F.DomagalaApproved By: H.R.ThreshRERTR Fabrication Procedure No. 21HANDLINGI. Purpose

Although in large measure this procedure may be considered redundant, it does seem in order to emphasize the need for care in handling all the materials used for the production of miniplates as well as the miniplates themselves. Therefore, this document supplements the handling instructions associated with and recorded for individual Fabrication Procedures.

II. Materials & Equipment

As required for the particular task.

III. Procedure

RERTR miniplates are produced from the following materials: 6061 Al alloy, Alcan MD101 Al powder (or equal), uranium (depleted or enriched), pure aluminum and pure silicon. Of these, the last three are alloyed by arc melting as either binary (U + Si) or ternary (U + Si + Al) "pancake" ingots which are ultimately comminuted into powder.

Specific procedural descriptions do identify precautions to be observed in handling, but to re-emphasize these, particular attention should be paid to the following issues:

- A. The 6061 aluminum alloy whether as stock to be prepared for frames and covers or after it is integrally bonded as a miniplate, should always be handled with care. In the cold rolled or aged condition, this alloy is reasonably resistant to dents and scratches, but like all aluminum alloys, it does deface rather easily. Furthermore, in the 0-temper (dead-soft) condition, it is very soft and very easily defaced. It is safest to always handle this material as though it was in the 0-temper condition. Plates should not be stacked without interleaving them with paper or plastic.

- B. Fuel plates require the greatest care. By the time a fuel plate has been generated a great deal of time and expense have gone into its production and a defect generated by improper handling should rarely occur. Plates should be handled by edges, preferably with gloved hands. Tools used for measurements should not apply enough force to dent or scratch the surfaces or to bend the plate. It is impossible to detail every precaution which must be taken to preclude generating defects. Ultimately, the responsibility for protecting the plates from damage resides with the person handling and storing the plates.
- C. Aluminum powder used as the matrix material for the fuel meat is a potentially hazardous material. Good common sense, good housekeeping, and working with small batches at a time will preclude any problem. Airborne particles are pyrophoric and if an ignition source is present they may react explosively.
- D. The raw materials for alloying (U, Si & Al) should also be handled with care. The Si and Al are of sufficiently high purity that carelessness can lead to contamination. Again, common sense and care in handling and storing will maintain the purity level consistent with the needs of the program.
- E. Uranium base alloys used as the fuel for plates are made from either depleted or low-enriched uranium arc melted together with silicon or silicon and aluminum. Normal precautions and accountability must be followed when producing and handling the alloy ingots which are, typically 200 grams or less.

However, during fragmentation of the ingots and especially during comminution to powder, it must be recognized that alloys in the U-Si and U-Si-Al systems have a definite tendency to be pyrophoric. This propensity for reaction with oxygen seems to vary with composition,

heat treatment and particle size but not enough experience has been generated to define this property quantitatively. In massive (ingot) form, experience to date suggests no problem with pyrophoricity. However, in fragmenting and comminuting (in air) it does seem clear that the fine particles do "spark" or "burn" at a visible rate.

In order to preclude any serious problem, these alloys should be converted to powder in small quantities if the work is done in air. If "burning" initiates, it is wise to allow the reaction to proceed and after the powder is cool, to put such reacted powder into a separate, identified container (glass jar with aluminum insert lid). It is worth noting that the only time reactions (burning) have been observed has been during the conversion of an ingot to powder. Once powder has been generated and stored, there has never been an instance of spontaneous ignition. Nevertheless, such ignition should be presumed possible and appropriate action should be planned.

Revision No: 0
Revision Date: June 2, 1980
Written By: R. F. Domagala
Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 22

SERIALIZATION
(Identification)

I. Purpose

All plates produced on this program must carry a unique identification. Such identification, when referenced to appropriate data sheets &/or logbooks must permit a complete determination of the materials contained in the plate, the weight and volume percent fuel alloy, the volume percent porosity, etc. The identification, then, is a simple code for referencing interested personnel to determine every pertinent parameter of each plate.

II. Materials & Equipment

Plates to be identified, metal number and letter stamps, scribing tools, small hand tools as required.

III. Procedure

During assembly and production, miniplates must be uniquely identified by whatever system works most effectively. That is, during initial assembly and rolling a scribed identification (which will of course be obliterated during rolling) should be placed well outside the area which will be part of the finished plate. Special care must be taken to place plates or assemblies in the furnace used for rolling in a specific order and that order must be retained. If tandem assemblies are rolled, shearing is usually required after the fourth rolling pass. The Front and Rear of the assembly then will carry forward an F or R suffix to the original designation.

Finished plates produced with alloys prepared from enriched uranium will carry a designation A-XXX. The letter prefix defines ANL as the producer, the X's represent a two or three digit number starting with 01 and proceeding through 999. This designation will likewise be recorded on a "RERTR Miniplate Data Summary Sheet". No two plates will ever have the same designation. Plates made with enriched uranium, but rejected for any reason will still be identified in the A-digit sequence.

Plates produced with depleted uranium alloy fuel will never carry an "A" number. These plates, which are used to determine fabrication parameters or for any other experimental purpose will carry one of three designations:

change to include all alloys

1. DUMB-XXF (or-XXR)

(Depleted Uranium Miniplate Binary (U_3Si) alloy)

XX's represent one or two digit chronological sequence. Front or Rear of assembly.

2. DUMT-XXF (or-XXR)

(Depleted Uranium Miniplate Ternary (U_3SiAl) alloy)

XX's represent one or two digit numbers assigned in chronological order. Front or Rear of assembly.

3. DUMX-XXF (or-XXR)

Depleted Uranium Miniplate X alloy (U_3Si_2)

The XX's represent one or two digit numbers assigned in chronological order. Front or Rear.

All depleted plates will be numbered in a single numerical sequence. Thus there cannot be a DUMB-4F as well as a DUMT-4F or a DUMX-4F

The actual inscription of a plate number on a plate shall always be outside the fuel zone. For depleted plates any convenient method is acceptable, stamping, scribing etc. For the enriched plates the designation may also be stamped or scribed, but it must be done in a location and to a size and depth which is specifically defined by ORNL Document No. Q-11821-ET-002-S-0 and drawings ORR-HFED X3E 11821-0105-A and ORR-HFED X3E11821-0101A.

Revision No: 0

Revision Date: June 2, 1980

Written By: R. E. Domagala

Approved By: H. R. Thresh

RERTR Fabrication Procedure No. 23

Shipping

I. Purpose

Finished miniplates will, from time to time, be shipped to ORNL (or elsewhere) for irradiation, testing, inspection, or for any other purpose. This document briefly describes the procedures for sending such plates.

II. Materials and Equipment

Plates to be shipped, X-rays of finished plates showing location and geometry. Summary Data Sheet for each plate.

III. Procedure

RERTR miniplates are shipped with the 6061 bonding alloy in the O-temper condition. This means that the plates are very soft and easily damaged. Further, the specifications for the plates are very restrictive as to the possible existence of "dents or dings" and require the plates to be almost perfectly flat. Hence, great care must be exercised in handling, storing, and shipping.

For shipping, each plate must have an identification number stamped or scribed in an appropriate location. Currently, the location and geometry of the identification is defined in ORNL document Q-11821-ET-002-S-0 (1-31-80) and drawing No. ORR-HFED Experiment Plate Details X3E11821-0105-A as well as drawing No. X3E-11821-0101-A.

The identified plates, after all fabrication steps have been completed, are to be placed in individual zip-lock bags, identified with an indelible marker and sealed. The plates are then transferred to SPM through appropriate channels and with the required accountability documentation. The SPM "Shipment Work Sheet" shall be filled out. Plates are to be shipped to the person and address identified in ORNL Document Q-11821-ET-002-S-0 (or any other location defined at a date subsequently identified). Accountability will likewise be transferred according to written instructions in

Zip-lock
bags,
identified
with marker
not pen

the ORNL document (or other appropriate written instructions).

In the "Shipment Work Sheet" the batch No. for the uranium contained in the plates should be recorded, and in the section identified as "Special Shipping Instructions", the following statement should be recorded

"Plates are to be carefully packed in a double can configuration with plenty of packing material. The plates should be handled such that no scratches or nicks are put into the surfaces and that no bending occurs".

If convenient, copies of Summary Data Sheets for each and every plate should be included with the plate shipment. It is equally acceptable to forward such documentation to the cognizant recipient of the plates under separate cover. The X-rays showing fuel geometry and location are best sent under separate cover with appropriate precautions to prevent damage to the X-ray film.

General:

It is wise, if not mandatory, to follow-up on a shipment. Determine that the plates have left SPM, have left the ANL site, and finally, have arrived at their destination.

Just before delivering plates to SPM for shipment reweigh (new weight) each plate & check the weight against that recorded on the Summary Data Sheet. If not within ± 2 to 3 mg, enter new weight on sheet. Balance must be checked with standard reference weights before weighing plates.

APPENDIX C: CALCULATIONS FOR PHASES PRESENT

APPENDIX C

Formulas for calculating percentages of phases present in the U-Si system.
Alloys at equilibrium. Densities and compositions rounded off to the first decimal. w/o = wt.%; v/o = vol.%.

1. For alloys in the two phase field U_3Si (3.9 w/o Si) plus U_3Si_2 (7.3 w/o Si). Alloys annealed below the peritectoid temperature (925°C) for the "proper" time.

$$(a) \quad w/o \, U_3Si_2 = \frac{w/o \, Si - 3.9}{3.4} \times 100$$

$$w/o \, U_3Si = 100 - w/o \, U_3Si_2$$

$$(b) \quad v/o \, U_3Si_2 = \frac{\frac{w/o \, U_3Si_2}{12.2}}{\frac{100 - w/o \, U_3Si_2}{15.2} + \frac{w/o \, U_3Si_2}{12.2}} \times 100$$

$$v/o \, U_3Si = 100 - v/o \, U_3Si_2$$

2. For alloys in the two phase field U_3Si_2 (7.3 w/o Si) and USi (10.6 w/o Si)

$$(a) \quad w/o \, USi = \frac{w/o \, Si - 7.3}{3.3} \times 100$$

$$w/o \, U_3Si_2 = 100 - w/o \, USi$$

$$(b) \quad v/o \, USi = \frac{\frac{w/o \, USi}{10.9}}{\frac{100 - w/o \, USi}{12.2} + \frac{w/o \, USi}{10.9}} \times 100$$

$$v/o \, U_3Si_2 = 100 - v/o \, USi$$

*Note 4 wt.% Si value, not 3.9 wt.% value.

3. For as-cast alloys between U (0 w/o Si) and U_3Si_2 (7.3 w/o Si)
(alloys not heat treated)

$$(a) \quad w/o U_{ss} = \frac{7.3 \text{ w/o Si}}{7.3} \times 100$$

$$w/o U_3Si_2 = 100 - w/o U_{ss}$$

$$(b) \quad v/o U_{ss} = \frac{\frac{w/o U_{ss}}{19.1}}{\frac{100 - w/o U_{ss}}{12.2} + \frac{w/o U_{ss}}{19.1}} \times 100$$

$$v/o U_3Si_2 = 100 - v/o U_{ss}$$

APPENDIX D: CHEMICAL ANALYSIS

APPENDIX D

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 1 of 7)

Alloy ⁽¹⁾	Melt No.	Analyzed	Analysis ⁽²⁾								
			Total U	U-235 ⁽³⁾	Si	Al	W	C	O	Other	~Total
U ₃ Si(DU)	106	10/79 → 12/79	NA	NA	3.95	<0.01*	~0.12*	~0.7	NA	~0.01Co*	-
U ₃ SiAl (DU)	108	10/79 → 12/79	NA	NA	3.49	1.46	~0.03*	~0.5	NA	~15ppmCo*	-
U ₃ Si(LEU)	112+113	1/80 → 3/80	94.31	19.88	3.98	0.01	1.3	0.17	NA	~0.02Co*	99.79
U ₃ SiAl(LEU)	114+115	1/80 → 3/80	94.19	19.89	3.46	1.48	0.5	0.14	NA	~0.1Co*	99.87
U ₃ Si ₂ (LEU)	118	5/80 → 6/80	92.27	19.87	7.49	25ppm*	0.01	0.027	NA	~0.01Fe*	99.81
U ₃ Si(LEU)	116	3/81 → 5/81	94.55	19.89	3.90	300ppm*	~0.09*	0.044	~0.59	~0.01Fe*	99.21
U ₃ SiAl(LEU)	117	3/81 → 5/81	94.32	19.89	3.50	1.52	~0.025*	0.058	~0.46	-	99.88
U ₃ SiAl(LEU)	120(A+B)	9/81	94.16	19.51	3.44	1.52	~0.03*	NA	NA	-	99.15
U ₃ SiAl(LEU)	E128 thru E132	5/82	94.38	19.52	3.51	1.35	100ppm*	NA	0.445	23 ppm H 488 ppm N	99.75
U ₃ SiAl(LEU)	E133 thru E152	8/82 → 10/82	94.21	19.52	3.45	1.47	80ppm*	NA	0.552	30 ppm H 510 ppm N	99.74
U ₃ Si ₂ (LEU)	E158 thru E165 (5)	4/83 → 6/83	92.18	19.84	7.58	30 ppm*	NA	NA	316 ppm	5 ppm H 75 ppm N 0.03* all others	99.83

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 2 of 7)

Alloy	Melt No.	Analyzed	Analysis ⁽²⁾								~Total
			Total U	U-235 ⁽³⁾	Si	Al	W	C	O	Other	
U ₃ Si ₂ (LEU)	E158 thru E165	10/84	NA	NA	NA	NA	NA	NA	430 ppm	<5 ppm H 120 ppm N	-
U ₆ Fe (DU)	D157	5/83	NA	NA	NA	NA	NA	NA	NA	4.13 Fe	-
U ₃ Si (LEU)	E172 + E173	9/83	95.43	19.83	3.88	128ppm*	180ppm*	0.022	0.53	22 ppm Co* 179 ppm Fe* 33 ppm H 240 ppm N	99.94
U ₃ Si (HEU)	E177	9/83	95.41	92.62	3.91	43ppm*	380ppm*	NA	0.43	94 ppm Fe* 320 ppm Ni* 18 ppm H 330 ppm N	99.87
	E177(14)	9/87							0.35	4 ppm H 229 ppm N	
U ₃ Si ₂ (HEU)	E178	9/83	92.32	92.95	7.44	20ppm*	NA	NA	560 ppm	58 ppm Fe* 9 ppm H 66 ppm N	99.83
	E178(14)	9/87							427 ppm	2 ppm H 79 ppm N	
U ₃ Si (MEU)	E179	9/83	95.43	40.06	3.92	25ppm*	110ppm*	NA	0.34	158 ppm Fe* 14 ppm H 290 ppm N	99.75
U ₃ Si ₂ (MEU)	E180	9/83	92.30	40.11	7.48	19ppm*	NA	NA	410 ppm	131 ppm Fe* 6 ppm H 100 ppm N	99.85
UAl ₂ (DU)	D181	9/83	NA	NA	NA	19.65	NA	NA	NA		-

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 3 of 7)

Alloy	Melt No.	Analyzed	Analysis ⁽²⁾								~Total
			Total U	U-235 ⁽³⁾	Si	Al	W	C	O	Other	
U ₆ Fe (LEU)	E184	1/84	95.70	19.84	NA	110ppm*	NA	NA	0.23	4.02 Fe 26 ppm H 157 ppm N	99.98
	E184	10/84	NA	NA	NA	NA	NA	NA	0.23	15 ppm H 120 ppm N	-
UAl ₂ (MEU)	E185	1/84 → 3/84	79.19	44.81	NA	19.58	NA	NA	0.45	140 ppm Fe* 22 ppm H 0.59 N	99.82
U ₃ Si ₂ (DU)	D187 thru D192 (6)	3/84	92.33	0.213	7.51	36ppm*	NA	NA	NA	No major imp*	99.84
U ₃ Si (DU)	D193 + D194	7/84 → 8/84	95.20	0.223	3.94	110ppm*	NA	NA	0.52	74 ppm Fe* 32 ppm H 605 ppm N	99.74
U ₃ Si (LEU)	E195 + E196	7/84 → 10/84	95.36	19.88	3.96	270ppm*	NA	NA	0.35	200 ppm Fe* 12 ppm H 240 ppm N	99.39
U ₃ Si _{1.5} (LEU)	E197	10/84	93.74	19.83	5.70	600ppm*	NA	NA	0.22	190 ppm Fe* 8 ppm H 140 ppm N	99.75
U ₃ Si _{1.5} (MEU)	E198	9/84 → 10/84	93.32	40.04	5.86	620ppm*	NA	NA	0.40	170 ppm Fe* 12 ppm H 370 ppm N	99.73

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 4 of 7)

Alloy	Melt No.	Analyzed	Analysis ⁽²⁾								
			Total U	U-235 ⁽³⁾	Si	Al	W	C	O	Other	~Total
U ₃ SiCu (LEU)(7)	E-199	10/84 → 11/84	91.78	19.86	5.36	0.48*	NA	NA	1.34	0.17 Cu* 0.19 Cu ('wet') 380 ppm Fe* 17 ppm H 700 ppm N	99.24
U ₃ SiCu (MEU)(7)	E-200	10/84 → 11/84	92.42	40.06	5.32	0.42*	NA	NA	1.22	0.17 Cu* 0.17 Cu ('wet') 320 ppm Fe* 480 ppm N 14 ppm H	99.63
U ₃ SiCu (LEU)(8)	E-201	3/85 → 6/85	95.17	19.84	3.99	45ppm*	530ppm*	NA	0.40	0.18Cu* 220 ppm Fe* 42 ppm H 261 ppm N 220 ppm N(9)	99.85
U ₃ SiCu (MEU)(8)	E-202	3/85 → 6/85	95.21	39.96	3.93	37ppm*	320ppm*	NA	0.36	0.17Cu* 170 ppm Fe* 8 ppm H 493 ppm N 240 ppm N(9)	99.77
USi (DU)(8)	D-203	3/85 → 6/85	89.25	0.23	10.40	62ppm*	NA	NA	469ppm	130 ppm Fe* 5 ppm H 279 ppm N	99.75
USi (LEU)(8)	E-204	3/85 → 6/85	89.26	19.82	10.48	68ppm*	NA	NA	350ppm	280 ppm Fe* 0 ppm H 164 ppm N	99.84
USi (MEU)(8)	E-205+ E-217	3/85 → 6/85	89.27	40.11	10.34	44ppm*	NA	NA	401ppm	140 ppm Fe* 5 ppm H 246 ppm N	99.71

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 5 of 7)

Alloy	Melt No.	Analyzed	Analysis ⁽²⁾									
			Total U	U-235 ⁽³⁾	Si	Al	W	C	Mn	O	Other	~Total
U ₃ Si ₂ (DU)(10)	D220 → D224	2/86 → 4/86	92.03	0.25	7.70	34ppm*	NA	NA	5ppm*	NA	56ppmFe*	99.73
U ₇₅ Ga ₁₅ Ge ₁₀ (LEU)(12)	E229	4/87 → 5/87	90.79	19.84	NA	50ppm*	NA	NA	10ppm*	883ppm	5.42 Ga* 3.81 Ge* 445ppmFe+Ni 19ppm H 306ppm N	100.19
U ₇₅ Ga ₁₀ Si ₁₅ (LEU)(12)	E230	4/87 → 5/87	93.86	19.84	220	36ppm*	NA	NA	10ppm*	754ppm	3.69 Ga* 433ppm Fe+Ni* 34ppm H 273ppm N	99.9
U ₆ Mn _{1.3} (DU)(11)	D235	3/86 → 4/86	93.21	0.22	NA	<20ppm*	NA	NA	6.18	0.46	47ppm Fe+Ni* 20ppm H 493ppm N	99.9
U ₆ Mn _{1.3} (LEU)(11)	E236	3/86 → 4/86	93.25	19.79	NA	<20ppm*	NA	NA	6.08	0.39	314ppmFe+Ni* 9ppm H 393ppm N	99.9
U ₆ Mn _{1.3} (MEU)(11)	E237	3/86 → 4/86	93.32	40.00	NA	<20ppm*	NA	NA	6.11	0.14	139ppm Fe+Ni* 0ppm H 107ppm N	99.6
U ₃ Si _{1.6} (LEU)(11)	E247	1/87 → 2/87	93.81	19.84	6.02	<52ppm*	NA	NA	13ppm*	0.10	420ppm Fe+Ni* 28ppm H 110ppm N	100.0
U ₃ Si(LEU)(11)	E248	1/87 → 2/87	95.80	19.84	3.96	<50ppm*	NA	NA	14ppm*	0.12	590ppm Fe+Ni* 21ppm H 141ppm N	99.9
U ₃ Si(DU)(13)	D-253	9/87 → 10/87							660ppm*		220ppm Fe+Ni*	

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

(Aug. 1988, p. 6 of 7)

(1) Nominal Alloy Compositions (Densities):

$U_3Si = U + 4 \text{ w/o Si } [(15.2 \text{ g-cm}^{-3}), \text{ heat treated}]$

$[(14.55 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_3SiAl = U + 3.5 \text{ w/o Si} + 1.5 \text{ w/o Al } [(14.9^{-3} \text{ g-cm}^{-3}), \text{ heat treated}]$

$U^3Si_2 = U + 7.5 \text{ w/o Si } [(12.2 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_6Fe = U + 4 \text{ w/o Fe } [(17.4 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$UAl_2 = U + 20 \text{ w/o Al } [(7.9 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_3Si_{1.5} = U + 5.5 \text{ w/o Si } [(13.7 \text{ g-cm}^{-3}), \text{ heat treated}]$

$U_3Si_{1.6} = U + 6.0 \text{ w/o Si } [(13.00 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_3SiCu = U + 4.0 \text{ w/o Si} + 0.17 \text{ w/o Cu } [(15.2 \text{ g-cm}^{-3}), \text{ heat treated}]$

$USi = U + 10.6 \text{ w/o Si } [(10.9 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_6Mn = U + 4.0 \text{ w/o Mn (Lit value } \sim 17.8 \text{ g-cm}^{-3})$

$U_6Mn_{1.3} = U + 6.5 \text{ w/o Mn } [(16.8 \text{ g-cm}^{-3}), \text{ as-arc-cast}]$

$U_{75}Ga_{15}Ge_{10} = U + 5.3 \text{ w/o Ga} + 3.7 \text{ w/o Ge } [(15.8 \text{ g-cm}^{-3}), \text{ heat treated}]$

$U_{75}Ga_{10}Si_{15} = U + 3.7 \text{ w/o Ga} + 2.2 \text{ w/o Si } [(15.6 \text{ g-cm}^{-3}), \text{ heat treated}]$

DU = Depleted Uranium

LEU = Low Enrichment U (<20% U-235; Typically $19.7 \pm .2\%$ U-235)

MEU = Medium Enrichment U (Typically 40 to 45% U-235)

HEU = High Enrichment U (Typically 93% U-235)

(2) Values in wt. pct. except as noted

*Indicates value determined spectrographically

For spectrographic analyses, major impurities only recorded.

NA = Not Analyzed

(3) As a percent of total U

- (4) Analyses of melt nos. 106 thru 120(A+B) conducted on -100 + 325 mesh sample. Analyses of melt nos. E-128 thru E-132 conducted on sample 79% -100 + 325 mesh and 21% -325 mesh. Analyses of melt nos. (E133 thru E152) conducted on sample 83% -100 + 325 mesh & 17% -325 mesh. Analyses of melt nos. (E158 thru E165) & (D187 thru D192) conducted on sample 75% -100 + 325 mesh and 25% -325 mesh. Analyses of (E172 + E173); E177; E178; E179; E180; E184; E185; (D193 + D194); (E195 + E196); E197; E198; E199; E200; E-201; E-202; D-203; E-204; (E-205 + E-217); (D-220 → D224); D-235; E-236; E-237; E-247; E-248 conducted on sample 85% -100 + 325 mesh and 15% -325 mesh. Analyses of D-157 (U_6Fe) & D-181 (UAl_2) conducted on piece of as-arc-cast ingot. Note also rerun of H-O-N on (E158 thru E165) ~16 months after initial analysis. Also, rerun of H-O-N on E184 (U_6Fe) ~9 months after initial analysis.

SUMMARY OF ANALYSES OF RERTR FUEL ALLOY POWDERS PRODUCED & ANALYZED AT ANL

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- (5) Same powder as shipped to B&W. (Ingots not heat treated.) (6) Same powder as shipped to RISØ. (Ingots not heat treated.)
- (7) These ingots comminuted in mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) mortar and pestle. Powder surface "contaminated" with Al_2O_3 & SiO_2 .
- (8) The ACL reported some difficulty with H-O-N analysis equipment prior to these analyses. Recorded H-O-N values are believed to be accurate. See footnote (9).
- (9) Nitrogen determination by Kjeldahl technique to serve as check against values determined with H-O-N Line.
- (10) Target composition 7.7 wt.% Si. Ingots not heat treated. 5.0 kg sent to RISØ (Feb. '86). (11) Ingots not heat treated.
- (12) Ingots heat treated 800°C, 96 hrs, air cool (in retort). Sample analyzed was 30% (-60 + 100) mesh, 60% (-100 + 325) mesh, 10% -325 mesh.
- (13) Ingot arc melted, heat treated & Shatterbox-comminuted by Mr. C. K. Kim (KAERI). Spectrographic check for metallic impurities run.
- (14) Recheck of H-O-N four years after original analyses. Sample -100+325 mesh powder.
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APPENDIX E: MINIPLATE CHARACTERISTICS

APPENDIX E

Tables E-1 through E-13 list the most important characteristics of the 260 miniplates fabricated for irradiation in the ORR. Those actually irradiated are indicated by a listing of the ORR irradiation module which contained the plate. The plates of each fuel type are listed in order of increasing uranium density. Table E-14 provides a list of all of these miniplates ordered according to plate number in order to facilitate finding the listing for any individual plate in the tables. Table E-15 provides a list of the densities of the constituents of these plates, which were used in determining the fuel, matrix, and porosity volume fractions listed in the tables. In all cases but one the experimentally determined ingot densities, discussed in Section 2.8.1, were used. The fuel ingot numbers provide a reference to the chemical analysis data in Appendix D, from which the fuel uranium content data were taken. The one exception in which a measured fuel density was not used directly was for the first set of U_3SiCu plates. Anomalous amounts of Al, Si, and O were found in the fuel sample submitted for chemical analysis, and the uranium content of the sample was correspondingly low. It is assumed that the surfaces of these fuel particles had become contaminated with Al_2O_3 and SiO_2 from the mullite ($3Al_2O_3 \cdot 2SiO_2$) mortar and pestle used for comminution of the ingot to powder. Since the Al-to-extra Si ratio was different than that for mullite, it has been assumed that the mullite constituents were separated during comminution. The coated particle densities listed in Table E-5 note were determined using the results of the chemical analyses and the foregoing assumptions.

The fuel meat volumes were determined through use of the Archimedes principle. The volume of the miniplate was determined from the difference in dry and submerged weights divided by the density of water at the measurement temperature. The volume of Al-6061 cladding was determined by dividing the weight of the cladding (plate weight minus fuel weight and matrix weight) divided by the density of the cladding. The fuel meat volume was determined by subtracting the cladding volume from the plate volume. The uranium density is with respect to the fuel meat and is determined by dividing the product of the fuel weight and the uranium weight fraction in the fuel by the fuel meat volume. The fuel, matrix, and porosity volume fractions are also with respect to the fuel meat volume. The fuel (matrix) volume was calculated by dividing the fuel (matrix) weight by the fuel (matrix) density, and the fuel (matrix) volume fraction was

determined by dividing the fuel (matrix) volume by the fuel meat volume. Some plates, designated by a plate number ending in the letter P, also contained 36 mg (0.6 vol.%) of natural B_4C powder as a burnable poison. The porosity volume fraction is just the difference between 100% and the sum of the fuel, matrix, and poison volume fractions.

Fuel plates were fabricated by first hot rolling and then cold rolling to final size. The amount of cold reduction is listed in the "% Cold Work" column. Plates Nos. A1 - A68, except Nos. A39, A57, and A64, were subjected to an O-temper anneal after cold rolling in order to provide uniform cladding properties for all plates being irradiated. As discussed in Section 2.8.4, this anneal produced fuel zone growth. The fuel meat volumes and constituent volume fractions listed are for the final condition (annealed or unannealed) of the plate. No reaction was assumed to have occurred during the O-temper anneal, so all of the increase in fuel volume was assumed to result from increased porosity.

Uranium surface densities were determined from densitometer measurements of film density of X-ray radiographs. Readings were taken for thirty 3-mm-diameter spots dispersed over the fuel zone. Uranium-aluminum alloy step wedges were placed next to the miniplates during radiography for calibration.

For a few of the plates listed some parameters were not measured, either because of defects or because the plate was designated for destructive examination prior to completion of fabrication. These parameters are designated by "N/M" in the tables. Those parameters which could not be calculated in the absence of one or more "N/M" parameters are designated by "N/D" (not determined) in the tables.

Table E-1. U₃SiAl Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A43	4.50	114+115	11.168	94.19	19.89	3.588	28.409	2.336	33.7	56.9	9.4	1.29	16	233	218	248	9/80	
A42	4.51	114+115	11.154	94.19	19.89	3.580	28.442	2.328	33.7	57.0	9.3	1.29	15.4	228	216	252	9/80	7
A22	4.59	114+115	11.152	94.19	19.89	3.580	32.313	2.287	34.3	58.0	7.7	1.53	11	230	211	258	5/80	7
A17	4.62	114+115	11.178	94.19	19.89	3.578	28.516	2.280	34.5	58.1	7.4	1.29	11.5	238	215	263	4/80	4
A30	4.62	114+115	11.160	94.19	19.89	3.578	32.688	2.276	34.5	58.2	7.2	1.54	13.8	224	206	238	9/80	7
A26	4.64	114+115	11.150	94.19	19.89	3.581	28.428	2.264	34.7	58.6	6.7	1.28	14	235	215	273	5/80	7
A31	4.64	114+115	11.156	94.19	19.89	3.589	32.634	2.264	34.7	58.7	6.6	1.54	13.9	231	205	260	9/80	
A10	4.65	114+115	11.157	94.19	19.89	3.580	32.371	2.258	34.8	58.7	6.5	1.53	11	226	213	244	4/80	3
A18	4.65	114+115	11.159	94.19	19.89	3.585	32.468	2.258	34.8	58.8	6.4	1.54	10.4	225	202	246	4/80	4
A8	4.66	114+115	11.164	94.19	19.89	3.587	32.480	2.258	34.8	58.8	6.3	1.54	10.2	230	211	245	4/80	3
A9	4.66	114+115	11.160	94.19	19.89	3.582	32.483	2.256	34.8	58.8	6.4	1.54	10	226	210	247	4/80	3
A25	4.66	114+115	11.152	94.19	19.89	3.587	28.495	2.254	34.8	58.9	6.2	1.28	12.6	235	208	271	5/80	2
A5	4.67	114+115	11.165	94.19	19.89	3.577	28.582	2.250	34.9	58.9	6.2	1.28	11.2	232	201	259	4/80	3
A21	4.68	114+115	11.167	94.19	19.89	3.584	32.482	2.247	35.0	59.1	5.9	1.54	10.5	232	211	276	5/80	3
A6	4.68	114+115	11.169	94.19	19.89	3.587	28.560	2.247	35.0	59.1	5.9	1.28	11.6	228	205	242	4/80	3
A7	4.68	114+115	11.169	94.19	19.89	3.584	28.597	2.247	35.0	59.1	5.9	1.29	11.4	233	211	258	4/80	3
A3	5.61	114+115	14.885	94.19	19.89	2.938	34.780	2.498	42.0	43.6	14.5	1.53	9.3	304	265	424	4/80	2
A50	5.74	114+115	15.115	94.19	19.89	2.616	34.892	2.481	42.9	39.1	18.0	1.54	15.3	316	287	441	7/81	10
A4	5.78	114+115	14.894	94.19	19.89	2.937	35.053	2.429	43.2	44.8	12.0	1.53	9.1	293	262	327	4/80	
A58	5.80	117	15.130	94.32	19.89	2.614	31.034	2.460	43.3	39.4	17.3	1.29	16.7	318	311	414	7/81	10
A59	5.83	117	15.124	94.32	19.89	2.617	30.739	2.445	43.6	39.6	16.8	1.27	17.5	323	293	384	7/81	10
A2	5.88	114+115	14.871	94.19	19.89	2.944	31.294	2.383	43.9	45.8	10.3	1.29	8.9	297	260	354	4/80	
A1	5.88	114+115	14.876	94.19	19.89	2.940	31.087	2.382	44.0	45.7	10.3	1.28	11.1	295	270	385	4/80	2
A52	5.90	114+115	15.126	94.19	19.89	2.621	35.051	2.415	44.1	40.2	15.7	1.53	14.2	330	281	425	7/81	10
A60	5.90	117	15.125	94.32	19.89	2.622	30.923	2.416	44.1	40.2	15.7	1.28	18.2	319	293	369	7/81	13
A82	6.11	120	14.540	94.16	19.51	2.515	31.148	2.239	45.7	41.6	12.7	1.30	19	310	N/M	329	1/82	13
A83	6.15	120	14.540	94.16	19.51	2.522	31.165	2.226	46.0	42.0	12.0	1.29	19	324	N/M	353	1/82	13
A84	6.15	120	14.540	94.16	19.51	2.522	31.151	2.225	46.0	42.0	12.0	1.29	19	310	N/M	345	1/82	13
A57	6.16	117	15.126	94.32	19.89	2.619	37.048*	2.315	46.0	41.9	12.1	N/M	17.5	325	285	415	7/81	

Table E-1. U₃SiAl Miniplate Characteristics (Continued)

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol.%	Matrix Vol.%	Porosity Vol.%	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A81	6.18	120	14.534	94.16	19.51	2.517	31.304	2.215	46.2	42.1	11.7	1.30	19	318	N/M	345	1/82	13
A63	6.23	117	16.805	94.32	19.89	2.306	32.163	2.546	46.5	33.5	20.0	1.29	17.3	346	304	465	7/81	13
A61	6.28	117	16.813	94.32	19.89	2.297	32.214	2.527	46.9	33.7	19.5	1.29	17	346	302	422	7/81	10
A62	6.33	117	16.799	94.32	19.89	2.307	32.265	2.503	47.3	34.1	18.6	1.29	15.9	342	292	437	7/81	10
A65	6.41	117	17.472	94.32	19.89	2.172	36.522	2.572	47.8	31.3	20.9	1.54	15	354	285	488	7/81	10
A66	6.43	117	17.475	94.32	19.89	2.172	37.268	2.564	48.0	31.4	20.6	1.55	15.1	368	276	529	7/81	
A67	6.44	117	17.479	94.32	19.89	2.172	36.820	2.559	48.1	31.4	20.5	1.55	14	360	291	477	7/81	10
A68	6.53	117	17.471	94.32	19.89	2.178	36.824	2.524	48.7	32.0	19.3	1.55	13	361	273	535	7/81	
A64	6.67	117	16.804	94.32	19.89	2.300	37.824*	2.376	49.8	35.9	14.3	N/M	16.6	346	300	423	7/81	
A69	6.88	120	17.775	94.16	19.51	1.906	37.164	2.431	51.5	29.0	19.5	1.55	7	369	N/M	447	1/82	13
A77	6.92	120	17.442	94.16	19.51	1.962	37.120	2.374	51.7	30.6	17.7	1.55	16	380	N/M	467	1/82	13
A71	6.93	120	17.762	94.16	19.51	1.902	37.296	2.412	51.9	29.2	18.9	1.55	17	379	N/M	486	1/82	13
A80	6.96	120	17.442	94.16	19.51	1.972	37.095	2.358	52.1	31.0	16.9	1.54	16	366	N/M	446	1/82	
A72	6.98	120	17.772	94.16	19.51	1.910	37.321	2.399	52.2	29.5	18.3	1.55	17	373	N/M	491	1/82	
A78	6.98	120	17.439	94.16	19.51	1.963	37.159	2.353	52.2	30.9	16.9	1.54	16	364	N/M	493	1/82	13
A79	6.98	120	17.436	94.16	19.51	1.964	37.178	2.352	52.2	30.9	16.9	1.54	16	366	N/M	493	1/82	13
A70	6.99	120	17.776	94.16	19.51	1.906	37.288	2.395	52.3	29.5	18.3	1.54	17	366	N/M	455	1/82	13
A75	7.05	120	17.764	94.16	19.51	1.904	33.292	2.372	52.7	29.7	17.5	1.29	16	393	N/M	538	1/82	
A73	7.06	120	17.758	94.16	19.51	1.907	33.325	2.369	52.8	29.8	17.4	1.29	16	385	N/M	462	1/82	
A74	7.07	120	17.763	94.16	19.51	1.914	N/M	2.367	52.8	29.9	17.2	N/M	16	371	N/M	455	1/82	
A76	7.07	120	17.768	94.16	19.51	1.903	N/M	2.366	52.9	29.8	17.3	N/M	16	382	N/M	472	1/82	

*Plate not machined to final size.

NOTE: Plates Nos. A1 - A68, except Nos. A39, A57 and A64, received an O-temper anneal prior to fuel meat volume determination.

Table E-2. U₃Si Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol.%	Matrix Vol.%	Porosity Vol.%	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A163D	6.09	D193+D194	14.395	95.20	0.22	2.938	31.327	2.252	42.1	48.3	9.6	1.27	18	4	3	4	11/84	24
A164D	6.18	D193+D194	14.381	95.20	0.22	2.938	31.427	2.215	42.7	49.1	8.2	1.27	18	4	3	4	11/84	24
A257	2.92	E195+E196	6.527	95.36	19.88	4.465	71.957*	2.128	20.2	77.7	2.1	N/M	12	177	130	224	7/87	
A258	2.92	E195+E196	6.529	95.36	19.88	4.464	72.102*	2.134	20.1	77.5	2.4	N/M	12	164	136	206	7/87	
A259	2.92	E195+E196	6.524	95.36	19.88	4.463	72.661*	2.127	20.2	77.7	2.1	N/M	13	172	134	208	7/87	
A260	2.92	E195+E196	6.527	95.36	19.88	4.463	71.864*	2.133	20.1	77.5	2.4	N/M	13	172	130	213	7/87	
A44	4.72	112+113	11.102	94.31	19.88	3.584	32.703	2.217	32.9	59.9	7.2	1.54	12.3	237	223	254	9/80	
A27	4.72	112+113	11.086	94.31	19.88	3.577	33.015	2.213	33.0	59.9	7.2	1.56	9.5	234	197	279	5/80	
A40	4.74	112+113	11.102	94.31	19.88	3.580	28.726	2.209	33.1	60.0	6.9	1.29	15.4	236	217	254	9/80	
A41	4.76	112+113	11.074	94.31	19.88	3.580	28.677	2.193	33.2	60.5	6.3	1.28	13.6	236	205	264	9/80	
A51	4.76	112+113	11.100	94.31	19.88	3.582	28.890	2.197	33.2	60.4	6.4	1.28	13.8	224	197	260	5/80	
A45	4.77	112+113	11.110	94.31	19.88	3.580	32.692	2.197	33.3	60.4	6.4	1.55	16.3	235	208	255	9/80	
A14	4.77	112+113	11.083	94.31	19.88	3.578	32.669	2.191	33.3	60.5	6.2	1.54	9.4	238	208	278	4/80	
A23	4.77	112+113	11.081	94.31	19.88	3.578	32.583	2.189	33.3	60.5	6.2	1.53	10.3	221	188	284	5/80	7
A39	4.78	112+113	11.082	94.31	19.88	3.589	N/M	2.186	33.3	60.8	5.9	N/M	16.5	238	201	255	9/80	
A20	4.79	112+113	11.094	94.31	19.88	3.574	32.600	2.186	33.4	60.6	6.1	1.53	10.6	224	208	241	4/80	4
A29	4.79	112+113	11.101	94.31	19.88	3.585	32.794	2.187	33.4	60.7	5.9	1.54	14.3	227	199	274	9/80	
A13	4.79	112+113	11.090	94.31	19.88	3.579	28.627	2.184	33.4	60.7	5.9	1.28	13	237	208	265	4/80	3
A24	4.80	112+113	11.090	94.31	19.88	3.584	28.607	2.180	33.5	60.9	5.6	1.27	12.8	236	217	261	5/80	7
A16	4.80	112+113	11.085	94.31	19.88	3.583	32.690	2.177	33.5	61.0	5.5	1.54	11.4	240	206	284	4/80	3
A19	4.81	112+113	11.097	94.31	19.88	3.580	28.601	2.175	33.6	61.0	5.5	1.28	12.7	221	191	257	4/80	4
A28	4.81	112+113	11.090	94.31	19.88	3.582	32.804	2.174	33.6	61.0	5.4	1.54	14.1	231	210	269	9/80	7
A38	4.81	112+113	11.096	94.31	19.88	3.582	28.774	2.174	33.6	61.0	5.4	1.29	16.8	224	195	281	9/80	7
A15	4.82	112+113	11.090	94.31	19.88	3.584	32.645	2.172	33.6	61.1	5.3	1.54	12	230	203	265	4/80	3
A12	4.83	112+113	11.083	94.31	19.88	3.582	28.530	2.165	33.7	61.3	5.0	1.27	11.3	225	206	240	4/80	3
A11	4.83	112+113	11.076	94.31	19.88	3.581	28.702	2.161	33.7	61.4	4.9	1.28	11.3	222	208	238	4/80	3
A48	5.65	116	14.753	94.55	19.89	2.877	30.838	2.470	39.3	43.1	17.6	1.29	16.3	319	270	381	7/81	10
A53	5.67	116	14.751	94.55	19.89	2.882	34.740	2.460	39.4	43.4	17.2	1.53	15.4	314	264	387	7/81	10

Table E-2. U₃Si Miniplate Characteristics (Continued)

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A55	5.70	116	14.750	94.55	19.89	2.872	35.621	2.446	39.7	43.5	16.8	1.54	14.9	311	274	412	7/81	
A49	5.71	116	14.747	94.55	19.89	2.874	30.914	2.441	39.7	43.6	16.6	1.29	14.6	333	295	362	7/81	10
A54	5.72	116	14.749	94.55	19.89	2.877	34.977	2.440	39.8	43.7	16.6	1.54	15.5	322	291	388	7/81	10
A56	5.73	116	14.752	94.55	19.89	2.876	34.980	2.433	39.9	43.8	16.3	1.54	15.2	314	284	370	7/81	
A221	6.05	E195+E196	15.380	95.36	19.88	2.807	35.845	2.425	41.7	42.7	15.6	1.53	13	344	293	484	4/86	34
A222	N/D	E195+E196	15.383	95.36	19.88	2.807	N/M	N/D	N/D	N/D	N/D	N/M	13	322	270	397	4/86	
A211	6.07	E195+E196	15.383	95.36	19.88	2.808	31.890	2.418	41.9	42.9	15.3	1.26	16	346	294	476	4/86	34
A212	N/D	E195+E196	15.385	95.36	19.88	2.807	N/M	N/D	N/D	N/D	N/D	N/M	16	334	278	432	4/86	
A209	6.11	E195+E196	15.386	95.36	19.88	2.808	32.018	2.401	42.2	43.2	14.7	1.27	17	342	284	458	4/86	34
A210	6.16	E195+E196	15.386	95.36	19.88	2.807	32.002	2.382	42.5	43.5	14.0	1.28	17	334	300	443	4/86	34
A117	6.23	E172+E173	15.109	95.43	19.83	2.815	32.020	2.316	42.9	45.0	12.1	1.30	15	329	289	360	9/83	18
A101	6.23	E172+E173	15.110	95.43	19.83	2.813	36.098	2.315	42.9	45.0	12.1	1.55	13	329	273	418	9/83	33
A103	6.25	E172+E173	15.111	95.43	19.83	2.812	36.124	2.309	43.1	45.1	11.8	1.55	14	329	296	405	9/83	18
A195P	6.30	E195+E196	15.385	95.36	19.88	2.757	32.116	2.328	43.5	43.9	12.0	1.28	16	331	279	411	8/85	
A102	6.33	E172+E173	15.111	95.43	19.83	2.816	36.184	2.277	43.7	45.8	10.5	1.55	13	325	302	374	9/83	
A118	6.33	E172+E173	15.112	95.43	19.83	2.816	31.894	2.277	43.7	45.8	10.5	1.27	15	329	284	367	9/83	18
A104	6.33	E172+E173	15.108	95.43	19.83	2.815	36.075	2.276	43.7	45.8	10.5	1.55	14	321	282	415	9/83	18
A193P	6.34	E195+E196	15.380	95.36	19.88	2.758	32.095	2.312	43.8	44.2	11.4	1.28	17	338	302	406	8/85	31
A196P	6.35	E195+E196	15.383	95.36	19.88	2.758	32.206	2.311	43.8	44.2	11.4	1.28	16	336	288	395	8/85	
A194P	6.42	E195+E196	15.388	95.36	19.88	2.760	32.228	2.285	44.3	44.7	10.3	1.28	17	338	300	403	8/85	31
A197P	6.47	E195+E196	15.385	95.36	19.88	2.757	36.210	2.269	44.6	45.0	9.8	1.53	8	341	288	399	8/85	31
A198P	6.48	E195+E196	15.387	95.36	19.88	2.755	36.282	2.265	44.7	45.0	9.6	1.54	8	343	304	414	8/85	
A155	6.64	E195+E196	15.733	95.36	19.88	2.608	32.379	2.261	45.8	42.7	11.5	1.28	18	355	331	436	11/84	
A156	6.73	E195+E196	15.733	95.36	19.88	2.608	32.520	2.229	46.4	43.3	10.2	1.28	18	339	328	388	11/84	
A157	6.92	E195+E196	16.436	95.36	19.88	2.422	32.987	2.265	47.7	39.6	12.7	1.28	19	361	333	414	11/84	23,29
A158	6.97	E195+E196	16.435	95.36	19.88	2.422	32.806	2.247	48.1	39.9	12.0	1.27	19	357	324	424	11/84	
A107	7.09	E172+E173	17.978	95.43	19.83	2.304	38.049	2.419	48.9	35.3	15.8	1.55	13	386	342	531	9/83	17
A119	7.10	E172+E173	17.979	95.43	19.83	2.304	38.046	2.418	48.9	35.3	15.8	1.55	13	374	328	551	9/83	22,25

Table E-2. U₃Si Miniplate Characteristics (Continued)

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A127	7.13	E172+E173	17.283	95.43	19.83	2.210	33.516	2.313	49.2	35.4	15.5	1.27	17	428	318	640	4/84	
A105	7.13	E172+E173	17.983	95.43	19.83	2.303	37.709	2.406	49.2	35.5	15.4	1.52	2	418	363	512	9/83	22,25
A108	7.16	E172+E173	17.985	95.43	19.83	2.302	38.226	2.396	49.4	35.6	15.0	1.55	13	372	329	486	9/83	17,25
A120	7.18	E172+E173	17.977	95.43	19.83	2.298	38.082	2.388	49.5	35.6	14.8	1.55	13	378	330	609	9/83	
A106	7.19	E172+E173	17.981	95.43	19.83	2.303	37.785	2.386	49.6	35.7	14.7	1.52	2	411	367	526	9/83	
A128	7.26	E172+E173	17.281	95.43	19.83	2.211	33.591	2.270	50.1	36.1	13.8	1.27	17	414	335	496	4/84	
A113	4.51	E179	10.069	95.43	40.06	3.709	28.506	2.130	31.1	64.5	4.4	1.30	15	444	409	501	9/83	17
A114	4.52	E179	10.072	95.43	40.06	3.705	28.277	2.125	31.2	64.6	4.2	1.30	15	438	383	529	9/83	17,33
A217	5.79	E179	9.254	95.43	40.06	1.847	27.248	1.524	39.9	44.7	15.3	1.28	16	447	293	738	4/86	
A218	5.91	E179	9.251	95.43	40.06	1.846	27.112	1.494	40.7	45.6	13.7	1.27	16	441	335	675	4/86	33
A109	6.23	E179	9.518	95.43	40.06	1.773	27.837	1.457	43.0	45.1	12.0	1.30	14	433	385	562	9/83	17
A111	6.29	E179	9.512	95.43	40.06	1.774	27.810	1.442	43.4	45.6	11.0	1.30	14	452	371	620	9/83	
A110	6.36	E179	9.520	95.43	40.06	1.771	27.708	1.429	43.8	45.9	10.3	1.30	14	428	384	552	9/83	17
A112	6.40	E179	9.519	95.43	40.06	1.772	27.714	1.420	44.1	46.2	9.7	1.30	14	428	369	571	9/83	17
A115	1.98	E177	4.312	95.41	92.62	4.730	23.680	2.073	13.7	84.5	1.8	1.30	17	514	384	566	9/83	17,33
A116	1.99	E177	4.319	95.41	92.62	4.729	23.714	2.070	13.7	84.6	1.7	1.30	17	504	410	610	9/83	17

*Plate not machined to final size.

NOTES: (1) Plates Nos. A1 - A68, except Nos. A39, A57 and A64, received an O-temper anneal prior to fuel meat volume determination.

(2) Plates with numbers ending in "P" contained 36 mg (0.6 vol.%) of natural B₄C uniformly dispersed in the fuel meat.

(3) The matrix of plates Nos. A209 - A224 is Al-6061.

Table E-3. U_3Si_2 Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A165D	4.75	D187-D192	11.258	92.33	0.22	2.939	32.556	2.188	42.2	49.7	8.1	1.53	12	3	2	3	11/84	24
A166D	4.77	D187-D192	11.258	92.33	0.22	2.938	32.546	2.177	42.4	50.0	7.6	1.53	12	3	2	3	11/84	24
A46	3.72	118	8.674	92.27	19.87	3.583	30.413	2.150	33.1	61.7	5.2	1.54	13.3	184	167	195	9/80	7
A37	3.74	118	8.678	92.27	19.87	3.584	30.554	2.140	33.2	62.0	4.7	1.54	16.4	184	176	196	9/80	
A47	3.74	118	8.692	92.27	19.87	3.583	30.478	2.142	33.3	62.0	4.8	1.54	13.4	189	179	198	9/80	
A36	3.75	118	8.678	92.27	19.87	3.583	30.540	2.135	33.3	62.2	4.5	1.54	15.5	185	174	200	9/80	7
A32	3.75	118	8.676	92.27	19.87	3.579	26.587	2.133	33.3	62.2	4.5	1.29	15.8	179	159	197	9/80	7
A33	3.75	118	8.668	92.27	19.87	3.588	26.577	2.131	33.3	62.4	4.3	1.29	15.6	182	169	198	9/80	
A34	3.76	118	8.679	92.27	19.87	3.583	26.446	2.130	33.4	62.3	4.3	1.28	15.7	165	138	186	9/80	7
A35	3.77	118	8.678	92.27	19.87	3.582	26.642	2.126	33.5	62.4	4.1	1.29	16.4	157	143	176	9/80	
A223	4.92	E158-E165	12.907	92.18	19.84	2.807	33.402	2.420	43.7	42.8	13.5	1.53	14	271	242	317	4/86	34
A213	4.94	E158-E165	12.910	92.18	19.84	2.807	29.495	2.410	43.9	43.0	13.1	1.28	18	274	248	341	4/86	34
A214	N/D	E158-E165	12.905	92.18	19.84	2.805	N/M	N/D	N/D	N/D	N/D	N/M	18	256	226	294	4/86	
A215	4.95	E158-E165	12.910	92.18	19.84	2.805	29.556	2.405	44.0	43.0	13.0	1.29	18	268	240	345	4/86	
A224	4.98	E158-E165	12.905	92.18	19.84	2.808	33.296	2.388	44.3	43.4	12.3	1.52	14	263	242	340	4/86	34
A216	4.99	E158-E165	12.908	92.18	19.84	2.807	29.567	2.385	44.4	43.4	12.2	1.28	18	269	242	332	4/86	34
A201P	5.09	E158-E165	12.912	92.18	19.84	2.759	29.593	2.340	45.2	43.7	10.5	1.27	19	266	244	319	8/85	
A203P	5.09	E158-E165	12.909	92.18	19.84	2.756	33.636	2.337	45.3	43.7	10.4	1.53	15	263	235	299	8/85	
A199P	5.10	E158-E165	12.970	92.18	19.84	2.756	29.651	2.344	45.4	43.5	10.5	1.28	18	266	250	324	8/85	30
A85	5.10	E158-E165	12.408	92.18	19.84	2.682	29.345	2.241	45.4	44.3	10.3	1.29	13	260	253	274	7/83	17,25
A87	5.13	E158-E165	12.398	92.18	19.84	2.686	29.295	2.229	45.6	44.6	9.8	1.29	12	263	247	279	7/83	18,34
A202P	5.13	E158-E165	12.909	92.18	19.84	2.756	29.518	2.320	45.6	44.0	9.8	1.27	19	269	244	306	8/85	30
A204P	5.13	E158-E165	12.909	92.18	19.84	2.756	33.437	2.320	45.6	44.0	9.8	1.52	15	275	240	338	8/85	31
A86	5.13	E158-E165	12.393	92.18	19.84	2.687	29.551	2.226	45.6	44.7	9.7	1.30	13	263	250	276	7/83	
A200P	5.13	E158-E165	12.911	92.18	19.84	2.757	29.701	2.318	45.7	44.1	9.7	1.28	18	270	253	319	8/85	30
A88	5.15	E158-E165	12.398	92.18	19.84	2.682	29.371	2.220	45.8	44.7	9.5	1.29	12	268	249	286	7/83	18
A99	5.17	E158-E165	18.588	92.18	19.84	4.026	37.998	3.317	45.9	45.0	9.1	1.55	12	394	353	414	7/83	17
A97	5.18	E158-E165	18.590	92.18	19.84	4.024	38.041	3.308	46.1	45.1	8.9	1.55	7	371	350	417	7/83	

Table E-3. U_3Si_2 Miniplate Characteristics (Continued)

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A100	5.20	E158-E165	18.590	92.18	19.84	4.027	37.960	3.296	46.2	45.3	8.5	1.55	12	394	365	420	7/83	17
A98	5.22	E158-E165	18.582	92.18	19.84	4.028	38.099	3.284	46.4	45.4	8.2	1.55	7	372	349	394	7/83	
A91	5.59	E158-E165	14.081	92.18	19.84	2.302	30.440	2.320	49.7	36.7	13.5	1.30	17	291	275	327	7/83	18
A89	5.60	E158-E165	14.087	92.18	19.84	2.303	30.574	2.319	49.8	36.8	13.4	1.29	12	295	283	328	7/83	18,34
A90	5.61	E158-E165	14.082	92.18	19.84	2.300	30.401	2.314	49.9	36.8	13.3	1.29	12	296	282	316	7/83	18,34
A95	5.62	E158-E165	14.082	92.18	19.84	2.302	34.396	2.310	50.0	36.9	13.1	1.55	13	291	272	344	7/83	
A93	5.63	E158-E165	14.090	92.18	19.84	2.303	34.420	2.308	50.0	37.0	13.0	1.55	12	291	275	335	7/83	18,34
A92	5.63	E158-E165	14.081	92.18	19.84	2.305	30.608	2.306	50.1	37.0	12.9	1.30	17	291	278	324	7/83	18
A96	5.67	E158-E165	14.086	92.18	19.84	2.300	34.481	2.292	50.4	37.2	12.5	1.55	13	286	267	335	7/83	27
A94	5.67	E158-E165	14.082	92.18	19.84	2.300	34.476	2.290	50.4	37.2	12.4	1.55	12	293	273	322	7/83	18
A124	3.94	E180	8.997	92.30	40.11	3.449	26.901	2.106	35.0	60.7	4.3	1.27	16	392	362	421	4/84	23,29
A123	3.95	E180	9.007	92.30	40.11	3.449	27.023	2.104	35.1	60.7	4.2	1.27	16	393	362	420	4/84	22
A219	4.91	E180	8.135	92.30	40.11	1.689	25.945	1.530	43.6	40.7	15.7	1.28	16	358	277	552	4/86	
A220	4.95	E180	8.132	92.30	40.11	1.692	25.557	1.515	44.0	41.2	14.8	1.27	16	341	281	522	4/86	33
A125	5.13	E180	7.313	92.30	40.11	1.512	25.446	1.315	45.6	42.6	11.8	1.27	18	345	252	459	4/84	23,29
A126	5.18	E180	7.320	92.30	40.11	1.515	25.403	1.305	46.0	43.0	11.0	1.27	18	331	240	425	4/84	23,29
A121	1.66	E178	3.672	92.32	92.95	4.662	22.997	2.044	14.7	84.5	0.8	1.27	16	428	354	476	4/84	22
A122	1.66	E178	3.666	92.32	92.95	4.664	22.891	2.044	14.7	84.5	0.8	1.27	16	426	370	488	4/84	23,29

NOTES: (1) Plates Nos. A1 - A68, except Nos. A39, A57 and A64, received an O-temper anneal prior to fuel meat volume determination.

(2) Plates with numbers ending in "P" contained 36 mg (0.6 vol.%) of natural B_4C uniformly dispersed in the fuel meat.

(3) The matrix of plates Nos. A209 - A224 is Al-6061.

Table E-4. USi Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A187D	3.71	D203	9.934	89.25	0.23	3.230	26.960	2.389	38.1	50.1	11.8	1.28	16	2	2	3	5/85	
A189D	3.73	D203	9.938	89.25	0.23	3.235	26.926	2.378	38.3	50.4	11.3	1.28	17	2	2	3	5/85	27
A191D	3.74	D203	9.937	89.25	0.23	3.232	30.836	2.369	38.5	50.5	11.0	1.53	13	2	2	3	5/85	
A188D	3.76	D203	9.938	89.25	0.23	3.235	27.080	2.357	38.7	50.8	10.5	1.29	16	2	2	3	5/85	27
A190D	3.79	D203	9.937	89.25	0.23	3.230	27.005	2.339	39.0	51.1	9.9	1.28	17	2	2	3	5/85	27
A192D	3.82	D203	9.938	89.25	0.23	3.235	30.951	2.324	39.2	51.6	9.2	1.52	13	2	2	3	5/85	
A177	3.78	E204	9.938	89.26	19.82	3.229	27.056	2.349	38.8	50.9	10.3	1.28	17	200	186	238	5/85	
A175	3.78	E204	9.940	89.26	19.82	3.230	27.046	2.348	38.8	50.9	10.2	1.28	14	207	189	230	5/85	
A179	3.81	E204	9.937	89.26	19.82	3.232	30.998	2.326	39.2	51.5	9.3	1.53	8	205	185	242	5/85	27
A178	3.86	E204	9.938	89.26	19.82	3.231	27.040	2.300	39.6	52.0	8.3	1.27	17	198	184	232	5/85	27
A176	3.87	E204	9.944	89.26	19.82	3.231	27.131	2.295	39.8	52.1	8.1	1.28	14	207	193	248	5/85	27
A180	3.90	E204	9.938	89.26	19.82	3.230	31.036	2.275	40.1	52.6	7.3	1.53	8	202	190	235	5/85	27
A183	3.81	E205+E217	9.940	89.27	40.11	3.235	26.826	2.329	39.2	51.4	9.4	1.26	19	403	373	438	5/85	28
A181	3.82	E205+E217	9.941	89.27	40.11	3.231	31.069	2.326	39.2	51.4	9.3	1.53	12	423	385	494	5/85	28
A185	3.82	E205+E217	9.942	89.27	40.11	3.228	26.892	2.324	39.2	51.4	9.3	1.27	20	409	387	460	5/85	
A186	3.89	E205+E217	9.945	89.27	40.11	3.227	26.828	2.281	40.0	52.4	7.6	1.26	20	403	369	468	5/85	
A184	3.89	E205+E217	9.945	89.27	40.11	3.233	26.856	2.280	40.0	52.5	7.5	1.26	19	397	365	448	5/85	
A182	3.90	E205+E217	9.937	89.27	40.11	3.229	31.118	2.274	40.1	52.6	7.3	1.53	12	413	383	466	5/85	28

Table E-5. U_3SiCu Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A139	5.31	E199	14.679	91.78*	19.86	2.920	31.017	2.539	44.1	42.6	13.3	1.28	14	305	276	355	1/85	27
A143	5.36	E199	14.686	91.78*	19.86	2.920	35.074	2.513	44.6	43.0	12.4	1.53	14	317	277	396	1/85	
A140	5.37	E199	14.681	91.78*	19.86	2.918	31.142	2.508	44.7	43.1	12.2	1.27	14	309	278	358	1/85	27
A144	5.41	E199	14.688	91.78*	19.86	2.919	35.141	2.494	44.9	43.3	11.7	1.53	14	316	272	398	1/85	
A142	5.72	E199	17.052	91.78*	19.86	2.791	36.791	2.736	47.6	37.8	14.7	1.53	13	349	296	481	1/85	
A141	5.82	E199	17.229	91.78*	19.86	2.611	36.850	2.715	48.4	35.6	15.9	1.53	13	342	298	510	1/85	
A145	3.78	E200	9.796	92.42*	40.06	4.101	27.606	2.394	30.5	63.4	6.1	1.28	15	389	369	437	5/85	28
A146	3.80	E200	9.786	92.42*	40.06	4.099	27.610	2.383	30.6	63.7	5.7	1.28	15	395	373	447	5/85	
A169	5.94	E201	14.683	95.17	19.84	2.917	35.465	2.351	41.1	46.0	13.0	1.54	10	339	277	400	5/85	28
A171	6.10	E201	14.686	95.17	19.84	2.919	31.536	2.290	42.2	47.2	10.6	1.28	17	338	293	411	5/85	28
A170	6.13	E201	14.681	95.17	19.84	2.914	35.592	2.279	42.4	47.4	10.3	1.54	10	346	307	442	5/85	
A172	6.13	E201	14.681	95.17	19.84	2.933	31.620	2.278	42.4	47.7	9.9	1.28	17	342	291	424	5/85	28
A205	6.73	E201	16.139	95.17	19.84	2.268	32.467	2.283	46.5	36.8	16.7	1.29	17	356	294	404	10/85	
A207	6.81	E201	16.783	95.17	19.84	2.364	36.906	2.346	47.1	37.3	15.6	1.52	17	364	303	451	8/85	31
A208	6.84	E201	16.784	95.17	19.84	2.360	37.073	2.336	47.3	37.4	15.3	1.53	17	364	301	461	8/85	31
A206	6.86	E201	16.140	95.17	19.84	2.271	32.656	2.238	47.4	37.6	15.0	1.29	17	366	324	414	10/85	31
A167	6.91	E201	17.480	95.17	19.84	2.360	37.494	2.408	47.8	36.3	15.9	1.54	8	382	290	600	5/85	
A168	7.03	E201	17.481	95.17	19.84	2.363	37.597	2.367	48.6	37.0	14.4	1.54	8	378	299	500	5/85	28
A173	4.11	E202	9.793	95.21	39.96	4.092	27.752	2.269	28.4	66.8	4.8	1.27	17	442	392	500	5/85	28
A174	4.15	E202	9.792	95.21	39.96	4.100	27.955	2.248	28.7	67.5	3.8	1.28	17	448	394	504	5/85	28

*The fuel particles were coated with alumina and silica from the mullite mortar and pestle used during comminution. Using the chemical analysis data, coated particle densities of 13.1 and 13.4 g/cm³ for 19.88%-enriched and 40.06%-enriched fuels, respectively, have been determined. The density of the uncoated fuel is 15.2 g/cm³.

Table E-6. $U_3Si_{1.5}$ Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A151	5.07	E197	12.921	93.74	19.83	2.980	33.501	2.389	39.5	46.2	14.3	1.52	10	290	266	366	11/84	23,29
A153	5.09	E197	12.918	93.74	19.83	2.982	29.812	2.378	39.7	46.4	13.9	1.28	15	283	258	321	1/85	
A152	5.15	E197	12.919	93.74	19.83	2.981	33.700	2.350	40.1	47.0	12.9	1.52	10	285	264	335	11/84	27
A154	5.17	E197	12.913	93.74	19.83	2.983	29.724	2.343	40.2	47.2	12.6	1.28	15	281	264	327	1/85	27
A149	5.83	E197	15.762	93.74	19.83	2.355	35.584	2.534	45.4	34.4	20.2	1.52	11	324	292	437	11/84	23,29
A150	5.96	E197	15.748	93.74	19.83	2.357	35.691	2.476	46.4	35.3	18.3	1.53	11	317	289	417	11/84	23,29
A147	3.84	E198	9.768	93.32	40.04	3.849	27.338	2.375	30.0	60.0	10.0	1.28	15	405	376	461	5/85	28
A148	3.91	E198	9.767	93.32	40.04	3.849	27.408	2.332	30.6	61.1	8.3	1.28	15	401	380	415	5/85	28

Table E-7. UAl_2 Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A131	N/D	E185	8.983	79.19	44.81	2.209	N/M	N/D	N/D	N/D	N/D	N/M	16	N/M	N/M	N/M	4/84	
A132	2.95	E185	8.984	79.19	44.81	2.211	24.974	2.408	47.2	34.0	18.8	1.27	16	393	347	436	4/84	23,29
A138	2.98	E185	9.092	79.19	44.81	2.236	24.851	2.416	47.6	34.3	18.1	1.26	18	383	360	430	11/84	
A137	2.99	E185	9.087	79.19	44.81	2.236	25.052	2.406	47.8	34.4	17.8	1.28	18	383	351	451	11/84	23,29

Table E-8. U₆Fe Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A161D	6.91	D157	16.469	95.87	0.22	2.939	37.478	2.285	41.4	47.6	10.9	1.53	18	4	4	5	11/84	24
A162D	7.10	D157	16.471	95.87	0.22	2.938	37.471	2.224	42.6	48.9	8.5	1.52	18	4	4	5	11/84	24
A129	7.03	E184	16.616	95.70	19.84	2.705	33.562	2.261	42.2	44.3	13.5	1.27	16	418	342	474	4/84	23
A130	7.26	E184	16.618	95.70	19.84	2.704	33.646	2.192	43.6	45.7	10.7	1.27	16	402	361	450	4/84	
A133	7.76	E184	18.991	95.70	19.84	2.333	39.104	2.342	46.6	36.9	16.5	1.52	15	466	364	614	4/84	
A159	7.77	E184	19.213	95.70	19.84	2.359	39.413	2.366	46.7	36.9	16.4	1.53	19	428	386	549	11/84	
A135	7.78	E184	18.991	95.70	19.84	2.335	39.119	2.335	46.7	37.0	16.2	1.52	14	474	408	578	4/84	22
A134	7.93	E184	18.993	95.70	19.84	2.334	39.208	2.293	47.6	37.7	14.7	1.52	15	463	361	572	4/84	
A136	7.95	E184	18.986	95.70	19.84	2.336	39.330	2.285	47.8	37.9	14.4	1.52	14	451	370	556	4/84	22
A160	8.02	E184	19.212	95.70	19.84	2.359	39.384	2.293	48.2	38.1	13.7	1.52	19	430	384	500	11/84	23

Table E-9. U₆Mn_{1.3} Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A227	6.89	E236	17.389	93.25	19.79	2.546	37.786	2.354	44.0	40.1	16.0	1.52	14	387	323	495	4/86	33
A225	6.92	E236	17.395	93.25	19.79	2.546	33.275	2.344	44.2	40.2	15.6	1.24	19	379	312	486	4/86	33
A228	7.05	E236	17.389	93.25	19.79	2.546	38.236	2.300	45.0	41.0	14.0	1.54	14	391	351	461	4/86	33
A226	7.12	E236	17.389	93.25	19.79	2.545	33.895	2.279	45.4	41.4	13.2	1.27	19	376	332	446	4/86	
A229	6.19	E236	8.915	93.32	40.00	1.647	26.813	1.345	39.5	45.4	15.2	1.25	19	413	356	475	4/86	33
A231	6.22	E236	8.916	93.32	40.00	1.647	26.723	1.338	39.7	45.6	14.7	1.25	21	392	275	511	4/86	33
A232	6.26	E236	8.909	93.32	40.00	1.647	27.234	1.329	39.9	45.9	14.2	1.28	21	407	302	643	4/86	33
A230	6.35	E236	8.913	93.32	40.00	1.646	27.378	1.310	40.5	46.5	13.0	1.29	19	422	370	577	4/86	

Table E-10. $U_3Si_{1.6}$ (As-Cast) Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A240	3.59	E247	8.772	93.81	19.84	3.776	26.351	2.292	29.4	61.0	9.5	1.26	15	197	179	221	3/87	
A239	3.61	E247	8.777	93.81	19.84	3.776	26.488	2.280	29.6	61.3	9.0	1.26	15	205	173	236	3/87	
A238	3.66	E247	9.723	93.81	19.84	4.038	27.091	2.492	30.0	60.0	10.0	1.26	14	220	203	244	3/87	
A237	3.67	E247	9.723	93.81	19.84	4.038	27.102	2.483	30.1	60.2	9.6	1.26	14	218	198	239	3/87	
A242	4.70	E247	13.168	93.81	19.84	3.325	29.596	2.631	38.5	46.8	14.7	1.26	16.1	269	254	287	3/87	
A244	4.72	E247	12.548	93.81	19.84	2.997	32.896	2.495	38.7	44.5	16.8	1.51	13.2	261	235	317	3/87	
A241	4.72	E247	13.171	93.81	19.84	3.325	N/M	2.615	38.7	47.1	14.2	N/M	16.1	274	250	351	3/87	
A243	4.77	E247	12.543	93.81	19.84	2.996	32.947	2.468	39.1	45.0	15.9	1.51	13.2	272	243	348	3/87	

Table E-11. U_3Si (As-Cast) Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A234	4.63	E248	12.282	95.80	19.84	3.778	29.210	2.543	33.1	55.0	11.9	1.25	13.5	277	200	324	3/87	
A233	4.65	E248	12.277	95.80	19.84	3.776	29.300	2.532	33.2	55.2	11.6	1.27	13.5	276	254	331	3/87	
A235	4.67	E248	11.579	95.80	19.84	3.453	28.729	2.377	33.4	53.8	12.8	1.26	14.8	273	217	316	3/87	
A236	4.73	E248	11.582	95.80	19.84	3.454	28.853	2.346	33.8	54.5	11.7	1.26	14.8	274	243	309	3/87	
A246	5.21	E248	14.392	95.80	19.84	3.388	N/M	2.648	37.2	47.4	15.4	N/M	13.4	315	237	475	3/87	
A245	5.23	E248	14.392	95.80	19.84	3.388	34.758	2.637	37.4	47.6	15.0	1.51	13.4	306	246	426	3/87	
A247	5.26	E248	13.693	95.80	19.84	3.062	34.192	2.496	37.6	45.4	17.0	1.51	13.6	322	282	437	3/87	
A248	5.28	E248	13.696	95.80	19.84	3.062	34.178	2.487	37.7	45.6	16.7	1.51	13.6	309	245	399	3/87	

Table E-12. $U_{75}Ga_{15}Ge_{10}$ Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A254	2.70	E229	6.773	90.79	19.84	4.463	63.795	2.275	18.8	72.7	8.5	N/M	14	155	139	186	7/87	
A253	2.71	E229	6.781	90.79	19.84	4.465	64.182	2.270	18.9	72.9	8.2	N/M	14	157	149	174	7/87	
A255	2.71	E229	6.778	90.79	19.84	4.464	64.280	2.272	18.9	72.8	8.3	N/M	14	154	138	191	7/87	
A256	2.73	E229	6.781	90.79	19.84	4.463	63.493	2.253	19.0	73.4	7.6	N/M	14	154	141	169	7/87	

NOTE: Plates not machined to final size.

Table E-13. $U_{75}Ga_{10}Si_{15}$ Miniplate Characteristics

Plate No.	U Dens. (g/cm ³)	Fuel Ingot No.	Fuel Wt. (g)	Fuel Wt.% U	Fuel U Enr. (%)	Matrix Wt. (g)	Plate Wt. (g)	Fuel Meat Vol. (cm ³)	Fuel Vol. %	Matrix Vol. %	Porosity Vol. %	Pl. Thk. (mm)	% Cold Work	²³⁵ U Surface Density (g/m ²)			Fab. Date	Irrad. Mod.
														Ave.	Min.	Max.		
A251	2.78	E230	6.705	93.86	19.84	4.465	63.341	2.265	19.0	73.0	8.0	N/M	15	152	138	213	7/87	
A249	2.79	E230	6.702	93.86	19.84	4.465	62.908	2.257	19.0	73.3	7.7	N/M	15	153	139	181	7/87	
A252	2.82	E230	6.713	93.86	19.84	4.465	63.156	2.238	19.2	73.9	6.9	N/M	15	149	131	199	7/87	
A250	2.83	E230	6.706	93.86	19.84	4.463	61.558	2.221	19.4	74.4	6.2	N/M	15	153	120	202	7/87	

NOTE: Plates not machined to final size.

Table E-14. Miniplate Cross Reference by Plate Number

Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)
A1	U ₃ SiAl	5.88	A28	U ₃ Si	4.81	A55	U ₃ Si	5.70	A82	U ₃ SiAl	6.11	A109	U ₃ Si	6.23
A2	U ₃ SiAl	5.88	A29	U ₃ Si	4.79	A56	U ₃ Si	5.73	A83	U ₃ SiAl	6.15	A110	U ₃ Si	6.36
A3	U ₃ SiAl	5.61	A30	U ₃ SiAl	4.62	A57	U ₃ SiAl	6.16	A84	U ₃ SiAl	6.15	A111	U ₃ Si	6.29
A4	U ₃ SiAl	5.78	A31	U ₃ SiAl	4.64	A58	U ₃ SiAl	5.80	A85	U ₃ Si ₂	5.10	A112	U ₃ Si	6.40
A5	U ₃ SiAl	4.67	A32	U ₃ Si ₂	3.75	A59	U ₃ SiAl	5.83	A86	U ₃ Si ₂	5.13	A113	U ₃ Si	4.51
A6	U ₃ SiAl	4.68	A33	U ₃ Si ₂	3.75	A60	U ₃ SiAl	5.90	A87	U ₃ Si ₂	5.13	A114	U ₃ Si	4.52
A7	U ₃ SiAl	4.68	A34	U ₃ Si ₂	3.76	A61	U ₃ SiAl	6.28	A88	U ₃ Si ₂	5.15	A115	U ₃ Si	1.98
A8	U ₃ SiAl	4.66	A35	U ₃ Si ₂	3.77	A62	U ₃ SiAl	6.33	A89	U ₃ Si ₂	5.60	A116	U ₃ Si	1.99
A9	U ₃ SiAl	4.66	A36	U ₃ Si ₂	3.75	A63	U ₃ SiAl	6.23	A90	U ₃ Si ₂	5.61	A117	U ₃ Si	6.23
A10	U ₃ SiAl	4.65	A37	U ₃ Si ₂	3.74	A64	U ₃ SiAl	6.67	A91	U ₃ Si ₂	5.59	A118	U ₃ Si	6.33
A11	U ₃ Si	4.83	A38	U ₃ Si	4.81	A65	U ₃ SiAl	6.41	A92	U ₃ Si ₂	5.63	A119	U ₃ Si	7.10
A12	U ₃ Si	4.83	A39	U ₃ Si	4.78	A66	U ₃ SiAl	6.43	A93	U ₃ Si ₂	5.63	A120	U ₃ Si	7.18
A13	U ₃ Si	4.79	A40	U ₃ Si	4.74	A67	U ₃ SiAl	6.44	A94	U ₃ Si ₂	5.67	A121	U ₃ Si ₂	1.66
A14	U ₃ Si	4.77	A41	U ₃ Si	4.76	A68	U ₃ SiAl	6.53	A95	U ₃ Si ₂	5.62	A122	U ₃ Si ₂	1.66
A15	U ₃ Si	4.82	A42	U ₃ SiAl	4.51	A69	U ₃ SiAl	6.88	A96	U ₃ Si ₂	5.67	A123	U ₃ Si ₂	3.95
A16	U ₃ Si	4.80	A43	U ₃ SiAl	4.50	A70	U ₃ SiAl	6.99	A97	U ₃ Si ₂	5.18	A124	U ₃ Si ₂	3.94
A17	U ₃ SiAl	4.62	A44	U ₃ Si	4.72	A71	U ₃ SiAl	6.93	A98	U ₃ Si ₂	5.22	A125	U ₃ Si ₂	5.13
A18	U ₃ SiAl	4.65	A45	U ₃ Si	4.77	A72	U ₃ SiAl	6.98	A99	U ₃ Si ₂	5.17	A126	U ₃ Si ₂	5.18
A19	U ₃ Si	4.81	A46	U ₃ Si ₂	3.72	A73	U ₃ SiAl	7.06	A100	U ₃ Si ₂	5.20	A127	U ₃ Si	7.13
A20	U ₃ Si	4.79	A47	U ₃ Si ₂	3.74	A74	U ₃ SiAl	7.07	A101	U ₃ Si	6.23	A128	U ₃ Si	7.26
A21	U ₃ SiAl	4.68	A48	U ₃ Si	5.65	A75	U ₃ SiAl	7.05	A102	U ₃ Si	6.33	A129	U ₃ Fe	7.03
A22	U ₃ SiAl	4.59	A49	U ₃ Si	5.71	A76	U ₃ SiAl	7.07	A103	U ₃ Si	6.25	A130	U ₃ Fe	7.26
A23	U ₃ Si	4.77	A50	U ₃ SiAl	5.74	A77	U ₃ SiAl	6.92	A104	U ₃ Si	6.33	A131	UAl ₂	N/D
A24	U ₃ Si	4.80	A51	U ₃ Si	4.76	A78	U ₃ SiAl	6.98	A105	U ₃ Si	7.13	A132	UAl ₂	2.95
A25	U ₃ SiAl	4.66	A52	U ₃ SiAl	5.90	A79	U ₃ SiAl	6.98	A106	U ₃ Si	7.19	A133	U ₃ Fe	7.76
A26	U ₃ SiAl	4.64	A53	U ₃ Si	5.67	A80	U ₃ SiAl	6.96	A107	U ₃ Si	7.09	A134	U ₃ Fe	7.93
A27	U ₃ Si	4.72	A54	U ₃ Si	5.72	A81	U ₃ SiAl	6.18	A108	U ₃ Si	7.16	A135	U ₃ Fe	7.78

Table E-14. Miniplate Cross Reference by Plate Number (Continued)

Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)	Plate No.	Fuel Type	U Dens. (g/cm ³)
A136	U ₃ Fe	7.95	A161D	U ₃ Fe	6.91	A186	USi	3.89	A211	U ₃ Si	6.07	A236	U ₃ Si	4.73
A137	UAl ₂	2.99	A162D	U ₃ Fe	7.10	A187D	USi	3.71	A212	U ₃ Si	N/D	A237	U ₃ Si _{1.8}	3.67
A138	UAl ₂	2.98	A163D	U ₃ Si	6.09	A188D	USi	3.76	A213	U ₃ Si ₂	4.94	A238	U ₃ Si _{1.8}	3.66
A139	U ₃ SiCu	5.31	A164D	U ₃ Si	6.18	A189D	USi	3.73	A214	U ₃ Si ₂	N/D	A239	U ₃ Si _{1.8}	3.61
A140	U ₃ SiCu	5.37	A165D	U ₃ Si ₂	4.75	A190D	USi	3.79	A215	U ₃ Si ₂	4.95	A240	U ₃ Si _{1.8}	3.59
A141	U ₃ SiCu	5.82	A166D	U ₃ Si ₂	4.77	A191D	USi	3.74	A216	U ₃ Si ₂	4.99	A241	U ₃ Si _{1.8}	4.72
A142	U ₃ SiCu	5.72	A167	U ₃ SiCu	6.91	A192D	USi	3.82	A217	U ₃ Si	5.79	A242	U ₃ Si _{1.8}	4.70
A143	U ₃ SiCu	5.36	A168	U ₃ SiCu	7.03	A193P	U ₃ Si	6.34	A218	U ₃ Si	5.91	A243	U ₃ Si _{1.8}	4.77
A144	U ₃ SiCu	5.41	A169	U ₃ SiCu	5.94	A194P	U ₃ Si	6.42	A219	U ₃ Si ₂	4.91	A244	U ₃ Si _{1.8}	4.72
A145	U ₃ SiCu	3.78	A170	U ₃ SiCu	6.13	A195P	U ₃ Si	6.30	A220	U ₃ Si ₂	4.95	A245	U ₃ Si	5.23
A146	U ₃ SiCu	3.80	A171	U ₃ SiCu	6.10	A196P	U ₃ Si	6.35	A221	U ₃ Si	6.05	A246	U ₃ Si	5.21
A147	U ₃ Si _{1.5}	3.84	A172	U ₃ SiCu	6.13	A197P	U ₃ Si	6.47	A222	U ₃ Si	N/D	A247	U ₃ Si	5.26
A148	U ₃ Si _{1.5}	3.91	A173	U ₃ SiCu	4.11	A198P	U ₃ Si	6.48	A223	U ₃ Si ₂	4.92	A248	U ₃ Si	5.28
A149	U ₃ Si _{1.5}	5.83	A174	U ₃ SiCu	4.15	A199P	U ₃ Si ₂	5.10	A224	U ₃ Si ₂	4.98	A249	U ₇₅ Ga ₁₀ Si ₁₅	2.79
A150	U ₃ Si _{1.5}	5.96	A175	USi	3.78	A200P	U ₃ Si ₂	5.13	A225	U ₆ Mn ₁₃	6.92	A250	U ₇₅ Ga ₁₀ Si ₁₅	2.83
A151	U ₃ Si _{1.5}	5.07	A176	USi	3.87	A201P	U ₃ Si ₂	5.09	A226	U ₆ Mn ₁₃	7.12	A251	U ₇₅ Ga ₁₀ Si ₁₅	2.78
A152	U ₃ Si _{1.5}	5.15	A177	USi	3.78	A202P	U ₃ Si ₂	5.13	A227	U ₆ Mn ₁₃	6.89	A252	U ₇₅ Ga ₁₀ Si ₁₅	2.82
A153	U ₃ Si _{1.5}	5.09	A178	USi	3.86	A203P	U ₃ Si ₂	5.09	A228	U ₆ Mn ₁₃	7.05	A253	U ₇₅ Ga ₁₅ Ge ₁₀	2.71
A154	U ₃ Si _{1.5}	5.17	A179	USi	3.81	A204P	U ₃ Si ₂	5.13	A229	U ₆ Mn ₁₃	6.19	A254	U ₇₅ Ga ₁₅ Ge ₁₀	2.70
A155	U ₃ Si	6.64	A180	USi	3.90	A205	U ₃ SiCu	6.73	A230	U ₆ Mn ₁₃	6.35	A255	U ₇₅ Ga ₁₅ Ge ₁₀	2.71
A156	U ₃ Si	6.73	A181	USi	3.82	A206	U ₃ SiCu	6.86	A231	U ₆ Mn ₁₃	6.22	A256	U ₇₅ Ga ₁₅ Ge ₁₀	2.73
A157	U ₃ Si	6.92	A182	USi	3.90	A207	U ₃ SiCu	6.81	A232	U ₆ Mn ₁₃	6.26	A257	U ₃ Si	2.92
A158	U ₃ Si	6.97	A183	USi	3.81	A208	U ₃ SiCu	6.84	A233	U ₃ Si	4.65	A258	U ₃ Si	2.92
A159	U ₃ Fe	7.77	A184	USi	3.89	A209	U ₃ Si	6.11	A234	U ₃ Si	4.63	A259	U ₃ Si	2.92
A160	U ₃ Fe	8.02	A185	USi	3.82	A210	U ₃ Si	6.16	A235	U ₃ Si	4.67	A260	U ₃ Si	2.92

Table E-15. Densities of Miniplate Constituents

Material	Density (g/cm ³)
UAl ₂	7.9
USi	10.9
U ₃ Si ₂	12.2
U ₃ Si _{1.6} (As-Cast)	13.0
U ₃ Si _{1.5}	13.7
U ₃ SiAl	14.2
U ₃ Si (As-Cast)	14.6
U ₃ Si	15.2
U ₃ SiCu	15.2
U ₇₅ Ga ₁₅ Ge ₁₀	15.6
U ₇₅ Ga ₁₀ Si ₁₅	15.8
U ₆ Mn _{1.3}	16.8
U ₆ Fe	17.4
Al	2.70
Al-6061	2.71
B ₄ C	2.52
SiO ₂	2.65
Al ₂ O ₃	3.65

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAT-40-02F	A-01	5.9	.050	ORR (Module #2). PIE (ANL)
MEAT-40-02R	A-02*	5.8	.050	Reject - Given to AGHCF (ANL)
MEAT-40-03F	A-03	5.6	.060	ORR (Module #2) PIE (ANL)
MEAT-40-03R	A-04*	5.7	.060	Reject - Given to AGHCF (ANL)
MEAT-30-08R	A-05	4.7	.050	ORR (Module #3). PIE (ANL)
MEAT-30-09F	A-06	4.7	.050	ORR (Module #3). PIE (ANL)
MEAT-30-09R	A-07	4.7	.050	ORR (Module #3). PIE (ANL)
MEAT-30-10R	A-08	4.7	.060	ORR (Module #3). PIE (ANL) Sent to SRL
MEAT-30-11F	A-09	4.7	.060	ORR (Module #3). PIE (ANL) Sent to SRL
MEAT-30-12R	A-10	4.6	.060	ORR (Module #3). PIE (ANL)
MEAB-30-01F	A-11	4.8	.050	ORR (Module #3). PIE (ANL)
MEAB-30-01R	A-12	4.8	.050	ORR (Module #3). PIE (ANL) Sent to SRL
MEAB-30-04F	A-13	4.8	.050	ORR (Module #3). PIE (ANL)
MEAB-30-07F	A-14	4.7	.060	Reject - In H-wing [ARCHIVE]
MEAB-30-13F	A-15	4.8	.060	ORR (Module #3). PIE (ANL) Sent to SRL
MEAB-30-13R	A-16	4.8	.060	ORR (Module #3). PIE (ANL) Sent to SRL
MEAT-30-08F	A-17	4.6	.050	ORR (Module #4). PIE (ANL)
MEAT-30-11R	A-18	4.7	.060	ORR (Module #4). PIE (ANL)
MEAB-30-04R	A-19	4.8	.050	ORR (Module #4). Destructively tested at ORNL
MEAB-30-06F	A-20	4.8	.060	ORR (Module #4). PIE (ANL)
MEAT-30-10F	A-21	4.7	.060	ORR (Module #3). PIE (ANL) Sent to SRL
MEAT-30-12F	A-22	4.6	.060	ORR (Module #7). PIE (ANL)
MEAB-30-06R	A-23	4.8	.060	ORR (Module #7). PIE (ANL)

Note: PIE = Postirradiation evaluation; ANL = Argonne National Laboratory; ORR = Oak Ridge Research Reactor; AGHCF = Alpha-Gamma Hot Cell Facility (at ANL); SRL = Savannah River Laboratory
ORNL = Oak Ridge National Laboratory

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAB-30-05R	A-24	4.8	.050	ORR (Module #7). PIE (ANL)
MEAT-30-14R	A-25	4.7	.050	ORR (Module #2). PIE (ANL)
MEAT-30-14F	A-26	4.6	.050	ORR (Module #7). PIE (ANL)
MEAB-30-07R	A-27	4.7	.060	"Reject" (Scribed but may be OK) [ARCHIVE]
MEAB-30-15F	A-28	4.8	.060	ORR (Module #7). PIE (ANL)
MEAB-30-15R	A-29	4.8	.060	OK (Available) [ARCHIVE]
MEAT-30-16F	A-30	4.6	.060	ORR (Module #7). PIE (ANL)
MEAT-30-16R	A-31	4.6	.060	OK (Available ORR) <u>SRW 1&2-89</u>
MEAX-30-17F	A-32	3.8	.050	ORR (Module #7). PIE (ANL)
MEAX-30-17R	A-33	3.8	.050	Reject - Blister Tested & Sectioned
MEAX-30-18F	A-34	3.8	.050	ORR (Module #7). PIE (ANL)
MEAX-30-18R	A-35*	3.8	.050	Reject - Sent to AGHCF (ANL)
MEAX-30-19F	A-36	3.8	.060	ORR (Module #7 & Module #14). PIE (ANL)
MEAX-30-19R	A-37	3.7	.060	Reject - in H-Wing. Used for "miniplate soup" test
MEAB-30-20F	A-38	4.8	.050	ORR (Module #7). PIE (ANL)
MEAB-30-20R	A-39	4.8	.050	Reject - In H-Wing [ARCHIVE]
MEAB-30-21F	A-40	4.7	.050	OK (Available) [ARCHIVE]
MEAB-30-21R	A-41	4.8	.050	Reject - In H-Wing
MEAT-30-22F	A-42	4.5	.050	ORR (Module #7). PIE (ANL)
MEAT-30-22R	A-43	4.5	.050	OK. Blister Tested & Sectioned. <u>SRW 1&2-89</u>
MEAB-30-23F	A-44	4.7	.060	OK (Available) [ARCHIVE]

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAB-30-23R	A-45	4.8	.060	OK (Available) [ARCHIVE]
MEAX-30-24F	A-46	3.7	.060	ORR (Module #7 & Module #14). PIE (ANL)
MEAX-30-24R	A-47	3.7	.060	Reject - Sent to SRL
DUMB-50-25F	--	7.0	.050	Reject - Not Machined. Sent to SRL
DUMB-50-25R	--	7.1	.050	Probably a reject (?) - Not machined. Blister tested & sectioned
DUMT-50-26F	--	6.4	.050	Reject - Bright spot; mini- plate sectioned for Metallo- graphic Study
DUMT-50-26R	--	6.4	.050	Probably a reject (?) - Not machined. Sent to SRL
DUMT-50-27F	--	--	.050	Reject - Fuel in Rail - Not machined. Blister tested & sectioned. SRW 11-88
DUMT-50-27R	--	--	.050	OK - Not machined [ARCHIVE]
DUMT-55-28F	--	--	.050	Ruptured during 1 hr. anneal; Macros taken
DUMT-55-28R	--	--	.050	Severe dogboning; Broke at fuel zone when accidentally bent. Macros taken
DUMT-60-29F	--	--	.050	Severe Dogboning - Reject
DUMT-60-29R	--	--	.050	Ruptured during 1 hr. anneal; Miniplate sectioned. Micros and Macros taken
DUMT-52.5-30F	--	--	.060	OK - slight dogboning - Not Machined. Used for Miniplate Soup test
DUMT-52.5-30R	--	--	.060	OK - slight dogboning - cut for metallographic study
DUMT-52.5-31F	--	--	.060	OK - Altered rolling schedule; slightly crossrolled - Not Machined. Sent to SRL

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
DUMT-52.5-31R	--	--	.060	OK - Altered rolling schedule; slightly crossrolled. Cut for metallographic study
DUMB-50-32F	--	--	.060	Special rolling schedule. Max U density too hi - Not machined. Sent to SRL
DUMB-50-32R	--	--	.060	Same as - 32 F. Sectioned for metallographic study. Micros
DUMT-50-33F	--	--	.060	Special rolling schedule. Sent to AGHCF for pre PIE Studies
DUMT-50-33R	--	--	.060	Sectioned for metallographic study. Micros
DUMX-50-34F	--	--	.060	Special rolling schedule. Sectioned for metallographic study. 2 pcs. sent to SRL
DUMX-50-34R	--	--	.060	Special rolling schedule - Not machined. Sent to SRL
MEAB-41-35F	A-48	5.6	.050	ORR (Module #10) - PIE (ANL)
MEAB-41-35R	A-49	5.7	.050	ORR (Module #10) - PIE (ANL)
MEAT-45-36F	A-50	5.7	.060	ORR (Module #10) - PIE (ANL)
MEAB-30-05F	A-51	4.8	.050	Reject (Large pit) [ARCHIVE]
MEAT-45-36R	A-52	5.9	.060	ORR (Module #10) - PIE (ANL)
MEAB-41-37F	A-53	5.7	.060	ORR (Module #10) - PIE (ANL)
MEAB-41-37R	A-54	5.7	.060	ORR (Module #10) - PIE (ANL)
MEAB-41-38F	A-55	5.7	.060	Sectioned for metallographic study - Micros
MEAB-41-38R	A-56	5.7	.060	OK (Available) [ARCHIVE]
MEAT-45-39F	A-57	--	.050	Reject - blister in fuel zone (not machined) SRW 1&2-89
MEAT-45-39R	A-58	5.8	.050	ORR (Module #10) - PIE (ANL)

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAT-45-40F	A-59	5.8	.050	ORR (Module #10) - PIE (ANL)
MEAT-45-40R	A-60	5.9	.050	ORR (Module #13) - PIE (ANL)
MEAT-50-41F	A-61	6.3	.050	ORR (Module #10) - PIE (ANL)
MEAT-50-41R	A-62	6.3	.050	ORR (Module #10) - PIE (ANL)
MEAT-50-42F	A-63	6.2	.050	ORR (Module #13) - PIE (ANL)
MEAT-50-42R	A-64	--	.050	Reject - blister (not machined to miniplate). <u>SRW 1&2-89</u>
MEAT-52-43F	A-65	6.4	.060	ORR (Module #10) - PIE (ANL)
MEAT-52-43R	A-66	6.4	.060	Sectioned for metallographic study. Micros (two x-ray density spots too high). <u>SRW 1-89</u>
MEAT-52-44F	A-67	6.4	.060	ORR (Module #10) - PIE (ANL)
MEAT-52-44R	A-68	6.5	.060	OK (One x-ray density spot too high) [ARCHIVE]
DUMT-54-45F	--	7.0	.050 (d)	Not machined to final plate size. Sectioned for metallography. Micros. <u>SRW 11-88</u>
DUMT-54-45R	--	7.0	.050 (d)	Reject - Large U-rich particle in fuel zone. Probable clad penetration during etching. <u>SRW 11-88</u>
DUMT-54-46F	--	7.0	.065	Not Machined to final plate size. Sent to SRL
DUMT-54-46R	--	6.9	.060	Not machined to final plate size. Sent to SRL
DUMT-54-47F	--	6.7	.060	Not machined to final plate size. <u>SRW 11-88</u>
DUMT-54-47R	--	6.7	.060	Sectioned for metallographic study. Piece of plate to ORNL 7/85. <u>SRW 11-88</u>
MEAT-55-48F	A-69	6.9	.060	ORR (Module #13) - PIE (ANL)
MEAT-55-48R	A-70	7.0	.060	ORR (Module #13) - PIE (ANL)

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAT-55-49F	A-71	6.9	.060	ORR (Module #13) - PIE (ANL)
MEAT-55-49R	A-72	7.0	.060	One rail 0.090", otherwise OK [ARCHIVE]
MEAT-55-50F	A-73	7.1	.050 (d)	May be OK? [ARCHIVE]
MEAT-55-50R	A-74	7.1	.050 (d)	Reject - Clad crack over FZ. Not machined to final plate size. <u>SRW 1&2-89</u>
MEAT-55-51F	A-75	7.0	.050 (d) be thin.	'Crease' over FZ clad may (?) Two x-ray density spots too high. <u>SRW 1&2-89</u>
MEAT-55-51R	A-76	7.1	.050 (d)	Reject - Clad crack on FZ - Not machined to final plate size. <u>SRW 1&2-89</u>
MEAT-54-52F	A-77	6.9	.060	ORR (Module #13) - PIE (ANL)
MEAT-54-52R	A-78	7.0	.060	ORR (Module #13) - PIE (ANL)
MEAT-54-53F	A-79	7.0	.060	ORR (Module #13) - PIE (ANL)
MEAT-54-53R	A-80	7.0	.060	OK - Sectioned for Metallo- graphic study. <u>SRW 1&2-89</u>
MEAT-45-54F	A-81	6.2	.055	ORR (Module #13) - PIE (ANL)
MEAT-45-54R	A-82	6.1	.050	ORR (Module #13) - PIE (ANL)
MEAT-45-55F	A-83	6.2	.050	ORR (Module #13) - PIE (ANL)
MEAT-45-55R	A-84	6.2	.050	ORR (Module #13) - PIE (ANL)

NOTE: Assembly Nos. 56 through 63 were assigned to full-size (ORR-Type) plates all were made with DU or W (56 & 57). See separate files on full-size plates.

DUMX-50-64F	--	~5.5	0.060	Skewed fuel zone - Reject (?) Not machined. Thin meat, 0.0126". <u>To B&W 5-88.</u>
DUMX-50-64R	--	~5.5	0.060	Skewed fuel zone - Reject (?) Not machined. Thin meat, 0.0126"
DUMX-44-65F	--	5.0	0.060	Skewed fuel zone - Reject (?) Not machined. Thick meat, 0.030". <u>To B&W 5-88.</u>
DUMX-44-65R	--	5.0	0.060	Skewed fuel zone - Reject (?) Not machined. Thick meat, 0.030"

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAX-44-66F	A-85	5.1	0.050	ORR (Module #17) → (Module #25) → ANL-PIE
MEAX-44-66R	A-86	5.1	0.050	"Reject" (1 particle ~0.005" from rail)
MEAX-44-67F	A-87	5.1	0.050	ORR (Module #18) → (Module #34) ANL-PIE
MEAX-44-67R	A-88	5.2	0.050	ORR (Module #18) ANL-PIE
MEAX-50-68F	A-89	5.6	0.050	ORR (Module #18) → (Module #34) ANL-PIE
MEAX-50-68R	A-90	5.6	0.050	ORR (Module #18) → (Module #34) ANL-PIE
MEAX-50-69F	A-91	5.6	0.050	ORR (Module #18) ANL-PIE
MEAX-50-69R	A-92	5.6	0.050	ORR (Module #18) ANL-PIE
MEAX-50-70F ANL-PIE	A-93	5.6	0.060	ORR (Module #18) → (Module #34)
MEAX-50-70R	A-94	5.7	0.060	ORR (Module #18) ANL-PIE
MEAX-50-71F	A-95	5.6	0.060	"Reject" (one particle ~0.005" from rail)
MEAX-50-71R	A-96	5.7	0.060	ORR (Module #27) → ANL-PIE
MEAX-44-72F	A-97	5.2	0.060	<10% Cold Work. Thick meat, 0.030" OK - (Available)
MEAX-44-72R	A-98	5.2	0.060	<10% Cold Work. Thick meat, 0.030" Cut for CMT Irrad. Studies (12/87) Two quarters of plate to Janus then CMT.
MEAX-44-73F	A-99	5.2	0.060	ORR (Module #17). Thick meat, 0.030". Moved to Module #25 ANL-PIE
MEAX-44-73R	A-100	5.2	0.060	ORR (Module #17). Thick meat, 0.030". ANL-PIE
MEAB-42-74F	A-101	6.2	0.060	ORR (Module #33) → ANL-PIE
MEAB-42-74R	A-102	6.3	0.060	<u>ORNL - Not Irrad. To be Disposed of at ORNL (12-88)</u>
MEAB-42-75F	A-103	6.2	0.060	ORR (Module #18) ANL-PIE
MEAB-42-75R	A-104	6.3	0.060	ORR (Module #18) ANL-PIE

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAB-50-76F	A-105	7.1	0.060	ORR (Module #22) ~2 Cold Work -Skewed FZ Moved to Module #25 ANL-PIE
MEAB-50-76R	A-106	7.2	0.060	'Reject' Particle 0.005" from edge ~2% Cold Work
MEAB-50-77F	A-107	7.1	0.060	ORR (Module #17) ANL PIE
MEAB-50-77R	A-108	7.2	0.060	ORR (Module #17) → (Module #25) → ANL-PIE
MEAB-42-78F	A-109 (MEU)	6.2	0.050	ORR (Module #17). Thin meat, 0.0126". ANL-PIE
MEAB-42-78R	A-110 (MEU)	6.4	0.050	ORR (Module #17). Thin meat 0.0126". ANL-PIE
MEAB-42-79F	A-111 (MEU)	6.3	0.050	Sectioned for Metallographic study. Thin meat, 0.0126". Vault Storage.
MEAB-42-79R	A-112 (MEU)	6.4	0.050	ORR (Module #17). Thin meat, 0.0126". ANL-PIE
MEAB-28-80F	A-113 (MEU)	4.5	0.050	ORR (Module #17) ANL-PIE
MEAB-28-80R	A-114 (MEU)	4.5	0.050	ORR (Module #17) → (Module #33) ANL-PIE
MEAB-12-81F	A-115 (HEU)	2.0	0.050	ORR (Module #17) → (Module #33) ANL-PIE
MEAB-12-81R	A-116 (HEU)	2.0	0.050	ORR (Module #17) ANL-PIE
MEAB-42-82F	A-117	6.2	0.050	ORR (Module #18) ANL-PIE
MEAB-42-82R	A-118	6.3	0.050	ORR (Module #18) ANL-PIE
MEAB-50-83F	A-119	7.1	0.060	ORR (Module #22) → (Module #25) → ANL-PIE
MEAB-50-83R	A-120	7.2	0.060	OK (Available)
DUMF-48-84F	--	8.0	0.050	OK - Not machined
DUMF-48-84R	--	8.0	0.050	Sectioned for metallographic study, then used for "soup test". Sec- tions after soup test also.
DUML-50-85F	--	3.1	0.050	OK - Not machined
DUML-50-85R	--	3.1	0.050	Sectioned for metallographic study. Piece of plate to ORNL 7/85.

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAX-13-86F	A-121 (HEU)	1.7	0.050	ORR (Module #22) ANL-PIE
MEAX-13-86R	A-122 (HEU)	1.7	0.050	ORR (Module #23) → (Module #29) ANL-PIE
MEAX-32-87F	A-123 (MEU)	4.0	0.050	ORR (Module #22) ANL-PIE
MEAX-32-87R	A-124 (MEU)	3.9	0.050	ORR (Module #23) → (Module #29) ANL-PIE
MEAX-45-88F	A-125 (MEU)	5.1	0.050	ORR (Module #23) → (Module #29). Thin meat, 0.0126". ANL-PIE
MEAX-45-88R	A-126 (MEU)	5.2	0.050	ORR (Module #23) → (Module #29). Thin meat, 0.0126 in. ANL-PIE
MEAB-50-89F	A-127	7.1	0.050	Reject. Thin clad. Sectioned for metallographic study Piece of plate to ORNL 7/85
MEAB-50-89R	A-128	7.3	0.050	Reject. Thin clad
MEAF-42-90F	A-129	7.0	0.050	ORR (Module #23) → ANL-PIE
MEAF-42-90R	A-130	7.3	0.050	OK (Available)
MEAL-50-91F	A-131 (MEU)	3.1	0.050	Reject. Blister over FZ. Sectioned for metallographic study. Vault Storage.
MEAL-50-91R	A-132 (MEU)	3.0	0.050	ORR (Module #23) → (Module #29) ANL-PIE
MEAF-48-92F	A-133	7.8	0.060	Reject. Fuel uniformity poor
MEAF-48-92R	A-134	7.9	0.060	Reject. Poor surface quality. Sectioned for Metallographic study. Piece of plate to ORNL 7/85
MEAF-48-93F	A-135	7.8	0.060	ORR (Module #22) ANL-PIE
MEAF-48-93R	A-136	8.0	0.060	ORR (Module #22) ANL-PIE
MEAL-50-94F	A-137 (MEU)	3.0	0.050	ORR (Module #23) → (Module #29) ANL-PIE
MEAL-50-94R	A-138 (MEU)	3.0	0.050	OK - Vault Storage.
MEAC-42-95F	A-139 (e)	5.3	0.050	ORR (Module #27) → ANL-PIE
MEAC-42-95R	A-140 (e)	5.4	0.050	ORR (Module #27) → ANL-PIE

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAC-48-96F	A-141 (e)	5.8	0.060	OK - (Available)
MEAC-48-96R	A-142 (e)	5.7	0.060	Brite spot on density x-ray Probable Reject
MEAC-42-97F	A-143 (e)	5.4	0.060	OK - (Available)
MEAC-42-97R	A-144 (e)	5.4	0.060	OK - (Available)
MEAC-28-98F	A-145 (MEU)(e)	3.8	0.050	ORR (Module #28) ANL-PIE
MEAC-28-98R	A-146 (MEU)(e)	3.8	0.050	<u>ORNL - Not Irrad. To be Disposed of at ORNL 12-88</u>
MEAH-31-99F	A-147 (MEU)	3.8	0.050	ORR (Module #28) ANL-PIE
MEAH-31-99R	A-148 (MEU)	3.9	0.050	ORR (Module #28) ANL-PIE
MEAH-48-100F	A-149	5.8	0.060	ORR (Module #23) → (Module #29) ANL-PIE
MEAH-48-100R	A-150	6.0	0.060	ORR (Module #23) → (Module #29) ANL-PIE
MEAH-41-101F	A-151	5.1	0.060	ORR (Module #23) → (Module #29) ANL-PIE
MEAH-41-101R	A-152	5.2	0.060	ORR (Module #27) → ANL-PIE
MEAH-41-102F	A-153	5.1	0.050	<u>Sectioned. Pc. to IPNS for Diffraction Studies.</u>
MEAH-41-102R	A-154	5.2	0.050	ORR (Module #27) → ANL-PIE
MEAB-45-103F	A-155	6.6	0.050	Finished but questionable See data sheet
MEAB-45-103R	A-156	6.7	0.050	REJECT - see data sheet
MEAB-47-104F	A-157	6.9	0.050	ORR (Module #23) → (Module #29) ANL-PIE
MEAB-47-104R	A-158	7.0	0.050	OK - (Available)
MEAF-48-105F	A-159	7.8	0.060	OK - (Available)
MEAF-48-105R	A-160	8.0	0.060	ORR (Module #23) → ANL-PIE
DUMX-26.3-106F	-	3.2	0.058	Shipped to RISØ
DUMX-33.5-106R	-	4.1	0.058	" " "

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
DUMX-30.8-107F	-	3.8	0.058	" " "
DUMX-30.8-107R	-	3.8	0.058	Cut for metallographic study. <u>~1/2 to B&W 5-88</u>
DUMX-21.7-108F	-	2.7	0.060	<u>0.256" Meat. To B&W 5-88</u>
DUMX-21.7-108R	-	2.7	0.060	Shipped to RISØ, 0.0256" meat.
DUMF-40-109F	A-161D (DU)	6.9	0.060	ORR (Module #24) → ORNL-PIE
DUMF-40-109R	A-162D (DU)	7.1	0.060	ORR (Module #24) → ORNL-PIE
DUMB-40-110F	A-163D (DU)	6.1	0.050	ORR (Module #24) → ORNL-PIE
DUMB-40-110R	A-164D (DU)	6.2	0.050	ORR (Module #24) → ORNL-PIE
DUMX-40-111F	A-165D (DU)	4.8	0.060	ORR (Module #24) → ORNL-PIE
DUMX-40-111R	A-166D (DU)	4.8	0.060	ORR (Module #24) → ORNL-PIE
MEAC-48-112F	A-167	6.9	0.060	Sectioned for Metallographic Study. Piece of plate to ORNL 7/85
MEAC-48-112R	A-168	7.0	0.060	ORR (Module #28) ANL-PIE
MEAC-42-113F	A-169	5.9	0.060	ORR (Module #28) ANL-PIE
MEAC-42-113R	A-170	6.1	0.060	OK - (Available)
MEAC-42-114F	A-171	6.1	0.050	ORR (Module #28) ANL-PIE
MEAC-42-114R	A-172	6.1	0.050	ORR (Module #28) ANL-PIE
MEAC-28-115F	A-173 (MEU)	4.1	0.050	ORR (Module #28) ANL-PIE
MEAC-28-115R	A-174 (MEU)	4.2	0.050	ORR (Module #28) ANL-PIE
MEAS-40-116F	A-175	3.8	0.050	OK - (Available)
MEAS-40-116R	A-176	3.9	0.050	ORR (Module #27) ANL-PIE
MEAS-40-117F	A-177	3.8	0.050	REJECT - Pit over FZ. Sectioned for Metallographic study. Piece of plate to ORNL 7/85
MEAS-40-117R	A-178	3.9	0.050	ORR (Module #27) → ANL-PIE
MEAS-40-118F	A-179	3.8	0.060	ORR (Module #27) → ANL-PIE
MEAS-40-118R	A-180	3.9	0.060	ORR (Module #27) → ANL-PIE

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAS-40-119F	A-181 (MEU)	3.8	0.060	ORR (Module #28) ANL-PIE
MEAS-40-119R	A-182 (MEU)	3.9	0.060	ORR (Module #28) ANL-PIE
MEAS-40-120F	A-183 (MEU)	3.8	0.050	ORR (Module #28) ANL-PIE
MEAS-40-120R	A-184 (MEU)	3.9	0.050	Prob. OK - Vault Storage.
MEAS-40-121F	A-185 (MEU)	3.8	0.050	ORNL - <u>Not Irrad. To be Disposed</u> of at ORNL 12-88
MEAS-40-121R	A-186 (MEU)	3.9	0.050	Prob. OK - (length = 4.493 in. Vault Storage.
DUMS-40-122F	A-187D (DU)	3.7	0.050	OK - (Available)
DUMS-40-122R	A-188D (DU)	3.8	0.050	ORR (Module #27) → ANL-PIE
DUMS-40-123F	A-189D (DU)	3.7	0.050	ORR (Module #27) → ANL-PIE
DUMS-40-123R	A-190D (DU)	3.8	0.050	ORR (Module #27) → ORNL-PIE
DUMS-40-124F	A-191D (DU)	3.7	0.060	OK - (Available)
DUMS-40-124R	A-192D (DU)	3.8	0.060	ORNL - <u>Not Irrad. To be Disposed</u> of at ORNL 12-88
MEAB-44-125F	A-193P	6.3	0.050	ORR (Module #31) → ANL-PIE
MEAB-44-125R	A-194P	6.4	0.050	ORR (Module #31) → ANL-PIE
MEAB-44-126F	A-195P	6.3	0.050	Cut. Piece to AGHCF 1/88.
MEAB-44-126R	A-196P	6.4	0.050	OK - (Available)
MEAB-44-127F	A-197P	6.5	0.060	ORR (Module #31) → ANL-PIE
MEAB-44-127R	A-198P	6.5	0.060	OK - (Available)
MEAX-46-128F	A-199P	5.1	0.050	ORR (Module #30) → ANL (on hold)
MEAX-46-128R	A-200P	5.1	0.050	ORR (Module #30) → ANL (on hold)
MEAX-46-129F	A-201P	5.1	0.050	OK - (Available)
MEAX-46-129R	A-202P	5.1	0.050	ORR (Module #30) → ANL (on hold)
MEAX-46-130F	A-203P	5.1	0.060	Cut. Piece to AGHCF 1/88.
MEAX-46-130R	A-204P	5.1	0.060	ORR (Module #31) → ANL-PIE

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAC-48-131F	A-205	6.7	0.050 (d)	OK - (Available)
MEAC-48-131R	A-206	6.9	0.050 (d)	ORR (Module #31) → ANL-PIE
MEAC-48-132F	A-207	6.8	0.060	ORR (Module #31) → ANL-PIE
MEAC-48-132R	A-208	6.8	0.060	ORR (Module #31) → ANL-PIE
PLATES A209 THRU A224 MADE WITH 6061 AL POWDER MATRIX				
MEAB-44-133F	A209	6.1	0.050	ORR (Module #34) → ANL-PIE
MEAB-44-133R	A210	6.2	0.050	ORR (Module #34) → ANL-PIE
MEAB-44-134F	A211	6.1	0.050	ORR (Module #34) → ANL-PIE
MEAB-44-134R	A212	~6.1	0.050	Sectioned for Metallographic Study
MEAX-46-135F	A213	4.9	0.050	ORR (Module #34) → ANL-PIE
MEAX-46-135R	A214	~4.9	0.050	Sectioned for Metallographic Study
MEAX-46-136F	A215	5.0	0.050	Questionable quality-Probable Reject
MEAX-46-136R	A216	5.0	0.050	ORR (Module #34) → ANL-PIE
MEAB-42-137F	A217 (MEU)	5.8	0.050	0.013" Meat. Vault Storage.
MEAB-42-137R	A218 (MEU)	5.9	0.050	ORR (Module #33) 0.013" Meat → ANL-PIE
MEAX-46-138F	A219 (MEU)	4.9	0.050	0.013" Meat. Vault Storage.
MEAX-46-138R	A220 (MEU)	5.0	0.050	ORR (Module #33) 0.013" Meat T ANL-PIE
MEAB-44-139F	A221	6.0	0.060	ORR (Module #34) → ANL-PIE
MEAB-44-139R	A222	~6.0	0.060	Sheared oversize-Probable Reject
MEAX-46-140F	A223	4.9	0.060	ORR (Module #34) → ANL-PIE
MEAX-46-140R	A224	5.0	0.060	ORR (Module #34) → ANL-PIE
—				
MEAN-45-141F	A225	6.9	0.050	ORR (Module #33) → ANL-PIE
MEAN-45-141R	A226	7.1	0.050	REJECT - Fuel Streaking - Full Longitudinal Metallographic Section One Section to AGHCF

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAN-45-142F	A227	6.9	0.060	ORR (Module #33) → ANL-PIE
MEAN-45-142R	A228	7.0	0.060	ORR (Module #33) → ANL-PIE
MEAN-40-143F	A229 (MEU)	6.2	0.050	ORR (Module #33) 0.013" Meat → ANL-PIE
MEAN-40-143R	A230 (MEU)	6.4	0.050	0.013" Meat. Vault Storage.
MEAN-40-144F	A231 (MEU)	6.2	0.050	ORR (Module #33) 0.013" Meat → ANL-PIE
MEAN-40-144R	A232 (MEU)	6.3	0.050	ORR (Module #33) 0.013" Meat → ANL-PIE
DUMX-50-145F	--	~7.0	0.060	"Layered" Compact Experiment Plate Hot-Rolled Only.
DUMX-50-145R	--	~7.0	0.060	" "
MEAK-35-146F	A233	4.6	0.050	ORNL
MEAK-35-146R	A234	4.6	0.050	ORNL
MEAK-35-147F	A235	4.7	0.050	ORNL
MEAK-35-147R	A236	4.7	0.050	ORNL
MEAI-30-148F	A237	3.7	0.050	ORNL
MEAI-30-148R	A238	3.7	0.050	ORNL
MEAI-30-149F	A239	3.6	0.050	ORNL
MEAI-30-149R	A240	3.6	0.050	ORNL
MEAI-40-150F	A241	4.7	0.050	ANL - Cut for Metallographic Study pc to AGHCF
MEAI-40-150R	A242	4.7	0.050	ORNL
MEAI-40-151F	A243	4.8	0.060	ORNL
MEAI-40-151R	A244	4.7	0.060	ORNL
MEAK-40-152F	A245	5.2	0.060	ORNL
MEAK-40-152R	A246	5.2	0.060	ANL - Cut for Metallographic Study pc to AGHCF

**Not Irrad. To be
Disposed of
at ORNL 12-88**

**Not Irrad. To be
Disposed of
at ORNL 12-88**

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
MEAK-40-153F	A247	5.3	0.060	ORNL
MEAK-40-153R	A248	5.3	0.060	ORNL <u>Not Irrad. To be Disposed of at ORNL 12-88</u>
MEAZ-20-154F	A249	2.8	0.050	Retained in "sheared-oversize" Condition
MEAZ-20-154R	A250	2.8	0.050	↓
MEAZ-20-155F	A251	2.8	0.050	↓
MEAZ-20-155R	A252	2.8	0.050	Retained in "sheared-oversize" Condition
MEAQ-20-156F	A253	2.7	0.050	↓
MEAQ-20-156R	A254	2.7	0.050	↓
MEAQ-20-157F	A255	2.7	0.050	↓
MEAQ-20-157R	A256	2.7	0.050	↓
MEAB-20-158F	A257	2.9	0.060	↓
MEAB-20-158R	A258	2.9	0.060	↓
MEAB-20-159F	A259	2.9	0.060	↓
MEAB-20-159R	A260	2.9	0.060	↓
DUMX-40-160F	--	4.6	0.060	"KAERI Campaign" Plates-Sheared Oversize
DUMX-40-160R	--	4.6	0.060	" " " "
DUMX-40-161F	--	4.5	0.060	Machined to Final Size. <u>To B&W 5-88</u>
DUMX-40-161R	--	4.5	0.060	Sheared Oversize
DUMX-40-162F	--	4.5	0.060"	" " <u>Used for HIP Expts.</u>
DUMX-40-162R	--	4.5	0.060	" " <u>Used for HIP Expts.</u>
DUMX-40-163F	--	4.4	0.060	" " <u>Used for HIP Expts.</u>
DUMX-40-163R	--	4.4	0.060	" " <u>Used for HIP Expts.</u>
DUMX-40-164F	--	4.4	0.060	" "
DUMX-40-164R	--	4.3	0.060	" "

Status of ANL Miniplates as of Feb. 1989

I.D. (a)	ORNL No. (b)	U Loading (g/cm ³)	Thickness (in.)	Status (c)
DUMB-40-165F	--	5.6	0.060	Machined to Final Size
DUMB-40-165R	--	5.6	0.060	Sheared Oversize
DUMI-40-166F	--	4.9	0.060	" "
DUMI-40-166R	--	4.9	0.060	" "
DUMI-40-167F	--	4.8	0.060	Machined to Final Size
DUMI-40-167R	--	4.9	0.060	Sheared Oversize
DUMI-40-168F	--	4.8	0.060	" "
DUMI-40-168R	--	4.8	0.060	" "
DUMI-40-169F	--	4.5	0.060	" "
DUMI-40-169R	--	4.6	0.060	" "
DUMX-40-170F	--	4.5	0.060	Sheared Oversize
DUMX-40-170R	--	4.5	0.060	" "
DUMX-40-171F	--	4.5	0.060	" "
DUMX-40-171R	--	4.5	0.060	" "
DUMX-40-172F	--	4.6	0.060	" "
DUMX-40-172R	--	4.6	0.060	" "

Status of ANL Miniplates as of Feb. 1989

*Plates A-02, A-04, A-35, as well as two early D. U. Plates (DUMB-2B and DUMB-3F) have been delivered to ANL's AGHCF for pre-PIE experimental work. Later (Feb. 1982) plate DUMT-50-33F was also delivered to the AGHCF for pre-PIE work with a highly loaded plate.

(a) I.D. Code is as follows:

M = miniplate	X = U_3Si_2 (Heat Treated or As-Cast)
A = assembly	F = U_6Fe (As-Cast)
E = LEU, or MEU, or HEU used in fuel	L = UAl_2 (As-Cast)
D = depleted U used in fuel	B = U_3Si (Heat Treated)
U = uranium	T = ternary (U_3SiAl) (Heat Treated)
DUMB, DUMT, DUMX, DUMF, DUML, AND DUMS plates are made with depleted uranium.	C = (U_3SiCu) (Heat Treated)
	H = $U_3Si_{1.5}$ (Heat Treated)
S = USi (As-Cast)	
N = $U_6Mn_{1.3}$ (As-Cast)	
K = U_3Si (As-Cast)	
I = $U_3Si_{1.6}$ (As-Cast)	
Q = $U_{75}Ga_{15}Ge_{10}$ (Heat-Treated)	
Z = $U_{75}Ga_{10}Si_{15}$ (Heat-Treated)	

The two digits following the first four letters are the volume percent fuel in the compact used to make the fuel plate.

The last two or three digits and either F or R represent assembly designations important only during fabrication or tracing pedigree of plate.

- (b) 'A' Nos. are unique and are assigned with few exceptions to plates prepared with LEU, MEU, or HEU fuel. ORR plates prepared with DU fuel have a 'D' placed after the 'A' No. (e.g., A-161D through A-166D and A187D through 192D). ORR plates prepared with a small addition of natural B_4C (~0.6 vol.% B_4C in fuel zone) have a P (for "poison") placed after the 'A' no. (e.g., A193P through A204P). Acceptable & reject plates are serially numbered but need not be exactly in chronological order.
- (c) Plates for which a location is not given are in H-137 of Bldg. 212.
- (d) These plates rolled to 0.060 in. using 0.060 in. plate hardware and then chemically etched (Oakite Solution) to 0.050 in.
- (e) U_3SiCu for these plates comminuted in motorized mullite mortar and pestle. Al_2O_3 and SiO_2 "contamination" of powder.

NOTE ALSO: All plates through MEAT-52-44R were produced using flat punches. Plates DUMT-54-45F through DUMT-54-47R were produced using a 'Mark I' version of tapered punches. Plates MEAT-55-48F through MEAT-45-55R were produced using the 'Mark II' version of tapered punches. See other files for punch geometries used on plates beyond -55R.

APPENDIX E

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Status of ANL Miniplates as of Feb. 1989
ORR Modules with ANL Plates
Module Numbers

2	3	4	7	10	13	14	17	18	22
A 1 (ON)	A 5 (ON)	A17 (ON)	A22 (ON)	A48 (OM)	A60 (OM)	A36 (ON)	A 85 (N)+	A 87 (N)+	A 105 (N)+
3 (ON)	6 (ON)	18 (ON)	23 (ON)	49 (OM)	63 (OM)	A46 (ON)	110 (N)	88 (N)	119 (N)+
25 (ON)	7 (ON)	19 (ON)*	24 (OM)	50 (OM)	69 (MT)		109 (N)	89 (N)+	121 (N)
	8 (ON)	20 (ON)	26 (ON)	52 (OM)	70 (MT)		100 (N)	93 (N)+	123 (N)
	9 (ON)	28 (ON)	53 (ON)	71 (MT)			112 (N)	117 (N)	135 (NT)
	10 (ON)	30 (ON)	54 (OM)	77 (MT)			108 (N)+	104 (N)	136 (NT)
	11 (ON)	32 (ON)	58 (OM)	78 (MT)			116 (N)	118 (N)	
	12 (ON)	34 (ON)	59 (OM)	79 (MT)			107 (N)	103 (N)	
	13 (ON)	36 (ON)	61 (OM)	81 (MT)			115 (N)++	90 (N)+	
	15 (ON)	38 (ON)	62 (OM)	82 (MT)			99 (N)+	94 (N)	
	16 (ON)	42 (ON)	65 (OM)	83 (MT)			114 (N)++	91 (N)	
	21 (ON)	46 (ON)	67 (OM)	84 (MT)			113 (N)	92 (N)	

At ANL PIE Complete	At ANL PIE Complete	At ANL PIE Complete	At ANL PIE Complete	At ANL PIE	At ANL PIE	Two plates from Mod. 7 reinserted in ORR. At ANL PIE	+Plates transf. Mod.#25. Other 9 plates at ANL for PIE ++Back to ORNL	At ANL PIE	+Plates transf. to Mod. #25. Other 4 plates at ANL for PIE
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*Destructively tested at ORNL.

O = O Temper Anneal

M = Modified rolling schedule

Rolling

A01-A47 Normal
A48-A84 Modified
A85-A136 Normal
A01-A68

N = "Normal" rolling schedule

T = Tapered punches used for compact

O-Temper

A69-A84 Tapered Punches

A85-124 Flat Punches

A125-A136 Tapered Punches

A137- Flat Punches

Status of ANL Miniplates as of Feb. 1989
ORR Modules with ANL Plates
Module Numbers

23	24	25	27	28	29	30	31	33	34
A157 (N)	A161D (N)	A 99 (N)	A188D (N)	A171 (N)	A157 (N)	A199P (N)	A193P (N)	A231 (N)	A213 (N)
137 (N)	163D (N)	108 (N)	176 (N)	183 (N)	137 (N)	A200P (N)	A208 (M)	A218 (N)	A 90 (N)+
124 (N)	162D (N)	85 (N)*	179 (N)	182 (N)	124 (N)	A202P (N)	A207 (N)	A229 (N)	A221 (N)
149 (N)	164D (N)	105 (N)	139 (N)	148 (N)	149 (N)		A197P (N)	A227 (N)	A209 (N)
122 (N)	165D (N)	119 (N)	180 (N)	168 (N)	122 (N)		A206 (NT)	A114 (N)+	A 93(N)
160 (N)	166D (N)		154 (N)	174 (N)			A204P (N)	A228 (N)	A210 (N)
126 (NT)			152 (N)	169 (N)	126 (NT)		A194P (N)	A115 (N)	A223 (N)
150 (N)			140 (N)	173 (N)	150 (N)			A232 (N)	A211 (N)
125 (NT)			96 (N)	181 (N)	125 (NT)			A225 (N)	A224 (N)
151 (N)			178 (N)+	145 (N)	151 (N)			A220 (N)	A 87 (N)+
132 (NT)			189D (N)	147 (N)	132 (NT)			A101 (N)	A 89 (N)+
129 (NT)++			190D (N)+	172 (N)					A216 (N)
++Plates removed for PIE. Others to Mod. #29 At ANL PIE	At ORNL PIE	Plates from Mods. 17 & 22 At ANL PIE	+Plates removed early. Most plates at ANL PIE (Some at ORNL)	At ANL PIE	From Mod. #23 At ANL PIE	At ANL (on hold)	At ANL PIE	+From Mod. 17 At ANL PIE	+From Mod. 18 At ANL Pie

ANL FUELS DATA

Fuel Formula ^a	ANL Target Composition (wt.% U)	Experimentally Measured Immersion Density (g/cm ³)	Fuel U Density ^(b) (Total g/U/cm ³)
U ₃ Si	96.0	15.2 ^c	14.59
		14.6 ^d	14.02
U ₃ Si _{1.5}	94.5	13.7 ^c	12.95
U ₃ Si _{1.6}	94.0	13.0 ^d	12.22
U ₃ Si ₂	92.5	12.2 ^d	11.28
USi	89.4	10.9 ^d	9.74
U ₃ SiAl	95.0	14.9 ^c	14.16
U ₃ SiCu	95.83	15.2 ^c	14.57
UAl ₂	80.0	7.9 ^d	6.32
U ₆ Fe	96.0	17.4 ^d	16.70
U ₆ Mn _{1.3}	93.7	16.8 ^d	15.70
U ₇₅ Ga ₁₀ Si ₁₅	94.1	15.6 ^e	14.68
U ₇₅ Ga ₁₅ Ge ₁₀	91.0	15.8 ^e	14.38

^aFormulas should not be taken literally. Although some target compositions may be nearly single phase and may be very close to the formula composition, the notation is simply a convenient way to describe a particular alloy.

^bDensity x weight fraction U.

^cAfter heat treatment of 72 h at 800°C.

^dAs-arc-cast.

^eAfter heat treatment of 96 h at 800°C.

OTHER FUELS OF INTEREST

Fuel Formula ^a	Stoichiometric Composition (wt.% U)	Density Literature Value (g/cm ³)	Fuel U Density ^b (Total g/U/cm ³)
UAl ₂	81.52	8.1	6.60
UAl ₃	74.62	6.7	5.00
UAl ₄	68.80	6.0	4.13
UAl _x	≈70	Depends on proportions of UAl ₂ , UAl ₃ , & UAl ₄	
UO ₂	88.15	10.96	9.66
U ₃ O ₈	84.80	8.40	7.12
U	100.0	19.1	19.1

^aFormulas should not be taken literally. Although some target compositions may be nearly single phase and may be very close to the formula composition, the notation is simply a convenient way to describe a particular alloy.

^bDensity x weight fraction U.

APPENDIX F: SUMMARY OF HIP RUNS

APPENDIX F

Summary of HIP Runs

Page 1 of 4

Run	Date	Shape & Material	Size ^a	Cleaning ^b	Welded In	Time at Pressure (Hr.)	Temp. at Pressure °C	Chamber Pressurized	Initial Pressure psi	Maximum Pressure psi	Results & Comments
A	7/5/88	6061 Al	i	a	Air	1	500	Cold	5,500	10,400	No Bond - Inside Surface Shiny
		6061 Al	i	a	Air	1	500	Cold	5,500	10,400	No Bond - Inside Surface Shiny
B	7/7/88	99.99 Al	ii	a	Air	2	500	Cold	6,000	11,500	Bonded - Met Sample 2-6-3-9
		1100 Al	iii	a	Air	2	500	Cold	6,000	11,500	Bonded - Met Sample 2-6-4-0
C	7/13/88	99.99 Al	iv	a	Argon	2	500	Cold	6,000	10,680	Not Bonded - Inside Surface Slightly Dull
		1100 Al	iii	a	Glovebox	2	500	Cold	6,000	10,680	Not Bonded - Pillowed
D	7/14/88	99.99 Al	v	a	Argon	2	500	Cold	6,000	11,070	Not Bonded - Pillowed - Inside Discolored
		1100 Al	v	a	Glovebox	2	500	Cold	6,000	11,100	Slight Bond - Separated with Screwdriver - Shiny Inside. Met Sample 2-6-4-1
E	7/15/88	99.99 Al	v	a	Argon	2	500	Cold	6,200	11,100	No Bond - Shiny Inside. Met Sample 2-6-4-2
		1100 Al	v	a	Glovebox	2	500	Cold	6,200	11,100	No Bond - Discolored Inside
F	7/22/88	1100 Al (Rod)	vi	b	Air	2	500	Hot	280	10,600	Slight Bond - Machined to Tensile Specimen
		1100 Al (Rod)	vi	a	Air	2	500	Hot	280	10,600	Bonded - Machined to Tensile Specimen. Tested to Failure. Met Sample 2-6-4-4
G	7/26/88	6061 Al	v	a	Air	2	500	Hot	250	10,650	No Bond - Shiny Inside
		1100 Al	v	a	Air	2	500	Hot	250	10,650	Bonded. Met Sample 2-6-4-3
H	8/9/88	1100 Al (2 Rods)	vi	a	Air	2	500	Hot	250	10,700	Two 1100 Al 1-1/2" Dia. Rods - Bonded & Machined to Tensile Specimens. Tested to Failure.
I	8/17/88	1100 Al (Compact)	viii	a	Air	2	500	Hot	280	10,700	Bonded - W-Al Compact FS #3 V/O W = 55. Met Samples 2-6-4-6, 2-6-4-7, 2-6-4-8. 1100 Al Bond Met Sample 2-6-4-5
J	9/1/88	6061 Al (162 F&R)	ix	c	Air	2	300	Cold	10,200	17,100	First HIP of ...162F & ...162R. 40 V/O U ₃ Si ₂
K	9/2/88	1100 Al (Compact)	viii	a	Air	2	500	Hot	210	10,700	No Bond - Slightly Pillowed Compact FS #6 V/O W = 60

Summary of HIP Runs

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Run	Date	Shape & Material	Size*	Cleaning**	Welded In	Time at Pressure (Hr.)	Temp. at Pressure °C	Chamber Pressurized	Initial Pressure psi	Maximum Pressure psi	Results & Comments
L	9/8/88	6061 Al (162 F&R)	ix	c	Air	2	300	Cold	10,100	15,000	Rerun of HIP Run J. Second HIP of 162F & 162R
M	9/9/88	1100 Al (FS Compact)	viii	a	Air	2	500	Hot	210	10,600	Bonded (See Also HIP Runs R&S). Compact FS #6 V/O W = 60 8.8% Void after HIPping
N	9/14/88	6061 Al (162 F&R)	ix	c	Air	2	400	Hot	590	10,700	Rerun of HIP Run L. Third HIP of ...162F & ...162R
O	9/15/88	6061 Al (162 F&R)	ix	c	Air	2	500	Hot	630	10,700	Rerun of HIP Run N Fourth HIP of ...162F & ...162R
P	9/22/88	6061 Al (163 F&R)	ix	c	Air	2	500	Hot	520	10,800	~1% Void after HIPping, 40 V/O U ₃ Si ₂
Q	10/7/88	1100 Al (Wire) All Copper	x	a	Air	4	500	Hot	350	11,100	Bonded. Met Sample 2-6-5-2.
R	10/19/88	1100 Al (FS Compact) (Rerun of M)	viii	a	Air	4	500	Hot	210	11,200	15% Cold Work (21.1% Void) Plate severely warped in all three axes. Second HIP of Run M 5.3% Void
S	10/21/88	1100 Al (FS Compact) (2nd Rerun of M)	viii	a	Air	4	500	Hot	350	11,100	Third HIP of Run M 4.9% Void
T	11/2/88	1100 Al Wires 304 SS 4043 Al, U-Ga-Si	x	a,d	Air	4	500	Hot	250	11,000	Bonded. Met Sample 2-6-5-3

Summary of HIP Runs

Page 3 of 4

Run	Date	Shape & Material	Size*	Cleaning**	Welded In	Time at Pressure (Hr.)	Temp. at Pressure °C	Chamber Pressurized	Initial Pressure psi	Maximum Pressure psi	Results & Comments
U	11/23/88	1100 Al (2 Rods)	vi	a	Air	4	500	Hot	250	11,000	U-1 Bonded. Separated Al/Compact Joint During Machining Compact TT-60-02 U-2 Non-Bond - Visible Cracks in Weld Compact TT-60-06
V	2/14/89	1100 Al (FS Compact) (3rd Rerun of M)	viii	a	Air	1.5	500	Cold	11,100	25,800	Fourth HIP of Run M 2.1% Void
W	3/9/89	6061 Al	xi	a	Vacuum	3.5	500	Hot	330	11,300	Electron Beam Welded, No Bonding
X	4/6/89	1100 Al X1, X2 (Covers & Frames) 6061 Al Inserts)	xli	a	Vacuum	4	500	Hot	350	11,400	Electron Beam Welded, Leaked, No Bond, Faulty E.B. Unit Most Likely Cause of Poor Welds
Y	4/19/89	1100 annd	xli	a	Air	4	500	Hot	1100	11,700	No Bond
		6061 Al X2, Al Y1	xli	a	Air	4	500	Hot	1100	11,700	Possible Bond
		6061 Al Y2	xi	a	Air	4	500	Hot	1100	11,700	Bonded - To Be Sectioned
		6061 Al Y3	xi	a	Air	4	500	Hot	1100	11,700	Bonded - To Be Sectioned
Z	5/12/89	6061 Al	xi	a	Vacuum	4	500	Hot	550	11,800	Electron Beam Welded - No Bond No Filler Metal
AA	5/19/89	6061 Al	xi	a	Vacuum	4	500	Hot	550	11,800	Electron Beam Welded with 1100 Al Filler Metal - No Bond
BB	5/23/89	99.99 Al	xlii	n/c	—	1	670	Hot	500	12,300	Thermocouple Test - Melting
CC	5/25/89	99.99 Al	xlii	n/c	—	1	645	Hot	800	11,700	Thermocouple Test - No Melting

Summary of HIP Runs

Page 4 of 4

Run	Date	Shape & Material	Size*	Cleaning**	Welded In	Time at Pressure (Hr.)	Temp. at Pressure °C	Chamber Pressurized	Initial Pressure psi	Maximum Pressure psi	Results & Comments
DD	6/2/89	6061 Al	xl	a	Vacuum	4	500	Hot	300	12,200	Electron Beam Welded with 4043 Filler Rod - Bonded
EE	6/14/89	6061 Al	xl	a	Vacuum	4	500	Hot	250	12,600	Electron Beam Welded with 4043 Filler Rod - No Bond
FF	6/20/89	6061 Al	xl	a	Vacuum	4	500	Hot	400	12,800	Same as Above - No Bond
GG	6/29/89	6061 Al	vi	a	Air	4	500	Hot	500	11,800	GG1 - No Bond, GG2 - Bonded, Machined and Tension Tested to Failure
HH	7/3/89	6061	xl	a	Vacuum	4	500	Hot	400	11,900	Electron Beam Welded with 4043 Filler Rod - No Bond
II	7/25/89										
JJ	8/4/89	1100 Al Wire	x	a	Air	4	500	Hot	350	11,900	Tig Welded, Bonded, Sectioned for Metallography, Cleaned by Sanding
KK	8/8/89	1100 Al Wire	x	a	Air	4	500	Hot	350	11,800	Tig Welded, Bonded, Sectioned for Metallography, Annealed for 200 hr at 400°C, Cleaned by Sanding

ai = 1/8" Plate - 3" x 3"
ii = 1/8" Plate - 1" x 2"
iii = 1/16" Plate - 3" x 3"

iv = 1/8" Plate - 1" x 1"
v = 1/16" Plate - 2-3/4" x 2-3/4"
vi = 1-1/2" Diameter Rod

vii = Not Used in Code
viii = 4.5" x 3" x 0.080" Plate Tungsten Fuel
ix = 2" x 4.5" x 0.060" Miniplate
x = 2" x 4.5" x 0.085" Wire Concept
xi = 3" x 4.5"
xii = Cover/Frame/Cover of 1100 Al with Two 6061 Inserts
xiii = Approx. 1 cm Cube

ba = Oakite Etched & Wire Brushed
b = Wire Brushed Only
c = Oakite Etched Only
d = Abrasive Paper
n/c = Not Cleaned

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