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INITIAL DEVELOPMENT OF HFIR FUEL ASSEMBLIES

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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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METALS AND CERAMICS DIVISION

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OCTOBER 1967

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FOREWORD

This report presents results obtained during 1960 and 1961 in work to demonstrate the feasibility of making HFIR fuel elements to the specifications being considered at that time. The elements described were made for a critical test program and are now obsolete. Many of the remaining problems reported have since been solved or circumvented.

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R. J. Beaver, J. W. Tackett,[1] J. H. Erwin,

G. M. Slaughter and W. J. Kucera[2]

ABSTRACT

This report describes the initial development of HFIR-type fuel assemblies aimed at demonstrating feasibility and concluded with the fabrication of the 8-kg-^{235}U aluminum-base fuel assembly for the HFIR Critical Experiment No. 2.

Contoured fuel cores and a fuel element containing as many as 369 involute-shaped plates in one array had never before been attempted. The fuel elements made for the critical experiment were similar to but not the same as the fuel elements that ultimately were specified for the operating reactor. The inner-annulus element contained 171 fuel plates; the outer-annulus element contained 369 plates.

The fuel loading for this critical test was low enough that the alloy Al–24% U could be used as the fuel material for the outer-annulus plates. We chose to vacuum melt and cast this alloy and examine the novelty of hot pressing segments of extruded bars to obtain the specified contoured core.

Boron was specified as a burnable poison addition to the inner-annulus plates only. Therefore we selected powder metallurgy as the process for making a fuel mixture containing 26 wt % U_3O_8, 0.07 wt % B_4C, balance aluminum. These cores were first cold pressed to rectangular blocks and later hot pressed to the specified contour. Aluminum pieces were made to match the contours of both types of fuel cores.

Alclad plates containing these contoured core pieces were made by hot rolling, and the plates were shaped into involutes. The plates were assembled into fuel arrays and joined by mechanical fastening and welding.

The results of this program showed that processing HFIR fuel plates and elements with precise

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control of dimensions and fuel loading is feasible. Blistering of fuel plates was the major problem encountered.

INTRODUCTION

The 100-Mw High Flux Isotope Reactor is designed to produce in a "flux trap" thermal neutron fluxes in the order of 5×10^{15} neutrons cm^{-2} sec^{-1}. It is fueled with highly enriched uranium in aluminum, cooled and moderated by light water, and reflected with beryllium. The design is based on achieving, with reasonable economy, milligram quantities of ^{252}Cf from a limited supply of ^{242}Pu feed material.[3]

In 1960, the fuel elements for this reactor were in the early stages of development. The proposed compactness of this reactor, its intended high average power density of 2 Mw/liter, a heat flux of 0.8×10^6 Btu ft^{-2} hr^{-1}, and a possible hot-spot power density of 5 Mw/liter imposed demanding requirements in the metallurgical engineering and quality control of these fuel elements.[4]

Specific features of the design of the fuel assembly for Critical Experiment No. 2 are described in Fig. 1, which illustrates the two annular fuel elements. These two fuel bodies are combined by slipping the outer-annulus element over the inner-annulus element to form a fuel assembly containing 540 plates. The overall diameter is 17.124 in., and the "flux trap" (or target region), within the inner-annulus element, has a diameter of 5.067 in. To fit the composite 0.050-in.-thick fuel plates into these concentric annular arrays and at the same time maintain uniform spacings between plates, the plates must be involutes with

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[3]R. D. Cheverton, "Nuclear Design of the HFIR," Research Reactor Fuel Element Conference, September 17–19, 1962, Gatlinburg, Tennessee, TID-7642, Book 1, pp. 89–98.

[4]N. Hilvety and T. G. Chapman, "Thermal Design of the HFIR Fuel Element," Research Reactor Fuel Element Conference, September 17–19, 1962, Gatlinburg, Tennessee, TID-7642, Book 1, pp. 138–51.

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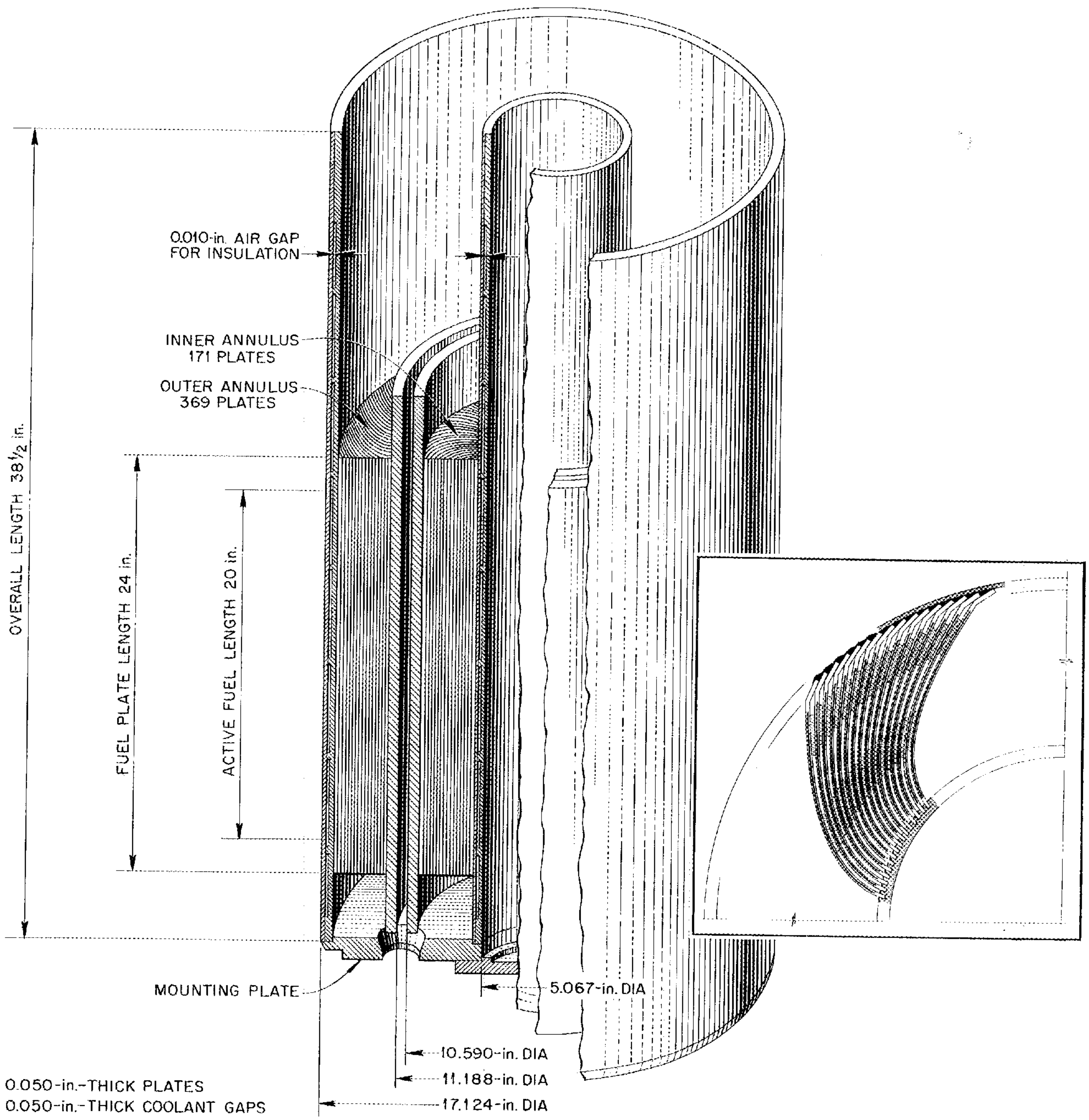

Fig. 1. HFIR Fuel Assembly for Critical Test.

closely controlled curvatures. Any individual measurement must be within ±0.010 of 0.050 in., and the average width of the water channel at any location must be controlled to within ±0.005 in. of the nominal.

Aluminum was selected as the basic metal in the construction of the fuel assembly, principally because of its low absorption of thermal neutrons and relatively high thermal conductivity, although corrosion products can build up with attendant increases in the central fuel temperature.[5] Type 6061 aluminum was selected for the fuel-plate cladding and side plates because of its superior mechanical properties compared with other aluminum alloys, particularly its elevated-temperature creep strength.[6]

The fuel investment, thought to be about 8 kg ^{235}U in the geometry described, requires the use of a burnable poison in the inner annulus.[3] Boron was selected as this poison. Problems were encountered in controlling the boron content in a U–30% Al alloy first considered for this application.[7] Therefore a powder-metallurgy process, which permitted discrete particles of B_4C to be mixed with the fuel, was selected for making cores for the inner-annulus plates. Using our experience in making fuel elements for the research reactor at the Puerto Rico Nuclear Center,[8] we selected U_3O_8 as the fuel compound. No boron was needed in the outer annulus, so for this fuel element the uranium-aluminum alloy system was an obvious choice. The outer-annulus element required 5.68 kg of ^{235}U, and we calculated that the concentration of uranium in the uranium-aluminum alloy nominally would be 24 wt %. At this level, we did not anticipate any gross segregation of uranium.

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[5]J. C. Griess et al., "The Corrosion of Aluminum Alloys Under Simulated ATR and HFIR Conditions," Research Reactor Fuel Element Conference, September 17–19, 1962, Gatlinburg, Tennessee, TID-7642, Book 2, pp. 612–34.

[6]Alcoa Aluminum Handbook, p. 34, Aluminum Company of America, Pittsburg, Pennsylvania, 1957.

[7]J. H. Erwin, W. J. Kucera, D. T. Bourgette and R. J. Beaver, "Development of an Aluminum-Base Fuel Element for the High Flux Isotope Reactor" Metallurgy Div. Ann. Progr. Rept. July 1, 1960, ORNL-2988, pp. 289–97.

[8]W. J. Kucera, C. F. Leitten, Jr., and R. J. Beaver, Specifications and Procedures Used in Manufacturing U_3O_8-Aluminum Dispersion Fuel Elements for Core I of the Puerto Rico Research Reactor, ORNL-3458 (Oct. 7, 1963).

To achieve as uniform a neutron flux as possible, the fuel section in each plate was contoured in the radial direction. The initial designs are specifically illustrated in Figs. 2 and 3, which detail the dimensions of the inner and outer fuel plates, respectively. In the inner-annulus plate, the fuel section is thinnest (0.007 in.) at the edge closest to the inner-annulus element; the thickness increases to a maximum at a distance of 2 in. from the inner edge of this plate and decreases to 0.024 in. at the radial location farthest from the target region. The thinnest portion of the outer-annulus plate is 0.015 in. and is located at the maximum distance from the target region.

Local segregation of fuel within a fabricated plate scheduled for reactor operations can cause a hot spot. For this critical test fuel assembly, however, segregation, within the expected limits, was unimportant and was not studied. Past experience with uranium-aluminum alloys near this concentration[9] and mixtures of U_3O_8 in aluminum[10] indicated that gross segregation was not likely.

To confirm the physics of a reactor core containing 8 kg ^{235}U with the boron burnable poison, fuel elements were prepared for a critical test. These components simulated the geometric pattern and materials of construction judged most suitable at the time for the reactor. We chose to build the fuel elements using the processing features embodied in a concept designated "Mark IIB." The pertinent identifying features of this concept are:

1. Only one side plate in each element is used into which fuel plates are inserted. Grooves for accepting plates are machined into the outside surface of this inner tube.

2. All plates but the last few are mechanically fastened to the inner tube by peening. The last few can be attached by cutting short

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[9]W. C. Thurber and R. J. Beaver, Segregation in Uranium-Aluminum Alloys and its Effect on the Fuel Loading of Aluminum-Base Fuel Elements, ORNL-2476 (Sept. 5, 1958).

[10]M. M. Martin and C. F. Leitten, Jr. "Dispersions of UO_2, U_3O_8, and B_4C in Type 1100 Aluminum," Metallurgy Div. Ann. Progr. Rept. July 1, 1960, ORNL-2988, pp. 287–88.

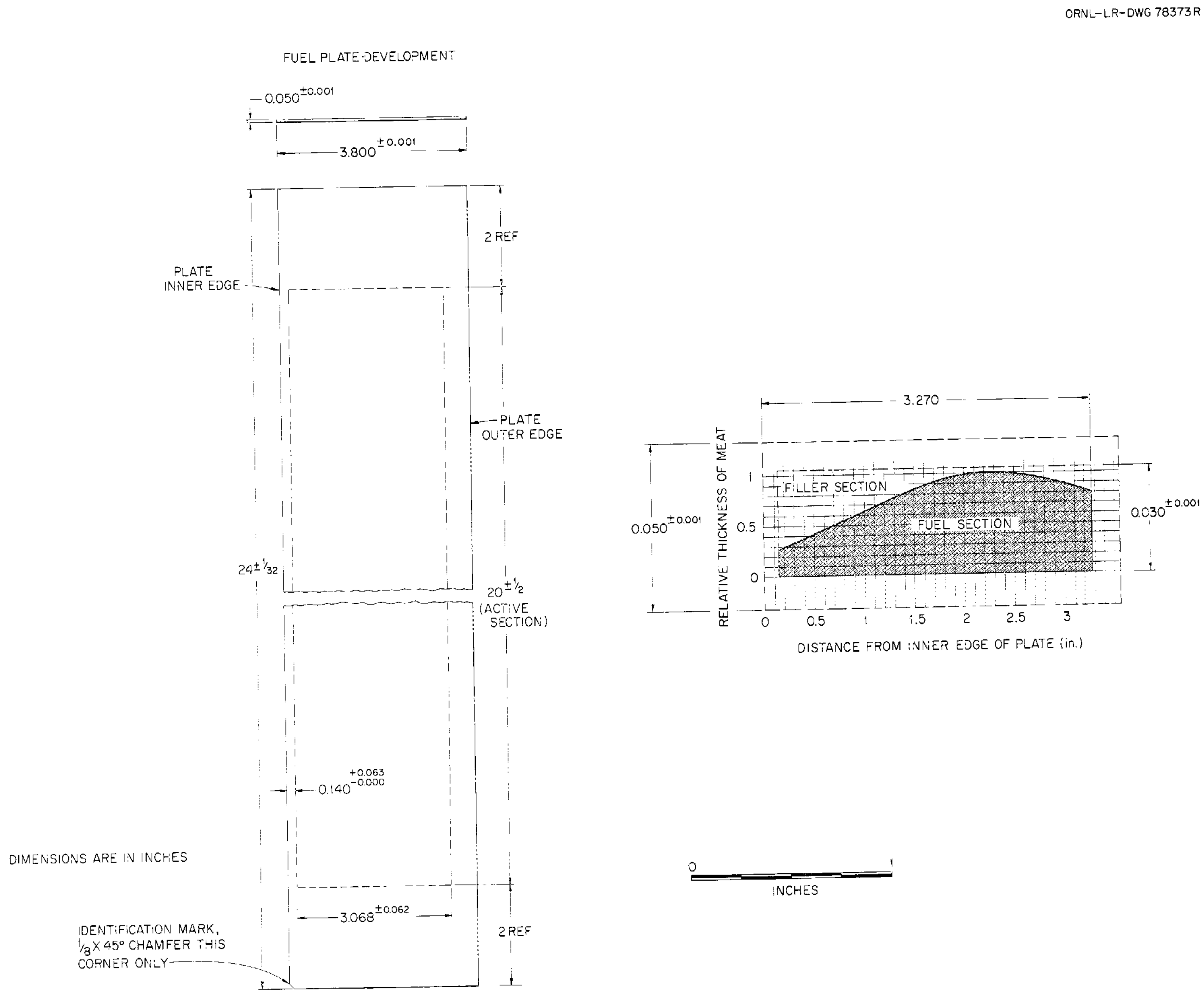

Fig. 2. Inner-Annulus Fuel Plate for Critical Test No. 2.

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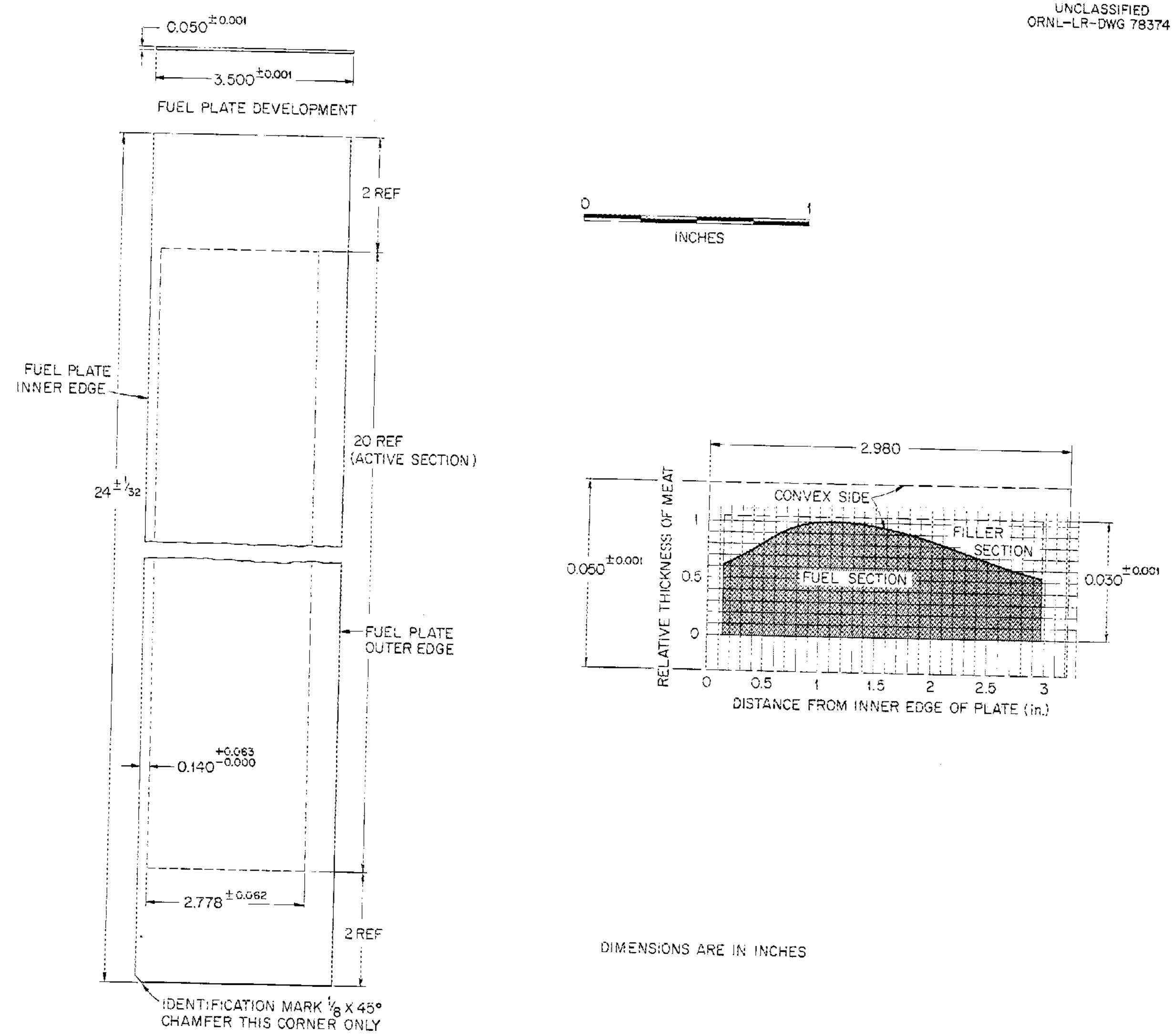

Fig. 3. Outer-Annulus Fuel Plate for Critical Test No. 2.

circumferential slots into the inside surface of the inner tube at 1-in. intervals along the length of the element and plug welding the fuel plates to the side plate. (Although feasibility had been demonstrated in the event this design was ultimately selected for reactor use, it was not done on the critical test assembly.)

3. The outer edges of the fuel plates are bent to form a lip and lay upon each other when assembled. Circumferential welds at 1-in. intervals along the length of the element tie these plates together quite effectively. This bent lip design incorporates the flexibility for correcting the spacing between plates by the use of shims between plates during assembly and prior to welding.

4. An outer tubular side plate is shrink-fitted onto the welded assemblage.

In both the inner and outer fuel elements for Critical Test No. 2, slots were provided in each 60° segment for insertion or removal of test plates. This feature is illustrated in Fig. 4, which shows the fuel assembly we made for this critical test.

The fuel and burnable poison loadings specified for the critical test assembly are listed below:

	^{235}U, g	^{10}B, g
Inner-Annulus Element	2345	1.669
Outer-Annulus Element	5683	none
Total	8028	1.669

A tolerance of ±1% of these values was desired.

Pertinent dimensional data and fuel and burnable poison loadings in the fuel plates are listed in Table 1. Material specifications are listed in Table 2.

Although we had not yet established a process for fabricating reactor-grade HFIR fuel plates to specifications, we proceeded to make the critical test assembly using methods under development at that time. Since this fuel assembly was made for a critical test, we were not required to meet dimensional specifications or other requirements, such as bonding and fuel homogeneity of reactor-grade parts. Our main objective was to prepare fuel assemblies with the specified fuel and burnable poison loadings. Our secondary objective was to make these components as close to design dimensions as possible. Problems that we pinpointed along the way were left for future resolution. We selected processing techniques primarily on the basis of our past experience in producing aluminum-base research reactor fuel elements and on the data available on the specific methods under development for the HFIR fuel assembly at that time. Conventional powder metallurgy was a likely method for producing inner-annulus fuel and filler blanks, which could readily be contoured by hot pressing. For the outer-annulus plate, we chose to make slugs from vacuum-cast extruded Al–24% U alloy. These slugs were also contoured by hot pressing. Conventional "picture frame" technique for cladding fuel plates by hot rolling was used, and low-pressure marforming was examined for shaping the composite fuel plates into involutes.

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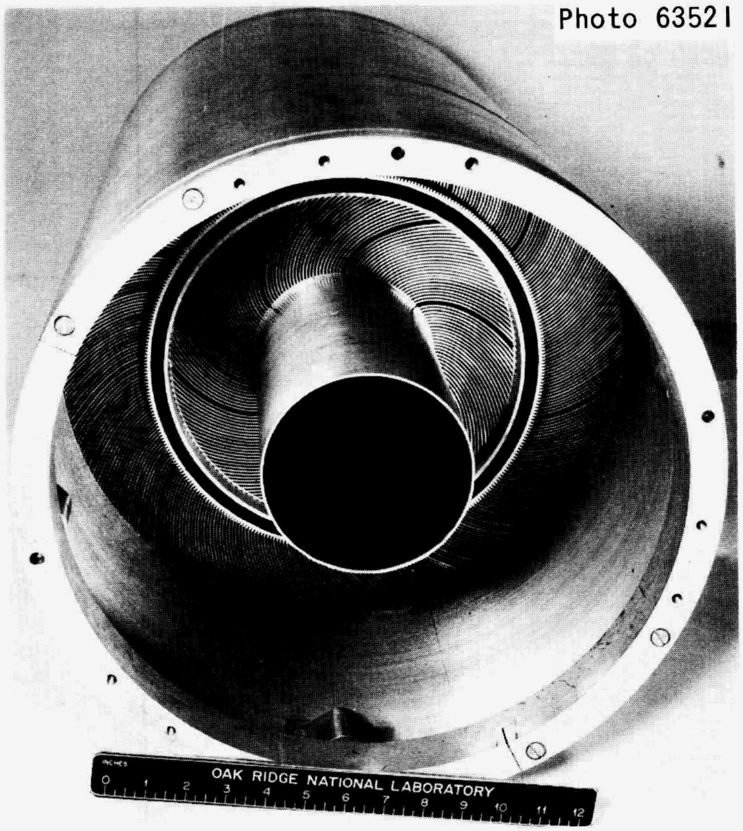

Fig. 4. Fuel Assembly Made for HFIR Critical Experiment No. 2.

Table 1. Pertinent Design Data of HFIR Fuel Plates

	Inner Annulus	Outer Annulus
Number of Plates per Fuel Element	171	369
Overall Dimensions, in.		
Length	24.000	24.000
Width	3.800	3.500
Thickness	0.050	0.050
Fuel Section Dimensions, in.		
Length	20 ± 1/2	20 ± 1/2
Width	3.068 ± 0.062	2.778 ± 0.062
Maximum Thickness	0.028	0.028
Materials		
Fuel Plate Cladding	Type 6061 Al	Type 6061 Al
Fuel Plate Frame	Type 6061 Al	Type 6061 Al
Fuel Section		
Fuel	U_3O_8	U-Al alloy
Burnable poison	B_4C (natural)	None
Aluminum	Type 1100	Type 1100
Filler Piece		
Burnable poison	B_4C (natural)	None
Aluminum	Type 1100	Type 1100
Fuel and Burnable Poison Content		
^{235}U, g	13.70	15.40
^{10}B, mg	9.78	None
Enrichment, wt %		
^{235}U	93	93
^{10}B	18.8	None
Nominal Concentration, wt %		
Fuel Core	26.31 U_3O_8, 0.072 B_4C, bal Al	24 U 76 Al
Filler Piece	0.065 B_4C bal Al	Type 1100

Table 2. Material Specifications

Aluminum in Fuel Plates

Frames and cover plates
Wrought type 6061 aluminum conforming to ASTM Designation: B 209 – 58

Melting stock for U-Al alloy of outer-annulus plate
Aluminum melting stock conforming to ASTM Designation: B 179 – 59, alloy 995 A

Aluminum powder as dispersant in inner-annulus plate
Aluminum powder equivalent to ALCOA Atomized Powder No. 101

Side plates, end fittings, combs
Wrought type 6061 aluminum conforming to ASTM Designation: B 209 – 58

Uranium Metal for U-Al Alloy of Outer-Annulus Plate

Uranium with an enrichment in the ^{235}U isotope of 93%. Carbon content less than 300 ppm.

U_3O_8 as Dispersoid in Inner-Annulus Plate

U_3O_8 manufactured by the Y-12 plant of UCNC. Particle-size range is 44 to 149 μ.

Boron Carbide as Dispersoid in Inner-Annulus Plate

High-purity grade B_4C containing approximately 76 wt % natural boron. Isotopic concentration of ^{10}B 18.8 wt % nominal. Particle size less than 44 μ.

GENERAL DESCRIPTION OF THE FABRICATION PROCESS

The process flow chart described in Fig. 5 shows the various fabrication sequences followed in manufacturing the fuel elements. The process for making the outer-annulus fuel element initiates with melting and casting in vacuum the Al–24% U alloy. Vacuum melting was selected to minimize the hydrogen concentration in the alloy and, hopefully, to eliminate blisters of fuel plates caused by hydrogen expansion, which may occur in subsequent 500°C heat treatment. After the removal of the feeding head, the casting was normally 11 in. long.

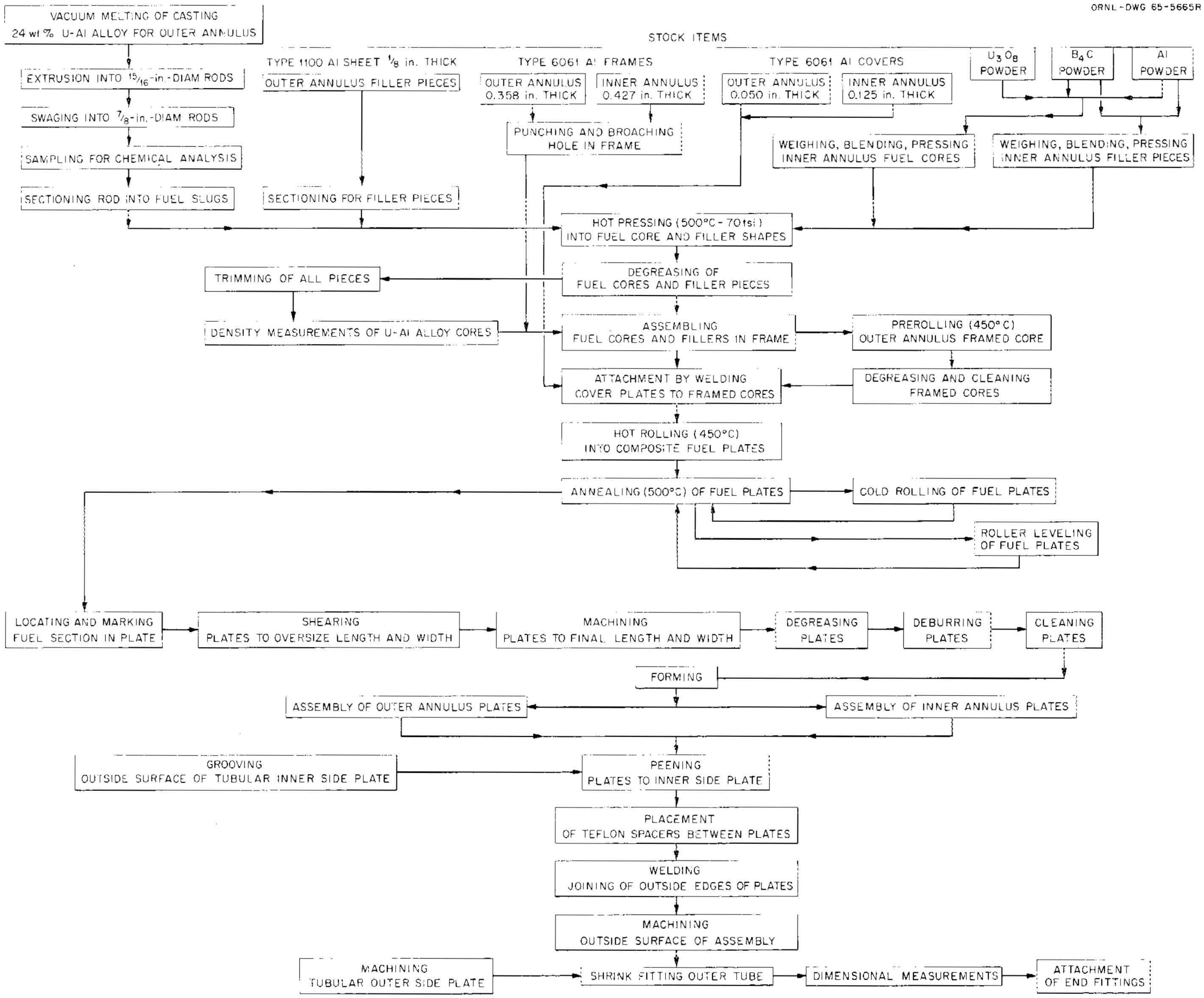

Fig. 5. Flow Pattern of Process used in Making Fuel Elements for HFIR Critical Experiment No. 2.

Extrusion and swaging into a 7/8-in.-diam rod was chosen because of its production potential in providing slugs that could later be pressed into contoured compacts. Before the swaged rod was cut into slugs, samples were taken at intervals along its length and chemically analyzed for uranium, to locate regions in the rod with unacceptably high uranium concentration. The results were also used to predict the average uranium concentration.

The aluminum pieces for matching the contour of the fuel compact were sheared from 1/8-in.-thick type 1100 aluminum sheet; and, like the fuel slugs, were hot pressed to the correct shape. When fitted together, the convex surface of the fuel core mated with the concave surface of the filler piece to form a rectangular parallelepiped. Prior to being placed into the picture frame, all of these hot-pressed cores were degreased in trichloroethylene vapor, the burr from the hot-processing operation was removed, and density of the fuel cores was determined. The density data were used to predict the ^{235}U content in each core.

The frame enclosing the fuel was a type 6061 aluminum plate, rolled to 0.358 in. thick. A hole for accepting the fuel-core—filler-piece assemblage was made by a combination of punching and broaching. The fuel core and matching filler piece were shrink-fitted into the frame. This framed assemblage was then hot rolled bare to half of the original thickness to obtain a closer fit between the core pieces and the frame. After degreasing in trichloroethylene vapor and wire brushing, the 0.050-in.-thick type 6061 aluminum cover plates were welded along the edge to each side of the frame.

Since plates for the inner-annulus element contain boron, powder metallury was selected for preparing the fuel compact and filler pieces. Previous work had indicated that to meet the HFIR specifications with U-Al-B alloys would be difficult.[11] The powder-metallury process for making compacts initiated with the weighing of the exact quantities of the ingredient powders (U_3O_8, Al, B_4C in the case of the fuel pieces; Al, B_4C in the case of filler pieces) specified for each fuel core. The

[11] D. T. Bourgette, W. J. Kucera, J. H. Erwin, and T. D. Watts, Metallurgy Div. Ann. Progr. Rept. May 31, 1961, ORNL-3160, pp. 101–103; T. D. Watts and A. L. Lotts, ibid. pp. 165–66.

powders for one fuel compact were placed in a jar. The jar was capped and, along with 23 other jars, was placed within containers attached to a double conical blender, and the powders in each of the jars were mixed. Afterwards, the mixture was pressed at room temperature to form a dense rectangular parallelepiped. The hot-pressing operation, previously cited for making both contoured alloy fuel cores and the aluminum-filler pieces, was also used to make the powder-metallurgy-fuel cores and fillers. Density measurements of the hot-pressed powder-metallurgy product were not needed. These cores went directly into the aluminum frames after minor trimming. As shown in Fig. 5, the frames for these cores were 0.427 in. thick, and the cover pieces were 0.125 in. thick. Also, the framed cores were not prerolled. The powder-metallurgy cores were simply shrink-fitted into the frame, and cover plates were attached in the same manner as for the outer-annulus plates.

From the hot rolling of plates until the completion of the process, both inner- and outer-annulus plates were handled similarly, but separately. Ultimately the alloy plates were assembled into the outer-annulus element and the powder-metallurgy plates were assigned to the inner-annulus element. These plates were all rolled at 450°C to bond the cladding to the fuel core and frame. The outer-annulus plate was reduced 84% in thickness; the inner-annulus plate was reduced 92% in thickness. Acceptable flatness of plates was achieved by sufficient passes through a roller leveler with an intermediate anneal at 500°C.

The fuel core in the plate was located fluoroscopically. The orientation of the plate was fixed by an eddy-current technique, which enabled us to determine the region of maximum fuel-core thickness. The plates were readied for forming by shearing slightly oversize in length and width, machining to the specified dimensions, degreasing in trichloroethylene vapor, and finally cleaning in a solution consisting of 2 parts concd HF, 10 parts concd HNO_3, and 100 parts water by volume. The acid was rinsed from the plate with water, and the plates were allowed to dry at room temperature.

The flow chart (Fig. 5) reflects the significant features of the assembly and joining process, which typifies this fuel-element design. Each plate was assembled into a groove of the inner tubular side plate and securely fastened to this side plate by peening the side-plate ledge onto the plate. A critical part of this operation was to control the volume occupied by the plates and the intermediate spacings during the buildup of the element, to avoid a finished diameter in excess of the specifications. We, therefore, used Teflon shims between plates. After assembly the outer edges of the plates were welded together. The welded surface was machined smooth, and the outside tubular side plate was shrunk onto the assemblage. The spacings between plates were inspected, and finally end fittings were attached for adapting the components into the critical test facility. We call attention to the fact that the last few plates to be assembled were not joined to the inner side plate, because this element was merely for a critical test. Had this been for the operating reactor, the specifications would have required that these plates be fixed to the inner side plate by short circumferential welds spaced at 1-in. intervals along the length of the fuel element. Preliminary work indicated that such an attachment was feasible.[12]

PREPARATION OF ALLOY FUEL SLUGS FOR OUTER ANNULUS

Slugs of an aluminum alloy containing nominally 24 wt % U and of a size 7/8 in. diam × approximately 2 1/8 in. long were made for subsequent hot pressing into contoured fuel cores. These slugs were made from vacuum castings 3 in. in diameter and generally 11 in. long. To prepare the casting, freshly cleaned uranium and aluminum melting stock were charged into a stabilized zirconia crucible. The metals were heated to 1000°C under a dynamic vacuum of 1 to 3 μ, and the molten mass was poured into a water-cooled copper mold.

After the top portion of the casting was cropped, the billet was heated to 550°C and extruded into a 1-in.-diam rod. Total reduction in the cross-sectional area was 89%. The rod was cold swaged to 7/8 in. in diameter. The length of the swaged rod after cropping generally ranged between 80 and 90 in. Samples approximately 2 in. long were removed

[12] J. W. Tackett, "Aluminum-Alloy Fuel Element Development," Metallurgy Div. Ann. Progr. Rept. July 1, 1960, ORNL-2998, pp. 465–68.

from this rod to obtain the average uranium concentration. Two were removed from each end and two at equal distances from each end. These distances were measured so that the rod could ultimately be sawed into three segments with a uranium analysis available for each end of each segment. Thus we could calculate an average uranium concentration for each segment. With this value the slug length with the highest probability of yielding cores containing close to 15.4 g of ^{235}U was determined. This length generally was 2 1/8 in. but frequently varied to 2 1/16 and 2 3/16 in.

The type of segregation pattern generally observed in the extruded rod is shown in Fig. 6. Most of the rod was quite homogeneous, although in one region the concentration was approximately 5 to 10% higher than in the balance of the rod. Although local segregations were masked by our averaging system, they were subsequently identified in density measurements of the hot-pressed core.

Figure 7 correlates the density of hot-pressed uranium-aluminum cores and the uranium concentration determined by dissolving a series of cores and chemically analyzing for uranium. Our calculations showed this correlation to be accurate within ±0.5% with a confidence limit of 95%. The densities were obtained on each hot-pressed trimmed compact by alcohol-displacement techniques. The uranium concentration was determined from the correlation. From the known weight of the core and enrichment of the uranium, assignment of the ^{235}U content was straightforward. The data are summarized in Fig. 8.

In the system used, 58.4% of the plates were within ±2% of the nominal value of 15.4 g and 91.5% of the fuel cores were within ±5%. The results obtained were acceptable for the critical test assembly. We feel that with additional process development, it is reasonable to predict that fuel plates containing Al–24% U alloy can be held to a ^{235}U specification of 15.4 g ± 2%, although recycling into subsequent melts will obviously be necessary.

During the course of this work, we examined the macroscopic segregation within hot-pressed Al–24% U alloy fuel cores by cutting each core into three pieces, measuring the density of each piece, and assigning a uranium value based on the correlation shown previously. The results, listed in Table 3, do not indicate any gross segregation.

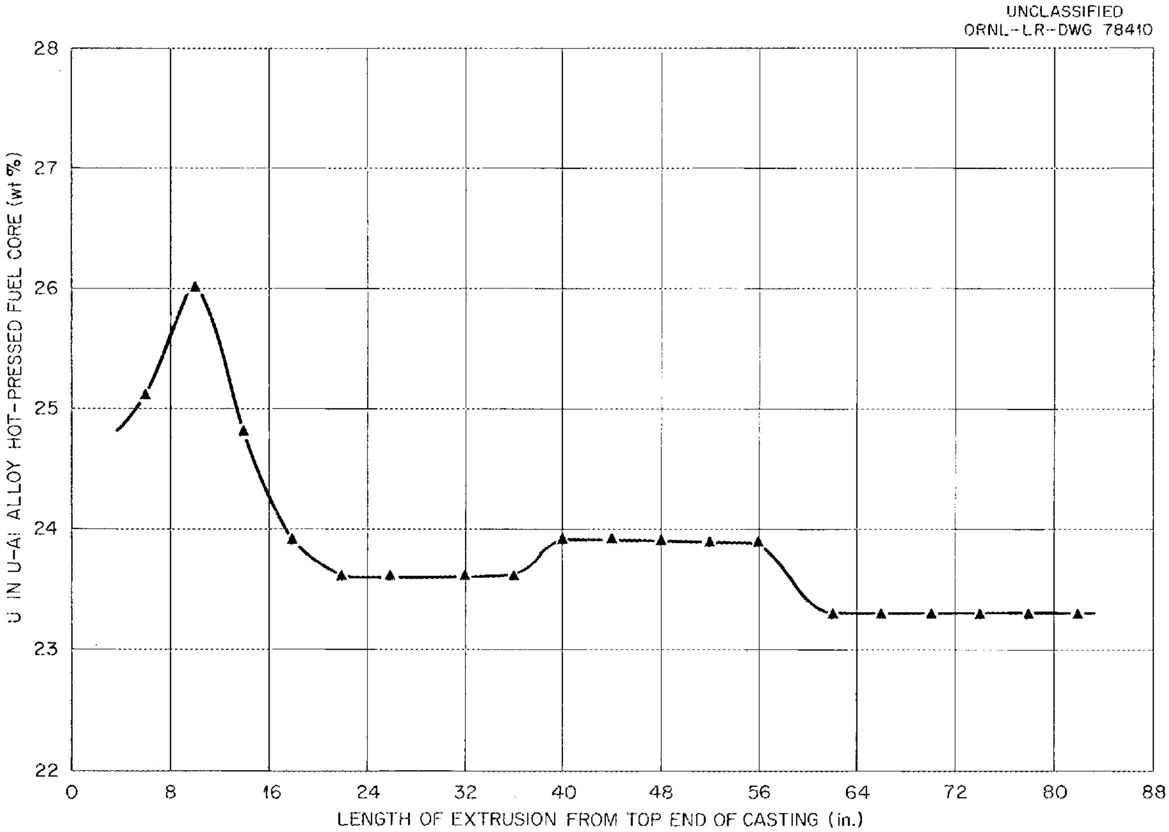

Fig. 6. Typical Uranium Segregation Pattern in Extruded Alloy Bar.

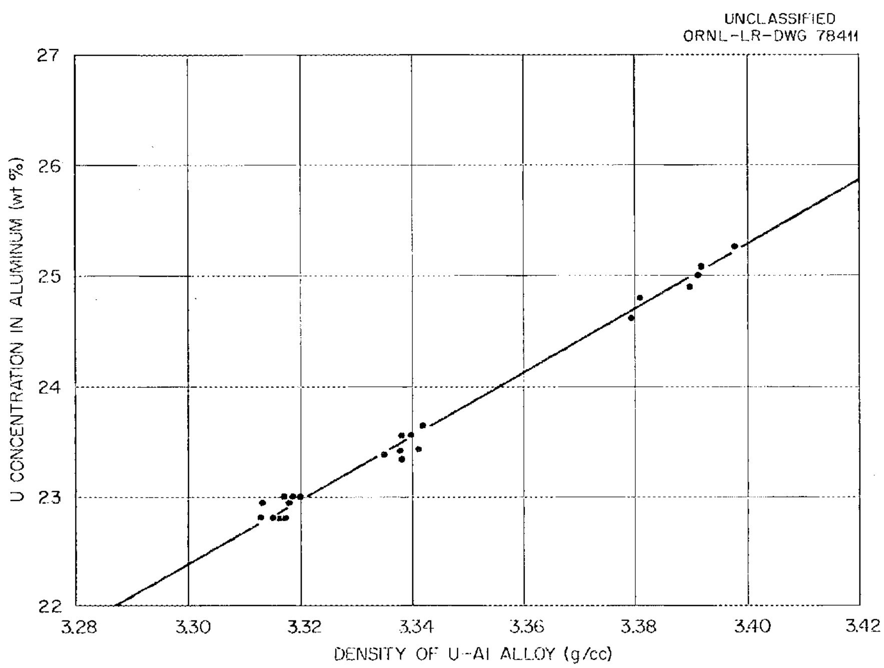

Fig. 7. Correlation Between Density and Uranium Concentration in Forged Uranium-Aluminum Alloy Compacts.

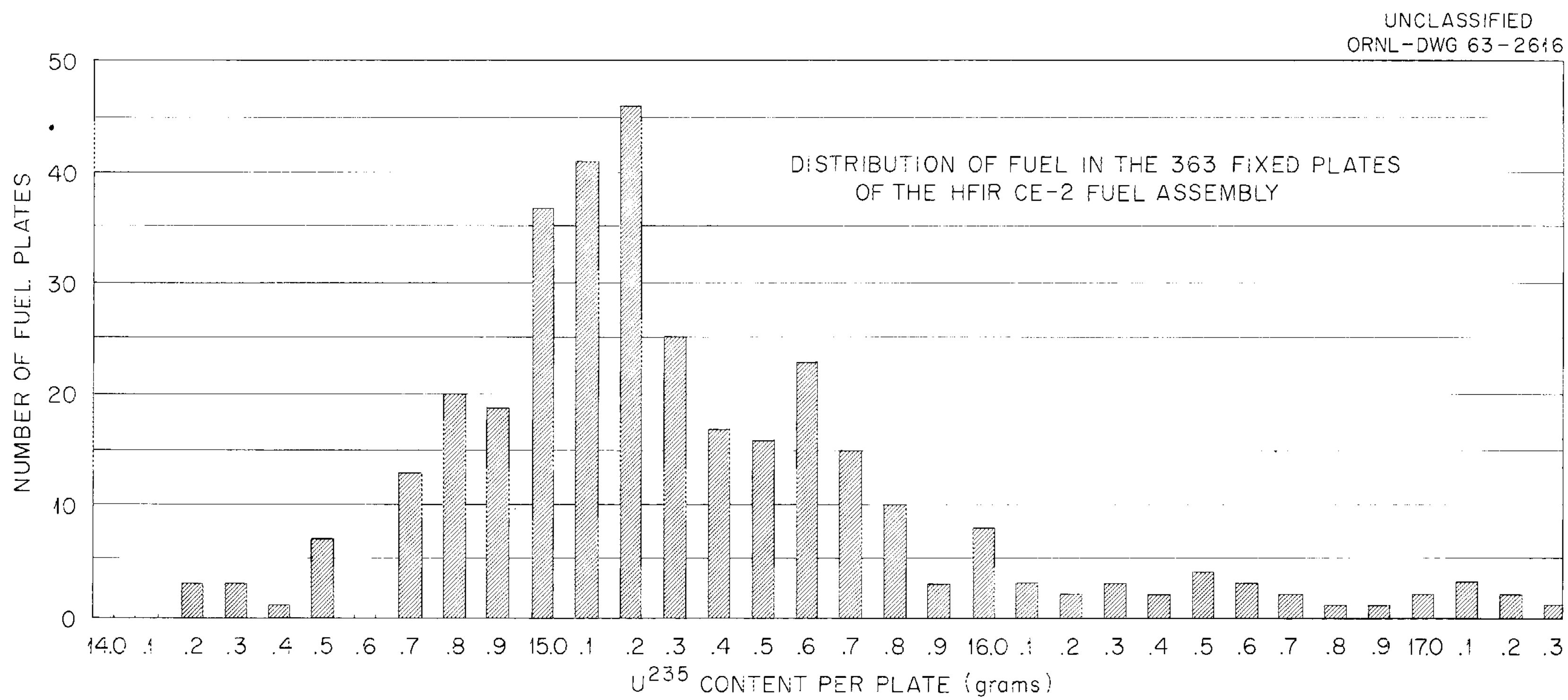

Fig. 8. Distribution of Fuel Contents in Outer-Annulus Plates.

Table 3. Homogeneity in Four Fuel Cores from the Same Melt

Sample	Density (g/cm^3)	Uranium Concentration (wt %)	Difference from the Average Analysis (%)
1 (entire)	3.389	24.96	
1-1	3.390	25.00	+0.16
1-2	3.391	25.02	+0.24
1-3	3.379	24.70	−1.05
3 (entire)	3.392	25.05	
3-1	3.398	25.23	+0.72
3-2	3.392	25.05	0.00
3-3	3.381	24.75	−1.20
11 (entire)	3.332	23.30	
11-1	3.338	23.60	+1.28
11-2	3.315	22.80	−2.15
11-3	3.340	23.55	1.07
13 (entire)	3.334	23.35	
13-1	3.342	23.60	+1.07
13-2	3.320	23.00	−1.50
13-3	3.335	23.40	+0.21

PREPARATION OF THE BORON-BEARING FUEL CORES AND FILLER PIECES FOR THE INNER-ANNULUS PLATES

The fuel cores and filler pieces for the inner-annulus plates contain boron as a burnable poison. The tolerances desired in the control of the boron content per plate and the homogeneity of boron within the plate eliminated the selection of the uranium-aluminum alloy or a boron-aluminum alloy for this application. By choosing a powder-metal-metallurgy process to prepare fuel compacts from U_3O_8, B_4C, and aluminum powders, we realized the advantage that exact quantities of these ingredients could be weighed, blended, and pressed into a fuel compact with maximum assurance that the loading requirements for each fuel plate were met. The fuel and burnable poison content in any specific plate did not depend upon homogeneity of an ingot of these materials as it would in alloy cores. The calculated quantities of U_3O_8 and B_4C for each aluminum-base fuel and filler blank were 17.401 g U_3O_8, 46 mg B_4C for the fuel piece, and 22.4 mg B_4C for the filler piece. Total weights of each part were 66.146 and 34.461 g, respectively. The concentrations were 26 wt % U_3O_8, 0.072 wt % B_4C for the fuel piece, and 0.065 wt % B_4C in the aluminum filler piece.

Because of the health hazards associated with handling finely divided U_3O_8 powder, this compound was weighed into the B_4C-aluminum mixture within a glove box as a last part of the weighing operation. This procedure was not necessary in preparing the filler piece, which otherwise was made in the same manner.

Although each fuel and filler compact was handled as a separate entity during weighing, 24 jars, each containing the proper mixture, were dry blended in one operation for 2 hr on a double oblique blender. Each mixture was then pressed at 30 tsi to form fuel compacts 1 × 2.8 × 0.425 in. The densities of these compacts averaged 95% of theoretical. Because of the health hazards associated with handling the toxic U_3O_8, the compacts were pressed within a glove box.

SHAPING OF CORES AND FILLER PIECES

Previous work in producing tapered uranium-aluminum alloy fuel cores by hot pressing indicated that this was a convenient and economical method for forming nonrectilinear shapes.[13] This method was therefore selected for making the contoured fuel compacts and fillers for both the inner and outer fuel plates. The process was applicable for cylindrical uranium-aluminum slugs, the powder fuel and filler compacts, and the aluminum plate stock used for filler pieces in the outer-annulus plates.

The profile design is shown in Fig. 9. When the two pieces for each plate are matched, they form a rectangular block for insertion into an aluminum picture frame, thus simplifying billet assembly and plate-rolling practice. The designs shown in Fig. 10 are calculated to produce fuel sections in rolled plates with contoured surfaces illustrated in Figs. 2 and 3.

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[13] T. D. Watts and A. L. Lotts, "Aluminum-Matrix Al-U_3O_8-B_4C Pressings with Symmetrical, Straight-Taper Geometry," Metallurgy Div. Ann. Progr. Rept. May 31, 1961, ORNL-3160, pp. 165–66.

The tooling for hot pressing is illustrated in Fig. 10 with a rectangular inner-annulus fuel compact ready to be pressed. The male die is contoured, whereas the female die contains a cavity with a flat bed. The piece to be hot pressed rests on this bed. With this arrangement we pressed the fuel-bearing compacts for both inner- and outer-annulus plates. Tooling design for making the filler pieces was similar except the male die was contoured convex instead of concave.

The dies were designed to produce compacts whose width was calculated to be 8% less than the width of the fuel section in the finished plate. This allowance was made for spread of the fuel section during rolling into the composite plate. For the powder-metallurgy compacts used for the inner-annulus plates the hot-pressing die was made 0.020 in. wider than the width of the cold-pressed compacts.

The dies were preheated to 150°C prior to pressing each batch. Palm oil was applied to the die surfaces before each fuel or filler piece was hot pressed. The fuel cores and fillers were heated for 30 min at 500°C, placed immediately in the die chamber, and pressed at 70 tsi.

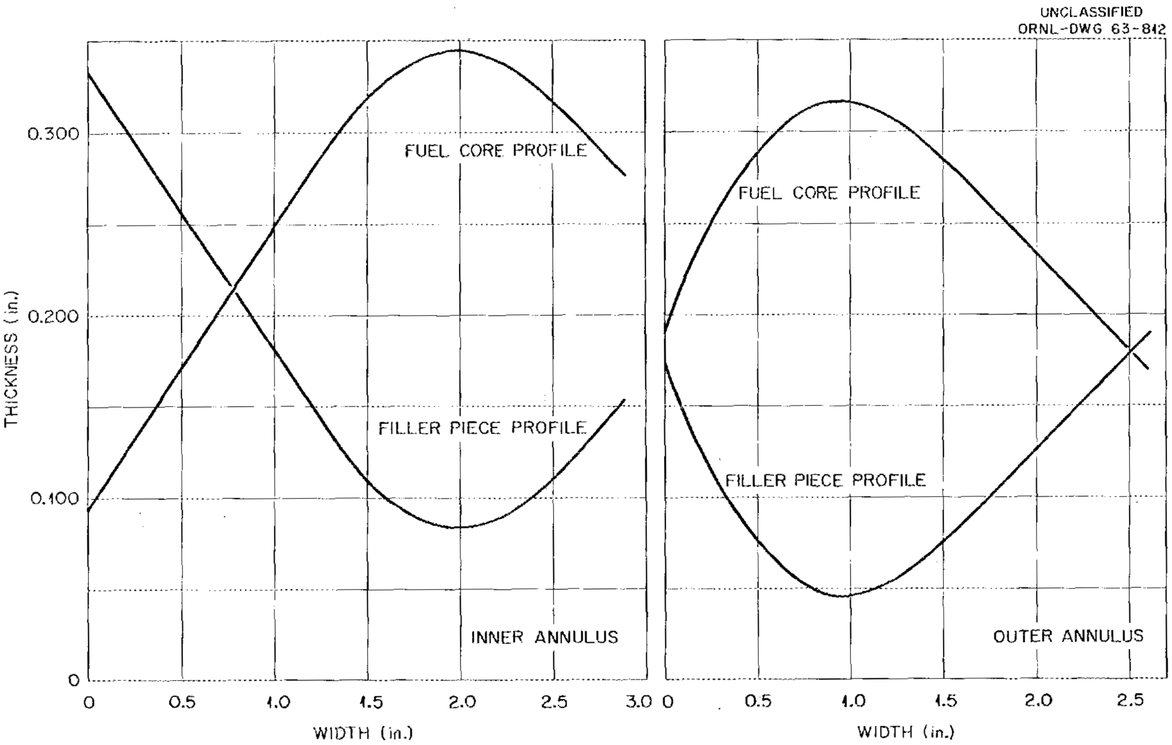

Fig. 9. Die Profiles for Fuel Core and Filler Pieces.

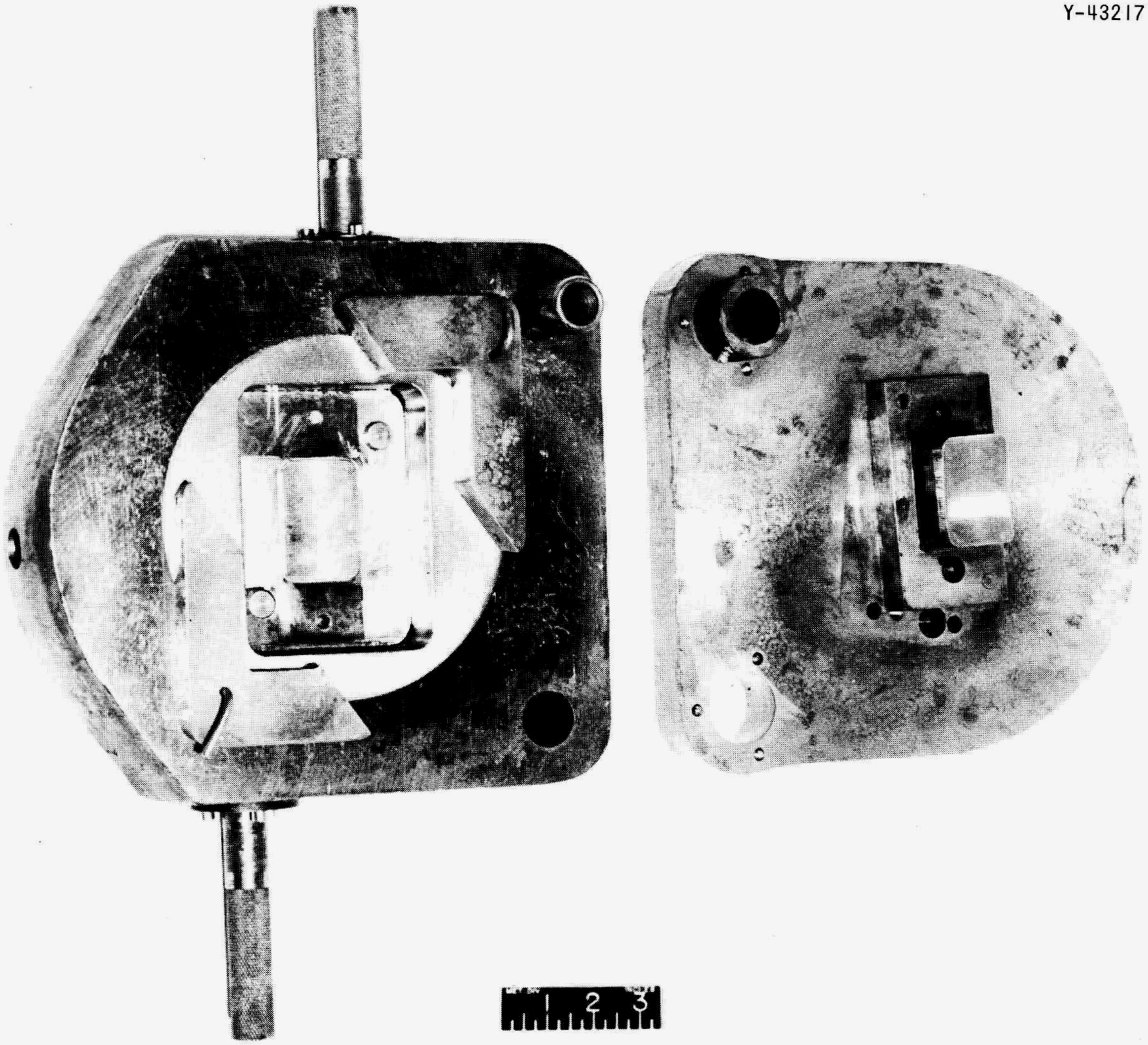

Fig. 10. Die Arrangement for Hot Pressing Compacts.

The burrs produced by hot pressing were removed by hand filing, and the compacts were degreased in trichloroethylene vapor.

Measurements of the profile of the inner-annulus fuel compacts and fillers after hot pressing are listed in Table 4. The data were obtained on four sets of compacts and fillers selected randomly during production. Although the results are limited, they indicate fairly good reproducibility. In nearly all cases, the thickness was slightly greater than specified. Measurements of the fuel compact profile from sections of the rolled fuel plates, shown in Fig. 11, revealed that the compact profile in the finished plate was slightly less than the thickness desired.

Table 4. Profile Measurements[a] of Hot-Pressed Inner-Annulus Parts

Location[b] (in.)	Core Thickness (in.)		Deviation (%)	Filler Thickness (in.)		Deviation (%)
	Design[c]	Production Average		Design	Production Average	
0	0.095			0.333	0.340	+2.1
0.055	0.101	0.104	+3.0	0.327	0.333	+1.8
0.239	0.127	0.129	+1.5	0.301	0.305	+1.3
0.423	0.155	0.157	+1.3	0.273	0.275	+0.7
0.607	0.184	0.187	+1.6	0.244	0.244	0
0.791	0.215	0.219	+1.9	0.213	0.212	−0.5
0.975	0.246	0.252	+2.4	0.182	0.178	−2.2
1.159	0.277	0.284	+2.5	0.151	0.147	−2.6
1.343	0.303	0.310	+2.3	0.125	0.119	−4.8
1.527	0.325	0.328	+0.9	0.103	0.100	−2.9
1.711	0.377	0.338	+0.3	0.091	0.089	−2.2
1.895	0.344	0.344	0	0.084	0.084	0
2.079	0.344	0.343	−0.3	0.084	0.086	+2.4
2.263	0.337	0.355	−0.6	0.091	0.093	+2.2
2.447	0.323	0.322	−0.3	0.105	0.107	+1.9
2.631	0.304	0.304	0	0.124	0.123	−0.8
2.875	0.275	0.297	+1.5	0.153	0.146	−4.6

[a]These data represent four sets of parts measured.

[b]Distance from thinnest edge of core

[c]Design thickness gradient based on percentage of maximum thickness.

Admittedly, these data are somewhat limited, but definite trends exist that are of significance in considering local regions where ^{235}U densities may be found. It is obvious from the concept of radial fuel distribution in the HFIR fuel plates that local fuel content within a plate must be examined in terms of ^{235}U mass per unit plate area. Meeting this type of distribution specification depends not only on the distribution of the uranium in the fuel mixture itself but also on variations in the thickness of the fuel section. Of the four plates examined, thickness reproducibility from one plate to another was generally within 1.5 mils and seems to be relatively independent of core thickness. However, in percentage terms, it can be seen that the thin (7.6 mils) edge of the fuel core was only controllable from one plate to another within

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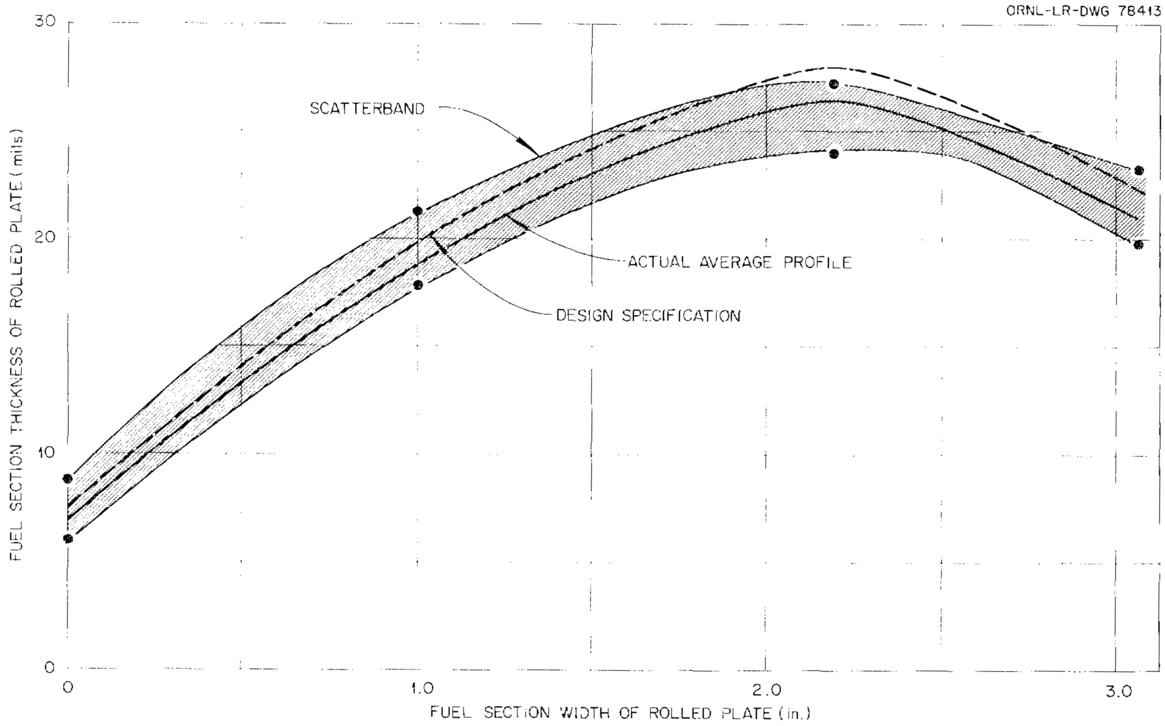

Fig. 11. Comparison Between the Actual and Specified Fuel Contours in Inner-Annulus Fuel Plates.

±8% of the overall average thickness at that location. The thicker portions of the core were generally controllable to within ±3%. Perhaps of even more significance is the comparison of sections of the same plate. Again, control was not nearly as good at the thin edge as in the thicker portions; deviations ranged between 5 and 17%. In the thicker portions, deviation was usually within ±3%, although a few higher values were observed.

Contour measurements of the hot-pressed fuel and filler pieces for the outer-annulus plate are listed in Table 5. The average profile of the fuel sections in three rolled outer-annulus plates selected at random are graphically illustrated in Fig. 12. Like in the inner-annulus plates, the average outer-annulus profile is less than the design specification. Although the data are again limited, the reproducibility from one plate to another appears to be similar to that observed in the inner-annulus plate. Deviations in reproducibility within a plate indicated that control to within ±3% is possible, However, at least one case shows a deviation of ±6%.

Table 5. Profile Measurements[a] of Hot-Pressed Outer-Annulus Parts

Location[b] (in.)	Core Thickness (in.)		Deviation (%)	Filler Thickness (in.)		Deviation (%)
	Design[c]	Production Average		Design	Production Average	
0	0.193	0.204	+5.7	0.170	0.163	−4.1
0.055	0.204	0.214	+4.9	0.159	0.148	−6.9
0.239	0.241	0.252	+4.6	0.122	0.108	−11.5
0.423	0.276	0.284	+2.9	0.087	0.077	−11.5
0.607	0.304	0.305	+0.3	0.059	0.056	−5.1
0.791	0.312	0.315	+1.0	0.051	0.047	−7.8
0.883	0.317	0.317	0	0.046	0.046	0
0.975	0.317	0.316	−0.3	0.046	0.046	0
1.067	0.314	0.315	+0.3	0.049	0.048	−2.0
1.159	0.311	0.312	+0.3	0.052	0.051	−1.9
1.251	0.307	0.307	0	0.056	0.056	0
1.343	0.301	0.302	+0.3	0.062	0.062	0
1.527	0.285	0.287	+0.7	0.078	0.077	−1.3
1.711	0.268	0.271	+1.1	0.095	0.095	0
1.895	0.247	0.252	+2.0	0.116	0.116	0
2.079	0.227	0.231	+1.8	0.136	0.136	0
2.263	0.206	0.211	+2.4	0.157	0.157	0
2.447	0.187	0.191	+2.1	0.176	0.179	+1.7
2.612	0.173	0.181	+4.6	0.190	0.196	+3.2

[a]These data represent ten sets of parts measured.

[b]Distance from thinnest edge of core.

[c]Design thickness gradient based on percentage of maximum thickness.

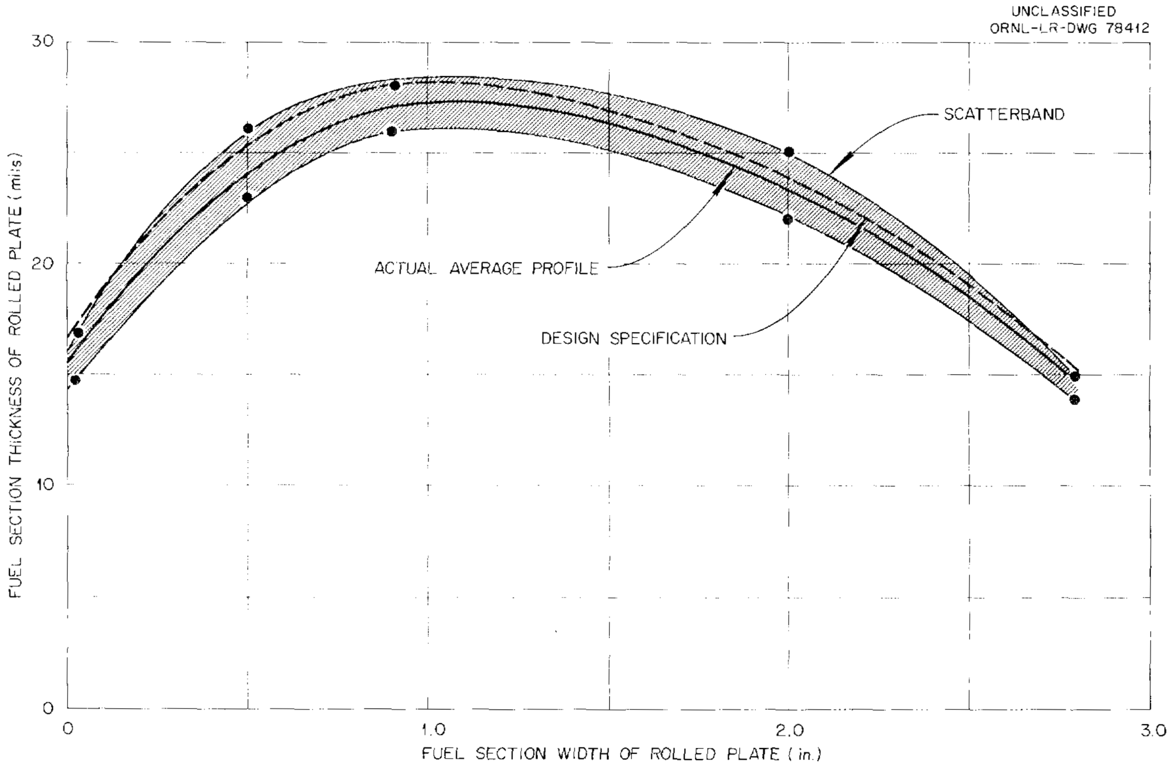

Fig. 12. Comparison Between the Actual and Specified Fuel Contours in the Outer-Annulus Fuel Plate.

ROLLING OF COMPOSITE FUEL PLATES

In previous work,[14] we had found difficulty in obtaining acceptable bonding between mating surfaces of type 6061 aluminum during hot rolling. At that time, we circumvented this problem by using type 6061 clad with a thin layer of type 1100 aluminum, which allowed us to prepare the plates so that the mating surfaces to be bonded were type 1100 aluminum. For expediency and since unbonded regions between fuel and cladding were acceptable for this critical test element, we decided to proceed with hot-roll bonding between surfaces of 6061 aluminum directly. Prior to production of plates, we heated electropolished type 6061 aluminum surfaces in air at temperatures ranging from 400 to 550°C to observe the character of the oxidation product that was formed. From these tests we

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[14]W. C. Thurber and R. J. Beaver, Development of Silicon-Modified 48 wt % U-Al Alloys for Aluminum Plate-Type Fuel Elements, ORNL-2602 (Mar. 9, 1959).

hoped to select a rolling temperature at which the oxide was not the loose porous variety that is detrimental to metallurgical bonding. The results are illustrated pictorially in Fig. 13. The oxide formed appears to change from adherent at 500°C to a loose blistering type at 515°C. Although we would have preferred to preheat and reheat our plates at 500 ± 5°C, we questioned controlling our furnace temperature that precisely, and therefore selected 450°C as the preheat and reheat temperature for rolling fuel plates for the critical test assembly.

Billet designs for the inner- and outer-annulus plates are shown in Figs. 14 and 15, respectively. In the assembly process, the frame is heated to 450°C, and the core pieces are placed in the cavity, thus achieving a tight fit. The cover plates are attached by welding. As shown, the corners are left unwelded to permit air in the billet to escape when the billet is passed through the rolls.

In the case of the outer-annulus plate (which contained the alloy fuel core), the framed section was prerolled through a two-high 20 × 30-in. mill in air at 450°C to 50% of its original thickness. The surfaces (including the fuel and filler portions) were cleaned with a stainless steel brush under an exhaust hood prior to attachment of the cover plates. The inner-annulus plate (which contained the powder-metallurgy-prepared core) was not prerolled. After the cover plates were fitted to the framed fuel and filler cores, both inner and outer billets were preheated in air for 1 hr at 450°C. They were then rolled through a two-high 12- × 14-in. mill with 5-min reheating at 450°C between successive mill passes. Reduction in thickness per pass was 25%. Total hot reduction was 92% for the inner-annulus plate and 82% for the outer-annulus plate. After annealing in air for 1 hr at 500°C (principally to determine whether any blisters would form), the plates were reduced 6% in thickness at room temperature through the same mill. Reduction per pass during this operation was limited to 1%.

Photomicrographs of transverse cross sections of finished inner- and outer-annulus composite plates are included in Figs. 16 and 17, respectively. The microstructure and dimensions are typical of the fuel sections in these plates. Although smaller and larger particles can be seen in the inner-annulus fuel section, the U_3O_8 particle-size distribution

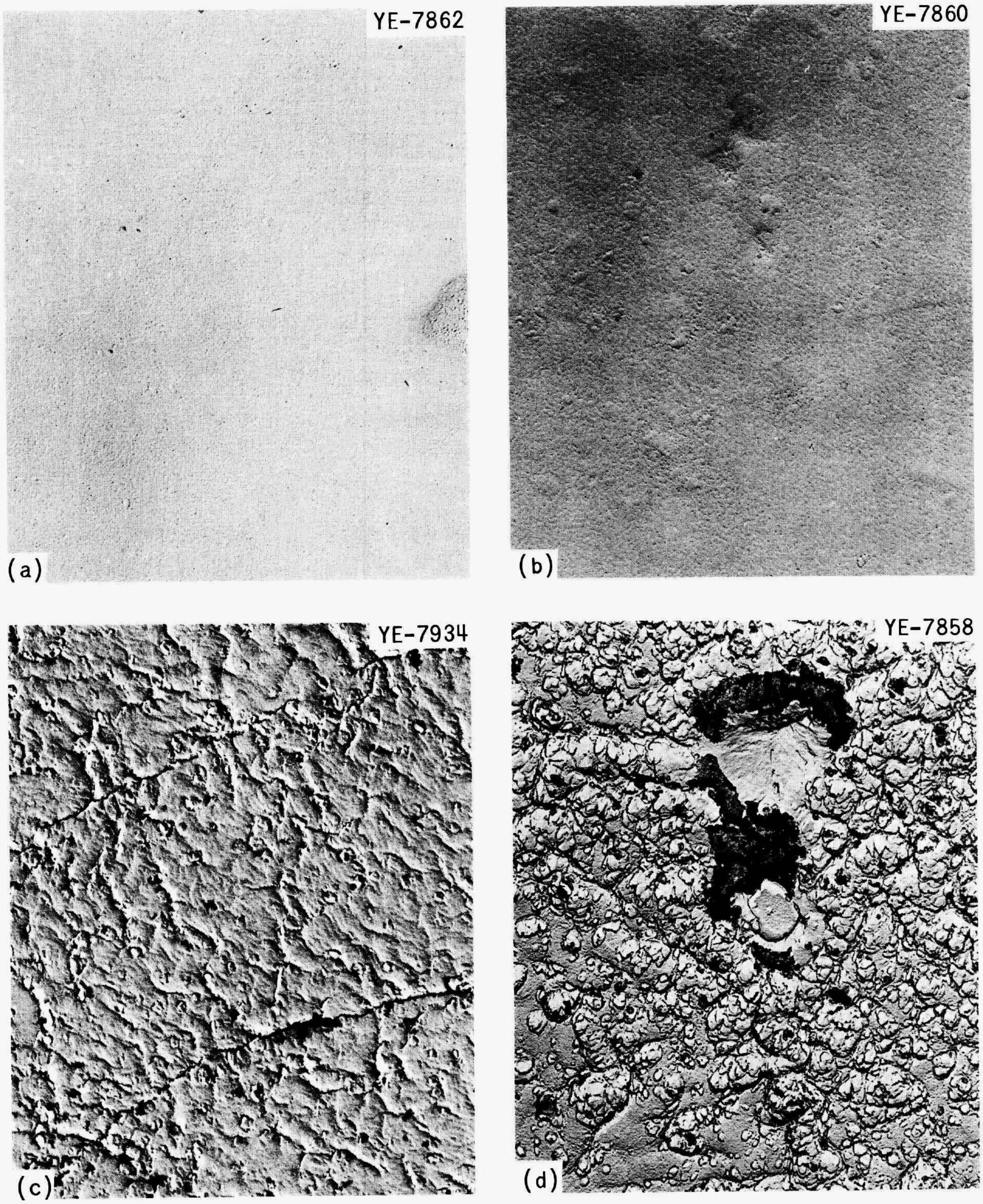

Fig. 13. Electron Micrographs Showing Appearance of Oxide on Surface of Type 6061 Aluminum After Electropolishing and Heating 1 hr in Air. 10,000×. (a) As electropolished. (b) Heated at 500°C. (c) Heated at 515°C. (d) Heated at 550°C.

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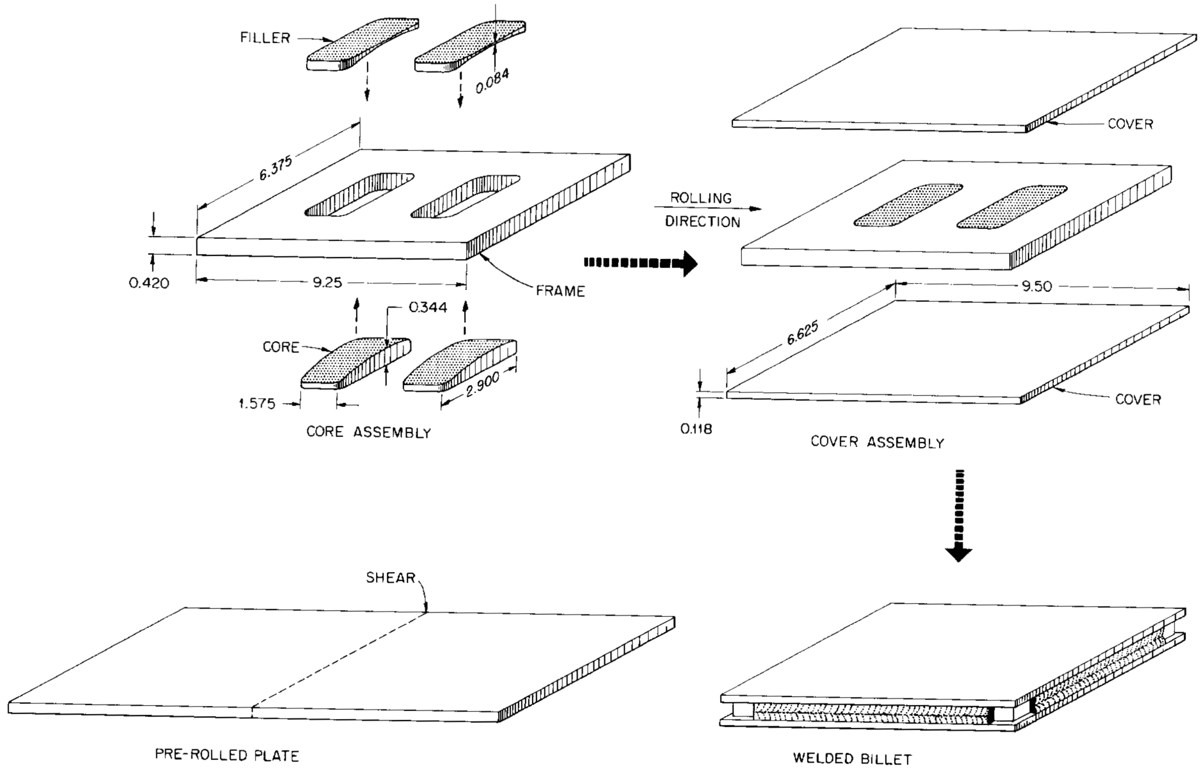

Fig. 14. Inner-Annulus Fuel-Plate Billet.

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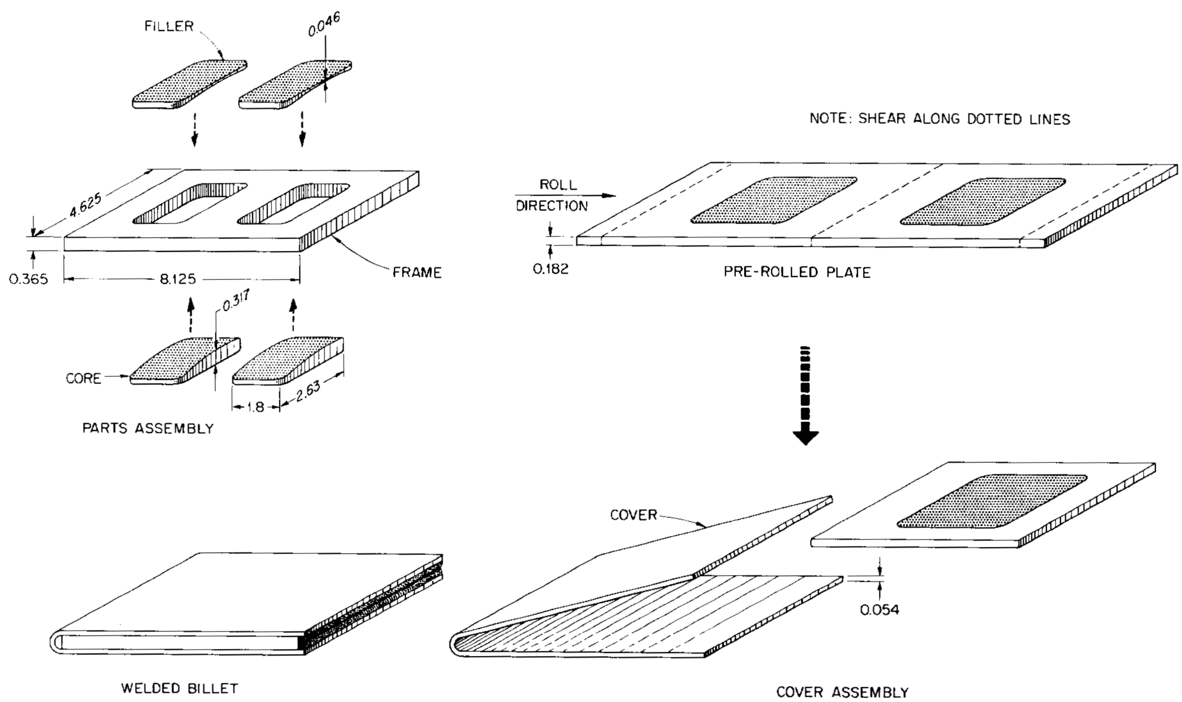


Fig. 15. Outer-Annulus Fuel-Plate Billet.

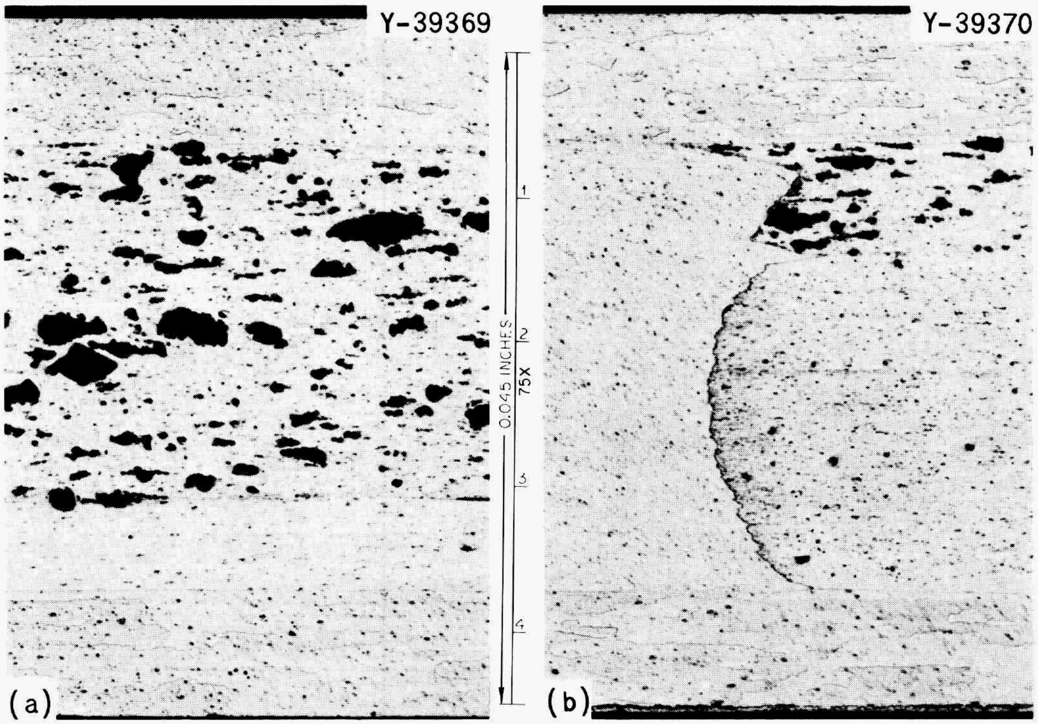


Fig. 16. Transverse Cross Sections of Inner-Annulus Plates of the Type Prepared for Critical Experiment No. 2. Etchant: 1 part concd $HClO_4$, 15 parts alcohol. (a) Thin filler section and near-maximum fuel section 0.027 in. thick. (b) Edge of filler section and 0.008-in.-thick fuel section near end of fuel.

range from 30 to 105 μ predominates. The spheroids in the filler section should not be mistaken for inclusions. These were identified as voids and are likely sites of gas accumulation. In the outer-annulus plate, nearly all of the uranium-aluminum intermetallic particles are less than 44 μ.

During the blister anneal at 500°C, most of the plates blistered. We will discuss this phenomenon subsequently. We believe, however, in those instances where gas accumulation did not interfere, that the 6061 aluminum cladding was soundly bonded to the frame, fuel core, and filler piece. The bonding between the cladding and the frame is shown at high magnification in Fig. 18. Although some demarcation at the bond line is visible, such appearance is not uncommon in bonded and etched specimens of aluminum. The bond could not be peeled by twisting or chiseling, which is good evidence of its integrity. In blister-free areas of plates, the bonding between the type 6061 aluminum and Al—24% U-alloy or the Al–26% U_3O_8–B_4C fuel section was acceptable. The occurrence of blisters during the 500°C blister test was not unexpected, because it is not an unusual phenomenon when a new kind of aluminum-base fuel plate is being developed. Certainly, these HFIR plates with their two-piece contoured cores fit this category. The blisters appeared to be related to the entrapment of gases. We postulate that during heating of the plate at 500°C the gas expanded, creating sufficient pressure locally on the thin cladding to create blisters. We categorized the blisters as

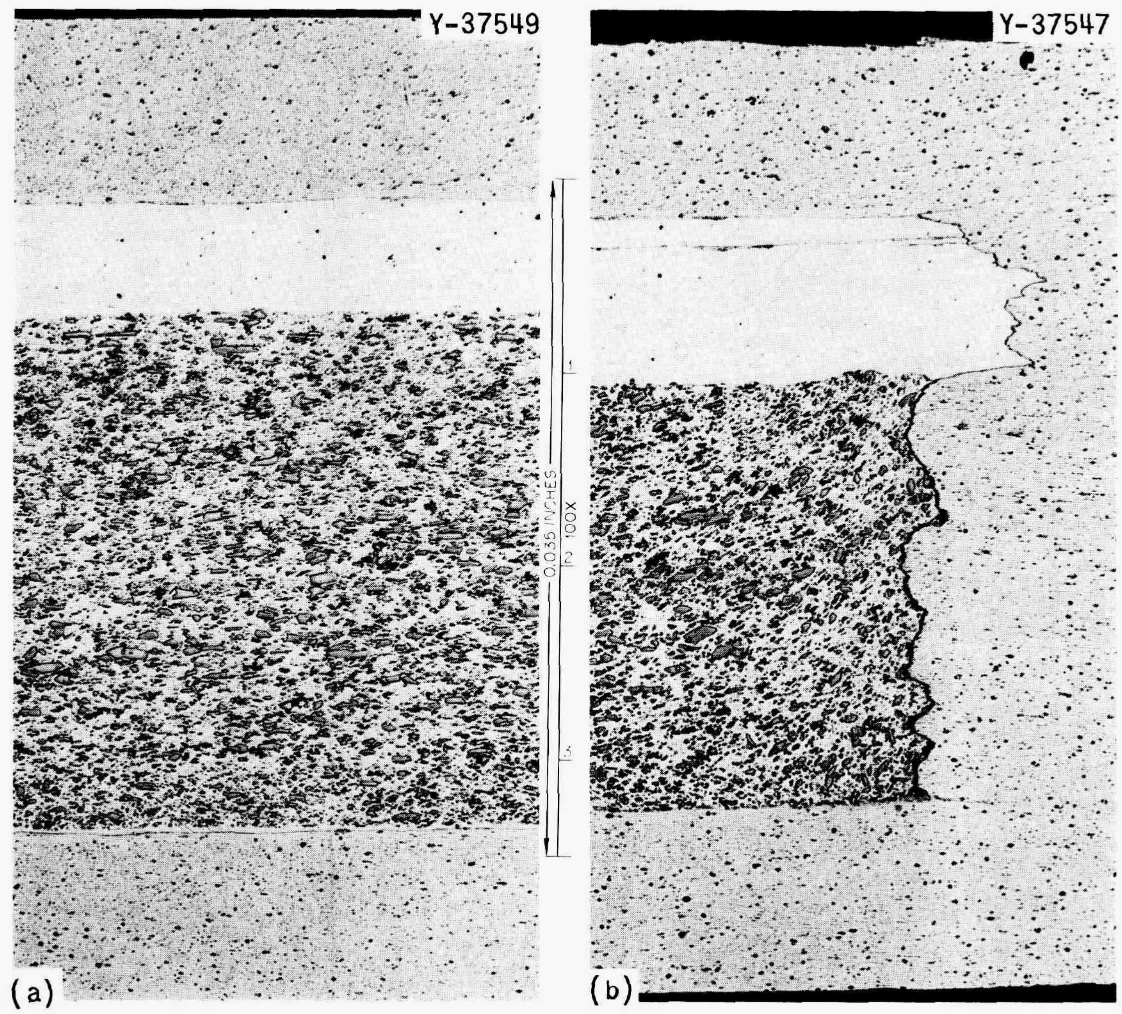


Fig. 17. Transverse Cross Sections of Outer-Annulus Plates of the Type Prepared for Critical Experiment No. 2. Etchant: 1 part concd $HClO_4$, 15 parts alcohol. (a) Thin filler section and 0.028-in.-thick maximum of fuel section. (b) Edge of filler and fuel sections; fuel 0.020 in. thick.

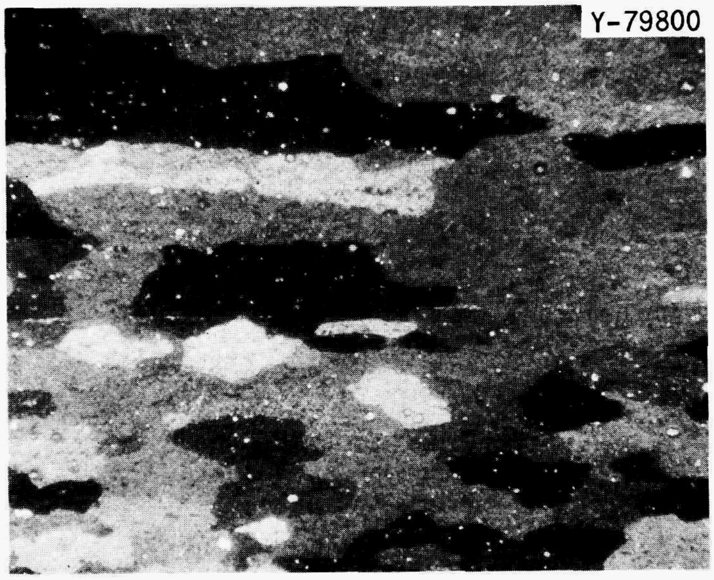


Fig. 18. Bonding at Interface Between 6061 Aluminum Alloy Cladding and Frame Sections after 82% Reduction in Thickness.

(1) fit blisters (those associated with interstices between the fuel and filler section and the frame), (2) interfacial blisters (those between the cladding and the fuel or filler sections), and (3) internal blisters (those within the cladding, the fuel core, or the filler section).

Most blisters in the outer-annulus plates were fit blisters. These are illustrated in Fig. 19. At least two effects were responsible for such blistering. The first is associated with the fit of the core sections in the frame. The general practice of prerolling the framed uranium-aluminum alloy core prior to cladding is conventional and designed to improve fit between core and frame, thus eliminating interfaces where gaseous species may be trapped. Unfortunately, in most cases prerolling did not accomplish this objective. Fig. 20 illustrates a prerolled component; the sites for potential gas entrapment are obvious.

Fit blisters in the outer-annulus plates were nearly always close to the ends or at the edges of the fuel section. Seldom were they found at the interface between the cladding and the fuel section. Figure 21 illustrates the unbonded interfaces between the edge of the core and frame in the rolled plate. This was caused by a cushion of air in the corners of the welded billet prior to rolling and prevented bonding between the core edges and the frame at these locations. The entrapped

Fig. 19. Surface of Outer-Annulus Fuel Plate Showing Typical Fit Blisters Near End of Fuel Section.

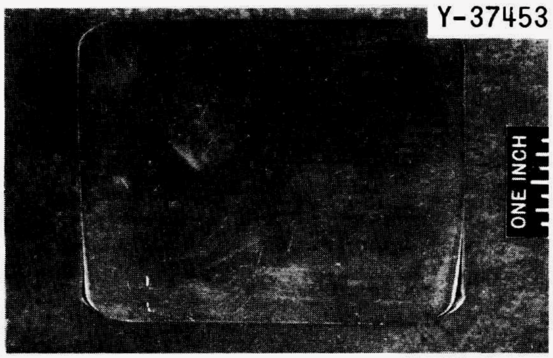


Fig. 20. Poor Fit Between Alloy Fuel Core and Type 6061 Aluminum Frame After Prerolling at 450°C to a Total Reduction in Thickness of 50%.

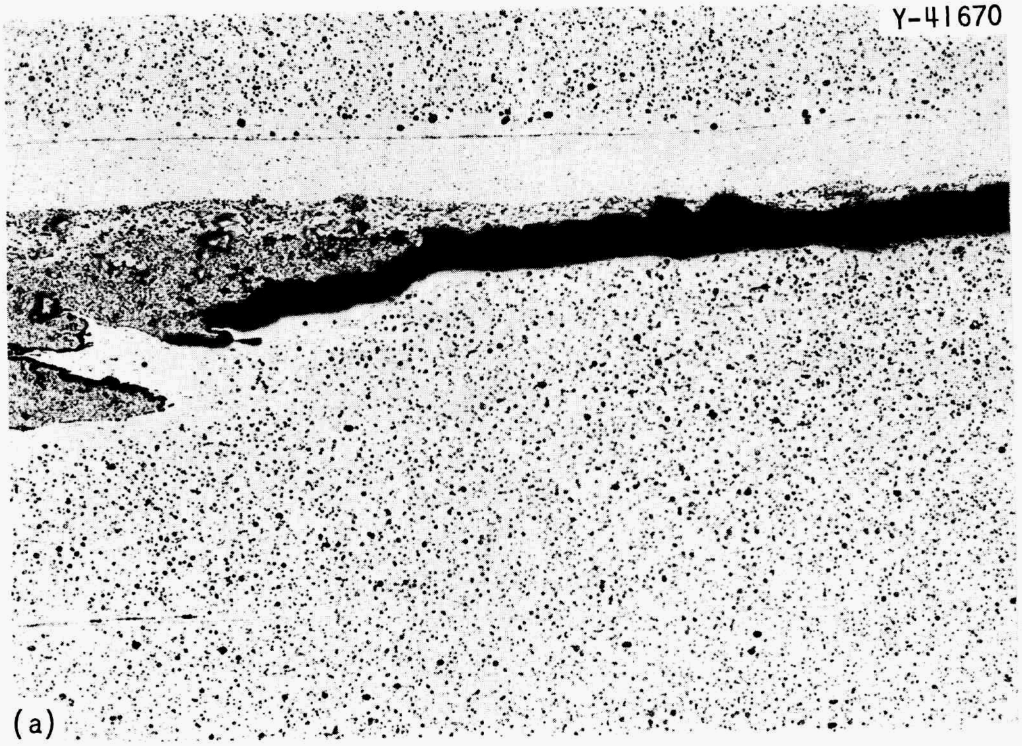
Cladding

Filler

Alloy Fuel

Frame

Cladding



Cladding

Alloy Fuel

Filler

Cladding

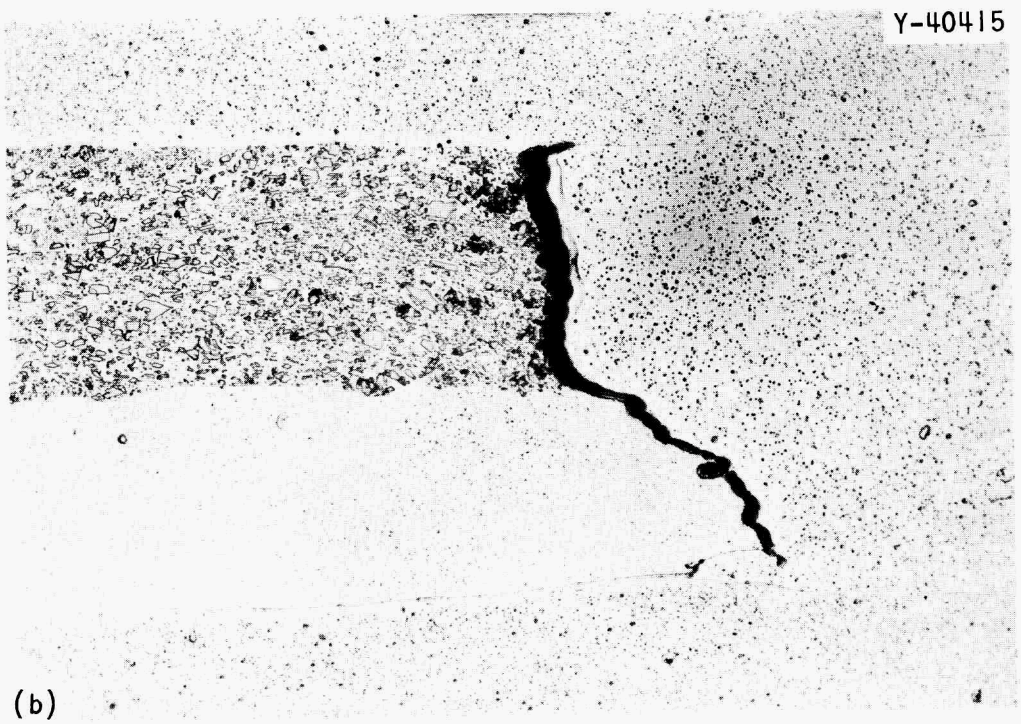


Fig. 21. Fit Blisters in Outer-Annulus Fuel Plates. Etchant: 1 part concd perchloric acid to 15 parts alcohol. (a) Longitudinal section showing blisters at end of fuel section. (b) Transverse section showing blisters at edge of fuel section. 75×.

air not only prevented bonding but also expanded during the 500°C annealing, creating localized stresses sufficiently high to cause local blistering. Although the cases cited represent the worst events, it is doubtful if those plates without visible fit blisters were truly metallurgically bonded at the ends and edges of the fuel section. In fact, random inspection of the bonding of several of the outer-annulus plates by ultrasonic through-transmission techniques indicated lack of bonding at the ends and at the edges.

In the inner-annulus plates, massive blistering occurred on the surface of the rolled plates, particularly after annealing for 1 hr at 500°C. The population of these blisters is dramatically shown in Fig. 22. Examination of the blistered regions indicated that rupturing was most prevalent at the interface between the type 6061 wrought cladding and either the powder metallurgically prepared filler piece or the fuel core, the effect is portrayed in Fig. 23. The numerous cracks in the wrought cladding are rather startling. It is also worth noting that they are associated with the region in the cladding adjacent to the fuel core or filler piece.

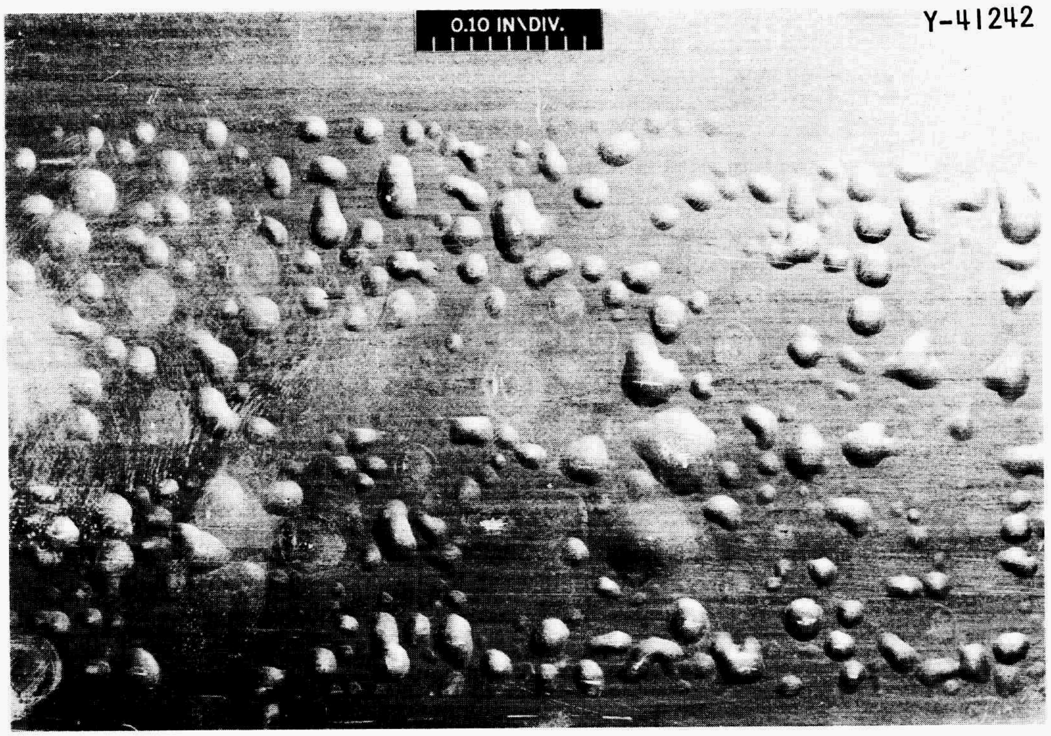


Fig. 22. Blisters on Surfaces of Inner-Annulus Fuel Plate Rolled at 450°C and Annealed 1 hr at 500°C.

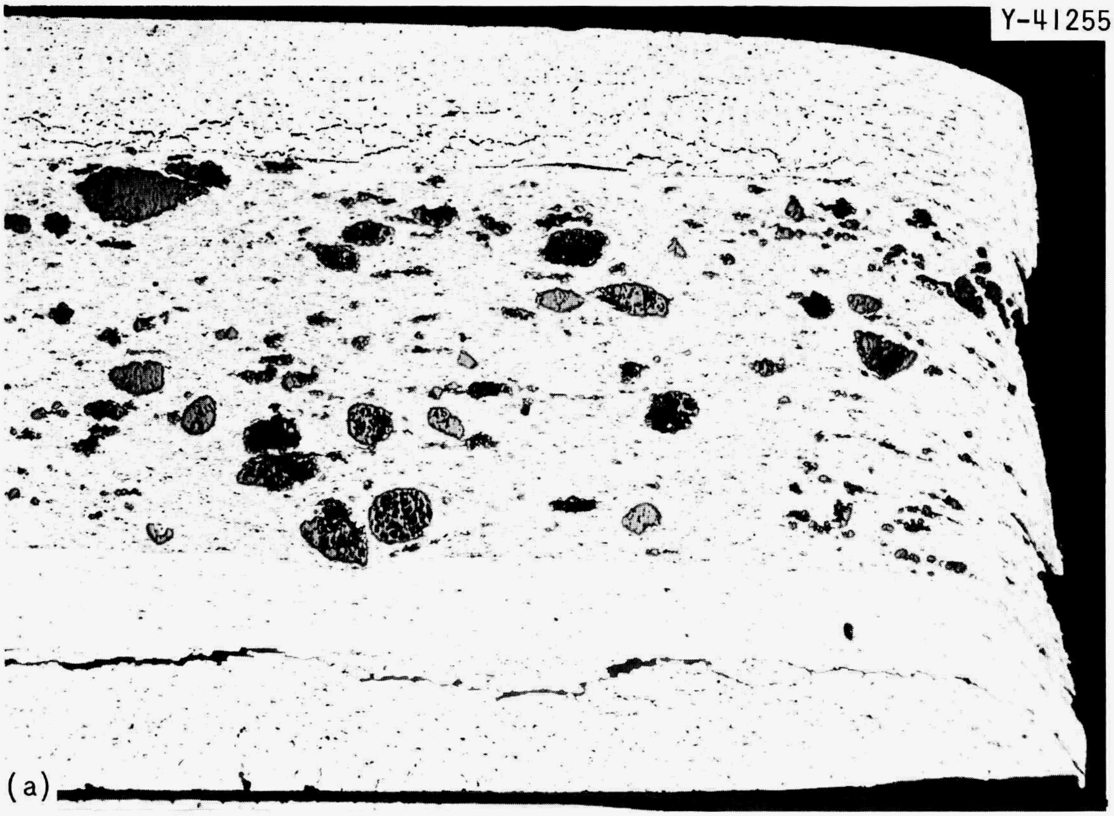


Fig. 23. Ruptures in Cladding of Inner-Annulus Plates. Etchant: 0.5% HF. (a) 75×. (b) 500×.

FLATTENING PLATES

We felt that for careful positioning in the forming die the rolled plates should be reasonably flat. We used a Stanat roller leveler to flatten the plates. The plates were annealed for 1 hr at 500°C and then passed through the roller leveler several times with the rolls as tight as possible. This annealing—roller-leveling operation was repeated if necessary. No quantitative measurement of the degree of flatness was taken; the only requirement was that most of the surface lay flat on a surface plate.

MARKING AND SHEARING PLATES

Previous illustrations show that two features of the HFIR fuel plates help identify an inner plate from an outer plate and that also aid in correct orientation in the fuel element. First, only one surface of the fuel section is contoured and underlies the filler piece, which is sandwiched between the type 6061 aluminum cladding and the fuel section. The opposite surface of the fuel section underlies the cladding. Secondly, the location of the thickest portion of the fuel section differs significantly in the inner- and outer-annulus plates. Our Nondestructive Testing Group developed an eddy-current method to locate the thickest portion of the core and the side of the plate covering the contoured surface of the fuel core.[15] Thus we were able to properly orient the plates. Since subsequent forming required knowledge of the core orientation and the location of the core hump, we established a marking system. A letter "C" was imprinted in indelible crayon on the cladding surface closest to the curved side of the fuel core at the position of the maximum fuel thickness. A letter "A" was then scribed at one end of the fuel plate 1/2 in. outside the edge of the fuel on an extension of the line of maximum core thickness. Although the crayon mark was subsequently dissolved, the scribed "A" identification was never removed. The edge of the plate

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[15] R. W. McClung, Development of Nondestructive Testing Techniques for the High Flux Isotope Reactor Fuel Element, ORNL-3780 (April 1965).

that was to be attached to the inner side plate of the fuel element was the farthest edge from the identifying mark. We marked the outer-annulus plate similarly.

The length and width of the fuel section were located fluoroscopically with a template. The template for the inner-annulus plate is illustrated in Fig. 24. Except for dimensions, the template for the

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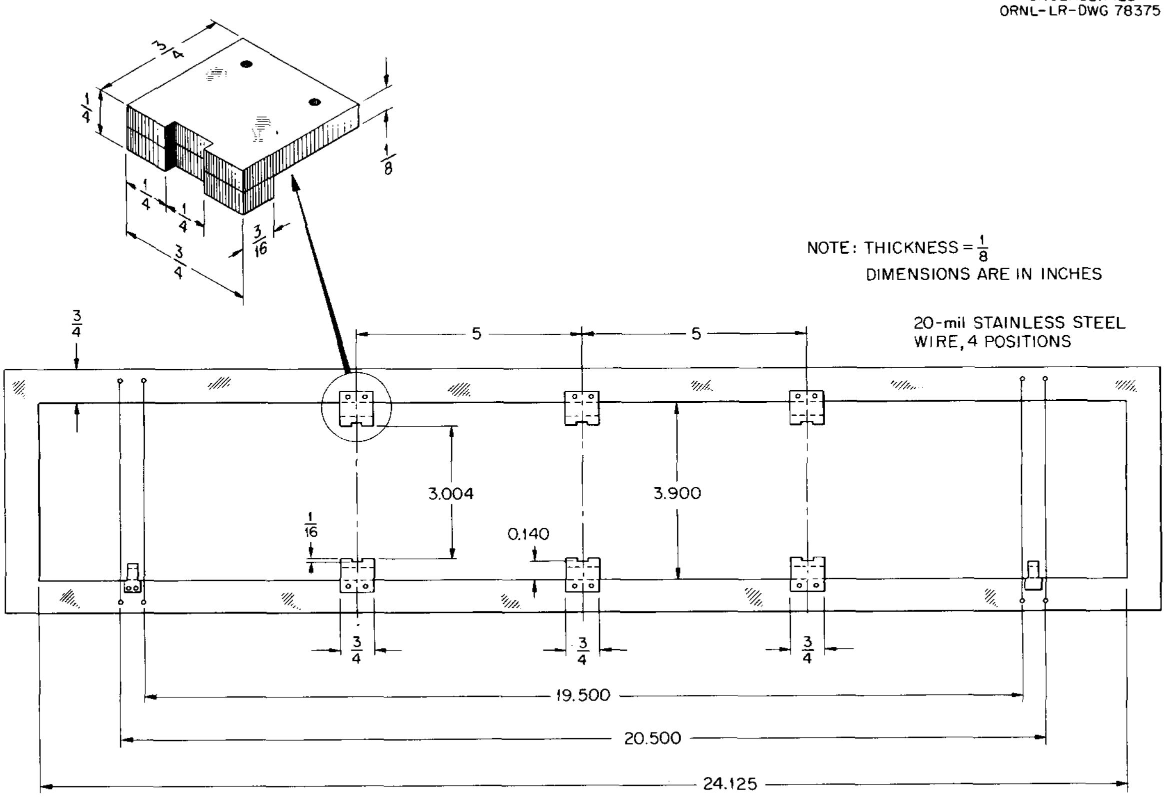

Fig. 24. Template used for Locating Position of Inner-Annulus Fuel Section During Fluoroscopic Inspection for Dimensions.

outer-annulus plate was identical. Since the width of the fuel section of the plate is offset from the longitudinal center line, it is important to locate the inner edge of the fuel section and at the same time determine that the width and length of the fuel section meet the dimensional specifications. Having already determined the orientation of the fuel section, the plate is readily oriented properly with respect to the template. The nominal width of the unfueled aluminum edge closest to the inner side plate of the element is 0.140 in., and the template allows 0.190 in. for the sheared plate with 0.050 in. excess for subsequent machining. The dimensional specifications actually permit this width of aluminum to be as much as 0.202 in., but at the same time, the desired width of the fuel section was 3.068 ± 0.062 in. The template was designed to inspect for these tolerances. Likewise, the length of the fuel section was to be held to 20 ± 1/2 in. The wires on the template form a gage for this inspection.

After location of the fuel section, scribe marks were made for shearing the plate to a width and length of 3.900 and 24.125 in., respectively. The sheared plates were stacked in batches of 36 and the excess stock was uniformly machined from all sides, that is, 0.50 in. from each side and 0.0625 in. from each end.

Each plate was deburred by hand filing and degreased in trichloroethylene vapor. The plates were then radiographed to verify that the width of the aluminum edging was within specifications. The widths and lengths of the fuel sections in 80 inner-annulus and 244 outer-annulus plates were measured from these radiographs. The widths of each type of plate were characterized by a "barreling effect," in which the width at the transverse center line was at a maximum and the width at the ends of the fuel section at a minimum. Data were collected at the transverse center line and at 9 in. on each side of it. The distribution of the measurements for the inner-annulus plate is shown in Fig. 25. The width at the transverse center line varied from 3.016 to 3.096 in., with the greatest population between 3.064 and 3.080 in. At 9 in. from each side of the center line the width had decreased to a range of 2.780 to 2.952 in., with the greatest population between 2.826 and 2.872 in. Generally the width 9 in. from the center line was about 1/4 in. less than at the center line. Although in all cases the width at the center line met the desired specification, it was out of tolerance near the ends.

The desired width of the core section in the outer-annulus plates was 2.778 ± 0.062 in. As shown in Fig. 26, the width at the center line ranged between 2.734 and 2.794 in., with most values grouped between 2.750 and 2.778 in. At 9 in. on each side of the center line the widths

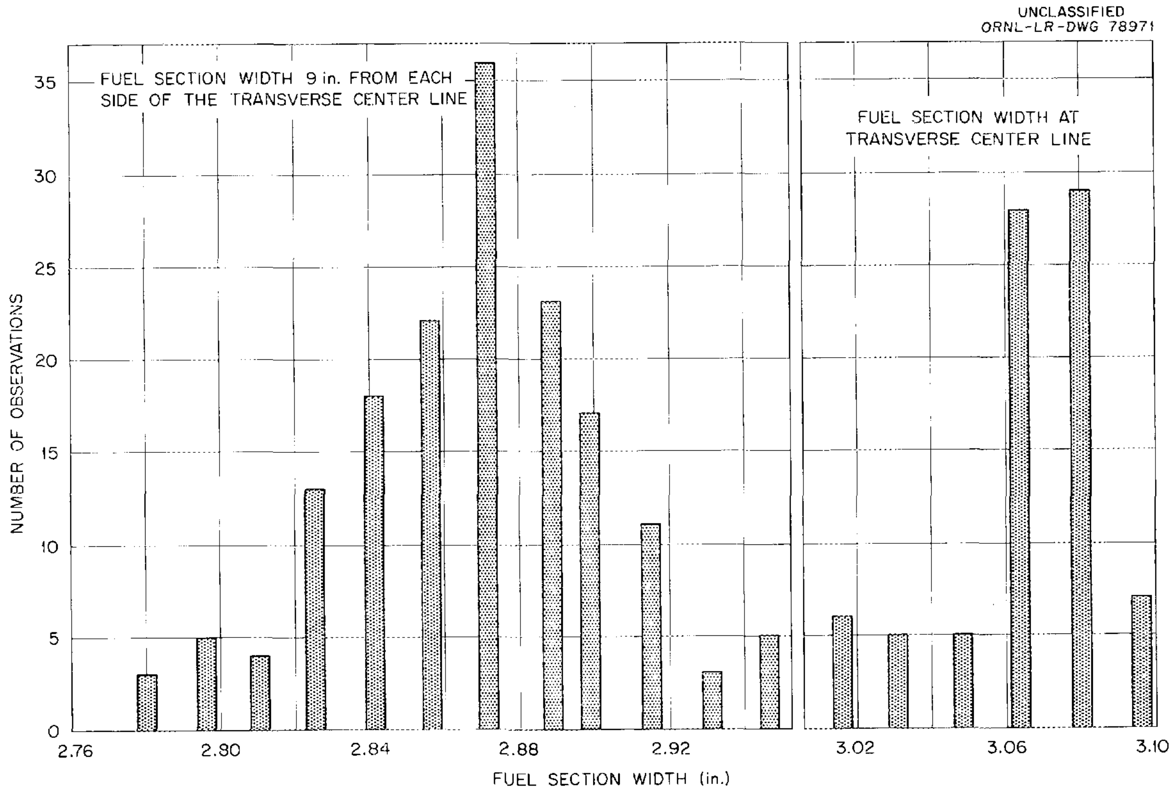

Fig. 25. Distribution of Fuel-Section Widths in Inner-Annulus Plates Rolled for the Critical Test Assembly.

were less and ranged between 2.140 and 2.656 in. Generally the fuel section width there was about 1/4 in. less than at the center line, the same as for the inner annulus. Again, although the width met the desired specification at the center line, it was out of tolerance near the ends of the fuel section.

The desired length of fuel section in plates for both annuli was 20 ± 1/2 in. The distributions of the fuel-section lengths in both types of plates are shown in Fig. 27. A normal distribution appears to exist for the outer-annulus plate, with the greatest population ranging between 19 7/8 and 20 1/8 in. On the other hand, the inner-annulus data showed a skewed distribution. Most of the lengths are greater than 20 in. and range between 20 and 20 1/4 in. In any event, the fuel-section lengths in all cases measured for both inner and outer plates met the desired specification.

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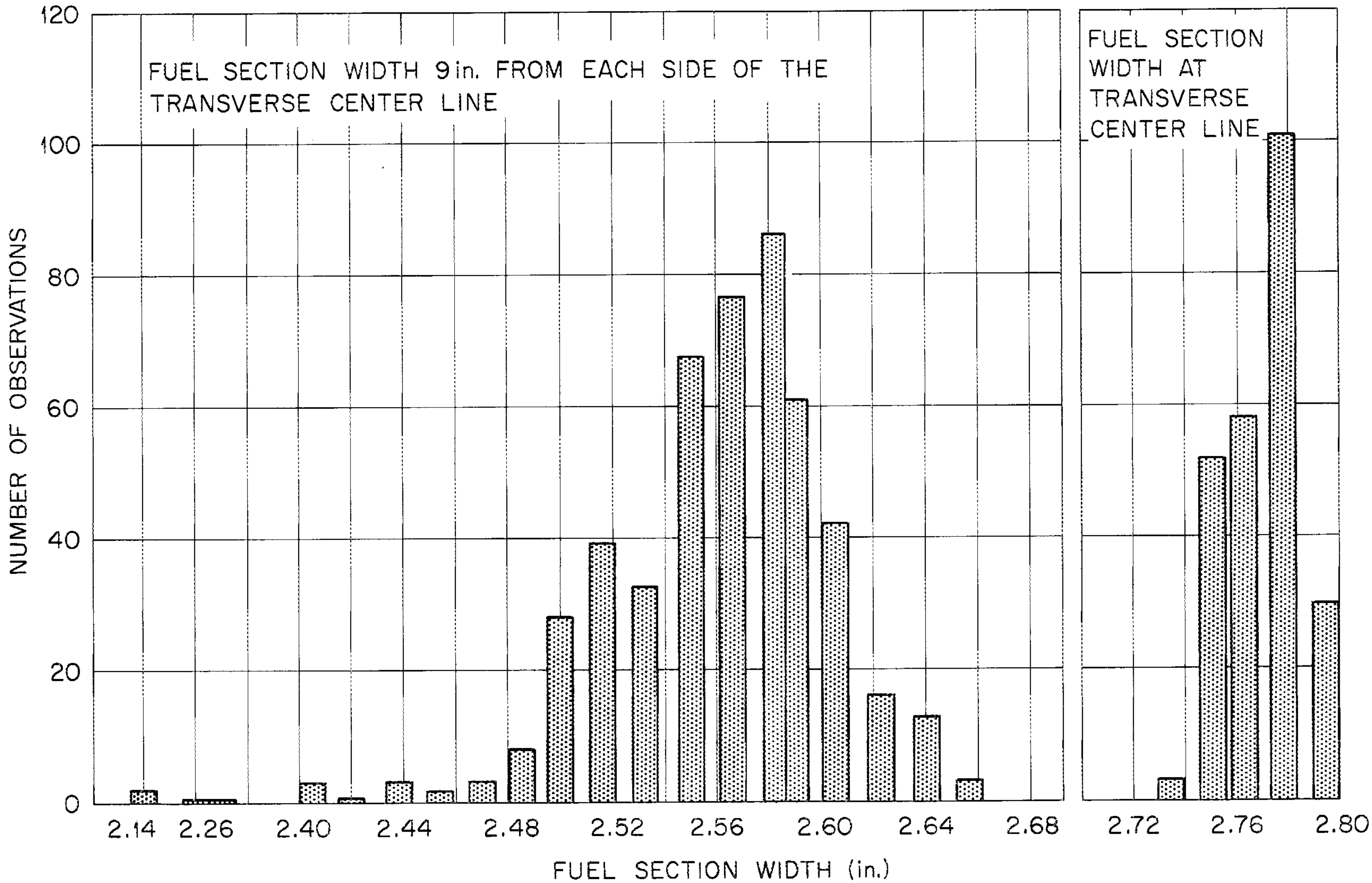

Fig. 26. Distribution of Fuel-Section Widths in Outer-Annulus Plates Rolled for the Critical Test Assembly.

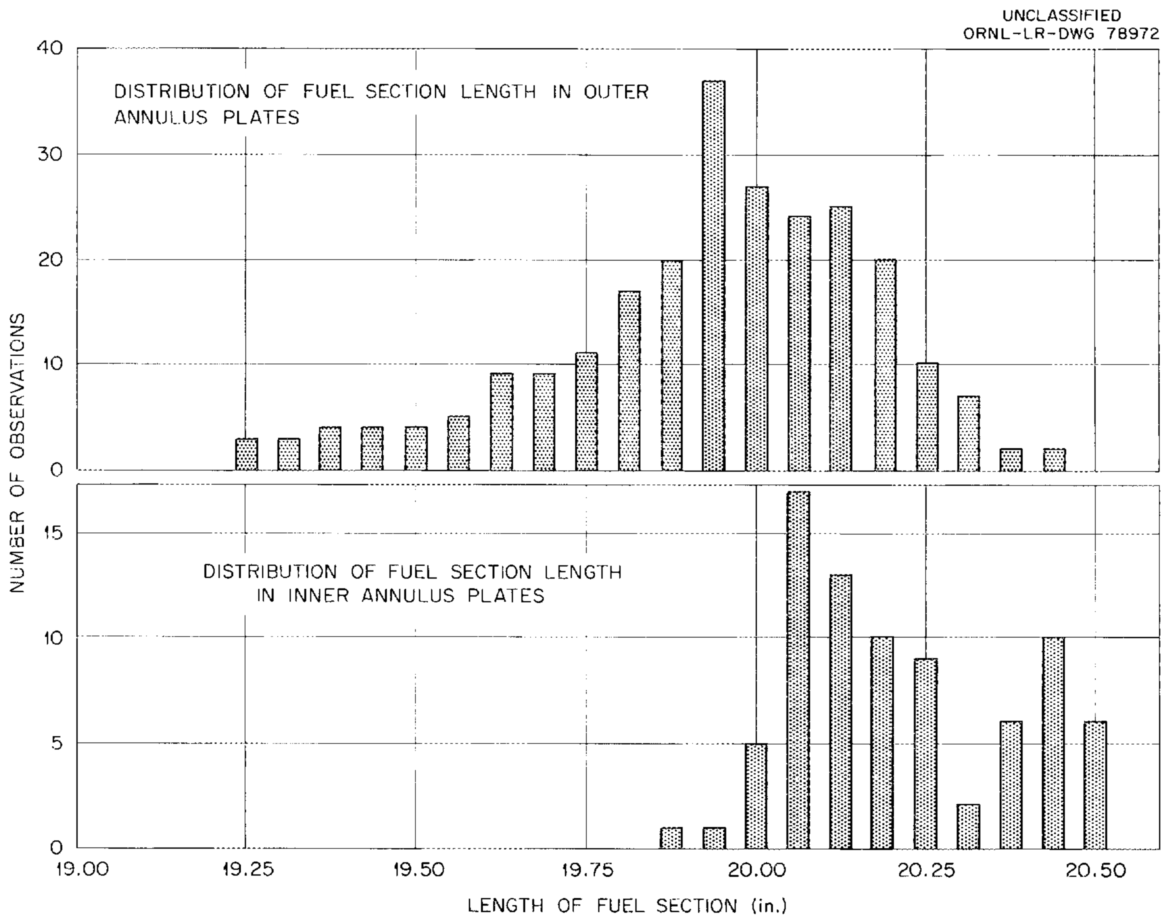

Fig. 27. Distribution of Fuel-Section Length in Plates Rolled for the Critical Test Element.

FORMING PLATES INTO INVOLUTES

The specified involute shapes for both inner and outer plates are shown in detail in Figs. 28 and 29. The "lip" at the outer edge of the plate is a unique feature of the type of plate for this assembly design. Previous work had shown that low pressure marforming produced acceptable results on unfueled type 6061-O plate.[16] Although only meager results had been obtained on fuel plates, it was generally agreed that the process would result in fuel plates formed well enough to satisfy the requirements for a critical test assembly.

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[16] J. H. Erwin, W. J. Kucera, D. T. Bourgette, and R. J. Beaver, "Development of an Aluminum-Base Fuel Element for the High Flux Isotope Reactor," Metallurgy Div. Ann. Progr. Rept. July 1, 1960, ORNL-2988, pp. 289–97.

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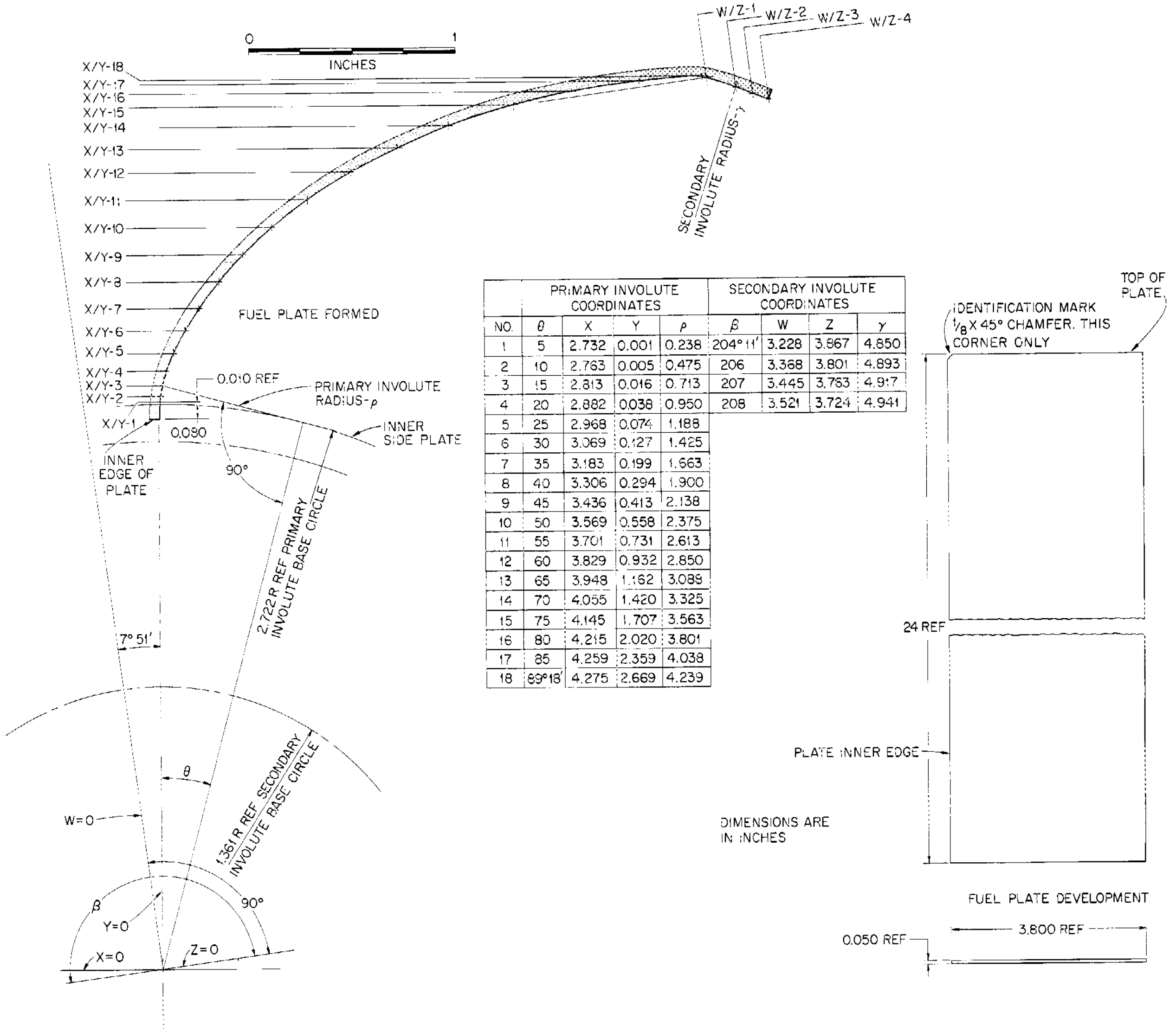

	PRIMARY INVOLUTE COORDINATES				SECONDARY INVOLUTE COORDINATES			
NO.	θ	X	Y	ρ	β	W	Z	γ
1	5	2.732	0.001	0.238	204° 11′	3.228	3.867	4.850
2	10	2.763	0.005	0.475	206	3.368	3.801	4.893
3	15	2.813	0.016	0.713	207	3.445	3.763	4.917
4	20	2.882	0.038	0.950	208	3.521	3.724	4.941
5	25	2.968	0.074	1.188				
6	30	3.069	0.127	1.425				
7	35	3.183	0.199	1.663				
8	40	3.306	0.294	1.900				
9	45	3.436	0.413	2.138				
10	50	3.569	0.558	2.375				
11	55	3.701	0.731	2.613				
12	60	3.829	0.932	2.850				
13	65	3.948	1.162	3.088				
14	70	4.055	1.420	3.325				
15	75	4.145	1.707	3.563				
16	80	4.215	2.020	3.801				
17	85	4.259	2.359	4.038				
18	89°18′	4.275	2.669	4.239				

Fig. 28. Inner-Annulus Fuel Plate.

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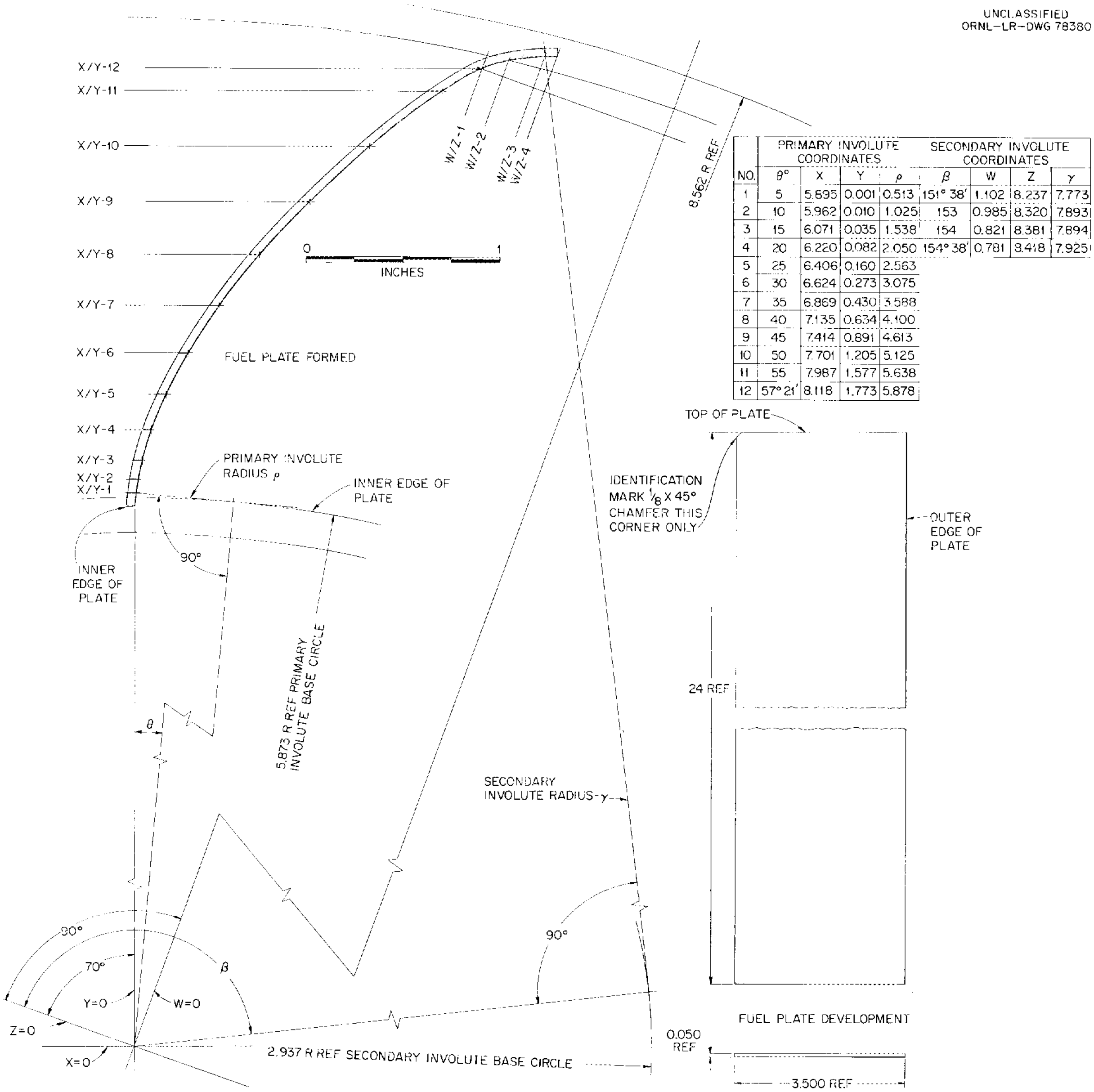

NO.	PRIMARY INVOLUTE COORDINATES				SECONDARY INVOLUTE COORDINATES			
	θ°	X	Y	ρ	β	W	Z	γ
1	5	5.695	0.001	0.513	151° 38′	1.102	8.237	7.773
2	10	5.962	0.010	1.025	153	0.985	8.320	7.893
3	15	6.071	0.035	1.538	154	0.821	8.381	7.894
4	20	6.220	0.082	2.050	154° 38′	0.781	8.418	7.925
5	25	6.406	0.160	2.563				
6	30	6.624	0.273	3.075				
7	35	6.869	0.430	3.588				
8	40	7.135	0.634	4.100				
9	45	7.414	0.891	4.613				
10	50	7.701	1.205	5.125				
11	55	7.987	1.577	5.638				
12	57° 21′	8.118	1.773	5.878				

Fig. 29. Outer-Annulus Fuel Plate.

In this process the flat fuel plate is placed on a rubber bed and the plate formed to an involute shape by means of a steel die machined to the required contour. The equipment is illustrated in Fig. 30. A 1 3/4-in.-thick bed of rubber as a permanent rubber base is topped with a replaceable 3/4-in.-thick slab of rubber, all held in a steel die. Mounted on top of the rubber is a plate-holding fixture in which each plate can be accurately positioned for maximum reproducibility. In the operation, the male die, attached to the upper platen of the press, descends onto the plate, exerting a pressure of 1600 psi. As the pressure is applied, the fuel plate and replaceable rubber pad wrap themselves around the male die. Maple Heights Hi-Temp Form Pad Rubber with a thickness uniformity of ±1/32 in. was found to be acceptable as the pad rubber, although it was replaced after forming approximately 20 plates because of mechanical damage.

We evaluated the uniformity and reproducibility of the marforming method in shaping the plate into the involute by inspecting plates selected at random. As shown in Fig. 31, the plates were inspected at four radial locations and at seven equally spaced intervals along the length of the plate; thus 28 measurements were recorded for each plate. The measuring equipment is illustrated in Fig. 32. Measurements were made by traversing the plate with the train of dial gages. Although this equipment permits a continuous longitudinal trace of the curved surfaces, only measurements at the locations noted above were recorded. The results accumulated from 36 inner-annulus plates and 101 outer-annulus plates are summarized in Table 6.

Uniformity of the radius can be observed by inspecting the results taken at each one of the specific radii reported. You will note that the only radius close to the theoretical is radius ρ_2 in the inner-annulus plate and radius ρ_1 in the outer-annulus plate. Even at this early stage of development, the summarized results for the inner-annulus plates show instances of control of radii in individual plates within a range of 2.4 mils (ρ_3 location). The uniformity data on the outer-annulus plates are not quite as impressive but are still creditable. Subsequent development of the method has led to improved curvature

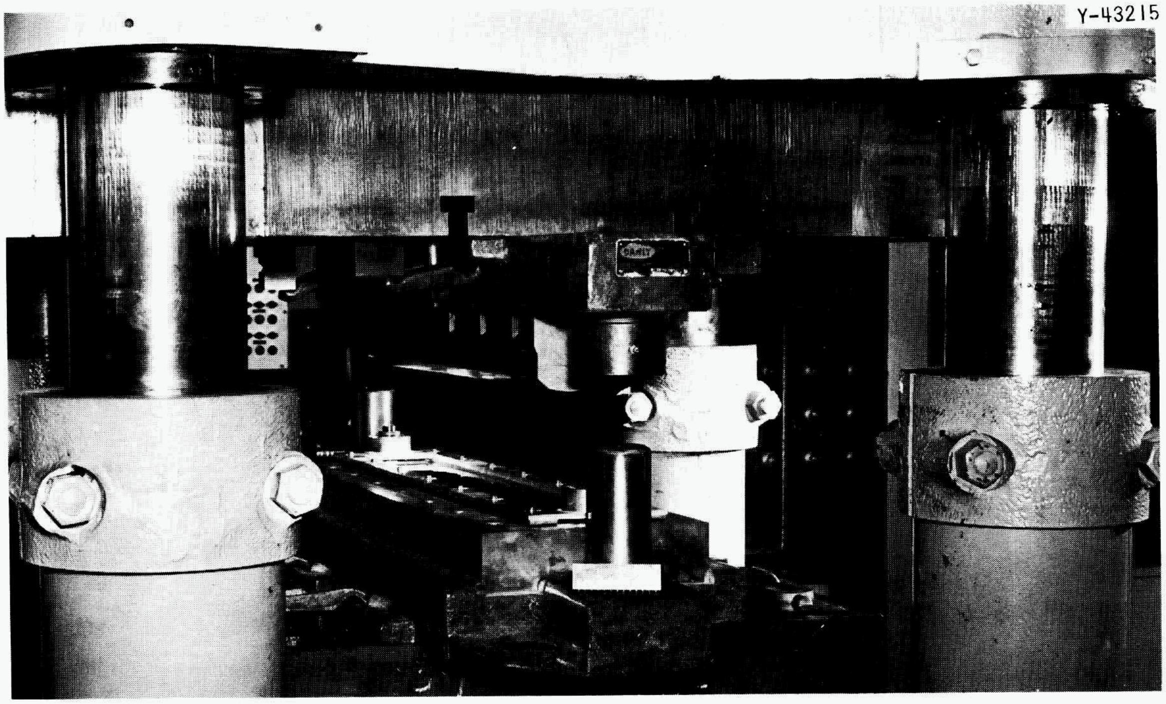

Fig. 30. Plate-Forming Dies in Press. Note contoured male die on upper platen and female die filled with rubber on bottom platen.

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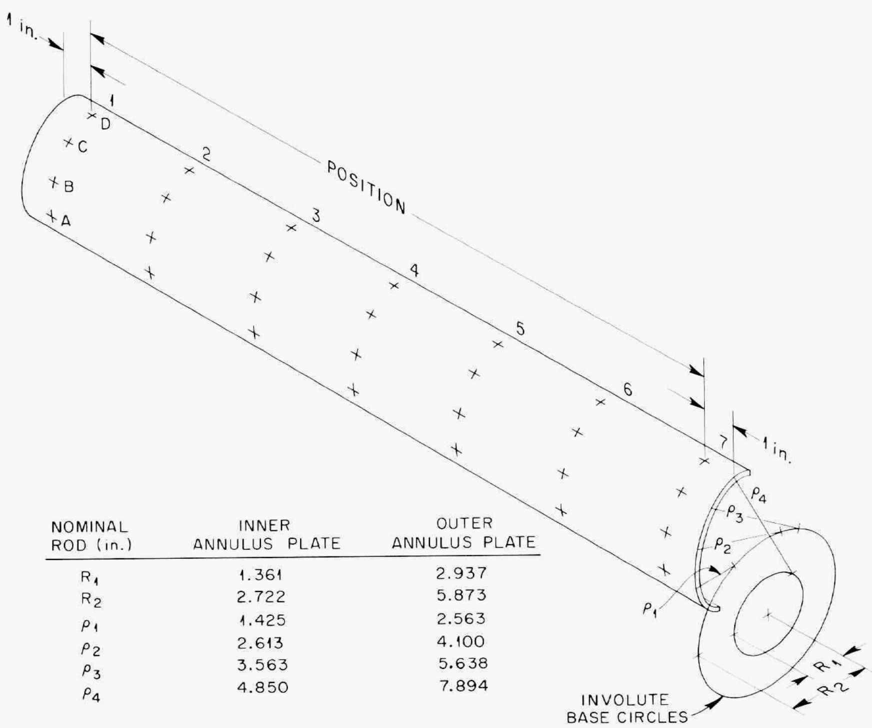

NOMINAL ROD (in.)	INNER ANNULUS PLATE	OUTER ANNULUS PLATE
R_1	1.361	2.937
R_2	2.722	5.873
ρ_1	1.425	2.563
ρ_2	2.613	4.100
ρ_3	3.563	5.638
ρ_4	4.850	7.894

Fig. 31. Location Pattern Used in Inspecting HFIR Fuel Plates for Uniformity and Reproducibility of Involute Shape.

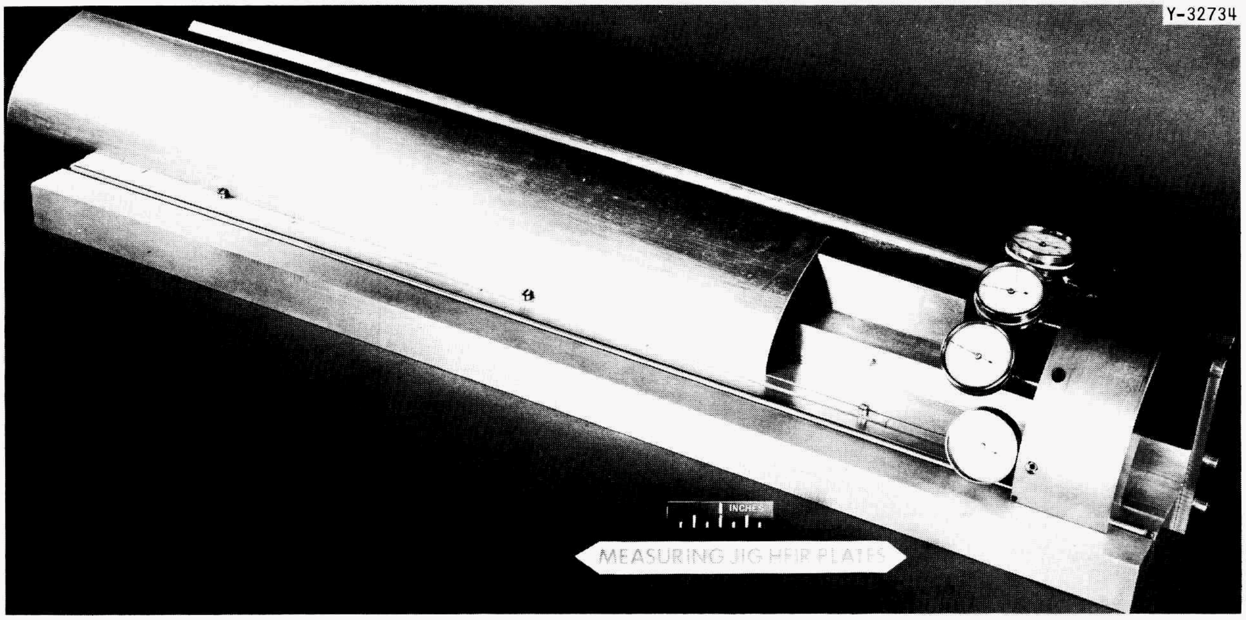

Fig. 32. Jig for Measuring Shape of HFIR Fuel Plates.

Table 6. Summarized Data on Curvature Reproducibility

Axial Location	Average Deviation[a] (mils)				Range of Values[b] (mils)			
	ρ_1	ρ_2	ρ_3	ρ_4	ρ_1	ρ_2	ρ_3	ρ_4
				Inner Annulus				
1	+8.5	−3.6	+7.5	+13.7	20	13	24	15
2	+6.2	−1.3	+8.8	+12.2	14	12	22	12
3	+5.6	−1.8	+8.7	+13.5	18	15	25	12
4	+5.9	−2.1	+9.2	+12.5	19	16	28	14
5	+6.7	−1.7	+9.3	+13.3	25	18	31	17
6	+7.6	−0.6	+9.8	+13.3	24	19	34	20
7	+10.2	−1.8	+9.6	+16.0	23	24	36	20
				Outer Annulus				
1	−5.4	+2.6	+0.4	+0.1	46	18	15	17
2	−2.6	+11.8	+6.2	+6.9	39	23	18	18
3	−0.4	+16.2	+8.2	+7.5	39	19	17	18
4	−0.8	+17.3	+8.5	+5.8	44	19	15	21
5	−1.7	+15.7	+7.7	+6.9	40	19	14	20
6	−5.4	+11.1	+4.9	+7.2	34	15	16	25
7	−5.4	+2.4	−1.0	+1.8	29	24	20	16

[a]Negative or positive average deviation from radii of curvature given in Fig. 31.

[b]From lowest to highest of all individual measurements.

reproducibility for a newer design of HFIR fuel plates[17] and plates of similar composition for a different reactor.[18]

The duplication between plates can be estimated by inspecting the table for ranges of values. The ranges for the inner-annulus plates varied from 12 to 36 mils, whereas the outer-annulus plates showed a somewhat greater range of 15 to 46 mils.

An important consideration in making this type of element is the formation of the correct angle of the lip at the outer edge of the plate. However, during this program, time did not permit improvement of dies to exactly accomplish this objective. Instead, the first die available was used to produce the angle as closely as possible. Then a box-brake was used to correct to the angle that gave the best fit during assembly. The brake equipment was designed so that after the lip was produced the angle could be measured with a depth micrometer. This setup was designed to simulate the relative positions of the inside edge of the plate and the lip edge of the plate with respect to their positioning in the actual assembly.

ASSEMBLY OF FUEL PLATES AND MECHANICAL JOINING

The general scheme of assembly and mechanical attachment of fuel plates in this design is to (1) mount the tubular side plate on an engine lathe, (2) insert the fuel plate in the groove, and (3) peen the plate in the groove. Because of limited space in the last stages of assembly, one cannot peen the last few plates into the assembly. The preplacement of Teflon plastic strips between plates helped to control the spacings between plates. After all plates were assembled, the element was banded.

In making the elements for the Critical Test Facility, two changes were required to make the assembly more amenable to critical experiments. The critical test design required that 0.010-in.-thick air gaps be

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[17]J. H. Erwin, M. M. Martin, W. J. Werner, J. P. Hammond, and C. F. Leitten, Jr., "Fuel Plate Fabrication," Metals and Ceramics Div. Ann. Progr. Rept. June 13, 1965, ORNL-3870, pp. 215–18.

[18]J. H. Erwin, S. Peterson, and C. F. Leitten, Jr., Development of a Forming Method for Curved ATR Fuel Plates, ORNL-3983 (August 1966).

incorporated in the inside side plate of the inner annulus and the outside side plate of the outer annulus. The inside side plate of the inner annulus, prior to grooving, was reduced in diameter and another aluminum tube, 0.020 in. thick with 0.010-in. separators, was shrink-fitted to the side plate. Closures were welded at the ends of the tubes to prevent leakage of water into the air annulus. For the outer annulus, the air gaps were provided by machining eleven 0.010-in.-deep by 1 3/4-in.-wide cuts in the outside welded surface prior to press fitting the outside tube.

The other significant change incorporated in the critical test assembly was the allowance for vacancies in the fuel plate array to permit insertion and removal of six test plates in each element. This necessitated a change at the outer periphery of the elements at each of the six removable-plate positions. To close the gap at the periphery, a spacing strip, 0.050 × 0.375 × 24 in., was spot-welded to the plate adjacent to the vacancy. The spacer was ultimately welded when the fuel plates were welded together at the outer periphery.

Figure 33 shows the assembly equipment with the inner annulus partially assembled. The assembly fixture consists of a support mandrel with the involute backup bar and the peener mounted on a 24-in. engine lathe. The peener is a fast-acting air-driven 1/16-in -diam wire activated by a ball and race mechanism. The rapid strokes applied by the tool plastically deform the edge of the aluminum groove onto the fuel plate. The result is a strong mechanical attachment of the fuel plate to the inner tube. The peening tool operates on a back pressure of air of 35 psi and traverses the length of the element at a rate of 5 in./min.

To start the assembly, we placed the tubular side plate on the mandrel and locked this grooved tube with relation to the position of the index plate with the involute backup bar. After indexing the tube to position the proper separator rib in correct relationship to the peening tool, we cleaned the groove with a small bristle brush. Before inserting the plate, we also wiped its inner edge with facial tissue to ensure freedom from dust or other foreign matter. Visually we ascertained that the plate was fully inserted. In addition, as illustrated

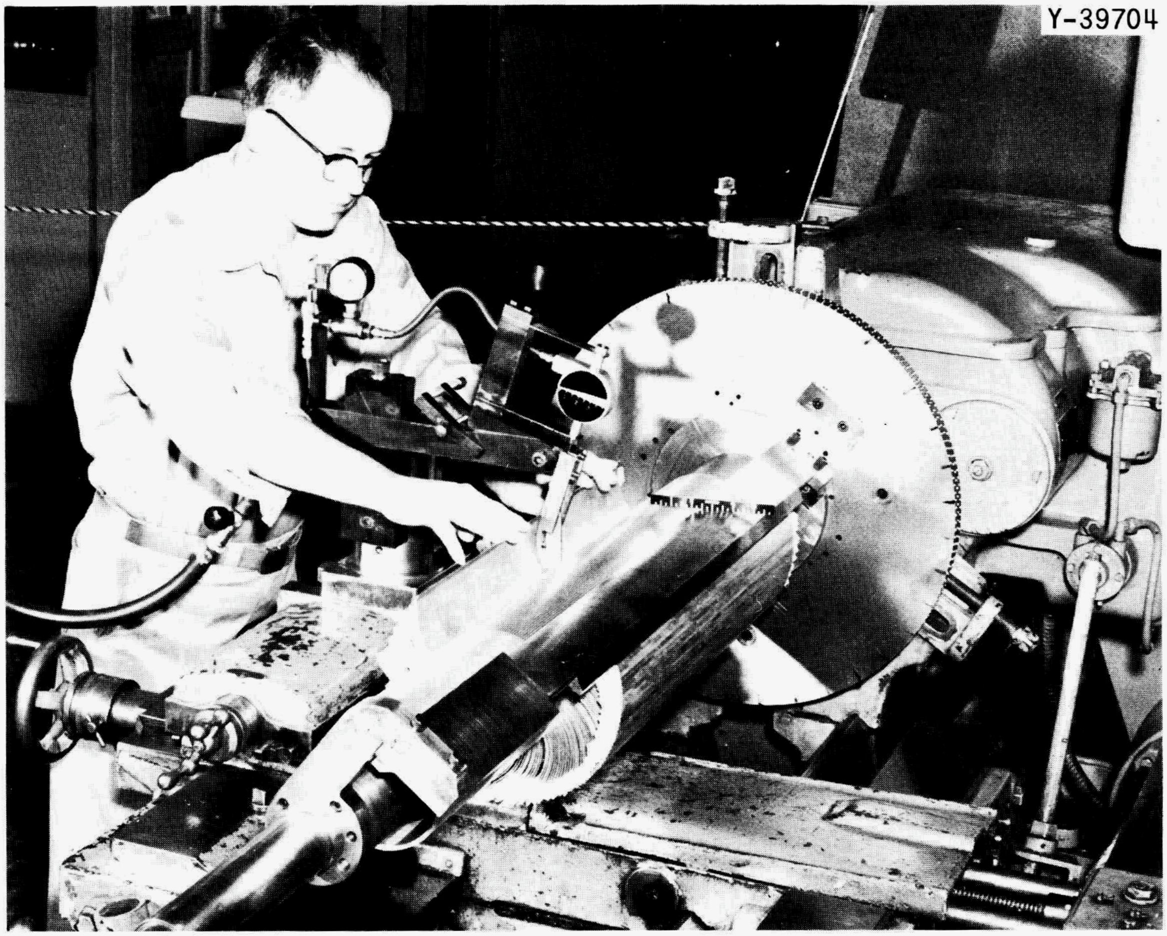

Fig. 33. Setup for Assembling and Peening Plates Into Fuel Arrays.

in Fig. 34, the relative position of the plate was checked at each end of the assembly as well as in the center with an involute gage to assure proper buildup of the assembly. We peened the plate to the side plate and then placed a Teflon spacer 0.040 in. thick × 0.75 in. wide in the resulting channel at a location adjacent to the lip of the lip of the plate. These strips were used mainly to control the spacing closest to the bent lip.

The banded and completely assembled inner-annulus element is illustrated in Fig. 35. Four of the six vacancies allowed for removable plates can be seen.

In the interest of expediency, the outer-annulus element was assembled before the inner-annulus element. During assembly, we encountered considerable difficulty in braking the lip to the proper angle.

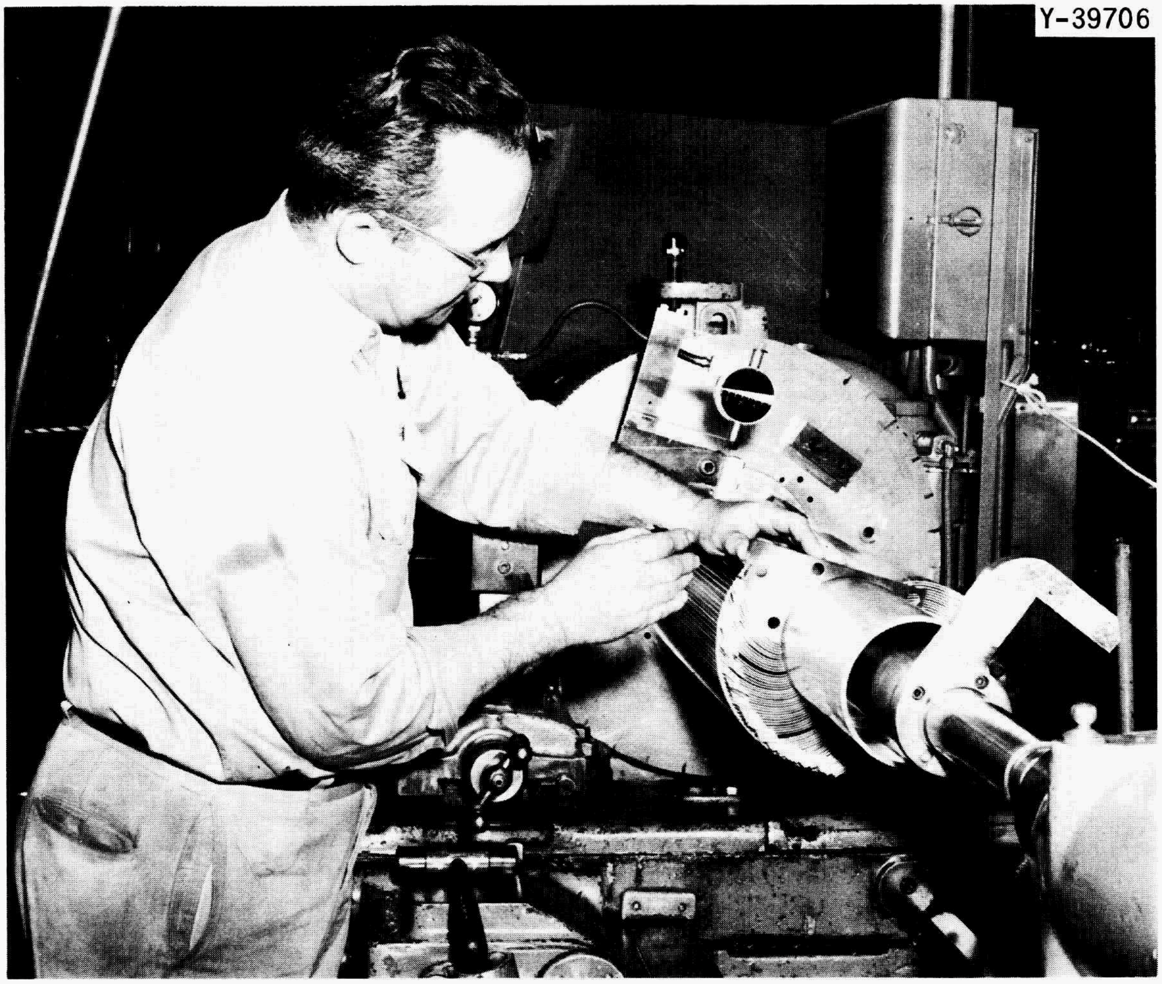

Fig. 34. Inspection of the Contour of Fuel Plates During the Buildup of Fuel Arrays.

Accumulation of small deviations caused the finished cylinder to be oversize in diameter by 0.140 in. To correct this condition we removed the Teflon shims and reduced the diameter 0.140 in. by a torsional deformation. The effect of this operation on distortion of the plate spacings was not investigated. Subsequent spacing measurements on the finished part when compared with measurements of the inner-annulus element (made later with the benefit of experience) indicate that distortion probably occurred during this repair, as might be expected. However, the spacing dimensions were acceptable for this critical test component. The completed outer annulus is shown in Fig. 36.

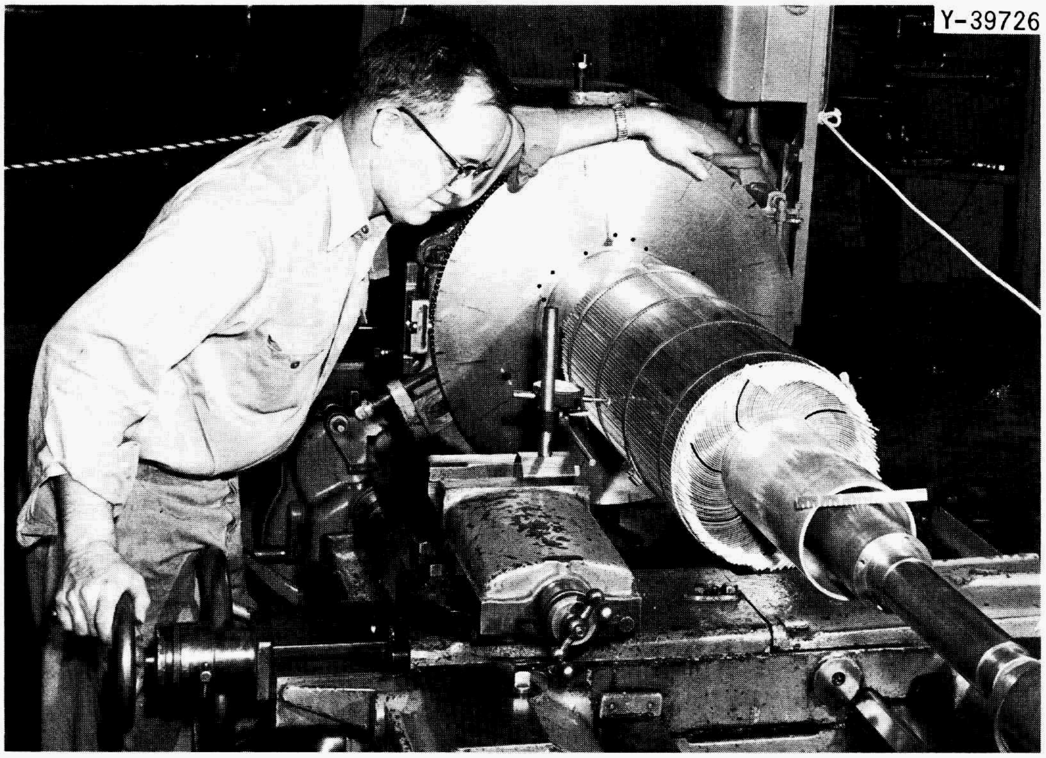

Fig. 35. Inner Annulus Assembled, Shown During Measurement of Diameter.

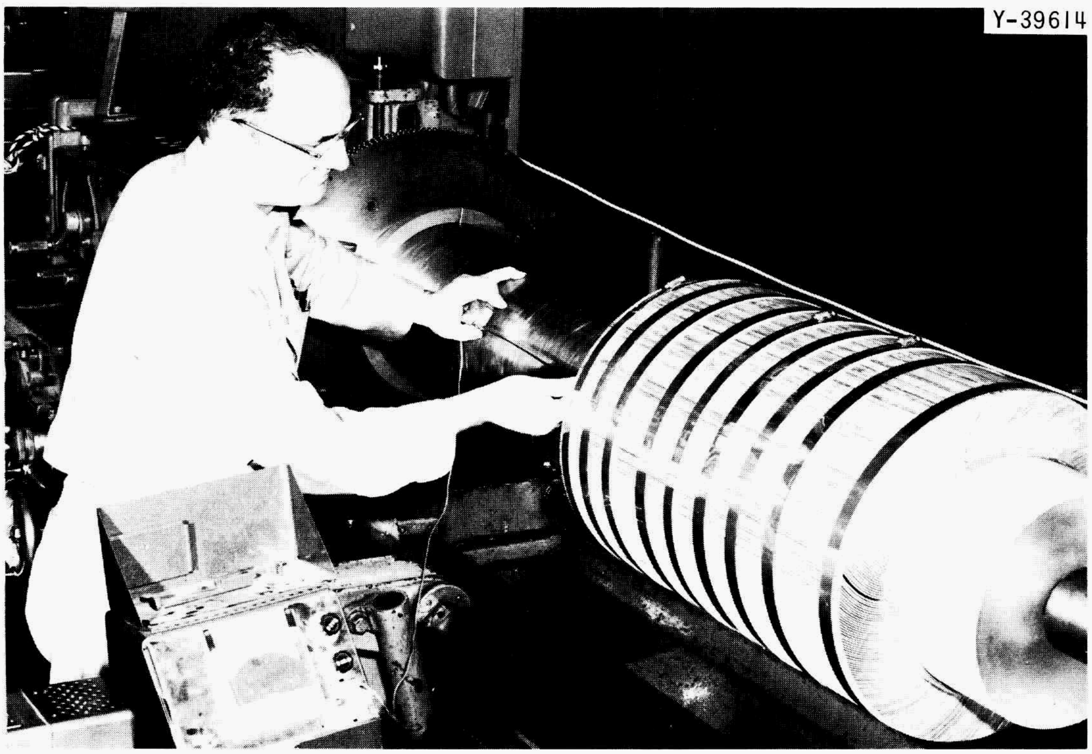

Fig. 36. Assembled Outer Annulus with Temporary Cadmium Insert.

A continuous cylinder of polyetheylene, 9 in. OD × 5 1/3 in. ID, covered with an 0.030-in.-thick sheet of cadmium resides within this fuel element. This combination was used to prevent a criticality accident during assembly.

WELDING OF ASSEMBLED ELEMENT

As cited previously, the Mark IIB fuel element design was distinctive from others under consideration because (1) the plates are assembled into only one tubular side plate, (2) the inner edges of all except the last few plates are joined to this side plate by peening, (3) the last few plates are welded to the side plate by short circumferential welds spaced at 1-in. intervals on the inside of this inner side plate, (4) the outer edges of the plates are bent to cause an overlap of one outer edge on another and then are welded together at 1-in. intervals along the length, and (5) an outer sheath is shrink-fitted over the welded assemblage.

The welded construction of this critical test assembly was essentially a prototype of the Mark IIB design, particularly the welding of the inner-annulus element. Except for elimination of the short circumferential welds on the inner side plate (for attaching the last few assembled plates), the process was quite representative. Although the outer-annulus element was welded similarly, after all the 3/4-in.-wide circumferential welds along the outer periphery were made at the specified 1-in. intervals, the remaining surfaces were subsequently puddled with weld metal. This was done so that the uniform air gaps, specified only for this critical test assembly, could be machined into this surface. We selected tungsten inert-gas techniques, using type 4043-aluminum filler wire, 3/16 in. in diameter, as the feed wire and found that a welding current of approximately 80 amp gave us acceptable results. Preparatory to welding, we degreased the fuel elements and wire brushed the outside surface. We also provided a means for passing cool air through the plates during welding. Figure 37 illustrates the banded assembly with a plug containing cadmium to prevent a criticality incident. The system for purging cool air through the element is also shown.

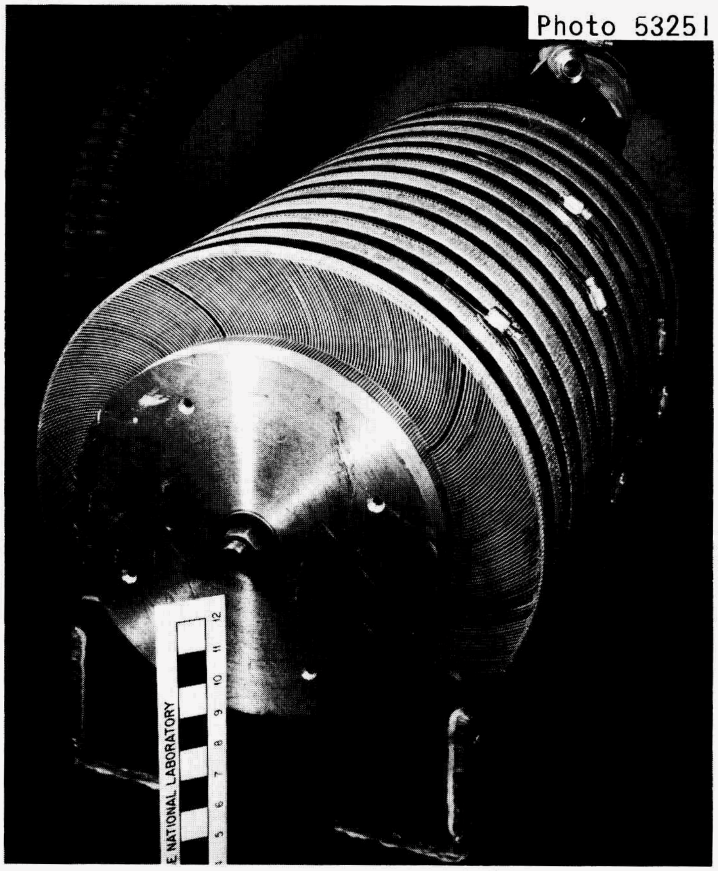

Fig. 37. Banded Outer Annulus Welding.

Figure 38 illustrates the joint design. This design is basically of the fillet type since the bent lips of the plates lay flush against each other around the circumference of the generated cylinder.

We felt that prior to welding, Teflon spacers should be placed between the fuel plates, not only to correct channels, which were obviously out of specification after assembly, but also to maintain uniformity throughout the welding operation. As illustrated in Fig. 39, the assembled inner-annulus element had Teflon strips located only near the bent lips as when received for welding. Figure 39a shows many spacings that are clearly distorted. We added Teflon spacers at each end to a depth of 8 in., located as illustrated in Fig. 39b. The improvement can be seen by the naked eye and is confirmed by the plate spacing measurements summarized in Table 7. Of 3339 individual measurements, 98% fulfilled the desired specifications of 0.050 ± 0.010 in. Even more

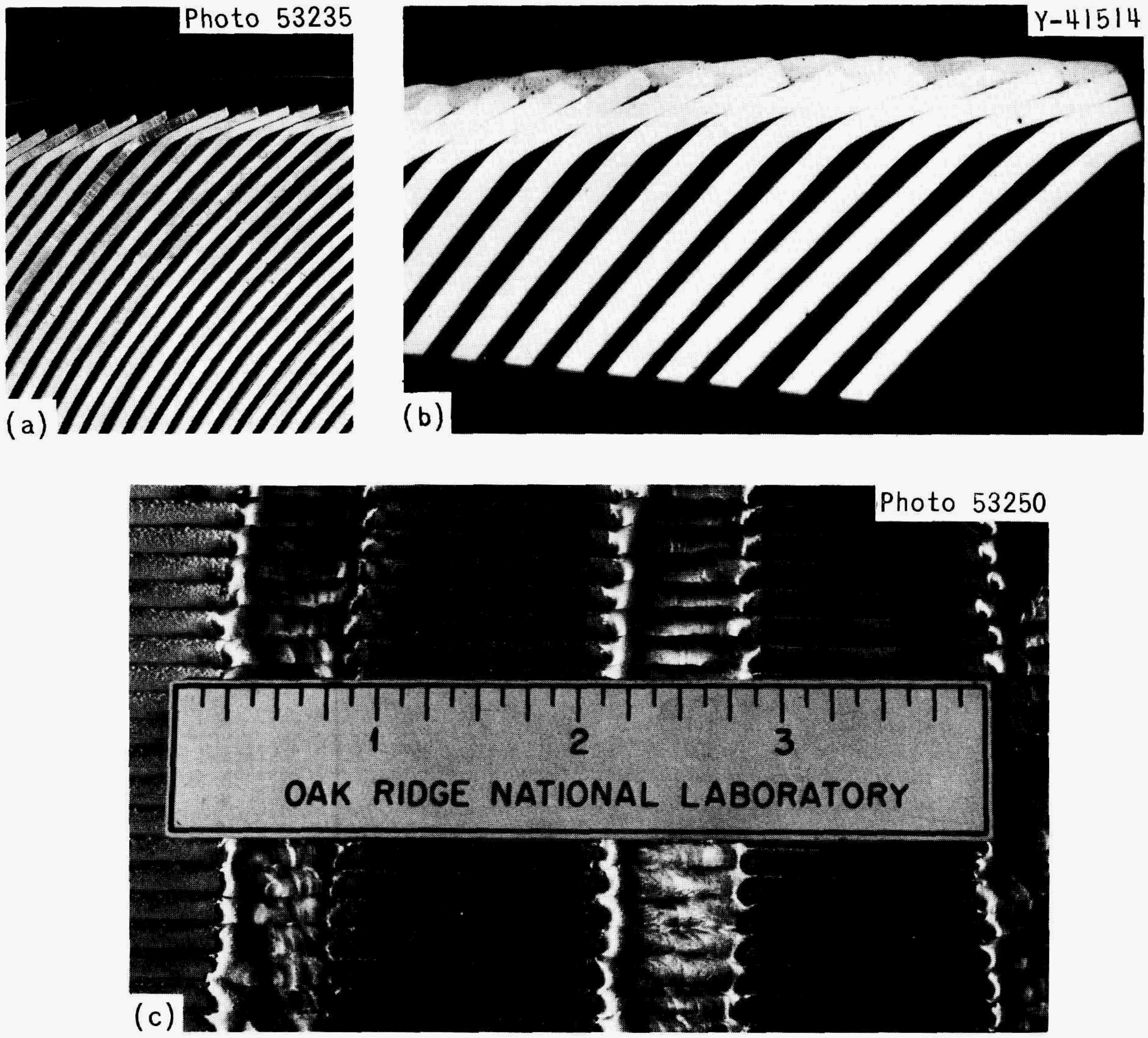

Fig. 38. Typical Weldments Joining the Fuel Plates. (a) Joints before welding. (b) Transverse section through welds. (c) As-welded surface, showing circumferential welds.

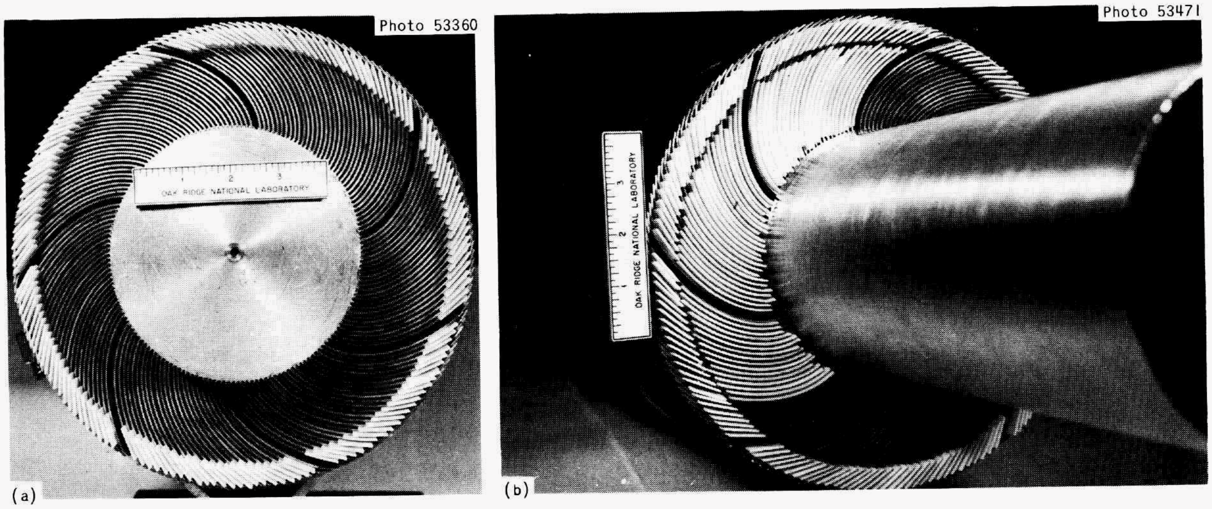

Fig. 39. Assembled Inner Annulus. (a) As assembled. (b) After insertion of additional spacers to improve plate spacings.

Table 7. Summary of Spacing Measurements on Fuel Elements for HFIR Critical Test No. 2

	Outer Annulus	Inner Annulus
Number of plates	369	171
Number of channels inspected	85	159
Number of widths inspected per channel	4	7
Number of individual measurements	1020	3339
Individual measurements within specifications,[a] %	84	98
Channel cross sections within specifications,[b] %	85	99.3

[a]Specifications for individual measurements: 0.050 ± 0.010 in.

[b]Specifications for channel widths: 0.050 ± 0.005 in.

impressive, 99.3% of the channel cross-section averages met the specification of 0.050 ± 0.005 in. The inner tube shown in Fig. 39b is an adapter which we shrink-fitted to this inner-annulus element. This is specific with the critical test assembly and is not part of the reactor fuel element design.

Prior to welding, the element was banded. At that time the diameter measured with a pi-tape was 10.425 in. We attempted to minimize distortion of the involute fuel plates by first limiting the 24 circumferential welded rings to 1/8 in. We subsequently made additional 1/2-in.-wide rings in the regions near the ends that were supported by the 8-in.-long Teflon strips. The diameter changed only 0.003 in. When we added these 1/2-in.-wide welds in the region that did not have the support of the Teflon shims, the diameter shrank 0.010 in. Figure 40 illustrates the 1/8-in.-wide welds and Fig. 41 the completely welded part.

Figure 42 shows the fuel element in its final stages. The rough welded surface of the element was machined as illustrated and the outside tube was shrink-fitted onto the element. We made detailed measurements of the spacing between plates after removing the Teflon spacers and prior to machining the welds.

The outer-annulus element was welded in a manner similar to the inner annulus except that 3/4-in.-long welds were made initially, and

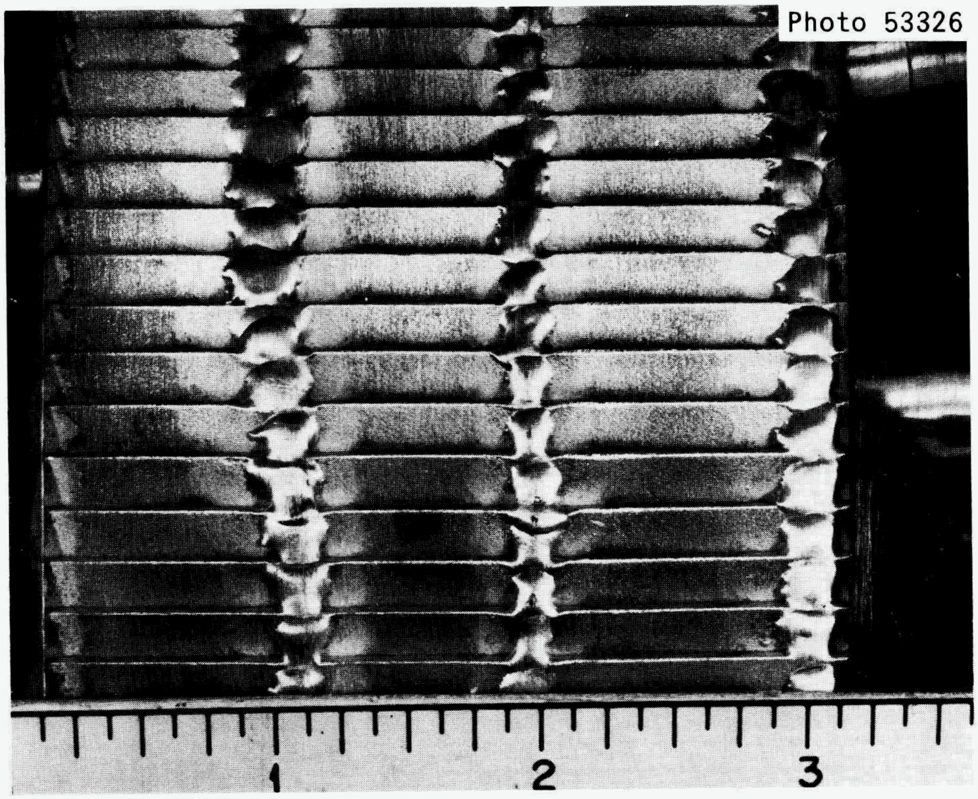

Fig. 40. Circumferential Welds 1/8 in. Wide on Completely Welded Inner Annulus.

Photo 53480

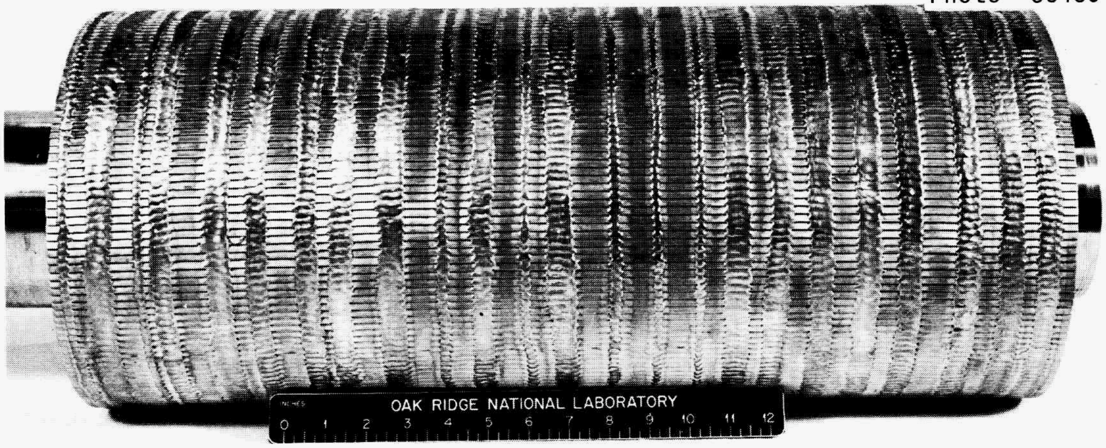

Fig. 41. Overall View of Completely Welded Inner Annulus.

Photo 53482

Photo 53519

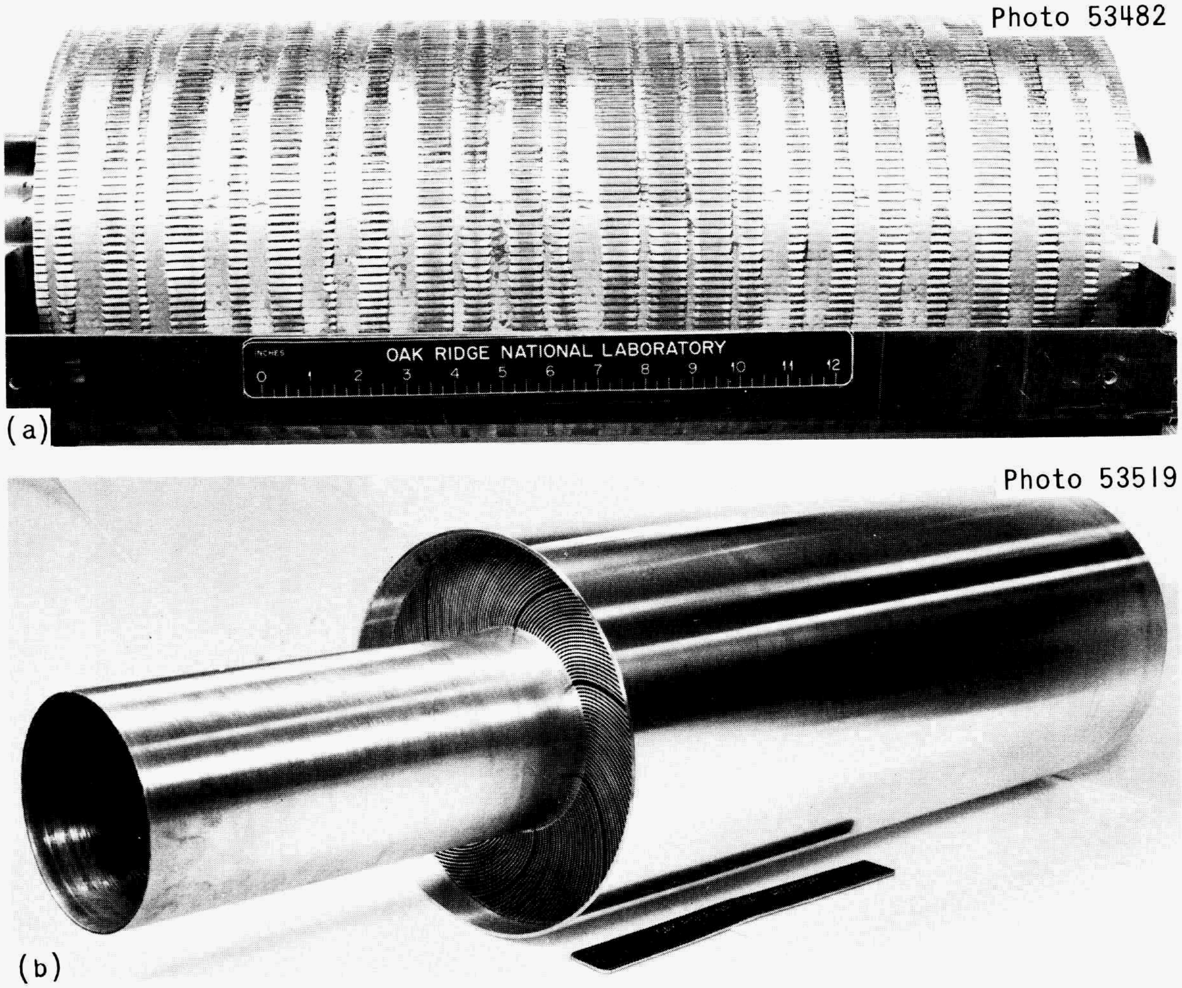

Fig. 42. Finished Inner Annulus. (a) After machining of outer surface prior to fitting into outer tube. (b) After shrink-fitting the outer tube onto the element.

the surface was completely puddled with weld metal as illustrated in Fig. 43. The element, with its surface now grooved and with the high spots removed by machining, is illustrated in Fig. 44. The end fittings shown adapt the fuel element in the critical test facility and were attached by tack welds.

The plate array, the slots for the removable plates, and the bottom mounting plate of the completed outer-annulus element are illustrated in Fig. 45.

The plate spacing measurements of this outer element are summarized in Table 7. The values are much less impressive than those for the inner element. This result was not unexpected because of the problem initially encountered in assembling this particular outer-annulus element. Based on our second experience in making the inner element for this critical test assembly, we feel that outer elements can be produced with the same control of tolerances we obtained with the inner-annulus components.

Photo 53466

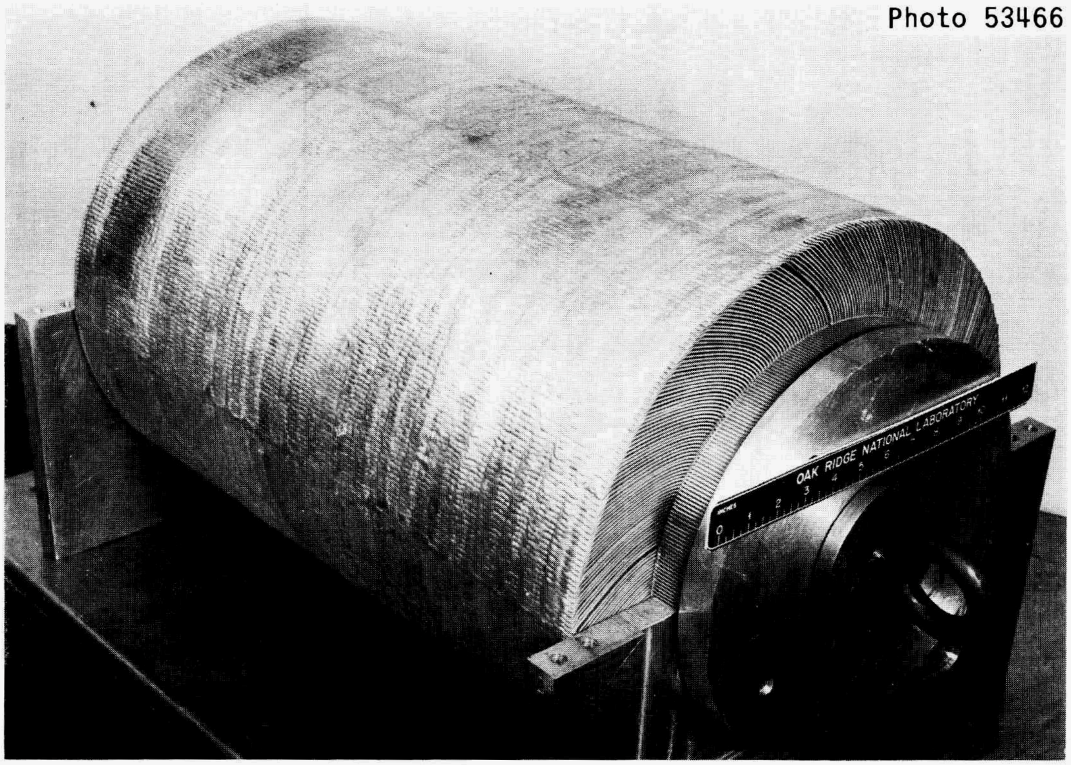

Fig. 43. Outer Annulus Showing Completely Puddled Surface.

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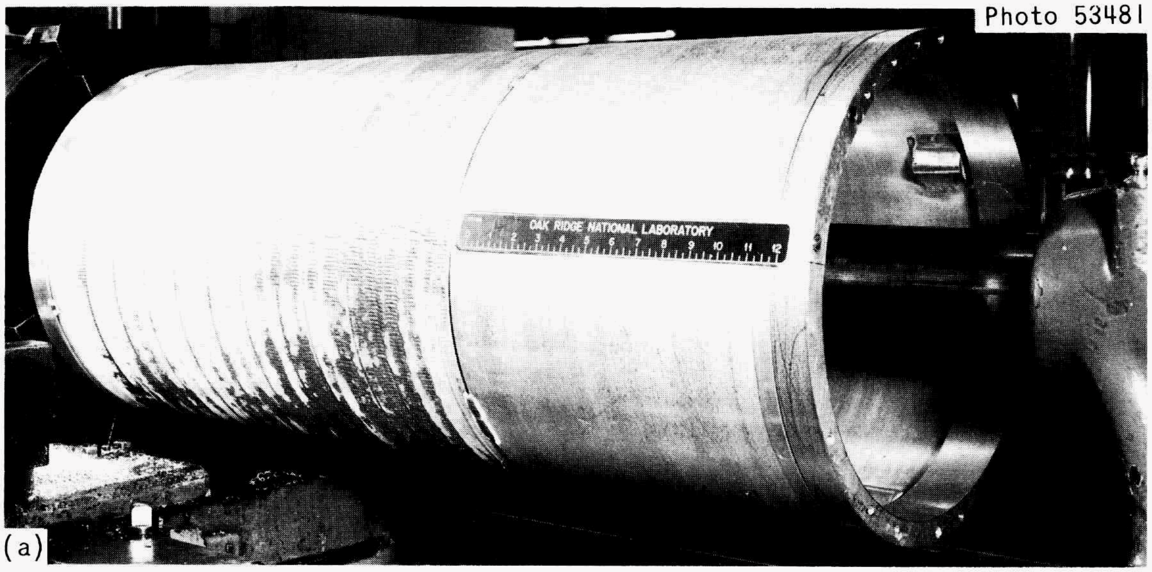

(a)

Photo 53472

(b)

Fig. 44. Outer Annulus Prior to Fitting on Outer Tube. (a) Overall view showing end fitting. (b) Closeup showing grooves in surface.

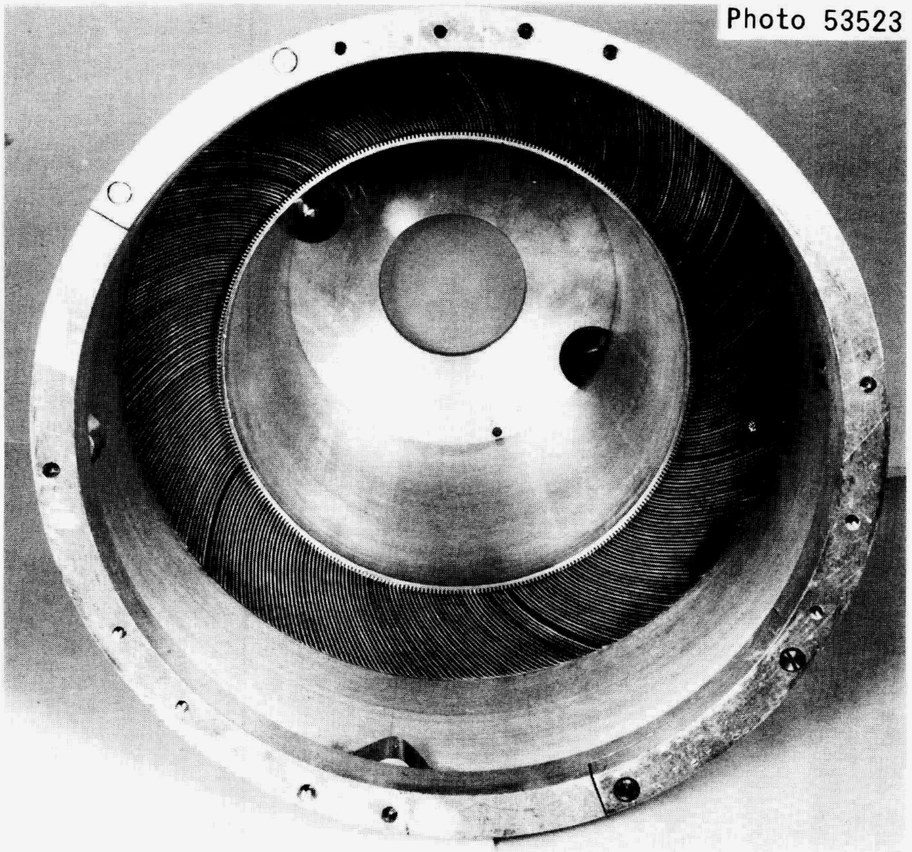

Fig. 45. Completed Outer Annulus

FUEL AND BURNABLE POISON LOADINGS

The quantities of fuel and burnable poison in this critical test assembly are given in Table 8. These values are slightly less than specified. The majority of the bias can be accounted for by the material lost in trimming the burr from the fuel compacts and filler pieces for the inner annulus. In these operations we lost an average of 1.25 g from each fuel compact and 1.00 g from each filler piece. Based on the assumption that the U_3O_8 and B_4C were homogeneously distributed, this loss reduced the ^{235}U content from 13.715 to 13.456 g per plate and the ^{10}B content from 9.760 to 9.568 mg per plate. The ^{235}U content assigned to the fuel compact for the outer-annulus plates was based on the weight and density of the deburred core; therefore, processing loss was not a factor in calculating the fuel loading. You will note that the ^{235}U

content in the outer annulus is within 1% of the specification. The variance in ^{235}U content from one plate to another in the 363 fixed plates was greater than that for inner-annulus plates and has been cited previously in this report. The six removable plates of this 369-plate assembly were carefully selected, each containing 15.4 g of ^{235}U.

Table 8. Fuel and Poison Contents in Fuel Elements for Critical Experiment

Fuel Element	Specified Content (g)		Actual Content (g)	
	^{235}U	^{10}B	^{235}U	^{10}B
Inner Annulus	2345	1.669	2301	1.636
Outer Annulus	5683		5628	
Total	8028	1.669	7929	1.636

RADIATION SAFETY

During the course of this work, care was exercised to be certain that ample protection from radiation hazards was maintained. We were especially concerned about the possibilities of a criticality accident in the event that the 369-plate outer-annulus element was accidentally flooded with water. As noted previously, we eliminated any chance of a criticality incident by lining the inside of the element with 0.020-in.-thick cadmium. Although the precaution was a wise one, subsequent tests in the Critical Test Facility revealed that the outer-annulus element, when filled with water, did not reach criticality.

CONCLUSIONS

Making the HFIR CE-2 fuel assembly both provided a fuel assembly for criticality testing and demonstrated feasibility of the fuel-element processing as concluded below:

1. The vacuum-cast extruded Al–24% U-alloy is a reasonable basic fuel form to consider for HFIR outer-annulus fuel compacts. The results

indicate that the ^{235}U content of each compact can be predicted by density determinations to within ±0.5%.

2. The concept of adding the burnable poison as B_4C and mixing it with U_3O_8 and aluminum powders to form compacts is a sound approach to processing plates for the inner-annulus element, especially from the standpoint of accurate knowledge of the boron content. In the hot-pressing process used to shape these compacts, burrs occurred, and subsequent removal of these burrs added some uncertainty in the actual fuel and boron content of each compact. In this respect, the process for shaping the compact needs to be improved.

3. The fuel-bearing compacts can be contoured to provide a radial fuel gradient in the fuel element by hot pressing.

4. The conventional hot-rolling process, which uses the common picture-frame technique, appears to be an acceptable method for preparing composite plates containing fuel cores contoured to achieve radial fuel gradients. The evidence indicates that the preheat and reheat temperatures should not exceed 500°C.

5. Blistering of fuel plates in the fabrication process was common and in the case of plates containing the fuel alloy is related to the poor fitup of the component billet parts, which resulted in subsequent air entrapment.

6. Low-pressure marforming offers promise as a method for reproducibly forming the fabricated fuel plates into involute shapes.

7. The results obtained, particularly in assembling and fastening the inner-annulus element, indicates that the Mark IIB fuel assembly design is a reasonable approach to the assemblage and joining of the fuel plates. A distinct advantage that it offers is the flexibility in adjusting gaps between plates to within the required specifications during welding of the plates together.

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