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**Fabrication Procedures
for Manufacturing
High Flux Isotope Reactor
Fuel Elements — II**

R. W. Knight
R. A. Morin

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**FABRICATION PROCEDURES
FOR MANUFACTURING
HIGH FLUX ISOTOPE REACTOR
FUEL ELEMENTS — II**

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December 1999

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ABSTRACT

The original fabrication procedures written in 1968 delineated the manufacturing procedures at that time. Since 1968, there have been a number of procedural changes. This rewrite of the fabrication procedures incorporates these changes.

The entire fuel core of this reactor is made up of two fuel elements. Each element consists of one annular array of fuel plates. These annuli are identified as the inner and outer fuel elements, since one fits inside the other. The inner element consists of 171 identical fuel plates, and the outer element contains 369 identical fuel plates differing slightly from those in the inner element. Both sets of fuel plates contain U_3O_8 powder as the fuel, dispersed in an aluminum powder matrix and clad with aluminum. Procedures for manufacturing and inspection of the fuel elements are described and illustrated.

1. INTRODUCTION

The High Flux Isotope Reactor (HFIR) is operated by the Oak Ridge National Laboratory (ORNL). The HFIR's original charter was to provide research quantities of several of the transplutonium elements. Today, the irradiation facilities have been expanded to include other isotopes as well as irradiation experiments. The reactor also has five beam experiment facilities. The reactor operates at a power level of 85,000 kW with a maximum unperturbed thermal neutron flux of approximately 4×10^{15} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ at a power density of approximately 1700 kW/L. The high-performance characteristics of the HFIR requires careful design and close control of the fuel element fabrication procedures. The reactor consists of a cylindrical fuel region surrounded by an annular control region and a beryllium reflector, all of which are water cooled. These components are contained within a carbon steel vessel clad with stainless steel.

The fuel element specifications¹ have been reported. The fundamental basis for fabrication was developed at ORNL. This fabrication base was expanded into a production process at Texas Instruments, Attleboro, Massachusetts. Since the early production, the fabrication process has been dynamic, and changes are continually being made to accommodate new equipment or to reduce cost; but in no case is the quality of the fuel element compromised because of these changes. The fabrication is now at Babcock and Wilcox Company, Lynchburg, Virginia.

The purpose of this report is to present the details of the fabrication process that are presently being used by the reactor. No attempt will be made in this document to justify the process or to discuss alternate procedures. Such information can be found in other reports. No warranty is offered that this is the only acceptable procedure. It is, however, one that has been shown to be satisfactory for producing these very complex fuel elements.

¹ORNL/TM-9220, G. A. Bowden and R. W. Knight, *Specifications for High Flux Isotope Reactor Fuel Elements HFIR-FE-3*.

2. GENERAL DESCRIPTION OF FUEL ELEMENTS

The entire fuel assembly of this reactor is shown in Fig. 1. It is made up of two aluminum-base fuel elements shown in Fig. 2, each consisting of an annular array of fuel plates. The annuli are identified as the inner and outer fuel elements. The inner element consists of 171 identical fuel plates and outer of 369 identical plates differing slightly from those in the inner element. Both sets of fuel plates contain U_3O_8 powder as the fuel, dispersed in an aluminum powder matrix and clad with aluminum.

Fig. 1. Top view HFIR fuel element assembly.

Fig. 2. HFIR inner and outer annulus fuel elements.

The fuel plates are fabricated by a conventional picture-frame technique and are shaped into an involute configuration to provide a uniform metal-to-water ratio and a high ratio of heat transfer surface to core volume and yet maintain a constant water-channel spacing.

The fuel elements are assembled by inserting formed fuel plates into slots in cylindrical side plates. The fuel plates are attached to the side plates by welds deposited in circumferential grooves. End adapters are required on each end of the fuel assembly to provide location and support of the fuel assembly within the reactor.

A fuel plate core constitutes a rectangular parallelepiped consisting of two mating sections: (1) a fuel section, which varies in thickness nonlinearly across the width and (2) a complementary aluminum filler section, which in the inner fuel element contains B_4C for burnable poison. The fuel and burnable poison area densities (amounts per unit area of fuel plate) are varied across the width of each plate to help control the power distribution. To help achieve satisfactory heat-removal characteristics, the fuel and burnable poison distributions

must be closely controlled and a sound bond must exist at all interfaces within the plates. In addition to contributing to power distribution control, the B_4C located in the filler section of the inner element fuel cores supplements the reactivity worth of the reactor control system. The high-performance requirements and smaller safety factors of this reactor have necessitated much tighter dimensional and quality specifications than are required for other research reactors. This has also required the measuring and recording of extensive quality-control information.

3. FUEL PLATE MANUFACTURE

Fuel plates for the HFIR elements are more complex in configuration and must be fabricated to tighter dimensional tolerances than those for any other research reactor. During fabrication, extreme care must be used to maintain plate recovery at a tolerable level.

Figure 3 presents the developed fuel-plate fabrication process flow chart. The fuel portion or core of the fuel plates is fabricated by blending, contouring, and cold compacting appropriate quantities of U_3O_8 , aluminum, and boron carbide (inner fuel plate only) powders. Each inner fuel plate contains 15.18 g ^{235}U and 0.0164 g ^{10}B ; each outer fuel plate contains 18.44 g ^{235}U . The pressed compacts are vacuum annealed and then assembled into picture frames, each of which accommodates two compacts. Cover plates are welded to the frames, and the resulting packages are bonded by hot rolling. After a blister anneal, the plates are cold rolled to gage, annealed, and inspected for fuel orientation and location. The plates are blanked to finished dimensions except for the 0.025-in. (0.64 mm) radius on the end, which is then machined on. The flat fuel plates are inspected for fuel orientation and location, surface defects, fuel homogeneity, surface contamination, and bond defects. Sample plates are selected for metallographic examination of cladding, fuel thicknesses, and bonding. Punchings are taken from the sample inner plates for boron analysis. The flat plates are then formed to the involute shape, pickled, and reinspected for surface defects at fuel element assembly. Flat fuel plates are fabricated in accordance with drawings 8-7146 and 8-7148 shown in Appendix A. The flat plates are then formed into involutes.

Throughout the process, extreme care must be taken to prevent foreign material pickup on the very soft aluminum fuel plates and components, since small pits and inclusions are a major cause of rejection. All tables on which material is placed are either covered with Formica and frequently and thoroughly wiped or covered with rubber mats that have rubber fingers to support the material. The rubber mats prove very effective, since small chips such as occur during a deburring operation fall down between the rubber fingers and, thus, do not come into contact with the surface of the fuel plate.

Furnace temperatures are critical, and all furnaces are checked periodically for conformance to temperature specifications. The check includes probing of the hot zone with instrumented assemblies and calibration of all temperature-indicating and -controlling instruments. The specified temperature limits must include variations in both the control instruments and the furnaces themselves. Temperature charts are maintained for each furnace load and are examined for any evidence of drift. Appendix B describes the furnace maintenance and qualification procedures.

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The Quality Control Group maintains control charts on boron analyses, fuel plate average and minimum cladding thicknesses, average compact weight loss, and fuel core location. Corrective action is taken immediately whenever the process begins to go out of control. In the case of acceptable quality level (AQL) inspections, 100 per cent inspection is performed whenever the particular attribute being studied violates the specification.

4. COMPONENTS

4.1 FRAMES AND COVER PLATES

Typical fuel-plate components are shown in Fig. 4. The frames for both inner (and outer) annulus fuel plates are 6.73-mm (0.265 in.) thick $\times$ 209.5-mm (8.25 in.) long $\times$ 152.4-mm (6.000 in.) wide. Each frame has two cavities to allow hot rolling of tandem plates through the seventh pass. The cavity sizes are 55.02 mm (2.166 in.) to 55.12 mm (2.170 in.) $\times$ 74.52 mm (2.934 in.) to 74.62 mm (2.938 in.) for the inner annulus and 55.09 mm (2.169 in.) to 55.19 mm (2.173 in.) $\times$ 67.23 mm (2.647 in.) to 67.33 mm (2.651 in.) for the outer annulus. The cover plates for both inner and outer annulus fuel plates are 2.806 mm (0.1105 in.) thick $\times$ 209.5 mm (8.25 in.) long $\times$ 152.4 mm (6.000 in.) wide.

Fig. 4. Fuel plate assembly components.

The stock is type 6061 aluminum, ordered in accordance with specifications shown in Appendix C, supplies in 1219-mm (4 ft) $\times$ 1219-mm (4 ft) sheets. The picture frame stock is 9.4-mm (0.370 in.) thick sheet. Frame stock has been ordered 152.4 mm (6.000 in.) wide by 1219 mm (4 ft) long. This saves time and money during fabrication.

Each lot of material is identified, and this identification is maintained throughout the process. The as-received sheets or strips are inspected on both surfaces for blisters, surface defects, and areas of containing foreign materials. The foreign material is removed by cleaning or

scraping any blister or otherwise unusable area, are clearly marked, and removed during sheering. The plate is discarded if it does not yield 70 per cent of usable material. The sheets are sheared into 152.4 mm (6.000 in.) wide × 1219 mm (4 ft) long strips. The strips are sheared so that the 1219-mm (4 ft) length is in the direction of the rolled sheet or plate at the manufacturer and to provide the best yield.

The frame-stack strips are cleaned using procedure 1 of Appendix D. A maximum of 0.1 mm (0.004 in.) is removed from the strips during pickling. The pickling operation is omitted if not required by the quality of the as-received plate. Pickling has not been required of the cover-plate strips.

The clean frame strips are cold rolled from the as-received gage of 9.39 mm (0.370 in.) to 6.77 mm (0.2665 in.) to 6.79 mm (0.2675 in.) to produce closer control of the gage than is available commercially and one that is compatible with the rolling schedule. The rolling is done on a 330-mm (13 in.) × 305-mm (12 in.) or a 330-mm (13 in.) × 406-mm (16 in.) mill with flat rolls. The mill operator keeps track of the gage by taking 12 measurements with a deep-throat micrometer, four down each edge and four down the center of each strip. The rolls are kept clean and lightly lubricated by procedure 2 in Appendix D. The strips are reduced in eight passes of 0.38 mm (0.015 in.), 0.38 mm (0.015 in.), 0.38 mm (0.015 in.), 0.38 mm (0.015 in.), 0.38 mm (0.015 in.), 0.25 mm (0.010 in.), 0.25 mm (0.010 in.), and 0.203 mm (0.008 in.). The cover-plate strips are rolled to a gage of 2.794 mm (0.110 in.) to 2.819 mm (0.111 in.) in the same manner and for the same reason as the picture frames. The strips are reduced in six passes of 0.2 mm (0.008 in.), 0.2 mm (0.008 in.), 0.2 mm (0.008 in.), 0.178 mm (0.007 in.), 0.178 mm (0.007 in.), and about 0.06 mm (0.0025 in.). A maximum camber of 6.35 mm (0.25 in.) per 1219 mm (4 ft) is permitted for both types of strips. Strips are wiped with isopropyl alcohol to remove oil. They are roller leveled on a nine-roll, 76.2-mm (3 in.) diameter roller leveler to limit the maximum longitudinal bow to 50.8 mm (2 in.) for the full length strip or 0.76 mm (0.030 in.) per 203 mm (8 in.) length. To prevent pickup of foreign material, particular care is taken to clean the roller leveler prior to use.

The cover and frame strips are sheared to 209 mm (8.235 in.) to 209.9 mm (8.265 in.) lengths in a manner to give the best yield. The frame stock is then blanked to produce a dual cavity and squared ends. Figure 5 shows the die mounted in the press. Transultex Oil² is brushed on the cutting edge of the punches and each frame, and the dies are periodically

²A trade name of Texaco, Inc., 135 East 42nd Street, New York, 17

Fig. 5. Fuel plate frame blanking die.

sharpened to ensure good cavity edges. For producing good sheared edges, punch and die clearances are maintained at 0.025 mm (0.001 in.) to 0.0508 mm (0.002 in.) per side. The type 6061 aluminum sides of the cavity are visually inspected for inclusions. Inclusions found at this operation are usually from the as-received stock. Type 6061 aluminum must be inspected prior to annealing since annealing this alloy results in a dull matted surface.

The frames are placed in special tote racks and cleaned to remove the oil and annealed at a minimum temperature of 500°C (932°F) for 2 hours total time. They stand on end (short dimension) with the other ends separated by stainless-steel furnace racks. The frames are pulled out of the furnace after annealing and allowed to cool in air. Any furnace capable of maintaining a uniform $500 \pm 5^\circ\text{C}$ (932°F) temperature is suitable for this operation. Electric furnaces with air blowers to circulate the hot air evenly are generally used. Approximately 150 frames are annealed in a batch, with care taken to maintain lot identity. The covers are annealed in a similar procedure, generally 200 covers are annealed in a batch.

The completed frames and covers are inspected per mil-STD-105D, 1% AQL level II for the following attributes:

1. All frame cavity dimensions are held to ± 0.05 mm (0.002 in.). The cavity edges and ends must be square within 0.05 mm (0.002 in.) total indicator reading (TIR). the cavity ends must be parallel with the reference edge of the frame within 0.127 mm (0.005 in.) TIR. All attributes of the cavity are checked with go-no-go gages.

2. All dimensions of the frame are checked with dial indicators. The reference edge and ends of the frame must be square within 0.127 mm (0.005 in.) TIR, and frame length and width within ± 0.38 mm (0.015 in.).

The cover plates are to be held to ± 0.38 mm (0.015 in.) in length, ± 0.5 mm (0.020 in.) in width, and ± 0.0127 mm (0.0005 in.) in thickness. The ends and reference edges are to be square within 0.152 mm (0.006 in.). All dimensions are checked with a dial indicator gage.

3. After the strips are rolled to final thickness, thicknesses are measured with micrometers. The surface and cavity edges of the frames are 100% inspected visually for laps, seams, blisters, and poorly sheared edges. Inclusions and foreign contamination are examined visually at a magnification of 3X. Any embedded contaminants on the frame area that would remain on the finished plates are removed with a tool-steel scraper. The inspected frames are wrapped in clean kraft paper and held in storage. The cover plates are treated in a similar fashion by inspecting and removing inclusion or contamination and also wrapped in kraft paper and held in storage.

4.2 ALUMINUM POWDER

Alcoa-type 101 aluminum powder or equivalent is purchased in 5-gal pails in accordance with the specification in Appendix C. A 150-g sample is removed from each lot of annealed aluminum powder and screened through a stack of 100-, 170-, 200-, 270-, and 325-esh (tyler) screens for 15 minutes. A Ro-Tap machine with a tapping action of 140 to 160 aps per minute is used. The screen analysis is recorded, and the powder is accepted if 76 to 84% of it is -325 U.S. standard mesh.

The as-received powder is vacuum annealed in a cold wall electric furnace equipped with an oil diffusion pump and mechanical roughing pump. The powder is loaded into a tray using the special funnel shown in Fig. 6. Note that the tray has an egg-crate type divider to separate the powder into small discrete units. The funnel is set on the tray, and each hole is filled level full. When the funnel is removed, the powder in each unit should be about 38-mm (1.5 in.) deep. This is done because at the annealing temperature, aluminum powder has a slight exothermic reaction; and by keeping the mass small in each unit, the heat rise is not enough to cause aluminum clumping. Six trays are loaded into the furnace, and the furnace is pumped down to a vacuum of at least 1×10^{-4} torr (0.1 μ Hg), the leak rate is checked, it must be less than 2×10^{-3}

Fig. 6. Aluminum powder pan and loading fixture for vacuum annealing.

torr (2 μ Hg) for a 4-minute test period. This test is made with the pumping system isolated from the furnace. After this test, the furnace is started, it is brought to a temperature of $500^{\circ}\text{C} \pm 10^{\circ}\text{C}$ (932°C). This temperature is maintained for 6.5 hours. The pressure during the annealing cycle must not exceed 7×10^{-4} torr (0.7 μ Hg). The temperature is critical, since too high a temperature will cause the powder to sinter while too low a temperature will not remove all of the water of hydration. After 6.5 hours, the furnace is turned off and allowed to cool to $49^{\circ}\text{C} \pm 11^{\circ}\text{C}$ (120°F) to prevent moisture condensation upon exposure to air. Care is taken to maintain the furnace free of scale and contamination. The powder is examined for any unusual discoloration or caking. If acceptable, the powder is immediately placed in clean stainless steel containers equipped with covers that have holes to equalize air pressure. The stainless steel containers are placed in storage containers (Fig. 7), which are connected to a vacuum manifold system. A mechanical pump maintains the vacuum at about 0.05 to 0.1 torr (50 to 100 μ Hg). The valves on all other storage containers are closed during the opening and evacuation of a storage container and then reopened after the new container is evacuated. Safety valves are incorporated in the system to prevent oil back streaming during a power failure.

A NOTE OF CAUTION: When the furnace is loaded with powder, when changes in pressure occur, the powder can become airborne. If this happens, the powder can foul the vacuum pump and collect on heaters. Open and close valves very slowly to prevent this from happening.

Fig. 7. Vacuum storage for aluminum powder.

4.3 BORON CARBIDE

While ^{10}B is specified as the burnable poison, natural-boron (boron carbide powder with a particle size less than 4μ) is purchased.³ The powder is screened through a 325-mesh screen and is stored in suitable containers to protect it from moisture and contamination. The detailed specifications are presented in Appendix C.

4.4 U_3O_8 POWDER

The U_3O_8 is supplied by ORNL (see Appendix C) and is a high-fired dead-burned oxide prepared by calcination of uranyl peroxide.⁴ As supplied, the oxide is -170 $+325$ mesh with a maximum of 25% -325 mesh. The enrichment is a minimum of 93%, the density is greater than 8.2 g/cm^3 by toluene pycnometer, and the surface area is 0.05 to $0.07 \text{ m}^2/\text{g}$ as measured by the static krypton BET method. About 2 kg of oxide is supplied in each container. The as-received oxide, when needed, is placed in a clean stainless steel container with a gasketed locking top. Just prior to use, the container is placed in one leg of a 12-qt V blender and the U_3O_8 is blended at 24 rpm for 30 minutes. The U_3O_8 in the container is used up in approximately three manufacturing days. The blended U_3O_8 powder is identified by a lot number and stored in a vault. For accountability, the weights of containers and powder are carefully recorded during these operations.

³The Norton Company, Worcester, Mass, is one source for satisfactory powder.

⁴ORNL-4052, W. J. Werner and J. R. Barkman, *Characterization and Production of U_3O_8 for the High Flux Isotope Reactor*, April 1967.

5. COMPACT FABRICATION

5.1 WEIGHING AND BLENDING

The fuel plate compacts are manufactured by conventional powder metallurgy methods, except that the fuel section is graded. As shown in Fig. 8, each core is a rectangular parallelepiped consisting of two sections: (1) a fuel section (varying in thickness across the width) and (2) a complementary aluminum filler section (which in the inner fuel plate contains burnable poison in the form of B_4C). The finished cores are: For the inner annulus 54.89 to 55.02 mm (2.161 to 2.166 in.) long by 74.37 to 74.47 mm (2.928 to 2.932 in.) wide and 6.73 to 6.93 mm (0.265 to 0.273 in.) thick; for the outer annulus, 54.99 to 55.09 mm (2.165 to 2.169 in.) long by 67.08 to 67.18 mm (2.641 to 2.645 in.) wide by 6.73 to 6.93 (0.265 to 0.273 in.) thick. The weight of each material to be used in a core is calculated from the isotopic analysis of each lot of U_3O_8 and B_4C , so that each inner compact will contain 15.18 g ^{235}U and 0.0164 g ^{10}B and each outer component will contain 18.44 g ^{235}U . The volume occupied by U_3O_8 and B_4C are calculated and subtracted from the fixed volumes established for the fuel and filler portion of the compacts. The remainder is aluminum powder and void volume. Roll spread and density changes are calculated and compensated for to establish the required volumes of aluminum powder. The weight of the aluminum powder for each portion of the compact is then determined. Typical charge weights are shown in Table 1. The compact lot size was established at 24 compacts or fuel plates.

Table 1. Compact loading details

	Inner fuel plate compact (g)	Outer fuel plate compact (g)
Fuel section		
U_3O_8	19.28	23.42
Al	44.59	35.00
Filler section		
B_4C	0.1188	None
Al	21.30	22.64

Sufficient U_3O_8 powder plus 1 g excess is issued from the vault to make either 24 inner compacts or 24 outer compacts. The total issued is weighed to 0.01-g accuracy. Before individual fuel-section charges of U_3O_8 are weighed, the powder is scooped from the vault container to the weighing cup and poured back into the vault container three times to provide a consistent coating on the scoop and cup. Each U_3O_8 charge is weighed to ± 0.01 -g accuracy on a Mettler PM 200 or equivalent balance in a dry box, and the weight is recorded. The oxides are added to color-coded glass jars (as shown in Fig. 9) that are used only for fuel charges. The threaded sections of the jar are carefully cleaned to remove any contamination. The glass jars are heated to $52 \pm 4^\circ\text{C}$ ($125 \pm 7^\circ\text{F}$) for 30 min prior to use. As soon as the heating is completed, clean caps are threaded firmly on the jars. If a new jar is used, it is thoroughly cleaned and coated with aluminum powder. This dusting is not removed when the jar is reused. After all charges for a 24-compact lot have been weighed, the remaining U_3O_8 is returned to the vault. A material balance is made to ensure that all U_3O_8 is accounted for.

Fig. 8. Compacts in transport tray.

From the vacuum storage containers, the aluminum powder is screened, and the aluminum powder is taken to a humidity- and temperature-controlled weighing, blending, and screening room. The room is maintained at 30 to 50% relative humidity and 21 to 24°C (70 to 75°F). The powder is first screened through one 100-mesh and two 120-mesh screens for 3 to 5 min on a Ro-Tap machine. Before the aluminum charges are weighed, scoops and weighing cups are coated in the same manner as described for the U_3O_8 powder. Glass jars for the aluminum filler sections of the compacts are prepared in the same manner as described for the U_3O_8 powder charge. These jars are color coded differently for outer and inner filler sections. Filler-section charges of aluminum powder are weighed (as shown in Fig. 10) on the same balance used to weigh the U_3O_8 and are placed in the properly color-coded glass jars. Fuel-section charges of aluminum powder are weighed to ± 0.01 -g accuracy and are placed directly in the jars containing the U_3O_8 fuel charges.

Fig. 9. Individual compact charges in tote tray.

Fig. 10. Weighing aluminum powder.

Fig. 11. Weighing B_4C powder.

The B_4C powder charges for the filler sections of the inner compacts are weighed with an analytical balance to ± 0.0005 -g accuracy on a tarred weighing paper (shown in Fig. 11) and added to the jars containing the inner aluminum filler-section charges. Starting weights for a lot of 24 compacts less charge weights and residue weights are maintained to 0.02-g accuracy for accountability.

The fuel-section charges and the inner-filler-section charges are blended for 2 hours in a U.S. Stoneware (Catalog Fig. 733, Serial No. BB50103) oblique blender at 20 to 25 rpm. Twelve jars in three tiers are placed in 6-in.-diam $\times$ 10-in.-long cylindrical cans on each arm of the blender (shown in Fig. 12). After blending, the jars are placed in handling racks, which in turn are placed on vibration-free tables. The powders must be compacted within 4 hours of blending or be reblended.

Fig. 12. Compact charges in the blender.

5.2 COMPACTING

The compacting of these cores is unique in that a two-component core with a curved interface between the components is produced in a single cold-pressing operation. The key to acceptable cores lies in the technique used to place the powders in the dies. The dies and punches are conventional rectangular powder-metallurgy components with the clearance between them kept to a minimum to prevent escape of the fine aluminum powder and subsequent galling. During filling, they are modified by the addition of die tops that have an upper surface shaped to the desired powder contour. The first die top has a curved surface for the fuel contour. The second has a flat upper surface for the filler but a curved lower surface to fit on the lower die top.

Compacting is performed with the die set, inner die, and inner die top (shown in Figs. 13 and 14). Die components are conditioned between pressings by removing any gross pickup with a razor blade and wiping with tissue [When pickup is severe, this procedure is followed by swabbing with caustic solution, wiping with water, wiping with alcohol (coating the die cavity lightly with a solution of 10% stearic acid and 90% methylene chloride). The coated cavity is wiped with a clean lint-free cloth. Even in the absence of pickup, this cleaning procedure is repeated routinely.]

Fig. 13. Tooling for making HFIR contour core compacts.

Fig. 14. Compacting die on die base and jack.

Just before the fuel charge is loaded into the die cavity, the fuel charge bottle is hand tumbled for five to ten revolutions to eliminate any segregation that may have occurred since blending. Fuel charges are loaded into the assembled die with the fuel (lower) die top in place. The jar containing a fuel compact charge is emptied into the die top cavity by pouring slowly with a minimum fall to prevent compacting. The cavity is filled to the contoured surface as

evenly as possible. A stainless steel leveling tool is used to smooth the blend to the same shape as the contoured surface of the die top (as shown in Fig. 15). The jack under the lower punch is adjusted to raise or lower the charge to the height just necessary to completely fill the die top cavity. The leveling tool is used in a back-and-forward stroke. The powder is moved across the die top by gathering it on the flat portion in front and then pushing with the leveling tool. At no time should the powder charge be tamped or patted, because this will increase the density of the powder in this area and result in a locally higher concentration of fuel in the final plate.

Fig. 15. Contouring the fuel section of the HFIR compact.

With the leveling of the fuel portion of the compact complete, the die top for the filler portion of the compact is assembled upon the fuel portion die top. The leveled fuel charge is raised slightly to provide a rolling down of the periphery. A jar containing a filler charge is opened, and approximately 20% of the charge is emptied onto the die top adjacent to the cavity edge with the greatest depth. The lip of the jar is used to gently push the emptied charge into the cavity in such a way that the surface of the fuel charge is not disturbed by the falling powder. This procedure is repeated until approximately 50 to 60% of the powder is pushed into that side of the cavity or remains mounded on the die top. The die is then rotated 180° and the process repeated for the opposite cavity edge (as shown in Fig. 16). Another leveling tool is used with the threaded jack to adjust the level of the charge to the top of the cavity (as shown in Fig. 17).

Fig. 16. Loading the filler section over the HFIR fuel core.

Fig. 17. The final leveling of the HFIR composite core.

The entire charge is smoothly lowered into the die cavity and the die tops removed. A top punch is inserted into the die cavity. A dummy-block is placed on the top punch and has two functions: (1) to protect the top punch and (2) this dummy-block has a slight taper and is positioned with the thickest portion of the taper on the hump edge of the die. The fuel section being graded across the width of the finished plate causes a density difference and during compacting the tapered dummy-block compensates for the density difference so that a uniformly thick compact can be produced. The compact is pressed at about 2600 psi to produce a thickness that is 0.04 mm (0.0015 in.) less than the desired annealed compact thickness (as shown in Fig. 18).

Fig. 18. Pressing the HFIR fuel core at approximately 22 tons per square inch.

The compacts are ejected and then identified by scribing a number on the filler side at the thin fuel edge. They are placed in a clean storage rack and stored in a vacuum box at about 0.05 torr (50 μ Hg) pressure. Compacts are handled only with rubber gloves.

This operation is very critical, and extensive operator qualification is required. This qualification consists of making aluminum compacts that for examination are separated at the fuel-filler interface. The separation is achieved by adding a thin layer of talc between the fuel section and the filler section during compacting. An analysis of this interface provides a preliminary determination of the operator's capabilities; a smooth continuous interface is required. Acceptable and unacceptable compacts are shown in Figs. 19a and 19b. A small amount of rollup on the edge of the fuel section is permitted. No disruption of the fuel section, such as splashes or leveling-tool marks, is permitted.

Fig. 19a. An acceptable HFIR compact.

Fig. 19b. An unacceptable HFIR compact.

5.3 VACUUM ANNEALING

To remove the lubricant entrapped during pressing and any moisture picked up during handling, all pressed compacts are vacuum annealed (as shown in Fig. 20). For this operation, the compacts are placed on cleaned stainless steel screens in a stainless steel annealing tray and then placed in a horizontal vacuum furnace equipped with a water-cooled outer wall and an ion pump. The furnace is programmable. The tray is loaded into the furnace, and the furnace evacuated to less than 1×10^{-4} torr (0.1 μ Hg). The leakage must be maintained at less than 2×10^{-3} torr (2 μ Hg) over a 4-minute period with the pumps isolated. The compacts are annealed at $590 \pm 10^\circ\text{C}$ ($1094 \pm 18^\circ\text{F}$) for 4 hours. The pressure must stay less than 1×10^{-4} (0.1 μ Hg) during the 6.5-hour cycle.

Fig. 20. HFIR compacts and annealing tray.

The annealed compacts are removed from the furnace slightly above room temperature to avoid condensation from collecting on them. They are visually inspected and returned to vacuum storage. Compacts must be hot bonded within 4 days after vacuum anneal or they have to be re-annealed. Compacts are handled whenever possible with stainless steel tongs. The maximum furnace load is 4 lots or 96 compacts.

5.4 COMPACT INSPECTION

One-hundred percent of the compacts from each lot of 24 are inspected for length and width with a dial-indicator inspection gage. These measurements are recorded. If a new compacting die is being used, the first two lots of compacts are inspected 100% with micrometers. All compacts are measured for thickness at the four corners. The thickness values for compacts are recorded. All compacts are examined for surface and edge defects and contamination. All compacts are weighed to ± 0.01 g and the weights are recorded. Weights must be within the specified limits established by the control charts. All inspectors handle compacts with rubber gloves. Compacts are returned to vacuum storage after inspection.

6.0 FUEL PLATE FABRICATION

6.1 PACK ASSEMBLY

To provide the required dimensional control while the cores are converted into plates and at the same time to provide complete sealing of the fuel, a picture-frame technique is employed. The frame provides both lateral support and material for the edge cladding. The compacts and frames are bonded to the covers by hot bonding.

Picture frames and cover plates are wiped with alcohol and further cleaned in an automatic cleaning station, which uses a water-based biodegradable detergent. Care is taken in stacking the frames and covers so that the faces are not in contact with the stainless steel rack or other pieces. The cleaning fluid is changed each day. Cleaned parts are handled with clean white cotton canvas gloves and are wrapped in clean Kraft brown paper in what will be a rolling lot.

The frames and covers are etched using a tank of 295 gal (0.65 lb/gal) solution of Oakite 160⁵ and water. This tank is kept at 71 to 77°C (160 to 170°F). The components are etched for about ½ minute, or enough time to remove 0.046 to 0.056 mm (0.0018 to 0.0022 in.). Note: This excess material must be left on the frames and covers during rolling the stock to gauge.

The frames and covers should be agitated at least twice during the etching process. After sufficient material has been removed, they are rinsed in cold deionized (DI) water that has a beginning resistivity of greater than 1.0×10^6 ohms. The frames and covers are now black and must be put into the nitric acid bath, which is reagent grade, 42 Baume, 70% (1.4 specific gravity) in the proportion 4.5 kg/L (37.5 oz/gal) of DI water for 2 minutes to remove the discoloration. Then the frames and covers are rinsed in DI water. We use ultrasonic cleaning heads in this tank to help remove residual black smut that was not removed by the nitric acid. At this point, it is advisable to go back to the Oakite solution for 5 seconds, repeating the process through the nitric acid to further facilitate removal of the surface contamination, then rinsing in DI water for 30 seconds. Next, rinse in hot water at 71 to 77°C (160 to 170°F) for 10 seconds or until hot. DO NOT dry with forced air. DO swing the frame and cover plate holder in air until the components are dry. Regardless of how clean plant air is, it is not clean enough. As the frames and covers are removed from the rack, they must be observed by the etching room operator. Any discoloration or appearance of embedded material is cause for rejection. When a bath is reconstituted or a new bath is made up, a single plate is etched and heated in the rolling

⁵Oakite 160 is a product of Oakite Products, Inc., 50 Valley Road., Berkeley Heights, NJ 07922.

furnace for 30 minutes, or until it reaches the rolling temperature. Any discoloration of the sample plate is cause for rejecting the nitric acid bath. Nitric acid can be contaminated with organic materials. During all of the etching operations, some agitation of the frames and covers is desirable. When the frames and covers are dry, they are wrapped in brown Kraft paper. Any handling of frames or covers after cleaning should be while wearing clean white gloves and handled by the edges only – never by the frame cavity.

The frames and covers are transferred to the assembly area and laid out in numerical order as shown in Fig. 21. Note that cotton gloves are worn when handling the frames and covers, and the frames are never handled by the cavity. The compacts are handled using tongs (Fig. 22). The frame is laid on the bottom cover. When everything is laid out in order, the compacts are inserted into the frames in numerical order to maintain accountability of materials. When all of the frames are loaded (2 components per frame), the top cover is laid on the assembly. A vibratool is used to premark the outside of each top cover with the lot number, compact number, and an *X* marks the hump side of the compact. This is done in a separate area. Each assembly, in turn, is carefully aligned and inserted into a welding vise (Fig. 23). The edges and ends of the packs are welded leaving a 19-mm (3/4-in.) gap at each corner and a 38-mm (1 ½ -in.) gap on what will be the trailing end on the first pass of the hot bonding. This is done in a separate area. After welding, the pack assemblies are held under vacuum until its time to load and roll the pack assemblies into plates (Fig. 24). Other gaps may be left as needed to vent the compact on the first rolling pass.

Fig. 21. Frames and covers ready to receive fuel compacts.

Fig. 22. Loading the frame with a compact.

Fig. 23. Welding frames to covers after compact loading.

Fig. 24. Assembled billets vacuum stored and ready for hot bonding.

6.2 HOT ROLLING

The assemblies are next hot-rolled to convert the pack assemblies into plates and to provide a bond between the cover plates and the frames and compacts. Hot rolling was selected as the method of reduction so as to minimize fuel particle fracturing and stringering and to improve the necessary bond quality. A minimum of 20% cold work was required for reproducible forming; otherwise, all hot working was used.

The assemblies are preheated for 1 hour at 482 ± 5 to -10°C ($900 \pm 13^{\circ}\text{F}$) in an electric furnace with a hot-air circulation blower. Temperature is critical. Lower temperatures result in nonbonding and higher temperatures result in less stable control of fuel width. A (330 mm $\times$ 406 mm (13 $\times$ 16 in.) hot rolling mill employing flat rolls is used for hot bonding. A roll guide is used at the entrance side of the mill. The heated rolls are kept clean and lubricated using Procedure 2 in Appendix D.

Before any plate is rolled, the rolls are heated to at least 54°C (180°F) to ensure stable rolling conditions for the entire lot. If the rolls have cooled, they are surface conditioned by rolling six 127-mm-wide $\times$ 304-mm-long $\times$ 13-mm-inch-thick (5-in-wide $\times$ 12-in.-long $\times$ ½-in.-thick) pieces of type 6061 aluminum plate that have been preheated to 482 ± 5 to -10°C ($900 \pm 13^{\circ}\text{F}$) for 30 minutes. These roll-conditioning blanks are rolled to essentially the same schedule as the fuel billets (see below). The blanks are further reduced to 0.5 mm (0.021 in.) by

taking reductions to give gages of 1.3 mm, 1.1 mm, 0.9 mm, 0.76 mm, and 0.5 mm (0.052-in., 0.043 in., 0.036 in., 0.030 in., 0.025 in., and 0.021 in.). The blanks are reheated 5 minutes between successive passes. The rolls must show a coating of aluminum oxide to prevent sticking of the billets. If the blanks remain flat and are free of roll defects, the rolls are properly conditioned. The rolls are lubricated with a combination of Pennacle cylinder oil⁶ and mineral spirits in a ratio of one part oil to three parts mineral spirits.

The preheated plates are rolled with the top cover up for the first pass and then flipped end for end on each succeeding pass. Plates are removed from the furnace and fed into the mill with tongs (as shown in Fig. 25). The catcher wears chain mesh gloves⁷ over two pairs of 8-oz. cotton canvas gloves and handles the plates with his gloved hand (as shown in Fig. 26). Plates were marred when attempts were made to catch them with mechanical devices; when asbestos gloves were used, particles flaked off the gloves onto the plates and were rolled into them. The hot-rolling schedule is given in Table 2. It was selected to provide reliable bonding with a minimum of fuel stringering.

Fig. 25. Hot bonding HFIR fuel plates, entry side.

Fig. 26. Hot bonding HFIR fuel plates, exit side.

Tungsten-carbide-tipped hot micrometers are used for measuring plate thickness after each pass. After the seventh pass, the tandem plates are sheared in half and about 51 mm (2 in.) is trimmed from each end on a three-bladed hand shear (shown in Fig. 27). The top of each plate

⁶A trade name of Texaco, Inc., 135 East 42nd Street, New York, N.Y.

⁷The chain mesh gloves are the extra large size manufactured by Whiting and Davis Company, Plainville, Mass.

is stamped with the plate identification number by use of an automatic numbering head. After the last plate has been sheared and inserted into the furnace, the plates are reheated for an additional 10 minutes and rolled to a final gauge of 1.61 to 1.58 mm (0.0635 to 0.0675 in.). After pass 11, the plates are placed in a rack and annealed for two hours at 500 +5 to -10°C (927 ± 13°F) in an electric furnace with air circulation. The plates are visually inspected for blisters. A plate is scrapped if a blister appear on any portion of the plate that will remain after blanking to final dimension.

Fig. 27. Shearing duplex fuel plates at the seventh pass.

Table 2. Hot rolling schedule for HFIR fuel plates

Pass	Reduction			Gage ^a		Roll heat time (min) preheat 1 h
	%	mm	in.	mm	in	
1	19	2.4	0.093	10	0.395	10
2	19	1.9	0.075	8.1	0.320	10
3	23	1.87	0.074	6.2	0.245	5
4	24.5	1.5	0.060	4.7	0.185	5
5	22	1	0.040	3.7	0.145	5
6	21.5	0.8	0.031	2.9	0.114	5
7	19	0.5	0.021	2.4	0.093	10
8	13	0.36	0.014	2	0.079	5
9	10	0.2	0.008	1.8	0.071	5
10	10.5	0.18	0.074	1.61–1.63	0.0635–0.064	0
11	Same mill setting as Pass 10.					
^a Values shown are at temperature.						

6.3 COLD ROLLING

To provide the close control and uniformity of thickness required for the forming operation, the final plate reductions are done cold. The amount of cold work specified was found to be necessary to provide a uniform condition throughout the plate after the subsequent anneal. Smaller amounts resulted in poor forming reproducibility, and larger amounts caused excessive fragmentation and stringering of the fuel.

The plates are cold rolled with either a 330 × 4.06 mm (13 × 16 in.) or a 330 × 304 mm (13 × 12 in.) cold rolling mill with flat-ground rolls as shown in Fig. 28. The rolls are kept clean and lubricated by procedure 2 in Appendix D. Cleanliness is extremely important in this operation and roll wipers are used. The plates are cold rolled in accordance with the schedule in Table 3, with four passes at each mill setting. The same roll lubricant is used as is used for the hot rolling.

Fig. 28. Cold rolling HFIR fuel plates 20%.

Table 3. Schedule for cold rolling of fuel plates

Passes	Reduction			Gage	
	%	mm	in.	mm	in.
1–4	5.6	0.089	0.0035	1.51	0.0595
5–8	3.5	0.051	0.0020	1.46	0.0575
9–12	3.5	0.051	0.0020	1.41	0.0555
13–16	3.5	0.051	0.0020	1.36	0.0535
17–20	2.8	0.05	0.0015	1.32	0.0520
21–24	1.9	0.025	0.0010	1.29	0.0510
24–28	1.9	0.025	0.0010	1.28	0.0505

After each pass during the rolling operation, the thickness of one plate per lot is measured with a deep-throat micrometer in three locations over the fuel, and the average is used as the plate gage. The three measurements are not permitted to differ more than 0.0254 mm (0.001 in.) from each other. The maximum plate camber permitted on completion of rolling is 0.254 mm (0.010 in.).

The plates are detergent cleaned while held in an aluminum rack. The degreased plates are flatten annealed in two stacks of 60 fuel plates each between 31.7 mm (1-1/4 in.) thick aluminum platens for four hours at 500 ± 5 to -10°C ($927 \pm 13^{\circ}\text{F}$) in an electric furnace with an air circulator. To obtain the zero temper condition, the plates are furnaced cooled to 100°C (212°F) at a maximum rate of 27°C (48°F) per hour. The plates are cooled to room temperature outside of the furnace before the platens are removed.

6.4 HUMP LOCATION

Fig. 29. Hump locator for HFIR fuel plates.

The plates are checked for fuel hump orientation by means of a Panametric 25DL thickness gauge,⁸ shown in Fig. 29. Calibration is checked at least once an hour. Both sides are checked for conductivity, with the unnumbered (fuel) side showing the lower conductivity reading. The numbered side of the plate is transversely scanned, and the "fuel hump" is located by the lowest conductivity reading; it should be displaced

toward the operator with the number to the right of the operator. When necessary, the plate is reinscribed to show the correct fuel orientation. The fuel contour of the outer fuel plate is sufficiently asymmetric to allow easy identification of the reference edge. However, the fuel contour of the inner fuel plate is close to symmetric and the reference edge is difficult to identify. On rare occasions, the fuel hump cannot be located on the inner annulus fuel plate by the conductivity probe. When this occurs, a Vidigage, using a 4 to 8 Mc oscillator and 9-Mc transducer, is used to determine the fuel hump. The fuel plate is transversely scanned with the use of a water coupling, and the area with the maximum reading is the fuel hump.

6.5 PLATE INSPECTION

At this point in the process, extensive inspection starts. Plates must be handled very carefully from this step on throughout the rest of the process to prevent bowing or kinking. All

⁸Magnatest FM 100, designed and manufactured by Magnaflux Corp., Chicago, Illinois.

operators are instructed on ways to pick up and lay down plates to prevent them from sagging.

The flat plates are inspected visually for blisters and surface damage before and after each operation by the operators, as shown in Fig. 30. The hump location is performed before fluoroscopy and sizing.

6.6 FLUOROSCOPY

The fuel plates are prepared for subsequent blanking and homogeneity scanning operations by punching alignment holes. To permit proper positioning, the fuel outline of the core is revealed by fluoroscopy. A Norelco MG 150 X-ray unit, shown in Fig. 31, is used as the power source. Settings for this unit are 135 ± 5 kV and 12 ± 1 ma. Clear plastic templates with tungsten boundary wires, shown in Fig. 32, are placed under the plate. The unit is then turned on, and the fuel boundary is best centered between grid wires in the template. The grid wires are segmented to improve fuel outline resolution. Three holes and one slot are then punched in the plate with the use of a specially designed fixture (as

Fig. 30. Visual inspection of HFIR fuel plates for blisters, scratches, dents, and inclusions.

Fig. 31. Fluoroscope for locating the HFIR fuel plate core.

Fig. 32. Fluoroscope template for inspecting and locating the HFIR fuel plate core.

shown in Fig. 33). The plate is rechecked for proper fuel location before the punches are released and the plate is removed from the fluoroscope fixture. Small inner holes serve as locating holes for the homogeneity scanning operation, and an outer hole and slot serve as locating holes for the blanking operation. It is very important that the fluoroscope punching fixture be matched with the fuel plate blanking die fixture, to avoid an accumulation of tolerances between the two fixtures.

Fig. 33. HFIR fuel plate after fluoroscope showing core locator holes.

The plates are permanently identified by engraving the plate type, lot number, and plate number with a Vibratool in accordance with the appropriate fuel-plate drawing (Appendix A). A template is used for proper location of this number. The specific location of the number serves to identify the reference edge as well as the fuel hump location.

6.7 SIZING

The fuel plates are blanked to size with a 150-ton brake press. A typical blanking die is shown in Fig. 34. The die faces have a recessed portion to permit reduced contact of the plate to die and thus reduce the possibility of a foreign particle being embedded in the fuel plate. The plates are cleaned thoroughly and examined under low magnification for contamination before blanking. After blanking, the plates are transferred from metal trays with interleaved paper to aluminum boxes containing plastic inserts to keep the plates separated as shown in Fig. 35.

Fig. 34. HFIR fuel plate blanking die.

Fig. 35. HFIR fuel plate carrying case with separators.

The holes, edges, and ends of the plate are deburred with a sharp Black Diamond special crosscut file. The holes are chamfered 0.25 mm (0.010 in.) maximum with a short 5.54- to 6.25-mm (7/32- to 1/4-in.) diam drill. The radius on the top edge of the plate is machined and deburred. Each plate is individually clamped firmly in a steel fixture and machined with a contoured high-speed cutter.

The plates are fluoroscopically inspected for proper fuel location by the same technique employed in the punching operation, except that three guide pins are inserted in the template. The plates are positioned against the guide pins. Parrallax corrections are taken into account. If there is a doubt as to the acceptance of a plate, it is designated for radiography.

6.8 RADIOGRAPHY

Three plates per fuel element are randomly selected for radiography, in addition to any plates designated for radiography from the final fluoroscope inspection. Radiographic equipment consists of a Norelco MC 300 x-ray unit in a lead-lined room. The film focal distance is 1372 mm (54 in.). Kodak type *M* film is placed in a hard cassette with 0.127 to 0.254 mm (0.005 to 0.010 in.) back lead. Number 25A penetrameters⁹ are placed on 1.27-mm (0.050-in.) thick pieces of aluminum at opposite corners of the film. Each film is identified by plate number,

⁹Penetrameter identification number 25 for aluminum in accordance with MIL-STD-271A (Ships), March 11, 1965.

date, and operation number. The plates are radiographed at 100 ± 20 kV and 10 ma for a time that produces a film density of 2.0 to 3.0 over the cladding at the ends of the plate. The 2-T holes 0.51 mm (0.020 in. diam) of the penetrameters must be visible.

The fuel plate radiographs are inspected for fuel core location. Film shrinkage and parallax corrections are made for this inspection by sectioning a radiographed fuel plate and actually measuring the widths of the cladding at the edges and ends with a toolmaker's microscope. The radiograph is then measured, and the difference in the measured dimensions and the radiograph dimensions is the bias. As a check, the bias was calculated from the angle subtended from the x-ray source. The cladding widths are checked for acceptance by go no-go templates by use of scribed limits on a radiograph segment that fits the end cladding configuration. Unless all areas of the fuel plate meet the requirements of the specification, the lot of plates is rejected and all plates must be radiographed and inspected. The minimum top and bottom end cladding widths are measured to the nearest 0.127 mm (0.005 in) with dividers and a scale and recorded. The two edge cladding widths are measured to the nearest 0.127 mm (0.005 in.) and recorded for locations 76 mm (3 in.) from each fuel end and at the center of the fuel length.

6.9 HOMOGENEITY

The plates are scanned for determination of uranium homogeneity by an ORNL-supplied x-ray scanner¹⁰ (shown in Fig. 36). The scanner system measures the intensity of an x-ray beam transmitted through the plate and, by comparing this signal intensity to that obtained from known x-ray attenuation standards, provides a measure of uranium concentration. The condenser circuit is designed such that an instantaneous but continuing change of +15% from nominal will reach an average value of +10% in approximately 12.7 mm (0.5 in.) of travel when a 1.98-mm (5/64 in.) diam beam is used

Fig. 36. HFIR fuel plate homogeneity scanner.

¹⁰B. E. Foster, S. D. Snyder, and R. W. McClung, *Continuous Scanning X-Ray Attenuation Technique for Determining Fuel Inhomogeneities in Dispersion Core Fuel Plates*, ORNL-3737 (January 1965).

with a scan speed of approximately 7620 mm (300 in.) min. The entire plate is scanned longitudinally with transverse indexing that provides a scan with overlap of approximately 0.4 mm (1/64 in.).

Three aluminum standards (+12, -12, +27%) shown in Fig. 37 are placed at each end of the plate holder with the fuel plate in the center. The standards are contoured to have a varying cross section thickness that is equivalent in X-ray attenuation to that produced by the varying uranium loading across a transverse section of a fuel plate. One standard is used for each limiting inspection value of fuel concentration. As the standards are scanned, the electrical signals that represent the x-ray attenuation are stored. As each traverse is made over a fuel plate, the attenuation of the plate is compared to the attenuations of the standards. All plates are scanned at 7620 mm (300 in./min) with the following standards: +27% spot and $\pm 12\%$ average. If a signal is received that exceeds the standard signal, the machine circuitry is tripped and prints out on a chart the location of the fuel limit violation. Red ink signifies a spot violation, green ink at +12% average violation, purple ink a -12% average violation, and blue ink an indication of fuel in the unfueled zone of the plate. All plates that are rejected for +12% indications are rescanned at 7620 mm (300 in./min) with +30% spot and $\pm 10\%$ average standard. The track that shows the +27% indication and the two adjacent tracks are scanned at 1626 mm (64 in./min) with a hard-copy readout of the actual instantaneous signals. Once a week, the machine is calibrated against a series of aluminum and uranium-aluminum standards (shown in Fig. 38). This calibration checks whether the attenuation of x-rays in the aluminum and in the aluminum-uranium samples is maintaining a constant ratio to each other. Before each plate is run, the machine is calibrated for voltage drift against a tool-steel standard. The

Fig. 37. Homogeneity scanner standards for scanning HFIR fuel plates.

Fig. 38. Standard calibration plate for the homogeneity scanner.

strip chart is adjusted to record predetermined values for two settings on the tool-steel standard, chosen to cover the full-scale range. The machine is checked for "trigger" response to ensure reject levels per specified accuracy before the start of each shift and after every lot by scanning an aluminum standard plate. The aluminum standard plate is designed to trigger local and average violations at known locations.

One scanner¹¹ has been converted to a digital unit with a small computer to analyze the data. Under normal operation, the accumulated data is the same as the analog scanner; however, when infractions accrue +12% average or +27% spot, this scanner will give the degree of the infraction. It is not a simple go no-go machine. The digital machine also allows one to scan a fuel plate, collect the data on a CD to be reproduced on a PC. This is an excellent tool for evaluating contoured fuel. We anticipate the use of more complex acceptance criteria based upon the thermal hydraulic calculations.

6.10 ULTRASONIC INSPECTION

The entire surfaces of the plates are inspected ultrasonically for bond defects. An immerscope, reflectoscope, or equivalent piece of equipment is used with lithium sulfate or ceramic transducers operating at 5 Mc. The beam size on the fuel plate is 2.54 mm (0.100 in.), the index between scans is 1.27 mm (0.050 in.), and through transmission is employed with water couplants. The equipment is calibrated against a standard defective plate at the beginning of each shift or after the equipment has been idle for more than 4 hours. The standard plate is a normal production plate that has seven flat-bottom holes drilled to a depth of about 0.25 mm (0.010 in.) (cladding-to-fuel interface). These holes are filled with Armstrong epoxy A-12 or Apiezon wax (shown in Fig. 39). The holes are 1.6 mm (1/16 in) in diameter, two on each side of the plate, and are drilled over the fuel portion of the plate. Two holes, one on

¹¹B&W Report.

each side of the plate, are located over the "hump" region of the plate. Three holes, 3.17 mm, 2.36 mm, and 1.6 mm (1/8, 3/32, and 1/16 in.) in diam, are located on the end cladding portion of the fuel plate. The equipment is calibrated such that two lines on electrostatic recording paper are broken by the 1.6 mm (1/16 in.) diam holes over the fuel portion and by the 3.17 mm (1/8 in.) diam hole over the cladding portion.

Figure 40 shows a typical scan of a defective plate.

6.11 ALPHA COUNT

The first two plates from each lot of 24 are alpha counted to ensure that during manipulation, the fuel plates have not picked up surface contamination or been heated to a temperature sufficient to permit uranium to diffuse to the surface. The maximum surface contamination allowed is the equivalent of 5 μ ^{235}U per square foot of surface area. A 20-min background count is taken.

If one lot of plates is rejected for an excessive alpha count, the plate thicknesses of two randomly selected plates are measured at nine locations and recorded. The entire lot of plates is cleaned ultrasonically in cold deionized water for 1 min, rinsed in hot water, dried, soaked in 50% HNO_3 -50% water for 1.5 min, rinsed in cold water, rinsed in hot water, and dried. The two sample plates are reinspected for plate thickness at the same nine locations. The lot of plates is accepted if the difference in average plate thickness before and after cleaning does not exceed 0.008 mm (0.0003 in.) and if the original two plates and two additional plates have acceptable alpha counts.

Fig. 39. Ultrasonic inspection standards.

Fig. 40. Ultrasonic scanner readout showing a defect in a fuel plate.

6.12 DIMENSIONAL INSPECTION

The fuel plates are inspected dimensionally and for surface defects in accordance with drawings 8-7146 and 8-7148 in Appendix A. Each fuel plate is inspected visually for proper identification number, proper location of identification number, end radius, and surface condition including presence of blisters. A depth microscope is used to determine depths of questionable surface defects.

Three plates from each lot are inspected for length at two locations, width at three locations, camber, and squareness, edge parallelism, and edge straightness. One plate from each lot is inspected at both ends for distance from the center line of the 3.17-mm (0.125-in.) diam holes to the reference edge of the fuel plate. Three plates are inspected for thickness to the nearest .003 mm (0.0001 in.) at nine locations per plate with specially made 76.2 mm (3 in.) deep throat micrometers with nonrotating spindles having chamfered edges. The nonrotating spindle is necessary to prevent cutting of the fuel plates. All of these dimensions are recorded.

Three plates are inspected for thickness at three locations along the plate longitudinal center line. The three measurements must be within the drawing thickness tolerance, and the difference or range between the measurements cannot exceed 0.015 mm (0.0006 in.) for any plate.

6.13 DESTRUCTIVE EXAMINATION

One fuel plate from each quantity sufficient for one fuel element is selected for destructive testing of cladding dimensions and bonding. The plate is scribed in accordance with sectioning diagrams, and an identifier is Vibratooled on each section. The samples are sheared and punched from the fuel plate.

The metallographic samples are deburred, and the thickness of each piece is measured and recorded. To permit anodizing, each sample is mounted between backup strips of aluminum with suitable screws and nuts. The assembly is rough ground to remove evidence of shearing and is mounted in Quick-Mount. The samples are prepared for examination by grinding through 600-grit paper, polishing with 600-grit aluminum oxide powder on *A. Beuhler* billiard cloth, polishing with 6- μ diamond on *A. Beuhler* Metcloth, polishing with magnesium oxide on *A. Beuhler* Microcloth, and anodizing for 30 to 45 sec in 4% aqueous HBF_4 with an *A.*

Beuhler electropolisher. The thickness of each piece is remeasured with a toolmaker's microscope, and if this measurement differs more than 0.013 mm (0.0005 in.) from the measurement taken before the samples were mounted and polished, the mount is repolished.

The top-cladding, fuel, and bottom-cladding thicknesses are measured at 75 × under bright-field illumination with a toolmaker's microscope. Each longitudinal sample is measured in two locations and each transverse section is measured in ten locations. The average top- and bottom-cladding thicknesses are measured. The minimum top- and bottom-cladding thicknesses are measured and recorded by scanning each section separately. These thicknesses are compared with control charts. The edge cladding widths and fuel width are measured and recorded for information for each of the transverse samples. Each sample is inspected for bond integrity at 30 × magnification under polarized light. There can be no visible separation between the bonding interfaces, and grain growth must be evenly distributed across a minimum of 50% of the aluminum-to-aluminum portion of the interface length.

6.14 BORON HOMOGENEITY

From the inner plates, 12.7-mm (½-in.) diam boron samples are selected according to an established pattern, punched, and analyzed for total boron content. Each sample must be within limits established by control charts. An ORNL procedure entitled, "Determination of Boron in Punchings from HFIR Fuel Plates," dated December 11, 1963, by W. R. Laing and B. Philpot¹² is used for the analysis. Essentially, the punchings are dissolved in HNO₃-HCl solution; the B₄C is separated by filtration and then solubilized by carbonate fusion. The boron is separated from interfering elements by ion exchange¹³ and determined by a potentiometric mannitol-sodium hydroxide titration.¹⁴

¹²Unpublished procedure available from Analytical Chemistry Division, ORNL.

¹³F. M. Hill, "Ion Exchange Separation of Boron from Other Elements," Method No. 1 00701 (R. 6-16-63), *ORNL Master Analytical Manual*, TID-7015, Suppl. 7 (March 1965).

¹⁴F. M. Hill, "Boron (Borate), Potentiometric Mannitol-Sodium Hydroxide Titration Method," Method Nos. 1 211220 and 9 00711220 (R. 5-15-63), *ORNL Master Analytical Manual*, TID-7015, Suppl. 7 (March 1965).

7.0 PLATE FORMING

Fuel plates that survive the rigorous testing program described above are cold formed into the desired involute shape by a modified marforming technique. A male die pushes the plate into a partially contained Elastacast or rubber, as shown in Fig. 41. A 150-ton press brake is used with a fixed-stroke setting. The press gap is set so that when the press is cycled the punch forces the fuel plate into the elastomer sufficiently to cause the fuel plate to wrap around the punch. The punch contour is designed to accommodate sufficient fuel plate spring back to produce the prescribed involute shape. The punches are made according to the criteria given in Table 4.

Fig. 41. Polyurethane elastomer for forming HFIR fuel plates.

Table 4. Criteria for shapes of forming punches

Type of Fuel plate	mm	Radius of base for circle punch form (in.)	Rotation (°)	mm	Radius of base aide for fuel plate form (in.)
Inner	49.21	1.9375	15.477	69.11	2.721
Outer	93.66	3.6875	37.767	149.23	5.875

A 6.35 mm (0.250-in.) flat extending toward the center of the base circle is added to the above involute forms, with the flat rotated 5° for the inner punch. The forming medium consists of two pieces of medium-grade (90 A durometer) Elastacast¹⁵ or equivalent material. The two

¹⁵Manufactured by Acushnet Process Company, New Bedford, Mass.

pieces are 75 mm (2 1/4 in.) and 6.4 mm (1/4 in.) thick and located such that the 6.4-mm (1/4-in.) piece is in contact with the fuel

plate. Before the plate is placed in the forming die (as shown in Fig. 42), the Elastacast, forming punch, and plate are thoroughly cleaned to prevent embossing of the plate by foreign material. Every sixth plate is trial fitted between assembled fuel element side plates to ensure proper fit of the fuel plate with the slot angles of the side

plates. The trial fitting is necessary because the involute inspection does not measure the shape of the plate edges. The inner edge of the plate may have a slight variation in angle when the plate is shifted in the forming die to produce the same involute inspection readings as described below. This variation in angle on the inner edge of the fuel plate is caused by the high variation in curvature across the forming due punch in the neighborhood of the inner edge and the need for lateral adjustment to compensate for variations in formability between different lots of plates. The lateral adjustment affects the inner edge of the fuel plate in two ways: (1) it shifts the fuel plate laterally in the area of greatest curvature variation causing an angle difference from the desire angle and (2) the elastomer pushes the fuel plate into the punch at a different radial position, causing a different spring back when the plate is released.

As the plates are formed, they are inspected for involute shape with an involute gage, as shown in Fig. 43. The dial indicators of the gage are calibrated on involute standards at the ends of the gage. Inner fuel plates are measured at four locations across the width and at seven locations along the length. Outer fuel plates are measured at three locations across the width and at seven locations along the length. All

Fig. 42. HFIR fuel plate forming die.

Fig. 43. HFIR fuel plate involute inspection fixture.

measurements are recorded. Each plate must be formed with all dimensions within 0.38 mm (0.015 in.) of the true involute shape and with the individual reading within 0.20 mm (0.008 in.) of the process nominal for that location.

Occasional lots of fuel plates do not form the same as the bulk of the fuel plate lots. When these lots occur, they are detected by the deviation shown in the inspection measurements. To correct this condition, the location of the plate is shifted in the forming die to produce the same involute readings on all fuel plates. Adjustments in the plate stops in the forming die are provided to permit these changes. Adjustments are made by moving the fuel plate back from the front edge of the forming punch when the fuel plate is over forming and vice versa.

The formed plates are inspected for proper orientation by ensuring that the identification number is on the convex surface of the plate. The plates are inspected for chord width at three locations, ½ in. from each end and at the center. All measurements are recorded and compared against control limits established for the process. Each fuel plate is inspected for surface defects.

8.0 FUEL ELEMENT MANUFACTURE

The fact that an entire HFIR core assembly contains only two fuel elements means that each element contains many more fuel plates than is customary in more conventional reactors. Therefore, a severe economic penalty occurs if an element is rejected for any cause. In addition, repair is very difficult and fraught with the danger of only making things worse. The assembly techniques have therefore been selected with reliability as the major criterion. Not all of the fuel elements have met all of the specifications. However, deviations have been minor and all fuel elements to date have run at full power.

The financial burden of this type fuel element requires that extreme care be taken in all phases of manufacture by extremely competent operators.

Whenever possible in-process inspection has been incorporated rather than waiting on a final inspection; such a final inspection is, however, also specified. The fuel elements are fabricated in accordance with B&W drawings 8-7213 and 8-7214, shown in Appendix A. The fuel element fabrication process flow chart is shown in Fig. 44. Cylindrical inner and outer side plates are machined from extruded-type 6061 aluminum tubing in the T6511 temper. Weld grooves are turned on one side of each tube and slots are milled on the other. The fuel plates are then assembled by being slid into the slots of the side plates. Dimensional control is aided by Teflon inserted between the fuel plates in the channels. The fuel plates are attached to the side plates by MIG (metal inert gas) welding with type 4043 aluminum filler wire. The outside tube of the fuel element is shrunk at the ends to compensate for the relatively smaller amount of weld shrinkage there than at the middle of the element. Similarly, the inside tube of the outer fuel element is expanded at the ends as required. The fuel element is inspected for weld quality and for channel spacing.

Adapters of type 6061 aluminum tubing are welded to the element by the MIG process with type 4043 aluminum filler wire. The fuel elements are final machined, engraved, inspected in the restrained and unrestrained conditions, cleaned, and prepared for shipment.

Because of the close tolerances, the large dimensions, and the large thermal expansion coefficient of aluminum, the machinist must compensate for temperature variations. All dimensions are referenced to 20°C (68 + 1°F), and all final inspections are done at this temperature. Most of the machining operations are performed in an air-conditioned room maintained at 20°C.

Fig. 44. Fuel element fabrication flow chart.

Carbide cutters are used for machining operations. All components are machined with Trim,¹⁶ lubricant free of chlorine, sulfur, and phosphorus. After assembly, the fuel elements are machined dry except for the occasional use of isopropyl or ethyl alcohol on finish cuts. The alcohol improves the surface finish.

Turning and similar operations are performed at about 200 rpm for inner fuel elements and at about 150 rpm for outer fuel elements. Less chatter occurs for the smaller diameter components and permits the higher speeds. Feed rates are about 0.2 mm (0.008 in.) per revolution for roughing cuts and 0.08 mm (0.003 in.) per revolution for finish cuts. Roughing cuts are about 1.27 mm (0.050 in.) and finish cuts are 0.127 to 0.254 mm (0.005 to 0.010 in.). All weld grooves are machined in two cuts with formed cutters. Slotting is performed in one cut with a formed cutter turning at about 700 rpm. The feed rate for slotting is about 15 in./min.

Elements are transported on critically safe carts (Fig. 45) from one operation to another. A tall wooden post is mounted within a slot in the base. The post can shift inward or outward and thus permit the placement of an inner or an outer assembly, but not both at the same time.

The elements are removed from a station and placed on the cart by the lifting fixtures (Fig. 46). The fixtures rotate so that the assembly may be picked up and let down in either the vertical or horizontal position. The hinged fixtures are rubber lined to prevent surface damage to the fuel element. To prevent marking on the element by the rubber, the finished assemblies must be wrapped with clean cloth or brown paper before they are gripped with the fixture.

Fig. 45. HFIR fuel element transport carts.

Fig. 46. HFIR fuel element lifting and rotation device.

¹⁶Trim Mist coolant concentrate, a product of Master chemical Corp., 501 West Broadway, Perrysburg, Ohio.

8.1 COMPONENTS

8.1.1 Side plates

The four cylindrical side plates are shown in Fig. 47. They will be identified in the text that follows by the numbers listed in Table 5.

Table 5. Side plate designations

Number	Description
1	Inner side plate — inner element
2	Outer side plate — inner element
3	Inner side plate — outer element
4	Outer side plate — outer element

Fig. 47. HFIR fuel element side plates.

Type 6061 aluminum tubes in the T6511 temper condition are used as the starting material. This temper provides maximum dimensional stability for the finished side plate. This is a T6 condition with a 1.5 to 3% stretch. The tubes are ordered to specifications shown in Appendix C. Note that lower impurity levels are specified for the side plate 4 material than for the other side-plate materials.

The slot dimensions and locations are determined by the following criteria: (1) the nearest approach of the fuel material in the fuel plate shall be a minimum of 1.14 mm (0.045 in.) from either side plate, as measured radially from the fuel-element center line; (2) sufficient aluminum

must be present to remove heat during welding; and (3) the fuel plates shall assemble readily in the side plates. The latter requirement is determined from chord and offset data obtained from formed fuel plates and verified by trial fitting of fuel plates. A chord is defined as the distance between the two edges of the formed plate. Offset is defined as the perpendicular distance of one edge of a formed plate from the opposite edge of the plate. To provide reliable plate attachment, the weld-groove diameters are based on the requirement that the fuel plates shall protrude a minimum of 0.38 mm (0.015 in.) into the weld grooves of the inner side plate and a minimum of 0.89 mm (0.035 in.) into the weld groove of the outer side plate in the assembled element. The three additional grooves in the side plates are wall-thickness-assurance grooves and are machined so that a maximum depth of 0.38 mm (0.015 in.) will extend into the final side-plate thickness. The final element wall thickness is calculated from the final wall-assurance-groove depth on the finished element and the initial wall-assurance-groove depth on the finished side plate.

8.1.1.1 Machining

The as-received tubes are 28-in. long. As received they are mounted in a lathe, as shown in Fig. 48. One end is faced and the inside edge is chamfered $45^\circ \times 6.35 \text{ mm}$ (0.25 in.). The tubes are mounted on bull centers and the outside surfaces are rough turned up to a steady rest diameter. At this point, the outside diameters are $140.44 \pm 0.25 \text{ mm}$ ($5.529 \pm 0.010 \text{ in.}$) for side plate 1, $279.15 \pm 0.25 \text{ mm}$ ($10.990 \pm 0.010 \text{ in.}$) for plate 2, $302.01 \pm 0.025 \text{ mm}$ ($11.890 \pm 0.010 \text{ in.}$) for plate 3, and $447.29 \pm 0.25 \text{ mm}$ ($17.610 \pm 0.010 \text{ in.}$) for plate 4. The tubes are turned end-for-end and the inside edge is chamfered $45^\circ \pm 6.35 \text{ mm}$ (0.25 in.). The tubes are machined to $646.40 \pm 0.76 \text{ mm}$ ($26.630 \pm 0.030 \text{ in.}$) in length to complete the rough machining operation.

Fig. 48. Machining a HFIR side plate.

Fig. 49. Machining the weld grooves in an outer HFIR side plate.

The outside surfaces of side plates 1 and 3 are turned to 139.73 to 139.7 mm (5.501 to 5.500 in.) and 299.72 to 299.69 mm (11.800 to 11.799 in.) in diameter, respectively, and are shrunk into restraining tubes with about 0.08 mm (0.003 in.) interference. The side plates and restraining tubes are remounted on the lathe, the inside is bored to final dimension, and the 24 weld grooves and 3 wall-assurance grooves are machined with form cutters, as shown in Fig. 49.

The insides of side plates 2 and 4 are bored to 251.97 ± 0.025 mm (9.920 ± 0.010 in.) and 418.34 ± 0.025 mm (16.470 ± 0.010 in.) in diameter, respectively. They are then bored on each end to fit 101 mm (4-in.-long) Plexiglas plugs, which are 252.73 mm (9.950 in.) and 419.1 mm (16.500 in.) in diameter, respectively. The Plexiglas plugs are shrink fitted into the tube ends. The outside surfaces of the side plates are turned to final dimensions and the 24 weld grooves and 3 wall-assurance grooves are machined with form cutters. A stepped cutter may be used for roughing if access chatter is experienced.

Every side plate is identified by vibratooling and identification number between one end and the first weld groove. This end is then called the top end of the side plate. Each side plate is inspected dimensionally for concentricity, diameter, weld grooves, and wall-assurance grooves. Concentricity (TIR) is measured at the 27 weld- and wall-assurance-groove locations and recorded. It is measured with respect to the inside surface for side plates 1 and 3 and outside surface for plates 2 and 4. Minimum and maximum diameter measurements are recorded for the 27 weld- and wall-assurance-groove locations. Also, outside and inside diameters are measured at three locations. Weld and wall-assurance grooves are also measured for location, width, and angle.

Side plates 1 and 3 are removed from the restraining tubes by packing them inside with dry ice. The side plates are mounted on mandrels, which consist of two Plexiglas plugs, one mounted on each end of a 76 mm (3-in.) diam steel shaft. The adapter shoulders are turned on a lathe. The outside of each side plate is turned to final diameter.

The Plexiglas plugs are removed from side plates 2 and 4. The concentricity of the plug inner bore to the outer surface on each end is inspected and must be within 0.051 mm (0.002 in.) TIR. Each side plate is shrink fitted into a slotting restraining tube (Fig. 50) and bored to final inside diameter.

Fig. 50. HFIR side plates in restraining tubes for machining.

Every side plate is inspected for concentricity, diameter, and adapter shoulder dimensions. Concentricity (TIR) is measured and recorded at both adapter shoulder locations with respect to the inside surface on side plates 2 and 4 and the outside surface on side plates 1 and 3. Minimum and maximum inside and outside diameters are recorded for both adapters for three locations. Side plate and both shoulder lengths are measured and recorded.

8.1.1.2 Slotting

The side plates are then ready for slotting. This operation is performed with formed cutters. The position of the cutters is mechanically aligned and optically checked, as shown in Fig. 51, to satisfy the slot coordinates. Each slot is indexed by holes machined in the restraining tubes for side plates 2 and 4 and by holes machined in a concentrically mounted template for plates 1 and 3. The total number of holes is equal to one-third the number of slots, and three indexing pin locations are provided for each hole. Side plates 1 and 3 are slotted on a rise and

Fig. 51. Setting up the slotting machine to slot HFIR inner side plates.

fall milling machine with rotating fixed-position cutters, as shown in Fig. 52. Plates 2 and 4 are slotted on a modified horizontal-bed milling machine with rotating fixed-position cutters, as shown in Fig. 53. For identification, a $45^\circ \times 1.6 \text{ mm}$ (1/16-in) deep notch is filed on the land between the first and last slot at the bottom end of each side plate.

Fig. 52. Slotting in inner HFIR side plate.

Fig. 53. Slotting an outer HFIR side plate.

Three locations on eight equally spaced slots are measured for coordinates, straightness, and width. All measurements are recorded. Spacings between the last and first slots and between the first and second slots are inspected. All slots are visually inspected.

The mandrels and restraining tubes are removed from the side plates. The side plates are air dried and wiped with alcohol. All weld grooves are deburred and chips are removed from the side plates (as shown in Fig. 54). The side plates are detergent cleaned and degreased.

Fig. 54. Deburring an outer HFIR side plate.

8.1.1.3 Inspection

The reference surface for all diametral dimensions on the side plates is the adapter shoulder. This surface, being an extension of the side plates at both ends, provides a convenient reference. After side plates 2 and 4 have been removed from the restraining tubes and 1 and 3 from the mandrels, concentricities of the inner surfaces of side plates 1 and 3 and the outer surfaces of plates 2 and 4 are taken with reference to the adapter shoulder. These dimensions are recorded in the flowsheets and used for reference during final machining. All side plates are inspected for burrs, chips, and physical damage. Groove depths and side-plate wall thicknesses are measured and recorded at 12 equally spaced slot locations for the three wall-assurance grooves and weld grooves 2, 12, and 23. Plate protrusion is measured at the same 12 slot locations for the same three weld grooves. Plate protrusion is determined by inserting a 1.4 mm (0.055-in.) thick "Jo" block in the slots and measuring the height of this "dummy" plate above the bottom of the weld groove with a special dial indicator. The dimensional requirements of plate protrusion and side-plate thickness at the wall-assurance grooves are listed in Table 6.

Table 6. Dimensional requirements in slotted side plates

Side plate — plate protrusion		Minimum wall assurance groove wall thickness	
mm	in.	mm	in.
1. 0.69 to 0.84	0.027 to 0.033	0.84	0.022
2. 1.09 to 1.24	0.043 to 0.049	2.29	0.090
3. 0.69 to 0.84	0.027 to 0.033	2.34	0.092
4. 1.09 to 1.24	0.043 to 0.049	2.87	0.113

8.1.2 Adapters

Adapters are rough machined from extruded type 6061 aluminum tubing of T6511 temper, as specified in Appendix C. The adapters are final machined in conjunction with the fuel element to ensure proper mating of components. Note that the impurity levels of the tubing for the two outer adapters of the outer fuel elements are specified at a lower level than the impurity levels for the other tubing. The tubes are sawed or turned to rough length. The outside is turned, one end is faced, the inside is turned, and the other end is then faced to length. The rough machined adapters are returned to storage.

8.1.2.1 Circular Weld-Test Specimens

Circular weld-test assemblies are fabricated along with the fuel elements as an essential quality control measure. They consist of short half sections of side plates in which diminutive dummy aluminum plates are inserted. Three tensile plates are included in each assembly. The plates are held in place by the half section of side plate and a slotted heavy aluminum fixture. The fixture is intended to simulate the heat sink of a full-size element.

8.1.2.2 Component Fabrication

Weld-test ring side plates are fabricated from corresponding side plates; that is, weld-test ring 1 is fabricated from side plate 2, etc. Rejected side plates are used whenever possible. A side plate is mounted on a lathe and cut off with a 0.125-in.-thick cutoff tool in accordance with the drawing. The rings are inspected for length and sawed into two half rings. All edges and slots are deburred. An identification number is Vibratooled on each test ring. The test rings are degreased.

Weld-test plates are blanked from the side strips sheared from the skeleton plate scrap remaining from the fuel plate blanking operation. Weld-tensile plates are sheared to $2 \times 1 \frac{7}{8}$ in. from the side strips and then machined. The pieces are deburred with a file and degreased. Representative samples of the weld-test plates are inspected for width. The weld-test plates are visually inspected for flatness. All the weld-tensile plates are inspected to the drawing requirements.

8.1.3 Assembly

The circular weld-test components are prepared for assembly shortly before a fuel element is to be welded. The weld-test rings, weld-test plates, and weld-tensile plates are pickled and rinsed according to Procedure 1 in Appendix D. A maximum of 0.01 mm (0.0004 in.) of material is removed in pickling. The fuel element weld-test assembly consists of assembling a pair of weld-test rings with associated components, as shown in Fig. 55. Short pieces of about 1.19 mm (0.047 in.) thick Teflon are inserted between the fuel plates to wedge and lock the plates in the correct positions.

Fig. 55. Components for circular weld verification.

8.1.4 Welding and evaluation

The fuel element is assembled using isopropyl alcohol as a lubricant, which getters water from the air. To remove this moisture, the fuel element is baked out in a modified pizza oven for 4 hours at 250°F (121°C). After this bake out, the fuel element is mounted in the welding lathe. The circular weld-test assembly is mounted on the tailstock ring of the assembled fuel element (as shown in Fig. 56). The circular weld test assembly is heated to 135°F (57°C) using a hair dryer and is welded using the same parameters as those to be used on the fuel element. The test-weld fixture is removed from the tailstock and the test assembly allowed to cool. The face and root of each weld segment are inspected visually.

The face of the weld is inspected for cracks, irregular bead contour, oxidation, terminal craters, voids and porosity, amount of fill, and undercut. Any cracks are cause for rejection, except on the terminal crater area. Porosity or voids on the exposed surface cannot exceed half the amount shown on the ASME Boiler and Pressure Vessel Code, Section VIII, Appendix IV, "Porosity Charts of Plates 6.35 mm (1/4 in.) or Less and Size Assorted." The remainder of the weld attributes are accepted or rejected by comparison against a visual weld standard. The root of each weld is inspected for excess sag or warpage of the side plate, gross oxidation, and weld drop-through. Weld droptrough cannot exceed 0.25 mm (0.010 in.) as determined visually.

The force required to break the circular weld-test plates is recorded. The weld-tensile plate is pinned between two flat plates, which in turn are attached to a hydraulically operated mechanism, as shown in Fig. 57.

As the pressure is increased, tension is placed on the tensile weld plate and the pressure is indicated on the gage. The amount of pressure indicated before failure of the tensile sample is shown by a static indicator on the gage. The corresponding hydraulic pressure applied is precalibrated on a Tinius Olson tensile tester. The pressure is converted to force and recorded. A

Fig. 56. Welding the circular weld test units.

Fig. 57. Tensile testing apparatus for checking the strength of the weld.

previous method of determining tensile strength was to hang weights until the tensile sample broke. The minimum permissible force before breaking is 49.9 kg (110 lb).

After the fuel element is welded, the circular test assembly is remounted on the tailstock ring. The test assembly is preheated to 57°C (135°F), and the "after" segments are welded in the same manner as the "before" segments. The "after" weld segments are inspected and the tensile samples are pulled in the same manner as the "before" segments. If one of the weld-tensile plates is pulled out of its slot before the minimum strength is reached, two additional specimens must be welded and tested. This is done to determine the worth of the fuel element and also to determine whether the welding machine is functioning properly.

Fig. 58. Circular weld test plates welded and sectioned.

The circular weld-test segments are machined at the weld center line to expose the longitudinal cross sections of the weld beads, the polished and etched to show weld attachment, as shown in Fig. 58.

Each segment is inspected for plate attachment in accordance with the following criteria. A minimum of 95% of the plates shall be welded to the side plate across the entire thickness of the fuel plate; the other 5% shall be joined for at least 75% of the thickness of the fuel plate.

One unwelded fuel plate is allowed if it

occurs in the start-overlap area of the weld. The segments are inspected for weld overpenetration; the weld metal cannot penetrate more than 0.25 mm (0.010 in.) below the fuel-plate side of the side plate. The amount of weld fill of the groove is measured from the fuel plate side of the side plate. A minimum of 6.36, 7.47, 7.37, and 7.47 mm (0.250, 0.294, 0.290, and 0.294 in.) is required for side plates 1, 2, 4, and 4, respectively.

Before assembly and after all other operations have been completed, components are prepared for assembly. All components must be cleaned and the oxide must be removed from both side plates and fuel plates to assure that the highest quality of weld possible is obtained. In conjunction with these operations, the fuel plates are again inspected for dirt and foreign material that may have been missed in previous inspections.

Side plates are cleaned by Procedure 1 in Appendix D. To speed up fuel-plate cleaning, plates are racked in groups of 12. Teflon spacers at the end of the stainless steel rack prevent

the plates from rotating and touching. The plates are ultrasonically cleaned for 1 min in cold deionized water, rinsed in hot water, and then cleaned by Procedure 1. A maximum of 0.01 mm (0.0004 in.) is removed in pickling.

The cleaned fuel plates are removed from the rack one at a time and examined at 3x magnification for dirt and foreign inclusions. Surface contaminants are removed by a steel scraper, and the scraped area is blended with a fine grade of aluminum wool, rubbed in a longitudinal direction with only sufficient pressure to burnish the surface. Plates with removed inclusions are reinspected for depth of pits where inclusions had been removed.

The procedure for assembling the fuel plates with the side plates has been developed so that its careful repetition by plant operators leads to fuel elements of consistent quality.

A head stock monitoring ring is mounted on top of an exhaust manifold for fume removal. The inner side plate is set on the headstock mounting ring with the top end up. One fuel plate is inserted into a slot on the inner side plate and bottomed on the fuel plate stop. The distance from the end of the slot to the plate is measured with a depth micrometer. It should be 5.46 ± 0.25 mm (0.215 ± 0.010 in.) for side plate 1 and 5.72 ± 0.25 mm (0.225 ± 0.010 in.) for side plate 3. If the depth is wrong, the side plate or fuel plate stop is shimmed as necessary. The inner side plate is then secured to the mounting ring with set screws. The fuel plate is removed and the outer side plate is placed on the mounting ring, top end up. The two side plates are oriented so that the number 1 slots on each side plate are aligned. The number 1 slot is defined as the slot adjacent to the beveled land in a counterclockwise direction. A stainless steel strap is placed between the bottom weld groove and the headstock and tightened with an airplane clamp. A fuel plate is inserted in the reference slots, and the outer side plate is rotated until the fuel plate slides easily in the slots but has a minimum 0 to 0.125 mm (0 to 0.005 in.) amount of side play. The distance from the end of the slot to the fuel plate for the outer side plate is measured with a depth micrometer. It should be 7.29 ± 0.25 mm (0.287 ± 0.010 in.) for side plate 2 and 7.49 ± 0.25 mm (0.295 ± 0.010 in.) for side plate 4. If necessary, the side plate is shimmed to obtain the above dimensions. The top ends of both side plates should be even within ± 0.51 mm (± 0.020 in.).

Plexiglas segments are inserted at the top ends of the side plates to hold the side plates concentric during initial plate assembly. Fuel plates are inserted so that, including the fuel plate in the reference slot, at least one slot in each quadrant or 120° sector is occupied. This should verify that the orientation of side plates permits maximum plate protrusion into the grooves consistent with not forcing the plates down the slots. Isopropyl is used liberally in the slots and on the edges of the fuel plates as a lubricant to prevent galling.

Fig. 59. Loading HFIR fuel plates into side plates.

Fuel plates are inserted with identification numbers up. Until at least ten plates are in each of the three or four sectors, plates are distributed equally among the sectors to ensure a concentric assembly, as shown in Fig. 59. The remainder of the fuel plates is then inserted in any convenient sequence (Fig. 60). The location of each plate is recorded. Location is determined by counting slots sequentially from the number 1 slot in a counterclockwise direction. To facilitate the assembly process, a template is mounted on the inside of the inner side plate and is numbered to identify the slots.

The distances from the ends of the slots in the side plates to the fuel plates are rechecked. Seating of the fuel plates in the slots and spacing of the fuel plates are inspected visually. Plates are repositioned as required. If a particular plate results in poor setting or poor channel spacing even after repositioning, it is scrapped. A random check is made for agreement of fuel-plate locations in the assembly with recorded fuel-plate locations.

The outer side plate is rotated as much as possible in a direction to improve plate seating by tapping the clamp on the stainless steel strap. To help establish proper channel spacing and minimize changes during welding, Teflon strips are then inserted into the channels, as shown in Fig. 61. The Teflon strips are 630 mm (25 in.) long and 5.08 mm (0.200 in.) narrower than the channel width. The strips are varied in thickness at 6.35 mm (1/4 in.) intervals across their width; a thin section is 0.76 mm (0.030 in.) and a

thick section is 1.22 to 1.24 mm (0.048 to 0.049 in.) for the outer element and 1.21 to 1.23 mm (0.0475 to 0.0485 in.) for the inner element. These sections run the full length of the strip. The top end of the strip is cut to give a 12.7 × 12.7 mm (1/2 × 1/2 in.) tab on one corner and the

Fig. 60. Inspectors and operators are both required during assembly.

bottom end has 12.7 mm (1/2 in.) × 45° removed from each corner. The strips are ordered 0.025 mm to 0.076 mm (0.001 to 0.002 in.) oversize and rolled to gage. Each rolled strip is measured for thickness at three locations along its length. The measurements are averaged, and the average thickness to the nearest 0.012 mm (0.0005 in.) is stamped on the strip 25.4 mm (1 in.) from the pointed end. Lubricated with alcohol, the Teflon is inserted with the pointed end down. It is inserted by working in a clockwise direction for the outer element and in a counter clockwise direction for the inner element. This tends to seat the fuel plates and prevent the channels from closing as the insertion of strips progresses. Steel shims were used initially to center the Teflon strips in the

Fig. 61. Loading Teflon spacers to maintain channel spacing during welding.

channels. When the shims were used, the Teflon strips were narrower than the newer ones. Strips are now usually inserted without the aid of shims or guides and are centered visually. During assembly, a lead shield is placed around the element to prevent prolonged exposure of the operators to gamma radiation.

A tailstock mounting ring is installed and locked only to the outer side plate by tightening set screws. The tailstock mounting ring has a spring-loaded pusher to maintain a small amount of pressure on the fuel-plate ends to help prevent the plates from sliding in the slots, as they could otherwise do during handling, heating, and welding.

A long bar wrench, made with two plugs that fit into the holes in the top surface of the tailstock mounting ring, is then used to rotate the outer side plate with respect to the inner side plate in a direction that seats the fuel plates. The tailstock and headstock mounting rings are held firmly in position during rotation to prevent them from lifting off the side plates. This is accomplished by a large bolt, which goes through the center of the assembly and is threaded on both ends to accommodate washers and nuts, which bear against the rings. After rotation, the tailstock ring is now locked to the inner side plate with set screws and the headstock ring is locked to the outer side plate with set screws. The headstock and tailstock rings are checked for cocking and the fuel plates are visually checked for seating before the assembly is released for fuel-plate protrusion measurements.

Plate protrusion is measured with a dial indicator by determining the height of the fuel plate above the bottom of the weld groove, as shown in Fig. 62. Plate protrusion into both side plates is measured for each fuel plate in the center and two outer weld grooves. The measurements are recorded for every 20th plate. Plate protrusion limits are 0.38 mm (0.015 in.) minimum for the inner side plate and 0.89 mm (0.035 in.) minimum for the outer side plate. The outer and inner diameters of the as-assembled elements are measured at 16 locations (32 measurements) are recorded.

Fig. 62. Inspecting fuel plate penetration into the side plate weld groove.

The locations are concentrated on the ends and center of the fuel element. The distance between the inner and outer surfaces at six locations at each end is measured and recorded. These latter measurements must be within a spread of 0.25 mm (0.010 in.).

The side plates are pinned to the mounting rings to help prevent rotation of the side plate with respect to the mounting rings during welding. Three equally spaced 3.17 mm (1/8 in.) diam holes are drilled in each side plate to a depth of about 9.53 mm (3/8 in.). Pilot holes are located in the mounting rings. Then 3.17 mm (1/8 in.) diam roll pins are driven into the plates and seated flush with the mounting-ring surfaces.

An identity number is Vibratooled on the fuel element between the top end and first weld groove on the outer side plate. The fuel element is baked out at 121°C (250°F) for four hours. This removes any residual alcohol or water that may have resulted from the assembly operation.

8.1.5 Welding

The assembly is then mounted on the welding lathe, as shown in Fig. 63. It is lifted and placed in position with an overhead crane with nylon straps and a spreader bar. The headstock mounting ring is bolted to a Micarta drive plate, backed up by a copper grounding ring. Copper grounding straps connect the mounting ring and copper ring. Micarta prevents grounding through the ball bearings of the rotating mechanism. Brushes of 93% silver—7% graphite are held firmly against the copper ring. The grounding system is completed by connecting the brushes to a pipe buried several feet in the ground and to the ground in the welding machine.

Fig. 63. Fuel element in the welding fixture being preheated prior to welding.

The tailstock mounting ring is placed on a steady rest fitted with rollers to permit rotation of the assembly. The height of the rollers is adjustable to permit level mounting of the fuel element. The steady rest slides along the ways of the lathe and is locked in a position to permit free rotation of the assembly. The fuel element is checked for level. A dial indicator is placed on the inner welding torch, and while the element is rotating, its inside surface is indicated at both ends to establish a zero reference. A maximum indication of ± 0.190 mm (± 0.0075 in.) from the zero reference is permitted. The fuel plates are checked visually for proper seating. The mounting rings are checked to be sure that they are not cocked.

Four 500-W quartz heaters are placed inside the fuel element. They are connected to a temperature controller and to a timer that permits from 0 to 100% duty cycle.

The fuel element is heated to 57°C (135°F) prior to welding. While the preheating is being done, the before weld-test assembly is welded and evaluated as described above.

With the temperature at 57°C (135°F), the depth of the spring-loaded pressure ring to the fuel plates is measured in several locations to ensure that the fuel plates did not slide in the side-plate slots during previous operations. Depth measurements cannot vary by more than 0.51 mm (0.020 in.).

Welding is performed with a 400-amp 3-phase full-wave-rectifier Sciaky¹⁷ welder, as shown in Fig. 64. It is capable of metal inert gas (MIG) welding in the constant-current, constant-voltage, and constant-wire-feed modes. The constant-current mode is used for welding the fuel plates to the side plates. Filler wire is 0.76 mm (0.030 in.) type 4043 aluminum purchased to a specification given in Appendix C. The wire diameter is critical and must be maintained as close as possible to the 0.76 mm (0.030 in.) diam to minimize porosity. Separate torches are used on the inner and outer side plates. The inner torch was designed at ORNL and is mounted on the ways of the lathe for horizontal motion. A screw drive is also provided to raise and lower the torch. The outer torch is mounted on a side-beam carriage for horizontal motion. The mounting is slotted, so the torch can be vertically and angularly adjusted by loosening wing nuts, positioning as desired, and tightening the nuts.

Fig. 64. Programmable welding machine for welding HFIR fuel elements.

¹⁷Product of Sciaky Bros., Inc., 4915 W. 67th St., Chicago 38.

Each torch has a separate wire-feed supply. The wire is pulled through a Nylaflow liner in the barrel of the inner torch and is driven at right angles by a wide V-grooved roll and idler roll assembly through a Teflon liner, the nozzle and copper guide tube. The copper guide tube¹⁸ are Linde type 12N27. The roller assemblies are powered by 1/6-hp dc reversible servomotors equipped with tachometers and proportional and integral feedback systems.

Wire-feed speeds are adjustable continuously from 1 to 100 in./min. Allowable wire-feed variation is $\pm 1\%$ from a given setting. Wire approaches the work very slowly when the weld cycle is started and until the arc strikes. The wire then attains an initial preset speed in a maximum time of 5 cycles or 0.08 sec. The initial preset value of wire feed is sloped to the run preset speed after the arc is struck. The slope rate and time are adjustable. An adjustable slope rate is provided for the wire-feed speed after the weld-sequence stop cycle is initiated (see Appendix E).

Argon is used as the shielding gas. Argon and helium flowmeters were provided with the equipment, and the flow rate is controlled by standard regulators. Timers permit a given pre- and post-flow of shielding gas for each weld cycle. Current is preset in the constant-current mode of operation. Provision is made for initial preset current, for an adjustable slope rate to a different preset current, and for an adjustable decay rate after the weld sequence stop cycle is initiated. Currently, voltage and wire-feed speed are continuously monitored. Current and voltage are recorded on charts. The machine is calibrated at least once every six months. Prior to welding each element, the operator checks current and rotational and wire-feed speeds. If the ammeter shows a difference of more than 2 amp from the present current or if the wire feed for both torches is more than 3% off the preset wire feed, the equipment is completely recalibrated. The wire-feed speed is adjusted as required to be within 1% of the specified speed. Voltmeters must agree within 0.5 V of previous voltmeter readings for a given set of weld parameters or the machine is recalibrated.

Table 7 and Appendix E give the weld parameters for attaching the fuel plates to the side plates.

Initial current, wire-feed, and rotation values and initial slope rates are selected to provide starts that ensure good plate attachment without overpenetration and with a smooth transition from the start of the weld bead to the normal weld bead. Similarly, the final parameter values and slope rates are selected to provide a smooth transition from the weld start to the overlap without cold shuts and without the arc snuffing out.

¹⁸Linde Company, Division of Union Carbide Corp., 30 East 42nd St., New York 17

Table 7. Run weld parameters for fuel plate attachment

Parameters	Side plates			
	1	2	3	4
Voltage V ^a	18–20	19–21	18–19	19–21
Argonne gas flow	45 CFH	45 CFH	45 CFH	45 CFH
Nozzle diam	15.9 mm (5/8 in.)	19 mm (3/4 in.)	15.9 mm (5/8 in.)	19 mm (3/4 in.)
Nozzle height	6.3 mm (1/4 in.)	6.3 mm (1/4 in.)	6.3 mm (1/4 in.)	6.3 mm (1/4 in.)
Guide tube extension	0–1.6 mm (0–1/16 in.)	0–1.6 mm (0–1/16 in.)	0–1.6 mm (0–1/16 in.)	0–1.6 mm (0–1/16 in.)
Torch angle to work surface	90°	87.5°	90°	90°

^aCurrent is adjustable as necessary to maintain reference arc voltage.

All elements are adjusted to a temperature of 49 to 57°C (120 to 135°F) before each seam is welded. Between seams the fuel element is cooled or heated as needed. The guide tubes are oriented so that they are centered in the nozzle and cause the filler wire to point in the direction of rotation at the angle given in Table 7. To minimize weld overpenetration, the direction of rotation is chosen such that the edge of the fuel plate approaches the arc for the outer side-plate weldments. Either direction of rotation is satisfactory for the inner side-plate welds, since the fuel plate approaches the side plate at about 90°. The torch nozzle is oriented so that the wire feeds into the middle of the seam. Mirrors are used to help position the torch correctly for the inner side-plate welds. The operator carefully watches the weld bead during welding and maintains it centered in the weld groove by shifting the welding torch left or right as required. The weld beads must be flat to slightly convex, and the voltage is adjusted within the specified range to ensure proper bead contour. Only one pass is used per seam to minimize distortion and shrinkage.

If the arc snuffs out during the weld cycle, a restart is made in the same manner as a normal start except that the torch is positioned on the welded seam about 1 in. back from the end of the weld and the arch is struck without rotation. Rotation at normal run speed is started as soon as the welding arc strikes. Other defects are repaired by procedures specifically qualified for the type of defect.

Fuel-plate protrusion measurements are made and recorded as welding progresses. Minimum protrusion is 0.025 in. (0.64 mm) for the outer side plate and 0.010 in. (0.254 mm) for the inner side plate. Table 8 gives the welding sequence. After the last seam is welded, the circular test assembly is remounted and the "after" segments are welded and evaluated as described above.

The welded fuel element is removed from the lathe and allowed to cool in the vertical position to room temperature. The mounting rings are removed. Weld splatter is sanded or filed from the inside and outside surfaces. Particular care is taken to remove the weld splatter from the ends of the element back to the first few weld grooves.

8.1.6 Diameter Correction

The maximum and minimum inside diameters of the outer fuel element are measured with inside micrometers and recorded for locations between the top end and weld groove 1, the bottom and groove 24, and the pairs of adjacent grooves 1-2, 2-3, 4-5, 6-7, 10-11, 12-13, 14-15, 18-19, 20-21, 22-23, and 23-24.

To ensure that the wall thickness is not violated during final machining, the inside of the outer fuel element is mechanically expanded at room temperature to a minimum diameter of 11.030 in. (280.16 mm). This expansion is necessary to correct for weld shrinkage. An expansion tool is inserted inside the fuel element at each end and positioned in the area of greatest shrinkage. They are then tightened until the inside diameter is expanded to approximately 11.035 in. (280.29 mm). These expansion tools are left in the element during a subsequent shrinking and stress relieving operation, which stabilizes the element at the new diameter. Generally, only the ends of the element require this expansion; however, if other areas require it, the expanding tools are repositioned and the operation is repeated. The inside diameter is measured after expansion at the same locations measured before expansion and recorded. It is not necessary to expand the ends of the inner element; its inside diameter after welding is at least 4.784 in. (121.51 mm), which is sufficient to ensure proper wall thickness.

The outside diameter of both the inner and outer element is measured and recorded for locations between the top end and weld groove 1, the bottom and groove 24, and the pairs of adjacent grooves 1-2, 2-3, 5-6, 19-20, 22-23, and 23-24. The mounting rings restrain weld shrinkage at the ends of the fuel element. Shrinkages on the outside are most severely restricted from the ends of the element to the first two weld grooves. Shrink rings shown in Fig. 65 are installed on the outside of both ends of both inner and outer fuel elements. An element with shrink rings in place is installed vertically in an oven with a hot-air circulator.

Table 8. Sequences for welding fuel plates to side plates

Weld	Inner fuel element			Outer fuel element		
	Side	Seam		Side	Seam	
1	Inner	13	(middle)	Inner	13	(middle)
2	Outer	13	(middle)	Outer	13	(middle)
3	Inner	12		Outer	12	
4	Inner	14		Outer	14	
5	Inner	11		Outer	11	
6	Outer	12		Outer	15	
7	Outer	14		Outer	10	
8	Outer	11		Outer	16	
9	Outer	15		Outer	9	
10	Outer	10		Inner	12	
11	Outer	16		Inner	14	
12	Outer	9		Outer	17	
13	Inner	15		Outer	8	
14	Inner	10		Outer	18	
15	Inner	16		Outer	7	
16	Inner	9		Outer	19	
17	Inner	17		Outer	6	
18	Inner	8		Outer	20	
19	Outer	17		Outer	5	
20	Outer	8		Inner	11	
21	Outer	18		Inner	15	
22	Outer	7		Inner	10	
23	Outer	19		Outer	21	
24	Outer	6		Outer	4	
25	Inner	18		Outer	22	
26	Inner	7		Outer	3	
27	Inner	19		Outer	23	
28	Inner	6		Outer	2	
29	Outer	20		Outer	24	
30	Outer	5		Outer	1	
31	Outer	21		Inner	9	
32	Outer	4		Inner	16	
33	Outer	22		Inner	8	
34	Outer	3		Inner	17	
35	Inner	20		Inner	7	
36	Inner	5		Inner	18	
37	Inner	21		Inner	6	
38	Inner	4		Inner	19	
39	Inner	22		Inner	5	
40	Inner	3		Inner	20	
41	Outer	23		Inner	4	
42	Outer	2		Inner	21	
43	Outer	24		Inner	3	
44	Outer	1		Inner	22	
45	Inner	23		Inner	2	
46	Inner	2		Inner	23	
47	Inner	24		Inner	1	
48	Inner	1		Inner	24

Fig. 65. Outer fuel element with outer shrink rings in place.

Shrinkage occurs because the thermal expansion of the aluminum side plates is greater than that of the steel rings. The fuel element is in the vertical position during heating to reduce any tendency to sag.

The outer elements are heated for a period of 3 hr at 177°C (350°F) for two purposes. One is to shrink the element in outside diameter at the ends. The other purpose is to partially stress relieve the welded assembly to minimize the amount of ovality that occurs during subsequent machining. Inner elements are only heated to 121°C (250°F) and permitted to cool as soon as the temperature has been reached.

The element is cooled in a vertical position to room temperature, and the shrink rings are removed. The outside diameter of the element is measured at the same locations measured before the shrinking operation. It must be 17.415 to 17.450 in. (442.34 mm to 443.23 mm) for the outer fuel element and 10.820 in. to 10.839 in. (274.83 mm to 275.31 mm) for the inner fuel element to ensure proper side plate wall thicknesses after final machining. Special pliers are used to grip the end tabs of the Teflon and pull it out of the channels. Care must be taken not to damage the fuel plate ends.

The face and root of each weld segment are inspected visually. The face of the weld is inspected for cracks, irregular bead contour, oxidation, terminal craters, voids and porosity, amount of fill, and undercut. Any cracks are cause for rejection except on the terminal crater area. Porosity or voids on the exposed surface cannot exceed half the amount shown on the *ASME Boiler and Pressure Vessel Code, Section VIII, Appendix IV, "Porosity Charts of Plate 1/4 in. or Less and Size Assorted."* The remainder of the weld attributes is accepted or rejected

by comparison against a visual weld standard. The root of each weld is inspected for excess sag or warpage of the side plate, gross oxidation, and weld droptthrough. Weld droptthrough cannot exceed 0.010 in. as determined visually.

The inside and outside diameters of the welded element are measured at the same 16 locations (32 total measurements) as for the as-assembled element and recorded. The diameters must satisfy the following requirements: outer element ID, 11.023 in. (279.98 mm) minimum; outer element OD, 17.450 in. (443.23 mm) maximum; inner element ID, 4.784 in. (121.51 mm) minimum; inner element OD, 10.839 in. (270.97 mm) maximum. The plate ends at the top and bottom of the element are inspected for location; they must lie within a band 0.020 in. wide at each end.

8.1.7 Channel Spacing Measurement

The coolant channel thickness is measured continuously along the length of every channel except for 0.50 in. (1.27 mm) at either end of the fuel plates with the apparatus shown in Fig. 66. The channel thickness is measured at within ± 0.10 in. (± 0.25 mm) of the five radial locations shown in Table 9.

Table 9. Radial location of inspection probes

Fuel element	Radial location, in.				
Inner	3.10 (78.74 mm)	3.56 (90.42 mm)	4.05 (102.87 mm)	4.40 (111.76 mm)	4.80 (121.92 mm)
Outer	6.20 (157.48 mm)	6.64 (168.66 mm)	7.22 (183.39 mm)	7.61 (193.29 mm)	7.90 (200.66 mm)

The radial distances between adjacent measurement locations must be within ± 0.10 in (± 0.25 mm) of the distances derived from the above table.

Channel spacing is measured by a capacitance probe technique. The spacing measurement is a function of the channel thickness variation on the capacitor and the alloy of the fuel plates. Variations in the proximity of the metal to the capacitor due to fuel-plate spacing variations will vary the capacitance. The capacitance changes are then electronically converted to an analog voltage output, which is recorded on a strip chart.

Five such capacitors mounted on separate probes and assembled into one unit, shown in Fig. 67, are used to simultaneously measure the five tracks in each channel, spaced as described above. Each probe is digitally recorded continuously as the probes are withdrawn

Fig. 66. Checking channel spacing after welding, shrinking, and stress relieving.

Fig. 67. Checking HFIR water channels using a five-finger probe.

vertically. A continuous sixth track is also recorded; it is an electronic average of the five spacing values.

The average coolant channel thickness for any individual cross section is specified at 0.050 in. (± 1.27 mm) ± 0.006 in. (± 0.15 mm). Each individual or spot coolant channel measurement is specified at 0.050 in. (1.27 mm) ± 0.010 in. (± 0.25 mm) when measured at any point.

The fuel element is placed in a vertical position with the bottom end upon a turntable. The probes are lowered into the water channel until they reach 0.50 in. (1.27 mm) from the bottom of the channel. The drive motor is reversed automatically at this point, the probes are vertically withdrawn, and the digital readouts are activated. Each channel is measured in this fashion by proceeding from channel 1 in a counterclockwise direction. Prior to starting on each element and after a maximum of 25 channels have been probed, each probe is recalibrated against a step gage in which spacing are varied from 0.040 in. (1.02 mm) to 0.060 in. (1.52 mm) in 0.005-in. (0.127-mm) increments. The readings for each probe must be within ± 0.001 in. (± 0.025 mm) of the proper value, and the average reading must be within 0.0005 in. (0.013 mm) of the proper value.

In addition to reading each probe for channel spacing, the computer calculates the overall average thickness of each channel from the average readout. These averages, in turn, are averaged to provide the average channel spacing for the fuel element.

Channel spacing deviations may be repaired. First, the channels adjacent to the defective channel are backed up with Teflon spacers. An oversize Teflon-coated wand is then drawn through the channel; this tends to bend the offending plate in a direction to correct the spacing. A series of wands of various thicknesses is maintained for this purpose.

8.1.8 End Adapter Attachment

The fuel element is next mounted in a lathe to prepare the ends of the element for adapter welding. The top and bottom ends of the outer element are faced to 0.263 in. (6.68 mm) from the slot shoulder at the top and 0.388 in. (9.86 mm) from the slot shoulder at the bottom, with 30° chamfers. For the inner annulus, these dimensions are reversed.

The above machining is inspected for compliance with the appropriate drawing. The average inside diameter of the outer side plate and outside diameter of the inner side plate are inspected and recorded. Weld preparation on the rough-machined adapters are then turned per the appropriate drawings. The adapters are cleaned, pickled, and assembled to the fuel element. The fit must be tight, and the adapter must be seated against the fuel element slots. The assembled adapters are inspected for alignment, joint geometry, and cleanliness. The root opening is 0.125 in. (3.17 mm) to 0.145 in. (3.68 mm) with the adapters seated against the slots. Mirrors are used as necessary to ensure proper seating.

Fig. 68. Welding the end fittings onto the fuel element assembly.

A special adapter welding fixture is installed on the annulus. The fuel element is mounted in the welding lathe and adjusted until the TIR at the tailstock end of the lathe is 0.025 in. (0.64 mm) or less. The adapters are welded (Fig. 68) in the same manner as the side plates to the fuel plates. Weld parameters are given in Table 10 and Appendix E. They were chosen to effect the best compromise between porosity, weld penetration, and adequate fill. To minimize distortion and shrinkage, only one weld pass is used.

Table 10. Parameters for welding end adapters to fuel elements

Parameter	Side plate			
	1	2	3	4
Voltage, v	18-19	18-19	18-20	18-20
Argon gas flow, cfh	45	45	45	45
Nozzle diameter, in.	5/8 (15.87 mm)	3/4 (19.05 mm)	5/8 (15.87 mm)	3/4 (19.05 mm)
Nozzle height, in.	3/8 (9.53 mm)	1/4 (6.35 mm)	3/8 (9.53 mm)	1/4 (6.35 mm)
Guide tube extension, in.	0-1/16 (1.60 mm)	0-1/16 (1.60 mm)	0-1/16 (1.60 mm)	0-1/16 (1.60 mm)
Torch angle to work surface, deg	90	87.5 in direction of rotation	90	90

^aCurrent is adjusted as necessary to maintain voltage.

The completed welds are inspected visually to the same requirements as the welds of side plates to fuel plates. They are radiographed with a Norelco MG 300 unit located in a lead-lined room and Kodak Type M film in flexible cassettes with 0.005 in. (0.127 mm) to 0.010 in. (0.254 mm) back lead. To shield against backscattering, a 1/6-in. (1.6-mm) to 1/8-in. (3.16-mm) thick sheet of lead is formed to fit the inside of the adapter being radiographed, as shown in Fig. 69. To radiograph the welds in six sections, the fuel element is rotated under the fixed x-ray tube. The welds are x-rayed at 100 ± 25 kv (10 mA) to result in a film density between 1.5 and 3.0. The x-ray tube is offset 2 in. back of the fuel plates for the outer adapters and 10 in. in front of the fuel plates (off the element) for the inner adapters. The film focal distance is at least 36 in. (914.4 mm), and the focal spot is about 4 mm. Penetrator size¹⁹ 50A is used for the inner top

Fig. 69. X-raying the end fitting welds on a HFIR fuel element.

¹⁹Penetration identification numbers for aluminum in accordance with MIL-STD-271A (Ships) (March 11, 1965).

and outer top adapters of the inner element. Size¹⁹ 62A is used for the inner bottom adapter of the inner element and all three adapters for the outer element.

The radiographs are inspected by comparison with standard radiographs selected for each type of adapter weld. In general, (1) the welds must be free of cracks; (2) local area, 1/4 in. (6.35 mm) or less, containing lack of fusion at the root of the weld are acceptable for welds of side plates 2, 3, and 4 to adapters; (3) no lack of fusion is permitted for the weld of side plate 1 to the adapter except in the start-overlap area; (4) welds must have acceptable starts per standard radiographs; and (5) welds must have acceptable porosity per standard radiographs. These standards are roughly equivalent to *ASME Boiler and Pressure Code, Section VIII, Appendix IV, "Porosity Charts of Plate 1/4 in. (6.35 mm) or Less and Size Assorted."*

8.1.9 Final Machining

To prepare the elements for machining, plastic inserts are placed over the ends of the fuel plates on both ends of the element; this minimizes the opportunity for chips to collect in the channels.

The elements are set up on spider arbors in a lathe; these are mandrels with spiders on each end. Each spider consists of four circular segments that fit the inside of the fuel element. Each segment is attached to the mandrel with an adjustable screw. The spiders are located lengthwise on the arbor so that they fit about 1 to 2 in. inside the two end wall-assurance grooves on the inner side plate. The best average center line of the element is established by adjusting the spider segments until the least total indicator reading is obtained with respect to

Fig. 70. Inner annulus fuel element ready to start final machining.

the end wall-assurance grooves on the inner side plate. The total indicator readings on the outer side-plate wall-assurance grooves are checked to be sure the readings are within 0.005 in. (0.127 mm) of the established center line. The outside is turned to 10.698 in. (271.73 mm) to 10.702 in. (271.83 mm) and 17.197 in. (436.80 mm) to 17.200 in. (436.88 mm) in diameter for the inner and outer fuel element, respectively. The adapters are rough machined to within 0.050 in. (1.27 mm) of final dimensions, as shown in Fig. 70.

The element is placed in a restraining tube on the lathe, as shown in Fig. 71. The element is centered by establishing the best average center line with respect to the top and bottom wall-assurance grooves on the inner side plate. The maximum amount of stock removal from the inside surface is calculated by subtracting the minimum permissible finished wall thickness from the minimum measured side-plate thickness for the particular inner side plate involved. The inside is bored to final dimension. Isopropyl is used as a lubricant for the final cuts to give a good finish. The wall-assurance depth requirements are maintained. The top inner adapter on the outer element is machined only enough to clean it up and make it concentric with the inside surface.

Fig. 71. Boring a HFIR outer annulus fuel element.

The inside diameter is inspected in position on the lathe, and necessary corrections are made for temperature. The element inside diameter is reinspected, and the inside wall-assurance groove depths are measured. The dimensions are recorded while the element is still on the lathe.

Expanding mandrels (as shown in Fig. 72) are inserted in the element, which is then mounted between centers in a lathe.

Fig. 72. Expandable mandrill for machining HFIR inner annulus fuel elements.

The elements are final machined as follows.

1. Check concentricity of mandrel to inner bore at each end.
2. Rough machine so that all diameters and angles are within 0.050 in. of drawing requirements.
3. Final machine bottom end details. Leave 0.015 in. (0.38 mm) on outside for final cleanup. Do not remachine "B" diameter of adapter, (drawings 8-7213 and 8-7214, Appendix A).
4. Final machine overall length and all details of inner top adapter. Do not remachine "B" diameter of adapter.
5. Check concentricity of all finished sections on both ends.
6. Final machine outer adapter, top end. Leave 0.010 in. (0.25 mm) over the 10.915-in. (277.74-mm) diameter for inner fuel element and over the 16.757-in. (425.63-mm) and 16.4725-in. (418.4-mm) diameters for outer fuel element for final machining after angles are complete. Do not remachine "B" surface of adapter.
7. Final machine outside surface to correct diameter and maintain wall-assurance groove depth requirements.

8.1.10 Inspection

The elements are inspected at 20°C (68 ± 1°F) in the restrained condition for all dimensions needed to ensure accurate construction. Dimensions required for certification are recorded.

The elements are removed from the mandrel. The six pads on the top end inner adapter for the outer fuel element are machined. A portable router following a template is used for this operation, as shown in Fig. 73.

Both elements are engraved with identification numbers by using a Vibra tool and template and with channel-locating index marks by hand with a rotary carbide burr. The elements are deburred, small nicks and dents are blended, and the masking tape is removed. The elements are final inspected at 20°C (68 ± 1°F) in the unrestrained condition for several pertinent dimensions and again deburred. The dimensions required for certification are again recorded.

Fig. 73. Machining pads on the outer annulus fuel element using a router and template.

The side plate wall thickness is calculated at the three wall-assurance grooves on each side plate. The calculation is made as follows:

Starting side plate wall thickness	$= T_s$
Starting wall-assurance groove depth	$= W_s$
Wall-assurance groove depth after machining	$= W_F$
Stock removal at final machining	$R = W_s - W_F$
Final wall thickness	$T_F = T_s - R$

8.1.11 Cleaning

The fuel elements are prepared for cleaning. They are lifted by special fixtures. The outer lifting fixture contains a cadmium neutron poison as an added safety for preventing criticality.

All tape is removed from the element. All available surfaces are wiped clean with a lint-free cloth dampened with alcohol. Acetone is used to clean contamination that resists alcohol. The lifting fixture is attached, and the element is lowered into a cold rinse where the element is flushed out with deionized water (500,000 ohm minimum). This cycle is repeated twice. The element is blown dry with filtered air at a maximum pressure of 60 psi. The lifting fixture is removed, and each channel is examined for chips. Any chips are carefully pushed out of the channels with 0.020-in. (0.51-mm) -thick spring steel stock or dental explorers.

The element is final inspected for cleanliness. A light placed at one end of the element assists in the visual examination of channels. The element must be free of chips, and surfaces must be free of weld splatter, slag, moisture, dirt, oil, scale, paint, marking ink, pencil markings, and similar foreign matter.

The element is wrapped in clean polyethylene and lowered into ORNL-supplied shipping containers. The fixture for lowering the elements into the containers consists of a shaft with a plate mounted on its end. Slotted segments are bolted to the plate. The slots permit the segments to be extended and withdrawn radially. For the outer element, the plate is inserted completely into the element and the segments are extended under the bottom adapter. For the inner element, the plate is inserted in the top outer adapter only, and the segments are extended to engage the slot in the top outer adapter.

8.1.12 Certification

A fuel-element certification report with the following information is prepared for each element.

1. certification statement,
2. ^{235}U and ^{10}B fuel element loadings,
3. minimum and maximum cross section average channel thickness and minimum and maximum spot channel thickness for each coolant channel, overall average fuel element channel thickness,
4. inner and outer side-plate wall thicknesses at 30° increments around the circumference, inner and outer side plate minimum wall thickness and location,
5. measured values of fuel element dimensions 1, 21, 41, 42, 63, and 64 called for by drawing 8-7213 and 1, 22, 43, 44, 63, and 64 called for by drawing 8-7214 in Appendix A,
6. acceptance-rejection summary of pre- and postweld circular weld-test specimens - visual inspection, metallographic attributes, and measured values of weld tensile strength,
7. inspection data for control fuel plates from fuel-plate lots represented in the fuel element:
 - fuel core location
 - ^{235}U surface contamination
 - flat-plate dimensions
 - flat-plate thickness, .
8. involute data for fuel plate lots represented in the fuel element, and
9. summary of cladding thickness data and analytical results of boron samples (inner element only) from fuel plates sectioned to represent fuel-plate lots used in the fuel element.

8.1.13 Yields

Fuel Plates

The fuel-plate rejection rate remains low with the rejection rate remaining at about 7%. In order to achieve this rate of yield (93%) with a complex fuel plate, it requires training of the operator and diligence on their part. If a compactor loses his touch, it may take weeks to find his problem and correct it. The fuel (U_3O_8) is purchased in large quantities, generally a year's supply at one time. This allows the compactor to adjust his technique at the beginning of a new batch of U_3O_8 and that technique will remain constant for a year's production.

The compact rejection rate is low. About 50% of the scrapped compacts are for thickness violations, the remainder for surface defects and weight. The causes of the rejections are varied, with no single cause being responsible for most of the rejects.

Surface defects are a major cause for scrapping fuel plates. Most plates scrapped for surface defects have imbedded metal chips. Handling damage between and after processing operations contributes very little to the rejection rate. Care at all times must be taken to maintain cleanliness at all operations. The plates, the equipment, the tote boxes, and the

surfaces on which the plates are placed must be kept free of dirt. The weld metal that joins the cover plates to the frames is a source of metal chips, since it is harder and produces jagged edges during rolling. Close attention must be paid to obtaining smooth weld beads during assembly of the billet for rolling. The as-received material must be inspected carefully for foreign material, which must be removed before cover plates are fabricated if the inclusions are not too deep.

Bond defects are another cause for scrapping fuel plates. Approximately 60% of the bond defects reported are found by visual examination for blisters. The remainder of the reported bond defects is defects plates rejected at ultrasonic inspection. Not all the plates rejected at ultrasonic inspection have bond defects, since abnormal fuel configurations can result in ultrasonic indications.

Most blisters occur at the interface between the compact and a cover plate. However, the as-received stock is very carefully screened for blisters before the stock is committed to picture frames and cover plates. The causes of blisters are many; lack of cleanliness is foremost. Other factors such as fit of compact to assembled package, bonding temperatures, and amount of reduction during bonding are all important. The plates rejected for blisters occur at random. Improvements over the present rejection rate can be achieved.

Approximately 75% of the plates rejected for fuel location are due to end defects, primarily overlength fuel and feathered ends. The remaining 25% are for excessive edge closures. To maintain the low rejection rates experienced, it is extremely important to roll the plates straight with no camber and to a closely controlled thickness. Also, plates must be maintained flat and straight during hot rolling to maintain the ends of the fuel square to the plate edges.

Homogeneity rejects are divided evenly between average violations and local violations; most are small and scattered. These plates normally are placed on waiver for further examination. After a detailed examination by ORNL designers and materials engineers, about 50% of the waived plates are acceptable if they are distributed among accepted plates during fuel element assembly. The low rejection rates result from carefully controlled blending conditions and well-trained compacting operators. Extreme care must be taken at the compacting operation to prevent any precompaction of fuel during die filling.

Almost all of the plates rejected for plate dimensions are violations of the involute shape. Not all plate lots form the same; the forming parameters must be adjusted occasionally for certain plate lots to achieve consistent involute shapes. These necessary adjustments require a thorough knowledge of the forming parameters. An involute inspection of each plate during the forming operation must be made to detect any variation from the nominal.

8.1.14 Fuel Elements

Not all fuel elements meet all of the specifications. However, all fuel elements that have been used in the reactor have operated at full power. To date 353 fuel elements have been used. Originally the reactor operated at 100 MW; it is presently operating at 85 MW.

The off-specification diameters are due mostly to an out-of-roundness condition. However, elements 1 through 9 were inspected with the element horizontal; we subsequently found that the weight of the element was causing changes that in some cases resulted in violations. Elements are now inspected in the vertical position, and the number of violations has decreased sharply.

The frequency of wall violations has also been reduced by the expansion operation for outer elements, which was started on element 9-0, and the amount of expansion was increased on element 12-0. This expansion eliminated most thin-wall violations for outer elements, which account for a large number of the reported violations. The wall violations were up to 0.005 in. (0.127 mm) in local areas. We expect that wall violations of about 0.001 in. (0.025 mm) will occur occasionally in the future. Concentricity and miscellaneous dimensional rejections occur at a very low rate. These rejections are random and have not been a source of trouble.

Plate protrusion violations are normally on the order of 0.002 in. (0.051 mm). From one to ten plates in one to three weld grooves may show local violations. Any serious unseating is cause for reassembly of the element. Some plate protrusion violations will always result from small changes in side-plate dimensions, small changes in the involute shape of a plate, and occasional chamfer of the plate edges during deburring.

Channel spacing violations are in the range of 0.0005 in. (0.0127 mm) to 0.0015 in. (0.0381 mm) for local areas and about 0.0005 in. (0.0127 mm) to 0.001 in. (0.254 mm) for the average of the channel. One to two channels may have violations. These low-magnitude violations will occasionally occur. Small local violations have been repaired by pulling oversized Teflon-coated strips through the appropriate channels. All the element violations for cleanliness are due to water stains, chips in channels, or chips entrapped between the fuel plate and side plate slot. The unremovable stains are normally within the element and thus cannot be removed without causing possible damage to the element. One element was discolored slightly due to a breakdown of the deionized water system during the cleaning procedure. Chips cannot be completely removed from the element; many hours are spent removing the major portion of the chips. The violations for cleanliness could be reduced by the establishment of standards. However, process engineers wish to survey the element prior to shipping, and this inspection operations serves as the best occasion for final examination of the element.

Surface violations other than weld seam porosity are normally due to miscellaneous nicks and scratches. Scratches on fuel plates can be very serious, and care must be taken during all handling and reworking operations. One element had a scratch on a fuel plate over the fuel.

The overpenetration violations for fuel plate attachment welds (Type A welds) reflect overpenetration of about 0.010 in. (0.25 mm) in 3 to 11 locations for each off-specification element. The locations are often associated with weld starts. These violations have not been serious to date, with the new welding machine porosity and overpenetration ceasing to be a problem.

The surface violations are due to porosity in excess of the standard or due to failure of the element to "clean up" on final machining (i.e., insufficient weld metal in the welding groove). The insufficient fill is at the edges of the weld and is usually due to a weld bead that is humped rather than flat or to the weld bead climbing one side of the weld groove wall rather than remaining centered.

All of these violations have been small in magnitude. Circular weld-test specimen rejects have been due to a low-tensile pull on one of the weld-tensile tests. When one of these tensile-test specimens fails, two new circular weld-test specimens are made, and the test is rerun. To date no fuel element has been rejected due to low-tensile strength of the weld joint.

The adapter welds (Type B) are one of the main sources of violations. About 70% are due to excessive porosity and the remaining 30% to small areas of lack of fusion. One adapter was removed, and a new adapter was rewelded because of copper contamination of the weld. However, a freak accident was the cause; copper contamination is not normally a problem. The weld metal from one adapter weld that had a large amount of porosity was removed down to within 0.005 in. (0.127 mm) of the original adapter surface and then the adapter was rewelded. As explained above, the adapter weld parameters were chosen to effect the best compromise between porosity, weld penetration, and adequate fill.

In reviewing these violations to determine the worth of the specification as written, we found that no single violation occurred with sufficient frequency to warrant downgrading the specifications.

8.1.15 Components

Almost all rejections on cover plates and picture frames are for surface imperfections. Dimensional rejections are very few.

A yield of about 90% has been obtained for picture-frame and cover plate stock that has been thoroughly inspected prior to shipment to the fuel element fabrication.

Rejections on other components have been small and have not been significant. For example, suspect aluminum powder is scrapped rather than used, since its cost is relatively low.

Approximately 13.5% of the side plates started are rejected and diverted to use as circular weld-test specimens. It has been necessary twice to cut up acceptable side plates for use as circular weld-test specimens. The rejections have been evenly distributed among the four types of side plates. The reasons for not using a side plate are violations of slotting dimensions (58%), weld groove dimensions (21%), wall-assurance groove depth (10.5%), and miscellaneous (10.5%). About 3% of the side plates used in elements contained violations for wall-assurance groove depth; the deviations did not exceed 0.005 in.

The causes for all of the above rejections have been mostly operator error. Tooling defects and side plates going out of round upon release from the restraint tubes have been other causes. The rejection rate should drop about 10% as the experience of operators increase.

9.0 CONCLUSIONS

Fuel elements can be made to the specifications provided constant, and close supervision is maintained on all operations. This close surveillance must be on the part of the operators, the foreman, and the technical staff. If troubles are not noted by the operators before they are found in the formal inspection, the losses will be very large. The chances of producing a fuel element completely free of specification violations are very low, but no one specific violation occurs for every fuel element. To date 400 fuel assemblies have been manufactured and 353 have been operated either at 100,000 kW or 85 MW satisfactorily.

Appendix A
DESIGN DRAWINGS

INNER FUEL ELEMENT FUEL PLATE DEVELOPMENT

FUEL PLATE INNER FLAT (ENRICHED)
8-7146-A

COORDINATES		
"X"	"Y"	"Z"
.050	.389	4.06
.100	.411	3.95
.123	.423	3.89
.200	.465	3.68
.300	.518	3.41
.400	.570	3.15
.500	.620	2.90
.600	.668	2.66
.700	.714	2.43
.800	.758	2.21
.900	.799	2.01
1.000	.837	1.82
1.100	.872	1.64
1.200	.903	1.49
1.300	.931	1.35
1.400	.955	1.23
1.500	.974	1.13
1.600	.988	1.06
1.700	.997	1.02
1.800	1.000	1.00
1.900	.998	1.01
2.000	.993	1.04
2.100	.984	1.08
2.200	.972	1.14
2.300	.957	1.22
2.400	.939	1.31
2.500	.919	1.41
2.600	.897	1.52
2.700	.873	1.64
2.800	.847	1.77
2.900	.819	1.91
3.000	.790	2.05
3.100	.760	2.20
3.127	.752	2.24
3.190	.732	2.34

INNER FUEL ELEMENT FUEL PLATE DEVELOPMENT

FUEL PLATE INNER FLAT (ENRICHED)	
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8-7146-B

NOTES:

1. FUEL PLATE SURFACES CONTAINING ANY PITS OR SCRATCHES GREATER THAN IN TABLE I OR DENTS LARGER THAN 0.50 IN DIA. SHALL BE CAUSE FOR REJECTION.
2. URANIUM SHALL NOT EXTEND BEYOND THE MAXIMUM CORE OUTLINE.
3. NO FUEL PLATE SHALL HAVE VISUAL EVIDENCE OF A BLISTER.
4. EACH FUEL PLATE SHALL BE ULTRASONIC TESTED WITH SUFFICIENT SENSITIVITY TO DETECT A .062" DIA. NON-BOND OR BLISTER LOCATED WITHIN THE FUEL CORE OUTLINE AND A .125 DIA. NON-BOND OR BLISTER LOCATED OUTSIDE THE FUEL CORE OUTLINE. THE SENSITIVITY AND REPRODUCIBILITY OF THE TECHNIQUE SHALL BE ESTABLISHED WITH CALIBRATION PLATES CONTAINING FUEL CORES AND REFERENCE DISCONTINUITIES. ANY RESPONSE LARGER THAN THAT WHICH IS RECEIVED FROM THE REFERENCE DISCONTINUITY SHALL BE CAUSE FOR REJECTION OF THE PLATE.
5. FUEL PLATES SHALL BE FREE OF EMBEDDED FOREIGN MATERIAL.
6. VIBRATOOL IDENTIFICATION NO. $\frac{1}{8}$ " - $\frac{1}{4}$ " HIGH REF., BY .005" REF. DEEP. PLATE IDENTIFICATION NOT TO EXCEED 1.85" FROM THE REFERENCE EDGE.
7. FUEL CORE LOCATION-EDGE DIMENSIONS:

LOCATION FROM EACH END OF PLATE	REF. PLATE EDGE TO ADJACENT FUEL EDGE		OPP. PLATE EDGE TO OPP. FUEL EDGE	
1.761 TO 2.261	-----	(A) .171 MIN.	-----	(F) .327 MIN.
2.261 TO 4.017	(C) .452 MAX.	(A) .171 MIN.	(D) .608 MAX.	(F) .327 MIN.
BETWEEN 4.017	(B) .234 MAX.	(A) .171 MIN.	(E) .390 MAX.	(F) .327 MIN.

8. FUEL CORE LOCATION-END DIMENSIONS:

NO. PLATE END TO NO. FUEL END (G) 1.761 MIN., (H) 2.261 MAX.

OPP. PLATE END TO OPP. FUEL END (K) 1.761 MIN., (J) 2.261 MAX.

9. THE FUEL CORE LOCATION IS BASED ON THE FOLLOWING RADIOGRAPH BIASES:

REF. EDGE TO REF. EDGE OF FUEL +.001
 OPP. EDGE TO OPP. EDGE OF FUEL +.001
 REF. EDGE TO OPP. EDGE OF FUEL +.009
 REF. END AND OPP. END +.011

10. TOP OF DIGITS IN PLATE NUMBER TO BE TOWARD TOP OF PLATE.

11. WHEN FUEL PLATES ARE REJECTED FOR DIM. D, E AND F PER NOTE 7, THESE PLATES ARE TO BE REMEASURED FROM THE REF. EDGE TO THE FUEL LOCATION. PLATES ARE ACCEPTABLE IF CONFORMING TO THE FOLLOWING DIMENSIONS:

DIM. D = 3.028 MIN.
 DIM. E = 3.246 MIN.
 DIM. F = 3.309 MAX.

12. MAXIMUM PLATE THICKNESS VARIABILITY .001.

13. ACCEPTANCE LIMITS FOR URANIUM LOADING ARE AS FOLLOWS:

- A. AVERAGE LOADING LESS THAN +12%
- B. LOCAL LOADING LESS THAN +27%
- C. AVERAGE LOADING GREATER THAN -12% OR WHEN -12% LOADING INDICATIONS ARE OUTSIDE A RANDOMLY LOCATED AREA WITHIN THE MIN. FUEL BOUNDARY DESIGNATED BY PARALLEL LINES 2 INCHES APART WITH SEMI-CIRCULAR ENDS WITH A 1 IN. RAD. GIVING AN OVERALL LENGTH OF 18", ALLOWING A TOTAL OF 4 LINEAR IN. OF -12% INDICATION OR LESS INSIDE THE DESIGNATED AREA.

TABLE I		
	NO. SIDE	OPP. SIDE
1 1/2" FROM NO. END TO 1 1/2" FROM OPP. END FOR FULL WIDTH	.004	.003
NO. END OF PLATE TO 1 1/2" FROM NO. END AND OPP. END OF PLATE TO 1 1/2" FROM OPP. END BOTH FOR FULL WIDTH	.005	.005

FUEL PLATE INNER FLAT (ENRICHED)

8-7146-C

2.7215 RADIUS REF.
INVOLUTE BASE CIRCLE

FUEL PLATE INNER (ENRICHED)

8-7147-A

NOTES:

- 1, ALL MATERIALS OF CONSTRUCTION SHALL CONFORM WITH ORNL SPECIFICATION HFIR FE2
 - 2, THE SURFACE OF THE FUEL PLATES SHALL BE FREE OF PITS OR SCRATCHES GREATER THAN IN TABLE I OR DENTS GREATER THAN 0.50 INCHES IN DIAMETER.
 - 3, NO FUEL PLATE SHALL HAVE VISUAL EVIDENCE OF A BLISTER.
 - 4, FUEL PLATES SHALL BE CLEAN AND FREE OF FOREIGN MATERIAL.
 - 5, THE SURFACE CONTAMINATION OF A FINISHED PLATE SHALL BE LESS THAN THE EQUIVALENT OF THAT WHICH WOULD BE OBTAINED FROM 5 MICRO GRAMS OF U²³⁵ PER SQUARE FOOT OF SURFACE AREA.
 - 6, NO TREATMENT OF THE PLATE SURFACE WHICH REMOVES MORE THAN 0.001 INCHES IS PERMITTED.
 - 7, THE FUEL PLATES SHALL BE FORMED TO WITHIN 0.015 IN. OF THE TRUE INVOLUTE CURVATURE. THE DUPLICATION OF FUEL PLATES SHALL BE LIMITED TO ± 0.008 IN. AT 12 SEPARATE MEASURING POINTS. THREE MEASUREMENTS SHALL BE TAKEN AT EACH OF THE RADIAL LOCATIONS SHOWN BELOW.
 THE PERMISSIBLE TOLERANCE ON
 THESE RADIAL LOCATIONS IS
 ± 0.030 IN.
RADIAL LOCATION (IN.)			
POINT NO.			
1	2	3	4
3.18	3.77	4.38	5.14
- 8, THE AVERAGE CLAD THICKNESS ON EACH SIDE OF THE FUEL PLATE SHALL BE AT LEAST 0.010 INCHES.
 THE MINIMUM CLAD THICKNESS SHALL BE AT LEAST 0.007 INCHES.
 - 9, THE FUEL PORTION OF THE COMPACT SHALL FALL NEAREST THE CONCAVE SIDE OF THE FORMED FUEL PLATE.

TABLE I		
	# SIDE	OPP. SIDE
1/2" FROM # END TO 1/2" FROM OPP. END FOR FULL WIDTH	0.004	0.003
NO. END OF PLATE TO 1/2" FROM # END AND OPP. END OF PLATE TO 1/2" FROM OPP. END BOTH FOR FULL WIDTH	0.005	0.005

FUEL PLATE INNER (ENRICHED)

8-7147-B

OUTER FUEL ELEMENT FUEL PLATE DEVELOPMENT

FUEL PLATE OUTER FLAT (ENRICHED)
8-7148-A

COORDINATES	
"X"	"Y"
.060	.553
.095	.572
.108	.589
.185	.645
.285	.715
.385	.782
.485	.844
.585	.899
.685	.942
.785	.973
.885	.993
1.006	1.000
1.105	.997
1.185	.984
1.285	.963
1.385	.935
1.485	.903
1.585	.867
1.685	.828
1.785	.787
1.885	.744
1.985	.700
2.085	.656
2.185	.612
2.285	.569
2.385	.527
2.485	.486
2.585	.447
2.685	.410
2.785	.376
2.822	.364
2.870	.349

OUTER FUEL ELEMENT FUEL CONTOUR

SECTION "A-A"
ROTATED 90° CLOCKWISE
NOT TO SCALE

OUTER FUEL ELEMENT FUEL PLATE DEVELOPMENT

FUEL PLATE OUTER FLAT (ENRICHED)

8-7148-B

Appendix B

PREVENTIVE MAINTENANCE

BABCOCK & WILCOX
LYNCHBURG, VIRGINIA

PREVENTIVE MAINTENANCE

SCHEDULED MAINTENANCE PROGRAM

Schedule maintenance program for all equipment at B&W is maintained by the Industrial Engineering Department. Each piece of equipment is identified with a unique numbered tag for traceability.

The area supervisors are responsible for having the equipment calibrated and checked on a regular basis.

The following is a checklist for each of the furnaces listed:

1. Marshal and TM Furnace (Aluminum Power and Compact Annealing)

- a) Mechanical pump and fluid level
- b) Diffusion pump and oil
- c) Recorder operations
- d) Calibration performed
- e) Gages working properly
- f) Gradient performed

2. Trent Furnace (Blister Annealing)

- a) Fan operational
- b) "V" belts
- c) Thermocouples and connections
- d) Gradients performed when new heater coils installed
- e) Check Control Panel

3. Grieves-Hendry Furnace (Hot Rolling)

- a) Fan operational
- b) Thermocouples and connections
- c) Stack damper in proper position
- d) "V" belts
- e) Gradient performed after new coils installed
- f) Check Control Panel
- g) Door operating system

4. Hevi-Duty Furnace

- a) Fan operational
- b) Thermocouples and connections
- c) Gradient performed after new coils installed
- d) Instrumentation operating correctly
- e) Check temperature overrides
- f) Check spacing for hearth plates
- g) Door operating system
- h) Check control panel

Furnace	Temp (°F)	Location	Probes	Load
Grieves-Hendry	940 max. 914 min.	Front of plate 14" min. from door	3	24 plates
Hevi-Duty	940 max. 914 min.	Min. 1' from door	3	Pack assemblies Max of 24 compacts
Hevi-Duty	940 max. 914 min.	Min. 1' from door	3	Program anneal Max. of 144 plates

Appendix C
MATERIAL SPECIFICATIONS

DESCRIPTION OF MATERIAL:

6061 Aluminum Plate (frame stock)

SPECIFICATIONS:

All material shall conform to ASTM B-209-61 or QQ-A-250/11 aluminum alloy sheet and plate as amended or as herein noted.

OTHER REQUIREMENTS:

1. All plates shall be furnished in a fully annealed temper.
2. An edge produced by shearing or sawing.
3. Dimensions:

Thickness	—	0.388" max.	0.350" min.
Width	—	48.38" max.	47.62" min.
or	—	6.25" max.	5.75" min.
Length	—	48.38" max.	47.62" min.
4. Surface finish — surface to be smooth and free from pits, dents, scratches, cuts and foreign material.
5. The chemical composition shall meet the requirements listed in Table 1 of this specification.

The chemical specification is based on the chemistry of the melt. Actual analyses from the melt of the chemical elements listed shall be made.

The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Company Nuclear Division.

Duplicate samples of the melt material used in this analytical determination shall be furnished to Babcock & Wilcox Company Nuclear Division.

Representative samples, 8½" × 11", of each lot of the finished plate and sheet shall be furnished to Babcock & Wilcox Company Nuclear Division.

6. Results of all tensile properties including yield strength shall be furnished to Babcock & Wilcox Company Nuclear Division.
7. After heat treatment, each plate and sheet shall be inspected to determine whether blisters are present on the surface of the plate and sheet. Any plate or sheet 48" wide × 48" long that contains a single blister ⅛" diameter or larger shall be rejected. Any plate or sheet that contains more than four (4) blisters of less than ⅛" diameter shall be rejected.

8. The plates and sheets shall be packaged in 4000-lb maximum fiber enclosed skids with wooden sides and battens.
9. Identification
Each plate and sheet shall be marked as near both ends as possible with.
 1. Type of material.
 2. Lot number.
 3. Manufacturer's name and/or identification symbol.
10. No welding or weld repair on the aluminum furnished shall be permitted.
11. The chemical composition of the type 6061 aluminum of this order shall be within the limits below:

TABLE I. Chemical Composition

Element	Concentration (wt %)	
	Minimum	Maximum
Silicon	0.04	0.08
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.04	0.35
Iron	none	0.7
Zinc	none	0.25
Titanium	none	0.15
Manganese	none	0.15
Gallium	none	0.04
Lithium	none	0.008
Cadmium	none	0.003
Boron	none	0.001
Cobalt	none	0.001
Others		
Each		0.02
Total		0.15

DESCRIPTION OF MATERIAL:

6061 Aluminum Sheet (cover sheet stock)

SPECIFICATIONS:

All material shall conform to ASTM B-209-61 or QQ-A-250/11 aluminum alloy sheet and plate as amended or as herein noted.

OTHER REQUIREMENTS:

1. All sheets shall be furnished in a fully annealed temper.
2. An edge produced by shearing or sawing.
3. Dimensions:

Thickness	—	0.130" max.	0.122" min.
Width	—	48.12" max.	47.88" min.
or	—	6.25" max.	5.75" min.
Length	—	48.12" max.	47.88" min.
4. Surface finish — surface to be smooth and free from pits, dents, scratches, cuts and foreign material.
5. The chemical composition shall meet the requirements listed in Table 1 of this specification.

The chemical specification is based on the chemistry of the melt. Actual analyses from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Company Nuclear Division.

Duplicate samples of the melt material used in this analytical determination shall be furnished to Babcock & Wilcox Company Nuclear Division.

Representative samples, 8½" × 11", of each lot of the finished plate and sheet shall be furnished to Babcock & Wilcox Company Nuclear Division.

6. Results of all tensile properties including yield strength shall be furnished to Babcock & Wilcox Company Nuclear Division.
7. After heat treatment, each plate and sheet shall be inspected to determine whether blisters are present on the surface of the plate and sheet. Any plate or sheet 48" wide × 48" long that contains a single blister ⅛" diameter or larger shall be rejected. Any plate or sheet that contains more than four (4) blisters of less than ⅛" diameter shall be rejected.

8. The plates and sheets shall be packaged in 4000-lb maximum fiber enclosed skids with wooden sides and battens.
9. Identification
 Each tube, plate, or sheet shall be marked as near both ends as possible with.
 1. Type of material.
 2. Lot number.
 3. Manufacturer's name and/or identification symbol.
10. No welding or weld repair on the aluminum furnished shall be permitted.
11. The chemical composition of the type 6061 aluminum of this order shall be within the limits below:

TABLE I. Chemical Composition

Element	Concentration (wt %)	
	Minimum	Maximum
Silicon	0.04	0.08
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.04	0.35
Iron	none	0.7
Zinc	none	0.25
Titanium	none	0.15
Manganese	none	0.15
Gallium	none	0.04
Lithium	none	0.008
Cadmium	none	0.003
Boron	none	0.001
Cobalt	none	0.001
Others		
Each		0.02
Total		0.15

DESCRIPTION OF MATERIAL:

Aluminum Powder

SPECIFICATIONS:

All material shall be Alcoa Type 101 Aluminum Powder per Product Data Book 6-20-60 or the equivalent such as Reynolds Metals No. 120.

OTHER REQUIREMENTS:

1. 99.5% of powder must pass through a 100 U.S. standard mesh screen.
2. 80% of powder must pass through a 325 U.S. Standard mesh screen.
3. Powder must conform to Table 1 for Chemistry.

TABLE I. Chemical Composition

Element	Concentration (wt %) Maximum
Iron	0.4
Silicon	0.2
Al ₂ O ₃	0.6
Al	remainder

4. No foreign material or contaminants are acceptable.
5. ASTM B-214-63T Sieve Analyses of Granular Metal Powders is to be used to determine mesh sizes of powder.
6. The powder must be packed in clean steel drums each containing about 100 lbs.
7. All drums shall be labeled with the purchase order number and the type of material.
8. B&W Nuclear will send to the customer a 100-gram sample of each lot.
9. Material must represent one continuous run.

DESCRIPTION OF MATERIAL:

B₄C Particles

SPECIFICATIONS:

All material shall conform to High Boron B₄C as supplied by the Norton Company specification dated January 6, 1964.

OTHER REQUIREMENTS:

1. The boron carbide shall be made with natural boron (i.e., 18.78 max. to 18.22 min. wt % B¹⁰).
2. The chemical composition shall meet the requirements listed in Table I of this specification. The results of the chemical analysis shall be reported on the certification.
3. The B₄C shall be screened to less than 44 U.S. standard mesh size. Sieve analysis shall be performed per ASTM B-214-63T Sieve Analysis of Granular Metal Powders.
4. All B₄C shall be free of foreign material.
5. A certified isotopic analysis for B¹⁰ shall be provided for each batch of material. A batch of material is defined as that unit or quantity of homogeneously blended boron carbide particles presented for inspection at one time. No lot shall contain a quantity of particles in excess of the capacity of the manufacturer's facilities to homogeneously blend the particles.
6. Two samples, representative of the batch and each with a minimum size of 50 g shall be furnished the purchaser by the seller from each batch.
- * (B&W Nuclear will submit one sample to the customer.)
7. The certified isotopic analysis for B¹⁰ shall be made by a B&W nuclear-approved laboratory.

PACKING AND SHIPPING INSTRUCTIONS

1. The boron carbide particles shall be packed in non-contaminating containers and sealed moisture-free such that the requirements of this specification are maintained during shipment and storage. Quantity per container to be as specified on the purchase order. Containers to be glass bottles with rubber gaskets.

2. Each shipping container shall be plainly marked as follows:

Purchase Order No.
Specification No.
Gross weight
Tare weight
Net weight
Lot No.
Size range
Weight percent boron-10
Name of manufacturer

TABLE I. Chemical Composition

Element	Concentration (wt %)	
	Minimum	Maximum
Boron	76.5	--
Carbon	20.0	22.0
Boron plus carbon	98.0	99.5
B ₂ O ₃	--	0.2
Iron	--	0.5
Aluminum	--	0.2
Cadmium	--	0.1
Magnesium	--	0.05
Moisture content	--	200 ppm

DESCRIPTION OF MATERIAL:

Enriched U_3O_8 Powder

SPECIFICATIONS:

1. U_3O_8 powder shall be high-fired dead burned oxide.
2. The density shall be greater than 8.0 g/cm^3 as determined by a toluene pycnometer.
3. The surface area shall be 0.05 to $0.07 \text{ m}^2/\text{g}$ as determined by the static Krypton BET determination.
 - a. The technique for making these measurements is contained in the following article by J. L. Bolts, "Surface Area of Solids, Krypton Absorption Method," Method No. 1105 and 900605 (12-28-61) ORNL Master analytical Manual. TID-7015, Suppl. 5 (Sept. 1963).
 - b. This document may be obtained from the Clearinghouse for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22121.
4. The mesh size shall be -170 +325 U.S. Standard mesh and shall not contain more than 1% of +170 and 25% of -325 U.S. Standard mesh particles as determined by screening of a 100-g sample for one hour in a vibratory shaker.
5. The total uranium concentration shall not be less than 84.5 wt %.
6. The impurities in the U_3O_8 shall not exceed the limits specified in Table I.

TABLE I. Chemical Composition

Maximum Impurity Level for U_3O_8 (ppm)					
Aluminum	100	Cobalt	3	*Magnesium	100
Boron	0.2	Chromium	15	Manganese	5
Barium	10	Copper	20	Sodium	5
Beryllium	0.2	Iron	100	Nickel	20
Calcium	50	Potassium	20	Phosphorus	<100
Cadmium	0.5	Fluorine	<10	Silicon	50
		Lithium	1.0	Vanadium	2

Total of nickel, chromium, and iron shall not be greater than 150 ppm.

7. A chemical and spectrographic analysis shall be required for each batch of U_3O_8 .
- *8. The UO_2 content shall be less than 1.0%. The methods of analysis shall be submitted to Babcock and Wilcox in writing and approved by Babcock & Wilcox before the analysis for UO_2 is made. (Babcock & Wilcox must submit the methods of analysis to Lockheed Martin Nuclear Division in writing and approval received before approval is given the vendor per above).

9. The U_3O_8 shall be cross blended into as large a batch as possible, a minimum batch shall be 120 Kg.
- *10. All U_3O_8 shall be produced by the precipitation of a uranyl nitrate solution with hydrogen peroxide. Use of any other process must be approved in writing by Babcock & Wilcox. (Babcock & Wilcox must obtain approval from Lockheed Martin Nuclear Division before permitting the use of any other process). This approval will require the submission of photomicrographs showing that during rolling, stringing, and fragmentation of the oxide are comparable to what has been achieved with the above process.
- *11. A mass spectrographic analysis of ^{235}U enrichment shall be performed by a Babcock & Wilcox approved facility.
12. Ten certified copies of the chemical and mass spectrographic analyses of U_3O_8 , density, surface area, and size distribution of U_3O_8 shall be furnished along with a certification that they comply with the requirements of this specification.
13. No foreign material is to be present in any lot of U_3O_8 .

WEIGHING, PACKING, AND SHIPPING

1. Approximately 4 kg of U_3O_8 shall be contained within a closed, clean one-liter wide-mouth polyethylene bottle (typical LPE NALGENE 1000 ml - 32 oz).
2. The shipping container shall be a 55-gallon 6 M as per 49 CFR 173.396 (c) (2).

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (side plate No. 1)

SPECIFICATIONS:

All material shall conform to ASTM B-210-61 Drawn Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	5.562"
Wall thickness:	0.500"
Length:	28" multiple, 84" max.
Straightness:	0.010" per ft
All tolerances:	per ASTM B-210-61 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (side plate No. 2)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All plates shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	11.250"
Wall thickness:	0.938"
Length:	28" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (side plate No. 3)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or Federal Specification QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	12.250"
Wall thickness:	0.875"
Length:	28" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material. .
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (side plate No. 4)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or Federal Specification QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	17.875"
Wall thickness:	1.000"
Length:	28" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

TABLE I. Chemical Composition

Element	Concentration (wt %)	
	Minimum	Maximum
Silicon	0.40	0.80
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.04	0.35
Iron	none	0.7
Zinc	none	0.25
Titanium	none	0.15
Manganese	none	0.15
Gallium	none	0.04
Lithium	none	0.008
Cadmium	none	0.003
Boron	none	0.001
Cobalt	none	0.001
Others		
Each		0.02
Total		0.15

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (end fittings inner top and bottom, inner fuel element)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or Federal Specification QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	6.375"
Wall thickness:	1.000"
Length:	14" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (outer top inner fuel element)
(inner top outer fuel element)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or Federal Specification QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	12.250"
Wall thickness:	1.500"
Length:	12" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (outer top and bottom outer fuel element)

SPECIFICATIONS:

All material shall conform to ASTM B-221-63 or Federal Specification QQ-A-200/8F Extruded Tubing as amended or as herein noted.

OTHER REQUIREMENTS:

1. All tubes shall be furnished in the T6511 temper.
2. An end produced by sawing.
3. Dimensions:

Outside diameter:	17.875"
Wall thickness:	1.312"
Length:	12" multiple, 84" max.
Straightness:	0.020" per ft
All tolerances:	per ASTM B-221-63 or equal
4. Surface finish – surface to be smooth and free from pits, dents, scratches, and foreign material.
5. The chemical composition shall meet the requirements listed in the respective ASTM designation.

The Chemical Specification is based on the chemistry of the melt. Actual analysis from the melt of the chemical elements listed shall be made. The results shall be certified that they meet the requirements of this order. Copies of the results shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Duplicate samples of melt material used in this analytical determination shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Babcock & Wilcox Co. Nuclear Division.

Results of all tensile properties including yield strength shall be furnished.

The tubing shall be packaged in 1000-lb maximum fiber enclosed skid with internal protection.

No welding or weld repair on the aluminum furnished shall be permitted.

IDENTIFICATION

Each tube shall be marked as near both ends as possible with:

1. Type of material.
2. Lot number.
3. Manufacturer's name and/or identification symbol.

TABLE I. Chemical Composition

Element	Concentration (wt %)	
	Minimum	Maximum
Silicon	0.40	0.80
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.04	0.35
Iron	none	0.7
Zinc	none	0.25
Titanium	none	0.15
Manganese	none	0.15
Gallium	none	0.04
Lithium	none	0.008
Cadmium	none	0.003
Boron	none	0.001
Cobalt	none	0.001
Others		
Each		0.02
Total		0.15

DESCRIPTION OF MATERIAL:

Filler Wire 4043 Aluminum (Fuel Elements)

SPECIFICATIONS:

All material shall conform to AMS specification 4190 or AWS specification A5.10, "Aluminum and Aluminum-Alloy Welding Rods and Bare Electrodes."

OTHER REQUIREMENTS:

1. Dimension: diameter 0.031" max., 0.028" min.
2. All wire to be wound on 10-pound spools.
3. The material vendor is to supply a 60" representative sample of each lot.

This sample is to be furnished to Babcock & Wilcox Co., Nuclear Division, after receipt from material vendor by B&W Nuclear.
4. A copy of certification for each lot to be supplied to B&W Nuclear with each shipment.
5. Identification for wire per the proper specification. Each container and spool flange must be identified per the proper specification. Wire to be level and layer wound on flanged spools.
6. All electrodes shall be packed individually with a desiccant in hermetically-sealed containers before shipping.
7. A maximum of two weeks (14 days) shall elapse between manufacture and canning.

Appendix D

MISCELLANEOUS PROCEDURES

MISCELLANEOUS PROCEDURES

1. Cleaning

Various components are cleaned by a special water and detergent process; pickling with a solution made up of 15% by volume 70% HNO₃, 1% by volume 70% HF, and the balance water; rinsing in cold water until the water clears; rinsing in hot (about 90°C, 200°F) deionized water (500,000 ohm-cm minimum); and drying with oil-free air.

Material removal during pickling is controlled by coupons. These are prepared by shearing 1.5- × 1.5-in. squares from trimmings of bonded cold-rolled and annealed fuel plates. A 1/8-in. hole is drilled at a distance of 5/16 in. from two edges. The coupons are detergent degreased and maintained in groups of 100; one is used for each rack of plates. Its thickness is measured and recorded. It is then prepared in the same manner as the fuel plate, and its thickness is measured and recorded after pickling. A further check of material removal is made by measuring with special micrometers, before and after pickling, the thickness of sample fuel plates from the first rack of plates pickled. The micrometers have the anvil on the spindle ground to about a 2-in. radius so that the curved fuel plate can be measured accurately.

2. Rolling Mill Operation

The rolls are thoroughly cleaned before rolling starts, and roll wipers with a felt¹ facing are used to prevent accumulated dirt and chips from falling in the rolls during the operation. The rolls are thinly but evenly lubricated with a mixture of one part Texaco Pinnacle² cylinder oil and three parts kerosene, applied with the roll wipers.

¹No. F-10 White, Continental Felt Company, 22 West 15th Street, New York, NY.

²A trade name of Texaco, Inc., 135 East 42 Street, New York, NY.

Appendix E

WELDING PARAMETERS

Fuel Plate Attachment Weld, Side Plate 1
Fuel Plate Attachment Weld, Side Plate 2
Fuel Plate Attachment Weld, Side Plate 3
Fuel Plate Attachment Weld, Side Plate 4
End-Adapter Attachment Weld, Side Plate 1
End-Adapter Attachment Weld, Side Plate 2
End-Adapter Attachment Weld, Side Plate 3
End-Adapter Attachment Weld, Side Plate 4

* NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
FUEL PLATE ATTACHMENT WELD, SIDE PLATE 1. APPROXIMATE RUN TIME, 1 min 9 sec.

*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
FUEL PLATE ATTACHMENT WELD, SIDE PLATE 2. APPROXIMATE RUN TIME, 2 min 58 sec.

*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
FUEL PLATE ATTACHMENT WELD, SIDE PLATE 3. APPROXIMATE RUN TIME, 3 min 3 sec.

*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
FUEL PLATE ATTACHMENT WELD, SIDE PLATE 4. APPROXIMATE RUN TIME, 5 min 33 sec.

* NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION. END-ADAPTER ATTACHMENT WELD, SIDE PLATE 1. APPROXIMATE RUN TIME, 0 min 48 sec.

*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
END-ADAPTER ATTACHMENT WELD, SIDE PLATE 2. APPROXIMATE RUN TIME, 3 min 15 sec.

* NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
END-ADAPTER ATTACHMENT WELD, SIDE PLATE 3. APPROXIMATE RUN TIME, 3 min 37 sec.

*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.
END-ADAPTER ATTACHMENT WELD, SIDE PLATE 4. APPROXIMATE RUN TIME, 6 min 36 sec.