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FABRICATION PROCEDURES FOR MANUFACTURING HIGH FLUX ISOTOPE REACTOR FUEL ELEMENTS

R. W. Knight
J. Binns
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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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JUNE 1968

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FOREWORD

This report was previously issued as ORNL-TM-1628. In the previous report illustrations and photographs were omitted. This report contains illustrations and photographs and also process changes that have taken place since the previous report was issued.

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FABRICATION PROCEDURES FOR MANUFACTURING HIGH FLUX ISOTOPE REACTOR FUEL ELEMENTS

R. W. Knight, J. Binns,[1] and G. M. Adamson, Jr.

ABSTRACT

A production procedure was developed for manufacturing High Flux Isotope Reactor fuel assemblies.

The entire fuel assembly of this reactor is made up of two fuel elements, each element consisting of an annular array of fuel plates. These annuli are identified as the inner and outer fuel elements. The inner element consists of 171 identical fuel plates and the outer element consists of 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 manufacture and inspection of the element are described and illustrated.

The procedures described have been used to manufacture 46 fuel assemblies for operation at 100,000 kw. No fuel element has been rejected, but no fuel element has been manufactured that meets all of the specification requirements. The deviations that have been accepted are not serious enough to affect the reactor operation.

Fuel-plate recovery for 25,000 fuel plates has been 90%, with the largest losses occurring in blistered plates and surface damage.

INTRODUCTION

The High Flux Isotope Reactor has been built and is being operated by the Oak Ridge National Laboratory to provide research quantities of several of the transplutonium elements. The maximum unperturbed thermal neutron flux in the HFIR is over 5×10^{15} neutrons cm^{-2} sec^{-1} at a total power level of 100,000 kw and an average power density of approximately 2000 kw/liter. Since these performance characteristics represent a

[1]An employee of Metals and Controls, Inc., a Division of Texas Instruments, Inc., Attleboro, Mass.

significant extrapolation beyond the performance of present-generation research reactors, careful design and close control of the fuel element fabrication procedures are required. 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 pressure vessel clad with stainless steel.

Fuel element specifications have been reported.[2] The basic method of fabricating HFIR fuel elements was developed at ORNL. The adaptation of these procedures to a production process and the subsequent production of fuel elements was subcontracted to Metals and Controls, Inc. (M&C), Nuclear Division of Texas Instruments, Inc. under contract No. 91X-70500-C.

The purpose of this report is to present the details of the fabrication process as developed by ORNL and M&C for producing HFIR fuel elements on a production basis. No attempt will be made in this document to justify the process or to discuss alternate procedures. Such information will be found in a series of development reports that will follow. 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.

The process described has been shown to be acceptable by the production of 46 fuel assemblies. None of the fuel elements has met all of the specifications; however, no deviation or group of deviations has been considered serious enough to prevent the fuel elements from operating at their rated 100,000 kw. To date 15 have been operated satisfactorily at this level.

During the development and early production stages of the fuel-element manufacture an ORNL engineer was stationed at M&C as a consultant and coordinator. Also, ORNL personnel were used as troubleshooters and consultants. At present an ORNL Inspector is stationed at M&C to keep a constant check on the manufacturing process.

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[2]G. M. Adamson, Jr., and J. R. McWherter, Specifications for High Flux Isotope Reactor Fuel Elements, HFIR-FE-1, ORNL-TM-902 (August 1964).

The complexity of this job is illustrated best by the distribution of manpower which is shown below:

Task	Personnel Required
Manufacturing	25
Inspection	20
Engineering	4
Supervision of manufacturing and quality control	4
Production control and scheduling	3
Total	56

The value shown for engineering was that used on an average during the period of stable production. A much larger number were required during the initial stages of the contract.

Reports describing ORNL developments on various aspects of fuel element fabrication are in preparation. The development of nondestructive inspection methods has been reported.[3]

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 the outer of 369 identical plates differing slightly from those in the inner element. Both sets of fuel plates contain as the fuel U_3O_8 powder dispersed in an aluminum powder matrix and clad with aluminum.

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.

[3]R. W. McClung, Development of Nondestructive Testing Techniques for the High Flux Isotope Reactor Fuel Element, ORNL-3870 (April 1965).

Photo 57631

Fig. 1. Complete HFIR Fuel Assembly.

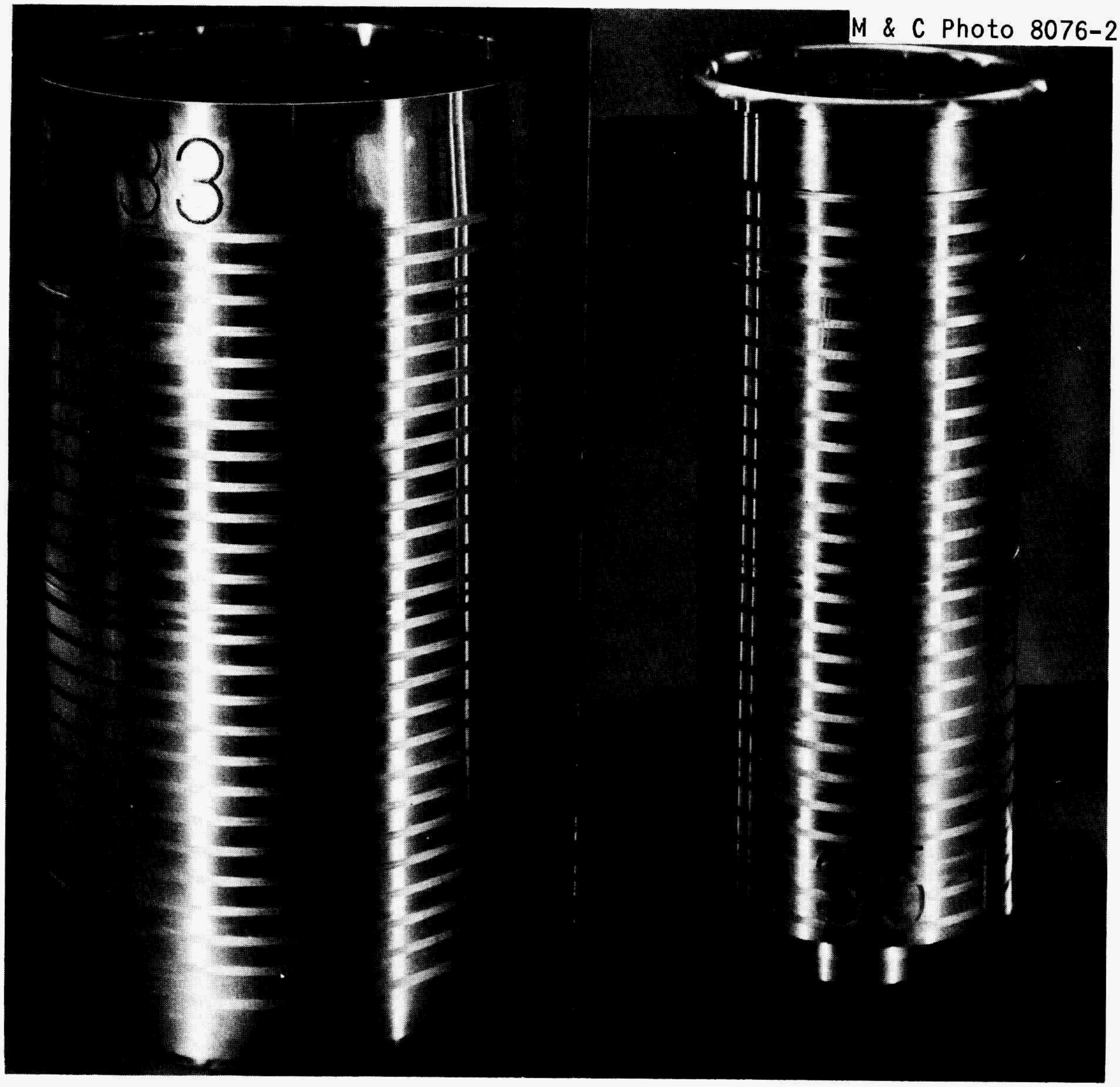

Fig. 2. Completed HFIR Fuel Elements. Left, outer annulus and right, inner annulus.

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. To stiffen the fuel plate ends, combs are attached to the plates at both ends. 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.

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

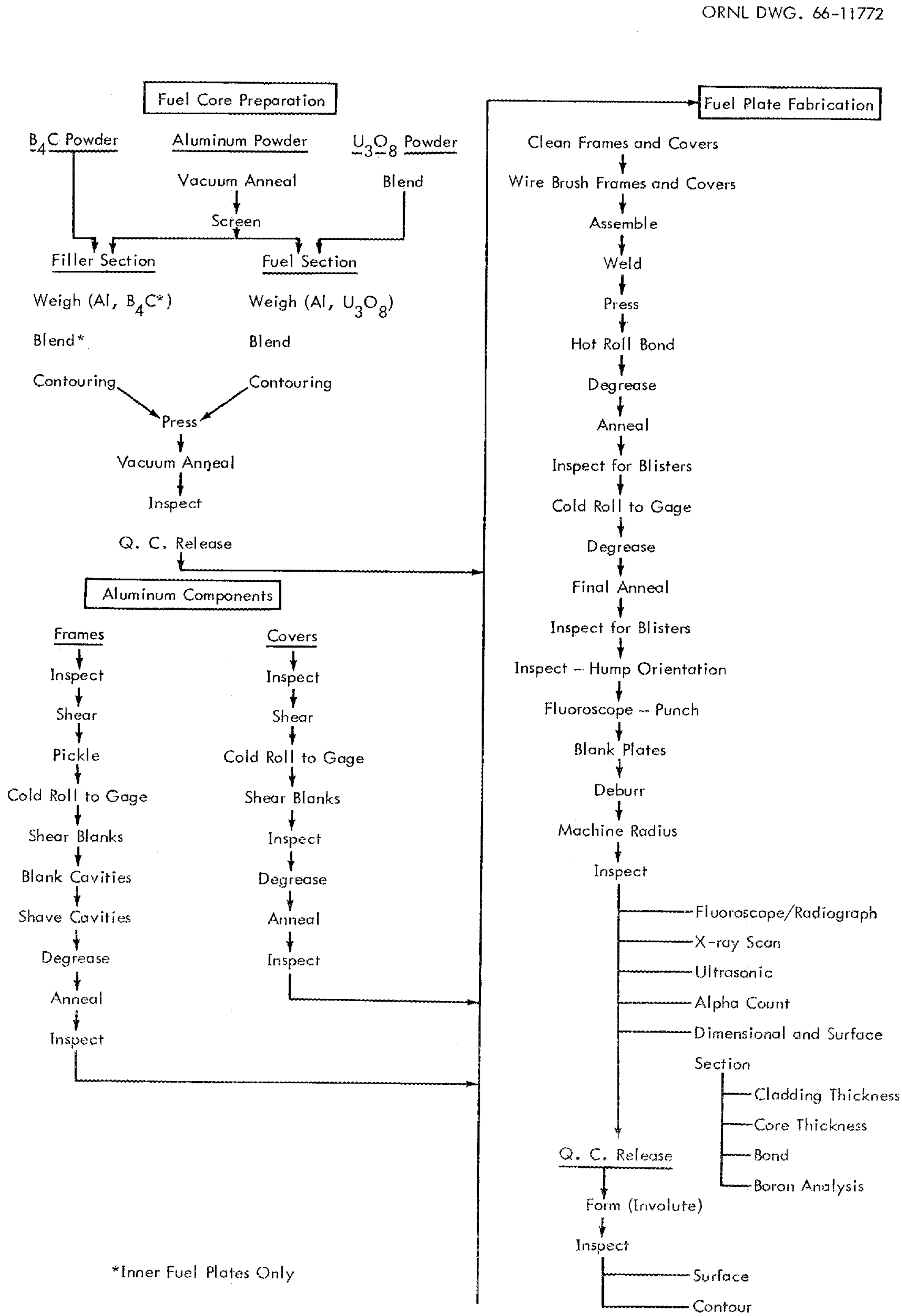

Fig. 3. Fuel-Plate Fabrication Process Flow Chart.

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. 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 and 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 M&C 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 material.

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.

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% inspection is performed whenever the particular attribute being studied violates the specification.

Components

Frames and Cover Plates

Typical fuel-plate components are shown in Fig. 4. The frames for both inner- and outer-annulus fuel plates are 0.265 in. thick × 8.000 in. long × 6.000 in. wide. Each frame has two cavities to allow hot rolling of tandem plates through the seventh pass. The cavity sizes are 2.157 to 2.153 × 2.922 to 2.918 in. for the inner annulus and 2.162 to 2.158 × 2.633 to 2.637 in. for the outer annulus. The cover plates for both inner and outer annulus are 0.1085 in. thick × 8.250 in. long × 6.000 in. wide.

The stock is alclad type 6061-0 aluminum, ordered in accordance with specifications shown in Appendix C and supplied in 3- × 8-ft sheets.

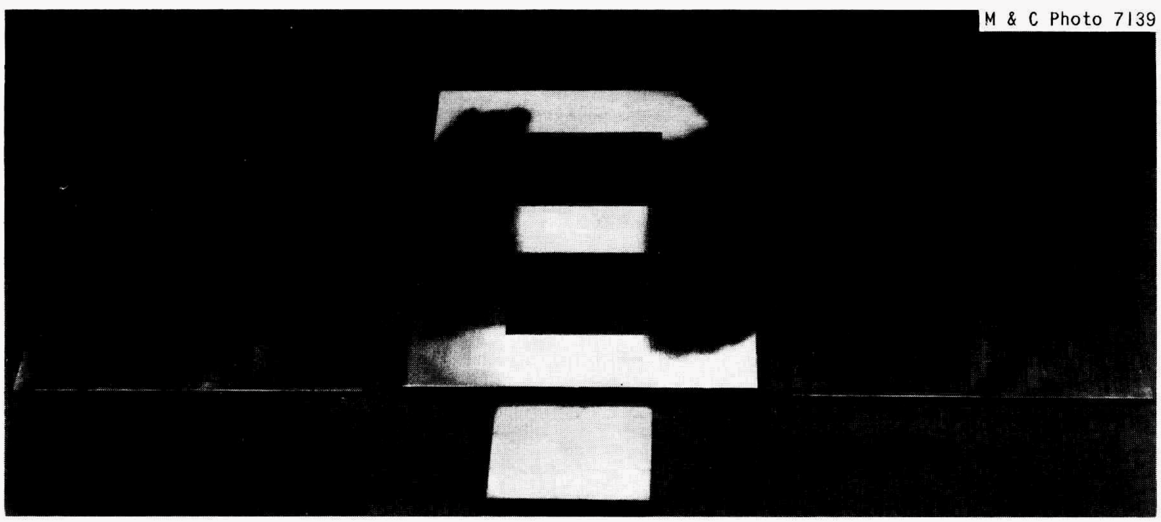

Fig. 4. Components of Fuel Billet.

The picture-frame stock is 0.350-in.-thick plate clad on both sides with type 1100 aluminum. The cover plate stock is 0.148-in.-thick sheet clad on one side with type 1100 aluminum. Specifications require that no cladding layer exceed 5.5% of the total thickness of the stock.

The as-received sheets are inspected on both surfaces for blisters and then sheared into 3- × 4-ft sheets. Each lot of material is identified, and this identification is maintained throughout the process. The 3- × 4-ft sheets are inspected for gage and surface imperfections. All contaminated areas are scraped to remove the contaminants, and any blistered and otherwise unusable areas are clearly marked. The plate is discarded if it does not yield 70% usable material. The sheets are sheared into 6-in.-wide × 4-ft-long strips. The shearing is done to align the 4-ft length in the direction in which the aluminum manufacturer had rolled the plate and also to provide the best yield.

The frame-stock strips are degreased and pickled by Procedure 1 of Appendix D. A maximum of 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 0.350 in. to 0.2645 to 0.2655 in. to produce a closer control of the gage than is available commercially, and one which is compatible with the rolling schedule. The rolling is done on a 13- × 12-in. or a 13- × 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 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 eight passes of 0.019, 0.015, 0.015, 0.013, 0.013, 0.010, 0.010, and about 0.005 in. The cover-plate strips are cold rolled to a gage of 0.109 to 0.108 in. in the same manner and for the same reasons as the picture frames. The strips are reduced in six passes of 0.008, 0.008, 0.008, 0.007, 0.007, and about 0.0025 in. A maximum camber of 0.045 in. per 4 ft is permitted for both types of strips. Strips are wiped with acetone to remove the oil. They are roller leveled on a nine-roll

3-in.-diam roller leveler to limit the maximum longitudinal bow to 2 in. for the full-length strip or 0.030 in. per 8-in. length. To prevent pickup of foreign material, particular care is taken to clean the roller leveler prior to use.

The cover strips are sheared into 8.265- to 8.235-in. lengths and the frame strips into 8.50- to 8.40-in. lengths in a manner to give the best yield. The frame stock is then blanked and shaved to produce a dual cavity and squared ends. Figure 5 shows the dies mounted in the presses. Transultex oil[4] is brushed on the cutting edges of the punches and each frame, and the dies are periodically sharpened to ensure good cavity edges. For producing good sheared edges, punch and die clearances are maintained at 0.001 to 0.002 in. per side. The type 6061 aluminum sides of the covers are visually inspected at 3X for inclusions. Inclusions found at this operation are usually from the "as-received" stock.

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

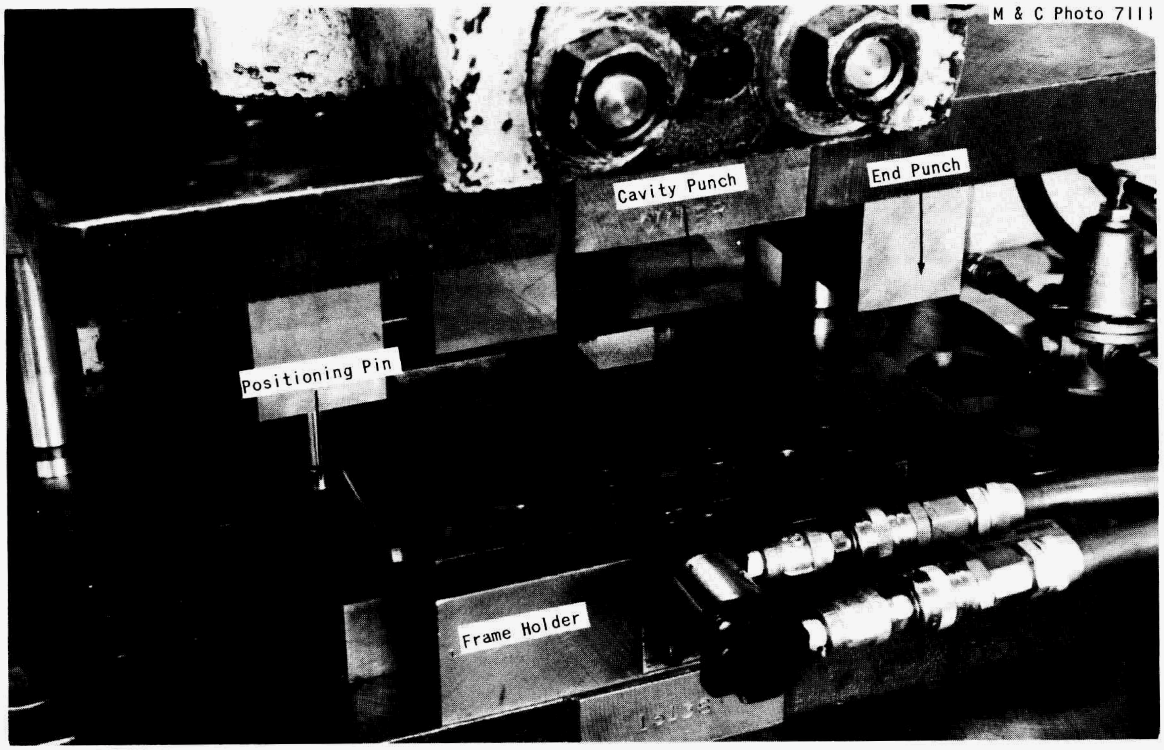

Fig. 5. Picture-Frame Shaving Die.

On the alclad side they are more readily detectable after cold rolling. However, the type 6061 aluminum side must be inspected prior to annealing, since annealing this alloy results in a dull mottled surface.

The frames are placed in special tote racks, dipped in perchloroethylene to remove the oil, and annealed at a minimum temperature of 500°C (932°F) for 2 hr 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. Any oven capable of maintaining a uniform $500\,^{+5}_{-10}$°C (932°F) temperature is suitable for this operation. Electric ovens with air blowers to circulate the hot air evenly are used at M&C. Approximately 150 frames are annealed in a batch, with care taken to maintain lot identity. The covers are vapor degreased with trichloroethylene and then annealed at a minimum of 500°C (932°F) for 2 hr. They stand on end (short dimension), stacked in groups of four with clad face to clad face. Approximately 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 ±0.002 in. The cavity edges and ends must be square within 0.002 in. total indicator reading (TIR). The cavity ends must be parallel with the reference edge of the frame within 0.005 in. TIR. All attributes of the cavities 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 0.005 in. TIR, and frame length and width are held to ±0.015 in.

The cover plates are to be held to ±0.015 in. in length, ±0.020 in. in width, and ±0.0005 in. in thickness. The ends and reference edge are to be square within 0.006 in. All dimensions are checked with a dial indicator gage.

(3) Thicknesses are measured at four corners 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 3×. Any embedded contaminants on the frame area that would remain on the

finished plate are removed with a tool-steel scraper. The inspected frames are wrapped in clean kraft paper and held in storage.

The alclad side of each cover is inspected for blisters and 100% inspected at 10× for surface imperfections in the final plate area. Any inclusions that may remain on the finished plate are removed with a tool-steel scraper. The inspected covers are wrapped in clean kraft paper and held in storage.

Aluminum Powder

Alcoa type 101 powder or equivalent is purchased in 100-lb drums in accordance with the specification in Appendix C. The as-received powder is vacuum annealed in a gas-fired horizontal vacuum furnace equipped with an oil diffusion pump and a water-cooled cold zone. The powder is spread evenly to a depth of about 1.5 in. in clean stainless steel trays and loaded into the cold zone of the furnace. The furnace is pumped down to a vacuum of at least 1×10^{-4} torr (0.1 μ Hg), and the leakage must be less than 2×10^{-3} torr (2 μ Hg) for a 4-min test period with the pump isolated. The trays are then loaded into the hot zone and kept there 5.5 hr with the furnace at 500 ± 10°C (932 ± 18°F). During the annealing cycle the pressure must not exceed 7×10^{-4} torr (0.7 μ Hg). Temperature is critical for this operation, since at too high a temperature powder will sinter and at too low a temperature the water of hydration will not be removed. After the 5.5-hr annealing cycle, the trays are removed to the cold zone, where the powder is cooled for 8 hr under vacuum. The temperature of the cold zone is regulated so that the powder is removed from the furnace at a temperature of 49 ± 11°C (120 ± 20°F) to prevent moisture condensation on exposure to the air. The top surface of the powder is scanned with a magnet to remove any small iron particles that might have been deposited during the cycle. Care is taken to maintain the furnace muffle 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, 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 and complete loss of vacuum during a power failure.

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-mesh (Tyler) screens for 15 min. A Ro-Tap machine with a tapping action of 140 to 160 taps per minute is used. The screen analysis is recorded, and the powder is accepted if 76 to 84% of it is –325 mesh.

Boron Carbide Powder

While ^{10}B is specified as the burnable poison, natural-boron boron carbide powder with a particle size less than 44 μ is purchased.[5] 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.

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.[6] As supplied, the oxide is –170 +325 mesh with a maximum of 10% –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 m^2/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 min. The U_3O_8 in the container is used up in approximately three manufacturing days. The blended U_3O_8

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[5]The Norton Company, Worcester, Mass., is one source for satisfactory powder.

[6]W. J. Werner and J. R. Barkman, Characterization and Production of U_3O_8 for the High Flux Isotope Reactor, ORNL-4052 (April 1967).

powder is identified by lot number and stored in a vault. For accountability, the weights of containers and powder are carefully recorded during these operations.

Compact Fabrication

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. 6, 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 element contains burnable poison in the form of B_4C. The finished cores are: for the inner annulus, 2.160 to 2.164 in. long × 2.925 to 2.929 in. wide × 0.265 to 0.271 in. thick; for the outer annulus, 2.1635 to 2.1675 in. long × 2.6395 to 2.6435 in. wide × 0.265 to 0.271 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 compact will contain 18.44 g ^{235}U. The volumes 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. Roll spread and density changes are calculated and compensated for to establish the required volumes of aluminum powder. The weight of aluminum powder for each portion of the compact is then determined. Typical charge weights are shown below. Furnace capacity limits each processing lot to 24 compacts.

	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

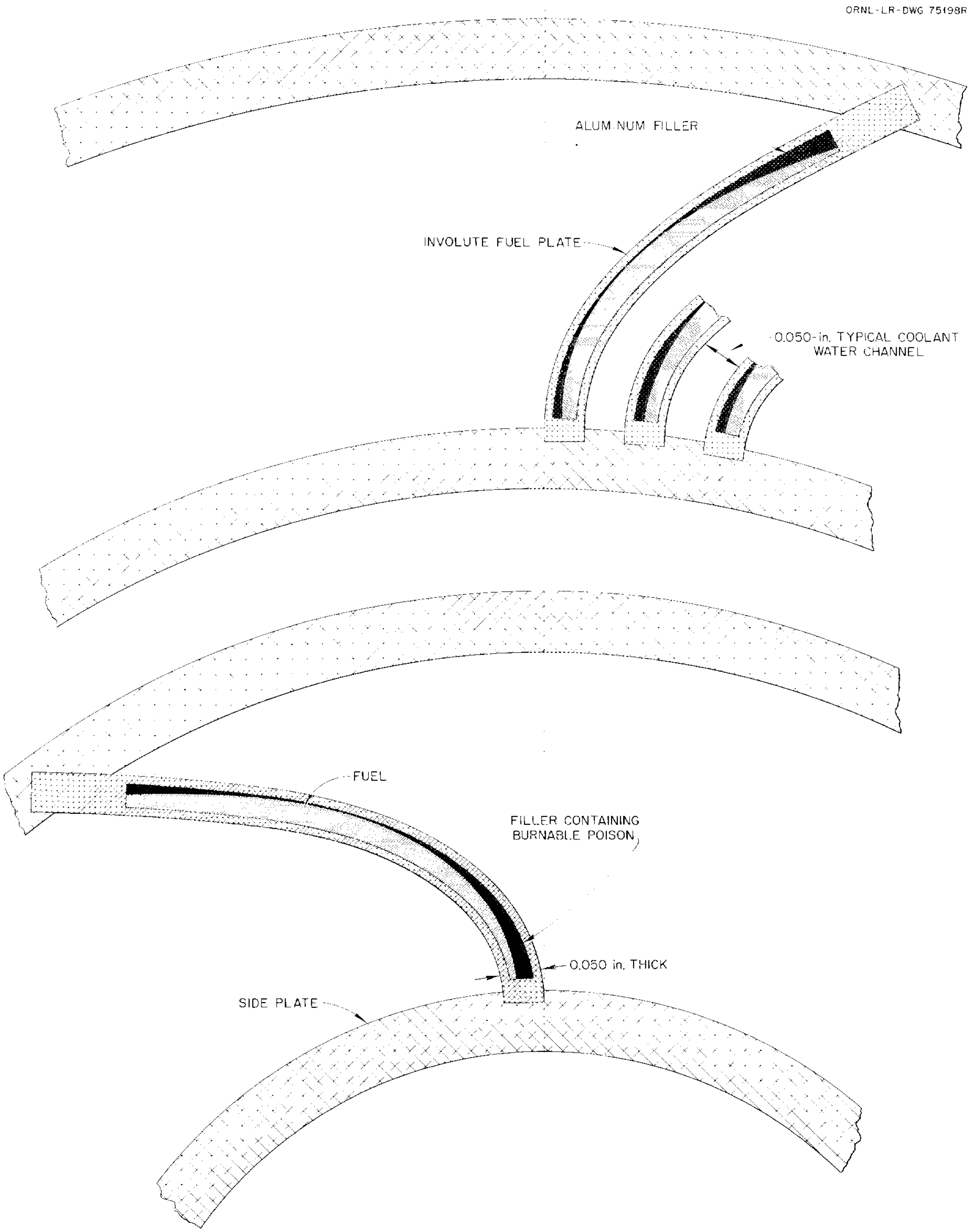

Fig. 6. HFIR Fuel-Loading Cross Section.

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 P-127 balance in a dry box, and the weight is recorded. The oxides are added to color-coded glass jars 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 ± 4°C (125 ± 7°F) for 30 min prior to use. As soon as the heating is completed, new clean caps are threaded firmly on the jars; old caps are not reused. 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.

From the vacuum storage containers the aluminum powder is screened and weighed in 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 two 100-mesh screens for 2 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. 7, 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.

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 and added to the jars containing the inner aluminum

Fig. 7. Weighing Aluminum Powder Charge in Dry Box.

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 hr 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 × 10-in.-long cylindrical cans on each arm of the blender, shown in Fig. 8. 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 hr of blending.

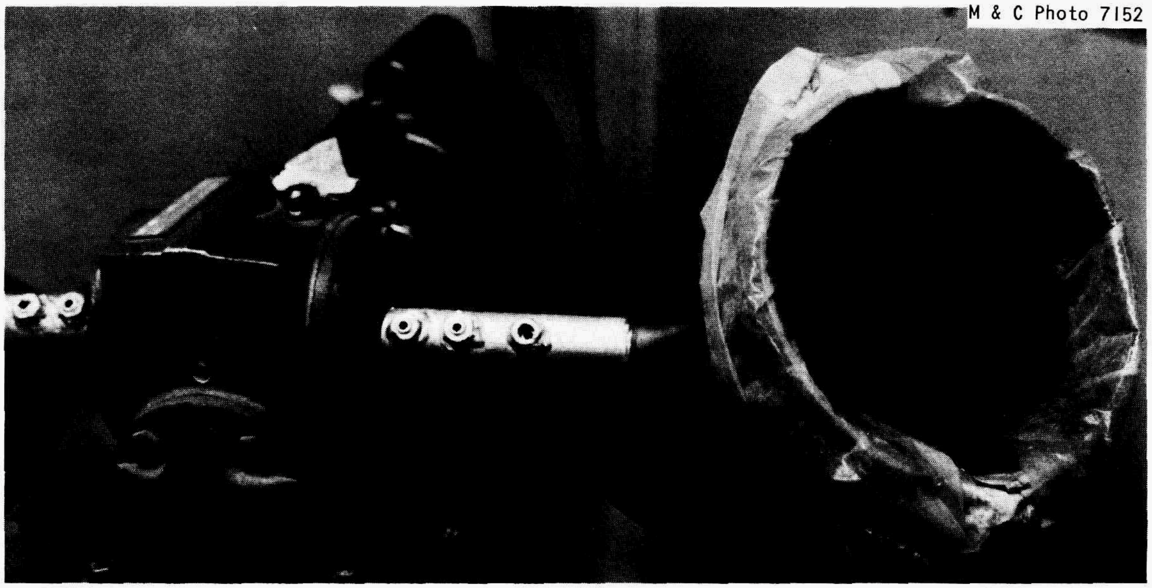

Fig. 8. Blender with Fuel Charges.

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. 9 and 10. 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% CCl_4, and baking for at least 30 min at 49°C (120°F). The coated cavity is wiped with a clean lint-free cloth. Even in the absence of pickup, this cleaning procedure is repeated weekly.

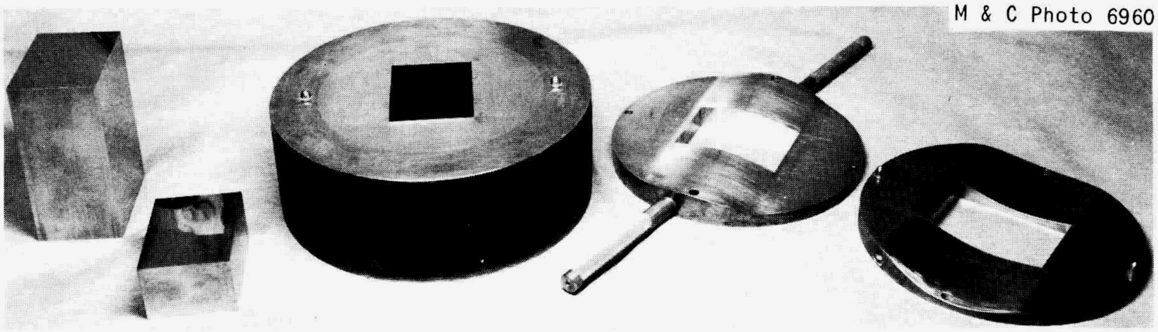

Fig. 9. Compacting Die Components. From left to right, bottom punch, top punch, die, fuel-section die top, and filler-section die top.

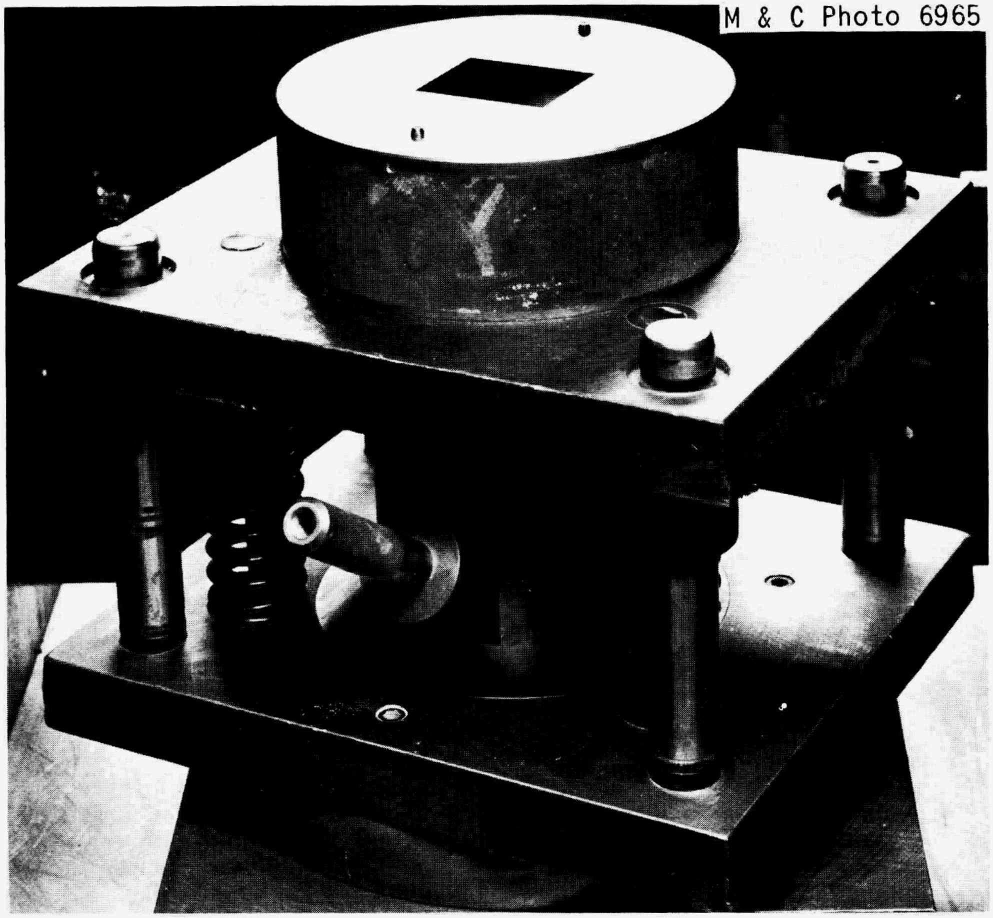

Fig. 10. Compacting Die, Die Set, and Leveling Jack.

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. 11. 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.

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. 12. The leveling tool is used again with the threaded jack to adjust the level of the charge to the top of the cavity.

The entire charge is smoothly lowered into the die cavity and the die tops are removed. A slightly tapered top punch is inserted with the tapered face down in the die cavity so that the thick edge of the punch is on the same side of the die cavity as the hump of the fuel. The

Fig. 11. Contouring Fuel Section of Compact.

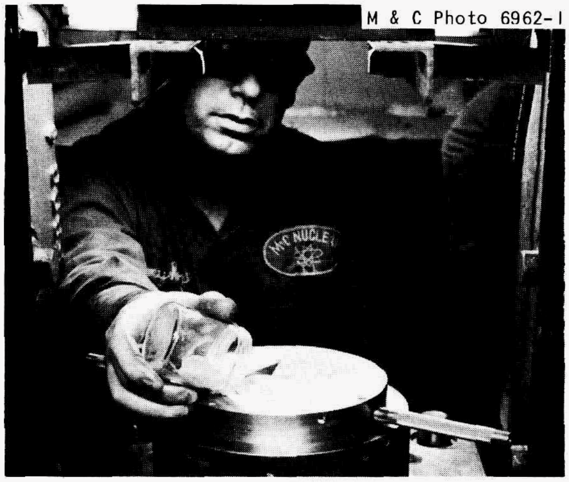

Fig. 12. Adding Filler Section of Compact.

tapered punch is required to produce a level compact with the M&C process and equipment. The compact is pressed at 2900 psi to produce a thickness that is 0.0015 in. less than the desired annealed compact thickness. 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 Fig. 13. 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.

Vacuum Annealing

To remove the lubricant entrapped during pressing and any moisture picked up during handling, all pressed compacts are vacuum annealed. For this operation the compacts are placed on clean stainless steel

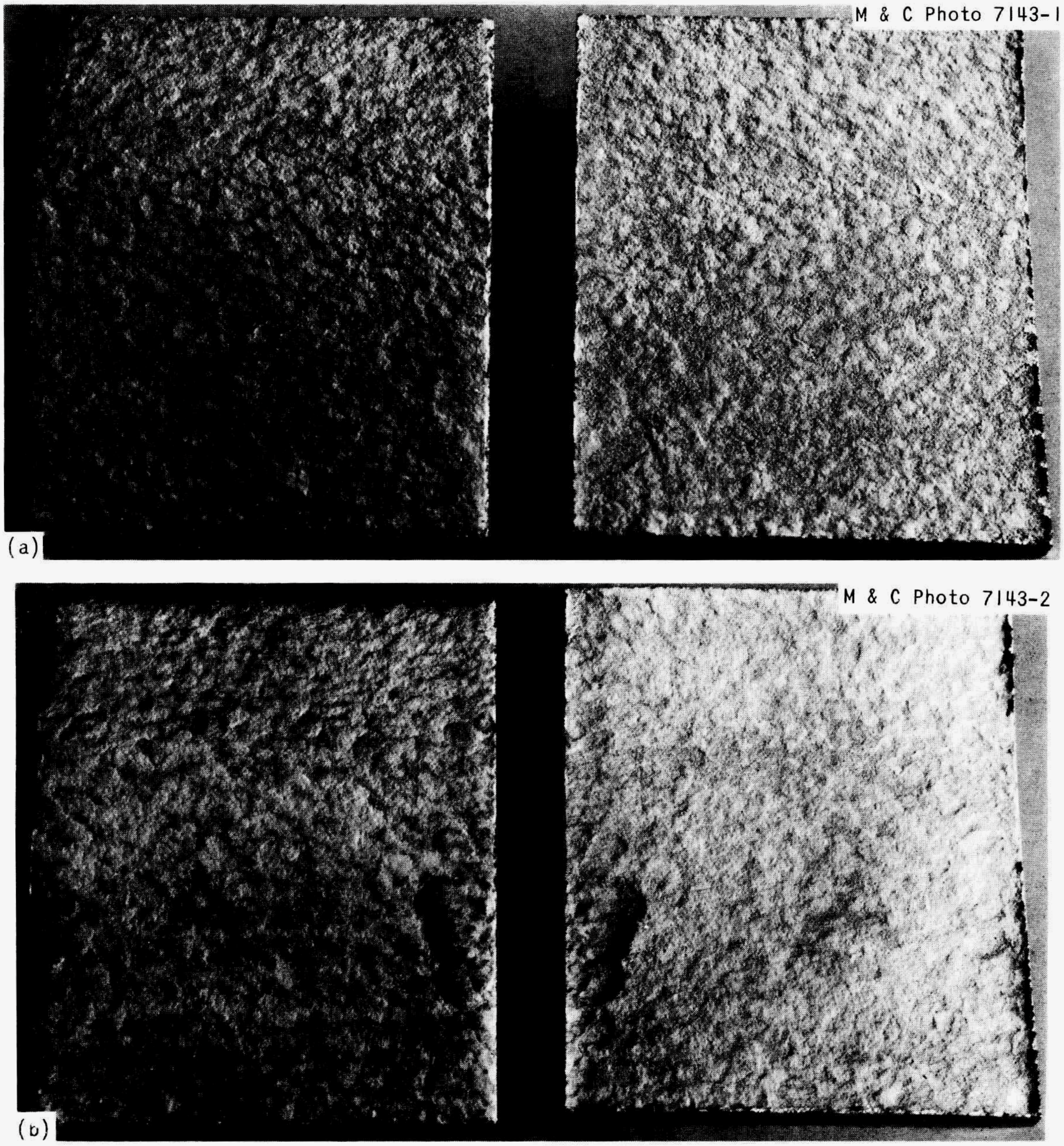

Fig. 13. Split Compacts Illustrating Interface Between Fuel and Filler Sections. (a) Acceptable interface. (b) Result of upset or splash during addition of filler charge.

screens in a stainless steel annealing tray and then placed in a gas-fired horizontal vacuum furnace equipped with a water-cooled cooling chamber and oil diffusion pumps. The tray is loaded into the cold zone of the furnace, and the furnace is 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-min test period with the pumps isolated. The tray is then pushed into the hot zone, where the compacts are annealed at 590 ± 10°C (1094 ± 18°F) for 4 hr. The pressure must stay at less than 1×10^{-4} torr (0.1 μ Hg) during the 4-hr cycle. The tray is removed to the cold zone and cooled for 9 hr under vacuum. Hot water is run through the cooling coils for the last hour of the cycle to prevent moisture condensation on the compacts when they are exposed to air. The annealed compacts are removed, inspected visually, freed from magnetic contamination with a magnet, and then returned to vacuum storage. Compacts must be hot bonded within five days after vacuum anneal or they have to be reannealed. Compacts are handled with stainless steel tongs.

Compact Inspection

Four randomly selected 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 the four randomly selected 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.

Fuel Plate Fabrication

Billet Preparation

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 rolling 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 rolling.

Picture frames and cover plates are wiped with acetone and vapor degreased in trichloroethylene for 5 min. Care is taken in stacking the frames and covers so that the faces are not in contact with the stainless steel rack or with other pieces. The degreasing fluid is changed each day. Degreased parts are handled with clean white cotton canvas gloves and wrapped in clean brown paper.

To further clean and to provide a slightly roughened surface for improved bonding, frames and covers are brushed at 1100 rpm with stainless steel wire brushes, as shown in Fig. 14. New brushes are degreased and baked at 204 to 288°C (400 to 550°F) for at least 30 min before use. Mating faces and outside edges of the components are brushed with 6-in.-diam 0.0109-in.-wire brushes and frame cavity edges are brushed with 1-in.-diam 0.010-in.-wire brushes. All edges and faces of the frames

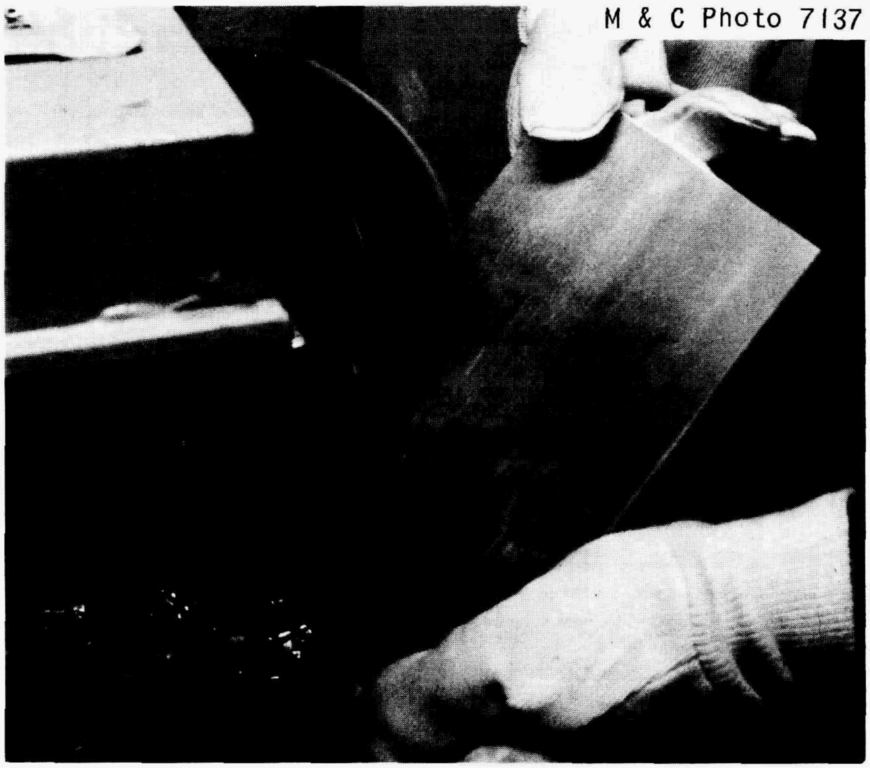

Fig. 14. Wire Brushing Cover Plate.

and the edges and alclad surface side of the covers are brushed. Frame faces are brushed across the ends and center and along the sides, and cover plates are brushed in longitudinal and transverse directions. Frames and covers are handled with white cotton gloves worn over polyethylene gloves. Frames and covers are wrapped in clean kraft paper in groups of 12 and 24, respectively. The covers are stacked so that the alclad sides face each other.

A shrink fit is used to assemble the compacts into the picture frames, in such a manner that voids are eliminated. Frames are placed on edge in a rack and preheated in a furnace for 35 min at 500°C (932°F) minimum. The lower cover is placed with the type 6061 aluminum side face down on an aluminum plate, and the heated picture frame is placed on top of it. As shown in Fig. 15, the compacts are then quickly inserted into the frame with their identification numbers in a specified location. A dummy aluminum compact is used whenever the number of compacts is odd.

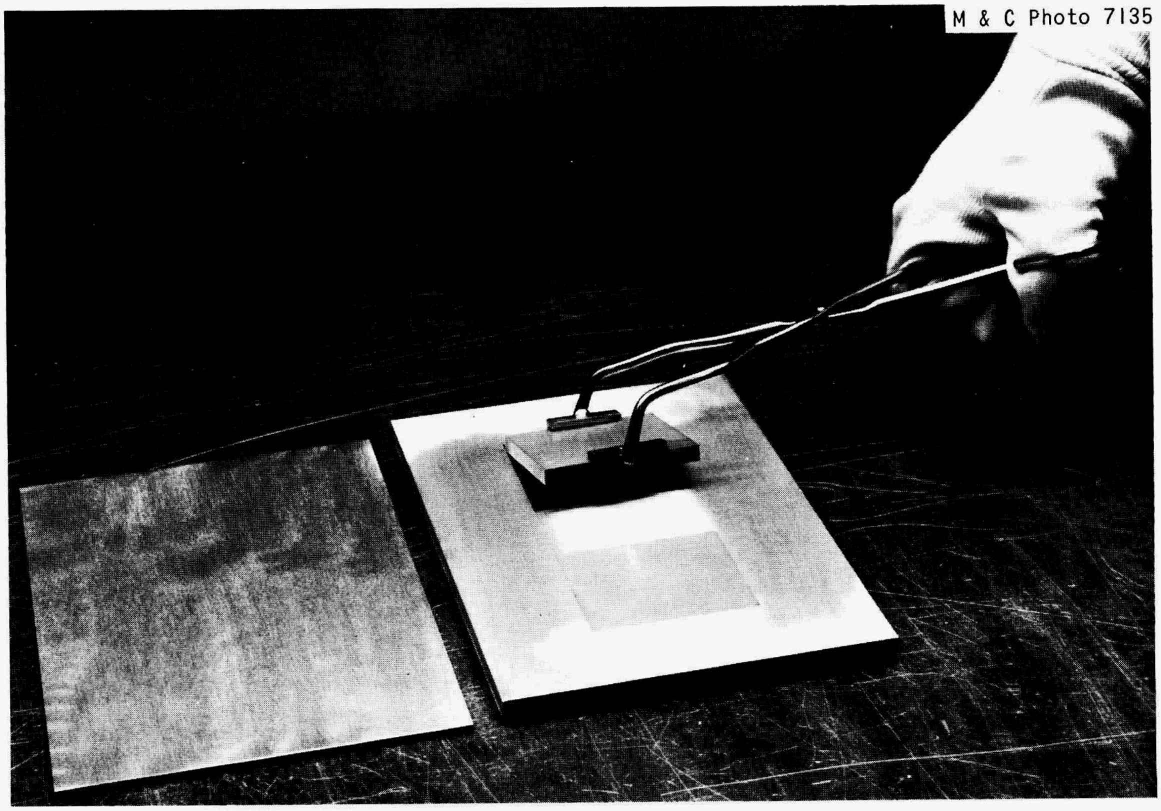

Fig. 15. Insertion of Fuel Compacts in Picture Frame.

Tongs are used to handle both frames and compacts. The top cover plate is held firmly on top of the assembled frame with a 1/2 × 5 × 10 in. aluminum plate. The 10-in.-long edge of the plate is placed along the longitudinal center line of the assembly, and the operator exerts sufficient pressure to hold the compacts in a seated position until the frame has cooled sufficiently to lock the compact in place. After the frames have cooled, the top cover is removed and the compacts are checked for seating and orientation. The top cover is replaced and identified with a Vibratool. The assembled package is carefully lined up and placed in a vise, and the edges are fusion welded by the TIG process with alternating current and argon gas shielding, as shown in Fig. 16. Approximately 3/4 in. from each corner of the billet is left unwelded to permit escape

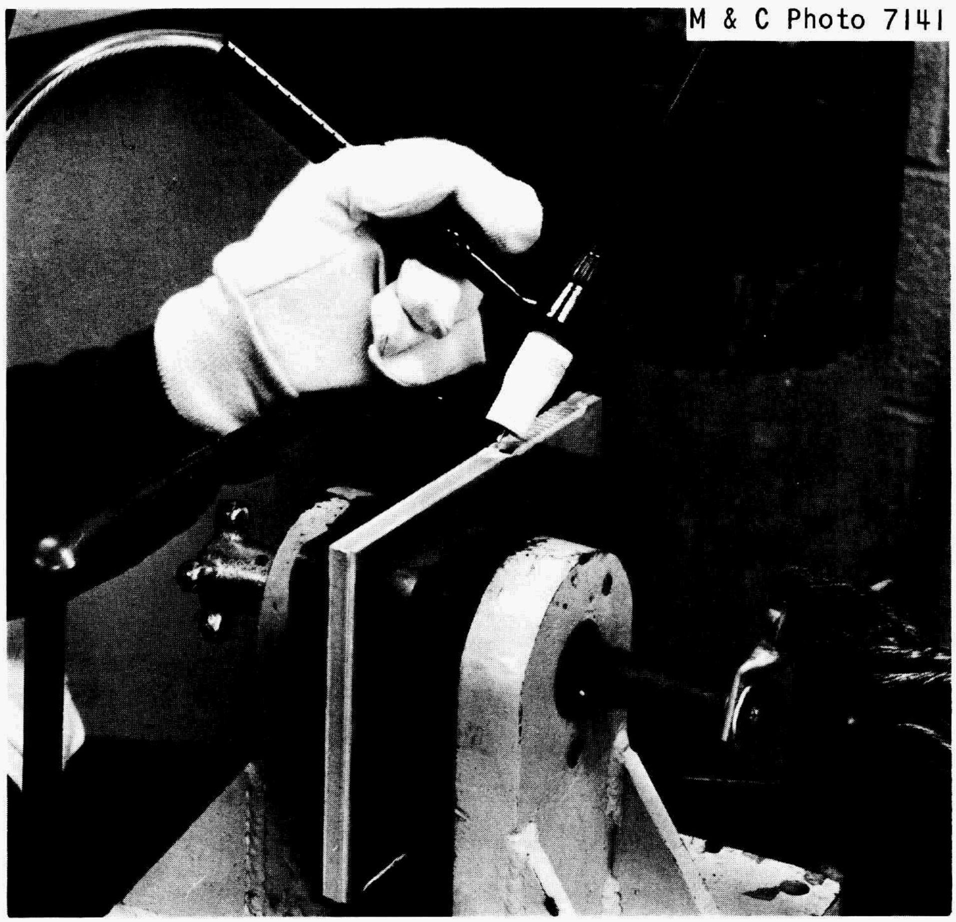

Fig. 16. Welding Assembled Fuel Package Billet.

of any entrapped air. The assemblies are stored under vacuum if not bonded within 4 hr. To assure proper positioning of the cores before rolling, the assemblies are pressed between clean flat platens at a total load of 113 tons.

Hot Rolling

The assemblies are next hot rolled to convert the compacts into plates and to provide a bond between the cover plates and the frames or compacts. Hot rolling was selected as the method of reduction so as to minimize fuel particle fracturing and stringering and to improve the 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 hr at $500\,^{+5}_{-10}$°C (927 ± 13°F) in an electric oven 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 13- × 16-in. hot rolling mill employing flat rolls is used for 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 (130°F) to ensure stable rolling conditions for the entire batch. If the rolls have cooled, they are surface conditioned by rolling six 5-in.-wide × 12-in.-long × 1/2-in.-thick pieces of type 6061 aluminum plate that have been preheated to $500\,^{+5}_{-10}$°C (927 ± 13°F) for 30 min. These roll-conditioning blanks are rolled to essentially the same schedule as the fuel billets (see below). The blanks are further reduced to 0.021 in. by taking reductions to give gages of 0.052, 0.043, 0.036, 0.030, 0.025, and 0.021 in. The blanks are heated 5 min at $500\,^{+5}_{-10}$°C 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 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. 17. The catcher wears chain mesh gloves[7] over 8-oz cotton canvas gloves and handles the plates with his gloved hand, as shown in Fig. 18. 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 1. It was selected to provide reliable bonding with a minimum of fuel stringering.

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 4 in. is trimmed from each end on a three-bladed hand shear, shown in Fig. 19. The top of each plate is stamped with the plate identification number by use of an automatic

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

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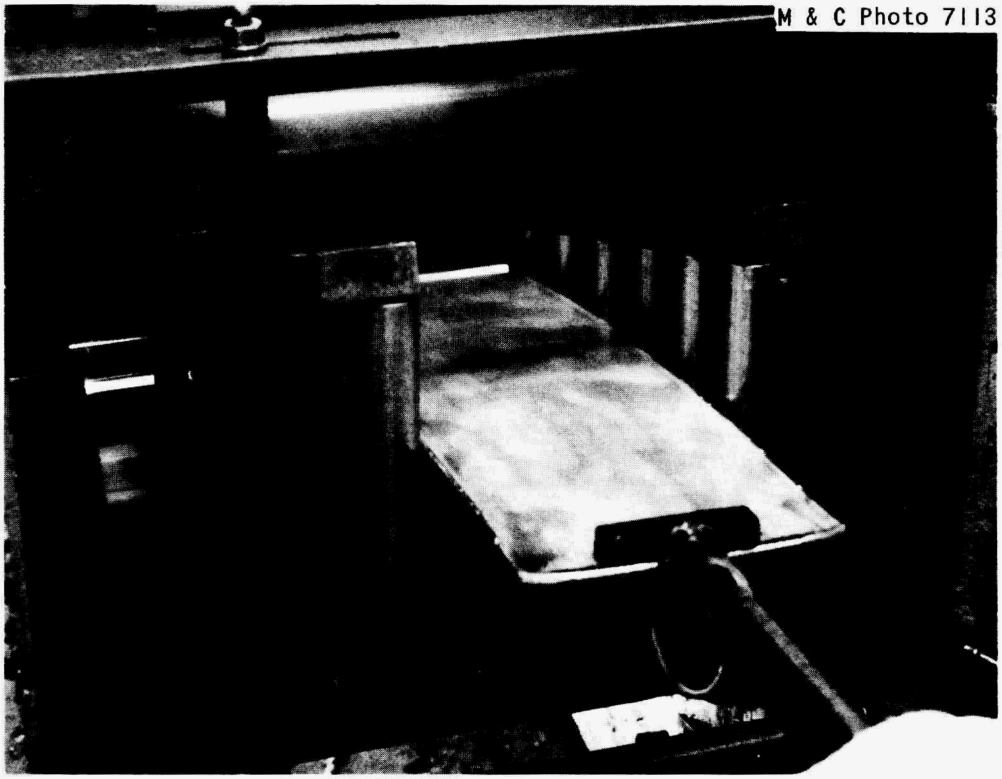

Fig. 17. Entry Side of Hot-Rolling Mill, Showing Plate Being Fed Between Roll Guides.

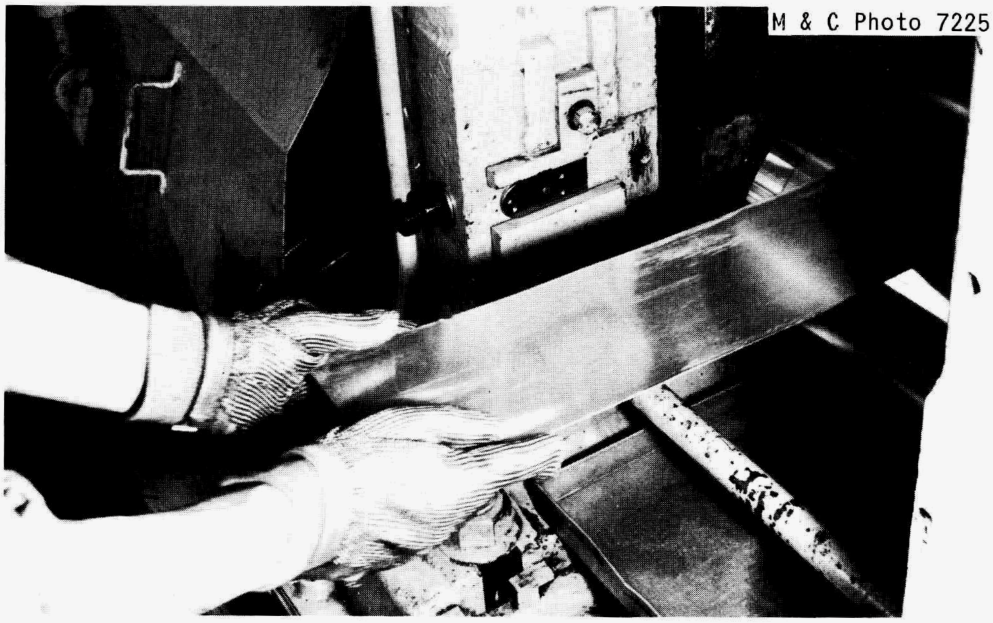

Fig. 18. Catching Hot-Rolled Plate with Chain Mesh Gloves.

Table 1. Schedule for Hot Rolling of Fuel Plates

Pass	Reduction (%)	Reduction (in.)	Gage[a] (0.482 in. start) (in.)	Reheat Time (min)
1	15	0.073	0.409	10
2	15	0.061	0.348	10
3	23	0.080	0.268	5
4	23.5	0.064	0.204	5
5	24	0.048	0.156	5
6	24	0.038	0.118	5
7	23.5	0.028	0.090	10
8	16	0.014	0.076	5
9	12	0.0095	0.0665	5
10	5	0.004	0.0635	0
11	Same mill setting as Pass 10			

[a]Values are for rolling temperature.

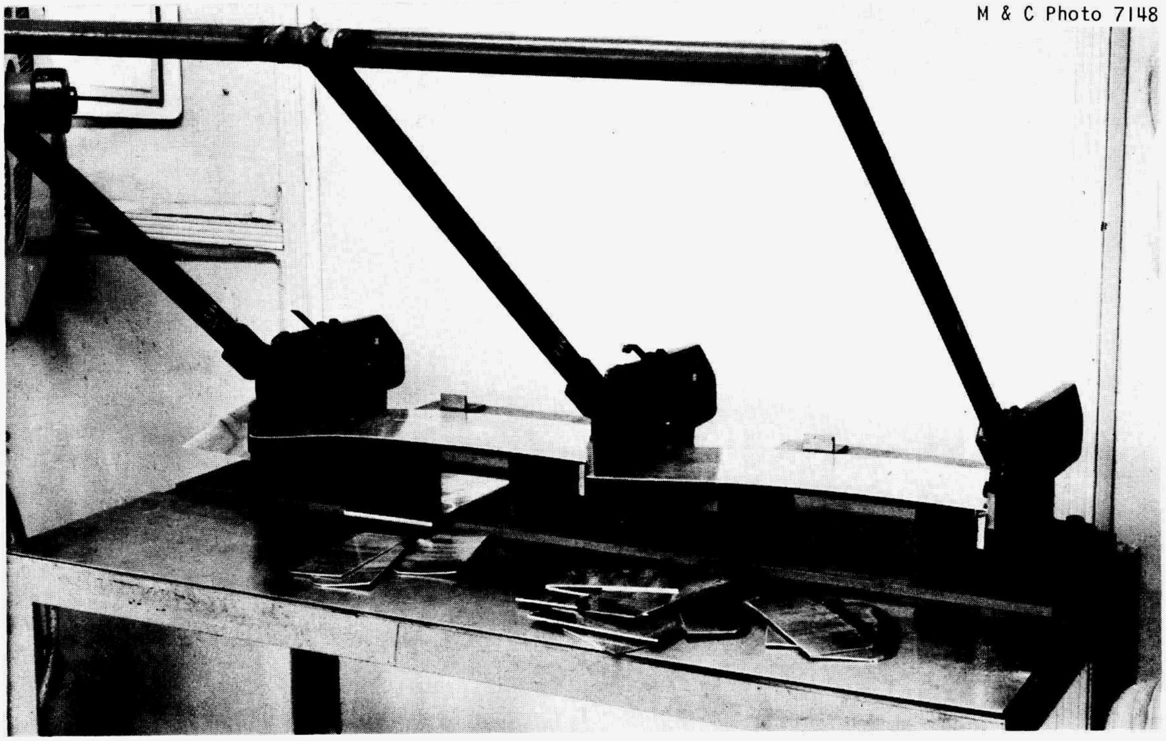

Fig. 19. Shearing Hot-Rolled Plates.

numbering head. After the last plate has been sheared and inserted into the furnace, the plates are reheated for an additional 10 min and rolled to 0.0623 to 0.0618 in. thickness in accordance with Table 1.

The plates are allowed to cool, placed in an aluminum degreasing rack, and vapor degreased with trichloroethylene. The degreased plates are stacked on aluminum platens and annealed for 2 hr at $500\,^{+5}_{-10}\,^{\circ}C$ ($927 \pm 13^{\circ}F$) in an electric oven with air circulator. The plates are visually inspected for blisters. A plate is scrapped if a blister appears on any portion of the plate that will remain after trimming to final dimensions.

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 13- × 16-in. or a 13- × 12-in. cold rolling mill with flat-ground rolls, as shown in Fig. 20. The rolls are kept clean and lubricated by Procedure 2 in Appendix D. A 6-in.-wide × 24-in.-long × 1/16-in.-thick piece of

Fig. 20. Cold Rolling Fuel Plate, Entry Side of Mill.

type 6061 aluminum sheet is cold rolled to final plate gage before a batch of fuel plates is rolled. The blank is inspected for surface defects generated by the rolls and for rolled-in contamination. Cleanliness is extremely important in this operation. The plates are cold rolled in accordance with the schedule in Table 2, with four passes at each mill setting.

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 0.001 in. from each other. The maximum plate camber permitted on completion of rolling is 0.010 in.

Table 2. Schedule for Cold Rolling of Fuel Plates

Passes	Reduction		Gage (in.)
	(%)	(in.)	
1–4	5.6	0.0035	0.0595
5–8	3.5	0.0020	0.0575
9–12	3.5	0.0020	0.0555
13–16	3.5	0.0020	0.0535
17–20	2.8	0.0015	0.0520
21–24	1.9	0.0010	0.0510
25–28	1.9	0.0010	0.0500

The plates are vapor degreased with trichloroethylene while held in aluminum racks. The degreased plates are flatten annealed in two stacks of 60 plates each between 1 1/4-in.-thick aluminum platens for 4 hr at 500 $^{+5}_{-10}$°C (927 ± 13°F) in an electric oven with an air circulator. To obtain the "O" condition, the plates are furnace 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.

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 plate is revealed by fluoroscopy. A Norelco MG 150 x-ray unit, shown in Fig. 21, is used as the power source. Settings for this unit are 135 ± 5 kv and 12 ± 1 ma. Clear plastic templates with platinum boundary wires, shown in Fig. 22, 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. 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

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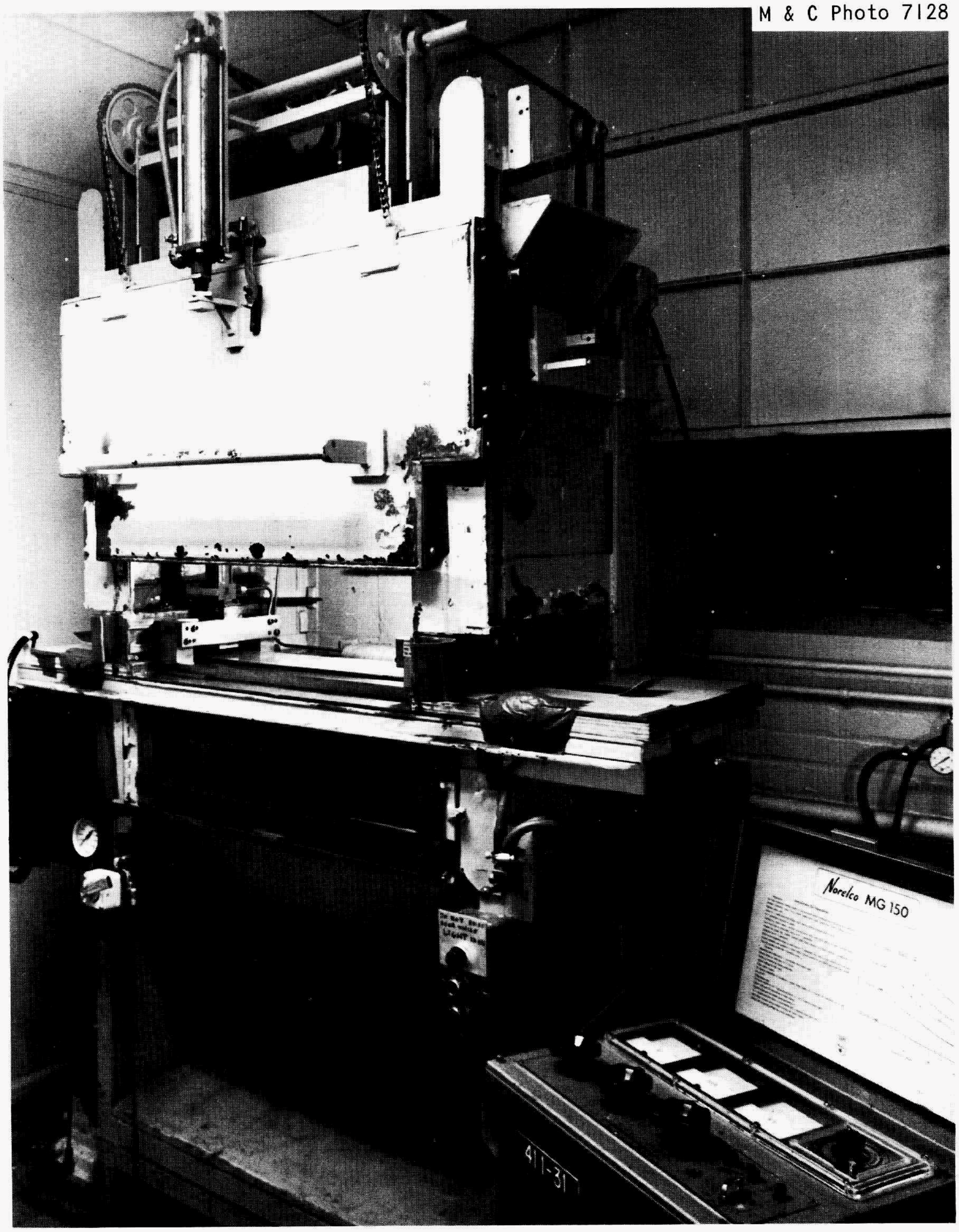

Fig. 21. Fluoroscope Equipment.

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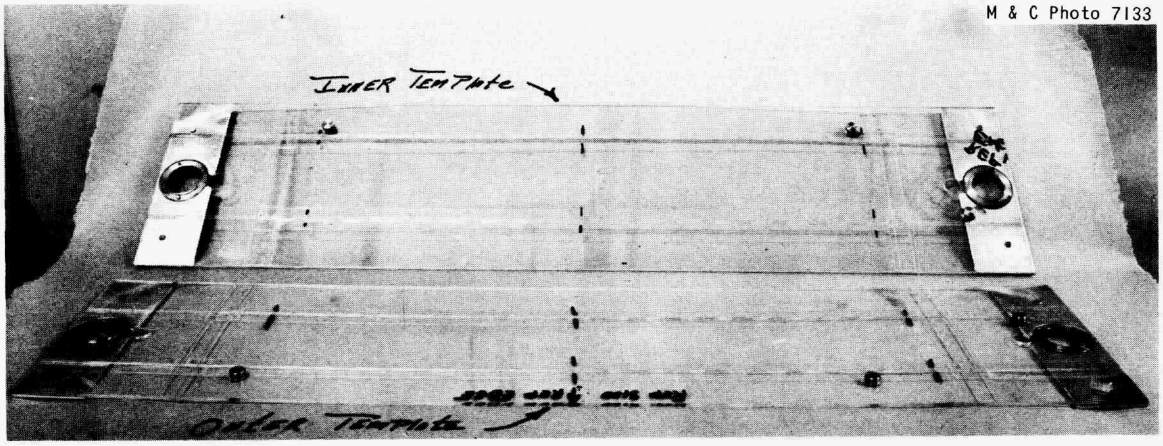

Fig. 22. Fluoroscope and Punch Templates.

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.

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.

Sizing

The fuel plates are blanked to size with a 150-ton press brake. A typical blanking die is shown in Fig. 23. The die faces have recessed portions to permit reduced contact of plate to die and thus reduce the possibilities of a foreign particle being embedded in the fuel plate. The plates are cleaned thoroughly and examined under low magnification for contaminants before blanking. After blanking, the plates are transferred from wooden boxes with interleaved paper to cardboard boxes containing plastic inserts to keep the plates separated, as shown in Fig. 24.

The holes, edges, and ends of the plate are deburred with a sharp Black Diamond special crosscut file. The holes are chamfered 0.010 in. maximum with a sharp 7/32- to 1/4-in.-diam drill. The radius on the

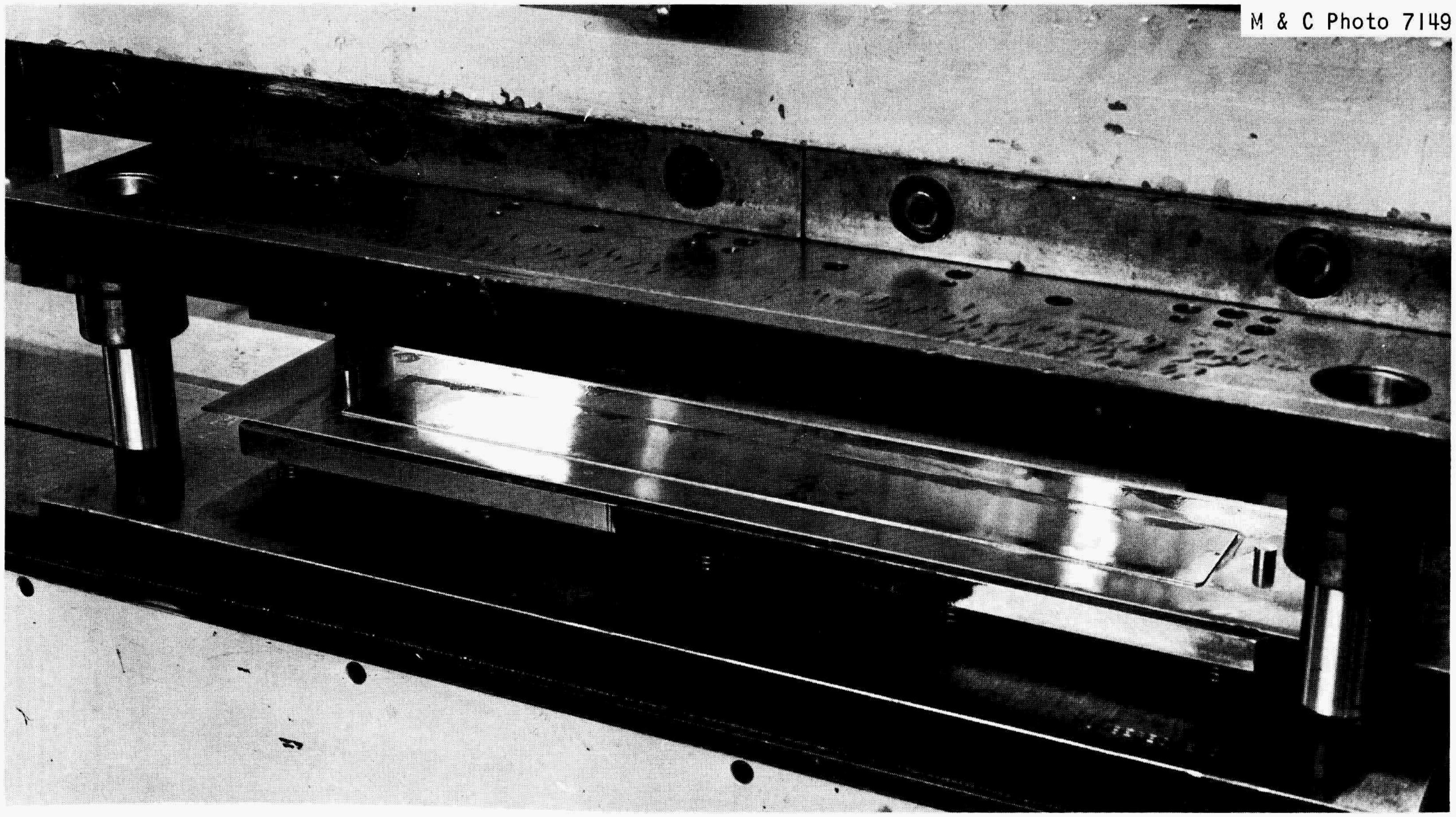

Fig. 23. Blanking Die and Blanked Fuel Plate.

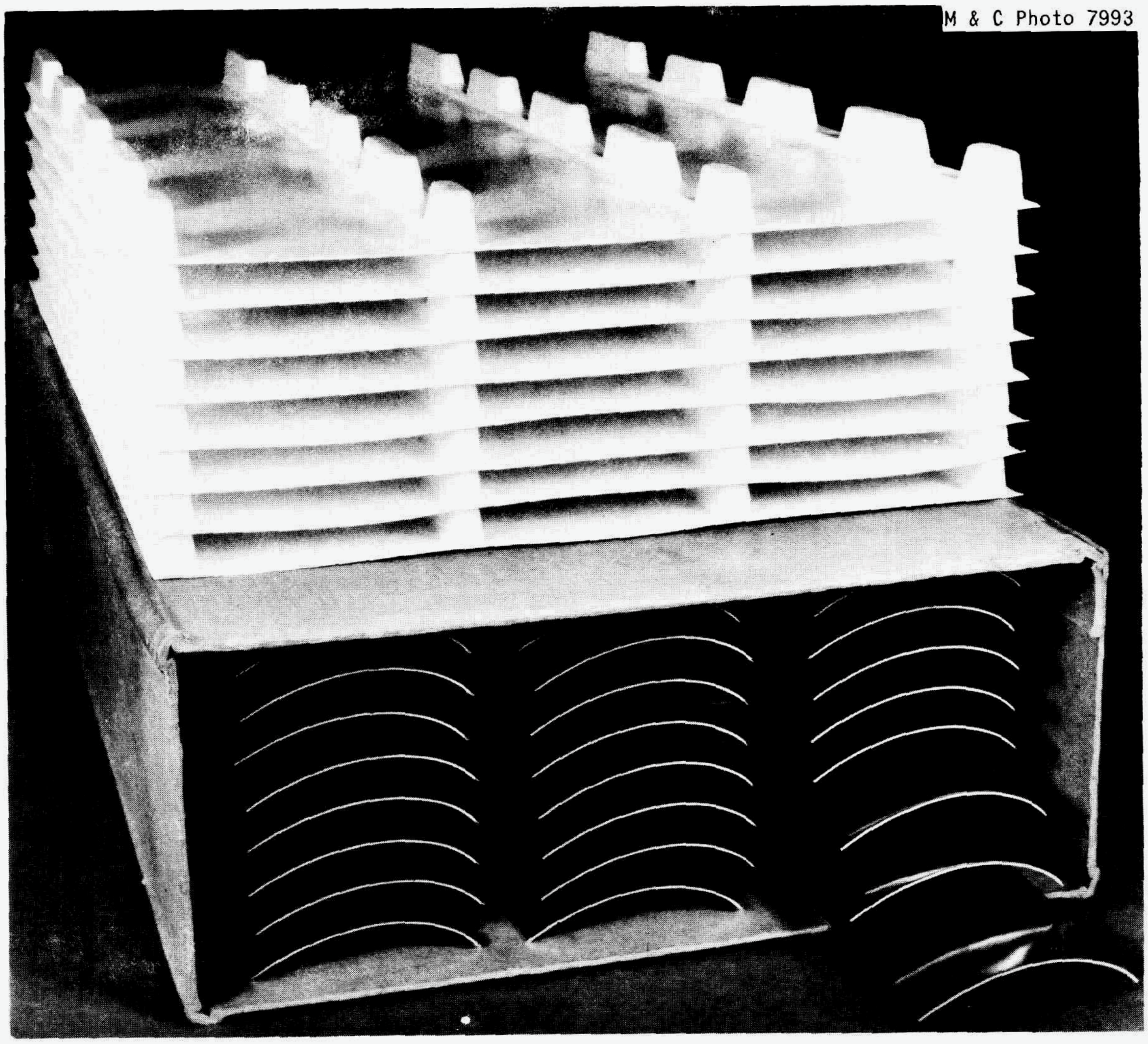

Fig. 24. Fuel Plates in Carrying Box and Spare Set of Separators for Use in the Box.

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. Parallax corrections are taken into account. If there is a doubt as to the acceptance of a plate, it is designated for radiography.

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 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. 25. The hump location is usually performed before fluoroscopy and sizing.

Hump Location

The plates are checked for fuel hump orientation by means of a FM-100 Magnatest conductivity meter,[8] shown in Fig. 26. 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.

Radiography

Three plates from each lot of 24 are randomly selected for radiography, in addition to any plates designated for radiography from the

[8]Magnaflux Corporation, 7300 W. Lawrence Avenue, Chicago.

Fig. 25. Surface Inspection of Cold-Rolled Fuel Plate, Showing Use of Special Rubber Mat to Prevent Scratches.

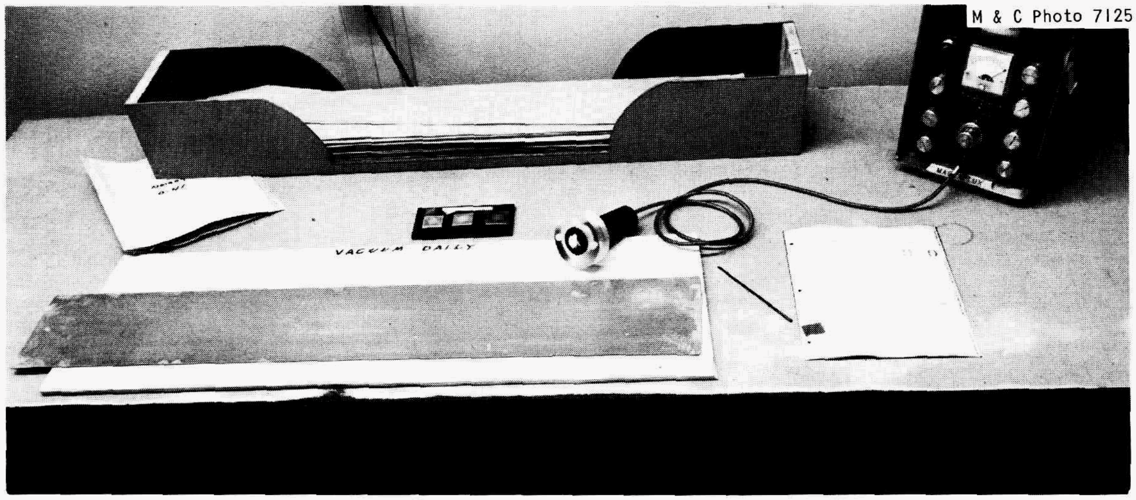

Fig. 26. Equipment for Determining Fuel Hump Orientation.

final fluoroscopic inspection. Radiographic equipment consists of a Norelco MC 300 x-ray unit in a lead-lined room. The film focal distance is 54 in. Kodak "Type M" film is placed in a hard cassette with 0.005 to 0.010 in. back lead. Number 25A penetrameters[9] are placed on 0.050-in.-thick pieces of aluminum at opposite corners of the film. Each film is identified by plate number, 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 (0.020 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

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

all plates must be radiographed and inspected. The minimum top end cladding and bottom end cladding widths are measured to the nearest 0.005 in. with dividers and a scale and recorded. The two edge cladding widths are measured to the nearest 0.005 in. and recorded for locations 3 in. from each fuel end and at the center of the fuel length.

Homogeneity

The plates are scanned for determination of uranium inhomogeneity by an ORNL-supplied x-ray scanner,[10] shown in Fig. 27. 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 1/2 in. of travel when a 5/64-in.-diam beam is used with a scan speed of approximately 240 in./min. The entire plate is scanned longitudinally with transverse indexing that provides a scan width overlap of approximately 1/64 in.

[10]B. 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).

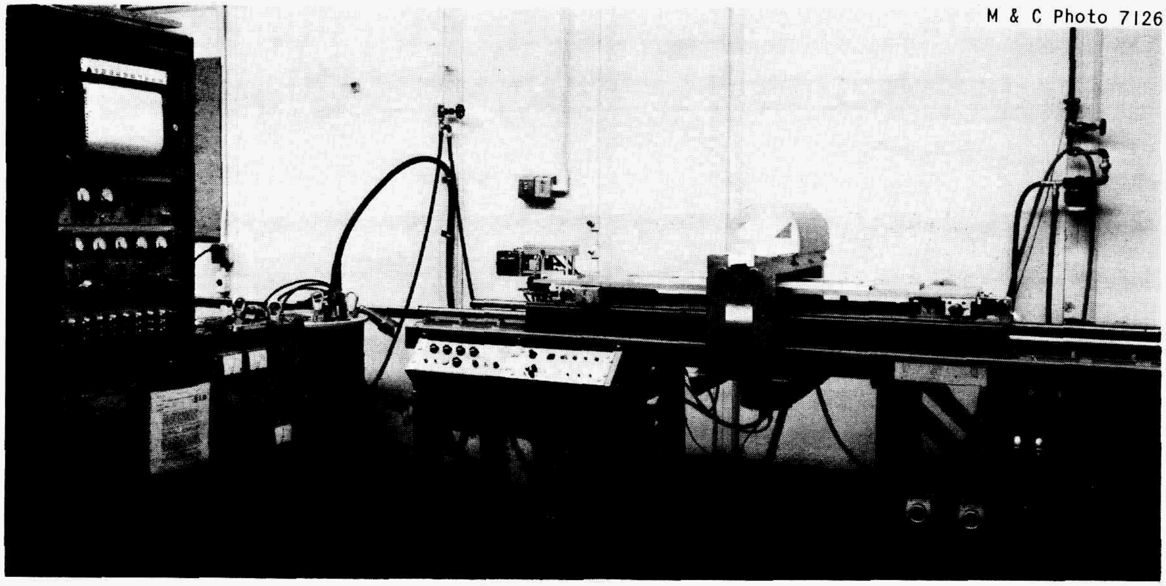

Fig. 27. X-Ray Homogeneity Scanner.

Three aluminum standards (+12, −12, +27%), shown in Fig. 28, 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 240 in./min with the following standards: +27% spot and ±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 a +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 +27% indications are rescanned at 240 in./min with +30% spot and ±10% average standards. In addition, the track that shows the +27% indication and the two adjacent tracks are scanned at 64 in./min with a strip chart recorder that records the actual instantaneous signals. Those plates with the first run indications of +12% average or +10% average are rescanned at 64 in./min with the same standards used as in the previous run. A strip chart and the

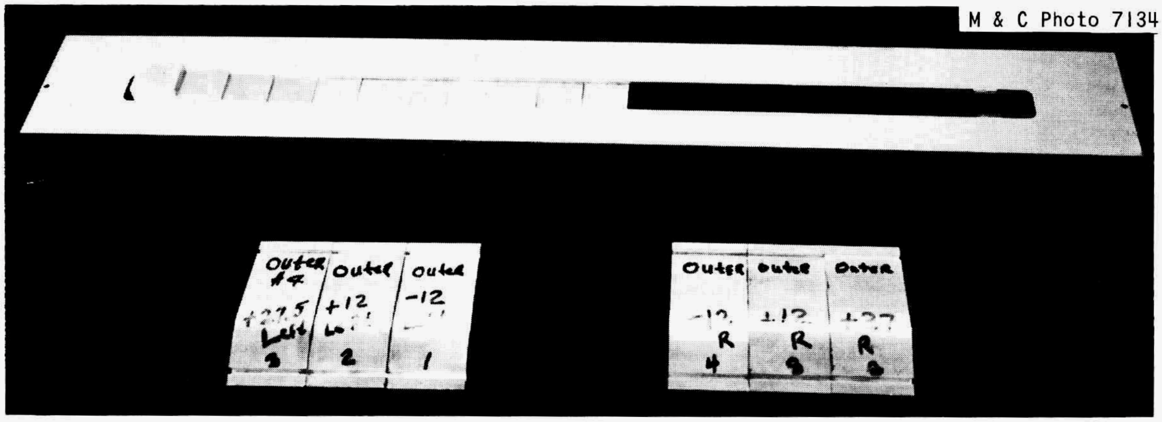

Fig. 28. X-Ray Homogeneity Standards. Top: aluminum and aluminum-uranium standards. Bottom: spot and average aluminum standards.

ink chart are obtained for these reruns. Once a week, the machine is calibrated against a series of aluminum and uranium-aluminum standards, shown in Fig. 28. 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 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 assure reject levels per specified accuracy before the start of each shift and after every 15 plates by scanning an aluminum standard plate. The aluminum standard plate is designed to trigger local and average violations at known locations.

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 0.100 in., the index between scans is 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 hr. The standard plate is a normal production plate that has seven flat-bottom holes drilled to a depth of about 0.010 in. (cladding-to-fuel interface). These holes are filled with Armstrong epoxy A-12 or Apiezon wax. Four 1/16-in.-diam holes, two on each side of the plate, are drilled over the fuel portion of the plate. Two holes, one on each side of the plate, are located over the "hump" region of the plate. Three holes, 1/8, 3/32, and 1/16 in. in diameter, 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 1/16-in.-diam holes over the fuel portion and by the 1/8-in.-diam hole over the cladding portion. Calibration end tabs are fabricated in the same manner as the standard plate. The end tabs are run with each fuel plate. If the calibration end tabs do not break two lines, the equipment is recalibrated. Figure 29 shows a typical scan of a defective plate.

Fig. 29. Ultrasonic Scan of Defective HFIR Fuel Plate. The broken lines in the center of the instrument record show the presence of an unbonded area in the fuel plate.

Alpha Count

The first two plates from each lot of 24 are alpha counted with an M&C Mark 1 dual-chamber alpha counter, shown in Fig. 30, 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 μg ^{235}U per square foot of surface area. The Mark 1 unit is a gas proportional dual chamber with removable 1-mg/cm^2 aluminized Mylar-covered face plates. The active area of each chamber is 37 1/4 × 6 1/4 in. The electronic console consists of a pulse counter, a timer, a high-voltage power supply, and a meter. The equipment is calibrated every 2 hr against NBS standard sources No. 7 (428 α/min ± 2%) and No. 2 (825 α/min ± 2%). A 20-min background count is taken. Each plate is individually counted for 20 min and the background count is subtracted from the recorded counts. The average counting rates are recorded and compared against previously calculated tables that list equivalent ^{235}U concentrations in micrograms per square foot for counting rates in counts per minute.

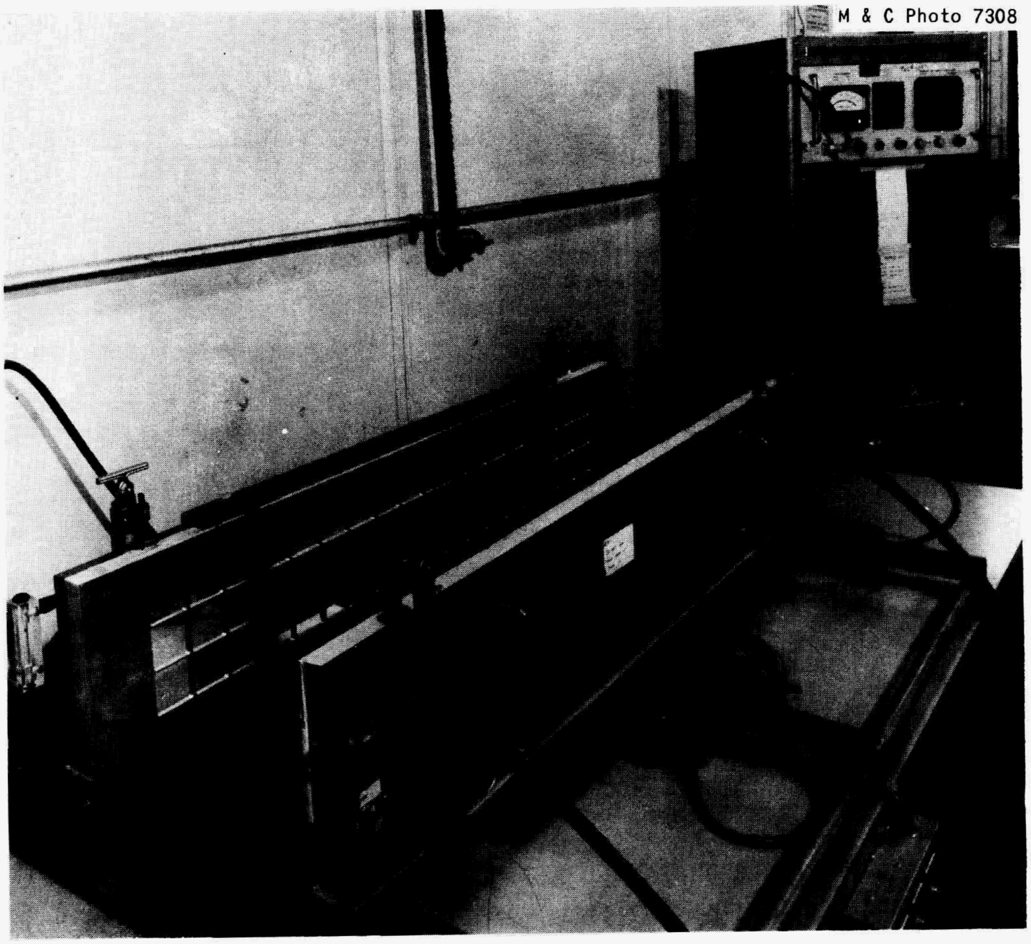

Fig. 30. Alpha Counting Equipment.

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, vapor degreased for 3 min, 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 0.0003 in. and if the original two plates and two additional plates have acceptable alpha counts.

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, end squareness, edge parallelism, and edge straightness. One plate from each lot is inspected at both ends for distance from the center line of the 0.125-in.-diam holes to the reference edge of the fuel plate. Three plates are inspected for thickness to the nearest 0.0001 in. at nine locations per plate with specially made 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.

All 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 0.0006 in. for any plate.

Destructive Examination

One fuel plate from each quantity sufficient for one fuel element is selected for destructive testing of cladding dimensions, fuel location, and bonding. The plate is scribed in accordance with sectioning diagrams, and an identity 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. Buehler billiard cloth, polishing with 6-μ diamond on

A. Buehler Metcloth, polishing with magnesium oxide on A. Buehler Microcloth, and anodizing for 30 to 45 sec in 4% aqueous HBF_4 with an A. Buehler electropolisher. The thickness of each piece is remeasured with a toolmaker's microscope, and if this measurement differs more than 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.

Boron Homogeneity

From the inner plates, 1/2-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. Philpot[11] is used for the analysis. Essentially, the punchings are dissolved in HNO_3-HCl solution; the B_4C is separated by filtration and then solubilized by carbonate fusion. The boron is separated from

[11]Unpublished procedure available from W. R. Laing, Analytical Chemistry Division, ORNL.

interfering elements by ion exchange[12] and determined by a potentiometric mannitol-sodium hydroxide titration.[13]

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. 31. 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 springback to produce the prescribed involute shape. The punches are made according to the criteria given in Table 3.

A 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 (90A durometer) Elastacast[14] or equivalent material. The two pieces are 2 1/4 in. and 1/4 in. thick and located such that the 1/4-in. piece is in contact with the fuel plate. Before the plate is placed in the forming die, 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 assure 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

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[12] F. M. Hill, "Ion Exchange Separation of Boron from Other Elements," Method No. 1 00701 (R. 6-16-63), <u>ORNL Master Analytical Manual</u>, TID-7015, Suppl. 7 (March 1965).

[13] F. M. Hill, "Boron (Borate), Potentiometric Mannitol—Sodium Hydroxide Titration Method," Method Nos. 1 211220 and 9 00711220 (R. 5-15-63), <u>ORNL Master Analytical Manual</u>, TID-7015, Suppl. 7 (March 1965).

[14] Manufactured by Acushnet Process Company, New Bedford, Mass.

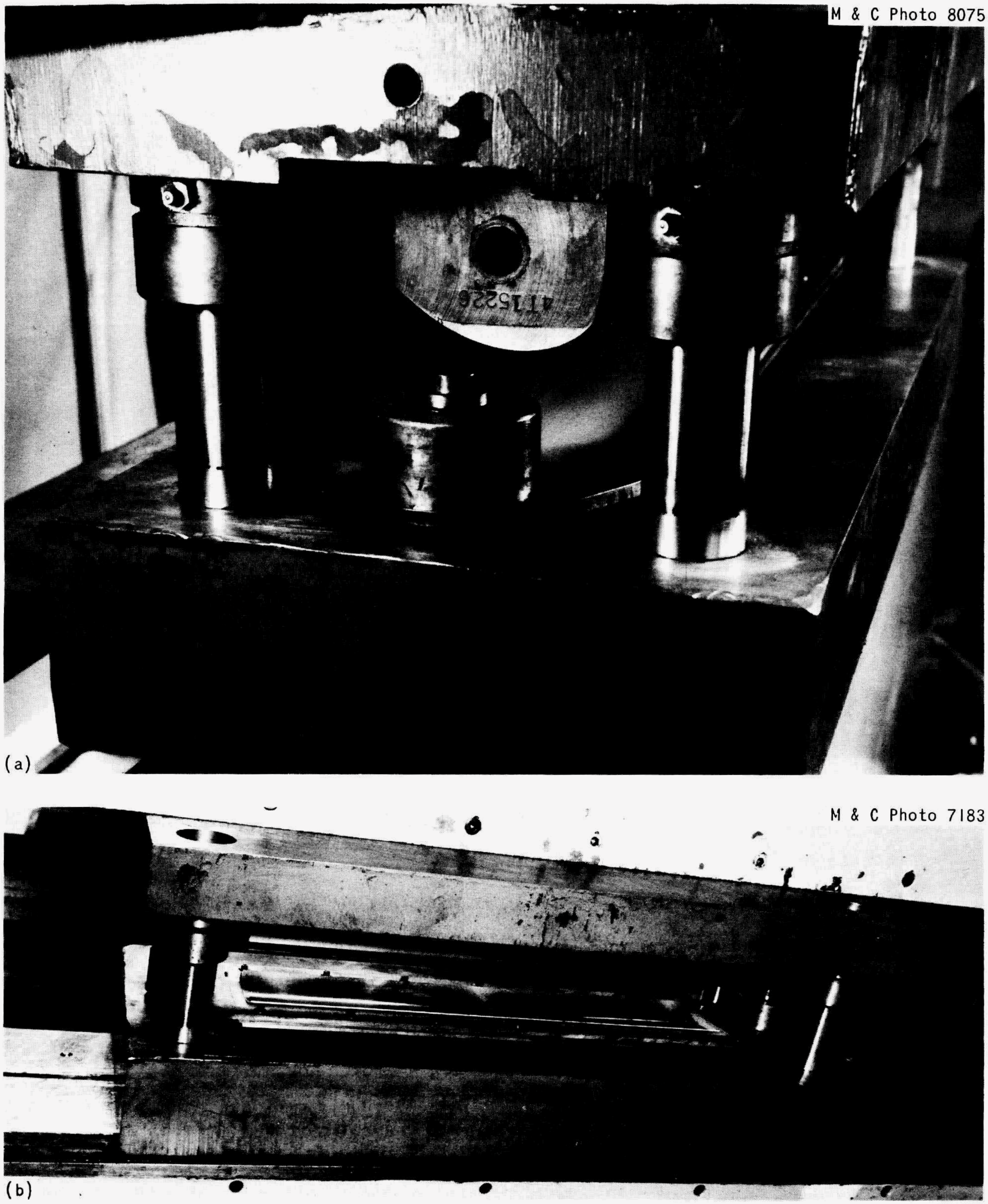

Fig. 31. Involute Forming of a Fuel Plate with a 150-Ton Press.
(a) End view showing die contour. (b) Front view showing formed plate.

Table 3. Criteria for Shapes of Forming Punches

Type of Fuel Plate	Radius of Base for Circle Punch Form (in.)	Rotation (deg)	Radius of Base Aide for Fuel Plate Form (in.)
Inner	1.9375	15.477	2.721
Outer	3.6875	37.767	5.875

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 plates is caused by the high variation in curvature across the forming die 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: it shifts the fuel plate laterally in the area of greatest curvature variation causing an angle different from the desired angle and the elastomer pushes the fuel plate into the punch at a different radial position, causing a different springback when the plate is released.

As the plates are formed, they are inspected for involute shape with an involute gage, as shown in Fig. 32. 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 measurements are recorded. Each plate must be formed with all dimensions within 0.015 in. of the true involute shape and with the individual reading within 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

Fig. 32. Inspecting Involute Shape of Inner Fuel 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 overforming and vice versa.

The formed plates are inspected for proper orientation by assuring that the identification number is on the convex surface of the plate. The plates are inspected for chord width at three locations, 1/2 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.

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. None of the 46 fuel elements produced to date have met all of the specifications; however, rejections that have occurred have been random and of such a nature that they have not been considered harmful to the reactor operation. 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 M&C drawings 8-7213 and 8-7214, shown in Appendix A. The fuel element fabrication process flow chart is shown in Fig. 33. 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. Combs that are fabricated from type 6061, T6 temper, aluminum sheet are installed and welded at the top and bottom of the fuel element. 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.

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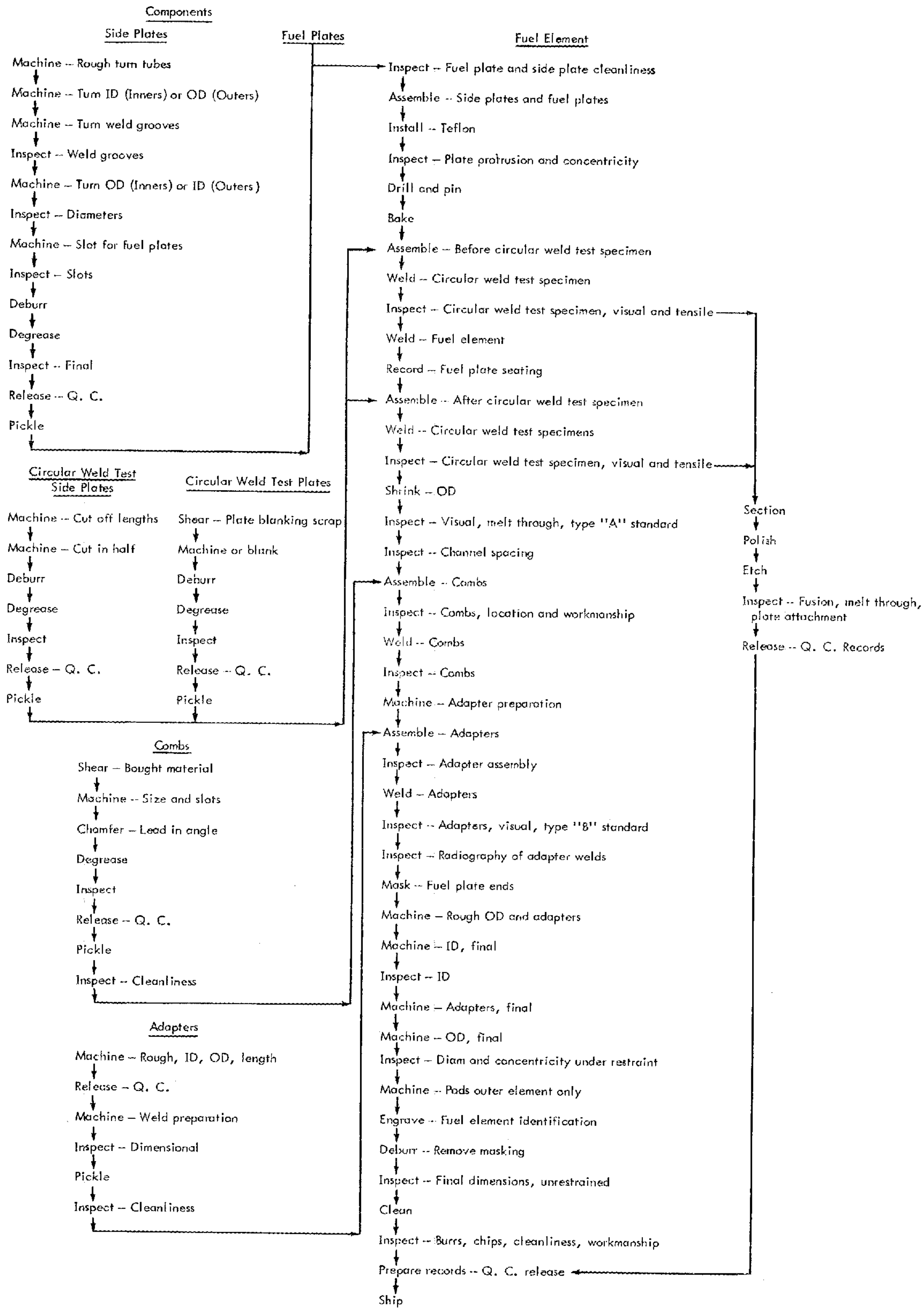

Fig. 33. Fuel Element Fabrication.

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.

Carbide cutters are used for machining operations. All components are machined with Trim,[15] 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 0.008 in. per revolution for roughing cuts and 0.003 in. per revolution for finish cuts. Roughing cuts are about 0.050 in. and finish cuts are 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. Combs are slotted in two cuts with formed cutters turning at 900 rpm. The feed rate for comb slotting is about 2.5 in./min.

Elements are transported on critically safe carts (Fig. 34) 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. 34). 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

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[15]Trim Mist coolant concentrate, a product of Master Chemical Corp. 501 West Broadway, Perrysburg, Ohio.

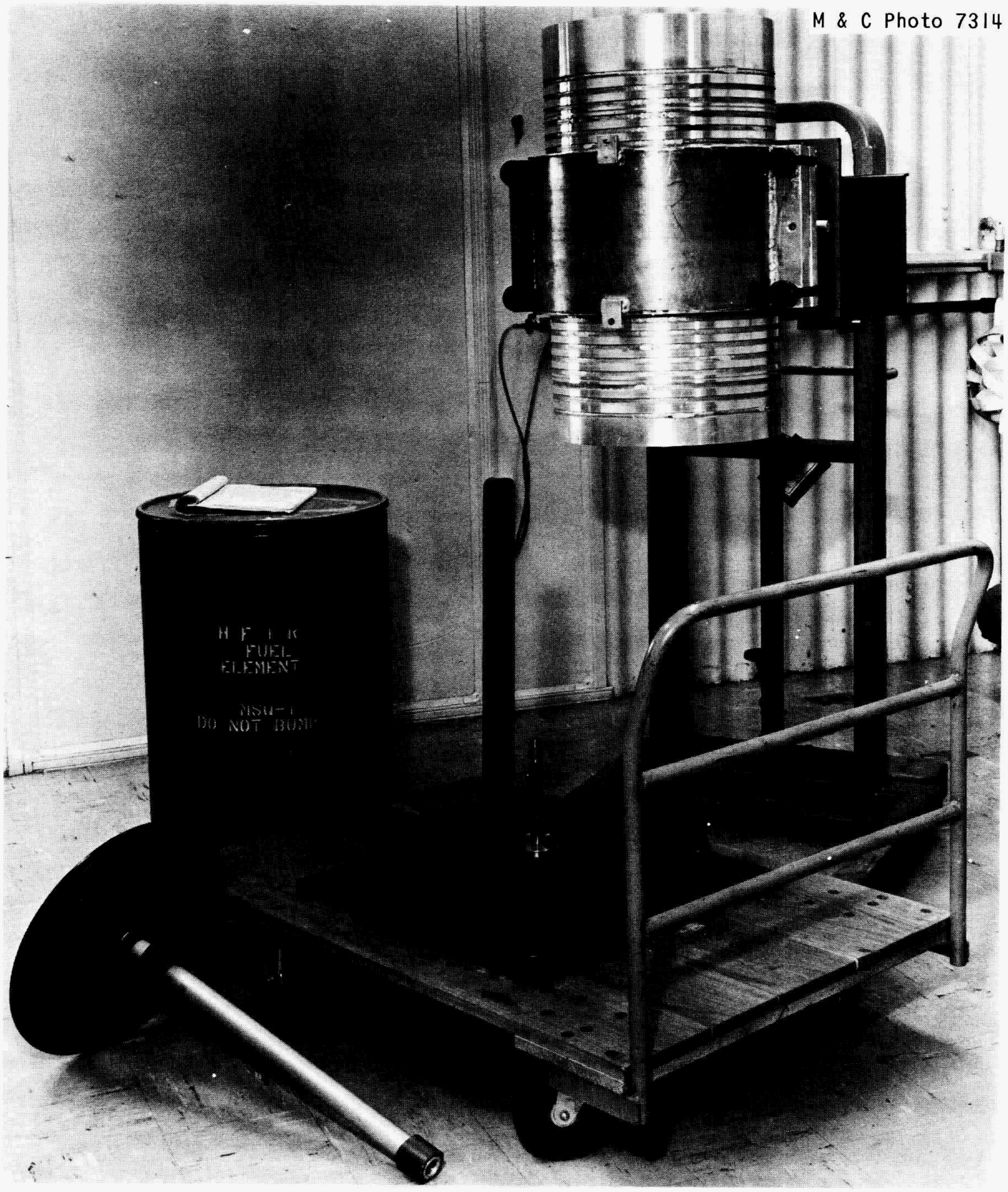

Fig. 34. Criticality Safe Transport Cart and Outer Fuel Element Lifting Fixture.

the fuel element. To prevent marking on the element by the rubber, the finished assemblies must be wrapped with clean cloth before they are gripped with the fixture.

Components

Side Plates

The four cylindrical side plates are shown in Fig. 35. They will be identified in the text that follows by the numbers listed in Table 4.

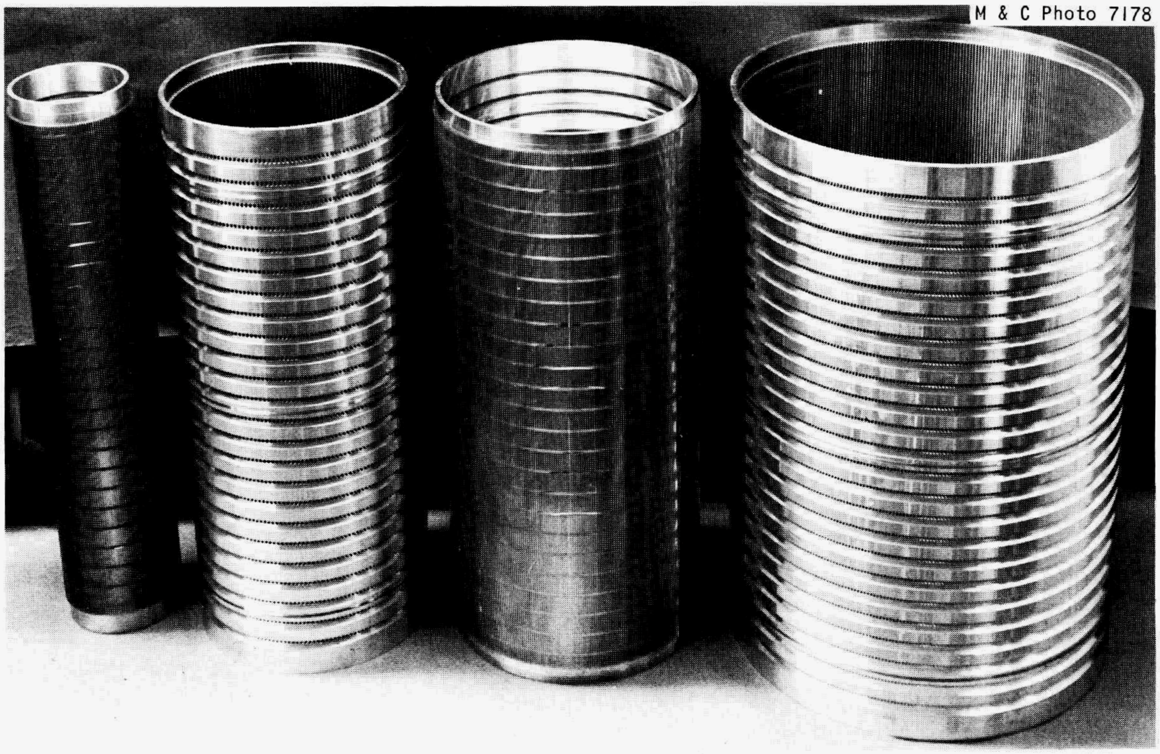

Fig. 35. Side Plates 1 Through 4 from Left to Right.

Table 4. 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

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 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 0.015 in. into the weld grooves of the inner side plate and a minimum of 0.035 in. into the weld groove of the outer side plate in the as-assembled element. The three additional grooves in the side plates are wall-thickness-assurance grooves and are machined so that a maximum depth of 0.015 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.

Machining. — The as-received tubes are sawed to 28-in. lengths as required and mounted in a lathe, as shown in Fig. 36. One end is faced and the inside edge is chamfered 45° × 0.25 in. The tubes are mounted on bull centers and the outside surfaces are rough turned up to a steady rest. At this point, the outside diameters are 5.529 ± 0.010 in. for side plate 1, 10.990 ± 0.010 in. for plate 2, 11.890 ± 0.010 in. for plate 3, and 17.610 ± 0.010 in. for plate 4. The tubes are then turned end for end and the inside edge is chamfered 45° × 0.25 in. The tubes are machined to 26.630 ± 0.030 in. in length to complete the rough machining operation.

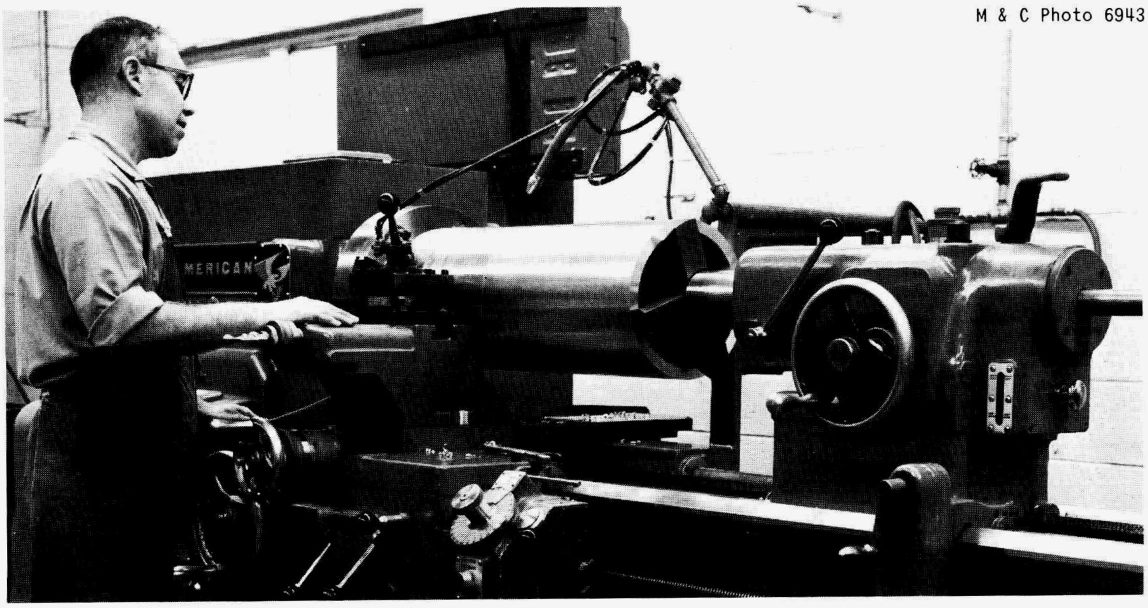

Fig. 36. Rough Machining of Side Plate.

The outside surfaces of side plates 1 and 3 are turned to 5.501 to 5.500 in. and 11.800 to 11.799 in. in diameter, respectively, and are shrunk into restraining tubes with about 0.003 in. interference. The side plates are packed in dry ice to accomplish the shrink fit. 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. 37.

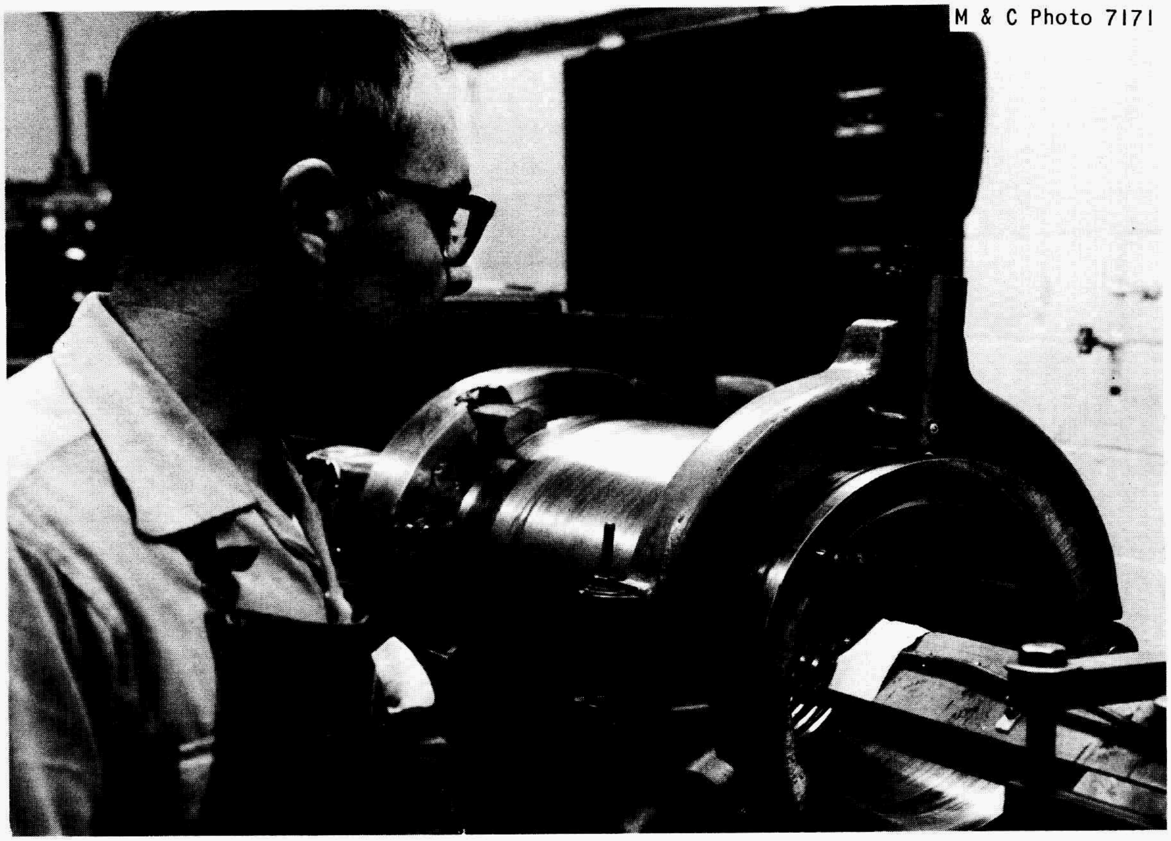

Fig. 37. Weld Grooves Being Turned on Side Plate 3 in Restraining Tube.

The insides of side plates 2 and 4 are bored to 9.920 ± 0.010 in. and 16.470 ± 0.010 in. in diameter, respectively. They are then bored on each end to fit 4-in.-long Plexiglas plugs, which are 9.950 and 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 is used for roughing and a finished form cutter is used to final machine the weld grooves. Every side plate is identified by Vibratooling an 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 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 0.002 in. TIR. Each side plate is shrink fitted into a slotting restraining tube (Fig. 38) and bored to final inside diameter.

M & C Photo 7170

Fig. 38. Side Plates 4 and 2 in Restraining Tubes.

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.

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. 39, to

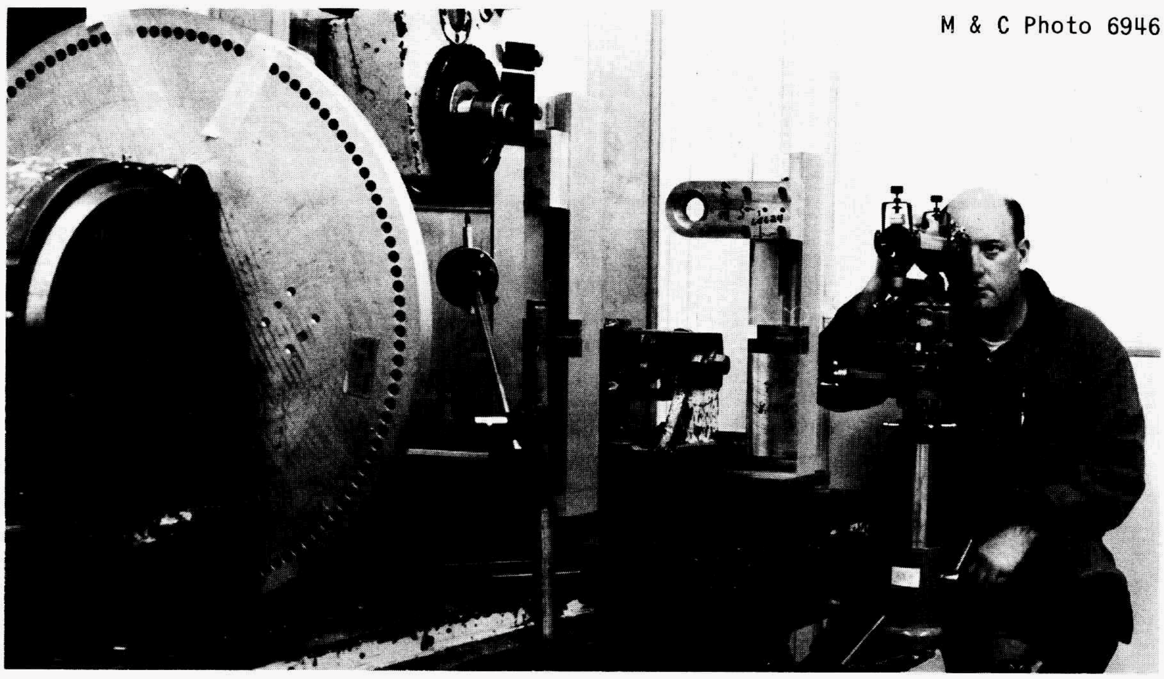

Fig. 39. Optical Inspection of Slotting Cutter Alignment for Side Plate 3.

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 fall milling machine with rotating fixed-position cutters, as shown in Fig. 40. Plates 2 and 4 are slotted on a modified horizontal-bed milling machine with rotating fixed-position cutters, as shown in Fig. 41. For identification, a 45° × 1/16-in.-deep notch is filed on the land between the first and last slot at the bottom end of each 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. The side plates are vapor degreased in trichloroethylene.

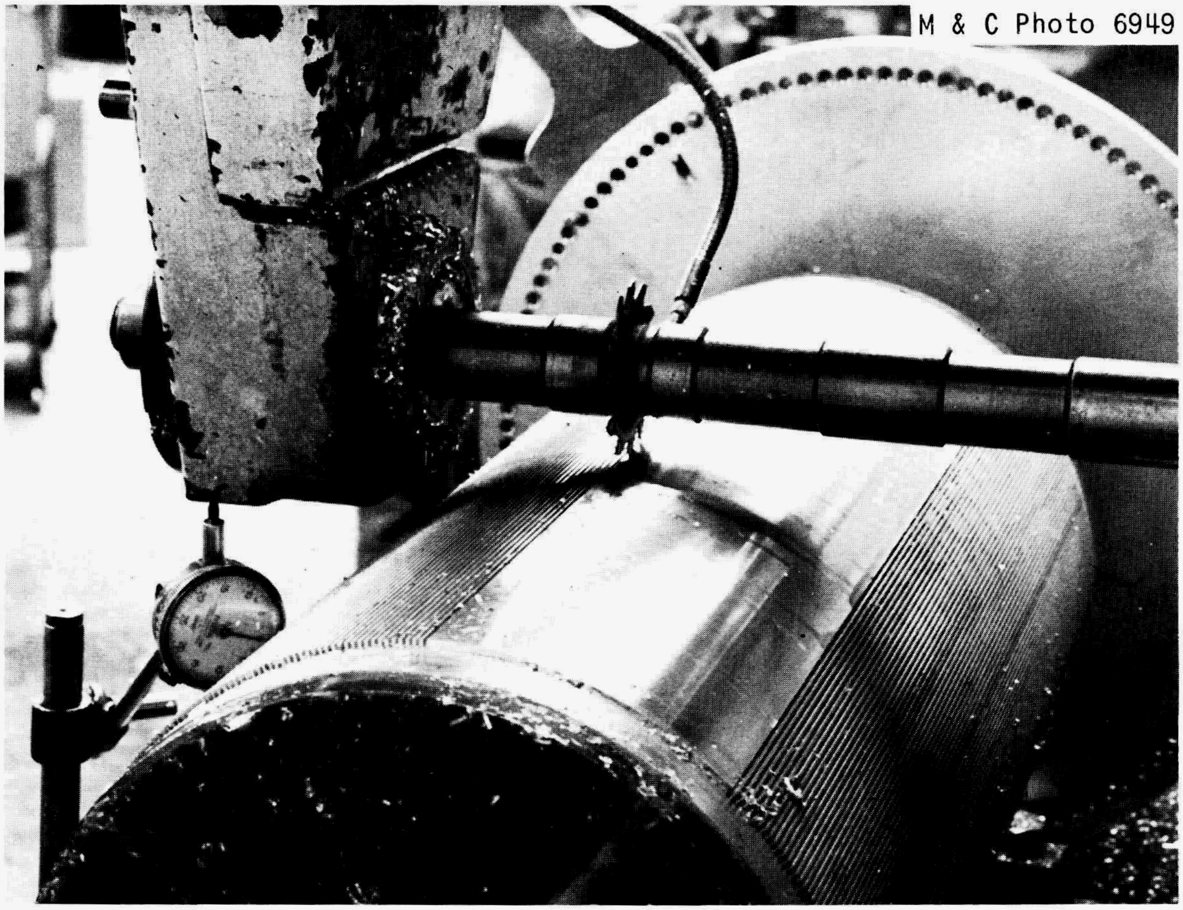

Fig. 40. Slotting of Side Plate 3.

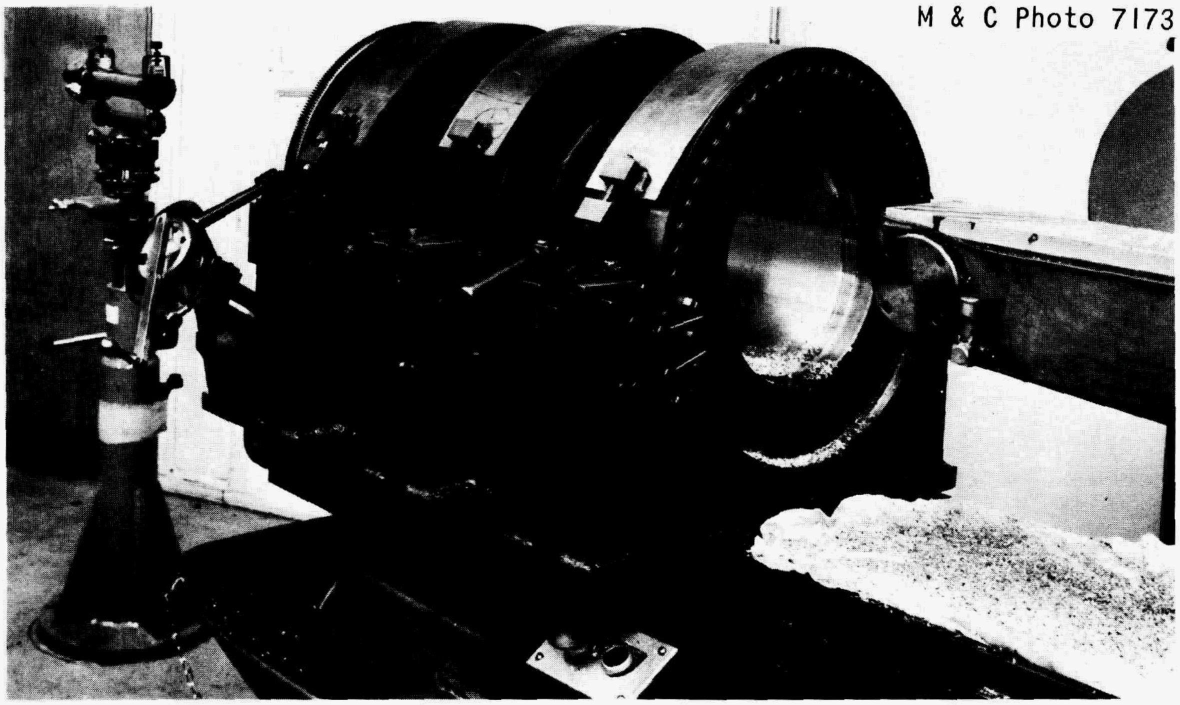

Fig. 41. Slotting of Side Plate 2.

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 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 5.

Table 5. Dimensional Requirements in Slotted Side Plates

Side Plate	Plate Protrusion, in.	Minimum Wall Assurance Groove Wall Thickness, in.
1	0.027 to 0.033	0.033
2	0.043 to 0.049	0.090
3	0.027 to 0.033	0.092
4	0.043 to 0.049	0.113

Combs

Type 6061-T6 aluminum plate 1/16 in. thick, in accordance with the specification in Appendix C, is used as comb material. Combs are machined in straight segments and then curved to the appropriate radii prior to being assembled to the fuel elements. Each fuel element has three sets of combs located at the bottom and two sets at the top.

Strips are sheared to 0.325 to 0.350 in. wide and to the appropriate length from the as-received plate stock. About 50 strips are clamped between 2-in.-thick aluminum plates, gang milled on a Bridgeport milling machine to produce a reference edge, and then gang milled to width. Then 63 slots are gang milled in the strips on a horizontal milling machine, as shown in Fig. 42. The comb teeth are hand filed to produce the required chamfer, and the combs are deburred and vapor degreased in trichloroethylene. One comb from each group is inspected for slot angle, slot width, and proper indexing. All combs are inspected for the remainder of the drawing requirements.

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

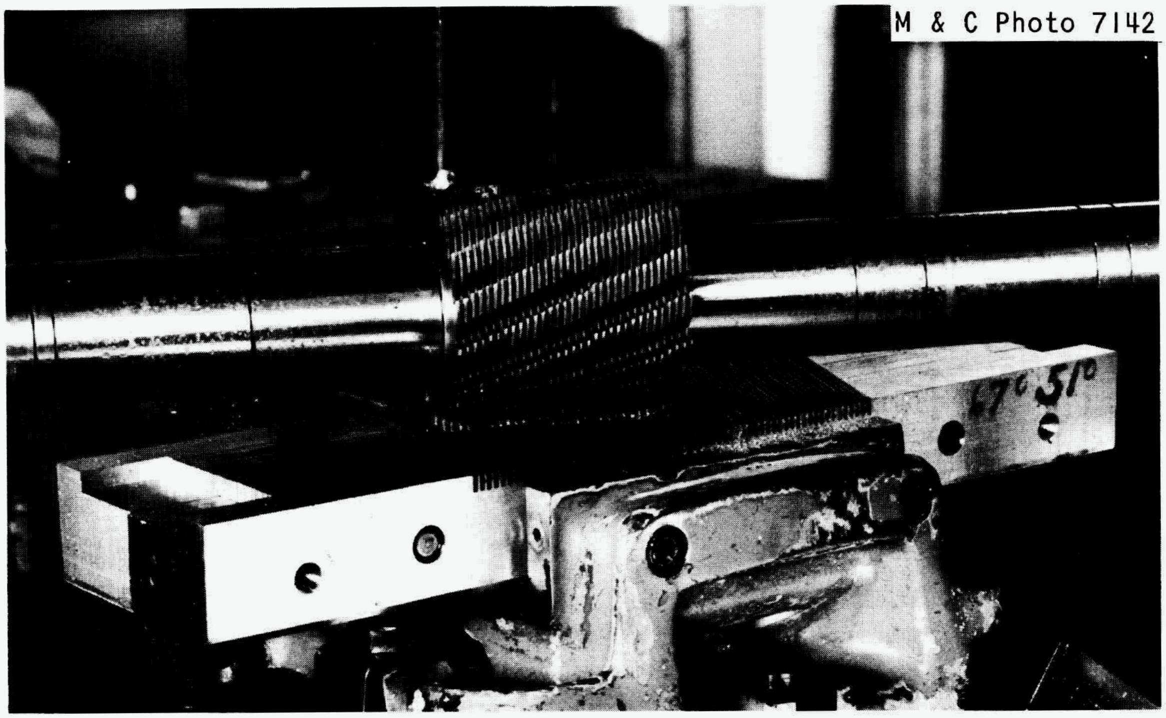

Fig. 42. Comb Machining.

inside is turned, and the other end is then faced to length. The rough-machined adapters are returned to storage.

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.

Component Fabrication

Weld-test ring side plates are fabricated from corresponding side plates; that is, weld-test ring 1 is fabricated from side plate 1, 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 vapor degreased in trichloroethylene.

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 × 1 7/8 in. from the side strips and then machined. The pieces are deburred with a file and vapor degreased with trichloroethylene. 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.

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 degreased, pickled, and rinsed according to Procedure 1 in Appendix D. A maximum of 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. 43. Short pieces of about 0.047-in.-thick Teflon are inserted between the fuel plates to wedge and lock the plates in the correct positions.

Welding and Evaluation

While the fuel element is baking out in preparation for welding, (see below) the circular weld-test assembly is mounted on the tailstock ring of the assembled element, also shown in Fig. 43, and preheated to 49°C (120°F) with a forced hot-air dryer. The circular weld-test assembly is welded by use of 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 is 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

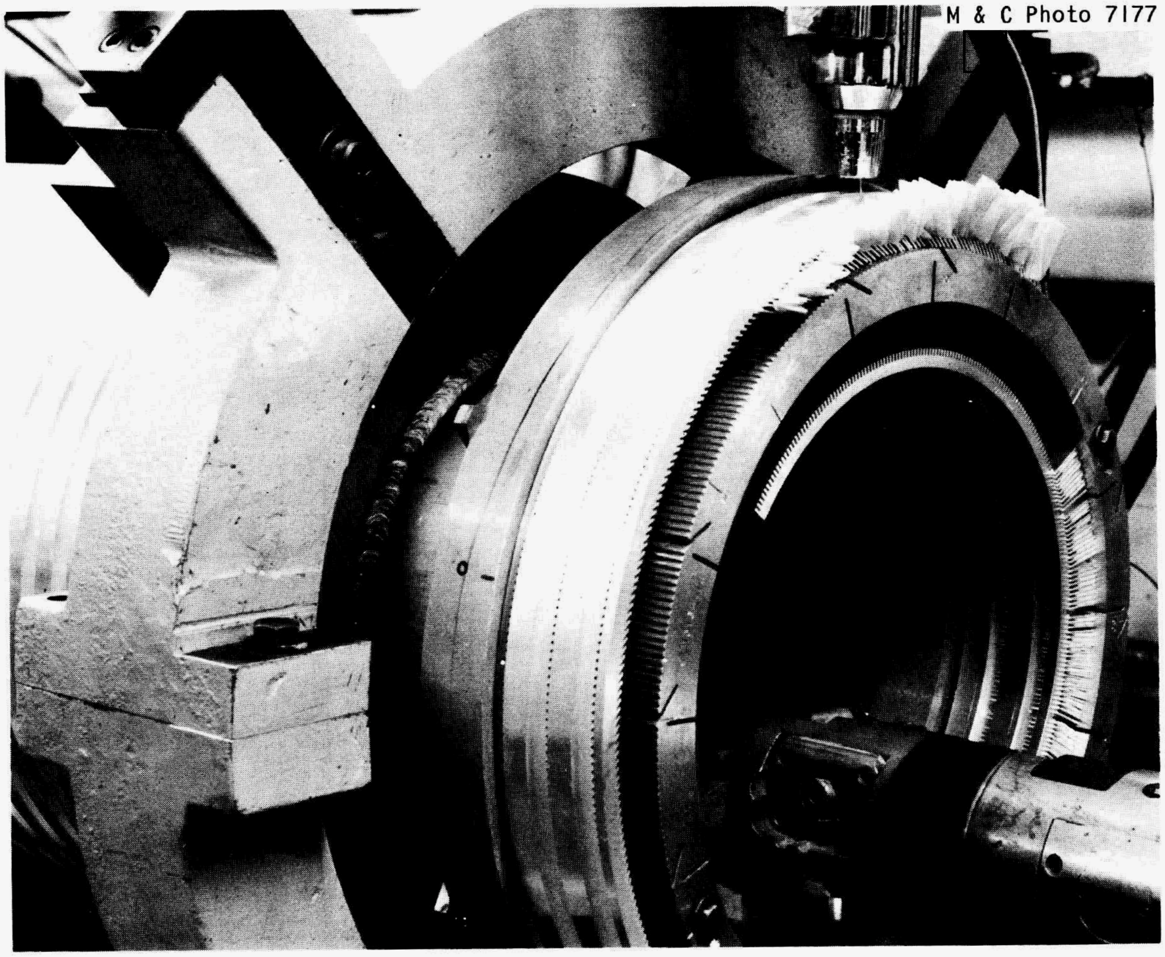

Fig. 43. Outer Fuel Element Circular Weld-Test Assembly Ready for Welding.

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 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 dropthrough. Weld dropthrough cannot exceed 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. 44.

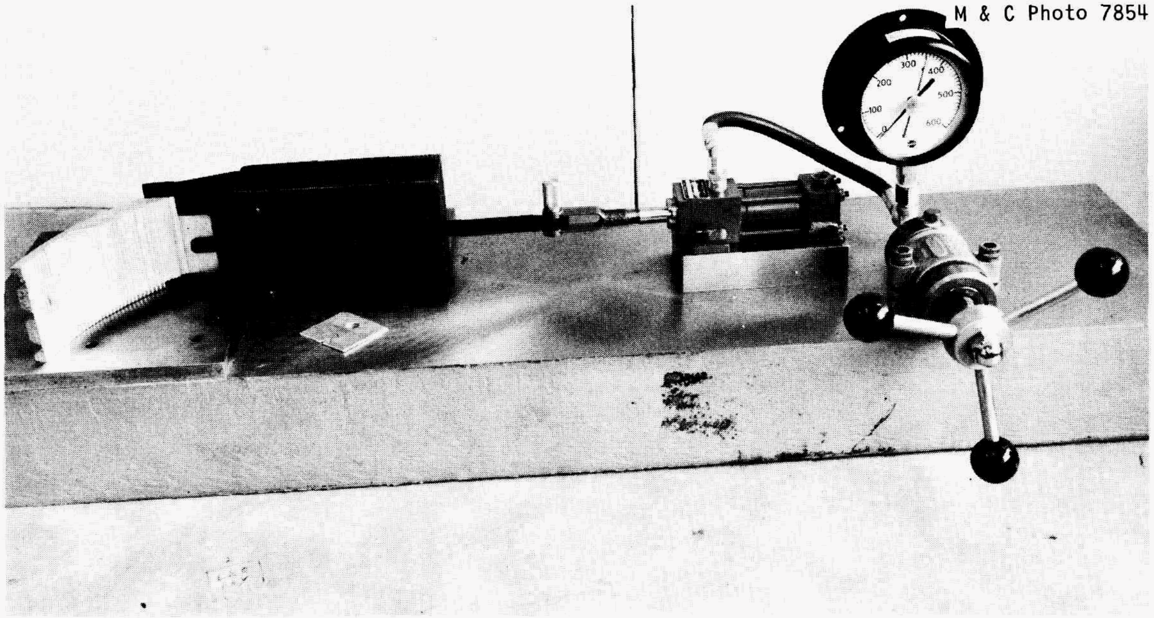

Fig. 44. Tensile Testing of Circular Weld-Test Tensile Plate.

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

After the fuel element is welded, the circular test assembly is remounted on the tailstock ring. The test assembly is preheated to 49°C (120°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 for 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.

The circular weld-test segments are machined at the weld center line to expose the longitudinal cross sections of the weld beads, then polished and etched to show weld attachment, as shown in Fig. 45. 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 0.010 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 0.250, 0.294, 0.290, and 0.294 in. is required for side plates 1, 2, 3, and 4, respectively.

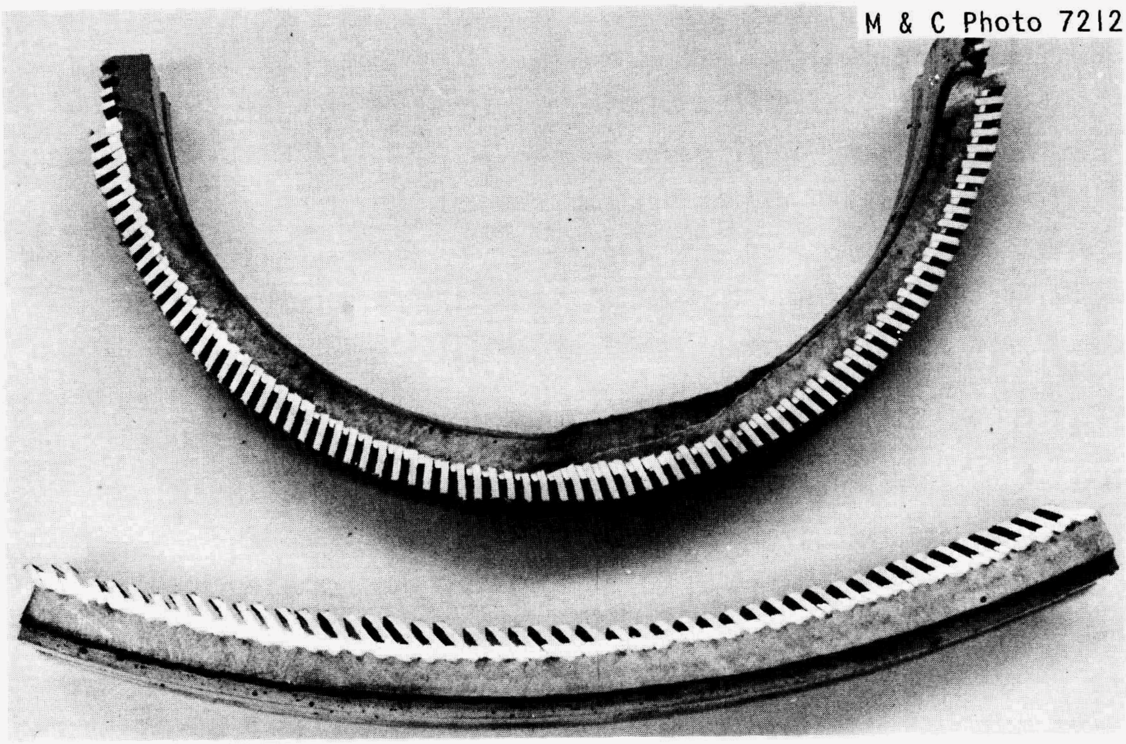

Fig. 45. Cross Sections of Circular Weld-Test Segments.

Fuel Element Fabrication

Assembly

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 0.0004 in. is removed in pickling.

The cleaned fuel plates are removed from the rack one at a time and examined at 3× 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 headstock mounting ring is mounted on top of a Syntron vibrator, which is lagged to a firm base. The vibrator helps seat the plates during assembly. 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 0.215 ± 0.010 in. for side plate 1 and 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. The outer side plate is rotated in small increments by tapping the 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 (from 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 0.287 ± 0.010 in. for side plate 2 and 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 ±0.020 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 or ethyl alcohol is used liberally in the slots and on the edges of the fuel plates as a lubricant to prevent galling.

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. 46. The remainder of the fuel plates is then inserted in any convenient sequence (Fig. 47). 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

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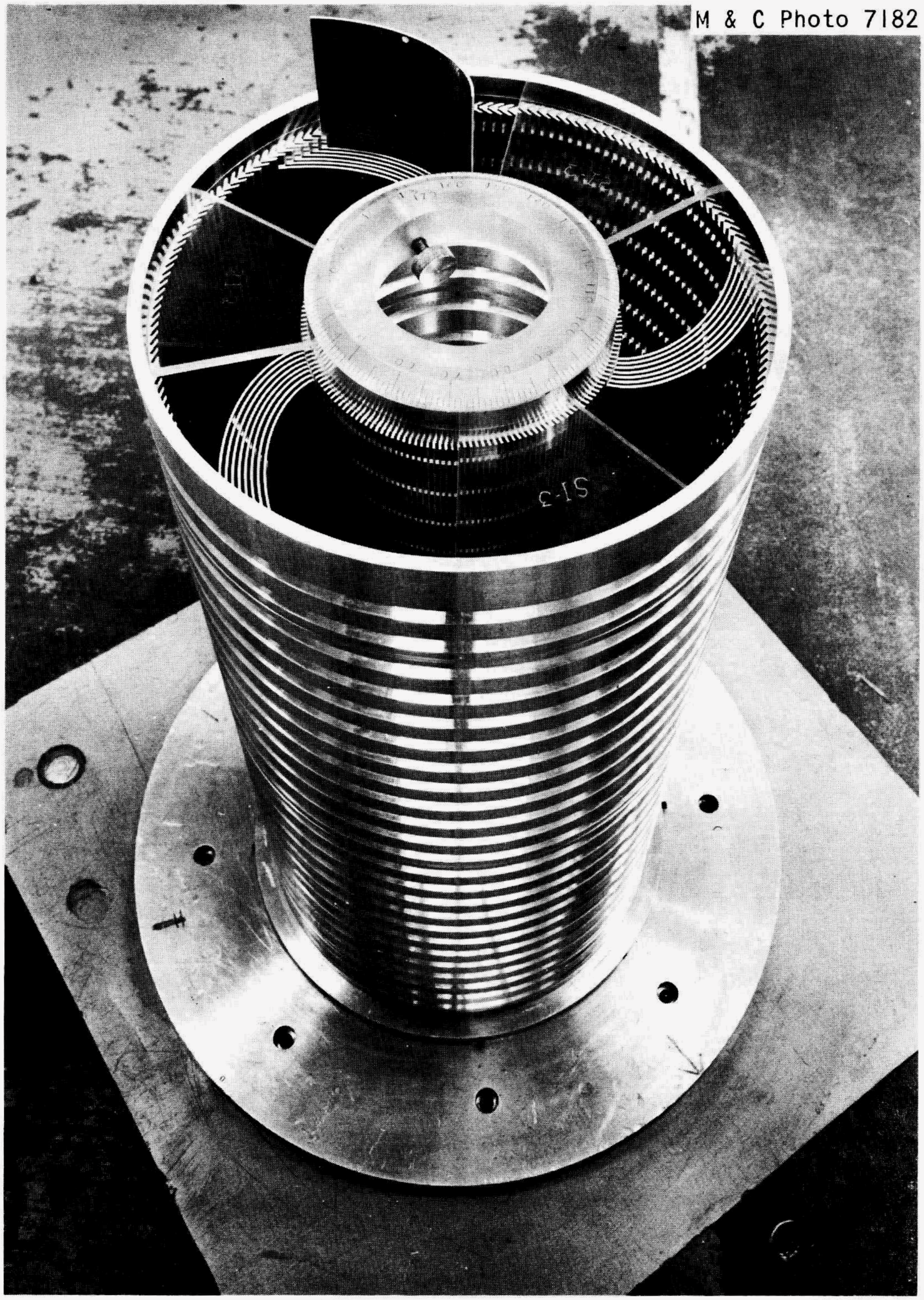

Fig. 46. Initial Assembly of Fuel Element.

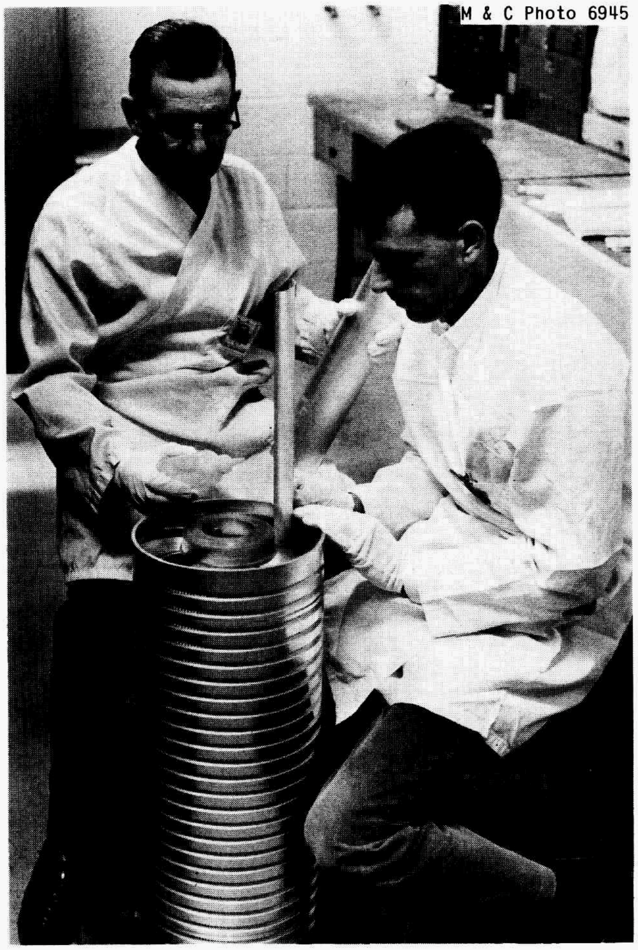

Fig. 47. Inspector and Assembler Assembling Fuel Plates in Fuel Element.

spacing of the fuel plates are inspected visually. Plates are repositioned as required. If a particular plate results in poor seating 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. 48. The Teflon strips are 25 in. long and 0.200 in. narrower than the channel width. The strips are varied in thickness at 1/4-in. intervals across their width; a thin section is 0.030 in. and a

M & C Photo 8087

Fig. 48. Inserting Teflon Spacers in the Presence of an Inspector.

thick section is 0.048 to 0.049 in. for the outer element and 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 1/2- × 1/2-in. tab on one corner and the bottom end has 1/2 in. × 45° removed from each corner. The strips are ordered 0.001 to 0.003 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 0.0005 in. is stamped on the strip 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 counterclockwise 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 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. 49. 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 0.015 in. minimum for the inner side plate and 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) and recorded.

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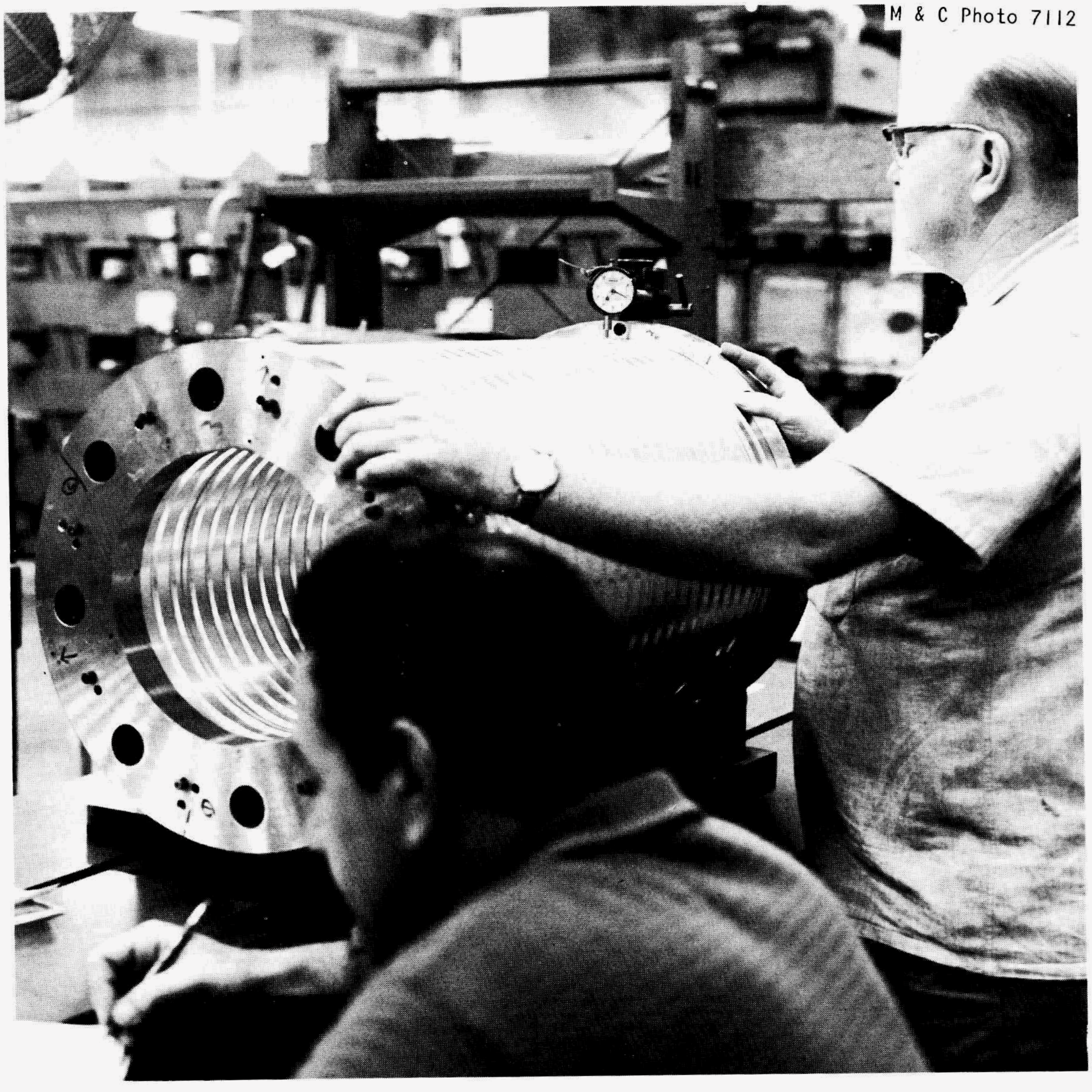

Fig. 49. Inspector Measuring Fuel-Plate Protrusion.

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 0.010 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 1/8-in.-diam holes are drilled in each side plate to a depth of about 3/8 in. Pilot holes are located in the mounting rings. Then 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.

Welding

The assembly is then mounted on the welding lathe, as shown in Fig. 50. 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% Ag–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.

The drive plate is mounted in ball bearing races, which in turn are mounted in the lathe headstock casting. A timing belt connects the drive plate with the gear drive of a 1/2-hp dc reversible servomotor fitted with a tachometer. The motor has a proportional and integral feedback servo system. The system is geared to provide continuous adjustment of the fuel-element rotation speed from 12 to 35 rph. The equipment must reproduce a given rotation within 1%. Initial rotational speed is preset and then sloped to a new preset speed after the welding arc is struck. The rotational speed is again sloped to a final preset speed after a weld sequence stop cycle is initiated. Both slope rates are adjustable.

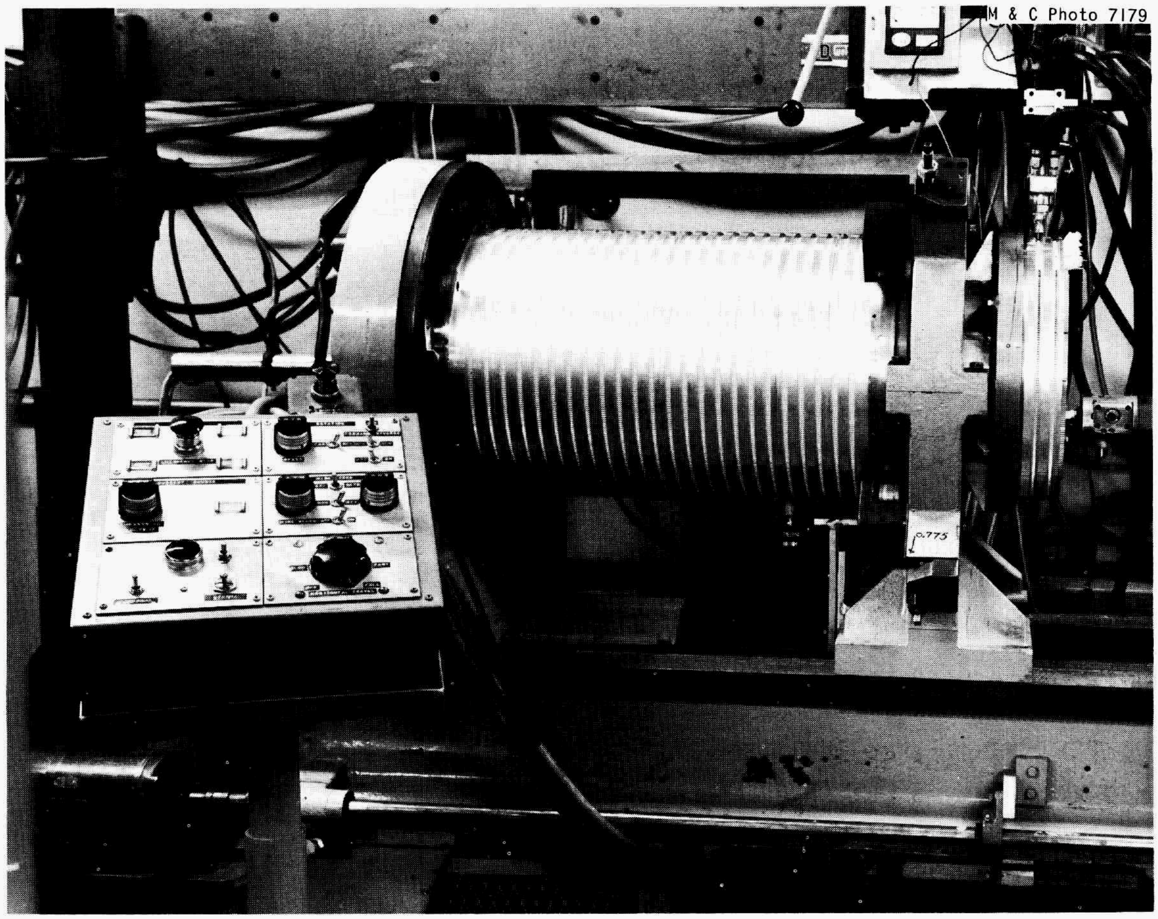

Fig. 50. Outer Fuel Element with Circular Weld-Test Assembly.

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 ±0.0075 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 element is rotated slowly at 1 to 2 rpm, heated to 104 to 127°C (220 to 260°F), and maintained at temperature for at least 4 hr to drive off water and alcohol. Temperature readings are fed to the controller from a sliding thermocouple, which is held firmly against the outside surface of the fuel element. Temperature is also periodically checked with a hand pyrometer. The fuel element is cooled down to 49°C (120°F) prior to welding. During the baking-out cycle, the "before" segments of the circular weld-test assembly are welded and evaluated as described above.

After the assembled fuel element has cooled down to 120°F from the baking operation, 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 the expansion and contraction of the fuel element. The depth measurements cannot vary by more than 0.020 in.

Welding is performed with a 400-amp 3-phase full-wave-rectifier Sciaky[16] welder, as shown in Fig. 51. 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 0.030-in. type 4043 aluminum purchased to a specification given in Appendix C. 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.

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 the nozzle and copper guide tube. The wire for the outer torch is fed vertically from a Sciaky "U"-drive roll and idler roll assembly through

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[16]Product of Sciaky Bros., Inc., 4915 W. 67th St., Chicago 38.

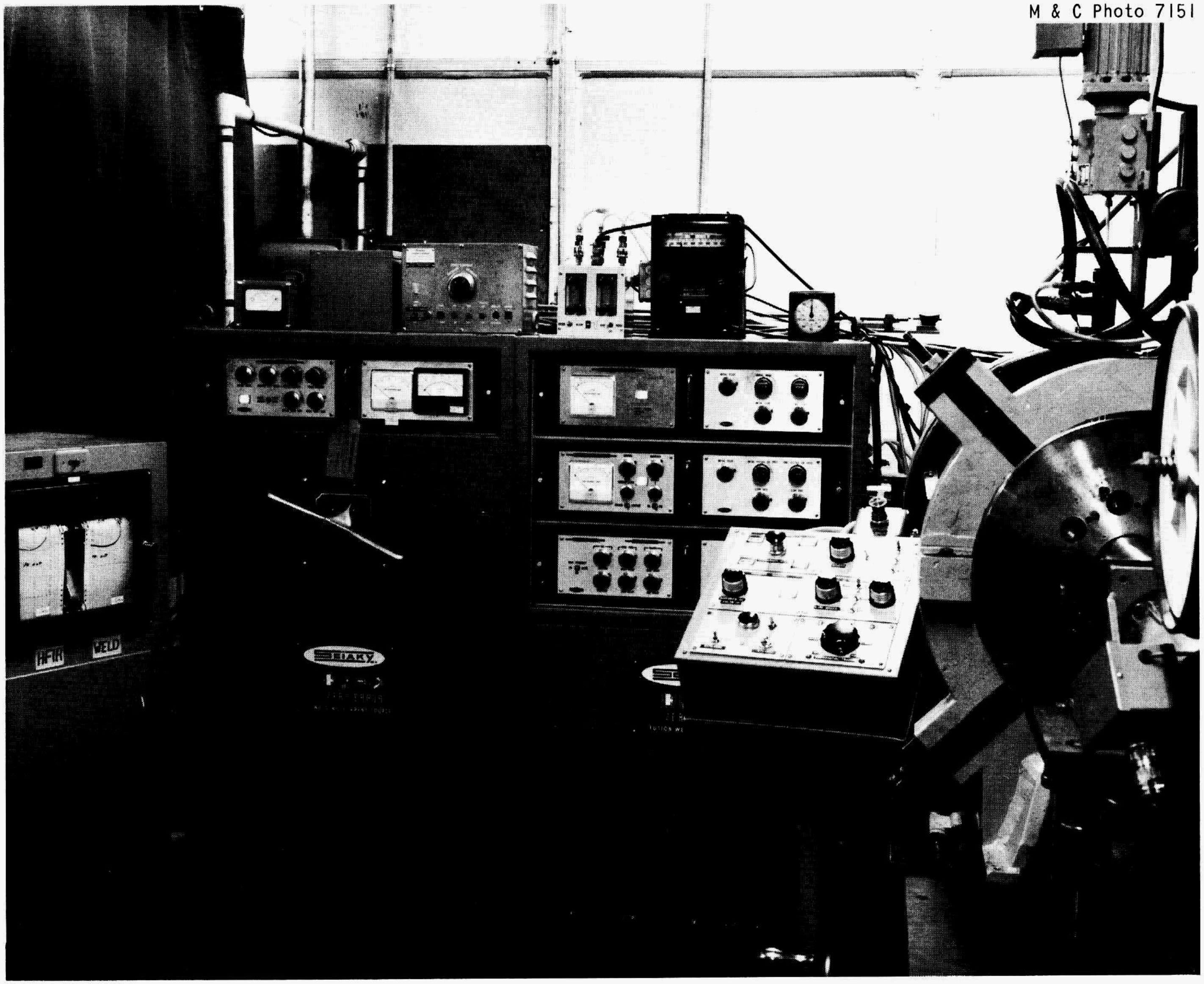

Fig. 51. Welding Console.

a Teflon liner, the nozzle, and the copper guide tube. The copper guide tubes[17] 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 1000 in./min. Allowable wire-feed variation is ±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 postflow 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 four weeks. 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 preset 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 6 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

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

Table 6. Run Weld Parameters for Fuel Plate Attachment[a]

Parameter	Side Plate			
	1	2	3	4
Voltage, v	18–20	19–21	18–19	19–21
Argon gas flow, cfh	45	45	45	45
Nozzle diameter, in.	5/8	3/4	5/8	3/4
Nozzle height, in.	1/4	1/4	1/4	1/4
Guide tube extension, in.	0–1/16	0–1/16	0–1/16	0–1/16
Torch angle to work surface, deg.	90	87.5 in direction of rotation	90	90

[a]Current is adjusted as necessary to maintain reference arc voltage.

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.

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 6. 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 arc 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. for the outer side plate and 0.010 in. for the inner side plate. Table 7 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.

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. 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. 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

Table 7. 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	8
13	Inner	15	Outer	17
14	Inner	10	Outer	7
15	Inner	16	Outer	18
16	Inner	9	Outer	6
17	Inner	17	Outer	19
18	Inner	8	Outer	5
19	Outer	17	Outer	20
20	Outer	8	Inner	11
21	Outer	18	Inner	15
22	Outer	7	Inner	10
23	Outer	19	Outer	4
24	Outer	6	Outer	21
25	Inner	18	Outer	3
26	Inner	7	Outer	22
27	Inner	19	Outer	2
28	Inner	6	Outer	23
29	Outer	20	Outer	1
30	Outer	5	Outer	24
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

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., which is sufficient to ensure proper wall thickness.

The outside diameter of both the inner and outer element is measured with a pi tape 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. 52 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

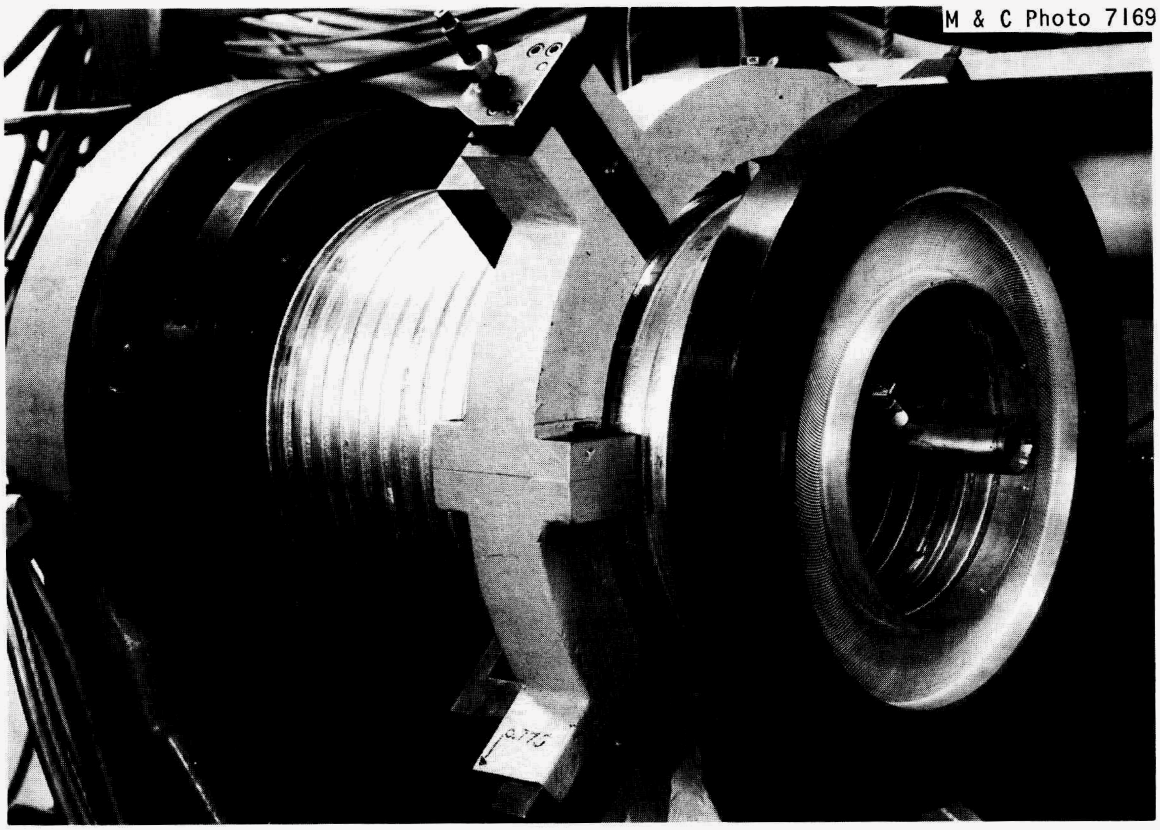

Fig. 52. Shrink Rings Installed on Outer Element.

with a hot-air circulator. Shrinkage occurs because the thermal expansion of the aluminum side plates is greater than that of the steel rings. The vertical position during heating reduces 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. for the outer fuel element and 10.820 to 10.839 in. 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 dropthrough. Weld dropthrough 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. minimum; outer element OD, 17.450 in. maximum; inner element ID, 4.784 in. minimum; inner element OD, 10.839 in. 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.

Channel Spacing Measurement

The coolant channel thickness is measured continuously along the length of every channel except for 1/2 in. at either end of the fuel plates with the apparatus shown in Fig. 53. The channel thickness is measured at within ±0.10 in. of the following five radial locations.

	Radial Location, in.				
Inner fuel element	3.10	3.56	4.05	4.40	4.80
Outer fuel element	6.20	6.64	7.22	7.61	7.90

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

Channel spacing is measured by an eddy-current probe technique using a pancake-type coil.[18] The spacing measurement is a function of the coil geometry, the alloy of the fuel plates, and the frequency of the alternating voltage fed to the test coil. A high-frequency alternating current is applied to the test coil, which produces an alternating magnetic field The magnetic field and the metal surrounding the coil determine the impedance of the coil. Variations in the proximity of the metal to the coil due to fuel-plate spacing variations will vary the coil impedance. The impedance changes are then electronically converted to an analog voltage output, which is recorded on a strip chart.

Five such coils mounted on separate probes and assembled into one unit, shown in Fig. 54, are used to simultaneously measure the five tracks in each channel, spaced as described above. Each probe is strip-chart recorded continuously as the probes are withdrawn vertically. A continuous sixth track is also recorded; it is an electronic average of the five spacing values.

[18]C. V. Dodd, Design and Construction of Eddy-Current Coolant-Channel Spacing Probes, ORNL-3580 (April 1964).

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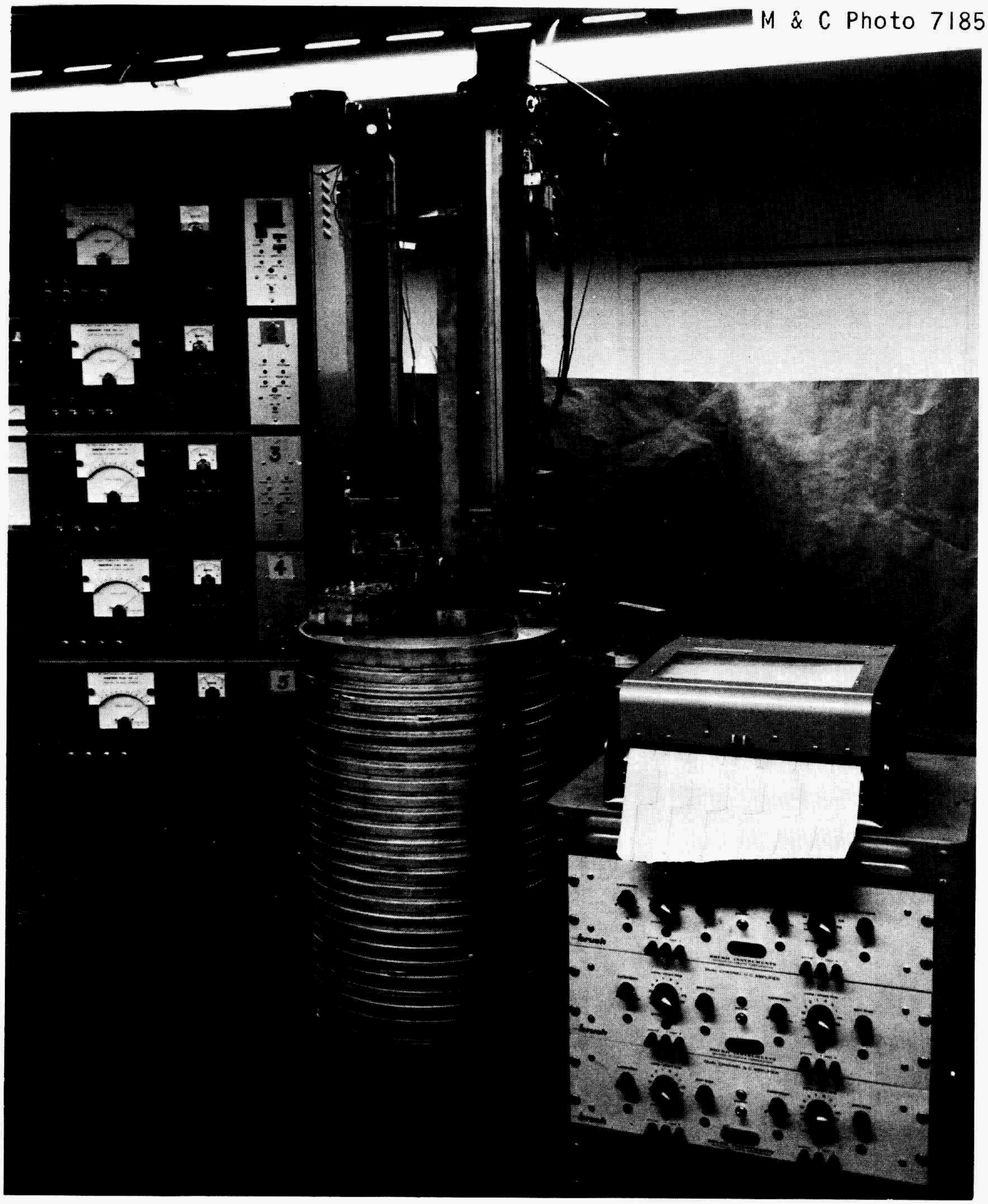


Fig. 53. Channel Spacing Measurement Equipment.

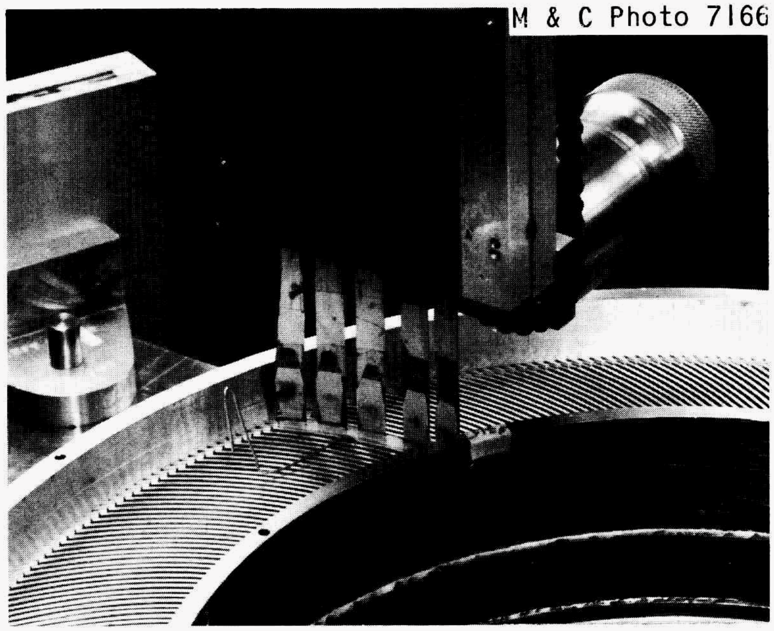


Fig. 54. Channel Spacing Probes for Outer Fuel Element.

The average coolant channel thickness for any individual cross section is specified at 0.050 ± 0.006 in. Each individual coolant channel is specified at 0.050 ± 0.010 in. 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 1/2 in. from the bottom of the channel. The drive motor is reversed automatically at this point, the probes are vertically withdrawn, and the recorder strip charts 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 spacings are varied from 0.040 to 0.060 in. in 0.005-in. increments. The chart readings for each probe must be within ±0.001 in. of the proper value, and the average chart reading must be within 0.0005 in. of the proper value.

In addition to reading each chart for channel spacing, the inspector visually estimates the overall average thickness of each channel from the average chart. These averages in turn are averaged to provide an estimate of 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 piece of Teflon is then drawn through the channel; this tends to bend the offending plate in a direction to correct the spacing. A series of Teflon pieces of various thicknesses is maintained for this purpose. Next the Teflon spacers are replaced in all the channels, the shrink rings are replaced, and the element is put in the furnace on end and stress relieved at 350°F for 4 hr. The suspect channels are again probed to determine that the channel spacing has been corrected. This correction sequence is applied only with the approval of the Buyer.

Comb Attachment

The fuel element is placed on a turntable in preparation for comb welding. The combs are cleaned according to Procedure 1, Appendix D. The combs are inspected for cleanliness, rough formed over circular cross-section mandrels, and fitted to the element with circular plastic templates of the proper diameter. The operator wears clean lint-free gloves. The outer combs are assembled first. The comb segments are formed and cut to make a full circle and are tapped lightly, as shown in Fig. 55, until they are evenly seated on the fuel plates. They must fit tightly to ensure good electrical contact for welding. To improve the thermal contact, the joint between the comb and fuel plate is Vibratooled.

The combs are inspected for proper location with templates, proper teeth alignment (vertical and not bent to one side), and cleanliness. The channel spacings on both sides of the combs are checked with a special manual single-probe eddy-current device to ensure 0.040-in. minimum spacing.

The combs are gas tungsten-arc welded manually (Fig. 56) with 45 to 60 amp, 11 to 14 v ac, 15 cfh argon shielding gas, 5/16-in.-ID nozzle, and a 3 3/32-in.-diam 1% thoriated tungsten electrode with a 1/32-in. flat. Fusion welding is employed, and 1/16-in.-diam 4043 aluminum filler wire is used only when necessary to bridge from one plate to the next and to repair cracks. The filler wire is purchased in accordance

Fig. 55. Installing Outer Comb on Outer Fuel Element.

Fig. 56. Comb Welding.

with specifications given in Appendix C. Fusion is controlled to keep the depth of melting to less than 1/8 in. from the plate edge. The weld-bead width is maintained as narrow as possible.

The welds are inspected for the following attributes.

1. Fusion. — Wetting between at least one side of the comb and the fuel plate must occur.

2. Penetration. — Comb teeth must not show more than 1/8 in. of melting below the end of the fuel plate.

3. Oxidation. — Weld must be free of excessive oxidation.

4. Cracks. — Welds must not contain cracks larger or more numerous than those on a visual weld standard, and cracks must not appear on both sides of a single tooth of a comb if they could allow that tooth to fall into the channel.

5. Channel blockage. — The projected width of any comb, including its teeth and all fused metal over any channel, must not be greater than 0.250 in. for bottom end combs and 0.150 in. for top end combs. The widths are inspected, as shown in Fig. 57, with a gage that has two parallel 0.040-in. pins appropriately spaced; these pins must be accepted in the same channel on both sides of a given comb. If required, excess metal is removed with a flat file. Care is taken to insert the file no more than 1/2 in. into the channel and to minimize plate scratching.

6. Location. — Combs must be located per drawing requirements.

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. from the slot shoulder at the top and 0.388 in. 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 and pickled in the same manner as the combs and assembled to the fuel element. The fit must be tight and

Fig. 57. Inspecting Welded Comb for Channel Blockage.

the adapter must be seated against the fuel element slots. The assembled adapters are inspected for alignmnent, joint geometry, and cleanliness. The root opening is 0.125 to 0.145 in. with the adapters seated against the slots. Mirrors are used as necessary to ensure proper seating.

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. or less. The adapters are welded (Fig. 58) in the same manner as the side plates to the fuel plates. Weld parameters are given in Table 8 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.

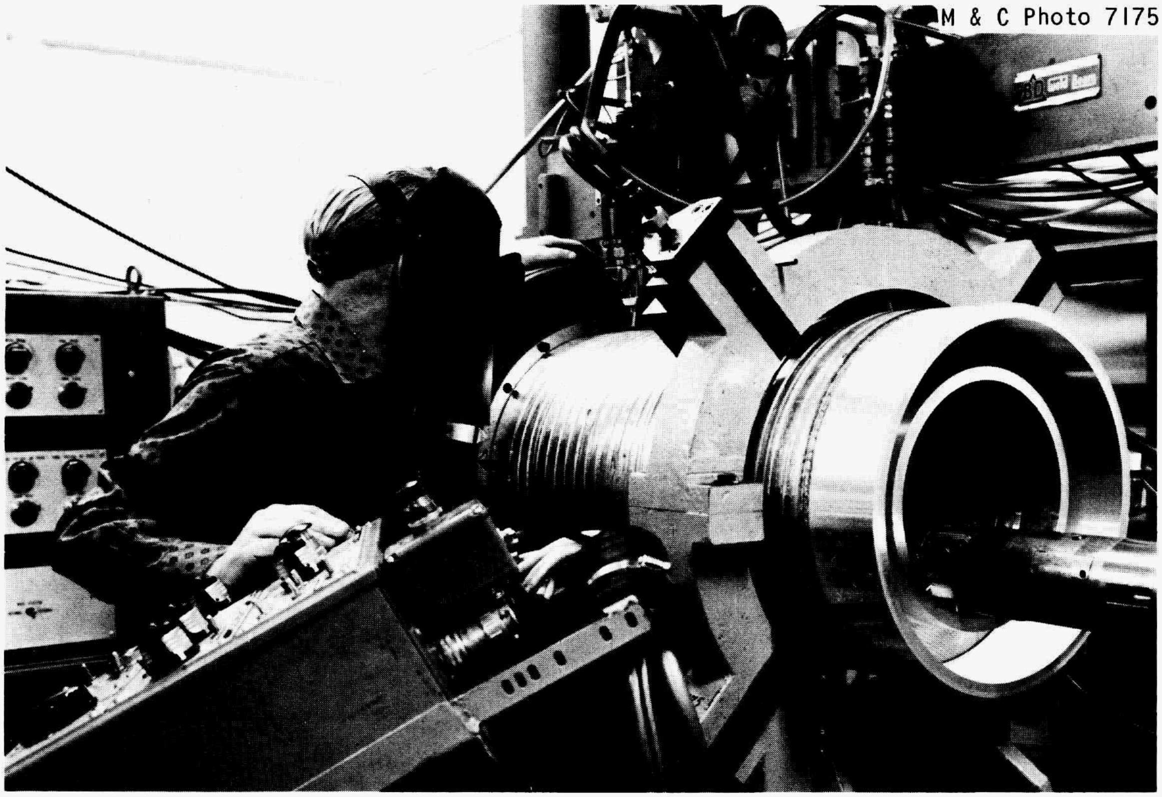


Fig. 58. Adapter Welding on Outer Fuel Element.

Table 8. Parameters for Welding End Adapters to Fuel Elements[a]

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	3/4	5/8	3/4
Nozzle height, in.	3/8	1/4	3/8	1/4
Guide tube extension, in.	0–1/16	0–1/16	0–1/16	0–1/16
Torch angle to work surface, deg	90	87.5 in direction of rotation	90	90

[a]Current 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 Kodal Type R film in flexible cassettes with 0.005 to 0.010 in. back lead. To shield against back scattering, a 1/16- to 1/8-in.-thick sheet of lead is formed to fit the inside of the adapter being radiographed, as shown in Fig. 59.

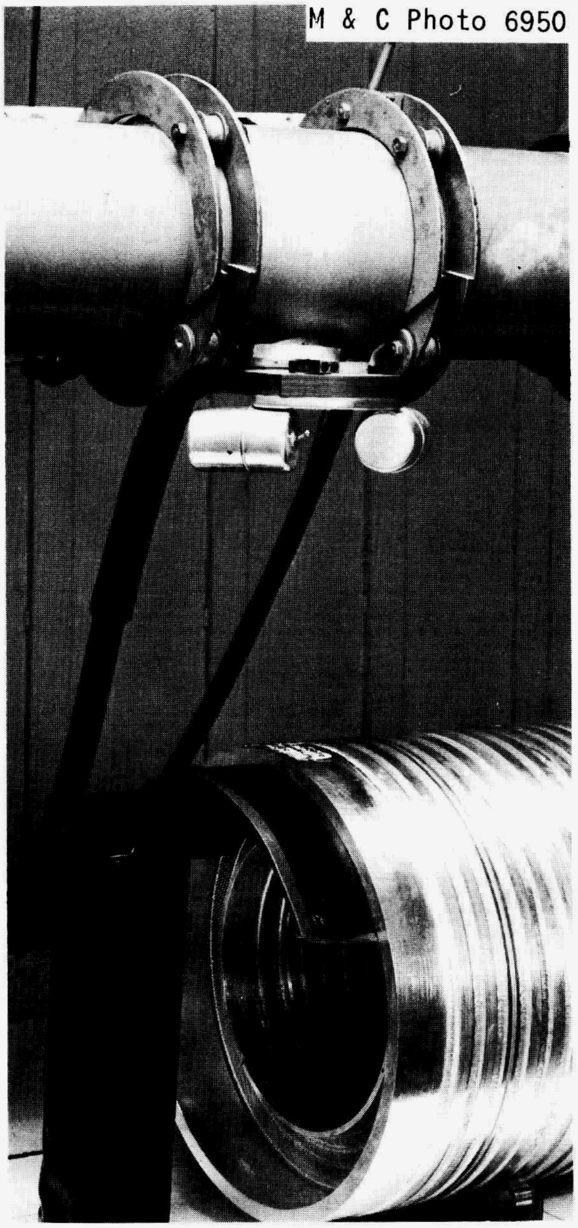


Fig. 59. Radiography of Outer Fuel Element Adapter Welds.

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 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. and the focal spot is about 4 mm. Penetrameter size[19] 50A is used for the inner top and outer top adapters of the inner element. Size[19] 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 areas, 1/4 in. 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. or Less and Size Assorted."

Final Machining

To prepare the elements for machining, masking tape is 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

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

the spider segments until the least total indicator reading is obtained with respect to 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. of the established center line. The outside is turned to 10.698 to 10.702 in. and 17.197 to 17.200 in. in diameter for the inner and outer fuel element, respectively. The adapters are rough machined to within 0.050 in. of final dimensions, as shown in Fig. 60.

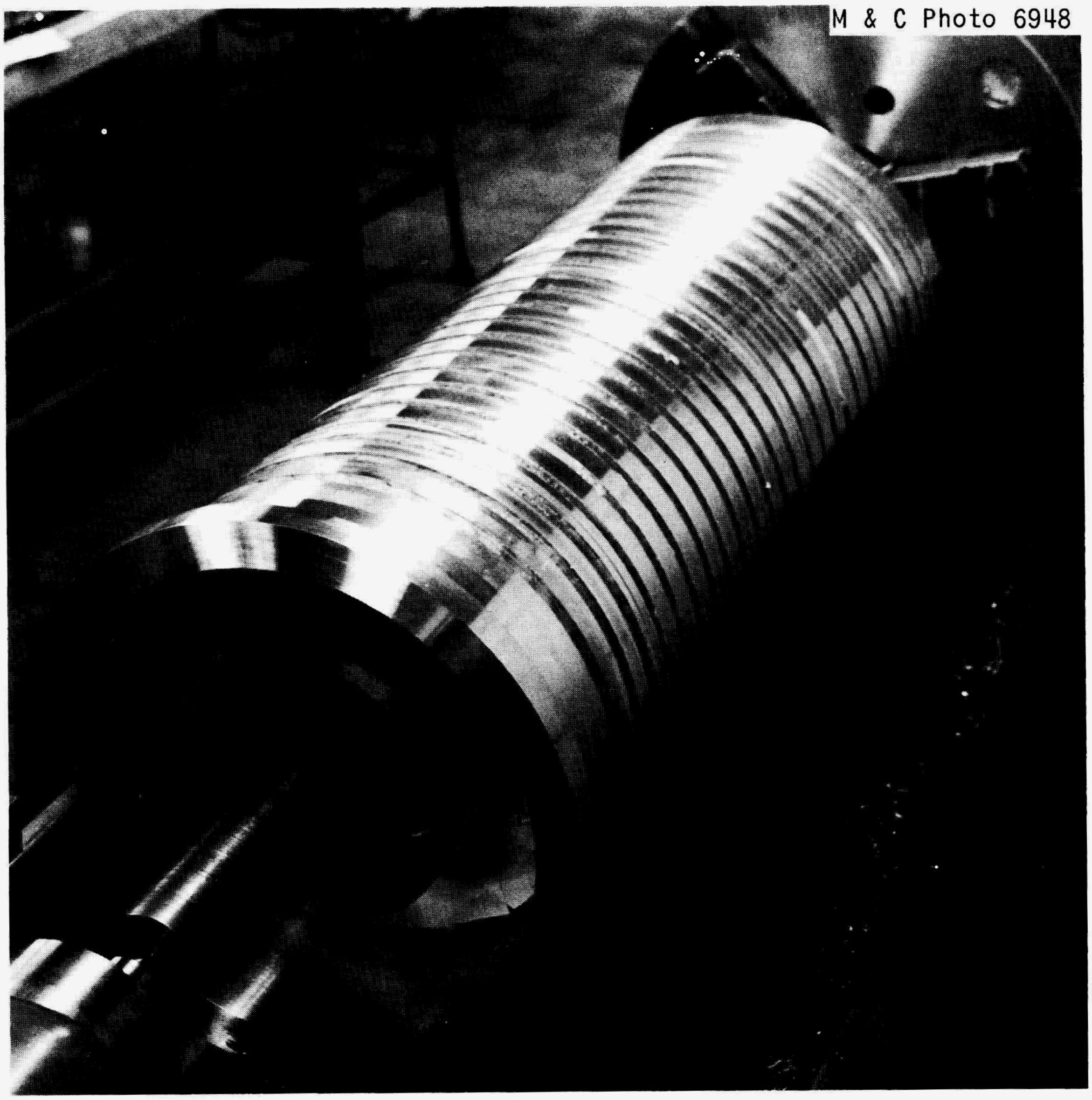


Fig. 60. Rough Machining of Adapter on Inner Fuel Element.

The element is removed from the lathe and set up on a cradle fixture on a horizontal boring mill, as shown in Fig. 61. 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 or ethyl alcohol 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.

The inside diameter is inspected in position on the boring mill, and necessary corrections are made for temperature. The element is

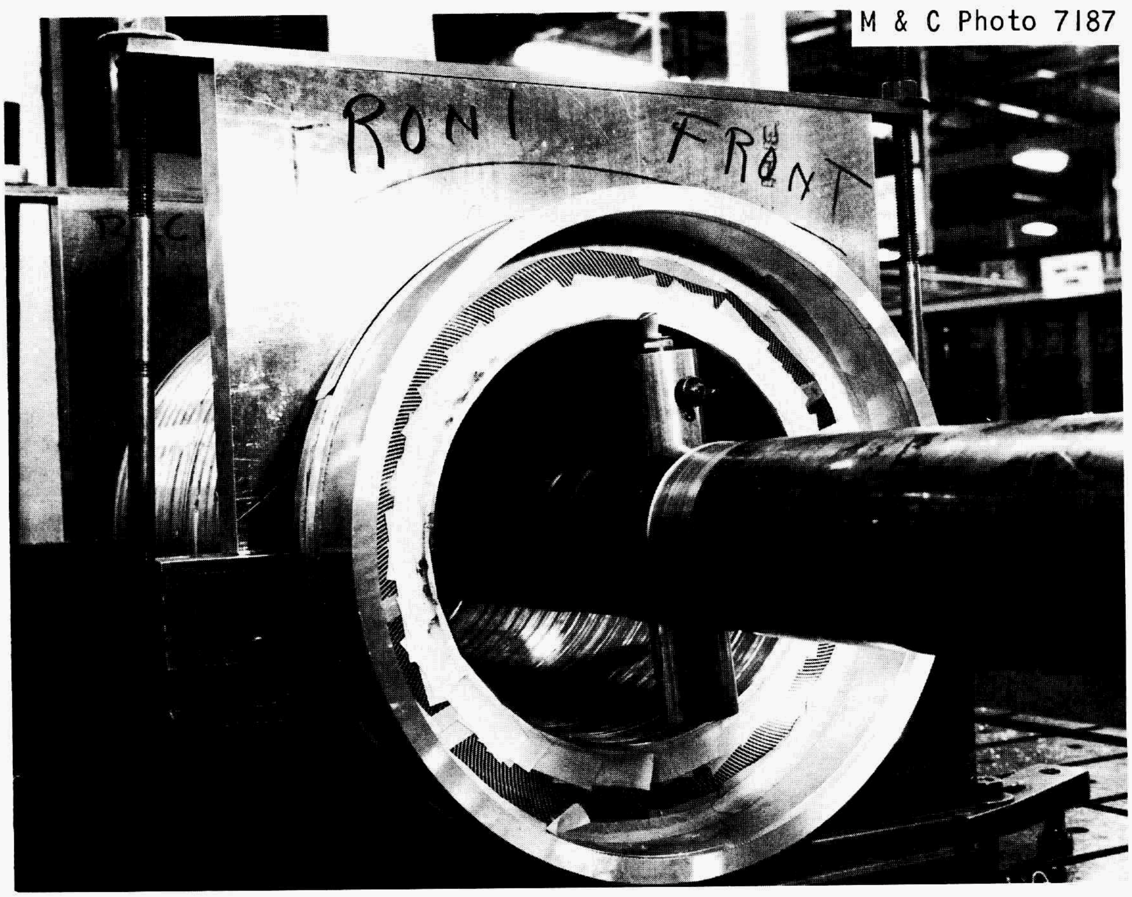


Fig. 61. Boring Inside of Outer Fuel Element.

removed to an inspection area maintained at 20°C (68 ± 1°F). The inside diameter is reinspected, and the inside wall-assurance groove depths are measured. The dimensions are recorded.

Expanding mandrels are inserted in the element, which is then mounted between centers in a lathe. 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. 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. over the 10.915-in. diameter for inner fuel element and over the 16.757- and 16.4725-in. diameters for outer fuel element for final chip 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.

<u>Inspection</u>

The elements are inspected at 20°C (68 ± 1°F) in the restrained condition for all dimensions needed to assure 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. 62.

Both elements are engraved with identification numbers by a pantograph machine 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

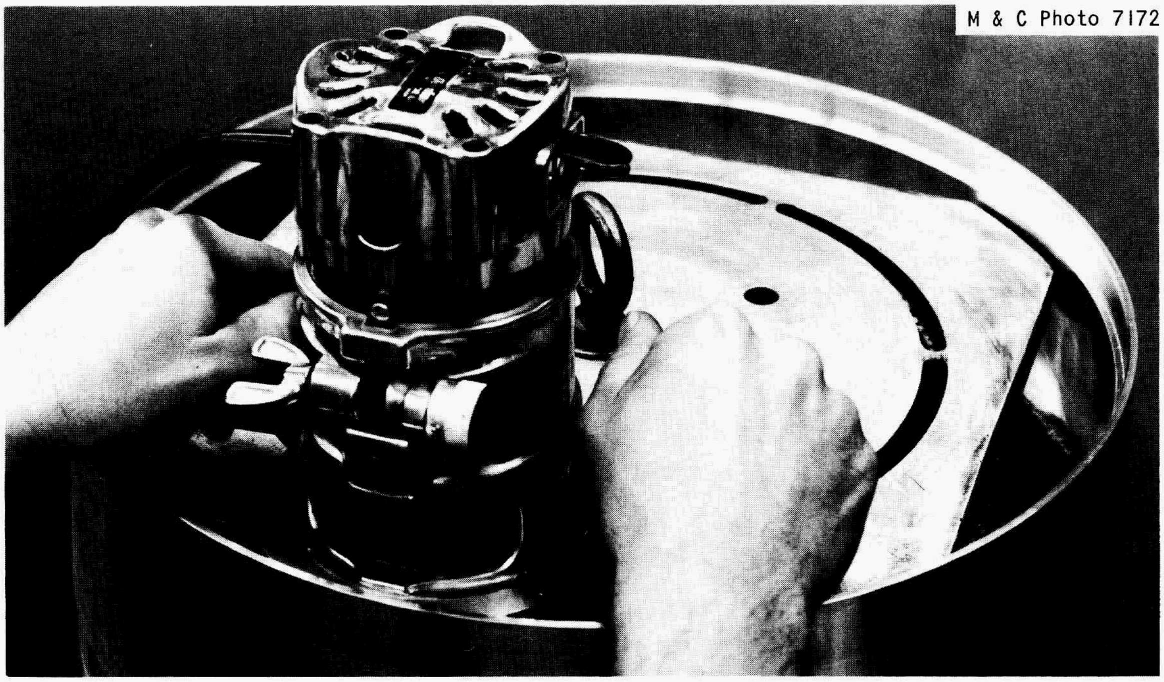


Fig. 62. Routing Adapter Pads on Outer Element.

(68 ± 1°F) in the unrestrained condition for several pertinent dimensions and again deburred. The dimensions required for certification are again recorded.

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	$T_F = T_S - R$

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. Dry nitrogen at 60 psi is blown through the channels to remove chips. 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 tank of deionized water (500,000 ohm-cm minimum) and withdrawn quickly. This cycle is repeated twice. The element is then lowered into a hot rinse tank of deionized water at 82°C (180°F), kept there until its temperature is about the same as that of the water, and then withdrawn quickly. The cycle is repeated twice. The element is blown dry with nitrogen 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.-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.

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. fuel-plate protrusion at weld grooves 1, 12, and 24 for inner and outer side plates of the assembled element prior to welding,
4. 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,

5. inner and outer side-plate wall thicknesses at 30° increments around the circumference, inner and outer side plate minimum wall thickness and location,
6. 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,
7. acceptance-rejection summary of pre- and postweld circular weld-test specimens — visual inspection, metallographic attributes, and measured values of weld tensile strength,
8. inspection data for sample fuel plates from each fuel-plate lot represented in the fuel element:

   fuel core location
   ^{235}U surface contamination
   flat-plate dimensions
   flat-plate thickness,

9. involute data for fuel plate lots represented in the fuel element,
10. 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,
11. radiographs of fuel-element adapter welds.

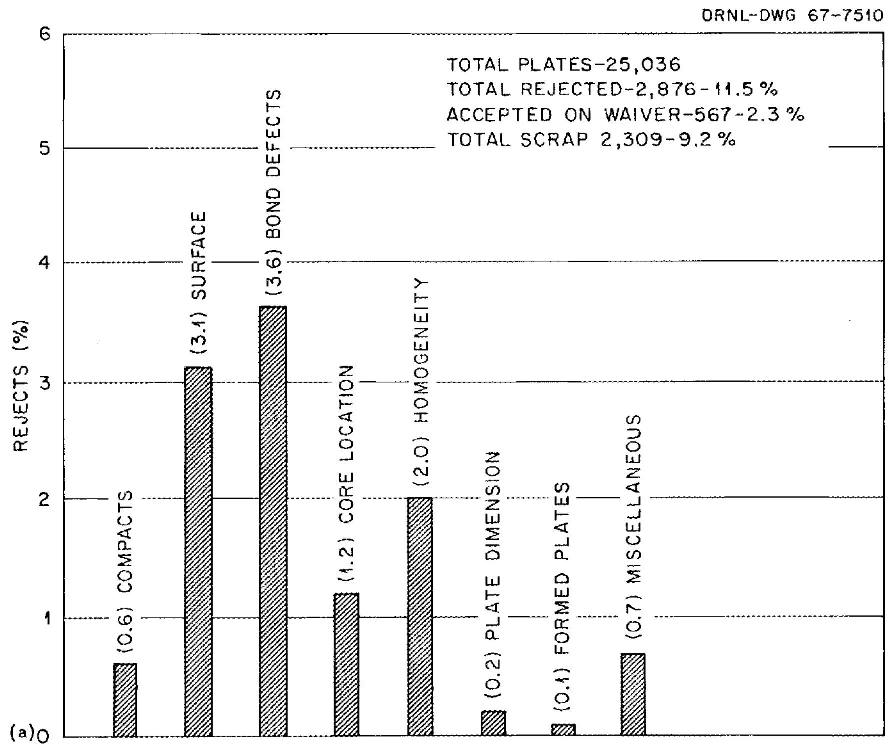
YIELDS

Fuel Plates

Fuel-plate rejections for the first 30 element loadings of fuel plates produced are analyzed in Fig. 63. In general, fuel-plate yields increased as more experience was gained. A yield of 90.8% was obtained for 25,000 fuel plates. The process appears to have stabilized at about 93% yield, but constant control is required to maintain this level.

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



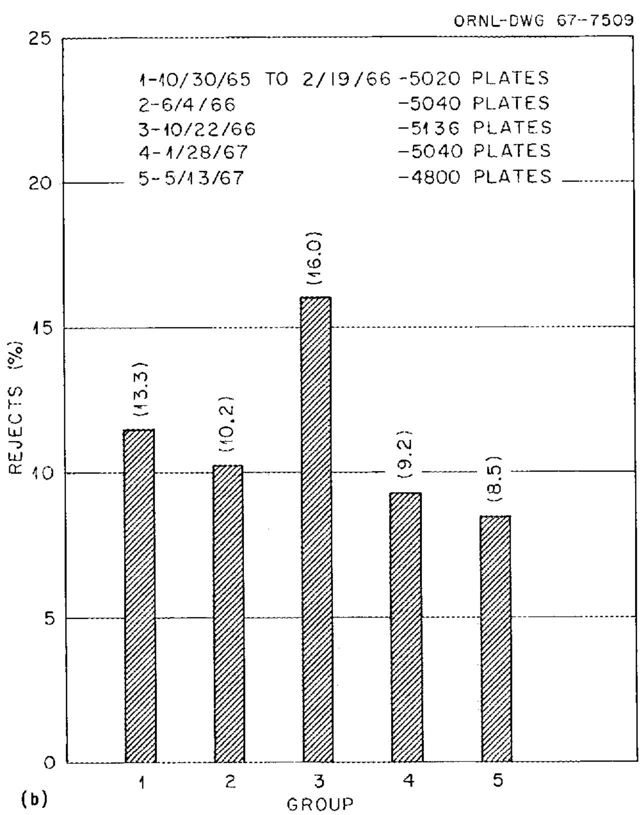


Fig. 63. Analysis of Rejections in Fuel Plates. (a) Distribution of rejections according to categories. (b) Trend with manufacturing experience.

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 may be removed before cover plates are fabricated if the inclusions are not too deep.

Bond defects are another major 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 plates rejected at ultrasonic inspection. Not all the plates rejected at ultrasonic inspection have bond defects, since abnormal fuel end configurations can result in ultrasonic indications.

Most blisters occur at the interface between the compact and a cover plate. However, the as-received alclad 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. Aluminum is difficult to bond, and it is doubtful whether any significant improvement 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. 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 70% 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.

Fuel Elements

None of the fuel elements produced to date has met all of the specifications. The violations of the specifications have been of such a nature that all of the fuel elements have been accepted by ORNL and several have operated routinely at 100 Mw. We anticipate that someday an element will be lost because of either machine or operator error in welding, operator error in machining, or operator error in handling (dropping an element).

Figure 64 represents the number of specification violations that occurred for the first 30 fuel elements of each type. The cross-hatched areas represent the number that occurred for the first ten fuel elements of each type. Note that in several of the categories most of the rejections occurred in the first ten cores. In some cases the number of rejections exceeds the number of fuel elements; this can occur because more than one violation for the same attribute may appear in a single fuel element.

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

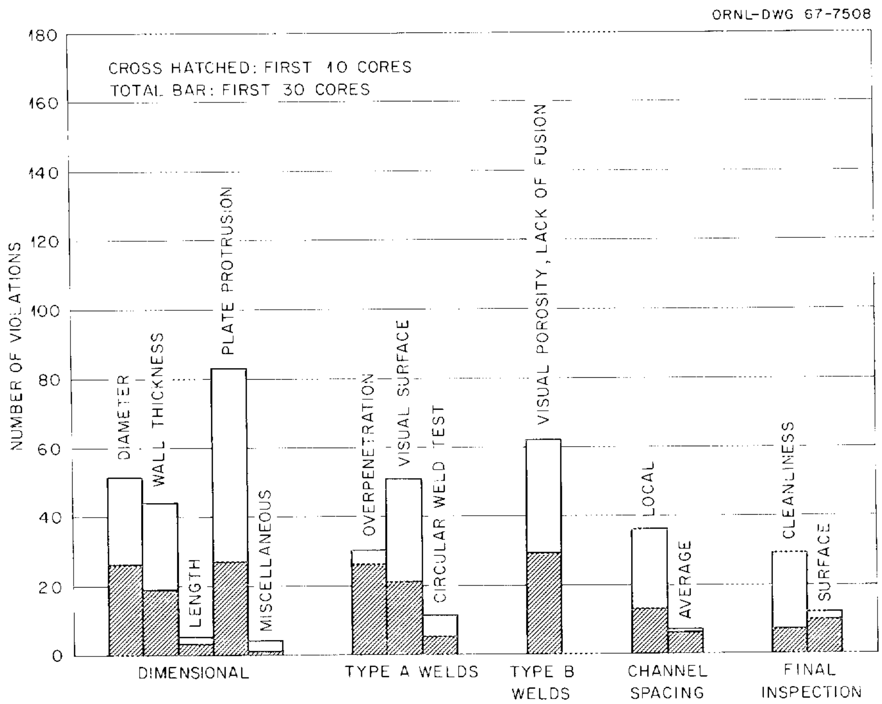


Fig. 64. Specification Violations for the First 30 Cores.

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. in local areas. We expect that wall violations of about 0.001 in. 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. 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 to 0.0015 in. for local areas and about 0.0005 to 0.001 in. 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 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 operation 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. These are the result of handling damage, the removal of excess comb weld metal, deburring, etc. 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. 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.

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.

Comb welding (Type C) has not resulted in any specification violations. However, many small cracks are repaired by the welder prior to inspection, and considerable time is spent on removing weld splatter. The removal of the weld splatter may cause surface defects as mentioned earlier.

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. 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.

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 stock that has been thoroughly inspected prior to shipment to M&C. The yield has been as low as 30 to 50% on other material. Yield figures are very dependent upon the quality of stock produced by the aluminum fabricator. It is known that the aluminum fabricator's yield is very low. Yields on cover plate stock have been fairly consistent at about 75%.

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 tooling becomes stabilized and the experience of operators increases.

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 46 fuel assemblies have been manufactured and 15 have been operated at 100,000 kw satisfactorily.

ACKNOWLEDGMENT

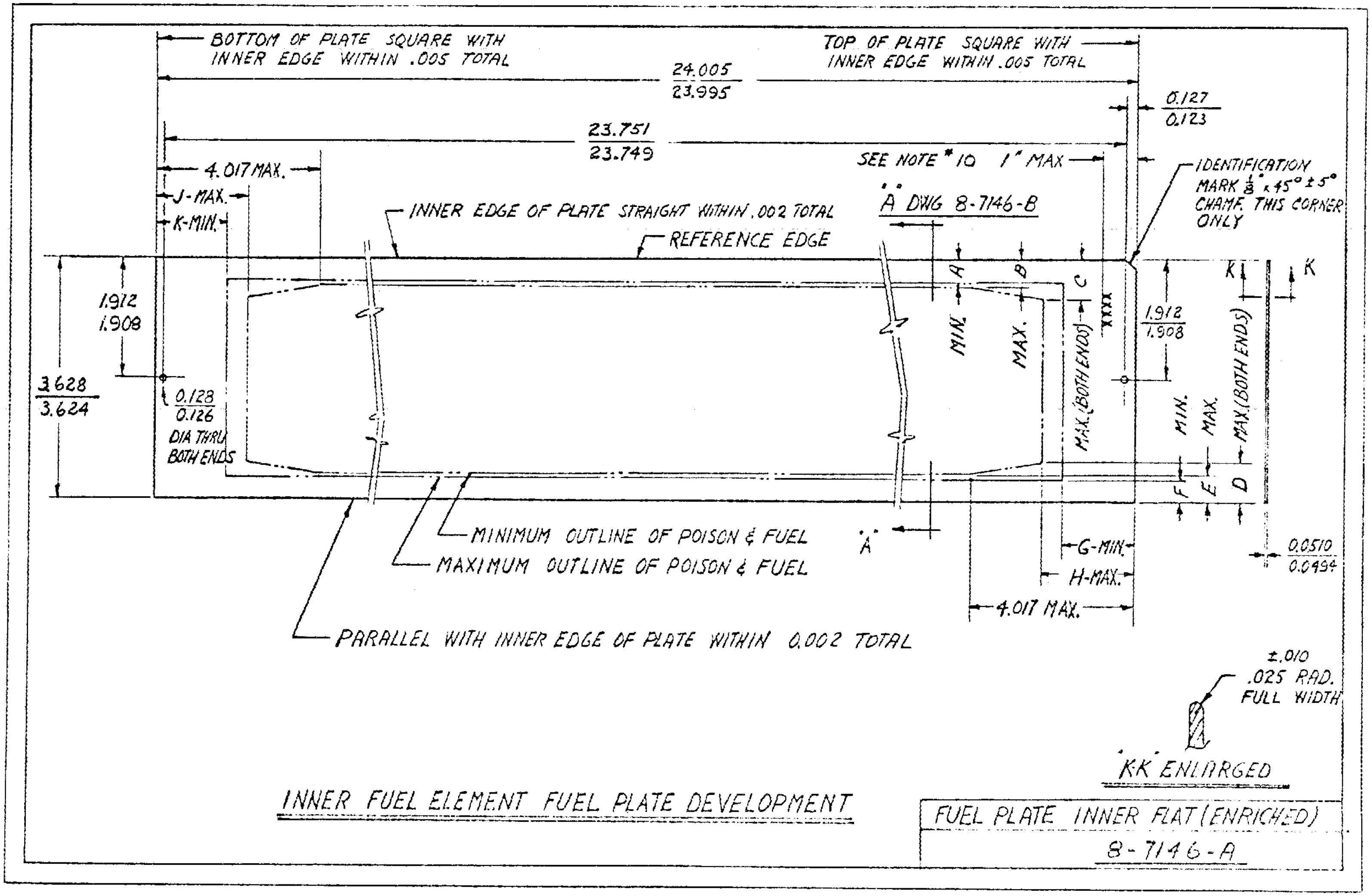
The authors have summarized the work developed by others at Metals and Controls, Inc. and ORNL. In particular, Fred Sherman, Jim Barker, and Brad Boyd of M&C were responsible for fuel plate fabrication, fuel element fabrication, and quality control, respectively, and J. W. Tackett[20] was responsible for much of the welding development.

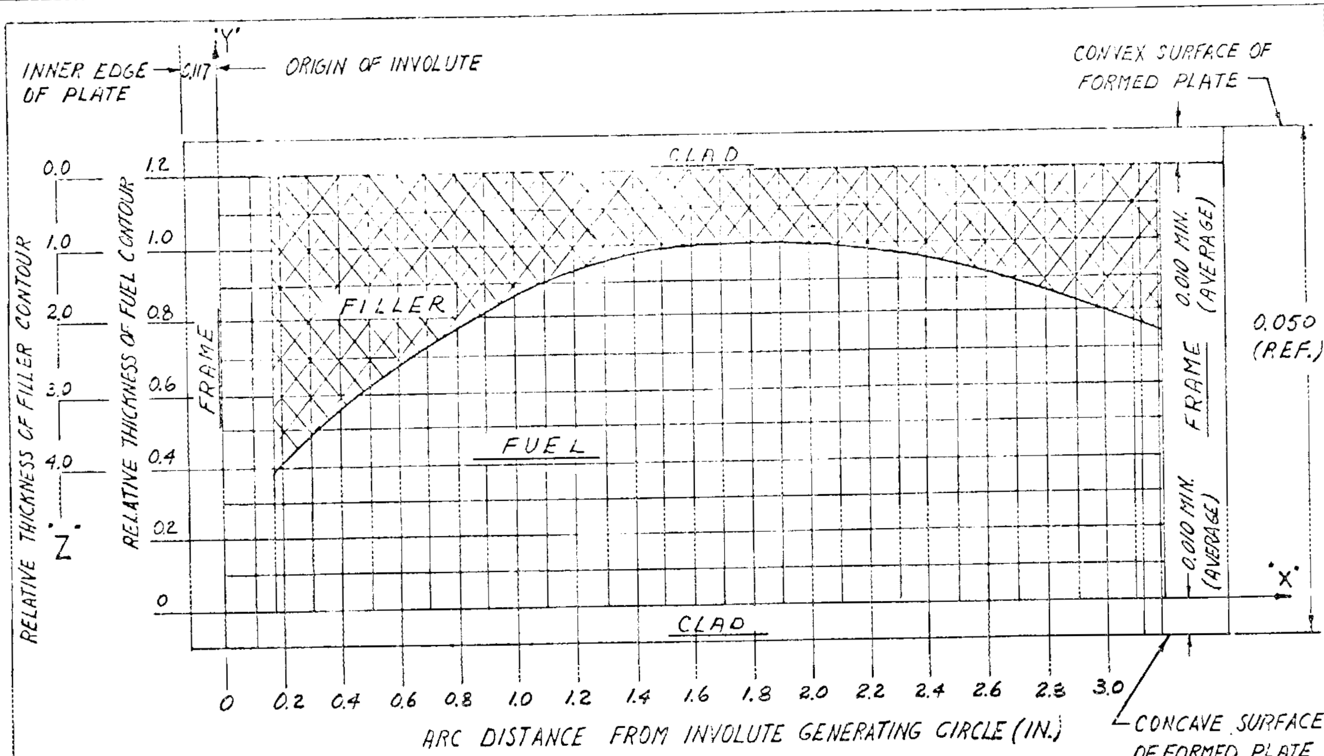
[20]Presently employed at Stellite Division, Kokomo, Indiana.

This report could not have been written without the constant advice from the above-mentioned people. We also wish to recognize the work of Gil Clark and Don Davidson, who made important contributions during the development and early production stages of the fuel element.
R. W. McClung and his Nondestructuve Testing Group at ORNL have reviewed and improved the treatment of inspection procedures. We also wish to acknowledge Sigfred Peterson and the Reports Office of the Metals and Ceramics Division of ORNL for the preparation of this report.

APPENDIX A

Design Drawings


BOTTOM OF PLATE SQUARE WITH INNER EDGE WITHIN .005 TOTAL
TOP OF PLATE SQUARE WITH INNER EDGE WITHIN .005 TOTAL
24.005 / 23.995
23.751 / 23.749
0.127 / 0.123
4.017 MAX.
J-MAX.
K-MIN.
SEE NOTE # 10 1" MAX
IDENTIFICATION MARK 1/8" x 45° ± 5° CHAMF. THIS CORNER ONLY
"A" DWG 8-7146-B
INNER EDGE OF PLATE STRAIGHT WITHIN .002 TOTAL
REFERENCE EDGE
1.912 / 1.908
3.628 / 3.624
0.128 / 0.126 DIA THRU BOTH ENDS
A MIN.
B MAX.
C MAX. (BOTH ENDS)
K
MIN.
MAX.
MAX. (BOTH ENDS)
F
E
D
MINIMUM OUTLINE OF POISON & FUEL
MAXIMUM OUTLINE OF POISON & FUEL
"A"
G-MIN.
H-MAX.
4.017 MAX.
0.0510 / 0.0494
PARALLEL WITH INNER EDGE OF PLATE WITHIN 0.002 TOTAL
±.010 .025 RAD. FULL WIDTH
"KK" ENLARGED
INNER FUEL ELEMENT FUEL PLATE DEVELOPMENT
FUEL PLATE INNER FLAT (ENRICHED)
8-7146-A



INNER FUEL ELEMENT FUEL CONTOUR

NOT TO SCALE

COORDINATES		
X	Y	Z
.060	.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
1.809	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

SECTION AA

SHOWN OUT OF TRUE POSITION

INNER FUEL ELEMENT FUEL PLATE DEVELOPMENT

FUEL PLATE INNER FLAT (ENRICHED)

8-7146-B

Notes

1. Fuel plate surfaces containing any pits or scratches greater than in Table I or dents larger than 0.25 in. in diameter 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 0.062 in. diam nonbond or blister located within the fuel core outline and a 0.125 in. diam nonbond or blister located outside the fuel core outline. The sensitiviy 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 number 1/8 in. high by 0.005 in. max deep.
7. Fuel core location-edge dimensions:

Location from Each End of Plate (in.)	Reference Plate Edge to Adjacent Fuel Edge (in.)	(in.)	Opposite Plate Edge to Opposite Fuel Edge (in.)	(in.)
1.761–2.261		(A) 0.171 min		(F) 0.327 min
2.261–4.017	(C) 0.452 max	(A) 0.171 min	(C) 0.608 max	(F) 0.327 min
Between 4.017	(B) 0.234 max	(A) 0.171 min	(B) 0.390 max	(F) 0.327 min

8. Fuel core location-end dimension:

   Numbered plate end to numbered fuel end — (G) 1.761 in. min (H) 2.261 in. max
   Opposite plate end to opposite fuel end — (K) 1.761 in. min (J) 2.261 in. max

9. The fuel core location is based on the following radiograph biases:

   Reference edge, ±0.001 in.
   Reference to opposite edge, ±0.001 in.
   Reference end, ±0.011 in.
   Reference to opposite end, ±0.011 in.

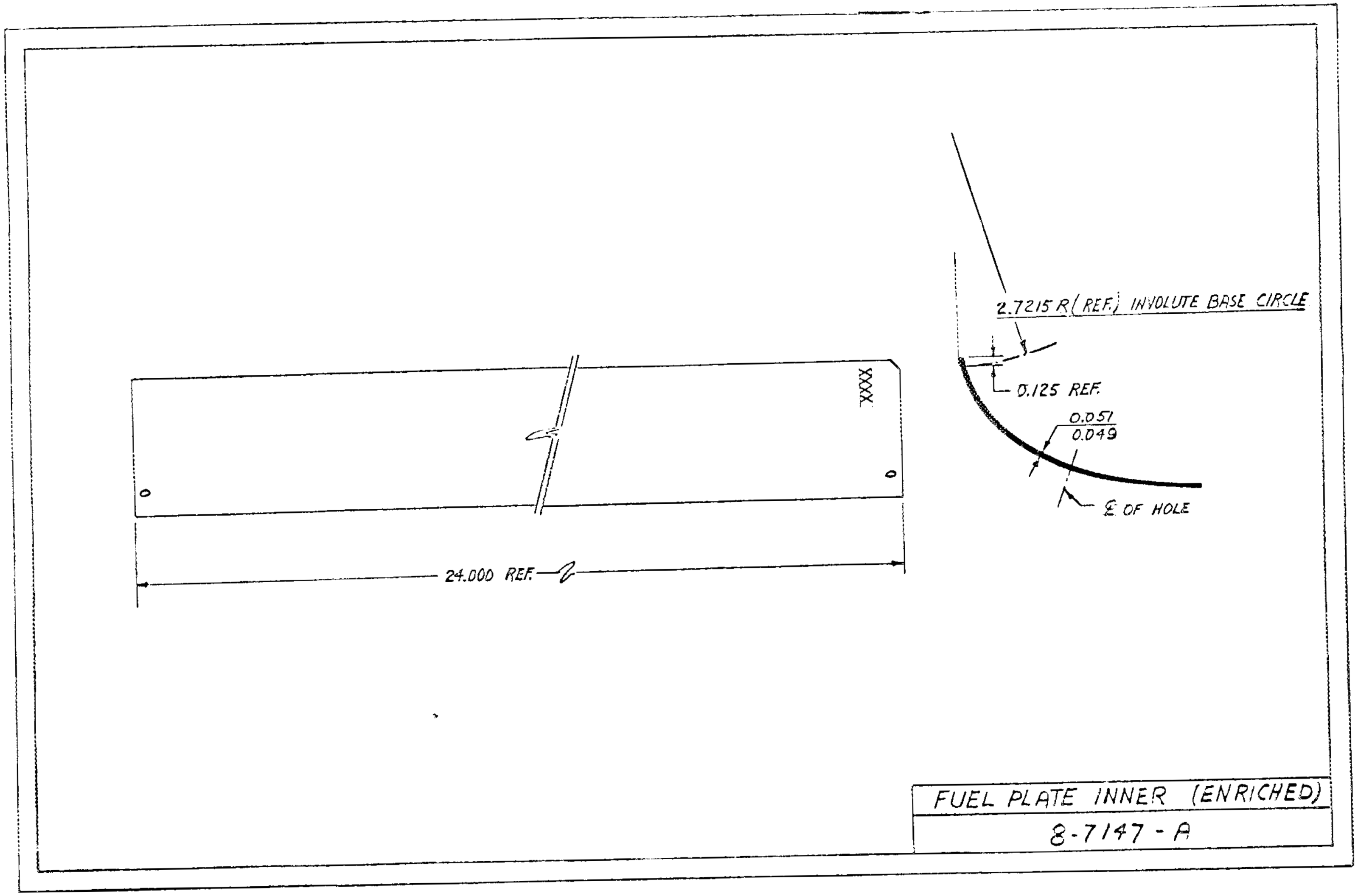
10. Top of digits in plate number to be toward top of plate.

Table I

	Numbered Side (in.)	Opposite Side (in.)
1 1/2 in. from numbered end to 1 1/2 in. from opposite end for full width	0.003	0.002
Numbered end of plate to 1 1/2 in. from numbered end and opposite end both for full width	0.0035	0.0035

FUEL PLATE INNER FLAT (ENRICHED)

8-7146-C


2.7215 R (REF.) INVOLUTE BASE CIRCLE
0.125 REF.
0.051
0.049
℄ OF HOLE
XXX
24.000 REF.
FUEL PLATE INNER (ENRICHED)
8-7147-A

Notes

1. All materials of construction shall conform with ORNL specification HFIR FE1.
2. The surface of the fuel plates shall be free of pits or scratches greater than in Table I or dents greater than 0.25 in. 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 μg of $^{235}U/ft^2$ of surface area.
6. No treatment of the plate surface which removes more than 0.001 in. 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 28 separate measuring points. Seven 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 Number			
1	2	3	4
3.18	3.77	4.58	5.14

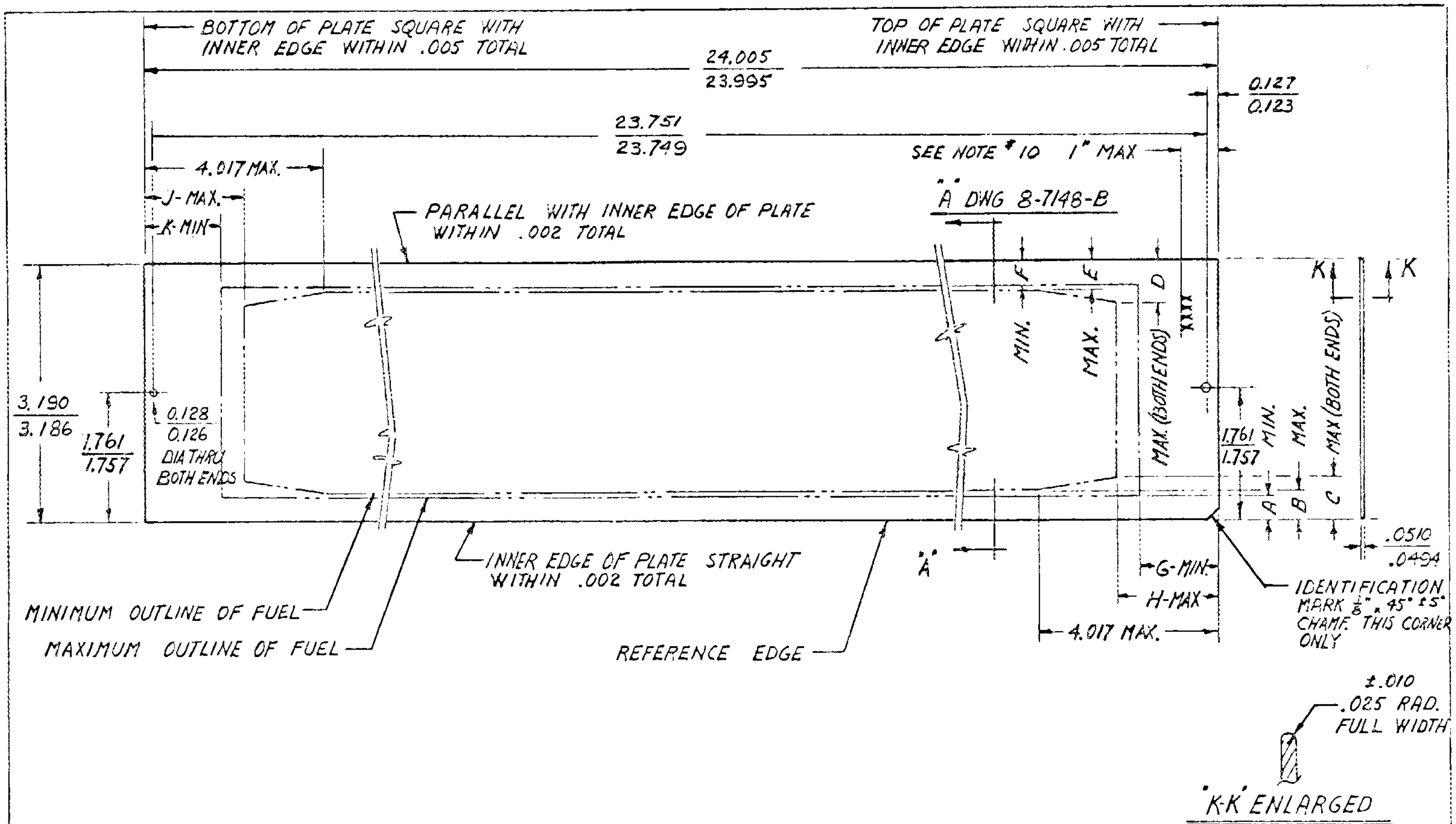
8. The average clad thickness on each side of the fuel plate shall be at least 0.010 in. The minimum clad thickness shall be at least 0.007 in.
9. The fuel portion of the compact shall fall nearest the concave side of the formed fuel plate.

Table I

	Numbered Side (in.)	Opposite Side (in.)
1 1/2 in. from numbered end to 1 1/2 in. from opposite end for full width.	0.003	0.002
Numbered end of plate to 1 1/2 in. from numbered end and opposite end of plate to 1 1/2 in. from opposite end both for full width	0.0035	0.0035

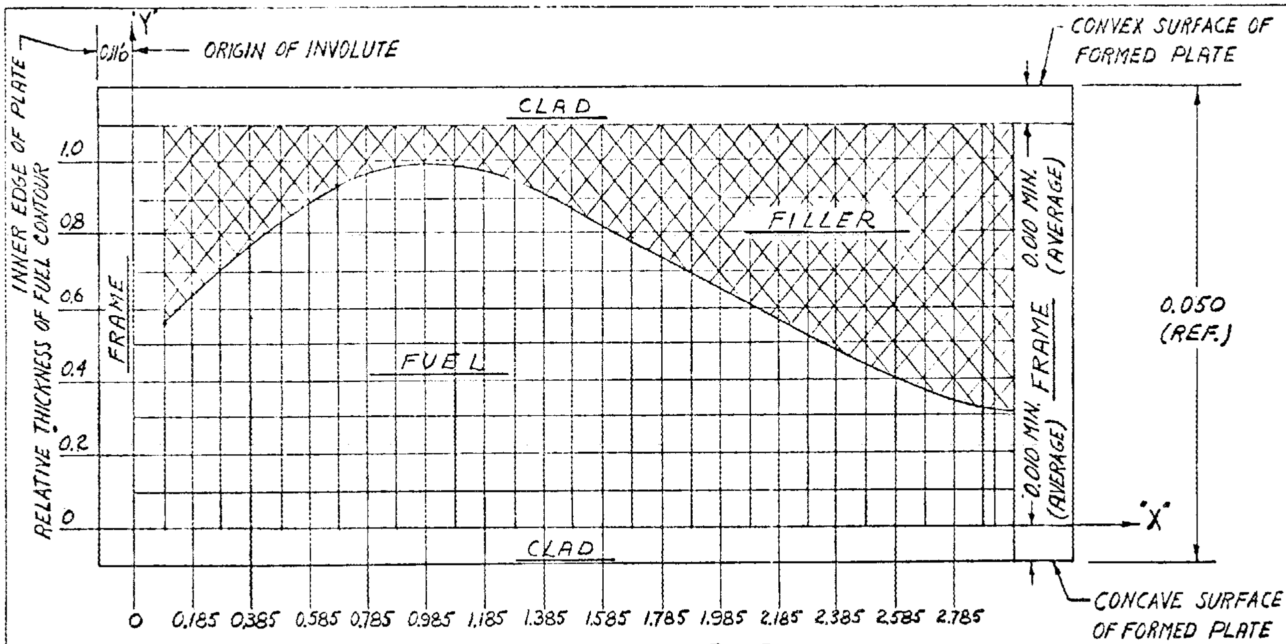
FUEL PLATE INNER (ENRICHED)

8-7147-B



OUTER FUEL ELEMENT FUEL PLATE DEVELOPMENT

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



OUTER FUEL ELEMENT FUEL CONTOUR

NOT TO SCALE

SECTION AA

SHOWN OUT OF TRUE POSITION

COORDINATES	
"X"	"Y"
.060	.553
.085	.572
.108	.589
.185	.645
.285	.715
.385	.782
.485	.844
.585	.899
.685	.942
.785	.973
.885	.993
1.006	1.000
1.085	.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

FUEL PLATE OUTER FLAT (ENRICHED)

8-7148-B

Notes

1. Fuel plate surfaces containing any pits or scratches greater than Table I or dents larger than 0.25 in. in diameter 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 0.062 in. diam nonbond or blister located within the fuel core outline and a 0.125 in. diam nonbond 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 number 1/8 in. by 0.005 in. max deep.
7. Fuel core location-edge dimensions:

Location from Each End of Plate (in.)	Reference Plate Edge to Adjacent Fuel Edge (in.)	(in.)	Opposite Plate Edge to Opposite Fuel Edge (in.)	(in.)
1.761–2.261		(A) 0.170 min		(F) 0.210 min
2.261–4.017	(C) 0.436 max	(A) 0.170 min	(D) 0.476 max	(F) 0.210 min
Between 4.017	(B) 0.218 max	(A) 0.170 min	(E) 0.258 max	(F) 0.210 min

8. Fuel core location-end dimensions:

   Numbered plate end to numbered fuel end – (G) 1.761 in. min (H) 2.261 in. max
   Opposite plate end to opposite fuel end – (K) 1.761 in. min (J) 2.261 in. max

9. The fuel core location is based on the following radiograph biases:

   Reference edge, +0.001 in.
   Reference to opposite edge, ±0.001 in.
   Reference end, ±0.011 in.
   Reference to opposite end, ±0.011 in.

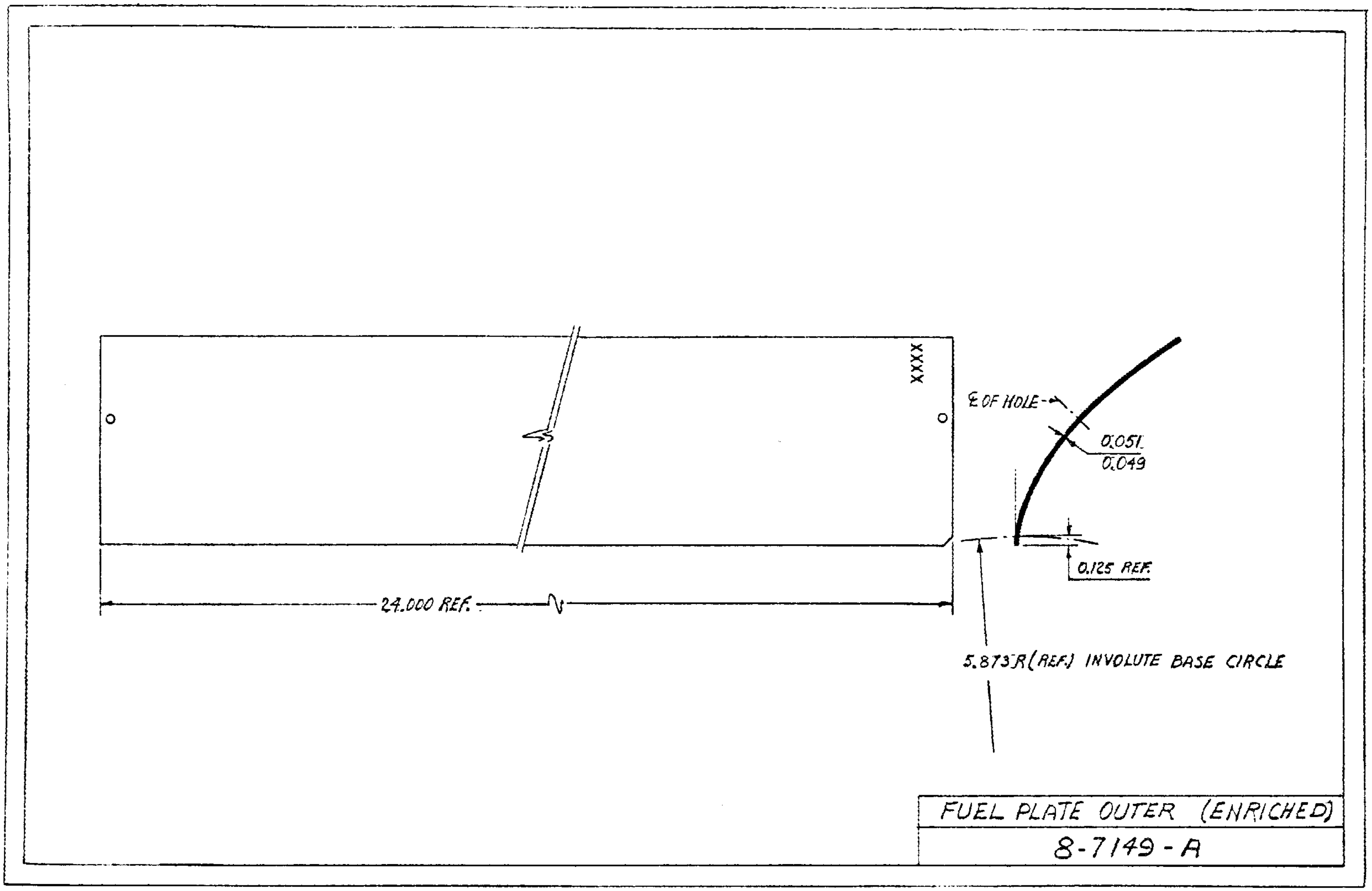
10. Top of digits in plate number to be toward top of plate.

Table I

	Numbered Side (in.)	Opposite Side (in.)
1 1/2 in. from numbered end to 1 1/2 in. from opposite end for full width	0.003	0.002
Numbered end of plate to 1 1/2 in. from numbered end and opposite end both for full width	0.0035	0.0035

FUEL PLATE OUTER FLAT (ENRICHED)

8-7148-C


XXXX
℄ OF HOLE
0.051
0.049
0.125 REF.
24.000 REF.
5.873"R (REF.) INVOLUTE BASE CIRCLE
FUEL PLATE OUTER (ENRICHED)
8-7149-A

Notes

1. All materials of construction shall conform with ORNL specification HFIR FE1.
2. The surface of the fuel plates shall be free of pits or scratches greater than in Table I or dents greater than 0.25 in. 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 µg of $^{235}U/ft^2$ of surface area.
6. No treatment of the plate surface which removes more than 0.001 in. 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 21 separate measuring points. Seven 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 Number		
1	2	3
6.35	6.78	7.99

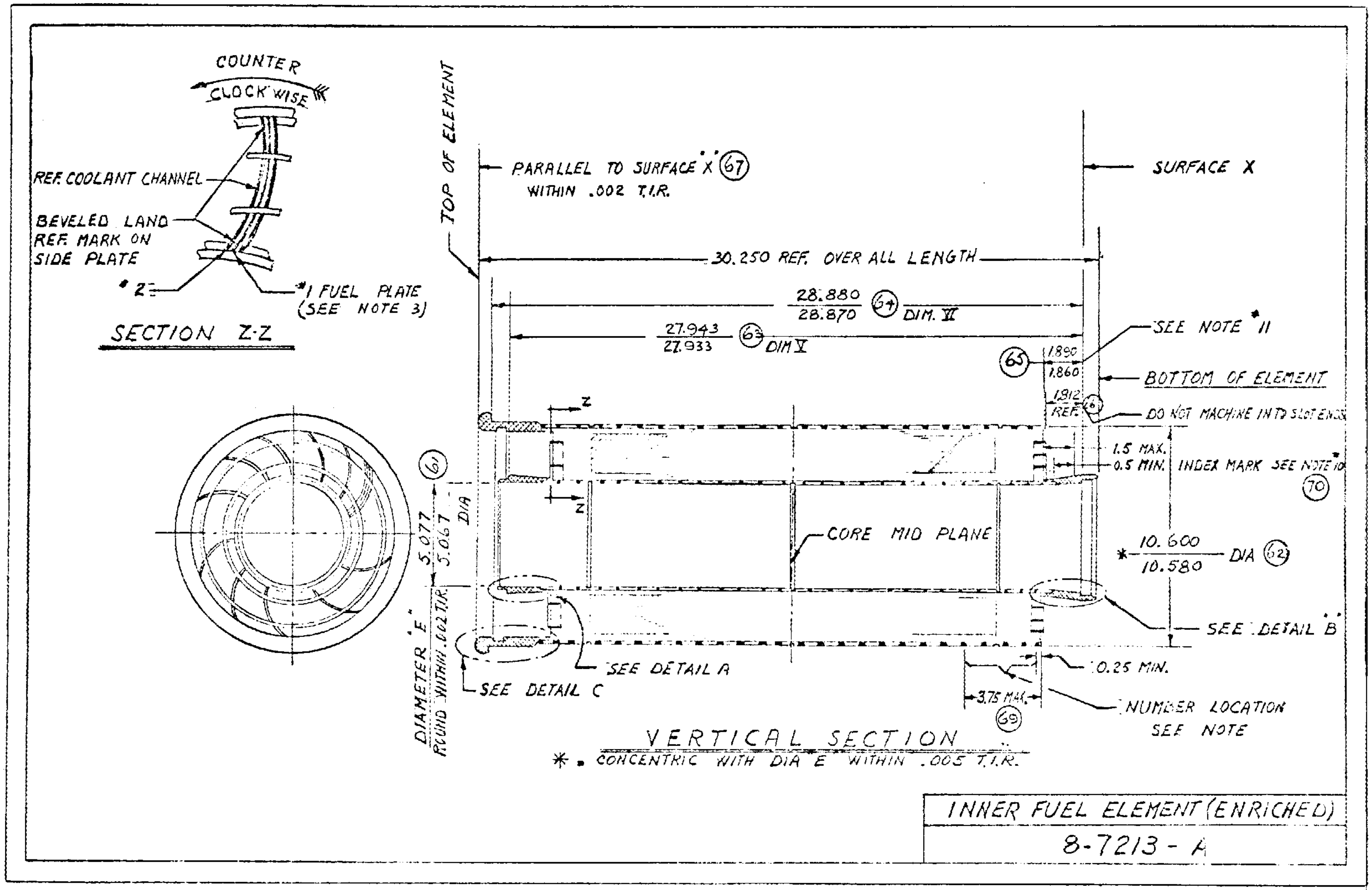
8. The average clad thickness on each side of the fuel plate shall be at least 0.010 in. The minimum clad thickness shall be at least 0.007 in.
9. The fuel portion of the compact shall fall nearest the concave side of the formed fuel plate.

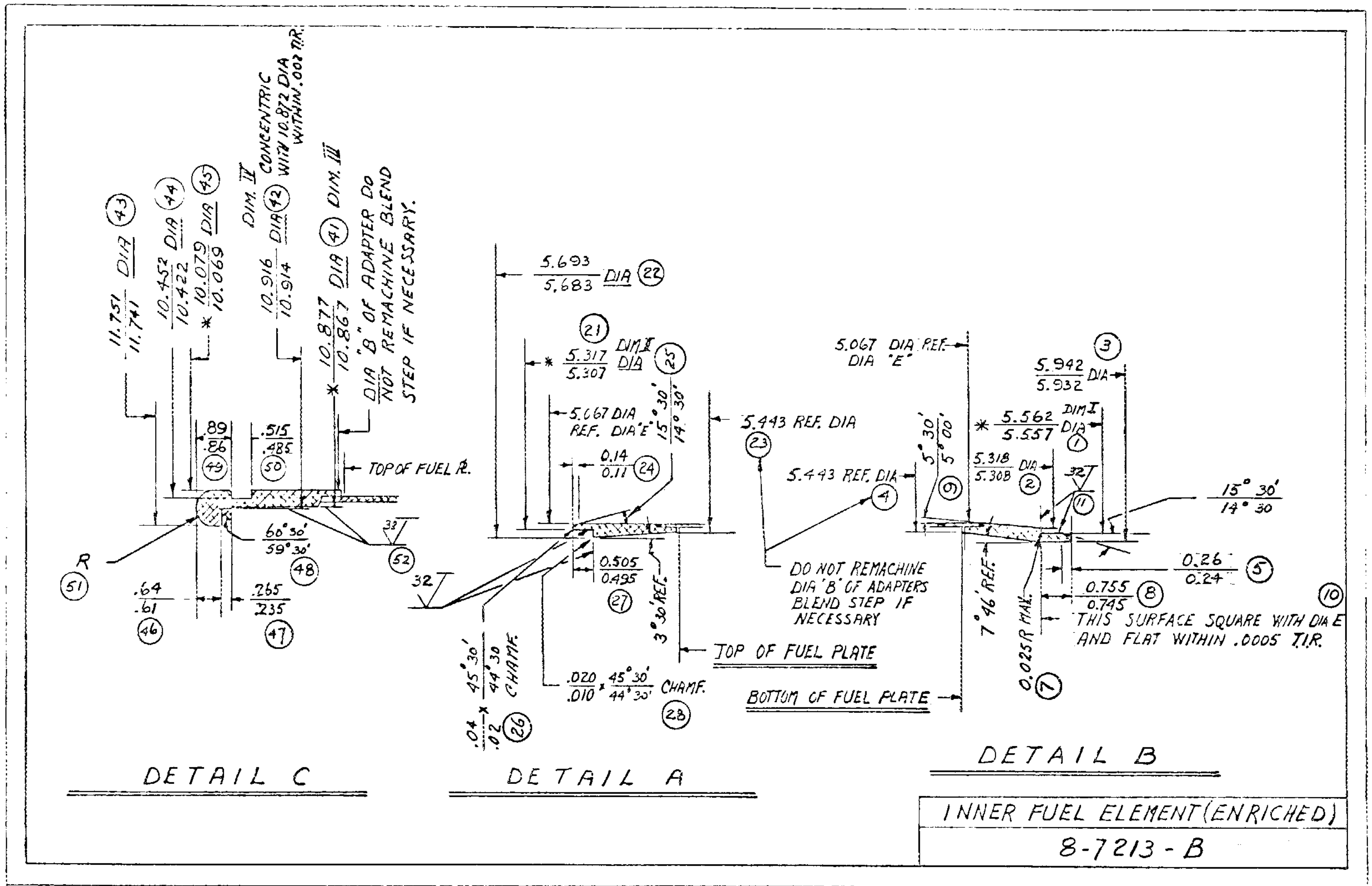
Table I

	Numbered Side (in.)	Opposite Side (in.)
1 1/2 in. from numbered end to 1 1/2 in. from opposite end for full width	0.003	0.002
Numbered end of plate to 1 1/2 in. from numbered end and opposite end of plate to 1 1/2 in. from opposite end both for full width	0.0035	0.0035

FUEL PLATE OUTER (ENRICHED)

8-7149-B


COUNTER CLOCKWISE
REF. COOLANT CHANNEL
BEVELED LAND
REF. MARK ON SIDE PLATE
* Z
*1 FUEL PLATE (SEE NOTE 3)
SECTION Z-Z
TOP OF ELEMENT
PARALLEL TO SURFACE X (67) WITHIN .002 T.I.R.
SURFACE X
30.250 REF. OVER ALL LENGTH
28.880 / 28.870 (64) DIM. VI
27.943 / 27.933 (63) DIM V
SEE NOTE *11
(65) 1.890 / 1.860
BOTTOM OF ELEMENT
1.912 REF.
DO NOT MACHINE INTO SLOT ENDS
1.5 MAX.
0.5 MIN.
INDEX MARK SEE NOTE 10
(70)
(61)
5.077 / 5.067 DIA
CORE MID PLANE
* 10.600 / 10.580 DIA (62)
DIAMETER "E" ROUND WITHIN .002 T.I.R.
SEE DETAIL B
SEE DETAIL A
SEE DETAIL C
0.25 MIN.
3.75 MAX.
(69)
NUMBER LOCATION SEE NOTE
VERTICAL SECTION
* = CONCENTRIC WITH DIA E WITHIN .005 T.I.R.
INNER FUEL ELEMENT (ENRICHED)
8-7213-A

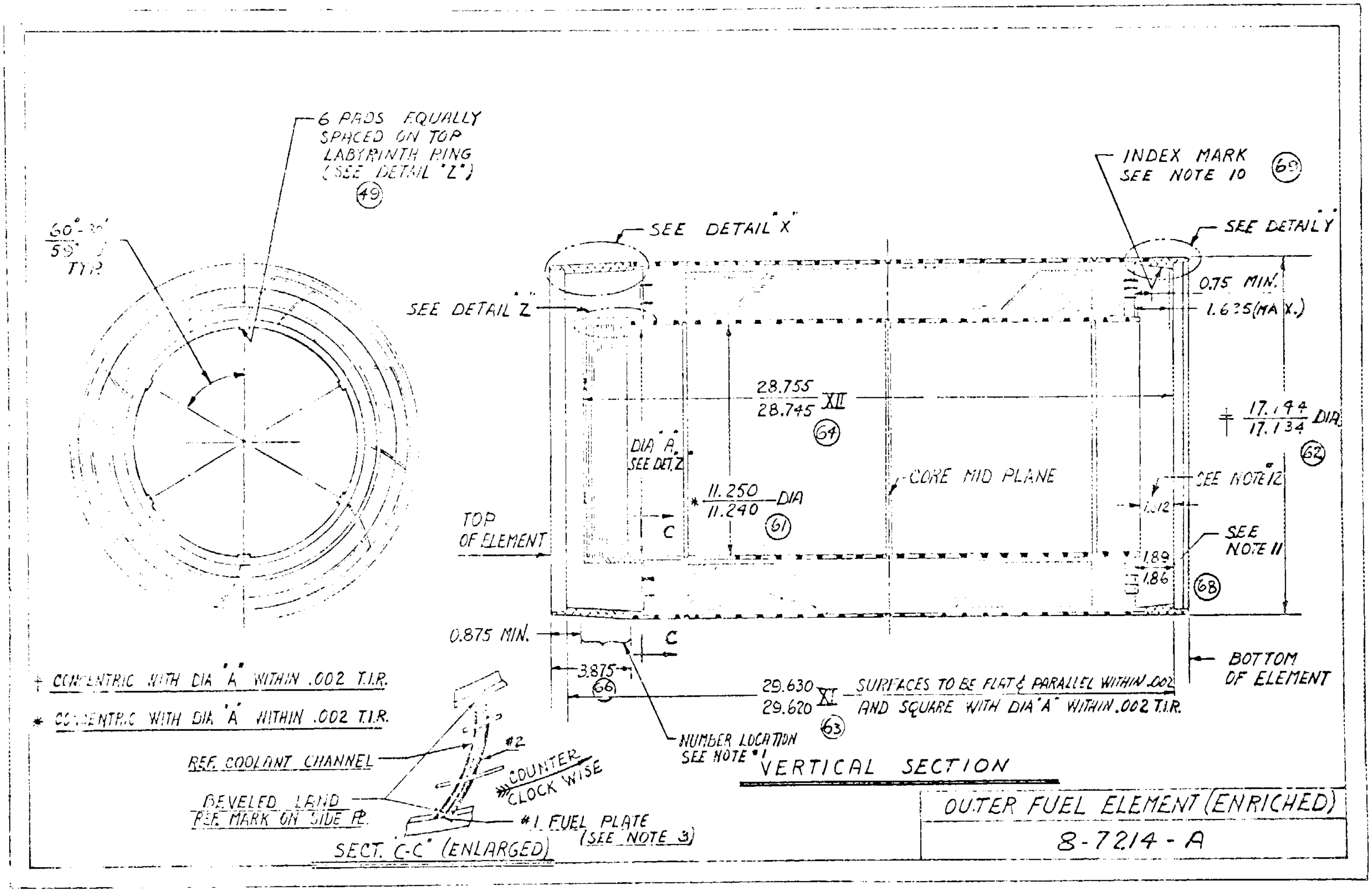

DETAIL C
DETAIL A
DETAIL B
TOP OF FUEL PLATE
BOTTOM OF FUEL PLATE
TOP OF FUEL ℞
DIA "B" OF ADAPTER DO NOT REMACHINE BLEND STEP IF NECESSARY.
DIM. IV CONCENTRIC WITH 10.872 DIA WITHIN .002 T.I.R.
DO NOT REMACHINE DIA 'B' OF ADAPTERS BLEND STEP IF NECESSARY
THIS SURFACE SQUARE WITH DIA E AND FLAT WITHIN .0005 T.I.R.
5.693 / 5.683 DIA
5.317 / 5.307 DIM II DIA
5.067 DIA REF. DIA 'E'
5.443 REF. DIA
5.942 / 5.932 DIA
5.562 / 5.557 DIM I DIA
5.318 / 5.308 DIA
15° 30' / 14° 30'
5° 30' / 5° 00'
0.26 / 0.24
0.755 / 0.745
0.14 / 0.11
0.505 / 0.495
3° 30' REF.
7° 46' REF.
0.025 R MAX.
.04 / .02 × 45° 30' / 44° 30' CHAMF.
.020 / .010 × 45° 30' / 44° 30' CHAMF.
11.751 / 11.741 DIA
10.452 / 10.422 DIA
10.079 / 10.069 DIA
10.916 / 10.914 DIA
10.877 / 10.867 DIA DIM. III
.89 / .86
.515 / .485
60° 30' / 59° 30'
.64 / .61
.265 / .235
R
INNER FUEL ELEMENT (ENRICHED)
8-7213-B

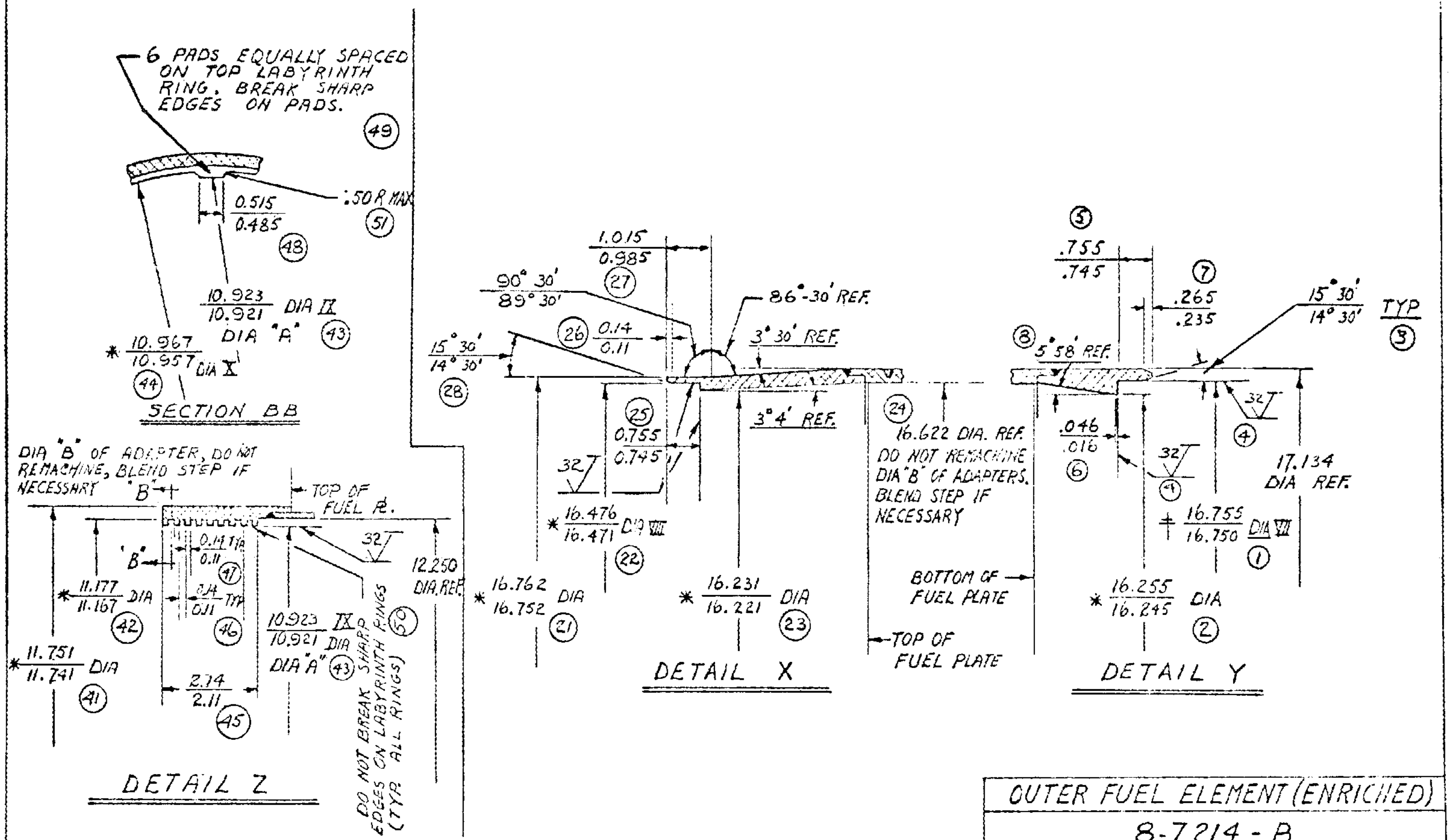
Notes

1. (69) Identification numbers 2.5–3.0 in. high with individual digits 1.5–2.0 in. wide shall be engraved to a depth 0.010–0.015 in. on each fuel element in a circumferential direction in two locations in the same circumferential band but 180° apart. The top of the fuel element is to be the top of the numbers. The characters are to be formed by two 1/16 in. wide cuts spaced 0.125–0.175 in. outer edge to inner edge to produce a double-image character. Vibratool surface between double image. Do not touch bottom of wall-assurance groove. All digits to be uniform in appearance.
2. (60) The wall-assurance grooves shall be a minimum of 0.015 in. deep at final machining on both ends.
3. Fuel plate locations are numbered counterclockwise looking at the top end and the reference fuel plate location (number 1) is the location immediately adjacent to the bevel land in a counterclockwise direction (viewed from the top) the reference coolant channel is the channel that contains the beveled land.
4. Fuel plate to side plate attachment is to be by circumferential welds on 1 in. centers. If any meltthrough exists, it shall be limited to 0.01 in. measured across the width of the fuel plate from the top of the fuel plate slot.
5. Minimum finished side plate thickness shall be as follows:

   Inner fuel element, inner side plate – 0.048 in.
   Inner fuel element, outer side plate – 0.105 in.
6. The coolant channel thickness (separation distance between adjacent fuel plates) shall be 0.050 ± 0.010 in. measured perpendicular to the surface of the fuel plates.
7. The average coolant channel thickness at any elevation from the core midplane shall be 0.050 ± 0.006 in.
8. All fuel plates shall be oriented such that their respective ends are within ±0.015 in. of parallel planes which are 24 in. apart and normal to the fuel element longitudinal axis.
9. Each comb shall be welded to all fuel plates.
10. (70) An index mark 0.235–0.265 in. long, 0.015–0.025 in. deep and 0.030–0.050 in. wide shall be engraved on the bottom end adapter opposite the reference coolant channel on each fuel element. An arrow 0.360–0.390 in. long and with 0.030–0.050 in. wide swath shall be engraved perpendicular to the index mark to indicate the direction of channel numbering sequence. This arrow shall be pointing in a clockwise direction as viewed from the bottom end and shall be within 0.2–0.3 in. of the index mark.
11. Reference from average of high and low fuel plates.

INNER FUEL ELEMENT (ENRICHED)
8-7213-C


6 PADS EQUALLY SPACED ON TOP LABYRINTH RING (SEE DETAIL "Z") (49)
60° 30' / 59° TYP
SEE DETAIL "X"
SEE DETAIL "Y"
INDEX MARK SEE NOTE 10 (69)
SEE DETAIL "Z"
0.75 MIN.
1.625 (MAX.)
28.755 / 28.745 XII (64)
17.194 / 17.134 DIA (62)
DIA "A" SEE DET. Z
11.250 / 11.240 DIA (61)
CORE MID PLANE
SEE NOTE 12
.12
SEE NOTE 11
1.89 / 1.86 (68)
TOP OF ELEMENT
BOTTOM OF ELEMENT
C
0.875 MIN.
3.875 (66)
29.630 / 29.620 XI (63) SURFACES TO BE FLAT & PARALLEL WITHIN .002 AND SQUARE WITH DIA "A" WITHIN .002 T.I.R.
NUMBER LOCATION SEE NOTE 1
VERTICAL SECTION
† CONCENTRIC WITH DIA "A" WITHIN .002 T.I.R.
* CONCENTRIC WITH DIA "A" WITHIN .002 T.I.R.
REF. COOLANT CHANNEL
#2
COUNTER CLOCK WISE
BEVELED LAND REF. MARK ON SIDE PL.
#1 FUEL PLATE (SEE NOTE 3)
SECT. "C-C" (ENLARGED)
OUTER FUEL ELEMENT (ENRICHED)
8-7214-A



OUTER FUEL ELEMENT (ENRICHED)
8-7214-B

Notes

1. (66) Identification numbers 2.5–3.0 in. high with individual digits 1.5–2.0 in. wide shall be engraved to a depth 0.010–0.015 in. on each fuel element in a circumferential direction in two locations in the same circumferential band but 180° apart. The top of the fuel element is to be the top of the numbers. The characters are to be formed by two 1/16 in. wide cuts spaced 0.125–0.175 in. outer edge to inner edge to produce a double image character. All digits to be uniform in appearance.

2. (65) The wall-assurance grooves shall be a minimum of 0.015 in. deep at final machining on both ID and OD.

3. Fuel plate locations are numbered counterclockwise looking at the top end and the reference fuel plate location (number 1) is the location immediately adjacent to the bevel land in a counterclockwise direction (viewed from the top) the reference coolant channel is the channel that contains the beveled land.

4. Fuel plate to side plate attachment is to be by circumferential welds on 1 in. centers if any melt-through exists it shall be limited to 0.01 in. measured across the width of the fuel plate from the top of the fuel plate slot.

5. Minimum finished side plate thickness shall be as follows:

   Outer fuel element, inner side plate – 0.108 in.
   Outer fuel element, outer side plate – 0.128 in.

6. The coolant channel thickness (separation distance between adjacent fuel plates) shall be 0.050 ± 0.010 in. measured perpendicular to the surface of the fuel plates.

7. The average coolant channel thickness at any elevation from the core midplane shall be 0.050 ± 0.006 in.

8. All fuel plates shall be oriented such that their respective ends are within ±0.015 in. of parallel planes which are 24 in. apart and normal to the fuel element longitudinal axis.

9. Each comb shall be welded to all fuel plates.

10. (69) An index mark 0.235–0.265 in. long, 0.015–0.025 in. deep and 0.030–0.050 in. wide shall be engraved on the ID of the bottom end adapter opposite the reference coolant channel on each fuel element. An arrow 0.360–0.390 in. long and with 0.030–0.050 in. wide swath shall be engraved perpendicular to the index mark to indicate the direction of channel numbering sequence. This arrow shall be pointing in a clockwise direction as viewed from the bottom end and shall be within 0.2–0.3 in. of the index mark.

11. Reference from average of high and low fuel plates.

12. Do not machine into slot ends.

OUTER FUEL ELEMENT (ENRICHED)
8-7214-C

APPENDIX B

Furnace Maintenance and Qualification

METALS & CONTROLS INC.
Attleboro, Massachusetts

PREVENTIVE MAINTENANCE AND QUALIFICATION PROGRAMS
FOR HFIR FURNACE EQUIPMENT

I. SCHEDULED MAINTENANCE PROGRAM

The following items shall be checked at least once a week by the supervision of the department responsible for the particular piece of equipment. A check list of the following items shall be posted near each piece of equipment and shall be initialed and dated by supervision after each check.

A. 8" and 14" Diameter Vacuum Furnaces

1. Check for proper oil level in mechanical pumps.
2. Check "V" belts on mechanical pumps for slack and proper operation.
3. Check mechanical pump for bearing noise.
4. Check mechanical pump for oil leaks.
5. Check motor of mechanical pump for overheating.
6. Check diffusion pump for proper water flow.
7. Check time of calibration for vacuum gages. Gages to be calibrated at least every two months.
8. Check vacuum charts.
   a. Pump down time - record average time for 8" furnace.
      record average time for 14" furnace.
   b. Leak rate - record average leak rate for 8" furnace.
      - record average leak rate for 14" furnace.
   c. Final vacuum - record averages for 8" furnace.
      - record averages for 14" furnace.
9. Check manometer gages on burner pressure against settings made at last calibration.
10. Check for proper cycling of burner control valves.
11. Check temperature gages for calibration, gages to be calibrated at least every two months.
12. Check temperature charts for range.
    Record average temperature range for 8" furnace.
    Record average temperature range for 14" furnace.

13. Check for proper operation of air blowers.

14. Check time of last furnace qualification.
    Furnace to be qualified at least every two months for 8" furnace.
    Furance to be qualified at least every two months for 14" furnace.

B. Trent Furnace

1. Check for proper fan operation.

2. Check for proper location of thermocouples.

3. Check for proper location of muffle in furnace.

4. Check "V" belts for slack and proper operation.

5. Check temperature gages for calibration.
   Gages to be calibrated at least every two months.

6. Compare temperature override and control instruments.

7. Check time of last furnace qualification.
   Furnace to be qualified at least every two months.

C. Grieves-Hendry Furnace

1. Check for proper fan operation.

2. Check "V" belts for slack and proper operation.

3. Check dampers for proper position.

4. Check for proper closing of door.

5. Check for spacing of hearth plates.

6. Check to be sure stack damper is closed.

7. Check temperature chart.
   Record average temperature range.

8. Compare temperature overide and control instruments.

9. Check temperature gages for calibration.
   Gages to be calibrated at least every two months.

10. Check time of last furnace qualification.
    Furnace to be qualified at least every two months.

D. Hevi-Duty Furnace

1. Check for proper fan operation.

2. Check for proper closing of door.

3. Check temperature chart. Record average temperature range.

4. Compare temperature on override and control instruments.

5. Check temperature gages for calibration.
   Gages to be calibrated at least every two months.

6. Check time of last furnace qualification.
   Furnace to be qualified at least every two months.

E. ORNL-Westinghouse Furnace

1. Check location and condition of roof baffle.

2. Check for proper closing of door.

3. Compare temperature on override and control instruments.

4. Check temperature gages for calibration.
   Gages to be calibrated at least every two months.

5. Check time of last furnace qualification.
   Furnace to be qualified at least every two months.

II. QUALIFICATION PROGRAM - EACH FURNACE TO BE QUALIFIED EVERY TWO MONTHS

Furnace	Temp. (°F)	Location	No. of Probes	Load	Purpose
8" Vacuum	950 max. 914 min.	Center and 3' from center in each direction.	3	Furnace trays no load	Annealing Aluminum Powder
Note: Gate valve must be open on rear cooling zone.					
14" Vacuum	1112 max. 1076 min.	Center and 4' from center in each direction.	3	Furnace trays no load	Annealing Fuel Compact
Note: No baffles.					
Trent	940 max. 914 min.	Minimum of 1' from door and 3' from door.	5	About 150 frames with 5 instr. picture frames on edge.	Fuel Plate Assembly and Fuel Plate Preheat. Anneal Frame & Cover Plts
Trent	940 max. 914 min.	Front of plate or min. of 1' from door	3	About 48 plts & 1 instr plt w/3 probes on platen in flat position	1st Anneal Fuel Plates
Grieves-Hendry	940 max. 914 min.	Min. of 14" from door.	3	3 instr frames w/about 12 frames on edge	Fuel Plate Preheat & Bond

Furnace	Temp. (°F)	Location	No. of Probes	Load	Purpose
Grieves-Hendry	940 max. 914 min.	Front of plate a min. of 14" from door	3	About 48 plts and 1 instr. plate w/3 probes on platen in flat position	1st Anneal Fuel Plates
Hevi-Duty	940 max. 914 min.	Min. of 1' from door.	5	About 150 frames w/5 instr. picture frames on edge	Anneal Frames & Cover Plts & Fuel Plate Preheat
ORNL Westinghouse	940 max. 914 min.	Minimum of 1' from door.	3	3 instr picture frames w/about 12 frames on edge	Fuel Plate Assy
Hevi-Duty	940 max. 914 min.	Min. of 1' from door.	3	About 96 plates w/1 instr. plt having 3 probes on top in flat position	Slow cool Anneal & 1st Anneal

J. Binns
10/29/65

APPENDIX C

Material Specifications

DESCRIPTION OF MATERIAL:

Alclad 6061 Aluminum Plate (frame stock)

SPECIFICATIONS:

All material shall conform to ASTM B209-61 Aluminum Alloy Sheet and Plate as amended or as herein noted. Reference PO #77X-73089-Alcon submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

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		36.38" max. - 35.62" min.
Length		96.38" max. - 95.62" min.
Camber		0.12" max. per 96"

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 I 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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Div.

   Representative samples, 8-1/2" x 11" of each lot of the finished plate and sheet shall be furnished to Union Carbide Corp. Nuclear Div.

6. Results of all tensile properties including yield strength shall be furnished to Union Carbide Corp. Nuclear Division.

7. The plate shall be clad on both sides with Type 1100 Aluminum (Reactor Grade). Thickness of the cladding shall not exceed 5.5% of the total thickness of the plate.

8. After heat treatment each plate and sheet shall be inspected to determine whether blisters are present on the surfaces of the plate and sheet. Any plate or sheet, 36" wide x 96" long, which contains a single blister 1/8" dia. or larger shall be rejected. Any plate or sheet which contains more than four (4) blisters of less than 1/8" dia. shall be rejected.

9. The first and last portion of each lot (a group of plates or sheets of one size, made from a single ingot, fabricated by a constant practice) of plates and sheets shall be qualitatively analyzed to ascertain that the type 1100 cladding is on the type 6061 aluminum.

10. The plates and sheets shall be packaged in 4000 lb. maximum fiber enclosed skids with wooden sides and battens.

11. 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.
4. DELETED

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

TABLE I

CHEMICAL COMPOSITION

The chemical composition of the type 6061 aluminum of this order shall be within the limits listed below:

Element	Concentration (wt. %) Minimum	Maximum
Silicon	0.40	0.80
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.15	0.35
Iron	None	0.40
Zinc	None	0.04
Titanium	None	0.04
Manganese	None	0.04
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:

Alclad 6061 Aluminum Sheet (cover plate stock)

SPECIFICATIONS:

* All material shall conform to ASTM B209-61 Aluminum Alloy Sheet and Plate as amended or as herein noted. Reference PO #77X-73089 - Alcoa submitted by Union Carbide Corp. Nuclear Division.

OTHER REQUIREMENTS:

1. All sheets shall be furnished in a fully annealed temper.

2. An edge produced by shearing or sawing.

3. Dimensions:

Dimensions:	Thickness:	0.154" max. - 0.142" min.
	Width:	36.12" max. - 35.88" min.
	Length:	96.12" max. - 95.88" min.
	Camber:	0.12" max. per 96"

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 I 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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

   Representative samples, 8-1/2" x 11", of each lot of the finished plate and sheet shall be furnished to Union Carbide Corp. Nuclear Division.

6. Results of all tensile properties including yield strength shall be furnished to Union Carbide Corp. Nuclear Division.

7. The sheet shall be clad on one side with type 1100 aluminum (Reactor Grade). Thickness of the cladding shall not exceed 5.5% of the total thickness of the sheet.

8. After heat treatment each plate and sheet shall be inspected to determine whether blisters are present on the surfaces of the plate and sheet. Any plate or sheet 36" wide x 96" long, which contains a single blister 1/8" dia. or larger shall be rejected. Any plate or sheet which contains more than four (4) blisters of less than 1/8" dia. shall be rejected.

9. The first and last portion of each lot (a group of plates or sheets of one size, made from a single ingot, fabricated by a constant practice) of plates and sheets shall be qualitatively analyzed to ascertain that the type 1100 cladding is on the type 6061 aluminum.

10. The plates and sheets shall be packaged in 4000 lb. maximum fiber enclosed skids with wooden sides and battens.

11. <u>IDENTIFICATION</u>

    Each tube, 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.
    4. Designation of the clad side on the single clad sheet.

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

TABLE I

CHEMICAL COMPOSITION

The chemical composition of the type 6061 aluminum of this order shall be within the limits listed below.

Element	Concentration (wt. %) Minimum	Maximum
Silicon	0.40	0.80
Copper	0.15	0.40
Magnesium	0.8	1.2
Chromium	0.15	0.35
Iron	None	0.40
Zinc	None	0.04
Titanium	None	0.04
Manganese	None	0.04
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 thru a 100 mesh screen.

* 2. 80% of powder must pass thru a 325 mesh screen.

3. Powder must conform to Table I for Chemistry.

TABLE I

Iron	-	0.4% max.
Silicon	-	0.2% max.
Al_2O_3	-	0.6% max.
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. M&C Nuclear will send to the customer a 100 gram sample of each lot.

9. Material must represent one continuous run.

* CHANGE

DESCRIPTION OF MATERIAL:

B_4C PARTICLES

SPECIFICATIONS:

All material shall conform to High Boron B_4C as supplied by The Norton Comparny 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. % B^{10}.

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 B_4C shall be screened to less than 44μ mesh size. Sieve analysis shall be performed per ASTM B-214-63T Sieve Analysis of Granular Metal Powders.

4. All B_4C shall be free of foreign material.

5. A certified isotopic analysis for B^{10} 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 50g shall be furnished the purchaser by the seller from each batch.

* (M&C Nuclear will submit one sample to the customer).

* CHANGE

7. The certified isotopic analysis for B^{10} shall be made by an M&C 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	22
Boron plus carbon	98.0	99.5
B_2O_3	--	0.2
Iron	--	0.5
Al	--	0.2
Ca	--	0.1
Mg	--	0.05
Moisture content	--	200 ppm

DESCRIPTION OF MATERIAL:

Enriched U_3O_8 Powder

PROPERTIES:

1. U_3O_8 powder will be enriched to a minimum of 93% U^{235} and enrichment shall be determined by an M&CN approved laboratory and reported for each lot with 8 copies.

* 2. U_3O_8 shall be a crystaline high-fired or dead-burned oxide having a density greater than 8.2 g/cc as determined by toluene pycnometer or equivalent M&CN approved method and a surface area of less than 0.05 m^2/g as determined by an approved krypton BET determination.

3. The total uranium concentration shall be 84.5 wt. % min.

* 4. An M&CN approved analysis shall be required for each batch of U_3O_8, and the actual results of all tests and analyses reported to M&CN (10 copies).

   Maximum UO_2 content of 1.0%.

   The impurities in the U_3O_8 shall not exceed the limits specified in Table I.

* TABLE I MAXIMUM IMPURITY LEVEL FOR U_3O_8 (PPM)

Al	30	Co	3	Mg	100
B	0.2	Cr	See Below	Mn	5
Ba	10	Cu	20	Mo	5
Be	<0.2	Fe	See Below	Ni	See Below
Ca	50	K	20	P	<100
Cd	0.5	Li	1.0	Si	50
		F	<10.0	V	2

The total of Cr, Fe, and Ni to be 150 ppm

5. No foreign material is to be present in any lot of U_3O_8.

6. A mass spectrographic analysis for U^{235} enrichment shall be performed by an M&C approved facility.

* CHANGE

No down grading of U^{235} enrichment (within 0.2% of the material will be permitted during conversion).

Size: The U_3O_8 shall be -170 +325 mesh size except that no more than 10% of -325 mesh particles as determined in a standard screening test is permissible.

ASTM-B214-56 Sieve Analyses of Granular Metal Powders is to be used to determine mesh sizes of powder.

8. Two samples representative of each lot with a minimum size of 25 gr. shall be furnished the purchaser by the seller for each lot. (M&C Nuclear will submit one sample to the customer).

PACKING AND SHIPPING:

The U_3O_8 shall be contained in a clean metal can with a full rubber gasket and the volume of the can shall not exceed one liter. The vendor is to limit the amount of U_3O_8, contained in one liter cans in a given shipping container, to maintain a safe maximum quantity in accordance with Oak Ridge Guide TID-7019 Guide to Shipments of U^{235} Enriched Uranium Material.

The shipping container must fulfill ICC requirements and be marked with a B/E permit number.

Approval of the proposed shipping container and configuration of fuel must be approved by the U.S. Atomic Energy Commission Division of License and Regulation and M&C Nuclear.

This material is to be supplied by a vendor with an approved AEC license.

Each shipping container must be marked with the purchase order number.

DESCRIPTION OF MATERIAL:

Tubing 6061 Aluminum (side plate No. 1)

SPECIFICATIONS:

All material shall conform to ASTM B210-61 Drawn Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

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 B210-61

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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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 B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

OTHER REQUIREMENTS:

1. All tubes 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 B221-63

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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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)

SPECIFICATION:

All material shall conform to ASTM B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corp. Nuclear Division dated 4-28-64.

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 B221-63

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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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)

SPECIFICATION:

All material shall conform to ASTM B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corp. Nuclear Division dated 4-28-64.

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 B221-63

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 Table I of this specification.

   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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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	0.15	0.35
Iron	None	0.40
Zinc	None	0.04
Titanium	None	0.04
Manganese	None	0.04
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 Plate (Combs)

SPECIFICATIONS:

All material shall conform to ASTM B209-61 Aluminum Alloy Sheet and plate as amended or as herein noted.

OTHER REQUIREMENTS:

1. Temper to be T-6.

2. An edge produced by shearing or sawing.

3. Dimensions:

Dimensions:	Thickness:	0.065" max.	0.060" min.
	Width:	4.06" max.	3.94" min.
	Length:	16.75" max.	16.62" min.

4. Surface finish: Surface to be 32 rms or smoother and free from pits, dents, scratches, cuts and foreign material. Allowable surface defect depth 2% of gage.

5. Ordering data: A copy of certification for each heat number to be supplied to M&C Nuclear with each shipment.

6. All pieces are to be packed in such a manner that no shipping or handling damage may be incurred including "traffic marks".

DESCRIPTION OF MATERIAL:

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

SPECIFICATIONS:

All material shall conform to ASTM B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

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 B221-63

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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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 B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-73089 Alcoa submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

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 B221-63

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 Union Carbide Corp. Nuclear Division.

   Duplicate samples of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. Nuclear Division.

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

The tubing shall be packagedin 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)

SPECIFICATION:

All material shall conform to ASTM B221-63 Extruded Tubing as amended or as herein noted. Reference PO #77X-7309 Alcoa submitted by Union Carbide Corporation Nuclear Division dated 4-28-64.

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 B221-63

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 Table I of this specification.

   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 Union Carbide Corp. Nuclear Division.

   Duplicate **samples** of melt material used in this analytical determination shall be furnished to Union Carbide Corp. Nuclear Division.

Representative sample of each lot of the finished tube shall be furnished to Union Carbide Corp. 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	0.15	0.35
Iron	None	0.40
Zinc	None	0.04
Titanium	None	0.04
Manganese	None	0.04
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)

SPECIFICATION:

All material shall conform to ASTM B 285-61T "Aluminum and Aluminum-Alloy Welding Rods and Bare Electrodes" and MIL-E-16053K, Electrode, Welding Bare, Aluminum Alloys" as amended or as herein noted.

OTHER REQUIREMENTS:

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

   This sample is to be furnished to Union Carbide Corp., Nuclear Division after receipt from material vendor by M&C Nuclear.
4. A copy of certification for each lot to be supplied to M&C Nuclear with each shipment.
5. Identification for wire per ASTM B-285-61T. Each container and spool flange must be identified per ASTM-B-285-61T. 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.

DESCRIPTION OF MATERIAL:

Filler Wire 4043 Aluminum (combs)

SPECIFICATION:

All material shall conform to ASTM B 285-61T "Aluminum and Aluminum-Alloy Welding Rods and Bare Electrodes" and MIL-E-16053K, Electrodes, Welding Bare, Aluminum Alloys" as amended or as herein noted.

OTHER REQUIREMENTS:

1. Dimension - diameter: 0.0635" max. 0.0605" min.

2. All wire to be wound on one pound spools.

3. The material vendor is to supply a 60" representative sample of each lot.

   This sample is to be furnished to Union Carbide Corp., Nuclear Division after receipt from material vendor by M&C Nuclear.

4. A copy of certification for each lot to be supplied to M&C Nuclear with each shipment.

5. Identification for wire per ASTM B-285-61T. Each container and spool flange must be identified per ASTM-B-285-61T. 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.

* CHANGE

APPENDIX D

Miscellaneous Procedures

Miscellaneous Procedures

1. Cleaning

Various components are cleaned by vapor degreasing with trichloroethylene; pickling with a solution made up of 15% by volume 70% HNO_3, 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 vapor 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 felt 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 Pinnacle[20] cylinder oil and three parts kerosene, applied with the roll wipers.

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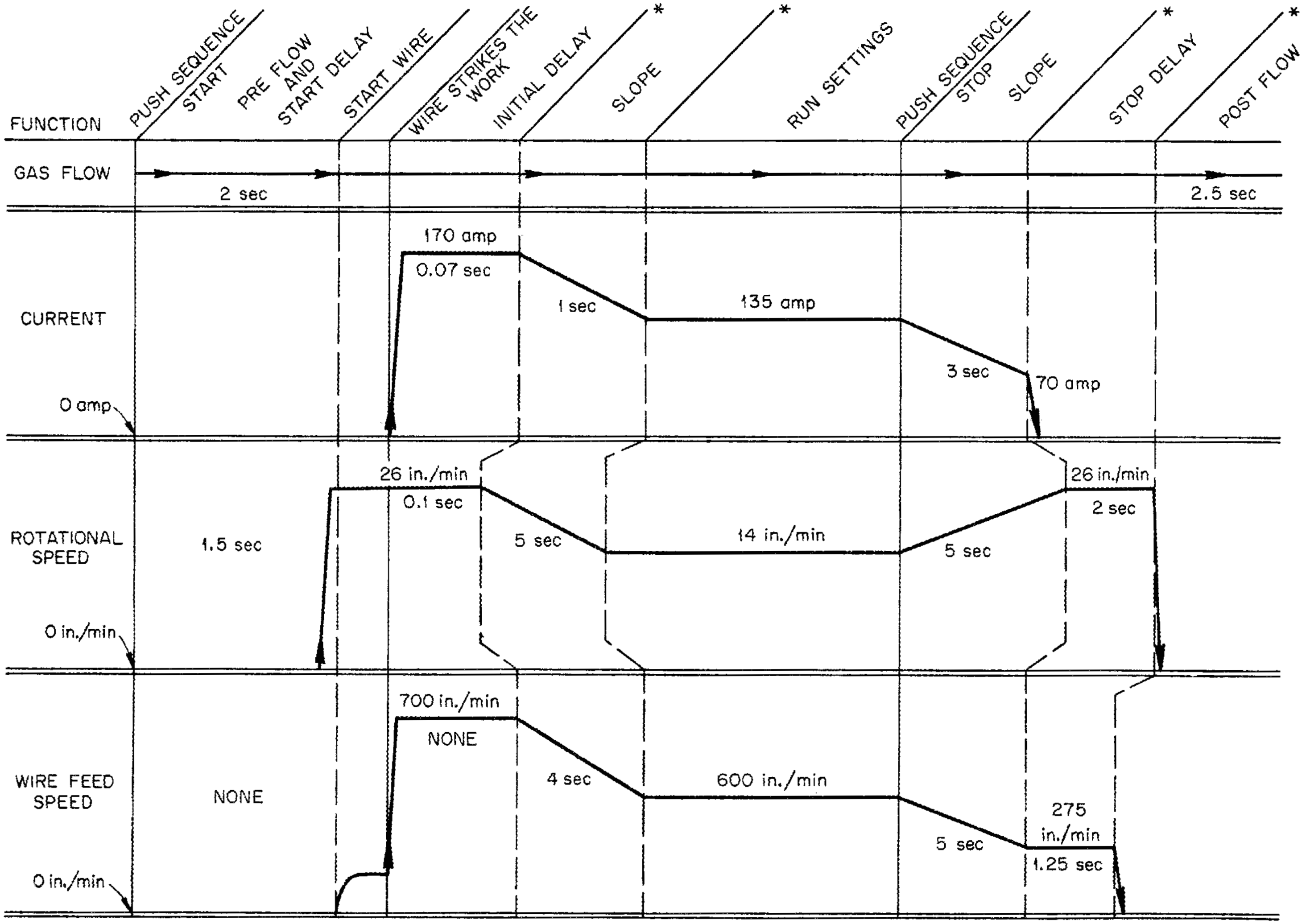
[20] A trade name of Texaco, Inc., 135 East 42 Street, New York 17.

APPENDIX E

Welding Parameters

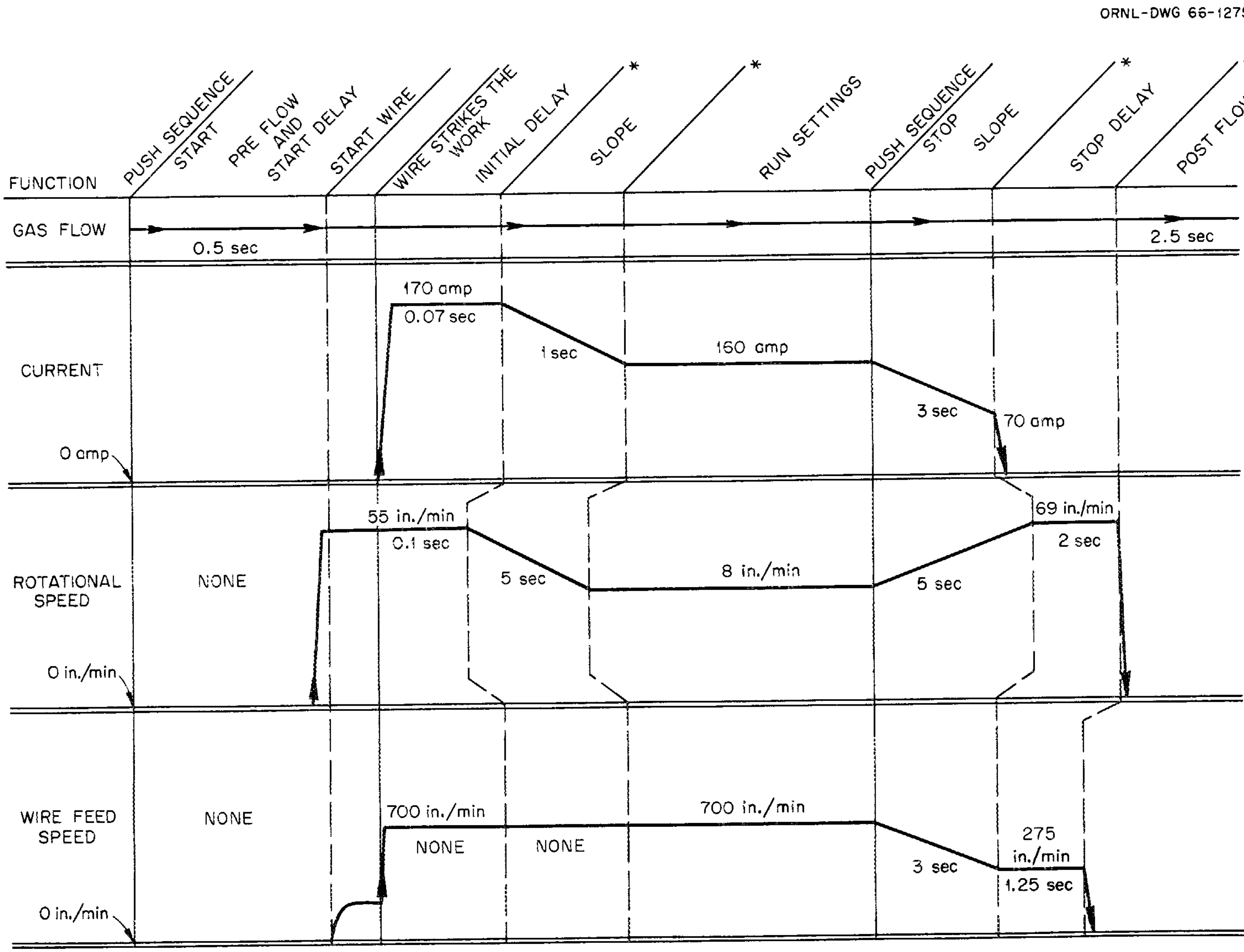
Fuel Plate Attachment Weld, Side Plate 1
Fuel Plate Attachment Weld, Side Plate 2
Fuel Plate Attachment Weld, Side Plate 3
Fuel Plate Attachment Weld, Side Plate 4
End-Adapter Attachment Weld, Side Plate 1
End-Adapter Attachment Weld, Side Plate 2
End-Adapter Attachment Weld, Side Plate 3
End-Adapter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

ORNL-DWG 66-12752



*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.

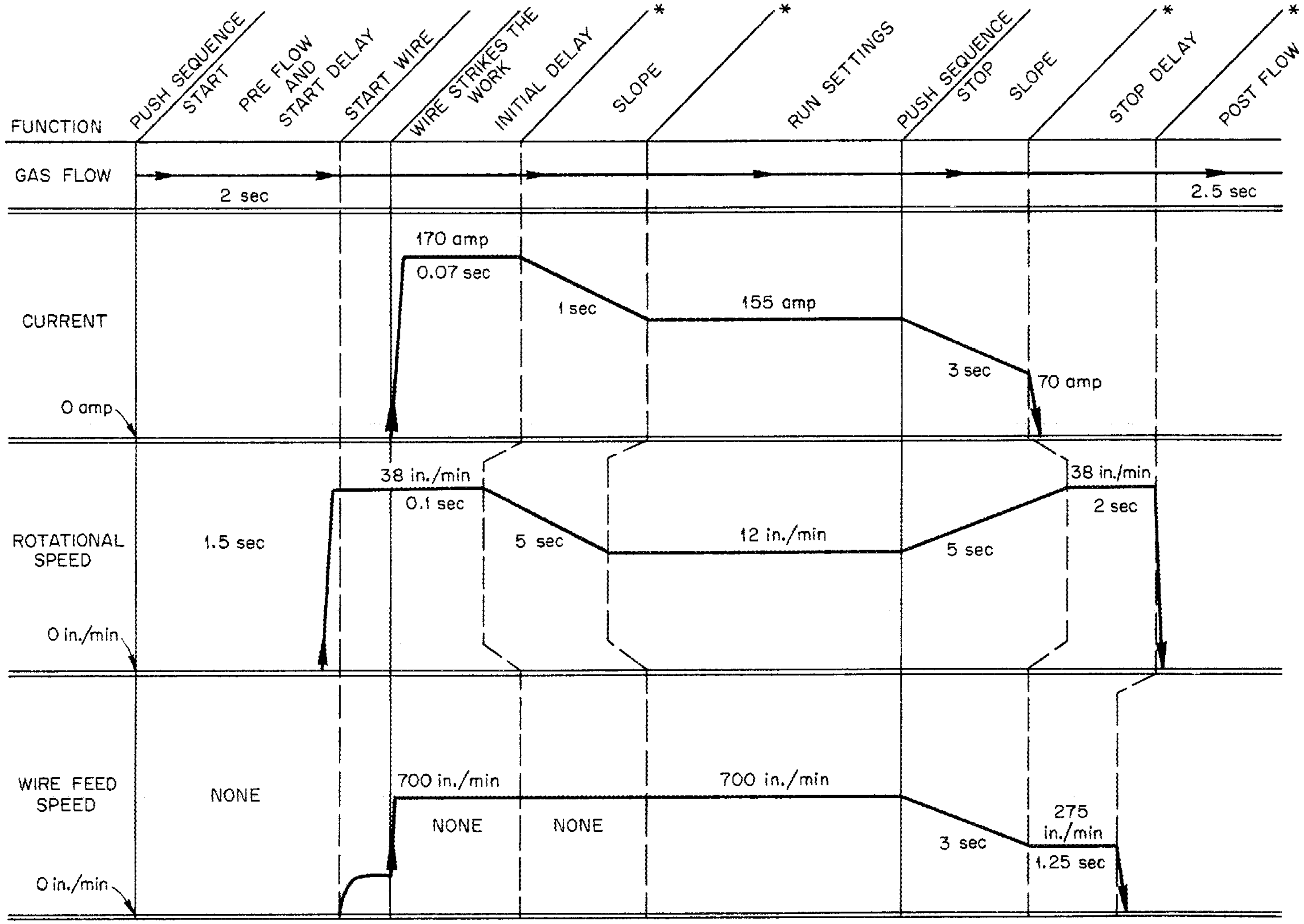
FUEL PLATE ATTACHMENT WELD, SIDE PLATE 1. APPROXIMATE RUN TIME, 1 min 9 sec.



*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.

END-ADAPTER ATTACHMENT WELD, SIDE PLATE 4. APPROXIMATE RUN TIME, 6 min 36 sec.

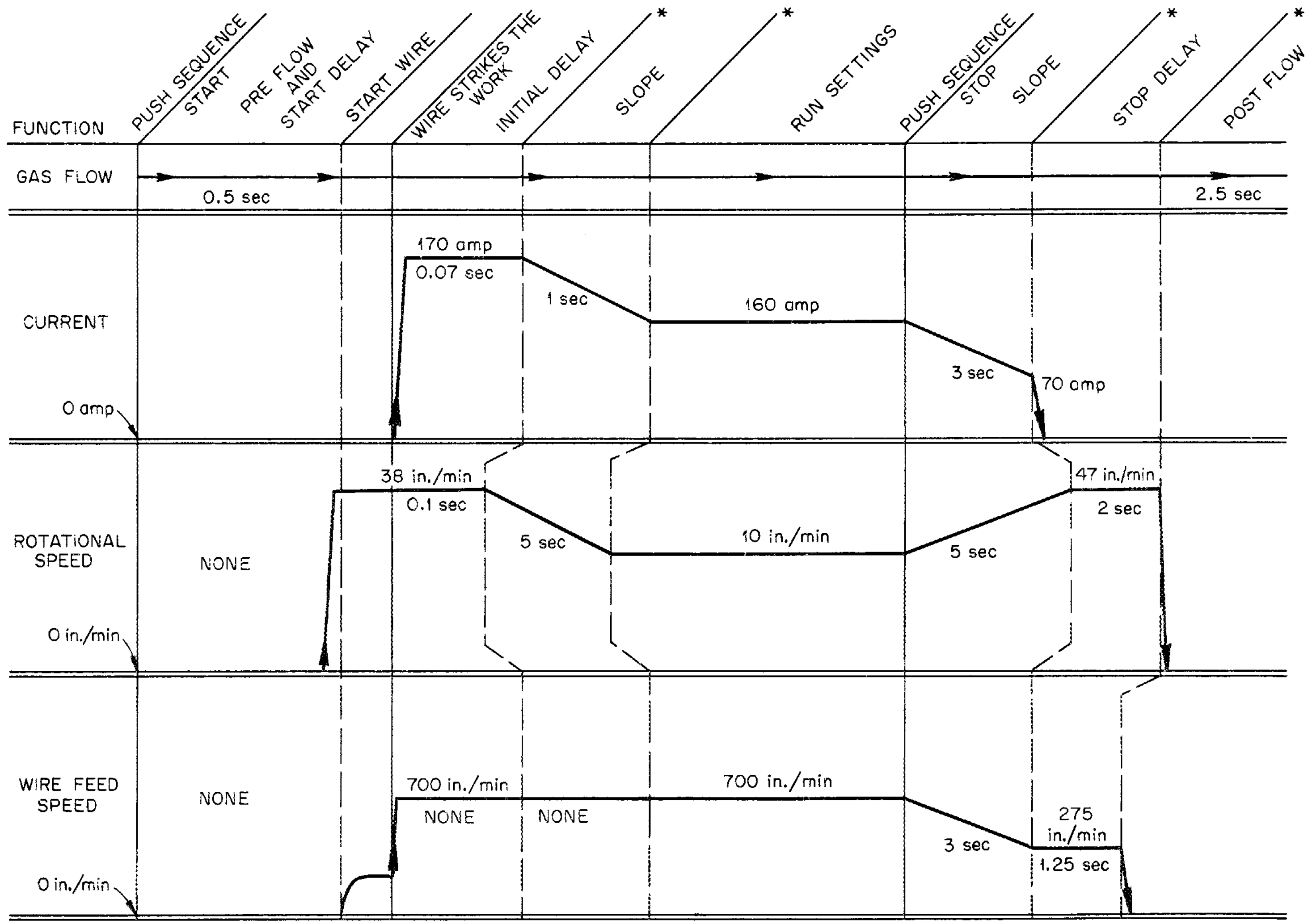
ORNL-DWG 66-12754



*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.

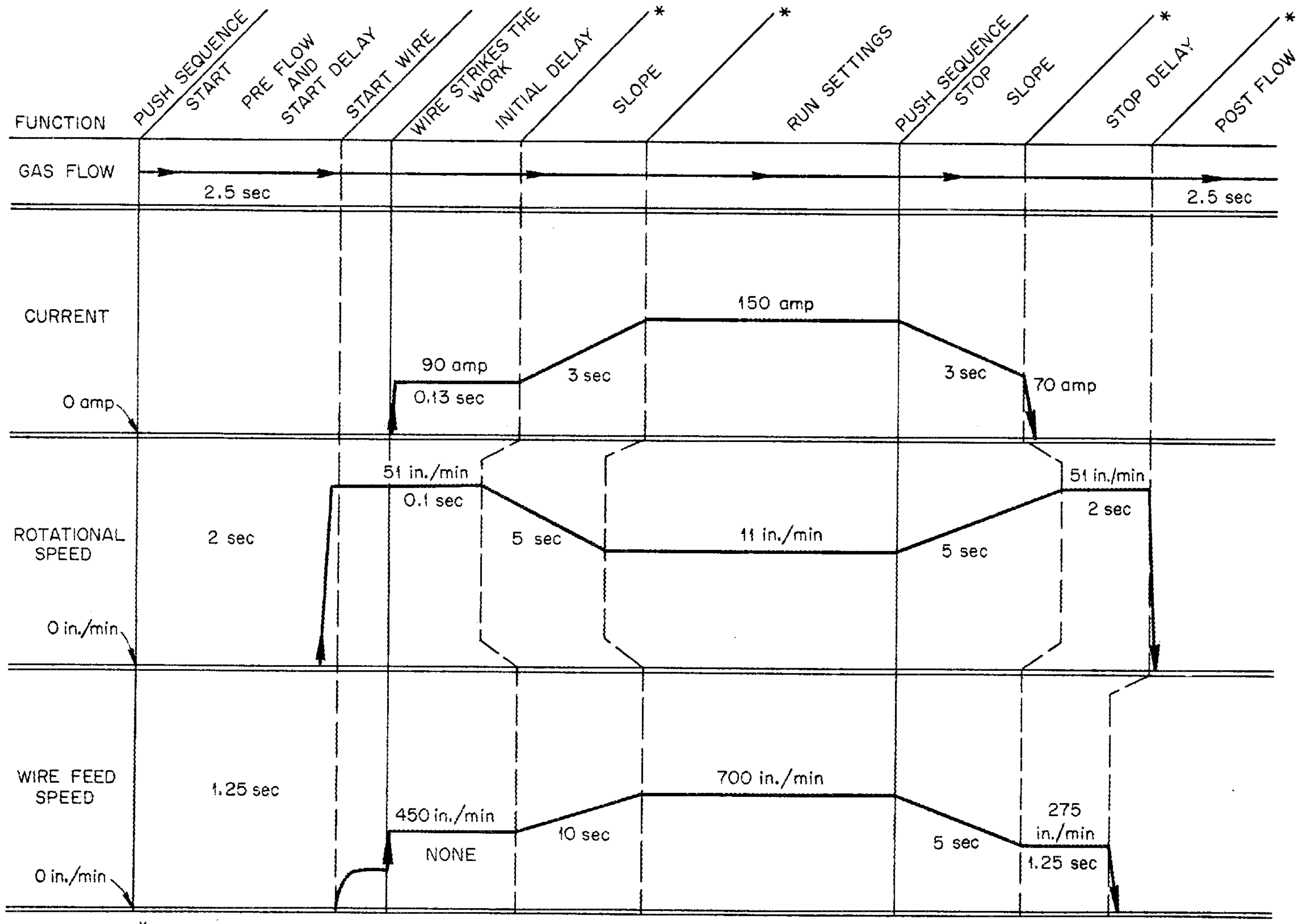
ORNL-DWG 66-12758



*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.

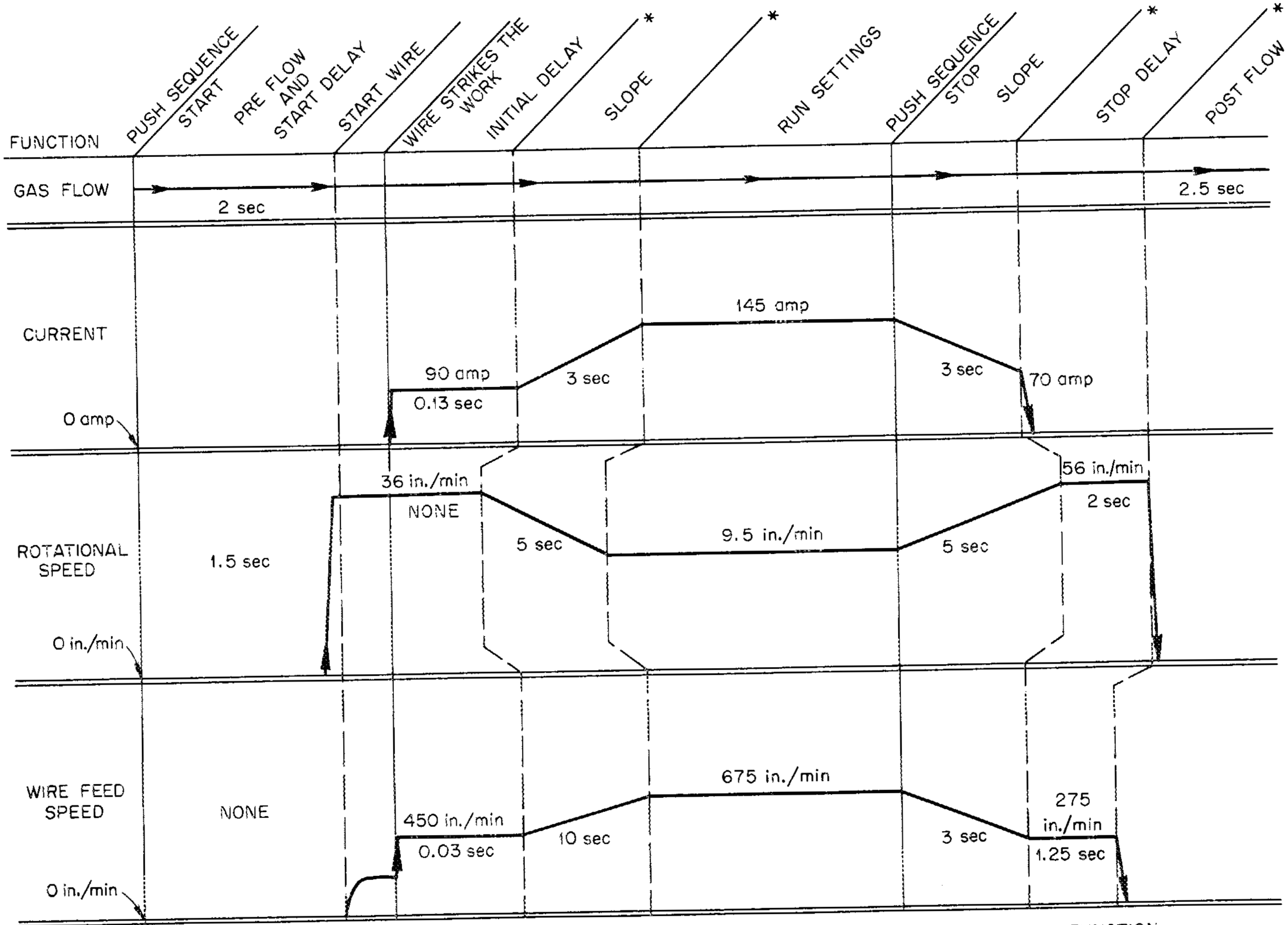
ORNL-DWG 66-12753



*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.

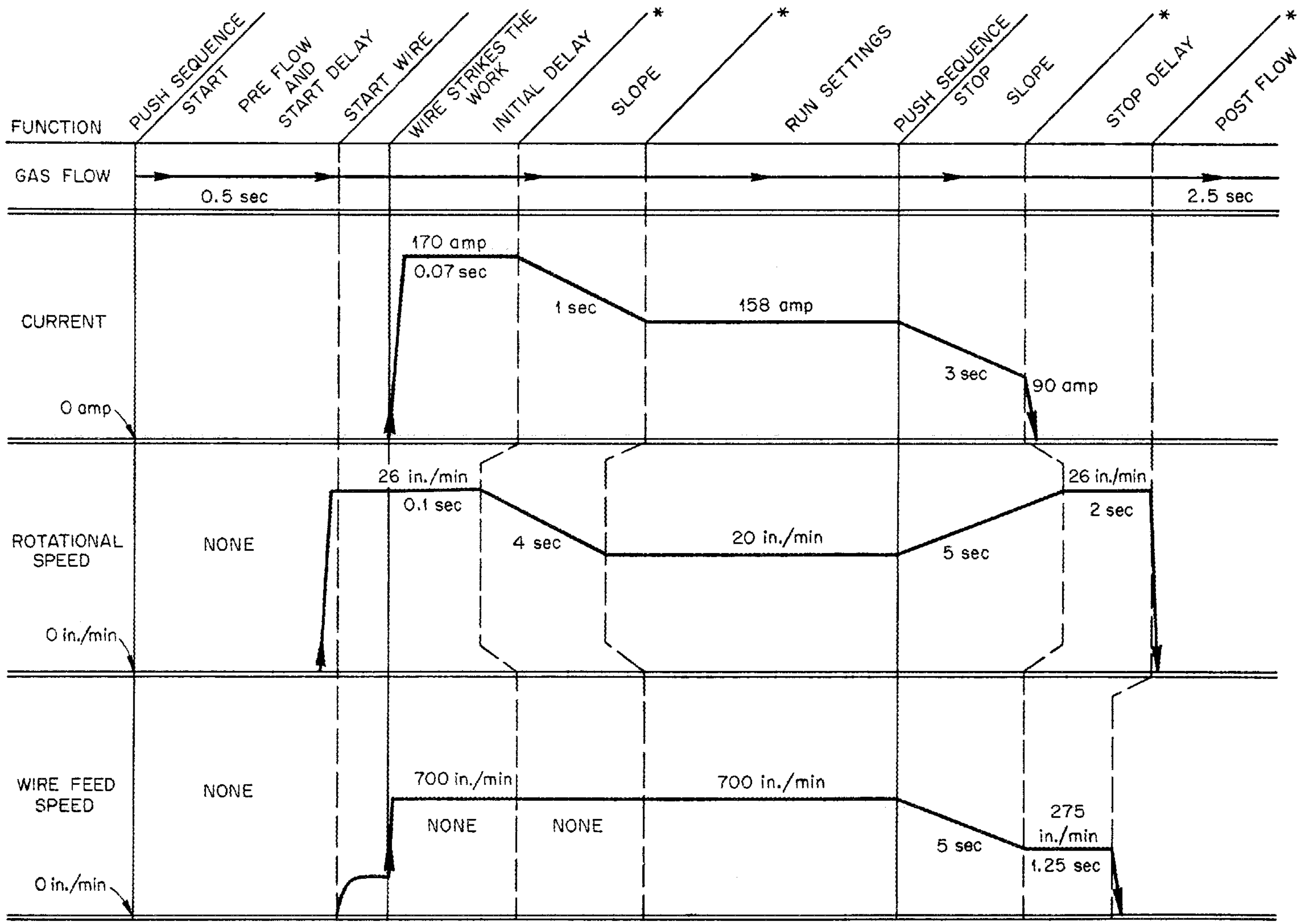
ORNL-DWG 66-12755



*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.

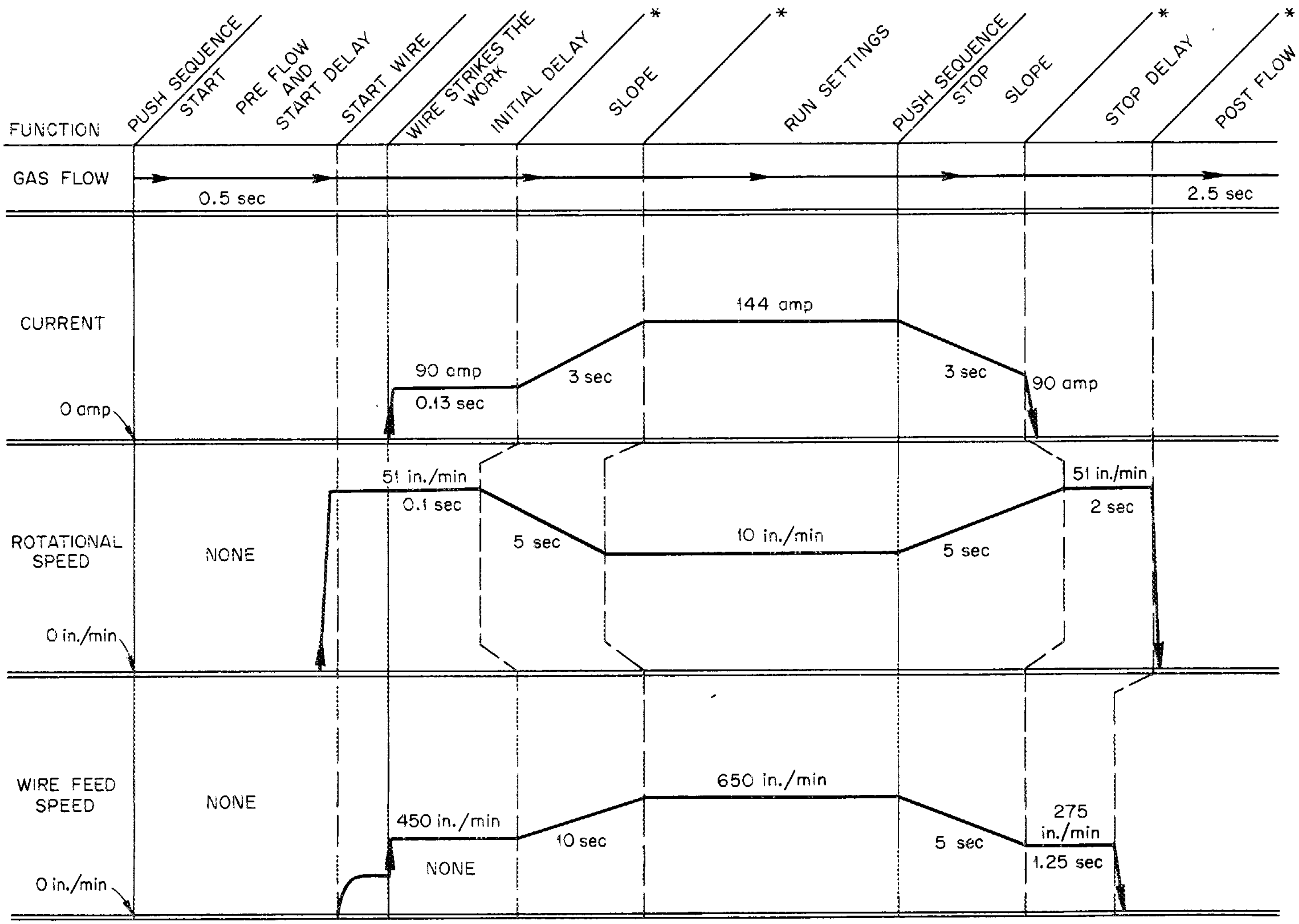
ORNL-DWG 66-12756



*NO TWO FUNCTIONS WILL REACH THESE POINTS AT THE SAME TIME. SEE TIMES FOR EACH FUNCTION.

<u>END-ADAPTER ATTACHMENT WELD, SIDE PLATE 1.</u> APPROXIMATE RUN TIME, 0 min 48 sec.

ORNL-DWG 66-12757



*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.

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