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MANUFACTURE OF FUEL PLATES FOR THE EXPERIMENTAL
BOILING WATER REACTOR

by

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ABSTRACT

The Experimental Boiling Water Reactor (EBWR), constructed on the site of the Argonne National Laboratory (ANL), is currently fueled with an uranium alloy containing 5 w/o Zr and 1.5 w/o Nb. The fuel is in the form of plates integrally clad with Zircaloy-2 by roll bonding and is divided into two isotopic concentrations, natural uranium and uranium enriched to the extent of 1.44% U^{235} . The plates are in two thicknesses, 0.210" and 0.273", with the width and length of all plates being 3-5/8" and 54", respectively. This paper describes the manufacturing practice used in the production of approximately 1100 plates, of which 888 were required to completely load the reactor.

Discussed in the paper are the production of the uranium fuel alloy, the fabrication of the cladding components from Zircaloy-2 ingot, the assembly, welding, evacuation, and sealing of the cladding billets, the jacketing of the cladding billets with steel, and the roll bonding, heat treatment, stripping, and cleaning of the fuel plates. Evaluation of the fuel plates produced is also included.

SUMMARY

During the period extending from January, 1956 to October, 1956, a total of 1120 EBWR fuel plates were produced with an average crew of 10 technicians and 4 staff members, augmented by 16,948 man-hours of machine-shop time.

The direct operating charges for the 930 fuel plates acceptable for reactor use in man-power, services, materials and supplies were as follows:

Labor (Technician)	17,740 man-hours
Supervision (Staff)	6,450 man-hours
Services (Machine Shop)	16,948 man-hours
Services (Analytical)	1,246 man-hours
Services (Testing)	2,388 man-hours

Services (Forging)	\$8,752.00
Materials (cladding, alloying elements, steel jackets)	\$334,020.00
Supplies (abrasives, acids, etc.)	\$16,733.00

The above cost figures do not include any costs in connection with the uranium. Equipment costs also are not included, but the equipment necessary for plate production will become apparent in succeeding sections of this report.

The plates were made in two isotopic concentrations, 0.7% and 1.44% U^{235} , designated normal and enriched, and in two over-all thicknesses, 0.210" and 0.273", referred to as thin and thick. Four types of fuel plates were therefore produced. The total production of plates was made up of 147 normal thin (0.7% U^{235} core alloy, 0.210" total thickness), 419 enriched thin (1.44% U^{235} , 0.210" total thickness), 134 normal thick (0.7% U^{235} , 0.273" total thickness), and 420 enriched thick (1.44% U^{235} , 0.273" total thickness). The over-all length of each plate was 54" and the width was 3.625", except for 69 thick plates which were 3.655" in width. The cladding specifications of all plates were 0.017" to 0.022" on each face, 0.110" minimum on each side, and 1-1/4" minimum on each end.

Of the 1120 plates produced, 930 were accepted for reactor use, constituting a recovery of 83.0%. The cause for rejection of the 190 unacceptable plates and the number in each category are listed below:

Type of Defect	No. Plates Rejected
Side Clad Undersize	30
Surface Inclusions or Depressions from Rolling	20
Questionable Bond on Ultrasonic Test	20
Nonbond on Ultrasonic Test	18
Seal Pin Not Bonded	18
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Side Plate to End Plug Not Bonded	9
Cover Plate to End Plug Not Bonded	8
Errors in Machining	6
Crack in Seal Pin	5
Face Cladding Damaged by Blasting	4
Failed in Corrosion Test	3
Tungsten Contamination in Assembly Weld	2
TOTAL	190

The cladding material, Zircaloy-2, was purchased in the form of conditioned, double arc-melted ingot. These ingots were nominally 12" dia, weighing approximately 1000 lb. A total weight of 13,464 lb of Zircaloy-2 ingot was used in the manufacture of the EBWR fuel plates.

A fabrication procedure was employed which produced material acceptable for use as cladding components without extensive surface machining. All the strip stock required for cladding billet cover and side plates was rolled essentially to thickness and cleaned only by wet abrasive blasting and pickling. The billet end plugs, however, were totally machined from plate.

The Zircaloy-2 fabrication procedure consisted of forging the 12" dia ingots to slabs of 3" x 9" cross section suitable for rolling on a 17" x 24" mill, scalping by machining to remove surface defects, hot rolling to an intermediate thickness except for end plug stock which was rolled 1/16" over thickness, cleaning by wet abrasive blasting, warm rolling to finish thickness plus 4 mils for cleaning, and finally cleaning by wet abrasive blasting.

The cladding billet side and cover plates were sheared slightly oversize and machined to width and length only. Final preparation of cladding components for billet assembly consisted of pickling in HNO_3 -HF bath followed by rinsing and drying.

Of the 13,464 lb of Zircaloy-2 ingot used in the production of EBWR fuel plates, 6,231 lb were converted to finished cladding components. The recovery from ingot to finished components amounted to 46.3%. The losses may be separated into two categories, heavy scrap* and machine turnings. Approximately 52% of the scrap generated fell into the heavy scrap classification. This type of scrap, if properly cleaned of contamination, could be remelted as a fraction of the sponge electrode used in a consumable electrode arc-melting furnace. The remaining 48% of the scrap was made up of turnings and saw chips. These turnings and saw chips were not only of little value, but also a burden and potential hazard to store.

These high scrap losses could have been reduced had appropriate equipment been available at ANL. An edge roller could have been employed to roll to much closer width tolerances, which would have reduced the 11% scrap produced in shearing components to a low value. Rolling the end plug stock in bar form instead of plate stock would have materially reduced sawing and machining losses. The 25% of the end plug stock converted to millings in the machining of the 90° included angle groove could have been reduced by rolling or forging the groove. Improvement in the physical quality of the ingot stock would also reduce scrap losses.

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*Heavy scrap is defined as croppings from the forgings and sheared trimmings from the rolled strip.

The core alloy was produced by the solution of the alloying elements, 5 w/o zirconium and 1.5 w/o niobium, in molten uranium. Melting and alloying was done in graphite crucibles protected from attack by a duplex ceramic coating. The rough dimensions of the billet core were achieved by casting in coated graphite molds which produced either ten or twelve billet cores per heat. Approximately $1/32$ " per face was allowed for grinding to width and thickness. Appropriate end geometry was pre-cast and milled on one end and generated by a combination of shaping and milling on the other. Cores were cleaned in preparation for assembly by wet abrasive blasting, using an especially designed blasting gun. Blast washing, alcohol rinse, and vacuum drying and storage completed the cleaning procedure.

The production of core alloy consumed 13,290 kg of uranium biscuit, both natural and enriched, 698 kg of zirconium sponge, and 209 kg of niobium pressed powder. These materials were converted into 1137 finished billet cores weighing 9,649 kg, for a recovery of 68%, 1,477 kg of melting skull, 2,752 kg machine turnings and grindings, and 319 kg of heavy scrap consisting of spectrographic samples and crop ends.

The average chemical composition of the billet core castings used for fuel plates was 4.87 w/o Zr, 1.55 w/o Nb, with the zirconium range 5.60 w/o to 3.71 w/o and the niobium 1.91 w/o to 1.23 w/o. The carbon and nitrogen were generally low in the alloy, averaging 22 ppm and 14 ppm, respectively. Acceptance of the core castings for production was based on chemical composition, soundness evaluated by a through transmission ultrasonic test, and visual examination. All castings judged unacceptable by above standards were recycled. No limit was placed on the number of times recycled.

The fuel plate was produced from a cladding billet which was made up of an uranium alloy core and the Zircaloy-2 cladding. The cladding was comprised of seven individual components, two each of cover plates, side plates, and end plugs, and the seventh a seal pin for closing a purge opening in one end plug. The components were assembled around the core in positions from which they derived their nomenclature; then the seams formed by these mating components were sealed by inert gas-shielded, tungsten-arc welding, employing a practice which minimized contamination to the bonding surfaces of the assembly. Subsequent to welding of the seams, billets were evacuated and the purge openings, which were used in part to accomplish the above objective, were sealed by a special vacuum-arc welding process.

The cladding billets were so designed and processing so established as to take advantage of the desirable and to minimize the undesirable properties of the components which made up the cladding billet. The alloying additions to the uranium fuel were retained, even after heat treatments

to develop both irradiation dimensional stability and corrosion resistance could not be found, because of their enhancement of the desirable rolling characteristics of the core. Consideration was given to the geometry of the ends of the billet core and mating geometry of the end plug so as to make possible rolled end closures, superior to other types of closures both in quality and ease of production. Even though the match in rolling characteristics between clad and core was greatly enhanced by the addition of alloying elements to the core, a transition zone in the form of a 90° included angle taper on the ends of the core and a matching "V" in the end plugs were required to compensate for minor difference in rolling characteristics of core and clad.

Recognizing the positive differential expansion of the uranium core alloy with respect to the Zircaloy-2 cladding, allowance was made for this expansion in design of the billet so that the prerolling welds which sealed the cladding around the core would not be ruptured as a result of the pressure exerted by the uranium alloy during heating for rolling. A gap of 0.020"/inch of core (found empirically) was provided between the core and internal surfaces of the cladding components.

The orientation of the end plugs within the rolled plate stock from which they were made was chosen to take advantage of the anisotropy of rolling characteristics resulting from texture in this plate. The direction of maximum spread was positioned within the end plugs so that maximum spread was developed in the end plug during roll bonding. This was found necessary to develop the pressure required for bonding between the end plug and side plate, the interface of which was positioned parallel to applied rolling pressure.

The billet assembly practice was so designed as to produce internal surfaces with the minimum amount of contamination and to provide protection of these surfaces from contamination, during heating, resulting from gas both entrapped within and evolved from the steel jacket. The cladding components were sealed around the billet core by shielded arc welding after an autodry box was made by pressing cladding components together hydraulically and entrained air was displaced by argon purging introduced through an opening in one end plug. Weld zones were restricted through the use of water-cooled chills.

Subsequent to the weld sealing of the seams in the cladding components, the argon gas used in purging was removed to prevent blister formation in the rolled fuel plates; inertness within the billets was established by evacuation and maintained by sealing the purge opening under vacuum.

The cladding billet was encased in a channel-type steel jacket closed by end plugs and sealed by welding. The product of this combination was designated a rolling billet. No attempt was made to evacuate the steel jacket. The function of the steel jacket was twofold. First, it

provided protection from atmospheric contamination so vitally necessary in the latter stages of rolling when the face cladding became thin. Second, it provided restraint of lateral deformation, spread, and aided in maintaining the relative positions of the cladding billet components during rolling. This steel jacket was the only means available for control of spread because of the lack of edge rolling equipment.

The rolling billets were converted to plates by a flat-rolling operation. Bonding of all components by diffusion and the development of dimensions suitable for machining to width and length only were accomplished by a reduction of 80% (5:1) in thickness at a temperature nominally 850°C (1560°F). Precision in the finished product was enhanced by having a stable rolling mill available and providing the necessary heating furnace and appropriate mechanical handling equipment to eliminate the sometimes erratic human element.

The final thicknesses of the fuel plates were developed by rolling, wet abrasive blasting, and pickling. No machining was employed to produce the desired thickness dimensions nor to generate an elevated temperature water corrosion resistant surface.

The average thicknesses of the fuel plates produced after rolling and cleaning were 0.210" and 0.278" for thin and thick plates, respectively. The average variation in the thickness of all plates was 0.0018". The maximum allowable camber in the as-rolled fuel plates was set at 1/32" over the full length. Of the plates produced, 90% had camber of the above value or less. The average camber of the acceptable plates was 0.0092". Plates having camber greater than 1/32" were salvaged by straightening warm on the 17" mill by reducing the thickness of the concave side.

The fuel plates were heat treated for dimensional stability only, since the heat treatment for corrosion resistance was found to develop a highly unstable structure which grew at a great rate when subject to irradiation; further, low values of burnup cause loss of most of the enhancement of corrosion resistance. The dimensionally stable structure was produced by transforming the gamma phase to a two-phase structure at a temperature high in the low-temperature, two-phase region. The cooling rate from the gamma phase apparently had little effect upon the stability of the transformed product. A long holding time was required, however, to effect complete transformation.

Heat treatment of the plates was done while encased in the steel jacket, since cooling rate was not a dominant variable in the formation of the desired structure. The steel jacket protected the fuel plates from both contamination and mechanical damage during the heat treatment. Heating into the gamma phase at 825°C was done in a box furnace in air. The isothermal quenching and extended holding period was performed in a tank-type furnace containing lead at 640°C. Cooling after the holding period was done by air.

The steel jackets were mechanically stripped from the fuel plate following heat treatment, and the plates were given a low temperature stress relief. The length and width of the plates were developed by machining after the uranium alloy core ends were located by X-ray radiography.

Corrosion resistance of the surfaces of the fuel plates was generated by wet abrasive blasting to promote uniform attack by the HNO_3 -HF pickle which followed.

Acceptance of the fuel plates for corrosion testing was based on the quality of Zircaloy cladding, integrity of all bonds, core to clad and clad to clad, and depth of cladding on faces, sides, and ends. The quality of the Zircaloy-2 was assessed by visual examination. The integrity of the bond between core and clad was evaluated by a through-transmission ultrasonic test and between clad and clad by both the ultrasonic test and microscopic examination. The side and end clad depths were measured from the film record made by X-ray radiography of the fuel plate; the face clad was evaluated by measurement of the soft beta radiation transmitted through the clad using a scintillation counter.

Final acceptance of the fuel plate was made after examination following corrosion testing in 550°F water for a minimum of two weeks.

After acceptance of the fuel plates, they were incorporated into a reactor fuel element, the preparation of which is the subject of another report. The fuel element consisted of six fuel plates welded in parallel between two perforated Zircaloy-2 side plates which extended lengthwise beyond the fuel plates for attachment of a nose fitting on the bottom end and element spacer fitting on the top. The spacing between fuel plates was nominally $3/8$ ".

Attachment of the fuel plates to the assembly side plates was done by tungsten-arc spot welding in an atmosphere of helium-argon contained in a leak-tight chamber. The bond was produced by fusion of metal through the assembly side plate into the side cladding of the fuel plate. Welds were spaced approximately 3" apart along the length of the plates, except for three welds in the end cladding which were spaced on $1/2$ " centers.

A final corrosion testing of the completed assembly at 550°F for a period of one week and an inspection readied the fuel element for attachment of the bottom and top fitting of stainless steel. These were attached by means of stainless steel rivets.

INTRODUCTION

The Experimental Boiling Water Reactor, constructed on the site of the Argonne National Laboratory, is a slightly enriched uranium, light water reactor designed to produce electrical power employing direct cycle steam produced by boiling in the core.⁽¹⁾ The plant has been calculated to produce 20 megawatts of heat. Its design can be extrapolated to sizes which become attractive for central station power plants.

The core of the reactor, essentially a slightly enriched uranium lattice, cooled and moderated by light water, is contained in a stainless steel clad pressure vessel, 7 ft I.D. x 30 ft.-11-1/2 in. high. The principal components which make up the EBWR plant are shown schematically in Fig. 1; the reactor and components are shown in perspective in Fig. 2. The loading unit of the fuel is an assembly containing six parallel plates welded between two perforated Zircaloy-2 side plates, as pictured in Fig. 3. The operating core was calculated as 4 ft dia. x 4 ft high, with the structure designed to accommodate a 5-ft maximum diameter core. The pressure vessel was constructed for 800 psi, 200 psi over the nominal operating pressure.

The reactor data pertaining to the fuel are tabulated below:

General

Heat Output	20,000 kw
Gross Electrical Output	5,000 kw
Operating Pressure	600 psig
Operating Temperature	480°F

Nuclear Data

Average Thermal Flux in Fuel	1.6×10^{13} n/cm ² sec

Heat Transfer of Fluid Flow

Core Avg. Heat Flux	45,500 Btu/(hr)(sq ft)
Max. Heat Flux in Thick Enriched Fuel Plate near Control Rod	155,000 Btu/(hr)(sq ft)
Estimated Burnout Heat Flux	750,000 Btu/(hr)(sq ft)
Avg. Surface Temperature of Fuel	497°F
Avg. Fuel Centerline Temperature Enriched Thick Plate	540°F
Avg. Fuel Centerline Temperature Enriched Thin Plate	529°F
Avg. Fuel Centerline Temperature Natural Thick Plate	526°F
Avg. Fuel Centerline Temperature Natural Thin Plate	513°F
Max. Fuel Centerline Temperature Enriched Thick Plate	660°F

The core was designed in such a way that a maximum of 148 fuel assemblies (888 plates) could be loaded into the reactor, making its diameter 60". An operational loading of the core was calculated to be

FIGURE 1. Principal Components of EBWR Power Plant.

FIGURE 2. Cutaway Perspective of EBWR and Components

FIGURE 3. EBMR Fuel Assembly and Fuel Assembly Components.
Fuel Plates are 3-5/8" wide x 54" long.

700-62

111-2930

112 assemblies arranged in a 50" diameter core. The fuel plates were made in two isotopic concentrations, 0.7% U^{235} (natural) and 1.44% U^{235} (slightly enriched), and in two over-all thicknesses, 0.210" and 0.273", with corresponding core thicknesses of 0.170" and 0.233". The width and length of all plates were nominally 3-5/8" and 54", respectively. A breakdown of the number of plates required in each type is given in Table I. The design of the plates in both thicknesses is presented in Fig. 4. The core was placed symmetrically within the Zircaloy-2 clad, leaving nominal cladding thicknesses of 0.020" on each face, 0.155" on each side, and 1-1/2" on each end.

Table I

THE NUMBER OF FUEL PLATES
REQUIRED FOR COMPLETE
LOADING OF THE EBWR

Plate Thickness	Number Required	
	Natural	Enriched
0.273"	108	336
0.210"	108	336

An alloy of uranium containing 5 w/o Zr and 1.5 w/o Nb has been selected as the fuel. This alloy was originally developed by Draley, Greenberg, and Ruther⁽²⁾ for the improvement of the corrosion resistance of uranium to water. These additions in small amounts did increase the water corrosion resistance many fold when the proper structure was developed by a suitable heat treatment. The corrosion rate of this alloy in the supersaturated alpha condition, developed by water quenching from the gamma phase, has been reported to be 14.2 mg/cm²/day at 290°C in the absence of irradiation. Irradiation, however, in amounts as little as 0.074 total a/o burnup destroyed most of the enhancement of corrosion resistance imparted by alloying additions and heat treatment.⁽³⁾

In addition to the loss of corrosion resistance under irradiation, the dimensional stability of the alloy in the supersaturated alpha condition was very poor. Kittel and Paine⁽⁴⁾ have measured growth and calculated rates as high as 470 microinches/inch/ppm burnup in wrought and gamma-quenched material. Heat treatments are available, however, which do greatly improve stability of this wrought alloy. Kittel⁽⁴⁾ reports growth rates reduced 87-fold (470 microinches/inch/ppm to 5.4 microinches/inch/ppm) by an isothermal quench from the gamma structure. This heat treatment, like irradiation, destroys most of the corrosion resistance of the alloy. Duplex heat treatments superimposing the optimum for corrosion resistance on the optimum for stability failed to produce an irradiation-stable and corrosion-resistant structure.

FIGURE 4. EBWR Fuel Plate Design and Dimensions.

DIMENSION	THIN FUEL PLATE	THICK FUEL PLATE
C CENTER THICKNESS	$0.210 \pm .000$	$0.273 \pm .006$
D CORE END TAPER	$2 \frac{1}{8}$ MAX.	3 MAX.

NOTE:

PLATE SYMMETRICAL ACROSS ALL AXIS
E.H.S.

The 5 w/o Zr-1.5 w/o Nb alloy, designated the reference alloy, was retained as the fuel for the EBWR, however, because of the close match in its rolling characteristics to those of the Zircaloy-2 cladding components. When compared with unalloyed uranium, this alloy greatly improves the uniformity of cladding, makes rolled end closures possible, and eliminates the extrusion of the core into the bonding interfaces of the cladding components. It has been found that the thickness variation in zirconium cladding on unalloyed uranium was $\pm 30\%$ ⁽⁵⁾ and cladding variations resulting from cladding uranium with a zirconium alloy such as Zircaloy-2 were suspected to be even wider. Variations in face-cladding thickness were greatly reduced by the addition of these small amounts of zirconium and niobium to uranium, which develop this closer match in rolling characteristics to those of Zircaloy-2. Variations in face-cladding thickness of the reference alloy plate clad with Zircaloy-2 were $\pm 10\%$.⁽⁶⁾

The ease with which rolled end closures could be produced was vastly improved by the alloy additions to the uranium core. Unalloyed uranium at the rolling temperature deformed so readily that it built up metalstatic pressure within the cladding to the extent that the core extruded a great distance between the cladding components (end plug to cover plate and side plate to cover plate interfaces) before bonding of the cladding components could be effected. In severe cases this extrusion of uranium extended to the outer surfaces of the cladding. The alloying additions improve the rolling characteristics of the core so as to eliminate this extrusion effect; also, the buildup in thickness of the core at its ends experienced during roll cladding unalloyed uranium was reduced with the alloy.

Zircaloy-2 was selected as the cladding material for the EBWR because of its low thermal neutron cross section, high corrosion resistance to water, and absence of intermetallic compounds in the zirconium-uranium system. The need for a low cross-section cladding material in a reactor competing with coal in the generation of power was obvious. Corrosion resistance of the cladding was of utmost importance, since the survival of the fuel plate was absolutely dependent upon the ability of the cladding to exclude water from the uranium core. Access of water to the uranium core alloy, heat treated for dimensional stability, caused complete conversion of the metal to oxide in less than two weeks, even in the absence of irradiation.

This vital corrosion resistance of cladding material was available in very high purity zirconium crystal bar; but its relatively high cost, its erratic behavior in high temperature water, and its low hardness level made crystal bar unattractive for this application. Zircaloy-2, on the other hand, costs considerably less in ingot form than crystal bar, its behavior in high-temperature water was unchanged from ingot to ingot, and the hardness level was raised over that of pure zirconium to where the roll-cladding operation was made easier. Ingot from zirconium sponge

was unacceptable because of its high and erratic corrosion rate. The absence of high-melting point intermetallic compounds in the uranium-zirconium system makes zirconium very attractive as a cladding for uranium. The presence of compounds such as exist in the uranium-aluminum system makes the mechanics of developing and maintaining a metallurgical bond extremely difficult by comparison.

The design of the cladding and rolling billet and the method of processing of the fuel plates were influenced by many factors. The prime objective in the manufacture of these fuel plates was to produce elements so far above the reactor service requirements as to make inspection and testing redundant; however, this objective was not possible because of economic limitations, present status of technology, quality of materials, and equipment limitations. For instance, in the design of cladding components for the EBWR fuel plates, a deviation from the conventional true picture-frame technique found so popular by many^(7,8) was required because of the end configuration of the core necessary for the production of the rolled end closure. The true picture frame would have eliminated the necessity of effecting Zircaloy to Zircaloy bonds across vertical interfaces. In billets of the EBWR thickness, the loss through generation of turnings in the machining of the cavity would be very high, over 50%. It is evident, therefore, that established cladding billet designs were either impossible to use or were excessive in cost. The true picture frame could not be used because a billet with tapered ends could not be inserted into this type of frame. The two-piece cladding technique, in which the core cavity was machined in plate stock, was unattractive because of the high loss in the machining of the cavities.

The practice used in the manufacture of most reactor fuel elements, where protection of the cladding billet components from atmospheric contamination was required, has featured the use of an evacuated and sealed steel jacket.^(9,10) It was speculated here, however, that even though a steel jacket be evacuated, which in itself is time consuming, contamination of the cladding billet bonding surfaces would result from evolution of gases and vapors during heating for rolling.⁽⁵⁾ The contamination resulting from the outgassing of a plain carbon steel (SAE 1020) jacket, even though previously evacuated to a pressure of 0.5 micron, has been found to be extremely severe.⁽⁶⁾ The pressure within the billet after evacuation to 0.5 micron and sealing was found to rise to a maximum of 8.2 mm at a temperature of 720°C then decrease on further temperature rise to 850°C. After prolonged heating at 850°C the pressure reduced to 95 microns. It was obvious from the quantity of contamination on the surface of the cladding components that the pressure reduction was brought about by the combination of the gases and billet components.

The amount of contamination originating from the jacket material could be materially reduced by outgassing plain carbon steel in vacuum at temperatures higher than the intended rolling temperature prior to use or

through the use of a titanium-killed steel (Ti-Namel) first employed by WAPD. Measurements of the internal pressure rise during the heating of billets jacketed with these two steels indicated the superiority of the Ti-Namel steel. Visible amounts of contamination, however, did result on billet components from both the Ti-Namel and the heated and outgassed SAE 1020 steel evacuated jackets.

Even less contamination, evaluated visually, resulted when heating cladding billets prepared by a procedure used at ANL.^(5,6) In this method, the cladding components were sealed around the core by welding, after purging the air from the autodry box billet with argon gas introduced through an opening in one end plug. The clad billet was evacuated and the purge opening welded under vacuum. Providing the billet was leak tight, all visible contamination of the bonding surfaces was eliminated. Any outgassing of the billet components was of no consequence, and contaminants entrapped within or evolved from the steel jacket could not enter the cladding billet and contaminate the bonding surfaces. In this way, clean surfaces essential for rapid establishment of diffusion were developed early in the rolling process. By establishing the bond early in the rolling, other factors affecting the quality of the plate, such as developing leakages in the prerolling welds and steel jacket and the shifting of the cladding billet components, were minimized.

The design of the cladding billet was arrived at after consideration of many factors, namely, the magnitude of reduction necessary to establish satisfactory bonds, limitations of equipment, cross section of core attractive for casting, ease and economy in fabricating cladding component stock, and economy in machining cores and jackets. The primary factor was the reduction required for bonding. The cladding billet thickness was limited on the minimum side by the reduction necessary to produce bonding and on the maximum side by the capacity of the mill available for the roll-bonding operation. Between these two limits, the other factors listed influenced the final design. The problems involved in the casting of the core exerted the maximum influence on these intermediate factors. The greater the separation of the width and thickness dimensions, the more difficult was it to obtain a sound casting; furthermore, the longer the time for a casting, the more difficult was it to cast sound metal. For these reasons a core size suitable for a 5:1 reduction in rolling was selected. Fortunately, fabrication, cleaning, and machining cost of the cladding components and machining cost of the core, both in time and metal loss, decrease with increasing billet thickness, because of the increase in volume to surface ratio of the billet components. In addition, the thickness variation in the face cladding of finished rolled plate decreased with increasing reduction.

Starting with the raw materials for the core alloy (the Zircaloy-2 ingot forged to a slab suitable for rolling of cladding components, and the steel for jacketing the cladding billet), the complete manufacture of the

EBWR fuel plates was performed on equipment and by personnel of the Argonne National Laboratory. The raw materials for the core alloy were uranium biscuit (both natural and enriched to 1.44% U^{235}), zirconium sponge, and niobium pressed powder. Material for the cladding components was purchased from commercial producers in the form of machined conditioned, consumable electrode, double arc-melted ingot. These ingots were forged to slab suitable for rolling at a commercial forge shop in Chicago. The steel for the billet jackets was bought as SAE 1020 plate and bar. Part of the jackets were machined elsewhere.

The operations performed in the processing of the uranium alloy fuel and the Zircaloy-2 cladding components, the preparation of the rolling billets, roll bonding and heat treatment of fuel plates, and final machining, cleaning and inspection of fuel plates are shown by means of a flow sheet in Fig. 5. Detailed descriptions of these manufacturing operations are contained in subsequent sections of this report.

FIGURE 5. Operations Comprising EBWR Fuel Plate Manufacture.

URANIUM ALLOY CORE PROCESSING

The uranium alloy used in the fuel was produced by dissolving the alloying elements, zirconium and niobium, in molten uranium. The rough dimensions of the cladding billet cores were generated by casting into multiple cavity molds. Final dimensions of the billet cores were developed by grinding and machining. Cladding billet cores were made in two isotopic concentrations as mentioned previously, natural with 0.7% U^{235} and enriched with 1.44% U^{235} , and in two sizes for the fabrication of plates in the two thicknesses required for flexibility in reactor loading. The finish machined cores for the thin billets were 0.833" x 3.115" x 10.440" and for the thick billets 1.181" x 3.133" x 10.300". The cores had a 90° included angle taper on each end as shown in Figure 6.

FIGURE 6.
Design and Dimensions
of Cladding Billet Cores

DIMENSION	THIN BILLET Core (in.)	THICK BILLET Core (in.)
T	0.833 $\pm$ 0.002	1.181 $\pm$ 0.002
W	3.115 $\pm$ _{-0.003} ^{+0.000}	3.133 $\pm$ _{-0.003} ^{+0.000}
L	10.440 $\pm$ 0.010	10.300 $\pm$ 0.010

The method of casting cores directly to size suitable for machining was chosen over the method of casting large billets and then fabricating them into bar suitable for cores by a working operation for two primary reasons. First, the losses incurred during rolling and machining to size were very high; and second, the high hardness developed in the alloy upon simple air cooling after hot rolling made machining difficult. The breakdown rolling of the cast uranium alloy containing 5 w/o Zr and 1.5 w/o Nb required heating into the gamma phase above 678°C.⁽¹¹⁾ At the temperature

of 850°C chosen for rolling, the reference alloy was attacked by the triple carbonate salt bath (39% K_2CO_3 , 33% Na_2CO_3 , 28% Li_2CO_3) at such a rate as to make losses appreciable. In addition to this direct loss to the salt, a very rough surface produced by oxidation required that a large excess be allowed for machining. These losses coupled with the high machining losses, resulting from the inability to control the width of the bar to close dimensions during rolling because of the lack of edging equipment, made this method of production of billet core stock unattractive. Experimental rolling of cast rectangular bars to billet resulted in machining losses of approximately 35%.⁽⁶⁾ The high hydrogen contamination, 40 ppm, resulting from salt heating was also considered detrimental to the finished product, even though no obvious defects traceable to this hydrogen contamination could be found in the finish-rolled fuel plates.

All that was necessary to overcome these losses discussed above was to make allowance for them; but the solution to the problem of high hardness was not so simple. The crystallographic structure developed in the reference alloy upon air cooling from the gamma rolling temperature was very hard. Hardness in sections approximately 1" thick were over 45 on the Rockwell C scale. Material of this hardness level was difficult to machine even with carbide tools. The high hardness could have been reduced by a water quench from the gamma phase, but sections of the billet size were difficult to quench rapidly. Overaging would also soften the hard structure; but because of the time required, special equipment would be necessary to keep oxidation at a reasonable rate.

The casting of billets from which cladding billet cores could be rolled would have been simple in comparison to casting the cores roughly to size. A billet which approaches a square cross section would have been much easier to cast free of pipe than one in which one cross-sectional dimension was very much smaller than the other, as was the case with the cladding billet core.

The solution to the problems of restricting the machining losses and of supplying relatively soft material for machining was easily solved by casting the core to rough size. Cores could be cast with surfaces which could be easily cleaned by removing a small amount of metal. Machining losses were reduced from an average of 35.8% incurred in the wrought product to 11% for the cast billet cores. The hardness of the as-cast cores was approximately 27 Rc, which could be handled in the machine shop without undue difficulty. The solution to the problems of internal metal quality and production rate were, however, not as readily solved.

The necessary production rate in finished fuel plates required a minimum of 20 billet cores to be cast in the foundry per day. Two vacuum furnaces were available for the production of the cladding billet core alloy which, therefore, set the manufacturing rate of 10 cores per day per furnace. These furnaces had more than adequate melting capacity, but because

of the small cross-sectional area of the billet core, a large mold volume was required for the casting of 10 cores from a single heat. The first attempts at casting into a single cavity mold (see Figure 7) of sufficient size to obtain only 7 billet cores were failures. The cross section of this mold cavity was $1\frac{5}{16}$ " x $11\frac{1}{8}$ ", the thickness and length of the billet core, and $34\frac{1}{2}$ " deep to yield 7 billet cores when cut into transverse sections the width of the core. Because of the high ratio of depth to the minor cross-sectional dimension (26:1) of the cavity, conditions could not be established within the cast metal to produce a sound casting. Because of high rate of solidification normal to the mold wall, microporosity as shown in Figure 8 resulted in a considerable volume of the cast slab. The extent of unsound metal in these castings is indicated by the reproduction of the through-transmission ultrasonic test record of a typical slab, also shown in Figure 8. Attempts to develop a greater vertical freezing component in the metal by altering the chill of the mold through changes in its section and the application of heat to the mold by means other than from the primary melting power were not completely successful. This type of mold was abandoned in favor of a multi-cavity mold which presented more favorable conditions for obtaining sound castings.

Molds

The type of mold adopted for the production of cladding billet cores is pictured in Figure 9. The molds were made up of wedge-shaped graphite segments which, when assembled, formed a cylindrical tube of $12\frac{3}{8}$ " dia. standing 18" high with a $3\frac{1}{2}$ " dia. hole running down the center. A groove the width and thickness of the desired casting plus shrinkage was cut into one side of each segment, the cavity being formed by the groove in one segment and the plane face of the adjacent segment. The bottom end of each cavity was closed by a graphite plug. A 90° included angle "V" was cut into the top side of each bottom plug for purposes of casting the taper on one end of the billet cores. The entire mold was held together top and bottom by means of tapered compression rings of graphite. For filling all cavities of the mold simultaneously from a single pouring hole in the crucible, a graphite distributor was provided. This distributor fitted leak tight into a counterbore at the top of the mold. The distributor contained a central pouring cup which was connected to each cavity by a slot. This type of distributor was self-regulating; for if one cavity filled before another, flow was automatically stopped when the metal level in that cavity reached the level of the metal in the distributor while the unfilled cavities continued to be filled. The split mold was selected over a one-piece mold because of its longer life, ease in removal of castings, simplicity in machining the cavities, and ease in application of washes used. The molds were made of fine-grained graphite having reasonable strength.

Because two different sizes of cores were required for the production of the fuel plates in two thicknesses, two molds differing in size and

FIGURE 7. Graphite Slab Mold, Right, and Slab Casting, Left.

106-3059

FIGURE 8. Photograph of Ultrasonic Test Traces of Slab Casting and Photomicrographs of Selected Areas.

FIGURE 9. Multi-Cavity Split Graphite Mold Used for the Production of EWR Cladding Billet Cores.

106-3060

Twelve-Cavity Mold with Front Segments and Top Compression Ring Removed. Mold coated with $\text{MgOZrO}_2\text{-ThO}_2$ wash.

106-3065

Twelve-Cavity Mold Assembled.

number of cavities were used. The billet cores for the thin fuel plates were cast into 12-section, 12-cavity molds; and the thick billet cores were poured into 10-section, 10-cavity molds. The cavities in the 12-section mold were machined to 0.925" x 3.280" cross section x 15-1/4" deep; and the cavities in the 10-section mold were machined to 1.285" x 3.313" cross section x 15-1/4" deep. The cross-sectional dimensions were arrived at by starting with the dimensions of the finish-machined cores and adding an allowance of 0.030"/face and 0.040"/side for grinding to thickness and width, an allowance of 0.030"/inch for shrink of the alloy, and an allowance of 0.010" for the duplex ceramic coating used. A drawing showing design and dimensions of these two sizes of molds used is presented in Figure 10.

All new molds were heated to 1700°C in vacuum to drive volatile constituents from the graphite to prevent formation of blowholes in the first castings made. The mold cavities were coated to minimize the attack on the graphite by the uranium alloy, and also to improve the surface quality of the casting. The duplex coating used was applied in two steps. First, a single coating of magnesium zirconate was applied by spraying and allowed to air dry for approximately one hour; second, a single spray coat of thoria was applied over the MgOZrO_2 . This coating was used air dried. Because this wash was easily damaged during removal of castings, the molds were brushed clean after each use and recoated.

Precise figures on mold life were difficult to arrive at because the parts from one mold were interchangeable with those of another of the same type. After 86 heats were poured into five 12-cavity molds, three molds remained in usable condition, making the average mold life greater than 17 heats. The number of heats poured into six 10-cavity molds was 79, with three molds still usable for an average of more than 13 heats per mold. The average cost of the molds was \$335.00 each. The prorated mold cost per billet amounts to \$1.64 and \$2.58 for thin and thick plates, respectively.

Crucibles

Melting and alloying were done in graphite crucibles protected from attack of the melt by a duplex ceramic coating. The crucibles, pictured in Figure 11 and detailed in Figure 12, were 14-1/2" O.D. and 15-1/2" total height. Both the walls and bottom had a maximum thickness of 1-1/2" and were tapered 1° to facilitate draining of the melt and removal of the skull. The bottom of each crucible was fitted with a plug which contained the 1/2" dia. hole for pouring, as shown in Figure 12. Damage to the pouring hole only required replacement of the plug and not of the whole crucible. A stopper rod was used for sealing the pouring hole during melting. A special tip on the stopper rod (see Figure 12) was designed so that the top of the stopper rod could be moved slightly, either horizontally or vertically, without causing the metal to leak from the crucible. The stopper rod was actuated by means of a tantalum rod, 1/4" dia., which fastened to the

FIGURE 10. Design and Dimensions of 12 Section-12 Cavity and 10 Section-10 Cavity Mold for Casting Billet Cores.

stopper rod by means of a clevis and pin. The tantalum pull rod passed through a compression-type vacuum seal in the furnace cover. All crucibles were made of ATZ grade graphite.

FIGURE 11

Graphite Crucible, Crucible Cover
and Stopper Rod Coated with
 $\text{MgOZrO}_2\text{-ThO}_2$ Wash

The use of graphite as a crucible material for the melting of the reference alloy was made possible by the duplex ceramic coating. The high temperature required for the solution of the niobium addition, coupled with the probable increase in the activity of the melt resulting from the alloy additions, caused very rapid attack upon an unprotected graphite crucible. The high concentration of carbon resulting from this practice then promoted the segregation and loss of the alloy addition, particularly of the zirconium. Protection of the graphite crucibles, stopper rods, and crucible cover from attack by the melt was provided in the form of a duplex ceramic coating. The base coat, applied by brushing, was a magnesium zirconate slurry supplied by the Titanium Alloy Manufacturing Division. The second coat was applied atop the MgOZrO_2 by spraying a water suspension of thoria. Lindsay Chemical Company Code 112 thorium oxide fired at 800°C and having an average particle size between 0.5 and 2.0 microns was preferred. The crucibles, covers and stopper rods were allowed to dry in air at room temperature before use.

The magnesium zirconate coating afforded good protection for graphite against attack by uranium up to about 1400°C . Above this temperature, the zirconate wash reacted with the melt and protection was lost.

FIGURE 12. Design and Dimensions of Graphite Crucible, Stopper Rod, and Cover.

The addition of the thoria wash atop the base coat reduced the rate of attack by the melt on the MgOZrO_2 to a point where the coating provided complete protection in a majority of the heats. Thoria alone was not used because it would not adhere to the graphite crucible sufficiently well to afford protection. The magnesium zirconate did adhere very well to the graphite, providing an excellent base for the thoria which constituted the necessary barrier. The MgOZrO_2 did remain on the graphite up to about 1650°C . Above this temperature, however, the wash reacted with the graphite crucible.

The duplex coating described above prevented the alloy melt, whose temperature was raised to 1550°C during the heat cycle, from attacking the graphite in 96% of the heats. The wash lasted only for a single heat and had to be applied each time the crucible was used. A small amount of dry lime was sprinkled on the bottom of the crucible to carry the load of the charge. If this was not done, the weight of charge in some instances broke through the wash, thus exposing graphite to attack.

The wash also simplified the task of cleaning the crucible after melting. The presence of wash prevented the sticking of the skull and splash to the crucible.

At the start of production, 14 crucibles were made at an average cost of \$90.00 each. Eight crucibles were still usable after 165 heats were made. The crucible charge per billet core casting amounted to \$0.30. Most of the failures occurred because of mishandling during melting, which resulted in the wash being mechanically dislodged from the crucible. More about this failure will be said in the discussion of the melt cycle.

Vacuum Melting Furnace

Melting, alloying and casting of the EBWR cladding billet cores were carried out in vacuum. Two similar vacuum, induction-melting furnaces were used in the production. The furnaces were of the quartz tube type, having the induction coil located outside the tube. Power for melting was supplied by a 50-kw, 440-v, 3000-cycle motor generator set. The furnaces were located on a balcony such that the furnace tops and quartz tubes were positioned above the balcony floor for observation and manipulation of the heats; the vacuum pumping systems and furnace bottoms were located beneath the balcony. Views of a furnace from above and beneath the balcony floor are shown in Figures 13 and 14.

A cutaway perspective drawing of the furnace, presented in Figure 15, shows details of the important components of the furnace. These components were the base, quartz tube, cover, insulation, and pumping system. The base of the furnace was a stainless steel tube 17-1/2" I.D. x 18" O.D. x 30" long to which was welded a flange for the sealing of the bottom plate

FIGURE 13. View of 20" Quartz Tube Vacuum Induction Furnace from Balcony Floor.

106-3066

FIGURE 14. View of Vacuum Melting Furnace Pumping System from beneath Balcony and Mold In Position on Lift Truck Ready for Raising into Furnace.

106-3067

FIGURE 15. Cutaway Perspective of Vacuum, Induction-Melting Furnace for Core Alloy Production.

and a flange on the top end for the support and sealing of the quartz tube. The connection between the furnace base and pumping system was made by means of a 10" stainless steel pipe welded perpendicular to the base tube.

The quartz tube, which was sealed by means of a flat silicone rubber gasket, was nominally 22" O.D. x 36" long with 1/2" minimum wall thickness. Both ends were ground free of defects perpendicular to the axis of the tube. A water-cooled cover closed the top end of the quartz tube, being sealed by means of a flat, silicone rubber gasket. The top cover contained fittings for sealing the stopper pull rod and two openings for mounting the rotating sight glass fittings.

The base of the furnace was lined with stabilized zirconia, tongue and grooved tile 3/4" x 3-1/4" x 5" curved to fit the tube inside diameter. These tiles were supported on the bottom flange which protruded inside the tube. The quartz tube was insulated by low density, stabilized zirconia bricks, 1-1/2" x 4" x 8-1/2", carried on a stainless steel ring resting on the top flange of the furnace base. The bricks were cemented in place with zirconia cement. The inside diameter of the insulation was 16". The thermal insulation afforded by 1-1/2" of stabilized zirconia was sufficient to keep the quartz tube below any color temperature.

Power from the high frequency generator was induced into the melting furnace by means of a coil surrounding the quartz tube. With the induction coil in this position instead of within the vacuum shell, the difficulties associated with the loss of power due to corona discharge or direct arcing were eliminated. This power interruption problem reaches major proportions when melting charges contain volatile materials, such as magnesium, which are good conductors.

The match between generator and load (crucible) was found in an appropriately dimensioned coil of eight and one-half (8-1/2) turns. This gave the proper ampere-turns for inducing the full power, 50+ kw, into the load. The dimensions of the coil were 23" I.D., required to fit the unround quartz tube, and 23" high, for distribution of flux over the crucible, crucible cover, and mold top. In order to obtain a reasonably uniform flux distribution, the coil was wound of four parallel strands of 1/2" O.D. x 1/16" wall copper tubing silver brazed together at intervals along its length. Using this quadruple strand winding, the turn spacing in coil was approximately 1/2". All four strands of the coil were connected directly to the power source and water cooled by means of copper terminal blocks silver brazed to each end of the coil.

Coil dimensions and turn spacing were maintained by four micarta bars, spaced 90° apart, to which each turn was bolted by means of a silver-brazed stud. The bars extended below the coil to serve as a support.

Power was transmitted from the generator to the condenser bank by means of a four-strand cable, cluster-connected, positive-negative-positive-negative, around a circle for reduction of inductive impedance. Power was transmitted from the condenser bank to furnace by means of $1\frac{1}{4}$ " x 4" cross sectional, water-cooled, copper bus bars. Power was transferred from one furnace to another by means of manually operated, high-capacity switch-gear. The variable capacitance condenser bank was used to balance the inductive load with capacitance to obtain a power factor close to unity. Of the total 160 microfarads of capacitance available, contactors controlled by push buttons were used to switch 128 microfarads in or out of the circuit in seven (7) steps ranging from 4 to 32 microfarads. The operation of the high-frequency motor generator and capacitor bank was controlled at a panel located on the furnace balcony.

The pumping systems of the two furnaces were capable of maintaining consistently a vacuum of 10 microns during melting; at times it was as low as 2 microns. One furnace pumping system consisted of a 6" booster pump, National Research Type B-6, capable of a maximum speed of 500 liters per sec at about 10 microns pressure, and a 100-cfm, single-stage Kinney mechanical pump No. 8-8-10. The second furnace was pumped by an 8" oil diffusion-ejector pump, Consolidated Vacuum Corporation Type KS-600, backed by a No. 8-8-10 Kinney. Even though this pump peaks at 750 liters per sec at about 8 microns, its pumping performance was little different than the B-6, whose speed is rated at 250 liters per sec less.

Both furnaces were equipped with chevron-type, water-cooled baffles to impede the diffusion of pump oil back into the furnace. The baffles were contained in a cubical housing connected to the furnace from one side by means of a 10" pipe and flanges and to the diffusion pump from the bottom by means of a 6" or 8" pipe and flanges. Isolation of the furnace from its mechanical pump was done by means of a 3" globe-type vacuum valve, pneumatically operated, solenoid controlled and bellows sealed. The purpose of the valve was to maintain a vacuum in the furnace after shutdown of the pump system.

Control of the pumping system for each furnace was performed at the furnace control panel shown in Figure 16. The functions of starting and stopping both mechanical and diffusion pumps, opening and closing the vacuum valve, and control of power level of the diffusion pump heater were performed at the panel. Meters which indicated power input to the diffusion pump and furnace vacuum were also located on the control panel.

The furnace pumping system was protected, by means of suitable interlocks and relays, against errors in starting sequence, water and power failures, and loss of vacuum in the furnace. The furnace wiring diagram is given in Figure 17.

FIGURE 16. Control Panel for 20" Quartz Tube Furnace.

106-3063

In addition to the thermocouple vacuum gage located on the control panel, a portable alphanatron gage was used principally for measurement of furnace pressure.

Charge Materials

The charge materials used in the production of the uranium alloy core were uranium biscuit, zirconium sponge, and niobium pressed powder. The uranium was received in the form of biscuit (Mg-reduced UF_4) of two general types. The first was normal uranium having a diameter of 12" and a thickness of about 4-1/2". The weight of the normal biscuits was roughly 135 kg. The second was slightly enriched uranium with a diameter of 10" and a thickness of 5-1/2", weighing approximately 110 kg. The enriched biscuit contained 1.44% U^{235} . The average chemical compositions of the normal and enriched uranium are contained in Table II. By deduction the normal uranium was 99.96 w/o and the enriched 99.06 w/o pure. A comparison of impurities listed in Table II shows the enriched biscuit to be lower in Cr, Fe, and Pb content, but higher in Cu and Mg.

Table II.

AVERAGE IMPURITY CONTENT OF ENRICHED AND NATURAL BISCUIT USED IN MAKING EBWR FUEL ELEMENT CORES

Impurity	Concentration, ppm*		Impurity	Concentration, ppm*	
	Enriched	Natural		Enriched	Natural
Ag	<1	<1	Mg	15	10
Al	7	10	Mn	4	4
As	<10	<10	Mo	<20	<20
B	<0.1	<0.1	Na	<2	<2
Be	<0.5	<0.5	Ni	19	17
Bi	<1	<1	P	<50	<50
Ca	<20	<20	Pb	<1	2
Co	<5	<5	Sb	<1	<1
Cr	1	20	Si	40	40
Cu	5	1.5	Sn	<5	<5
Fe	33	62	Ti	<50	<50
K	<20	<20	Zn	<50	<50
Li	<1	<1			

*Figures accurate to order of magnitude only.

The bulk of the uranium was prepared for charging by drilling a hole 1-1/4" dia. axially through the biscuit (see Figure 18). The purpose of this hole was to accommodate the 3/4" dia. stopper rod which passed down through the charge. This procedure was adopted in preference to sawing the biscuit into sections which could then be arranged around the stopper rod. The drilled biscuits were much easier to charge into the crucible than pieces; and drilling produced approximately 2 kg of scrap as opposed to 5 kg produced by sawing. In addition, drilling costs were less than sawing because of the lesser time required. A small amount of the uranium biscuit was sawed into quarters for makeup in the event recycle material was not available to arrive at the proper charge weight. All material was scrubbed with acetone for removal of the coolant used in drilling or sawing before charging.

The procedure for the production of the reference alloy was developed using two grades of zirconium sponge made by the Bureau of Mines, Albany, Oregon. It was found that the solution of the alloying elements was aided by agitation of the melt and that this agitation could be obtained by the use of alloying additions containing volatile constituents. Zirconium in the form of sponge containing magnesium and magnesium chloride was found to produce agitation in the melt in proportion to the quantity of volatile constituents present. The Bureau of Mines Grade A sponge produced only a small amount of agitation in the melt, while the Grade C produced such violent agitation that melts frothed up and out of the crucible if the temperature rise in the melt was rapid. The major differences in these two grades of sponge, as may be seen from the typical analyses given in Table III, were the magnesium and chlorine contents. By varying the amounts of these two grades in the charge the amount of agitation could be controlled. The proportion of Grade A to Grade C of 3:1 was found to be proper for a controlled amount of agitation.

Table III

AVERAGE ANALYSES FOR BUREAU OF MINES
ZIRCONIUM SPONGE GRADES A AND C

Impurity	Grade A	Grade C		Impurity	Grade A	Grade C	
	Max ppm	Max ppm	Min ppm		Max ppm	Max ppm	Min ppm
Al	100	100		Fe	200	100	
B	0.5	0.5		Pb	100	100	
Cd	0.5	0.5		Mg	500	4000	2000
C	500	500		Ni	50	50	
Cl	1300	1500		N	50	50	
Cr	150	150		Si	100	100	
Co	10	10		Ti	50	50	
Cu	50	50		V	50	50	
Hf	200	200					

FIGURE 18. Drilling 1-1/4" Diameter Stopper Rod Hole in Uranium Biscuit.

210-140

Attempts were made to secure zirconium sponge in Blends A and C in the above proportions for the production of EBWR fuel alloy. This material was not commercially available; however, the Carborundum Metals Company was able to supply blends of compositions shown in Table IV. The particle size of the sponge received ranged between $-1/2"$ and $+20$ mesh. Both these blends of sponge were used in the production of the uranium fuel alloy but the Blend C was preferred. Because of the higher magnesium and chlorine contents of this blend, more vigorous boiling took place. The increased recovery of alloying additions and reduction in segregation resulting when using Blend C sponge were attributed to the increase in agitation in the melt.

Table IV

AVERAGE IMPURITY CONTENT OF CARBORUNDUM METALS
COMPANY ZIRCONIUM SPONGE BLENDS A AND C
SUPPLIES FOR USE AS ALLOY ADDITION

Impurity	Blend A	Blend C	Impurity	Blend A	Blend C
Al	<75	< 20	Mn	23	18
B	-	-	N	104	96
Cl	239	874	Ni	<13	<13
Cr	44	50	Pb	<13	<13
Fe	184	125	Ti	<16	<16
Hf	<67	< 50	V	<13	<13
Mg	99	888			

The niobium used for alloy addition was purchased in accordance with chemical specifications contained in Table V. This material was supplied by the Fansteel Metallurgical Corporation in the form of cold-pressed powder bars, $3/4" \times 3/4" \times 24"$. This pressed powder was easily broken into small pieces, the form in which it was readily dissolved in the molten base metal. It was found that niobium in this physical form was more satisfactory and less costly than sintered or wrought material and less costly than the equally satisfactory pressed pellets. Loose powder was found inferior to the cold-pressed product for alloying purposes.

Table V

IMPURITY LIMITS ON NIOBIUM
USED IN MANUFACTURE OF
EBWR FUEL ELEMENT CORES

Impurity	Max. w/o
C	0.20
Ta	0.16
Ti	0.025
Si	0.015
Fe	0.010

Mold, Crucible, and Fixture Arrangement

The mold, crucible, and other fixtures were arranged in the vacuum induction furnace as shown in Figure 15. The mold was supported on, but insulated from, the furnace bottom plate by means of stabilized zirconia bricks. The height of the mold was adjusted so that, when the bottom plate was in position, the top 3" of the mold were within the bottom of the induction coil. The crucible was carried directly on top of the mold which positioned the crucible centrally, both vertically and horizontally, within the induction coil. A graphite crucible cover and 3" of stabilized zirconia insulating brick on top the cover provided the necessary insulation to block radiation from the top of the quartz tube. The stopper rod, seated in the crucible pouring hole and connected to the tantalum pull rod which passed through the seal in the top cover, completed the arrangement.

The thermal gradient in the mold necessary for obtaining castings free of pipe was established by applying heat to the top of the mold from two sources. First, the top of the mold, being 3" within the induction coil and having reasonably good coupling, was heated by induction from the primary power source. Second, heat was conducted from the crucible into the top of the mold because of the direct contact of the two. The heat lost through conduction from the mold bottom to the water-cooled furnace bottom plate was restricted by the insulating bricks used beneath the mold. In this manner a natural thermal gradient from top to bottom of the mold of 630°C (1230°C at top to 600°C at bottom) was established to develop a freezing pattern within the poured metal with an appreciable vertical component. The high temperature at the mold bottom was necessary to prevent cold shuts from forming on the surfaces of the casting and, even more importantly, to prevent the formation of blowholes in the casting. Upon melting the virgin materials in a charge, the magnesium and magnesium salt

contents of both the uranium and zirconium were vaporized and distilled from the melt. These vapors then condensed on surfaces which were below the condensation temperature. Since the mold was not gas tight, these vapors could find their way into the mold cavities; if conditions were right condensation would occur. At 10 microns pressure, condensation of magnesium will occur at about 400°C . Condensate found on the bottom of cool molds has been identified as magnesium.⁽¹²⁾ Now, if magnesium vapor has condensed in the mold cavities, it will be revaporized when the melt is poured and act as any vapor or gas evolving from a mold in producing blow-holes.

In placing the crucible atop the mold and having the crucible cover well insulated, the heat loss from the bottom of the crucible was greater than that from the top. This then produced a thermal gradient in the crucible. As will be discussed later, this higher temperature at the top of the crucible, instead of being a detriment, was suspected to be an aid in the solution of the alloying elements.

Charging

Because of the high reactivity of the alloying elements with atmospheric constituents, the high stability of the reaction products of zirconium with respect to those of uranium, and the wide difference in density of the charged components, the method of charging and vacuum furnace operation had marked influence upon the recovery and homogeneity of alloying elements in the melt. The high positive difference in melting points of the alloying elements (Zr 1850°C , Nb 2415°C) with respect to uranium (1130°C) required that the solution mechanism be diffusion between solid Zr and Nb and molten uranium at operating temperatures which were reasonable. The difficulty of dissolution was increased by the absence of low-melting eutectics or peritectics in the U-Zr, U-Nb, or Zr-Nb systems.

Since the mechanism of dissolution was by solid-liquid diffusion, the restriction of surface contamination of the solid state components was very important, doubly so in the case of zirconium, since uranium will not reduce its oxide or nitride. One practical means of restricting surface contamination of the alloying elements, and of uranium also, was the reduction of the activity of atmospheric contaminants by reduction of their pressure. The furnaces in which the fuel alloy was produced were capable of operating at an absolute pressure of 2 to 10 microns. Serious contamination resulted at pressure over 100 microns and solution was hopeless at pressures as high as 1000 microns.

Having restricted the surface contamination of the alloying elements, consideration had next to be given to the establishment of intimate contact between molten uranium and the additions. The chief difficulties were the great differences in densities of the alloy elements and uranium. The

charging procedure adopted for the making of the fuel alloy consisted of placing the mixed additions (Zr and Nb) on the bottom of the crucible, surrounding three pre-alloyed blocks, which also rested on the crucible bottom and extended about the level of the additions. Then, on top of these alloy blocks, the uranium biscuit was placed. With this arrangement the weight of the uranium was carried on the uranium alloy blocks; because the blocks contained the reference alloy additions, they melted after the virgin uranium charge. In this way the alloying additions sintered into a very porous mass which permitted the uranium to flow into the voids, wetting the particles. Through the reduction in diffusion distances, solution by this method of charging was considerably faster than by one in which the weight of uranium was carried directly on the alloy. Apparently, the weight of the uranium was sufficient to compact the alloy charge, thereby reducing the void volume and thus reducing the surface area of the alloy available for wetting.

In addition to maintaining the porosity of the alloying additions, solution was aided by keeping this sintered cake at the crucible bottom until wetted by the uranium. As discussed previously, a temperature gradient existed in the crucible. Having a higher temperature at the top, the virgin uranium melted from the top down. While the molten metal ran down and soaked into the alloy cake, the cake was not allowed to float because of the presence of the unmelted uranium above it.

The advantage of placing the alloy below the uranium charge becomes apparent upon inspection of the alloy compositions of four melts plotted in Figure 19. Two heats (C8 and C9) were made with alloy beneath the uranium charge, one taken to 1300°C and the other to 1400°C. Two heats (C10 and C12) were made with the alloy charged on top of the uranium and heated to the temperatures above. Insufficient time was allowed for complete solution of the alloy, so that position of alloying additions could be determined after melting.

The appearance of the melts after removal from their crucibles is shown in Figure 20. No alloy addition could be seen on top of the heats made by placing the alloy additions beneath the uranium charge; but in the melts where the Zr and Nb were charged above the uranium, much of the addition was present in its original form except for some oxidation. Heats C8 and C9 were sectioned longitudinally; as shown in Figure 20, the alloy additions were completely wetted by the uranium.

Mechanics of Melting

The first operation in the preparation for a heat was placing the coated and assembled mold in position. As shown in Figure 14, a graphite pedestal was placed on the furnace bottom to elevate the mold to its proper position, 2-1/2" of insulating zirconia brick were placed on top of the graphite, and the mold placed on top of all this. The assembly was then

FIGURE 19. Alloy Content vs. Distance from Bottom of Ingot for Melts with Alloy Additions Charged Above and Beneath Uranium.

FIGURE 20. Photographs of Alloy Solution Experiment Heats.

Max. Melt Temp. 1300°C

19968
1/2X
Ingot C-10 Alloy Charged above
U. Note undissolved alloy at
base of ingot.

19648
1/2X
Ingot C-8 Alloy Charged beneath U.

19659
2X
Vertical Section Thru Top of
C-8. Note light alloy addi-
tions wetted by U.

(These photographs have been reduced 30% for reproduction.)

Max. Melt Temp. 1400°C

19969
1/2X
Ingot C-12 Alloy Charged above
U. Note undissolved alloy at
base of ingot.

19649
1/2X
Ingot C-9 Alloy Charged beneath U.

19658
2X
Vertical Section Thru Top of
C-9. Note light alloy addi-
tions wetted by U.

raised into the furnace by means of a manually operated lift truck, the bottom bolted in place, and the cooling water lines connected. The mold when in final position was 3" within the induction coil coaxial with the furnace.

The coated crucible, having been previously loaded with alloy and uranium in correct proportion and amount, was then lowered onto the mold by means of an electric hoist as shown in Figure 21. The crucible cover and insulating zirconia bricks were then placed in position over the crucible. The stopper rod was fastened to the tantalum pull rod and seated in the pouring hole in the crucible. The final operation was lowering the furnace cover onto the quartz tube, threading the pull rod through the compression seal on the way down.

Two types of charges were used. The bulk of the heats were charged principally with virgin materials, and the remainder were charged with recycle scrap. Two sizes of heats were also made. The heats which were poured into the large cavity (10-cavity) molds were approximately 170 kg, while the heats poured into the small cavity (12-cavity) molds were 148 kg in size. No distinction was made between natural and enriched heats in the charging and melting practice. The initial charge of virgin materials was calculated to be 5% over the nominal composition in zirconium and niobium.

The melt cycle started with the turning on of the mechanical vacuum pump and the diffusion pump. One of two distinct melt cycles were used, depending on the constituents of the charge. A charge consisting wholly of alloy scrap from previous melts was taken to 1500°C, held for two hours, lowered to the pouring temperature, held for 15 minutes, and poured. The inductive power was left on for five minutes after pouring to hot top the mold with heat.

When the charge consisted chiefly of virgin materials, it was taken to 1550°C and held between 50 and 60 minutes for the dissolution of the alloying elements. During this period the melt boiled at a diminishing rate until quiescence was established. After the melt became calm, taken as an indication of completion of solution, the melt temperature was lowered to approximately 1300°C to allow the metal to solidify. The temperature was then raised to the pouring temperature, held for 15 minutes, and poured. As with the pre-alloyed heats, the power was left on for five minutes after pouring.

The purpose of dropping the melt temperature to the freezing range was to obtain castings with reduced amounts of microporosity. The mechanism by which freezing of the melt enhanced the properties is not fully understood; however, less porosity was found in heats which had been solidified and remelted for pouring than in those which had not. No sound

FIGURE 21. Graphite Crucible Being Lowered into Vacuum Melting Furnace.

106-3061

castings were produced from melts made up of virgin charge materials when the metal was not frozen in the crucible. One explanation of this improvement was the reduction of contained gas through decrease in its solubility upon freezing of the melt. Proof, however, is not available.

As was mentioned previously, most of the crucible damage resulted from dislodgement of the ceramic coating. In most cases, the wash was damaged because the melt was cooled too far below its solidification temperature range. Upon reheating, the expansion of the metal parallel to the mold wall abraded the wash, exposing unprotected graphite to the melt. This difficulty was solved by cooling the melt only to about 1300°C.

The pouring temperatures ranged from 1450° to 1500°C. The higher temperature was preferred for the 148-kg heats, which were poured into the small, 12-cavity molds, and 1475°C was favored for 170-kg heats, which were cast in the 10-cavity molds.

All temperatures were measured by means of an optical pyrometer through the quartz sight glasses mounted on the furnace cover. Because the mold extracted heat from the crucible, and the top surface of the melt received radiant heat from the crucible wall above the melt level, the top of the metal was hotter than the bottom. The temperatures reported, therefore, were those of the hottest portion of the melt.

The furnace vacuum was usually below 10 microns at the time of melting and dropped to approximately 2 microns at pouring. The log of a typical virgin melt is shown in Table VI, and the log of an average remelt is given in Table VII. Table VIII contains a summary of the more important heat data for all production castings.

The furnace was not opened until the day after pouring, to permit cooling to minimize the danger of a magnesium fire. The furnace was isolated from the mechanical pump by closing the vacuum valve; argon was used to backfill the furnace to minimize the danger of a magnesium fire. The top cover was removed, and the magnesium which had condensed on this water-cooled surface was ignited by scratching with a long pipe. The MgO was removed by brushing. The sequence of operations involved in unloading of the furnace was the reverse of that in loading. The crucible containing the skull was removed from the top of the furnace, and the mold containing the castings was dropped by means of a lift truck out of the bottom of the furnace.

The castings were removed by disassembly of the mold, the mold was prepared for reuse, and the castings machined for testing. The mold sections were brushed free of all coating under a hood and recoated with the duplex ceramic wash previously described. The castings were brushed under water to remove any wash clinging to their surfaces to minimize

Table VI

LOG OF A TYPICAL VIRGIN HEAT

HEAT NO.: COMPOSITION: 93.5 w/o normal uranium K-118 5 w/o Zr 1.5 w/o Nb			DATE: 2/2/56		
<u>CHARGE</u>			<u>WEIGHT, kg</u>		
U Biscuit #8396			134.90		
K-104 Remelt			11.42		
K-113 Remelt			3.67		
K-114 Remelt			1.66		
Zr Sponge			7.52		
Nb Batch No. 103 and M92			2.31		
			<u>161.48</u>		
<u>CRUCIBLE</u>			Graphite: 12-5/8" I.D. x 14-1/2" O.D. x 14", 1/2" pouring hole.		
			Wash: 2 coats MgOZrO ₂ , 1 coat ThO ₂ .		
<u>MOLD</u>			Graphite: 12-Core		
			Wash: MgOZrO ₂ , 1 coat ThO ₂ , each sprayed on.		
<u>FURNACE</u>			No. 1 Quartz Tube		

MELTING DATA				Remarks and Condition of Melt
Time	Power, kw	Optical Temp, °C	Vacuum, Microns	
11:05	50		200	Start of heat.
12:00	51		3.8	
12:35	52		3.2	
12:50	52	1180	3.2	Melting rapidly.
1:00	52	1250	3.2	Violent bubbling.
1:15	52	1325	3	Bubbling.
1:45	45	1450	2	Temp. taken at base of stopper rod; hold for 1/2 hr at 1450°C
2:15	55	1425	2	Small amount of bubbling.
2:40	45	1505	2	Lower power, hold for 1-1/2 hr.
3:10	47	1470	2	
3:30	47	1500	2	Quiet.
3:45	40	1570	2	
4:15	40	1500	2	Poured.

WEIGHT OF CASTINGS: 155.10 kg
 WEIGHT OF SKULL: 6.38 kg
 RECOVERY: 96.9%

CASTINGS
 Number Length, In.

1	12
1	12-1/2
10	15-1/4

SURFACE CONDITION: Good

Table VIII

SUMMARY OF CASTING DATA

Melt No.	Charge Wt, kg	Melting Time		Holding Time		Vacuum, Microns		Pouring Temp, °C	Casting Wt, kg	Data Recorded in Notebook	
		hr	min	at °C	for min	min	@ pour			No.	Page
E 1 ⁽¹⁾	144.6	-	-	-	-	-	-	-	-	775E	4
2	146.8	5	20	1550	54	1.5	6.0	1520	138.0		8
3	148.0	4	55	1550	50	1.8	2.0	1450	138.8		12
4	164.0	4	45	1550	50	0.3	2.0	1450	155.0		16
5	146.9	4	26	1555	50	0.4	4.0	1510	141.5		20
6	146.6	4	45	1550	50	1.2	1.8	1450	139.9		24
7	162.6	5	15	1550	55	2.0	3.0	1450	155.0		28
8	150.0	4	20	1565	60	1.0	1.6	1455	141.4		32
9	145.2	4	40	1550	50	1.5	2.0	1450	136.0		36
10	166.4	4	36	1550	50	3.4	3.4	1455	158.8		40
11	159.9	4	40	1570	58	1.2	1.4	1455	147.6		44
12	149.0	4	22	1565	60	0.4	1.2	1450	137.2		48
13	148.0	4	55	1550	50	2.0	2.0	1450	138.4		52
14	161.8	-	-	-	-	-	-	-	-		56
15	148.0	5	10	1550	50	1.5	3.0	1500	139.6		60
16	152.8	4	33	1550	50	1.3	2.0	1500	144.6		64
17	160.8	4	25	1550	50	0.4	3.0	1505	153.8		68
18	149.4	4	35	1575	50	1.3	3.0	1505	135.9		72
19	147.9	4	37	1550	50	1.8	3.0	1505	139.7		76
20	161.2	4	10	1560	50	0.4	2.0	1500	136.4		80
21	148.6	3	51	1550	50	0.5	1.2	1500	140.4		84
22	149.4	4	44	1550	55	2.5	2.8	1500	139.5		88
23	149.2	4	30	1550	48	1.0	1.8	1500	134.0		92
24	161.7	4	20	1545	50	0.5	0.5	1500	153.6		96
25	138.5	4	10	1555	50	0.2	0.8	1505	129.0		100
26	149.4	4	30	1550	50	1.8	2.0	1475	140.5		104
27	150.5	4	50	1545	50	1.8	2.0	1480	142.5		108
28	158.9	4	22	1550	50	0.3	1.2	1500	150.2		112
29	147.4	4	0	1560	50	0.2	0.6	1475	140.3		116
30	138.0	4	15	1550	50	2.6	3.0	1475	129.6		120
31	156.4	4	30	1555	46	2.5	2.9	1475	147.4		124
32	149.4	4	50	1550	65	0.5	2.0	1475	138.7		128
33	148.3	4	25	1560	50	1.2	1.6	1475	138.6		132
34	139.3	3	56	1550	50	0.5	1.0	1460	131.1		136
35	148.4	3	53	1550	50	0.4	0.4	1470	139.2		140
36	149.3	4	43	1550	50	1.2	1.8	1500	140.5		144
37	139.8	3	55	1500	115	4.0	4.0	1500	133.7		148
38	149.1	5	0	1545	50	1.0	1.5	1495	140.8		152
39	150.9	5	7	1560	58	0.4	1.0	1500	140.5		156
40	148.9	5	0	1550	50	1.3	3.6	1500	140.2		160
41	147.3	4	35	1550	53	1.7	1.7	1500	138.6		164
42	137.8	4	2	1550	50	1.4	1.4	1500	127.0		168
43	149.4	3	57	1550	50	1.0	1.0	1500	141.8		172
44	148.0	4	35	1550	54	1.0	2.0	1500	136.8		176
45	168.8	4	45	1520	120	4.3	4.3	1515	162.6		180
46	166.4	4	25	1515	40	0.8	2.5	1520	157.0		184
47	138.4	4	30	1560	55	1.0	2.0	1505	125.8		188
48	168.0	4	9	1565	47	1.0	1.0	1450	157.4		192
49	164.5	4	50	1550	50	1.8	2.0	1495	154.8		196
50	170.2	5	23	1550	50	1.0	1.6	1470	160.2	789E	2
51	169.0	4	30	1555	52	1.0	1.8	1470	160.0		6

(1) Enriched heat numbers prefixed with letter "E."

Table VIII (Contd.)

Melt No.	Charge Wt, kg	Melting Time		Holding Time		Vacuum, Microns		Pouring Temp, °C	Casting Wt, kg	Data Recorded in Notebook	
		hr	min	at °C	for min	min	@ pour			No.	Page
E52	162.6	4	17	1505	113	1.0	1.0	1475	158.0	789E	10
53	169.4	4	1	1555	50	1.0	1.8	1475	160.4		14
54	170.0	5	40	1555	50	2.5	2.5	1475	159.5		18
55	169.6	5	8	1550	53	1.4	1.6	1475	160.2		22
56	170.5	4	25	1550	55	2.5	2.8	1475	161.4		26
57	171.5	4	50	1550	50	3.2	3.6	1475	160.4		30
58	170.6	4	55	1550	50	1.0	1.6	1475	162.5		34
59	170.9	4	10	1550	50	1.0	1.4	1475	161.8		38
60	170.5	4	55	1550	50	1.3	1.5	1475	162.0		42
61	171.2	5	5	1545	50	1.5	1.8	1475	162.5		46
62	169.8	4	18	1550	50	1.0	1.2	1475	159.0		50
63	170.7	4	15	1550	52	0.6	1.0	1480	160.9		54
64	170.8	4	45	1550	50	1.0	1.3	1475	160.8		58
65	172.3	4	8	1550	50	0.6	0.6	1480	162.4		62
66	170.1	4	52	1550	50	1.0	1.2	1480	155.1		66
67	172.1	5	7	1540	40	0.8	0.8	1475	164.0		70
68	171.4	4	20	1550	50	1.0	1.0	1475	159.4		74
69	169.7	5	0	1550	50	1.4	2.0	1475	161.9		78
70	172.3	4	15	1550	50	1.8	2.0	1475	159.2		82
71	172.8	4	50	1550	50	1.4	2.0	1475	160.3		86
72	168.0	4	20	1500	120	1.0	1.5	1475	162.9		90
73	172.1	4	12	1550	50	0.6	0.8	1475	161.4		94
74	173.5	4	45	1550	50	1.2	1.2	1475	163.4		98
75	173.0	4	20	1545	45	0.8	1.0	1470	162.4		110
76	171.6	4	45	1550	50	1.0	2.0	1480	162.1		106
77	172.0	4	5	1550	50	0.5	1.0	1475	163.0		102
78	169.0	4	10	1475	117	1.0	1.0	1475	161.9		114
79	172.2	4	25	1550	45	1.2	1.2	1470	158.4		118
80	171.3	3	50	1560	50	0.5	1.4	1475	161.5		122
81	171.2	4	20	1515	135	1.0	1.0	1475	164.6		126
82	169.1	4	52	1510	120	4.0	4.0	1475	162.2		130
83	169.9	4	49	1500	120	3.8	3.8	1475	163.2		134
84	169.5	4	55	1515	120	3.0	3.0	1475	161.7		138
85	169.9	4	48	1500	128	3.1	3.1	1475	164.4		142
86	169.6	4	42	1500	120	7.0	7.0	1475	157.0		146
87	170.0	5	20	1500	120	3.0	3.0	1475	164.7		150
88	168.3	5	25	1505	120	6.8	6.8	1475	161.5		154
89	171.0	4	22	1500	120	9.0	9.0	1475	166.2		158
90	170.2	5	43	1500	123	1.0	1.4	1475	164.1		162
91	171.7	4	37	1500	120	6.0	6.0	1475	167.7		166
92	170.9	5	15	1505	120	6.5	6.5	1475	161.1		170
93	171.2	4	42	1505	120	7.0	7.0	1475	164.0		174
94	171.2	4	52	1505	120	6.0	6.0	1475	160.8		178+
95	169.0	4	53	1500	120	6.0	6.0	1475	162.1		182
96	171.2	4	17	1510	120	2.0	2.0	1475	160.4		186
97	171.3	5	17	1550	50	5.2	5.5	1475	161.5		190
98	171.8	4	37	1550	60	2.0	2.0	1475	161.2		194
99	144.3	4	19	1505	120	2.0	2.0	1475	139.1	777E	2
100	166.0	4	58	1505	120	5.0	5.0	1475	159.8		6
101	170.0	4	28	1550	60	2.0	2.0	1475	160.0		10
102	171.9	4	30	1550	52	2.0	2.0	1475	161.6		14

Table VIII (Contd.)

Melt No.	Charge Wt, kg	Melting Time		Holding Time		Vacuum, Microns		Pouring Temp, °C	Casting Wt, kg	Data Recorded in Notebook	
		hr	min	at °C	for min	min	@ pour			No.	Page
E103	171.6	5	14	1550	51	4.8	4.8	1480	162.6	777E	18
104	171.4	4	40	1550	50	2.0	2.0	1475	161.1		22
105	148.6	3	55	1550	55	1.0	1.0	1480	138.0		26
106	148.0	4	39	1537	119	2.0	2.0	1475	139.0		30
107	148.4	4	58	1507	120	3.1	3.1	1475	140.6		34
K95 ⁽²⁾	143.0	5	11	1555	60	1.2	2.4	1515	131.2	766E	182
96	140.1	6	10	1550	77	1.2	2.2	1470	130.6		186
97	165.3	6	0	1555	57	1.4	2.0	1500	153.5		190
98	139.0	5	20	1555	60	2.3	90.0	1500	122.5		194
99	166.4	5	35	1550	60	1.8	2.0	1505	155.5		196
100	165.3	3	50	1530	110	2.2	2.2	-	-	774E	2
101	168.2	-	-	-	-	-	-	-	-		6
102	167.0	-	-	-	-	-	-	-	-		10
103	168.6	4	56	1485	60	2.2	3.0	1520	150.2		14
104	165.5	3	30	1500	50	1.8	4.0	1455	160.4		20
105	167.0	4	0	1500	95	2.0	2.0	1490	158.5		24
106	165.5	4	5	1500	50	1.6	3.3	1500	161.3		28
107	119.2	4	22	1525	124	0.6	0.6	1505	112.7		32
108	163.7	4	27	1500	54	5.8	5.8	1505	155.3		36
109	158.9	4	47	1505	162	0.1	0.1	1500	152.6		40
110	155.3	5	1	1485	123	2.4	4.0	1500	150.2		44
111	131.0	4	20	1520	78	5.0	5.0	1485	125.6		48
112	159.6	4	28	1500	105	3.3	5.0	1515	154.7		52
113	137.8	4	20	1490	120	2.2	3.0	1505	132.5		56
114	161.7	4	53	1500	109	2.2	2.2	1500	156.0		60
115	139.0	4	28	1490	120	1.0	6.0	1500	129.6		64
116	162.0	4	30	1500	120	3.3	4.0	1505	154.8		68
117	120.0	4	25	1500	120	2.4	2.4	1500	114.0		72
118	161.5	5	20	1500	125	2.0	2.0	1500	151.2		76
119	160.0	3	50	1500	105	3.0	3.0	1510	154.3		80
120	173.0	5	15	1550	50	1.0	1.8	1475	158.5		84
121	170.2	5	0	1505	123	1.0	2.0	1475	164.5		88
122	172.7	5	15	1550	117	1.4	2.0	1475	158.4		92
123	173.3	4	25	1550	60	0.5	1.6	1475	164.5		96
124	171.3	4	58	1555	62	1.5	2.0	1475	156.8		100
125	172.0	5	0	1550	65	1.5	2.5	1475	149.8		104
126	172.2	4	23	1550	60	0.5	1.0	1450	142.8		108
127	174.7	5	25	1550	60	1.0	2.0	1450	159.0		112
128	172.4	4	25	1550	65	0.5	1.5	1470	150.7		116
129	173.8	5	10	1550	60	1.5	2.0	1455	155.0		120
130	173.7	4	15	1545	60	0.4	1.0	1450	156.4		124
131	172.1	4	4	1540	60	0.2	1.0	1465	162.0		128
132	172.6	4	40	1550	60	0.9	2.0	1475	155.8		132
133	171.2	4	52	1510	120	9.0	9.0	1475	164.9		136
134	171.0	5	15	1510	120	5.2	5.2	1475	164.0		140
135	170.1	4	28	1505	120	2.0	2.0	1475	160.0		144
136	171.3	4	57	1500	120	4.8	4.8	1475	165.3		148
137	171.0	5	2	1500	120	3.4	3.6	1475	166.0		152
138	173.0	5	0	1510	120	3.6	4.0	1475	168.3		156
139	149.3	4	44	1500	123	4.0	4.0	1475	141.9		160
140	148.3	4	23	1550	119	1.2	2.0	1480	131.2		164

(2) Normal heat numbers prefixed by letter "K."

contamination of the uranium grindings and turnings with thorium from the wash. The castings were stamped with the heat number and casting number (1 to 10 and 1 to 12 for thick and thin castings, respectively). Enriched casting numbers were prefixed with the letter E, and the natural castings were prefixed with the designation K. The castings were painted with a color code to designate U^{235} content. The castings were weighed and transferred to the machine shop for processing.

Following melting, the crucible was cleaned of skull and splash. Simple inversion of the crucible normally caused the skull to drop out. Any splash which stuck to the crucible was removed by scraping, and final removal was accomplished by oxidation with an air-gas torch in the burnout hood. Complete removal of all metal was absolutely essential to the satisfactory behavior of the wash which was applied for reuse of the crucible. Any metal beneath the coating caused spalling in that area. Stopper rods and crucible covers were also cleaned and recoated for reuse. Any damage to the tip of the stopper rods was repaired by remachining.

Machining and Testing of Castings

After weighing, the castings were transferred to the machine shop for preparation for testing and the taking of samples for chemical and spectrographic analyses. Chemical and spectrographic samples were taken from the top and bottom of two billets per heat which were cast in opposite cavities of the mold. These two selected billets from each heat were first sampled on the bottom, tapered end. A slice 1" long was taken by hacksawing transverse to the major axis of the billet. Slices were identified with the billet number and the letter "B" indicating bottom. Next, all castings from a single heat, including those already sampled, were sawed to rough length by removing the tops of the castings, allowing excess for final machining to that dimension. The thin (0.890" x 3.195" cross section) billets were sawed 10-11/16" in length, and the thick (1.240" x 3.210" cross section) billets were cut to a length of 10-9/16". All resulting pieces were marked with the casting number and the top sections were identified with the letter "T." Sampling was completed by taking a 1" long slice from the top discard sections of the same two billets from which the bottom samples were taken. The sample was taken from the end of the top crop which was adjacent to the top end of the resulting billet core. Two types of samples were made: turnings for carbon and nitrogen and minor impurities and a block sample for spectrographic analysis of the alloy additions, Zr and Nb. Great care was exercised in obtaining chip samples which were free of contamination. The end of each 1" slice which was adjacent to the usable portion (billet) of the casting was first turned to remove the rough sawed surface. Then one 5-gram and one 2-gram sample was turned from the cleaned face of each piece, collected on a stainless steel screen and transferred to sample bottles by means of tweezers. The 5-gram sample, placed in a glass-stoppered bottle, was for carbon and nitrogen determination; the

2-gram sample, placed in a plastic-capped bottle, was for determination of minor impurities. The face from which the samples were taken was then turned as smooth as possible in preparation for spectrographic analysis. All turning, including taking of samples, was done with carbide tool bits. The only coolant used was distilled water. The samples were forwarded to the Analytical Group of the ANL Chemistry Division for chemical and spectrographic analyses. The carbon determination was done using a combustion manometric method, and nitrogen was determined by the Kjeldahl method. The determination of the minor impurities was done spectrographically on an oxidized sample; the zirconium and niobium contents were evaluated by a spectrographic technique developed by J. Goleb.⁽¹³⁾ This spectrographic method used for determining zirconium and niobium was very rapid when compared with the wet analytical procedure, which first required the separation of zirconium and niobium. The spectrographic procedure was accurate to 5% of the amount present.

The top croppings were stored for remelting and the rough billet cores were finished to the dimensions shown in Figure 6 by grinding, shaping and milling. The width and thickness dimensions of the billet cores were developed by grinding on a No. 18 Blanchard Grinder having a 36" working diameter. The cores were first ground to width by removing approximately 0.040" from each side and then ground to thickness by removing about 0.030" from each face. The fixture used to clamp the cores during grinding could accommodate up to 12 cores for grinding to width or 6 cores for grinding to thickness (see Figure 22). Blanchard grinding wheels No. 9A-30-GH8U were used. A table speed of 33 rpm and a down feed of 0.008" were employed. After this grinding operation, the billet cores were inspected for soundness, which will be discussed later.

The length of the billet core and the 90° included angle taper on each end were produced by first shaping the top or untapered end and the bottom end of the cores which were sampled to rough tapered dimensions, then milling to develop final length. Six billet cores were clamped in a fixture carried on the milling machine table, as shown in Figure 23. A Milwaukee 2H plain mill was used for this operation. A face milling cutter having a 4" diameter and 6 carbide insert teeth was employed for cutting at a speed of 73 rpm and a table speed of 5-3/4" per min. Approximately 0.060" of metal was removed per pass. Cutters were reground after machining 12 cores. Following machining, the billet cores were weighed and stored, awaiting release for assembly.

As mentioned previously, the cores were inspected for soundness after grinding but before tapering in machining to length. This was done to eliminate scrap produced by this operation in the cases where billet cores were found unsound by the nondestructive testing. Grinding was found necessary before testing, because minor surface irregularities developed from wash and mold marks gave a false indication of internal defects. The non-destructive inspection used was the ultrasonic through-transmission method

FIGURE 22. Blanchard Grinder and Fixture for Grinding Billet Cores to Thickness and Width.

210-115

210-116

FIGURE 23. Milling Billet Cores to Length and Taper.

developed by Beck and McGonnagle.⁽¹⁴⁾ In brief, the method consisted of introducing the object to be tested into ultrasonic radiation generated by shocking a piezoelectric crystal (quartz) at its resonating frequency and receiving the radiation transmitted through the object by means of another matching crystal located on the opposite side of the object. The high-frequency electrical energy generated in proportion to the intensity of the ultrasonic radiation striking the receiving crystal was amplified, rectified and impressed upon the helix recorder. The recorder darkened electro-sensitive paper in proportion to the current flowing through it. Both crystals and object tested were submerged in water containing a wetting agent for good transmission of the ultrasonic radiation. The billet cores were inspected by passing the ultrasonic wave through their minor dimension (thickness). By moving the yoke which carried the receiving and sending crystals both vertically and horizontally and synchronizing these motions with those of the helix recorder and the electrosensitive paper, a two-dimensional plot was made of the intensity of the transmitted beam.

Each billet core was inspected using this ultrasonic through-transmission method. Traces, as shown in Figures 24 and 25, were obtained from which the cores were evaluated. If the trace was dark and uniform, the core was considered satisfactory; but if the trace showed white areas, the core was rejected. The dark areas indicated good transmission, while light areas indicated scattering of the radiation by some defect. Because of uncertainties engendered by anomalous ultrasonic traces of sound material, the sensitivity of the equipment was set using a standard billet containing both sound and porous material as evaluated metallographically. Apparently as discussed elsewhere⁽¹⁴⁾ the transmission of the ultrasonic beam was impeded by other physical characteristics besides unsoundness. For instance, a defective ultrasonic pattern could be converted to a sound one by heat treatment of some cast cores.

Cleaning of Castings for Billet Assembly

The billet core castings accepted for fuel plate cores with respect to chemical composition, internal soundness, surface quality, and dimensions were cleaned prior to billet assembly. This cleaning was required to remove small amounts of tarnish resulting from grinding and storage, since this tarnish would impede bonding of clad to core.

Wet abrasive blasting was selected as the means of removal of tarnish because of simplicity and safety. Alternate methods, such as sandblasting, polishing with abrasive paper, and pickling, were considered but not used. Sandblasting was not satisfactory because particles, even in the finest meshes practical for blasting in the type of equipment available, became imbedded in the uranium alloy core. Polishing with abrasive paper, which had to be restricted to a hand operation to prevent excessive heat generation, was very laborious, and complete removal of tarnish was

FIGURE 24. Ultrasonic Trace of Acceptable Billet Core and Representative Microstructure. Uniform dark trace indicates sound metal.

19781

Bright Field

250X

Sound Metal

19780

Bright Field

250X

Sound Metal

FIGURE 25. Ultrasonic Trace of Rejected Billet Core and Representative Microstructure. White areas indicate defects.

19785   Bright Field   250X
Microporosity and Segregation

19786   Bright Field   250X
Sound Metal

difficult. Removal of initial tarnish, while simultaneously preventing the formation of a secondary tarnish during pickling, made chemical cleaning unattractive. In addition to these difficulties in producing clean surfaces, the explosion hazard associated with pickling U-Zr alloys made chemical cleaning a poor choice.

The cleaning of the billet core casting was done in a wet abrasive blasting machine designed specifically for this purpose. Basically, this machine, as shown in Figure 26, was identical to those which are described later, except for the work drive mechanism and exhaust system. The work in the core blasting machine was blasted in a stationary position, thus eliminating the need for a work drive mechanism. Because of the possibility of radioactivity in the exhausted vapor, this machine was exhausted by means of the building system designed to handle radioactivity.

Blasting was done using a gun whose blast pattern was a rectangular ($1\frac{1}{2}$ " x 4"), instead of the conventional circular, pattern. This pattern was made rectangular to cover the width of the billets. In this way, uniform blasting could be obtained by simply reciprocating the gun back and forth horizontally along the length of the billet. The gun was driven by a double-acting air cylinder; reciprocation of the cylinder piston was obtained through the use of a solenoid-operated, 4-way air valve controlled by means of microswitches tripped at the limits of gun travel. The gun drive and control were located on the rear of the blasting machine cabinet.

The blasting medium used was 400 mesh alumina. The abrasive suspended in water was pumped into the gun by means of a centrifugal pump. At the gun, the abrasive was driven onto the work by means of high pressure air. Suspension of the abrasive was maintained by a second centrifugal pump whose output discharged into the hopper.

The use of very fine abrasive was necessary to prevent its being imbedded into the work. The relatively coarse particles (80 mesh) required for dry sandblasting imbedded in the work, making this method unsatisfactory. The billet cores were cleaned in the wet abrasive blasting machine described above by blasting a single side at a time. A billet core was placed beneath the gun, and the gun was permitted to reciprocate over each side for one minute. This operation removed all tarnish and produced a fine mat finish.

After abrasive blasting, the bulk of abrasive was washed from the cores with running tap water. Final removal of abrasive particles was done in the blast washing machine shown in Figure 27. In this machine tap water was run into jet type guns and driven onto the work by double-filtered, high-pressure air. The water used in this washing was not recirculated.

FIGURE 26. Wet Abrasive Blasting Machine for Cleaning Uranium Alloy Billet Cores.

FIGURE 27. Blast Washing Machine for Removal of Abrasive from Uranium Alloy Billet Cores.

106-2751

The billet cores, after blast washing, were rinsed in distilled water and then in absolute alcohol. The alcohol was permitted to evaporate in air for a short period. The billet cores were then placed in a vacuum chamber, where they were stored in the 10^{-6} mm of Hg pressure range until removed for billet assembly.

Results

During the production of EBWR fuel plates, 13,290 kg of uranium (9,525 kg of enriched and 3,765 kg of natural), 698 kg of zirconium and 209 kg of niobium were used to produce 9,868 kg of finished billet cores. The recovery from charge to finish-machined cores was therefore 69.5%.

Because of the higher monetary value of the enriched material used, more complete records were kept on the heats made from this stock than from natural uranium. Records of skull and casting weight and of soundness and chemical composition were recorded for all melts; but machining losses and amount recycled were recorded only for the enriched uranium heats. The material balance discussed below is for the enriched uranium only; but since more than 70% of the heats were enriched, the figures compiled for the enriched melts should be representative for the process.

Tabulated in Table IX are the losses and recycle croppings for the enriched heats made. From these data the material balances shown in Figure 28 were prepared. The balance for the 10-billet core melts shows an average of 42.7% of the charge going into billet assembly as acceptable cores, 40.8% recycled, and 16.5% converted to unusable skulls, machine turnings, and grindings. For the 12-billet core melts, 45.5% of the charge was converted to acceptable billet cores, 36.9% was recycled, and 17.6% ended in skull and machine scrap. Both skulls and machining scrap were sent to a recovery plant.

In terms of total materials, 9,525 kg of enriched uranium, 530 kg of zirconium sponge and 159 kg of niobium pressed powder were used to produce 9,524 kg of castings and 961 kg of skull. From this virgin material 827 acceptable castings, weighing 7,108 kg, were produced. Machining scrap amounted to 1790 kg, and 207 kg ended in chemical and spectrographic samples. At the end of production 147 kg in spectrographic samples remained. These samples, being heavy pieces, could be recycled if desired.

One attempt was made to recover the metallic portion of the skulls. A charge consisting wholly of crucible skulls from previous melts was taken to 1600°C, held for 53 minutes, and poured into a 6" diameter mold. The resultant casting was 41% of the charge and had a chemical composition acceptable for remelting, although the carbon content averaged 45 ppm. No attempt was made to recover skulls for reactor fuel plates, however.

Table IX
CASTING STATISTICS

Melt No.	Weight % of Charge to			No. of Castings	No. of Sound Castings	Good Chemistry
	Skull	Machining Loss	Recycled Croppings			
E1	-	-	-	-	-	-
2	5.99	11.2	22.3	12	12	Yes
3	6.21	10.7	23.5	12	12	Yes
4	5.49	15.0	25.7	12	12	Yes
5	3.68	10.5	25.7	12	12	Yes
6	4.56	8.9	-	12	10	Yes
7	4.66	12.7	25.7	12	10	Yes
8	5.74	9.4	25.2	12	12	Yes
9	6.34	9.8	-	12	11	Yes
10	3.97	-	-	-	-	No
11	7.69	15.8	18.0	12	11	Yes
12	7.91	8.0	22.5	12	9	Yes
13	6.48	12.2	21.5	12	9	Yes
14	-	-	-	-	-	Yes
15	5.67	10.4	17.4	12	12	Yes
16	5.35	11.7	25.1	12	12	Yes
17	4.35	16.3	24.5	12	11	Yes
18	9.05	10.1	21.7	12	11	Yes
19	5.54	11.9	22.7	12	9	Yes
20	15.4	12.2	15.5	12	10	No
21	5.50	9.7	24.5	12	11	Yes
22	6.64	10.6	23.5	12	12	Yes
23	10.8	9.3	25.1	12	10	Yes
24	5.00	15.8	24.2	12	12	Yes
25	6.85	9.7	17.7	12	10	Yes
26	5.97	12.4	22.3	12	12	Yes
27	5.33	12.8	22.5	12	9	Yes
28	5.47	15.7	22.6	12	11	Yes
29	4.83	12.5	22.7	12	11	Yes
30	6.09	10.0	18.7	12	10	Yes
31	5.75	15.6	20.6	12	8	Yes
32	7.16	12.4	20.5	12	10	Yes
33	6.55	10.6	21.1	12	5	Yes
34	5.89	11.1	19.5	12	12	Yes
35	6.20	13.3	20.8	12	11	Yes
36	5.90	10.3	24.3	12	4	Yes
37	4.36	11.4	20.2	12	10	Yes
38	5.57	13.4	20.8	12	8	Yes
39	6.89	13.1	21.2	12	12	Yes
40	5.83	10.3	23.9	12	11	Yes
41	5.92	11.6	19.8	-	-	Yes
42	7.75	7.9	16.8	-	-	Yes
43	5.11	9.9	25.7	12	12	Yes
44	7.58	13.0	19.7	12	6	Yes
45	3.67	8.2	29.9	10	5	Yes
46	5.66	11.1	21.9	10	7	Yes
47	7.70	9.3	16.7	12	10	Yes
48	6.31	11.2	21.3	10	10	Yes
49	5.93	10.4	21.5	10	8	Yes
50	5.90	11.3	22.2	10	9	Yes
51	5.33	10.8	22.0	10	9	Yes

Table IX. (Contd.)

Melt No.	Weight % of Charge to			No. of Castings	No. of Sound Castings	Good Chemistry
	Skull	Machining Loss	Recycled Croppings			
E52	2.83	12.3	25.9	10	9	Yes
53	5.32	12.0	22.6	10	3	Yes
54	6.18	11.8	21.1	10	6	Yes
55	5.52	11.6	21.9	10	10	Yes
56	5.35	11.5	22.5	10	10	Yes
57	6.46	9.9	22.3	10	7	Yes
58	4.74	11.3	23.3	10	9	Yes
59	5.32	11.0	23.0	10	7	Yes
60	4.41	11.3	23.0	10	7	Yes
61	-	-	-	-	-	No
62	6.36	8.8	-	10	10	Yes
63	5.75	10.5	23.0	10	8	Yes
64	5.84	10.5	23.2	10	9	Yes
65	5.78	9.4	23.9	10	9	Yes
66	8.82	7.0	20.0	10	3	Yes
67	4.71	10.9	25.0	10	7	Yes
68	7.03	10.8	22.4	10	8	Yes
69	-	-	-	-	-	-
70	7.64	10.4	22.4	10	8	Yes
71	7.22	10.2	22.9	10	7	Yes
72	3.03	10.8	24.4	10	8	Yes
73	6.23	10.8	24.2	10	10	Yes
74	5.81	-	24.0	10	7	Yes
75	6.13	8.2	23.7	10	6	Yes
76	5.54	10.8	23.8	10	8	Yes
77	-	-	-	-	-	No
78	4.20	11.2	23.9	10	9	Yes
79	8.03	9.3	21.4	10	6	Yes
80	5.74	9.2	26.7	10	5	Yes
81	3.88	11.8	22.6	10	10	Yes
82	4.08	10.2	23.6	10	8	Yes
83	3.95	10.3	25.2	10	10	Yes
84	4.59	11.4	22.3	-	-	Yes
85	3.24	11.4	25.3	-	-	Yes
86	7.36	10.9	20.4	10	9	Yes
87	3.11	9.4	25.8	10	7	Yes
88	4.04	11.2	23.5	-	-	Yes
89	10.37	9.4	19.1	10	8	Yes
90	9.40	10.1	19.6	10	9	Yes
91	2.34	9.2	27.0	10	6	Yes
92	5.72	10.0	24.0	10	9	Yes
93	4.19	7.1	24.6	10	1	Yes
94	6.09	9.6	22.6	10	7	Yes
95	4.05	11.4	23.9	10	10	Yes
96	6.32	9.5	22.6	10	9	Yes
97	5.74	9.8	23.2	10	8	Yes
98	5.57	10.0	23.0	10	8	Yes
99	3.59	10.3	24.3	12	11	Yes
100	3.75	11.1	23.2	10	10	Yes
101	5.88	11.7	21.7	10	9	No
102	6.01	10.7	23.1	10	8	Yes

Table IX. (Contd.)

Melt No.	Weight % of Charge to			No. of Castings	No. of Sound Castings	Good Chemistry
	Skull	Machining Loss	Recycled Croppings			
E103	5.26	11.5	22.8	10	10	Yes
104	6.02	10.7	22.8	10	10	Yes
105	7.20	9.2	21.6	-	-	No
106	6.07	13.0	19.7	12	8	Yes
107	5.22	11.2	22.8	12	6	Yes
K 95	8.25			10	7	Yes
96	6.77			10	8	Yes
97	7.15			12	9	Yes
98	11.90			10	6	No
99	6.55			-	-	Yes
100	-			-	-	-
101	-			-	-	-
102	2.34			12	2	Yes
103	10.90			-	-	No
104	3.08			12	12	Yes
105	5.10			12	9	No
106	2.54			12	12	Yes
107	5.44			10	10	Yes
108	5.14			10	7	Yes
109	3.96			10	10	Yes
110	3.28			12	12	Yes
111	4.11			12	10	Yes
112	3.07			12	12	Yes
113	3.84			12	10	No
114	3.51			12	12	Yes
115	6.76			12	10	Yes
116	4.44			12	8	Yes
117	5.00			10	4	Yes
118	6.38			12	11	Yes
119	3.56			10	7	Yes
120	8.39			10	10	Yes
121	3.36			10	10	Yes
122	8.28			10	9	Yes
123	5.08			10	10	Yes
124	8.50			-	-	No
125	12.90			10	9	Yes
126	17.35			10	5	Yes
127	8.98			10	9	Yes
128	12.59			-	-	No
129	10.80			-	-	No
130	9.95			-	-	No
131	5.82			10	10	Yes
132	9.71			10	8	Yes
133	3.69			10	10	Yes
134	4.09			10	9	Yes
135	5.88			10	5	Yes
136	3.51			10	10	Yes
137	2.93			10	9	Yes
138	2.72			10	10	Yes
139	4.96			12	11	Yes
140	11.53			12	11	Yes

FIGURE 28. Material Balance for Enriched Thin and Thick Billet Core Castings
Averages for Individual Heats

The surface quality of the as-cast cores (shown in Figure 29) was good. None of the billet cores in the as-cast condition were rejected because of cold shuts or blowholes. After machining, the billet cores in general were of acceptable surface quality. Only 0.7% of the billet cores produced were rejected for a surface porosity condition. The surface quality of an acceptable core is shown in Figure 30.

The cause of the highest number of rejected castings was internal unsoundness indicated by the ultrasonic test. Rejection from this type of defect amounted to approximately 11% of the billet cores produced. A major fraction of these rejects was the result of insufficient length to permit cropping of the unsound metal which usually occurred at the top of the casting. A contributing factor in this shortness was the fear of overfilling the mold, which usually resulted in destruction of both mold and crucible upon removal of the casting. This insurance against overfilling, coupled with variations in skull losses, caused some castings to be short. The close control necessary over the amount of metal poured is evident when considering that less than 1% variation in the weight would cause rejection of one casting in a heat.

Approximately 6% of the cores cast were rejected on alloy composition. Based on nuclear considerations, the average alloy composition and range was set at 5 w/o $\pm$ 1.5 w/o Zr and 1.5 w/o $\pm$ 0.26 w/o Nb. The average zirconium concentration of all acceptable alloy was 4.87 w/o, with a high of 5.60 w/o and a low of 3.71 w/o. The niobium concentration averaged 1.55 w/o and had a high value of 1.91 w/o and a low of 1.23 w/o. The average, high, and low values of carbon content were 22 ppm, 96 ppm, and 6 ppm, respectively; corresponding values for nitrogen were 14 ppm, 48 ppm and < 10 ppm respectively. The chemical and spectrographic analyses of all heats are given in Table X.

Typical metallographic structures of the reference alloy are shown in Figure 31 in the as-cast condition, both from the top and bottom of the castings. The structures as shown in these photomicrographs are two-phase, alpha uranium and zirconium-niobium rich gamma phase developed upon slow cooling from the gamma phase through the beta + gamma to the stable alpha + gamma phase.⁽¹¹⁾ The structure is basket weave typical of low zirconium alloys. Small variations in the content of either alloy does not markedly alter the structure. The largest difference lies in the grain size between top and bottom of the casting. This larger top grain size was developed by the slower cooling rate at the top of the mold than the bottom. The grain size observable in the photomicrographs originated in the gamma-phase field. The inclusions present in the structure were presumed to be compounds of the charge materials and impurities.

FIGURE 29. Cladding Billet Core Castings.

106-3068

FIGURE 30. Finish Machined Billet Core Casting.

106-3069

Table X

COMPOSITION OF HEATS FOR EBWR FUEL PLATE CORES

Heat No.	Alloy Content ⁽²⁾						Impurities												
	Zr, w/o			Nb, w/o			Minor Elements, ppm ⁽³⁾												
	High	Low	Avg.	High	Low	Avg.	Al	B	Cr	Cu	Fe	Mg	Mn	Ni	Si	Mo	Ca	C	N
El ⁽¹⁾	-	-	-	-	-	-													
2	5.07	4.45	4.87	1.62	1.48	1.55	10	0.1	1	5	50	1	4	10	40			27	11
3	5.50	4.90	5.17	1.64	1.53	1.59	10	0.3	1	10	50	1	4	30	30			24	10
4	5.25	5.05	5.17	1.92	1.88	1.90	10	0.2	1	10	50	1	4	25	30			14	12
5	5.23	4.95	5.07	1.94	1.83	1.91	10	0.2	1	10	50	1	4	30	30			25	11
6	4.60	4.22	4.34	1.87	1.68	1.76	10	0.2	1	5	50	2	4	15	20			15	<10
7	5.00	4.25	4.68	1.78	1.73	1.75	10	0.2	1	5	60	2	4	15	30			14	<10
8	4.85	4.60	4.72	1.86	1.74	1.80	10	0.2	1	5	55	2	4	10	35			16	11
9	5.60	4.35	4.69	2.05	1.70	1.80	10	<0.1	1	5	55	1	4	15	40			96	14
10	5.70	5.05	5.23	2.05	1.85	1.93	10	<0.1	2	10	50	2	6	15	30			15	<10
11	5.45	4.20	4.69	1.94	1.68	1.79	10	<0.1	1	5	55	1	4	15	35			42	11
12	5.05	4.90	4.94	1.90	1.73	1.82	10	0.1	1	5	40	1	4	10	25			36	<10
13	4.85	4.55	4.70	1.85	1.83	1.84	10	0.5	1	5	40	1	4	10	30	25		32	<10
14	-	-	-	-	-	-													
15	5.15	4.80	5.01	1.90	1.80	1.86	10	0.4	1	5	40	1	4	10	30			41	11
16	5.45	4.98	5.13	2.00	1.78	1.87	10	0.1	1	10	40	1	4	30	30			22	<10
17	5.50	4.25	4.93	1.92	1.55	1.74	10	<0.1	1	5	45	1	4	15	30			23	<10
18	5.05	4.75	4.96	1.95	1.80	1.87	10	<0.1	1	5	40	1	4	30	30			22	<10
19	5.40	5.05	5.25	1.91	1.82	1.87	10	0.2	1	10	30	2	5	15	25			18	<10
20	5.82	5.65	5.77	2.05	1.95	2.01	10	<0.1	2	10	35	2	6	10	30			22	11
21	4.80	4.45	4.68	1.52	1.42	1.50	10	<0.1	1	10	40	2	5	20	30			12	<10
22	5.10	4.90	5.02	1.52	1.47	1.50	10	0.1	1	10	40	2	5	15	30			12	<10
23	5.45	4.90	5.05	1.58	1.46	1.52	10	0.1	1	10	40	2	5	20	30			12	<10
24	5.20	4.90	5.07	1.56	1.43	1.51	10	0.2	1	10	40	2	5	15	30			14	13
25	5.20	5.05	5.11	1.54	1.47	1.50	10	0.1	1	10	30	2	5	10	20			10	11
26	5.70	4.90	5.24	1.64	1.45	1.53	10	0.1	1	10	30	2	5	10	30			12	<10
27	5.25	5.10	5.19	1.57	1.50	1.53	10	0.1	1	10	30	2	5	15	30			25	17
28	5.15	4.80	4.01	1.59	1.46	1.52	10	0.1	1	10	30	2	5	18	30			14	<10
29	5.55	4.95	5.13	1.55	1.48	1.52	10	0.2	1	10	35	2	5	10	30			14	<10
30	5.40	5.15	5.25	1.58	1.52	1.55	10	0.1	1	10	35	2	5	15	20			12	<10
31	4.80	4.60	4.69	1.50	1.42	1.46	10	0.1	1	10	40	2	5	15	20			13	<10

⁽¹⁾ Enriched uranium (1.44% U²³⁵) heats prefixed with letter "E."

⁽²⁾ Zr and Nb composition accurate within 5 w/o of amount present.

⁽³⁾ Minor impurities accurate to an order of magnitude.

Table X. (Contd.)

Heat No.	Alloy Content						Impurities												
	Zr, w/o			Nb, w/o			Minor Elements, ppm												
	High	Low	Avg.	High	Low	Avg.	Al	B	Cr	Cu	Fe	Mg	Mn	Ni	Si	Mo	Ca	C	N
E32	5.05	4.65	4.86	1.54	1.44	1.47	10	0.1	1	10	40	2	5	13	20			27	<10
33	5.00	4.68	4.83	1.53	1.40	1.48	10	<0.1	2	10	50	2	6	15	30			17	<10
34	5.05	4.75	4.94	1.50	1.43	1.47	10	<0.1	2	10	50	2	6	10	30			25	<10
35	5.80	5.32	5.46	1.62	1.49	1.54	10	0.1	2	10	50	2	6	15	30			20	<10
36	5.15	5.00	5.08	1.57	1.50	1.54	10	0.1	2	10	50	2	6	15	30		25	18	<10
37	5.33	5.25	5.30	1.63	1.57	1.60	10	0.1	2	10	60	2	6	15	30			21	<10
38	5.50	5.28	5.38	1.65	1.57	1.62	10	0.1	2	10	50	2	6	15	30			38	<10
39	5.90	5.25	5.55	1.70	1.56	1.61	10	0.1	2	10	50	2	6	15	30			32	<10
40	5.90	5.45	5.60	1.70	1.63	1.66	10	<0.1	2	10	50	2	6	15	30			34	<10
41	5.25	5.20	5.24	1.59	1.53	1.57	10	0.1	2	10	50	2	6	10	30		25	30	16
42	5.55	5.20	5.38	1.50	1.48	1.49	10	0.1	2	10	50	2	6	15	30			32	<10
43	5.15	5.00	5.07	1.60	1.58	1.59	10	0.1	2	10	50	2	6	10	30			26	<10
44	5.40	5.20	5.35	1.67	1.56	1.61	10	0.1	2	150	60	2	6	300	30	40		30	<10
45	5.42	5.18	5.24	1.64	1.61	1.62	10	0.1	2	7	55	2	6	10	30			20	<10
46	5.80	5.00	5.30	1.57	1.43	1.49	10	0.1	2	50	85	3	5	25	50			20	<10
47	5.85	5.50	5.64	1.56	1.52	1.53	10	0.2	3	30	50	3	5	150	50			14	<10
48	5.80	4.90	5.28	1.50	1.42	1.48	10	0.4	3	20	50	2	5	75	30			21	<10
49	5.55	4.90	5.25	1.60	1.34	1.46	10	0.4	3	15	160	3	5	20	30			12	<10
50	5.15	5.05	5.10	1.46	1.36	1.41	10	0.3	3	10	40	3	5	10	30			22	<10
51	5.10	5.00	5.07	1.52	1.46	1.50	10	0.3	3	15	45	3	5	30	30			77	<10
52	5.10	4.05	4.78	1.54	1.27	1.44	10	0.3	3	12	45	3	5	40	30			18	<10
53	5.30	4.85	5.02	1.53	1.43	1.49	10	0.2	2	25	40	3	5	30	40		25	14	<10
54	5.35	5.25	5.30	1.55	1.50	1.53	10	0.4	3	30	60	3	5	20	30			34	<10
55	5.20	4.90	5.00	1.52	1.40	1.46	10	0.2	2	150	60	3	5	150	40			22	<10
56	5.00	4.90	4.95	1.52	1.46	1.48	10	0.2	2	75	55	3	5	150	40			13	<10
57	5.00	4.80	4.89	1.53	1.40	1.46	10	0.2	2	40	70	3	5	50	40			18	<10
58	4.90	4.60	4.83	1.48	1.40	1.44	10	0.1	2	25	60	3	5	50	50			14	<10
59	5.30	4.65	5.05	1.55	1.42	1.49	10	0.2	2	20	60	3	5	50	45			14	<10
60	5.65	4.65	5.00	1.48	1.34	1.43	10	0.2	2	150	80	3	5	150	40			13	<10
61	5.35	4.15	4.86	1.53	1.13	1.34	10	0.5	3	7	60	2	27	20	40			64	16
62	5.35	5.00	5.12	1.48	1.41	1.45	10	0.5	3	20	70	2	5	100	50			10	<10
63	5.25	4.65	5.12	1.58	1.47	1.45	10	0.5	3	5	60	2	5	20	50			34	<10
64	5.05	4.75	4.91	1.52	1.40	1.45	10	0.5	3	15	55	2	5	55	50			8	<10
65	5.30	4.50	4.86	1.54	1.39	1.45	10	0.3	3	10	55	2	5	35	50			8	<10
66	4.95	4.65	4.80	1.50	1.46	1.48	10	0.5	3	15	50	2	22	30	75			78	<10
67	4.85	4.30	4.58	1.45	1.41	1.43	10	0.2	3	5	55	2	5	18	50			18	<10
68	4.70	4.15	4.45	1.43	1.34	1.40	10	0.2	3	5	250	2	5	20	75			7	<10
69	-	-	-	-	-	-													
70	4.85	4.50	4.66	1.49	1.39	1.45	10	0.4	3	5	60	2	5	20	50			8	<10

Table X. (Contd.)

Heat No.	Alloy Content						Impurities												
	Zr, w/o			Nb, w/o			Minor Elements, ppm												
	High	Low	Avg.	High	Low	Avg.	Al	B	Cr	Cu	Fe	Mg	Mn	Ni	Si	Mo	Ca	C	N
E 71	4.80	4.50	4.67	1.43	1.38	1.40	10	0.2	3	9	60	2	5	30	50			14	<10
72	4.70	4.65	4.66	1.53	1.48	1.51	10	0.4	3	10	60	2	5	20	50			19	11
73	5.00	4.65	4.78	1.51	1.39	1.42	10	0.4	3	10	55	2	5	70	40			6	10
74	5.10	4.85	4.95	1.47	1.43	1.45	10	0.2	1	10	50	2	5	10	50			23	<10
75	5.00	4.70	4.81	1.50	1.42	1.45	10	0.2	1	20	40	2	5	30	30			23	13
76	5.05	4.85	4.90	1.50	1.42	1.47	10	0.2	1	15	60	2	5	12	40		30	18	<10
77	5.40	4.15	4.70	1.69	1.10	1.34	10	0.1	1	20	60	2	5	30	50			32	<10
78	5.40	4.65	4.91	1.59	1.45	1.51	10	0.3	1	40	60	2	5	40	55			16	<10
79	4.90	4.75	4.81	1.41	1.36	1.38	10	0.1	1	30	50	2	3	50	45			24	10
80	5.35	4.70	4.98	1.58	1.50	1.54	10	0.1	1	20	50	2	3	12	40		25	26	20
81	5.40	4.88	5.06	1.63	1.54	1.59	10	0.2	1	15	40	2	6	20	30			17	<10
82	5.50	4.85	5.07	1.62	1.45	1.50	10	0.2	1	15	50	2	4	50	35			14	<10
83	4.79	4.52	4.66	1.49	1.43	1.47	10	0.1	2	15	40	2	8	50	20			16	<10
84	4.86	4.62	4.69	1.61	1.49	1.58	10	0.2	1	15	40	2	5	50	25			17	<10
85	5.36	3.89	4.63	1.72	1.35	1.52	10	0.2	1	15	45	2	7	50	25			10	13
86	5.13	4.68	4.91	1.63	1.54	1.58	10	0.4	1	15	50	2	9	50	35			14	10
87	4.98	4.59	4.82	1.60	1.51	1.58	10	0.3	1	15	45	2	9	15	40			15	<10
88	4.53	4.21	4.35	1.49	1.44	1.46	10	0.3	1	15	50	2	9	50	30			10	<10
89	4.95	4.65	4.87	1.63	1.58	1.60	10	0.4	1	15	55	2	9	50	40			18	<10
90	5.04	4.63	4.88	1.71	1.57	1.65	10	0.4	1	15	60	2	7	50	25			12	<10
91	5.20	4.98	5.04	1.74	1.67	1.70	10	0.3	1	15	40	2	6	50	25			12	<10
92	5.59	4.20	4.67	1.85	1.56	1.69	10	0.3	1	15	45	2	8	50	20			14	<10
93	5.12	4.65	4.81	1.64	1.52	1.58	10	0.2	3	10	50	4	6	30	105			20	10
94	4.72	3.83	4.35	1.57	1.35	1.46	10	0.2	1	15	40	2	6	50	50			20	11
95	4.77	4.63	4.67	1.74	1.67	1.70	10	0.1	3	10	50	4	5	20	40			60	10
96	4.95	4.53	4.76	1.72	1.66	1.69	10	0.2	3	10	55	2	4	18	60			23	<10
97	4.63	4.28	4.53	1.62	1.32	1.45	10	0.2	3	10	50	2	4	18	105			14	<10
98	4.75	4.53	4.62	1.56	1.46	1.50	10	0.3	3	10	45	2	4	18	150			18	17
99	5.03	4.53	4.66	1.68	1.53	1.58	10	0.5	3	10	65	2	4	20	70				
100	5.90	5.25	5.45	1.63	1.58	1.61	10	0.3	3	10	40	2	4	20	80				
101	5.50	5.10	5.23	1.14	1.10	1.12	10	0.3	3	10	40	2	4	18	75				
102	4.90	4.65	4.80	1.46	1.41	1.44	10	0.3	3	10	50	2	5	18	75				
103	4.85	4.55	4.78	1.45	1.30	1.39	10	0.2	3	10	50	2	5	20	98				
104	5.50	4.85	5.15	1.55	1.43	1.49	10	0.3	3	10	60	2	5	15	50				
105	5.20	4.50	4.89	0.98	0.94	0.96	10	0.3	3	10	55	4	5	20	55				
106	4.95	4.75	4.86	1.47	1.42	1.44	10	0.3	4	7	70	2	5	20	60				
107	5.15	4.80	4.98	1.42	1.38	1.40	10	0.2	4	7	70	2	5	15	60				

Table X. (Contd.)

Heat No.	Alloy Content						Impurities													
	Zr, w/o			Nb, w/o			Minor Elements, ppm													
	High	Low	Avg.	High	Low	Avg.	Al	B	Cr	Cu	Fe	Mg	Mn	Ni	Si	Mo	Ca	C	N	
K95 ⁽⁴⁾	5.50	4.40	4.77	1.70	1.46	1.53	10	<0.1	5	7	60	2	4	30	30			88	48	
96	5.35	4.75	5.05	1.68	1.58	1.64	-	-	-	-	-	-	-	-	-			-	-	
97	5.25	4.85	4.99	1.47	1.42	1.44	10	<0.1	5	7	60	2	3	20	60	200		17	<10	
98	4.20	3.00	3.71	1.60	1.15	1.43	10	0.1	5	7	60	2	3	20	40	200		18	<10	
99	5.50	4.85	5.14	1.55	1.48	1.52	10	<0.1	5	7	60	2	3	20	50	200		22	11	
100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	
101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	
102	5.00	4.50	4.74	1.64	1.44	1.52	10	0.2	5	7	80	2	3	20	100			15	<10	
103	5.10	3.75	4.73	1.58	1.28	1.50	10	0.1	3	10	50	2	2	80	50			61	21	
104	4.88	4.50	4.68	1.52	1.43	1.48	10	0.1	3	10	40	2	2	20	50			28	<10	
105	5.95	3.80	4.78	1.84	1.20	1.55	10	0.1	3	10	50	2	2	20	70			21	<10	
106	5.30	4.60	4.98	1.71	1.49	1.60	10	0.2	3	10	50	5	4	30	40			20	21	
107	5.35	5.10	5.18	1.75	1.50	1.61	10	0.1	3	10	50	3	4	20	50			12	<10	
108	4.80	4.65	4.73	1.62	1.52	1.58	-	-	-	-	-	-	-	-	-			-	-	
109	4.80	4.45	4.68	1.53	1.43	1.49	-	-	-	-	-	-	-	-	-			-	-	
110	6.15	5.30	5.56	1.70	1.55	1.62	10	<0.1	3	10	60	3	2	20	30			38	<10	
111	5.50	5.25	5.41	1.56	1.53	1.54	10	<0.1	3	10	50	3	2	30	30			38	<10	
112	5.40	5.17	5.21	1.68	1.65	1.66	10	<0.1	10	10	60	3	2	30	30			69	<10	
113	4.50	3.95	4.11	1.27	1.18	1.23	10	0.1	-	7	60	3	4	20	45			19	<10	
114	5.05	4.65	4.83	1.521	1.52	1.49	10	0.1	-	5	55	3	5	20	40			15	13	
115	5.10	4.85	4.93	1.72	1.60	1.67	10	0.1	-	33	65	3	4	20	40			22	<10	
116	5.15	4.90	5.05	1.58	1.50	1.55	10	0.1	7	10	65	3	2	20	40			41	<10	
117	5.10	4.65	4.89	1.54	1.47	1.51	10	<0.1	6	10	60	3	3	20	35			45	<10	
118	4.70	3.80	4.33	1.55	1.32	1.43	10	0.2	5	5	70	1	4	30	30	60		15	<10	
119	5.10	4.45	4.73	1.71	1.52	1.64	10	0.2	5	5	70	1	4	30	45	60		19	<10	
120	4.98	4.25	4.67	1.70	1.44	1.61	10	0.1	7	10	60	3	3	30	75			6	14	
121	4.95	3.69	4.32	1.75	1.34	1.54	10	0.1	3	10	50	3	2	30	150			22	<10	
122	4.75	4.34	4.54	1.63	1.44	1.53	10	0.1	3	10	50	3	3	30	100			6	12	
123	4.67	4.46	4.54	1.59	1.53	1.54	10	0.1	2	10	60	2	2	30	75			10	<10	
124	4.52	3.69	4.12	1.60	1.14	1.34	10	0.1	2	10	60	2	2	30	50			21	12	
125	4.74	4.39	4.52	1.53	1.46	1.50	10	0.1	4	10	60	2	5	30	75			8	13	
126	4.20	4.03	4.14	1.52	1.44	1.48	10	0.1	5	10	50	2	2	25	50			9	18	
127	4.75	4.11	4.45	1.66	1.40	1.54	10	0.1	5	10	55	2	3	30	40			10	22	
128	5.02	3.43	4.14	1.99	0.90	1.30	10	0.1	5	10	50	2	5	15	35			22	12	
129	4.46	3.62	3.99	1.70	0.93	1.22	10	0.1	6	10	50	2	5	30	65			14	13	
130	5.79	3.40	4.46	2.27	0.76	1.48	10	0.1	7	10	50	2	2	30	50			15	12	
131	4.81	4.60	4.74	1.63	1.58	1.60	10	0.2	5	10	60	3	4	30	60			8	13	
132	4.96	4.46	4.59	1.48	1.45	1.47	10	0.1	3	10	40	2	2	30	70			10	18	
133	5.25	4.80	4.94	1.64	1.52	1.56	10	0.3	12	7	125	3	6	20	150					
134	4.95	4.00	4.49	1.54	1.30	1.42	10	0.3	10	7	60	3	5	20	125					
135	5.20	4.85	4.99	1.55	1.42	1.49	10	0.3	10	7	85	3	5	20	100					
136	5.05	4.80	4.98	1.40	1.35	1.37	10	0.3	10	7	65	2	5	20	85					
137	4.95	4.65	4.85	1.47	1.40	1.44	10	0.3	10	7	65	2	5	20	60					
138	4.70	4.55	4.62	1.28	1.22	1.24	10	0.3	10	7	70	2	5	20	60					
139	5.05	4.85	4.96	1.62	1.53	1.58	10	0.3	10	7	65	2	5	20	60					
140	4.80	4.40	4.65	1.48	1.45	1.46	10	0.1	10	7	110	2	5	20	60					

(4) Natural Uranium (0.7% U²³⁵) heats prefixed with letter "K."

FIGURE 31. Microstructures of As-Cast Reference Core Alloy. Top Row from Top of Casting. Bottom Row from Bottom of Casting. Phases Present are Alpha U and Zr-Nb Rich Gamma.

20083 Bright Field 250X

5.05 w/o Zr-1.50 w/o Nb

20084 Bright Field 250X

4.96 w/o Zr-1.48 w/o Nb

20095 Bright Field 250X

5.00 w/o Zr-1.64 w/o Nb

20215 Bright Field 250X

5.10 w/o Zr-1.51 w/o Nb

20081 Bright Field 250X

5.00 w/o Zr-1.52 w/o Nb

20079 Bright Field 250X

4.95 w/o Zr-1.52 w/o Nb

20097 Bright Field 250X

4.98 w/o Zr-1.70 w/o Nb

20209 Bright Field 250X

5.15 w/o Zr-1.50 w/o Nb

Labor Burden

Three technicians and one staff supervisor were engaged in the foundry producing the billet core castings. A ten-hour staggered shift schedule was employed to obtain two heats (4-1/2 hour duration) with the single 50-kw, high-frequency generator available. The production capacity was approximately 22 cores per day. The labor burden per acceptable billet core casting was calculated to be 1.45 man-hours technician and 0.48 man-hour supervision.

ZIRCALOY-2 CLADDING COMPONENT PROCESSING

A major object in the production of the Zircaloy-2 components required for cladding was to evaluate, on a modest scale, a practice previously developed⁽⁶⁾ whereby stock could be produced acceptable for use without extensive surface machining to remove contamination and defects from the finished product. Attempts were made to find commercial producers who were willing and able to produce Zircaloy-2 cladding stock for the EBWR fuel plates which would meet the above requirement. The limited success in obtaining stock during trial runs by commercial producers which could be used without surface machining prompted the decision to fabricate the Zircaloy-2 ingot at Argonne.

The manufacturing sequence consisted in general of: (1) forging ingot to slab, (2) scalping slab on two major faces to remove ingot and forging defects, (3) hot rolling to an intermediate thickness, (4) cleaning by wet abrasive blasting, (5) warm rolling to final thickness plus cleanup, and (6) final cleaning by wet abrasive blasting.

Forging

Cladding component stock in the form of double arc-melted ingot was purchased from commercial producers. The ingots from Allegheny-Ludlum were nominally 12" diameter weighing approximately 1000 lb, and those from Firth-Sterling were 12" diameter weighing 275 to 650 lb. The Firth-Sterling ingots, however, were not used in the production of fuel plates. All ingots were produced in accordance with Westinghouse Atomic Power Division specifications. Chemical and spectrographic analyses and sonic test data for ingots used in production are given in Table XI. All ingots were conditioned by turning.

The first operation performed on the Zircaloy-2 ingots was forging to slabs of 3" x 9" cross section. The 3" dimension was established because of the capacity of the 17" x 24" mill available at ANL. The 9" dimension permitted the cutting of both cover and side plates in multiples across the width of the resulting rolled strip without resorting to undesirable⁽⁶⁾ cross rolling.

The forging was done at the Anderson-Shumaker Company of Chicago. This shop specialized in alloy and tool steel forging; because of the temperature controls available on their heating equipment and appreciation of the supervision and employees of the need for close temperature control and the more difficult forging jobs, this company was selected to do the work.

For forging, the ingots, singly or in groups, were preheated to 925°C (1700°F) in an automatically controlled, gas-fired furnace. The ingots were placed in the furnace after it had cooled overnight to perhaps 550°C (1000°F); the furnace was then turned on. Approximately two hours were required to bring the furnace to the control temperature of 925°C, and three hours were allotted for soaking. Total heating time was

Table XI
INGOT DATA FOR ZIRCALOY-2 INGOTS USED FOR EBWR PRODUCTION PLATE CLADDING

Ingot No.	Date Melted	Zr Sponge Blend No.	Gross Melted Weight (lb)	Conditioned Weight (lb)	Conditioning Loss		Wt. Rolled for Cladding Components (lb)	Composition								Impurities				Brinell Hardness		Reflectascope Results	
								Tin, %		Iron, %		Chromium, %		Nickel, %		Sum of Avg. Fe, Cr, Ni	Nitrogen, ppm		Carbon, ppm				
					(lb)	(%)		Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range		Avg.	Range	Avg.	Range	Top	Bot.	Avg.
5Y912	10-4-55	Q-79	971	915	56	5.77	440.2	1.40	1.37-1.43	0.102	0.100-0.104	0.105	0.100-0.105	0.047	0.044-0.048	0.254	43	28-55	200	200	165	163-170	Porosity in top 7"
5Y914	10-5-55	Q-79	978	933	45	4.60	760.1	1.40	1.38-1.44	0.099	0.097-0.101	0.106	0.102-0.112	0.047	0.044-0.048	0.252	33	25-40	190	190	170	163-179	Center voids in top 10"
5Y919	10-7-55	Q-79	1008	954	54	5.36	765.3	1.39	1.35-1.46	0.099	0.097-0.104	0.101	0.100-0.105	0.045	0.044-0.047	0.245	50	45-63	250	240	168	160-179	Center voids in top 10"
5Y921	10-8-55	Q-86	1027	953	74	7.20	856.0	1.38	1.35-1.44	0.100	0.098-0.106	0.102	0.098-0.106	0.046	0.044-0.047	0.248	58	45-63	280	250	167	161-174	Center voids in top 10"
5Y926	10-12-55	Q-86	994	934	60	6.04	807.4	1.34	1.29-1.38	0.107	0.103-0.113	0.106	0.102-0.110	0.047	0.044-0.048	0.260	54	50-58	200	360	173	166-179	Center voids in top 10"
5Y927	10-12-55	Q-86	1010	954	56	5.54	645.4	1.39	1.35-1.41	0.102	0.101-0.104	0.107	0.102-0.110	0.046	0.044-0.047	0.255	51	45-58	280	320	175	163-183	Porosity in top 10"
5Y931	10-14-55	Q-90	1030	967	63	6.12	530.5	1.43	1.37-1.50	0.118	0.107-0.125	0.108	0.106-0.110	0.046	0.044-0.047	0.272	51	45-55	200	220	167	163-176	Porosity in top 10"
5Y932	10-14-55	Q-90	1017	956	61	6.00	806.2	1.36	1.31-1.42	0.123	0.114-0.128	0.108	0.102-0.111	0.047	0.044-0.050	0.278	38	35-40	310	310	178	170-187	Porosity in top 10"
5Y938	10-18-55	Q-92	1017	953	64	6.29	873.6	1.39	1.36-1.42	0.125	0.114-0.130	0.108	0.105-0.115	0.046	0.044-0.048	0.279	43	35-48	260	350	175	170-183	Porosity in top 8"
5Y939	10-18-55	Q-92	995	937	58	5.83	858.4	1.41	1.36-1.45	0.126	0.116-0.135	0.108	0.102-0.112	0.047	0.044-0.050	0.281	42	38-50	280	300	170	163-179	Porosity in top 9"
5Y942	10-18-55	Q-92	1003	946	57	5.68	837.0	1.39	1.39-1.40	0.127	0.118-0.132	0.104	0.100-0.107	0.045	0.044-0.047	0.276	41	33-45	270	390	178	168-187	Porosity in top 9"
5Y943	10-20-55	Q-92	1021	964	57	5.58	876.1	1.41	1.35-1.46	0.127	0.120-0.131	0.100	0.098-0.102	0.044	0.042-0.047	0.271	32	28-38	220	310	178	170-187	Porosity in top 7"
5Y954	10-27-55	Q-93	1041	979	62	5.96	376.6	1.46	1.39-1.63	0.129	0.123-0.132	0.103	0.099-0.107	0.046	0.044-0.050	0.278	36	28-40	270	490	177	167-183	Porosity in top 7"
5Y960	10-31-55	Q-93	993	929	64	6.44	623.8	1.44	1.42-1.46	0.126	0.119-0.131	0.106	0.101-0.112	0.045	0.044-0.048	0.287	33	25-38	250	410	176	170-179	Porosity in top 10"
5Y963	11-2-55	Q-93	993	937	56	5.64	708.8	1.43	1.39-1.48	0.127	0.123-0.130	0.104	0.100-0.107	0.046	0.045-0.047	0.277	25	20-33	310	430	172	163-179	Porosity in top 28"
5Y967	11-3-55	Q-85	1028	967	61	5.93	78.7	1.38	1.35-1.43	0.115	0.107-0.126	0.104	0.100-0.107	0.046	0.044-0.047	0.265	33	25-40	270	220	176	170-179	Porosity in top 11"
5Y971	11-5-55	Q-85	954	906	48	5.03	211.9	1.46	1.40-1.56	0.110	0.101-9.126	0.101	0.098-0.105	0.047	0.044-0.048	0.258	32	23-38	390	450	178	174-179	Porosity in top 10"
5Y972	11-5-55	Q-85	1008	949	59	5.85	403.3	1.42	1.35-1.49	0.103	0.101-0.106	0.102	0.099-0.107	0.046	0.044-0.048	0.251	30	25-38	240	290	171	159-175	Porosity in top 11"
5Y977	11-8-55	Q-88	1033	972	61	5.90	467.4	1.43	1.35-1.51	0.110	0.103-0.117	0.103	0.102-0.106	0.046	0.044-0.047	0.259	34	30-43	200	220	177	167-187	Porosity in top 11"

therefore in the neighborhood of five hours. After heating to the forging temperature, the billets, one at a time, were removed from the furnace, as shown in Figure 32, and transported on a monorail to the 4000-lb steam forge hammer where reductions with heavy blows were made (Figure 33). Forging was initiated at roughly the center of the billet; work progressed toward one end, making reductions of about $3/4$ " per pass. Forging progressed in the pattern of one flattening pass followed by an edging pass, pictured in Figure 34, until one end of the billet was drawn down to the finish dimensions of 3" x 9" cross section.

The butt end of the billet, having cooled by time and tong grip, then required reheating before forging could be completed. The tongs were moved to the forged end of the billet, and the partially finished billet was moved to the forging furnace and entered for reheating the unforged end. Following a reheat of close to one hour, reduction of the unforged end, pictured in Figure 35, was accomplished in the pattern of facing and edging passes discussed previously. Following forging, the 3" x 9" x approx. 13' slabs were air cooled for return to ANL. Two finished forgings are shown in Figure 36. Forging data are contained in Table XII.

The only difficulty experienced during forging was cracking of the slab at or near its ends, as may be seen by inspection of Figure 37. In no case, however, was it necessary to discontinue forging for the removal of the defects.

Scalping

The second step in the sequence of operations in preparation of cladding stock was cutting and scalping of the forged slab. The cutting of the forged slabs into shorter block was essential so that a reasonable reduction could be made in rolling and still be able to employ intermediate reheatings in the seven (7)-ft long uniformly heated zone of the furnace used. Reheating was necessary in rolling a quality product on the single stand mill available. The scalping procedure was found necessary to the production of a satisfactory surface, for, if defects generated in the forging or originating from the ingot were permitted to accompany the blocks into the rolling operations, the same defects were found in the finished-rolled product, changed in shape of course, and perhaps magnified. The removal of surface defects at this early stage had the advantage of minimum surface area for machining and ease in clamping for machining. Machining was selected over spot grinding because in grinding complete removal of defects was difficult, since smearing obscured the defects. The slab was first cut into lengths convenient to handle in the mill and heating equipment available at ANL. A length of 13" was established as satisfactory to reheat during rolling. Next, the surface forging and residual ingot defects were removed by scalping approximately $1/16$ " from the two major (9" x 13") faces of the blocks. No machining was done on the sides of the original forging. The scalping was done either by planing or turning.

FIGURE 32. Withdrawing 1000-lb Zircaloy-2 Ingot from Furnace for Forging.

FIGURE 33. Start of Forging Zircaloy-2 Ingot on 4000-lb Steam Hammer

FIGURE 34. Edging Pass on Zircaloy-2 Slab.

FIGURE 35. Forging Butt End of Zircaloy-2 Slab.

FIGURE 36. Finished Zircaloy-2 Forgings, 3" x 9" x 13'.

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Table XII

FORGING DATA FOR CONVERSION OF 12" DIAMETER ZIRCALOY-2 INGOTS INTO 3" x 9" SLABS

Ingot No.	Ingot Wt, lb	Preheat		Forging and Reheating Cycle			No. of Passes		Remarks
		Temp, °C	Time, hr-min	1st Forging Time, min	Reheat Time, min	2nd Forging Time, min	Edged	Faced	
5Y912	915	925	4-0	16	50	13	16	26	Forged OK
5Y914	933	925	4-0	18	55	12	15	25	Forged OK
5Y919	954	925	4-0	15	50	12	16	28	Forged OK
5Y921	952	925	5-0	14	55	12	17	20	Forged OK
5Y926	934	925	5-15	16	50	12	15	17	Forged OK
5Y927	954	925	4-15	15	51	11	16	27	Forged OK
5Y931	966	925	4-15	15	50	11	16	27	Forged OK
5Y932	956	925	3-30	10	56	10	14	22	Forged OK
5Y938	952	925	4-30	9	49	11	15	29	Forged OK
5Y939	936	925	4-0	13	55	11	18	28	Forged OK
5Y942	946	925	4-15	8	51	8	16	26	Forged OK
5Y943	964	925	4-0	10	55	7	13	24	Forged OK
5Y954	979	925	4-15	14	49	12	15	28	Forged OK
5Y960	928	925	4-15	10	48	9	13	25	Forged OK
5Y963	937	925	3-45	11	55	10	14	23	Forged OK
5Y967	966	925	4-15	22	60	10	13	23	Crack 3" long in top 1/3
5Y971	906	925	4-30	15	60	7	14	26	Cracks on end & center in bottom 1/3
5Y972	948	925	4-0	12	60	10	16	27	Cracks in bottom 6 "
5Y977	972	925	4-15	14	55	9	16	27	Forged OK

FIGURE 37. Cracks Developed on the End of Zircaloy-2 Slab During Forging

106-2762

The blocks were inspected for surface defects by visual examination and a dye-penetrant method (Turco Products, Inc. dy-chek). Blocks found with defects other than gross cracks or laps were remachined and re-inspected.

The metal loss through generation of machine chips amounted to approximately 11%. This loss was equivalent to 14 mils in the 1/8" cover plate stock, which was probably about three-quarters the minimum scrap possible by surface machining of the finished product. In addition, machining at the three (3)-inch thickness stage was considerably less costly, because ordinary machining practice could be used and considerably less surface needed to be covered. A photograph of a scalped block is presented in Figure 38.

Hot Rolling

The third step in the sequence of manufacturing operations was the hot rolling of the scalped blocks to an intermediate thickness. Rolling was done on a 17" x 24", two-high mill and auxiliary equipment shown in Figure 39. A description of this equipment is given later in this report. The blocks, three at a time, were preheated two hours to the rolling temperature of 850° C (1562° F) in a box furnace heated by electrical resistance elements. Following preheating, rolling was done in a sequence of two passes per reheat with the exception of the first pass, which was single. Reheating was done three blocks abreast in a 150-kw roller hearth furnace on the opposite side of the mill from the preheat furnace. A reheating time of 10 min was allotted to bring work back to rolling temperature. Rolling reductions, limited by the capacity of the mill drive, ranged from 8% initially to 22% in the final passes.

Zircaloy-2 was hot rolled in four thicknesses for the various cladding components: (1) 1-5/16" plate for thick billet end plugs, (2) 1-1/8" plate for thin billet end plugs, (3) 0.40" plate for all side plates, and (4) 0.25" plate for all cover plates.

The plate for end plugs in both thicknesses was hot rolled to a thickness suitable for the complete machining of these parts (to be discussed later). Approximately 0.030" per face was allowed in the thickness of the plate stock for cleanup in machining the end plugs to length. The roll schedule for end plug plate stock is contained in Table XIII.

The materials which went into cladding billet side and cover plates were rolled to the above thicknesses to provide for a sizable reduction (37% to 50%) in subsequent rolling to finished thickness. The roll schedules used in the production of plates in these two thicknesses are given in Table XIV. A Zircaloy-2 plate after hot rolling to 0.40" thick is shown in Figure 40.

FIGURE 38. Zircaloy-2 Block after Scalping

106-2763

FIGURE 39. General View of 17" x 24" Mill and Auxiliary Equipment.

106-2343

FIGURE 40. Zircaloy-2 Plate after Hot Rolling to 0.40" Thick.

106-2756

Table XIII

ROLLING SCHEDULE - ZIRCALOY-2 CLADDING END PLUG STOCK

STOCK: Forged and Scalped Zircaloy-2 Blocks Approximately 2-3/4" x 9" x 13" ROLLING MILL: 17" x 24" 2-high ROLLING TEMPERATURE AND SPEED: 850° C - 125 ft/min REHEAT: 10 min after every other pass						
Pass No.	Roll Parting (in.)	Material Gage (in.)	Draft (in.)	Reduction (%)	Power Consumption (kw)	Remarks
1	2.682	1.320 ⁽²⁾	(1)	-	-	Final pass 1-5/16" end plug stock - thick billets Final pass 1-1/8" end plug stock - thin billets
2	2.468		0.214	8	120	
3	2.271		0.197	8	158	
4	2.044		0.227	10	168	
5	1.840		0.204	10	182	
6	1.583		0.257	14	192	
7	1.341		0.242	15	182	
8	1.143	1.125 ⁽²⁾	0.198	15	180	

¹Draft, reduction and power consumption varied with original thickness of block.

²Average thickness after cooling, including some scale loss.

Table XIV

ROLLING SCHEDULE - BREAKDOWN ROLLING ZIRCALOY-2 CLADDING SIDE
AND COVER PLATE STOCK

STOCK: Forged and Scalped Zircaloy-2 Blocks Approximately 2-3/4" x 9" x 13" ROLLING MILL: 17" x 24" 2-high ROLLING TEMPERATURE AND SPEED: 850° C - 125 ft/min REHEAT: 10 min after every other pass						
Pass No.	Roll Parting (in.)	Material Gage (in.)	Draft (in.)	Reduction (%)	Power Consumption (kw)	Remarks
1	2.682	0.400 ⁽²⁾	(1)	-	-	Final pass for 0.40" side plate stock.
2	2.468		0.214	8	154	
3	2.271		0.197	8	158	
4	2.044		0.227	10	168	
5	1.840		0.204	10	182	
6	1.583		0.257	14	192+	
7	1.361		0.222	14	182	
8	1.143		0.218	16	180	
9	0.960		0.183	16	192+	
10	0.787		0.173	18	163	
11	0.646		0.141	18	154	
12	0.517		0.129	20	144	
13	0.414		0.103	20	144	
14	0.323	0.240 ⁽²⁾	0.091	22	142	Final pass for 0.25" cover plate stock.
15	0.252		0.071	22	142	

¹Draft, reduction, and power consumption varied with original thickness of block.

²Average thickness after cooling including some scale removal.

The hot-rolling operations on the cover and side plate stock were terminated at this high thickness level to afford an opportunity for complete removal of surface contamination (oxide and nitride) and minor surface defects (seams, laps, etc.) prior to finish rolling. These thicknesses, which required 37% to 50% reduction in finish rolling to final thickness, were provided to afford an opportunity for rollout of surface asperities produced by the cleaning and spot grinding operations. Originally an allowance of 10% was established for the reduction in final rolling. This allowance was found adequate for high quality Zircaloy but inadequate for the lower quality material available for the production of EBWR fuel plates.

Cleaning Hot-Rolled Strip

The surface quality of Zircaloy-2 stock intended to be used as cladding components without extensive surface machining was a function of the completeness of removal of hot-rolling scale prior to finish rolling of the stock. The success of this fabricating practice was dependent upon the satisfactory removal of atmospheric contamination; for, if any quantity of contamination was permitted to accompany the strip into the finish-rolling operation, it could possibly be rolled deeper into the strip surface. The consequences of rolled in scale were two-fold. First, a very rough surface, which was not considered satisfactory for quality metallurgical bonds, even though clean, was generated; and second, the complete removal of this penetrating scale, which was absolutely essential to bonds which were free of inclusions, was extremely difficult except by extensive surface machining. The elimination of this over-all surface machining was the sole purpose of this practice.

Aside from machining, grinding being difficult and hazardous, the only practical means of complete removal of atmospheric contamination was by blasting with a sharp, hard abrasive. In addition, the selection of the blasting method was very important. Conventional dry blasting with steel shot, quartz or alumina as fine as 70 mesh was unsatisfactory.⁽⁶⁾ The rate of removal of superficial contamination was high using these methods, and a surface which appeared clean to the naked eye was produced. The removal of the deeply rooted contamination to produce a microscopically clean surface was extremely difficult with the dry blasting method. The results obtained by Roto Blasting (American Wheelabrator Corp.) with steel shot were much the same as those obtained by sand blasting. The residual contamination after blasting with steel shot is pictured in Figure 41. The superficial contamination, particularly that which lay on the peaks, was removed by blasting with these relatively coarse particles, but the contamination lying in the depressions was not removed. Length of blasting time was found not to be a major factor in the completeness of cleaning.

FIGURE 41. Residual Surface Contamination on Hot-Rolled Zircaloy-2 after Blasting with Steel Shot,

20847

1X

The difficulties associated with the removal of atmospheric contamination from zirconium was recognized at ANL in 1950 during attempts to salvage stock received in a severely contaminated condition. At the suggestion of R. A. Noland, wet abrasive blasting was tried, and the results obtained by this cleaning method were very promising. It was found that by using abrasives much finer than those possible with dry blasting equipment, the very tenacious surface contamination was absolutely removed and at a respectable rate. Initially it was not known whether it was the suspension of abrasive in water, type of abrasive, or mesh of abrasive which produced the superior cleaning power of this method. Later it was found that wet blasting with abrasives in particle sizes comparable to those used in sand blasting, even though a cleaner surface was produced did not effect absolute removal of contamination. This fact excluded the water suspension as a major factor. Likewise, comparing like abrasives in the two types of equipment did not reveal major differences. This then left the particle size of abrasive among those factors listed above as being the major factor, which was indeed found to be true. Wet abrasive blasting with fine, sharp particles, such as 400 mesh quartz or alumina,

produced microscopically clean surfaces on zirconium and Zircaloy-2. It was speculated that, because of the reduced ductility of the surface of Zircaloy-2, resulting from contamination, small fissures which could propagate into the uncontaminated base metal would be produced. The walls of these fissures then would be exposed to contamination at elevated temperature, introducing fingers of contamination into the metal; because of the acuteness of the fissure angle, large abrasive particles could not enter to dislodge this deeply rooted contamination. This contention is supported by metallographic evidence presented in Figure 42. These fingers of contamination are clearly visible. It is evident when comparing the various mesh sizes superimposed on the photomicrograph why the larger particle sizes were ineffective in removal of this contamination. In addition, abrasives in particle sizes larger than 100 mesh were embedded in the surface of Zircaloy-2 whether blasting was done wet or dry. An inspection which differentiates between embedded particles and residual contamination was difficult to find, but there was a particle size range lower than 100 mesh which neither embedded nor removed contamination completely.

Prompted by the successful results obtained by blasting with fine particles, wet abrasive blasting equipment was purchased from the Vapor Blast Mfg. Company of Milwaukee. The Model B-20 machines purchased consisted essentially of a hopper for containing the blasting mixture (water and abrasive) and a totally enclosed hood integral with hopper for containing the vapor. A blast gun for performance of work, a pump for both feeding the gun and maintaining suspension of the abrasive, an air supply, and an exhaust fan for clearing cabinet of vapor were the essential parts of the machine. In this equipment, a water suspension of abrasive was pumped into the jet type gun where it was driven onto the work by means of high pressure air.⁽¹⁵⁾ This type of equipment extends the blasting particle size into ranges far below those practical in conventional dry blasting equipment.

The equipment as purchased was designed for manual manipulation of both gun and the work. Cleaning of large areas of surface was slow, and even more critical was the inability of an operator to secure uniform removal of contamination without excessive examination of the work. To eliminate these two shortcomings, the two existing machines were modified so as to increase their capacity and to insure uniform coverage.

The original machine was equipped with one centrifugal pump which performed two functions, one being to feed the single gun and the other to maintain suspension of the abrasive in the hopper. Approximately $2/3$ of the pump capacity discharged into the hopper to secure the agitation necessary for suspension of the abrasive.

The machine was increased to three times its original capacity by the addition of two guns. The original pump was repiped so that its entire flow was used in supplying the three guns. To provide the necessary agitation for maintaining uniform suspension of abrasive, a second pump whose total flow discharged into the hopper was added.

FIGURE 42. Fissure Containing Atmospheric Contamination in Surface of Warm Rolled Zircaloy-2 Sheet and Various Abrasive Particle Sizes.

Transverse Section of 600°C Rolled Zircaloy-2 Strip

* 400 mesh abrasive contains particles 37 μ and finer

Uniform blasting of the work was obtained by moving the work at a uniform rate beneath the three guns which oscillated back and forth across the work. The interior of a machine showing the three blasting guns and their mounting, the shaft on which the guns were reciprocated, and the work positioned on the carriage is presented in Figure 43. The guns were driven by means of a double-acting, oil hydraulic cylinder controlled by means of a four-way solenoid valve and switchgear. Flow control valves were employed for control of speed of travel within wide ranges.

FIGURE 43

Interior View of Wet Abrasive Blasting Machine Showing Work, Feed Buggy, Blasting Guns, and Gun Drive Shaft Bellows Seal.

The carriage upon which the work was carried was built of a stainless tube rectangular in section 13 ft long carried on a frame equipped with six ball bearing wheels. These "V"-rimmed wheels rode on inverted angles fastened atop a double H-beam frame to guide the carriage in a straight line through the machine.

The H-beam support frame and the carrying mechanism for the carriage were surrounded by the rectangular stainless steel tube which formed the outer shell of the carriage. Travel of the carriage was limited so that its open ends never entered the blast cabinet. In this way, the need for complicated sealing of a work support and drive mechanism against entry of high velocity blast abrasive was eliminated.

The travel of the carriage was limited to seven (7) ft, which also set the limit to the length of work which could be blasted. The carriage was driven by means of a sprocket attached to the output shaft of a gear reducer and a roller chain coupled to both ends of the carriage by cables. Power was supplied by a variable speed drive, 6:1 speed range, and transmitted through a gear reducer and sprocket arrangement to give a carriage speed of 3.77"/min to 22.6"/min.

A general view of the automatic wet abrasive blasting equipment is shown in Figure 44, and a cutaway sketch of the same machine is given in Figure 45.

These machines perform at their best when operated at certain settings and abrasive concentration which have been established.⁽¹⁵⁾ The angle the blast strikes the work and the gun-to-work distance were two important settings. A gun angle of 60° and the gun-to-work distance of two (2) inches have been found to be optimum. The blasting rate was a function of the abrasive concentrations in suspension; concentrations were limited to 35% by volume. Adequate supply of high pressure air had to be provided to assure satisfactory performance. The air requirement of 600 cfm at 100 psi for supplying 6 guns in the two machines was satisfied by means of compressors and supply lines of adequate capacity. Air-borne oil was excluded from the equipment by means of double filtering.

In addition to the machine settings and abrasive concentrations established above, other parameters peculiar to this equipment and material being cleaned had to be maximized. The type and mesh of abrasives, the rate of gun travel, and the rate of work travel had been established for this equipment by extensive experimentation.⁽⁶⁾ A sequence of blasting operations using two meshes of Al_2O_3 abrasive were found to produce microscopically clean Zircaloy-2 surfaces at attractive rates. The first blasting operation was designed to remove the bulk of the contamination as rapidly as possible with the largest mesh abrasive capable of being uniformly suspended in the water carrier. This operation was performed with 100 mesh alumina using a gun speed of 12"/sec and an average work speed of 5"/min. On a 9" wide strip the cleaning rate was calculated at 9.38 sq ft/hr, both sides cleaned.

This coarse mesh blasting operation did not completely remove all contamination on the strip and multiple passes through the machine did not remedy this deficiency. The bulk surface contamination was adequately removed at a good rate, but the deeply imbedded oxide-nitride remaining in the inclusion pockets and fissures was not. Following the primary blasting operation a pickle in 35% HNO_3 -5% HF by volume was found to be very helpful in subsequent blasting operations of the material of poor surface quality.

The second blasting operation was done with 400 mesh Al_2O_3 at a gun speed of 12"/sec and an average carriage speed of $3\frac{1}{2}$ "/min. The cleaning rate for this operation was 6.57 sq ft/hr. This fine abrasive was capable of reaching in and dislodging the deeply seated contamination. The fine mesh abrasive also reduced the surface roughness of the strip.

In addition to the removal of the reaction products of air and Zircaloy-2, minor surface defects generated during rolling required removal before acceptable material could be finish rolled. Even though the surfaces of the blocks going into hot rolling were free of defects (dye

FIGURE 44. General View of Automatic Wet Abrasive Blasting Machine.

FIGURE 45. Cutaway Perspective of Automatic Wet Abrasive Blasting Machine

penetrant examination) except for gross cracking and end laps, some defects, principally laps and seams, resulted in some areas of the rolled strip. Examples of these defects are shown in Figure 46. These imperfections were removed with carbide burrs using small hand grinders.

Finish Rolling

Upon completion of the cleaning cycle, warm rolling was employed to produce the stock for 1/8" cover plates and 1/4" side plates. The 0.40" thick hot-rolled strip was rolled at a nominal temperature of 600° C to 0.254" thickness in the schedule of passes given in Table XV; the 0.250" thick hot rolled stock was rolled at the same temperature to 0.129" thickness according to the schedule given in Table XVI. Rolling was done at 125 ft/min in a cycle of two passes followed by a reheat. The stock for the finished 0.250" and 0.125" strip was rolled 4 mils over thickness to compensate for the thickness loss during blast cleaning and pickling.

Originally this finish rolling was accomplished at room temperature, but as stated previously, a 10% reduction was not sufficient to roll out grinding marks in areas which required grinding for cleanup. The final rolling reduction required increasing; therefore, the reduction was arbitrarily increased to a minimum of 37%. To make this reduction possible, the temperature of rolling also required increasing. A temperature of 600° C was selected, since at this temperature the work hardening rate was low enough to permit this reduction and the contamination produced was very thin and tightly adherent, providing control was exercised over the length of heating period.

This warm-rolling practice had three advantages over cold rolling. First, surface depressions, if properly ground, were removed during the 37% to 50% reduction. Second, the crown on a 9" wide strip was reduced from 4-5 mils for cold rolling to 2-3 mils; and third, the ductility of the material was higher after warm rolling, which eases subsequent operations such as trimming. The warm rolling, however, did produce a certain amount of surface contamination which needed removal, but this atmospheric contamination was very thin, 0.4 to 0.7 mil as compared with 2 to 7 mils on 800° C rolled material, as shown in Figure 47. Because of the thinness of the 600° C contamination and the absence of deep penetration of the scale, the surface of the 600° C rolled strip differed very little in appearance from cold-rolled strip after both had been cleaned (Figure 48).

A cleaning procedure identical to that used on hot-rolled material was used on the finish-warm-rolled stock, with the exception of removal of surface irregularities, such as laps and seams, by grinding. The duplex 100 mesh - 400 mesh Al_2O_3 blasting procedure was followed. Spot microscopic examination (90X) was employed to check general cleanliness of the

FIGURE 46. Surface Defects in Hot Rolled Zircaloy-2 Strip and Their Possible Cause.

21113

Short Seams

1X

20740

Pits

1X

21118

Long Severe Seams

1X

21111

Severe Laps

1X

20611

200X

Longitudinal Section. Severe stringers in metal
possible cause of laps and seams.

20780

250X

Longitudinal Section. Moderate stringers in
metal possible cause of laps and seams.

(These photographs have been reduced 28% for reproduction.)

Table XV

ROLL SCHEDULE - FINISH ROLLING OF ZIRCALOY-2 FOR
CLADDING SIDE PLATE STOCK

STOCK: Hot Rolled and Cleaned 0.40" Thick Plate ROLLING MILL: 17" x 24" 2-high ROLLING TEMPERATURE AND SPEED: 600° C - 125 ft/min REHEAT: 10 min after every other pass					
Pass No.	Roll Parting (in.)	Material Gage (in.)	Draft (in.)	Reduction (%)	Power Consumption (kw)
1	0.360	0.254 ⁽¹⁾	0.040	10	109.8
2	0.324		0.036	10	98.1
3	0.292		0.032	10	91.5
4	0.263		0.029	10	83.7
5	0.255		0.008	3	55.5

(1) Average Thickness After Cooling.

Table XVI

ROLL SCHEDULE - FINISH ROLLING OF ZIRCALOY-2 FOR
CLADDING COVER PLATE STOCK

STOCK: Hot Rolled and Cleaned 0.25" Thick Strip ROLLING MILL: 17" x 24" 2-high ROLLING TEMPERATURE AND SPEED: 600°C - 125 ft/min REHEAT: 10 min after every other pass					
Pass No.	Roll Parting (in.)	Material Gage (in.)	Draft (in.)	Reduction (%)	Power Consumption (kw)
1	0.216	0.129 ⁽¹⁾	0.034	14	89.7
2	0.194		0.022	10	68.5
3	0.174		0.020	10	62.9
4	0.156		0.018	10	47.8
5	0.140		0.016	10	59.2
6	0.130		0.010	7	44.4

(1) Average Thickness After Cooling.

FIGURE 47. Atmospheric Contamination on Zircaloy-2
Strip Rolled at 850°C and 600°C.

Specimen Mount

Scale

Zircaloy-2
Base Metal

20425

100X

Scale Formed on 850°C Rolling

Specimen Mount

Scale

Zircaloy-2
Base Metal

20689

200X

Scale Formed on 600°C Rolling

FIGURE 48. Surface Finish of Cold and Warm (600°C) Rolled Zircaloy-2 As Blasted with 400 Mesh Al_2O_3 .

21117

Cold Rolled

1X

21120

Warm (600°C) Rolled

1X

blasted strip. Strip not passed by this check was recycled through the final blasting (400 mesh) step. Persistent rejection after the first blasting cycle was corrected by slowing of the work travel speed and finally by replacement of spent abrasive.

Fabrication of Seal Pin and Electrode Stock

The assembly procedure developed for the production of EBWR cladding billets required the sealing of a purge opening in one end plug. The stock from which the sealing pins were made was in the form of 1/4" dia. Zircaloy-2 rod; the electrode used in the sealing process was produced from 3/4" dia. rod. The design of these items is discussed later in this report.

Since the seal pin became part of the finished fuel plate, only material of the highest quality was used. Selection was made from the best forged slab, and bars 1-1/2" dia. x 9" long were made by sawing and turning. These bars were hot rolled, at 850° C after salt bath heating, to approximately 3/8" dia. in a series of hand round passes. Rolling temperature was maintained by reheating after every other pass, and rolling was done on a 9" x 16", two-high mill. The hot-rolled rod was finished to 1/4" dia. by swaging cold, employing two intermediate anneals at 850° C. Hand straightening following swaging completed the fabrication of the rod.

The quality requirement of stock going into the Zircaloy-2 electrodes was much less stringent than that of the seal pins, since no part of the weld metal originating from the electrode was part of the finished plate. A small Zircaloy-2 ingot, 12" dia., weighing 275 lb. and considered inferior in quality, was used. This ingot was forged at approximately 925° C into a 1-1/2" dia. bar at Anderson-Shumaker. Inferior ingot quality was confirmed by the poor surface quality of the forged bar.

The forged bar was hot rolled at 850° C to 7/8" dia. in a sequence of hand round passes. Reheating was done after every other pass.

Cladding Billet Design

The cladding billet design objectives were to produce billets with a minimum amount of contamination to their bonding surfaces, to maintain these low levels of contamination during heating and rolling, and to take advantage of certain desirable and minimize undesirable properties of the billet components.

The design and dimensions of the cladding billet components for billets of both thicknesses are given in Figure 49. Inspection of the assembly drawing and component dimensions will reveal a discrepancy between the core and the corresponding dimensions of the cladding components.

FIGURE 49. Design and Dimensions of Cladding Billet Components.

E.H.S.

For example, the width of the thin billet end plug is 0.62" wider and 0.017" thicker than the corresponding dimensions of the uranium core alloy; and the distance between end plugs, when assembled in their respective positions in the cladding, is 0.213" greater than the length of the core. This gap between core and internal surfaces of the assembled cladding components was purposely provided as an allowance for the positive differential expansion of the uranium alloy core with respect to the Zircaloy-2 clad of 0.020"/inch of core during heating from room temperature to the rolling temperature of 850° C. This value of differential expansion was found empirically by measurement of plastic strain in the cladding after heating and cooling a tightly assembled billet.⁽⁶⁾

Without this gap, the cladding components would have been separated from each other at the rolling temperature, which would have made the task of bonding more difficult, particularly in the case of the already difficult bond between end plugs and side plates. Even more importantly, this gap eliminated the triaxial stress imposed upon the cladding welds during heating. This stress did rupture some welds in billets assembled without a gap, permitting entry of contaminating gasses causing bond line inclusions.

An opening was provided in one end plug of each billet assembly through which the purge gas was introduced. This opening, as shown in Figure 49, was 0.250" maximum diameter at the outboard side of the end plug and tapered 7-1/2° to insure a close fit of the seal pin. This large taper was used to obtain reproducibility of the projection of the seal pin beyond the end plug without individually lapping each pin and end plug. The importance of the projection of the seal pin beyond the end plug will be explained later in the discussion of the seal pin welding.

The tapered seal pin was selected in preference to the screwed type pin originally used for closing the purge opening. The seal pin bonds resulting from screwed type closures contained periodic voids when viewed in longitudinal section. These voids in the finished-rolled plate were presumed to originate as voids at the roots of the threads in the original assembly; being helical in nature, it was not impossible for the seal pin bond to have a water channel running its full length.

The billet design incorporating the expansion gap required removal of the air entrapped within the assembled billet to control contamination to the internal surfaces during the welding of the seams.⁽⁶⁾ In the original billet design, the cladding components were pressed tightly against the core, which minimized the quantity of air entrapped within the billet, thus controlling contamination sufficiently to obtain good bonds. The comparatively large quantity of air entrapped within the gapped billets, however, caused contamination during welding of the billet, which did interfere with satisfactory bonding. Control of this contamination required the removal of air before welding the seams in the cladding. The simple method of displacement

of air with an inert gas was used after an autodry box was made of each billet by pressing cladding components together. With this method an expensive and cumbersome dry box in which welding would have to be performed was eliminated.

The purpose of the annular groove surrounding the purge opening was to aid in the seal pin vacuum welding operation. The function of control of melt-off position of the seal pin during initiation of the arc and the increase in fusion zone into the end plug by this counterbore will become clear in a subsequent section.

The seal pins were machined from $1/4$ " dia. rod, as shown in Figure 49. These pins were pressed into the $3/4$ " dia. Zircaloy-2 electrodes. These two parts were machined separately to conserve stock, since the electrodes after remachining could be reused until approximately 50% of their length was consumed.

The end configuration of the billet cores and the mating configuration of the cladding end plug were necessary for the production of a satisfactory integral rolled end closure. This taper afforded a rolling transition zone between end plug and core to reduce the effect of the slight change in rolling characteristics between core and end plug. The 90° included angle nose on the billet core ends was found to be the maximum which would give reproducible, satisfactory results. Angles greater than 90° caused the cladding to thin in the end plug-core transition zone.⁽⁶⁾ Square core ends (180° taper angle) thinned the cladding to the point of rupture. Other core end geometries, such as truncated tapers and radii and even concave shapes more difficult to machine, showed no improvement over the straight taper. The 90° included angle taper in the billet increased to 2.08" and 2.95" in length during roll bonding of the thin and thick fuel plates, respectively. Core end tapers of less than 90° included angle gave excessive end taper to the core of rolled fuel plates.

Two types of bonds had to be effected in the production of integrally clad fuel plate, one being the uranium alloy core to Zircaloy-2 cladding and the other being Zircaloy-2 to Zircaloy-2. Of these two types, the Zircaloy-2 to Zircaloy-2 bonds, being self-diffusion, were the more difficult to make. The above two types of bonds were classified further with respect to the mill rolls, one being referred to as the face bonds and the other being the side bonds. The face bonds were produced across interfaces parallel to the roll faces. In this position the full roll pressure was utilized in establishing the intimate contact between components necessary for bonding. On the other hand, it was necessary to effect side bonds across interfaces positioned normal to the roll faces. In this position the roll pressure was ineffective in establishing contact.

The ease with which these bonds could be established vary from one type to another. With respect to this ease of bond establishment, the four types are listed in order of increasing difficulty as follows:

1. Core-to-clad face bonds
2. Clad-to-clad face bonds
3. Core-to-clad side bonds
4. Clad-to-clad side bonds.

Providing the bonding surfaces were reasonably free of contamination, no difficult problems presented themselves in the production of both types of face bonds. Adequate pressure to assure intimate contact could be obtained over a wide range of roll pass reductions, and bonding only required the proper selection of rolling temperature and reduction.

The side bonding, however, because of the lack of edge rolling equipment, was not as easily accomplished. Since direct roll pressure was ineffective, other means had to be relied upon to effect the necessary contact. The method used was based on differential spread in the various components. The design and mass of the steel jacket were employed to restrict the overall spread of the cladding billet. The problem of side bonding the core to the clad more or less solved itself through the particular dimensions of the billet and rolling characteristics of the clad, core and steel jacket. Apparently the physical properties of the core were such that at rolling temperature the core was just soft enough to spread against the side plates but not so soft as to extrude into the bonding interfaces.

In connection with the clad-to-clad side bond (end plug to side plate) advantage was taken of the anisotropy in rolling characteristics of the plate stock from which the end plugs were machined. Because of texture, the physical properties of this rolled plate stock differed in different directions.^(6,16) It was found that spread, the rolling characteristic of interest, differed widely in one direction from that of the other two directions.⁽⁶⁾

The spread upon subsequent rolling was found to be approximately 40% greater in both the directions parallel to the original rolling direction and normal to the rolling direction in the rolling plane than in the direction normal to the rolling plane. This showed that Zircaloy-2 "remembers" its prior hot-working history in its behavior during subsequent hot working, as has been reported.⁽¹⁷⁾

The position of the end plugs within the rolled-plate stock was selected as shown in Figure 50. The width dimension of the end plugs was placed in the original rolling direction, one of the directions of maximum spread, and the length dimension was placed normal to the rolling plane, direction of minimum spread. In this orientation sufficient spread developed in the end plug during roll bonding of the fuel plates to establish the contact necessary for initiation of diffusion.

FIGURE 50. Orientation of Cladding Billet End Plugs in Rolled-Plate Stock for Obtaining Maximum Spread during Roll Bonding of Billets.

The dimensions of the cladding billet core were calculated using the dimensions of the core in the finish-rolled fuel plate and the reduction ratio, then making adjustments for spread. The billet core thicknesses were five (5) times the thicknesses of the cores in the two sizes of finished plates. The width of the billet core was arrived at by adjusting the final width of the core in the fuel plate for spread developed during rolling. The spread was determined during the rolling of development plates. The spread factor for the thin billet cores was found to be 6.4% of the original width, and the spread factor for the thick billet cores was 5.5%. The length of the billet cores was found by adding the volume of core which spread upon rolling to one-fifth ($1/5$) the length of the finished plate core.

The dimensions of the cladding components were calculated using the dimensions of the cores at the rolling temperature and the reduction ratio, with allowances being made for obtaining a rolled-end closure, machining finished plates to width and cleaning of the plate surfaces. The thickness of the cover plates was five (5) times the sum of the finished plate thickness plus three (3) mils for blasting and pickling. The width of each billet side plate was twice that of the finish-machined side clad of the rolled plate. The length of the end plug was fixed at the length which would give satisfactory rolled end closures.

Inspection of Cladding Component Stock

To reduce the probability that cladding components containing heavy metal inclusions (tungsten) would be used in the fabrication of fuel plates, the Zircaloy-2 stock was radiographed using X radiation. The intensity of the transmitted radiation was recorded on film from which the location of tungsten inclusions could be determined. The positions of inclusions were transferred from film to cladding stock and locations were marked. Areas containing inclusions as well as folds, seams, and porosity were cut out of stock during shearing or sawing of the components.

The sensitivity of the radiographic procedure used was quite good. For example, a 5-mil diameter tungsten wire laid atop a $1/8$ " thick Zircaloy-2 strip was clearly visible on the film record.

The weight of metal lost through the cut-out of inclusions was small. Only 64.6 lb of scrap were produced, but approximately 90 areas containing inclusions were removed in the process. Each of these inclusion areas were potentially capable of causing rejection of a finished fuel plate. Elimination of the cause of this type of defect represented a saving of many thousands of dollars.

Machining of Cladding Components

Varying degrees of machining were required to produce the Zircaloy-2 cladding components, shown in Figure 49, from the rolled stock. Machining was used only to develop the dimensions or shape of a component when other methods such as rolling or shearing could not be used. The critical dimensions which required the use of machining were the width and length of the cladding billet cover and side plates and all dimensions and design of the end plugs, seal pins, and electrodes. The dimensions of the end plug required machining to close tolerances because the width of the cladding billet was established by pressing the side plates against the end plugs, and the thickness was established by pressing the cover plates against both the end plugs and side plates. Machining was necessary to produce a 90° included angle groove in the end plug which matched the taper on the ends of the uranium alloy core, and the tapered purge opening required precision machining. Since the length of the cladding billet was fixed by the length of the side plate, machining was used to develop that dimension.

During all operations in the production of cladding billet components, the identity of components was maintained. Components were segregated into batches identified by the parent ingot number and numbers of the ingot subdivisions.

The stock for the cover and side plates, 1/8" and 1/4" thick, respectively, was rolled in strips approximately 9" wide and 6 to 10 ft long. Following the wet abrasive blast cleaning operations, the locations of tungsten inclusions were marked and the strip was inspected for defects, such as laps, seams, porosity, etc. Blanks for finish machining to width and length only were then sheared from the strip stock, excluding defective areas. These components were sheared lengthwise with respect to the strip in multiples across the width of the strip. The 9" width of strip accommodated two widths of cover plates for both billet thicknesses, and six widths of side plates for the thick and eight widths for the thin billets. These multiples, of course, were not always possible, since defective areas in the strip were excluded.

The cover plates were sheared to their finished length, 11.928" and 10.802", for thin and thick plate billets, respectively. Using a squaring shear, 1/2" capacity in mild steel, equipped with hydraulic holddowns, it was possible to hold the length dimensions to the required tolerance of ± 0.010 ". All cover plates were sheared to 3-7/8" width, which was well in excess of the finish-machined widths given in Figure 49, to reduce the probability of errors in setup for machining. Shearing of this 1/8" thick material at room temperature gave little difficulty.

The side plates were sheared oversize in both length and width. The side plates were sheared to $1-11/32"$ x $12-1/4"$ for the thick billets and $1"$ x $12-1/4"$ for the thin billets for machining to the width and lengths given in Figure 49. The small allowance of approximately $5/32"$ for machining to width was made possible by shearing at an elevated temperature. Shearing this $1/4"$ thick stock at room temperature produced a very wide shear zone, as shown in Figure 51; in addition, shatter cracks running perpendicular to and $3/4"$ in from the sheared edge developed in some material. By heating the strip to 450°C the shear zone was reduced about 75%, as shown in Figure 51, and the shatter cracks did not develop.

FIGURE 51. Plate Sections Transverse to Shear Plane of $1/4"$ Zircaloy-2 Plate Sheared Cold (Top) and at 450°C (Bottom).

21162

2X

Shear Zone "Z" $1/8"$ for Cold Shearing.

Shear Zone "Z" $1/32"$ for Warm Shearing.

In preparation for warm shearing, the $1/4"$ strip stock was first cut into $12-1/4"$ lengths, approximately $3/8"$ excess length was allowed for machining. The plates were then heated for 5 min in an electric furnace at 450°C , after which the side plate blanks were sheared to width. The automatically controlled electric furnace and the $1/2"$ capacity squaring shear used for all production shearing operations are pictured in Figure 52.

FIGURE 52. Squaring Shear, 1/2" Capacity, and Heating Furnace for Warm Shearing of Zircaloy-2.

One interesting observation was made during the warm shearing operation. Side plate stock which was heated after wet abrasive blasting and drying developed a light straw coloring during heating, but stock heated after blasting, pickling, rinsing and drying remained bright throughout the heating and shearing operations.

The cover plates were machined only to widths in groups by straddle milling. The side plates were machined to width by straddle milling or shaping and were machined to length by shaping.

As discussed previously, the orientation of the cladding billet and plugs within the plate stock from which they were cut was important. Great care was exercised in maintaining the proper orientation throughout the machining operations.

The plate rolled for the end plugs was approximately 9" wide x 28" to 33" long in two thicknesses, 1-5/16" for the thick billet and 1-1/8" for the thin billet end plugs. The first operation was the machining of one long side square to serve as a reference in sawing the plate. Next, the plates, both thick and thin were hacksawed normal to the reference side (transverse to the rolling direction) into strips 3-1/4" wide. These cuts established the width dimension of the end plug and fixed one important orientation position (width dimension parallel to the rolling direction). This operation yielded strips 3-1/4" x 9" x one of the two thicknesses of the plate stock, 1-1/8" and 1-5/16". The blocks from the thick (1-5/16") plate were then sawed parallel to the rolling direction into blocks 1-3/8" wide, which yielded six pieces 1-3/8" x 3-1/4" x the rolled thickness of 1-5/16" from each strip. These cuts fixed the second orientation position and the thickness of the end plug (thickness dimension normal to rolling direction and parallel to rolling plane). The thickness and length dimensions of the end plugs were identified by distinguishing surface texture, sawed and rolled respectively.

The strips from the thin (1-1/8") plate were similarly sawed into blocks 1" wide, which likewise fixed the thickness dimension. Each strip yielded eight pieces, 1" x 3-1/4" x 1-1/8", the thickness of the rolled plate. As stated previously the blocks from each plate were kept in separate batches identified by the parent ingot and plate numbers.

Following the cutting of the plate into blocks, a sequence of machining operations was performed to produce the final dimensions and shape of the end plugs. The first operation was the shaping of one of the rolled faces of the blocks until free of defects and then using this face as a reference for setup in a milling machine; the thickness dimension of the end plugs was developed by straddle milling equal amounts from the two opposite faces, as shown in Figure 53. These thickness dimensions, as shown in Figure 49,

FIGURE 53. Straddle Milling Cladding Billet End Plugs to Thickness.

210-131

were 1.250" for the thick end plugs and 0.850" for the thin plugs. The third operation in end plug machining was the cutting of the 90° included angle "V" in the fourth side of the plug, which also established the over-all lengths of the plugs, 1.250" and 1.062", for thick and thin plugs, respectively. These grooves were machined using an end mill cutter, as shown in Figure 54. The final operation in the machining of the end plugs was the straddle milling to width, done in the same manner used in milling to thickness. The width dimension of the thick end plugs was 3.195" and 3.177" for the thin plugs.

End plug fabrication was completed with the machining of the tapered purge openings and counterbore surrounding the openings. Purge openings were machined in one-half of the total number of end plugs in each thickness (one per billet assembly). The openings as shown in Figure 49 were machined by first drilling a pilot hole, then reaming with a 15° reamer on a drill press, as shown in Figure 55. The reamed depth was carefully controlled to produce dimensions within the tolerances shown in Figure 49. These tolerances were necessary to obtain the proper projection of seal pin above the end plug necessary for successful seal welding. The annular groove surrounding the purge opening was turned on a lathe, as shown in Figure 55.

Seal pins and electrodes were turned to the dimensions and design shown in Figures 49 and 63. The seal pins, one required for each billet assembly, were machined from 1/4" dia. rod, and the reusable electrodes were turned from the 7/8" dia. rod rolled for that purpose. Seal pins and electrodes were pressed together after cleaning.

Pickling of Cladding Components

Prior to assembly, all cladding components required degreasing and pickling to develop surfaces suitable for satisfactory bonding.⁽⁶⁾ The degreasing was considered necessary to remove the oil coolant used in machining and the handling contamination to obtain uniform attack by the acid pickling bath used.

The pickling bath was concentrated nitric acid (1.42 sp. gr.) containing 1/2 to 1% concentrated hydrofluoric acid (49.2% assay). This bath was used at boiling temperature of approximately 86° C. The bath was contained in a Type 347 stainless steel tank surrounded with a jacket. Steam was circulated through this jacket for heating of the bath. These tanks had reasonable life, except for the weld heat affected zones which required periodic rewelding. Only the original and two replacement tanks were required for 1120 cladding billets, or a total of 7840 pieces.

All components were pickled approximately 20 seconds in the boiling acid bath which removed about one (1) mil from each surface. The bath strength was maintained by periodic additions of both HF and HNO₃ based on metal removal rate. Following pickling, the components were rinsed in four (4) separate circulating tap water rinses and two distilled water rinses.

FIGURE 54. End Milling 90° Groove in Billet End Plug.

210-141

FIGURE 55. Machining Tapered Purge Opening and Counterbore in Cladding Billet End Plug.

210-136

Reaming Purge Opening

210-138

Turning Counterbore

The final distilled water rinse was maintained at boiling temperature, to facilitate drying. The components were completely dried by circulating filtered air in an oven. Components were stored in trays and kept clean in a cabinet.

Following degreasing, the components were handled only with clean rubber gloves; following pickling the components were touched only with clean stainless steel tongs. Throughout the pickling and rinsing operations the cover and side plates were manipulated in groups of six (6), suspended, width dimension vertical, from their ends in stainless steel tongs, as may be seen in Figure 56. The end plugs were carried through these operations in groups of twelve (12) in a stainless steel screen basket. These components were placed grooved side down, resting on the edges formed by the intersections of the sides and tapered faces. The seal pins were pickled and rinsed individually, being gripped on the top projection which later was pressed into the electrode.

Prior to use, each component was inspected visually for defects such as cracks, stringers, laps, and residual contamination. All suspect material was examined microscopically. Material with defects other than residual contamination, if not severe, was recycled through the blasting and pickling operations and used if within dimensional tolerances.

Zircaloy-2 Yields and Losses

The yield of Zircaloy-2 cladding components and the losses at various stages of preparation from the forged, scalped and rolled stock are presented in Table XVII. In terms of totals, the 11,926.3 lb of stock were converted to 6,242.1 lb (52.34%) of finished-machined and cleaned cladding components and 5,684.2 lb (47.66%) of scrap. The scrap was made up of 3,745.8 lb of heavy material, 369.8 lb of saw chips and 1,568.5 lb of machine turnings and cleaning loss.

The high loss in the heavy scrap category, 31.41%, was caused by the poor quality of ingot, the necessity of rolling short lengths because of equipment limitations, the inability to control width and to produce sound metal at the sides because of lack of equipment which could perform side work. Surface defects such as laps, seams, stringers, porosity, and tungsten inclusions, as shown in Figures 46 and 57, were attributed to the poor quality of Zircaloy-2 ingot. The surface defects caused an estimated heavy scrap loss of 5%. Limitations imposed on the length of stock which could be rolled by the length of furnace heating zone or speed of rolling and reversing of the 17" mill used, required that short lengths, six (6) to ten (10) feet, be rolled. The high number of ends to weight ratio produced an estimated 10% loss due to defective end croppings. The inability to work the sides of the forged slab during rolling, perhaps coupled with the

FIGURE 56. Billet Cover Plates Carried in Gang Tongs Ready for Pickling and Being Pickled.

106-2747

106-2744

Table XVII
ZIRCALOY-2 CLADDING COMPONENT YIELDS, SHEARING AND MACHINING LOSSES

Component	For Billet Type	Number of Components Produced	Scalped Slab Wt, lb	Component Blank Wt, * lb	Heavy Scrap Loss		Sawing Loss		Machined & Pickled Component Wt, lb	Machining & Pickling Loss		Recovery Slab to Finished Components, %	Total Loss, %
					lb	%	lb	%		lb	%		
Cover Plate	Thin	1176							1553.1	123.9			
Cover Plate	Thick	1121	5026.8	$\left\{ \begin{array}{l} 1677.0 \\ 1517.8 \end{array} \right\}$	1832.0	36.44			1417.3	100.5	4.46	59.09	40.91
Side Plate	Thin	1231							732.4	172.9			
Side Plate	Thick	1202	2795.7	$\left\{ \begin{array}{l} 905.3 \\ 1177.0 \end{array} \right\}$	713.4	25.52			972.2	204.8	13.51	60.97	39.03
End Plug	Thin	1102	1544.7	946.0	439.4	28.44	159.26	10.31	583.4	362.6	23.47	37.77	62.23
End Plug	Thick	1152	2559.1	1587.5	761.0	29.74	210.55	8.23	983.7	603.8	23.59	38.44	61.56
TOTALS		6984	11926.3	7810.6	3745.8	31.41	369.81	3.10	6242.1	1568.5	13.15	52.34	47.66

*Calculated Weight

FIGURE 57. Reproductions of Radiographs Showing Presence of Tungsten Inclusions in Zircaloy-2 Cladding Stock.

21214 1X
Large Tungsten Inclusion

21213 1X
Small Tungsten Inclusions

21217 1X
Stringer of Tungsten Inclusions

21218 IX
Stringer of Tungsten Inclusions

poor surface quality of the ingot, caused defective material to extend $1\frac{1}{2}$ " to 1" in from each side of the rolled strip. These defects along the sides of the strip were heavy seams and laps, as shown in Figure 58. Part of this type of defect was caused by spread and part caused by the mode of deformation. The side surface which bulges during spreading becomes part of the rolling plane during subsequent passes. Because this surface was not deformed by rolling but, in part, dragged along by shear stress, these defects were produced. This side defect coupled with inexperience in handling of this material led to the excess allowance in width of strip rolled.

Bar products for the two sizes of end plugs would have been just as satisfactory as the plate stock rolled with respect to utilization of the desirable texture and would have eliminated a large portion of the 3.10% scrap generated in sawing the plate into blanks. In addition, the scrap produced in trimming the sides of the slab would have been eliminated. Rod rolls were available for the 17" mill, but, unfortunately, rectangular grooves of appropriate dimensions were not. In addition, much less scrap would have been produced in finish machining of the end plugs had it been immediately possible to form the "V" groove by rolling or forging. Approximately 45% of the scrap turnings produced in machining the end plugs came from the cutting of the "V" groove.

Labor Burden

The sawing of the end plug blanks and the machining of all cladding components consumed 4800 man-hours of machine shop time. A total of approximately 600 man-hours were expended in wet abrasive blasting, shearing, and pickling of the components.

FIGURE 58. Seams and Laps Developed along Sides of Zircaloy-2 Strip Rolled without Side Work (Edge Rolling).

21114

Normal Side Seams

1X

21115

Severe Side Seams and Laps

1X

CLADDING BILLET PROCESSING

The next step in the manufacturing procedure for EBWR plates was the assembly and sealing of the cladding billets. The sequence of operations established were: (1) assembly, (2) purging and welding of billet seams, and (3) billet evacuation and seal pin welding.

As discussed previously, the object of these operations was to close all seams formed by adjoining cladding components by welding with a minimum of contamination to the core and internal surfaces of the clad; and then evacuate and seal the billet so that the bonding surfaces would not be subjected to contamination by gas entrapped within the steel jacket nor outgassing therefrom.

Accomplishment of these objectives required the development and construction of certain pieces of special equipment. The first of these was a press-welder for the closing of the seams formed by mating cladding components. The second was an evacuation-welding chamber for removal of gas used to purge the billet during the first operation by evacuation, and then sealing the opening provided for the introduction of the purge gas by a vacuum-arc welding process.

Press-Welder

The first operations in the billet assembly, purging of the billet and welding of the components, were done in the double acting hydraulic press shown in Figure 59. The basic unit of this equipment was a commercial 50-ton hydraulic press, as a machine shop straightening press. The working distance between the two 2-1/2" x 8" channel uprights was 44" and between the ram and table was adjustable up to 40". The press had a single hydraulic cylinder carried by a 3" x 12" double channel cross head. Pressure in the main cylinder was developed by a small double-acting piston-type pump which was in turn driven by an air cylinder reciprocated automatically. This press was modified by the addition of a horizontal hydraulic press for applying pressure to the billet sides.

The billet was positioned vertically by a pedestal topped with a chill and horizontally by the stationary platen and chill of the horizontal press. Pressure in the vertical direction was applied by means of the vertical ram of the main press through a platen and chill. Pressure was applied to the billet sides by means of horizontal platens of the auxiliary press. Side pressure was developed by four cylinders located beyond each end of the platens. The cylinders were mounted on each of the four press heads. The two heads on the near side, Figure 59, were stationary, and the two opposite heads were movable. Pressure for the operation of these 2" dia. double-acting hydraulic cylinders was developed by a motor-driven pumping system capable of pressures controllable from 0 to 2000 psi.

FIGURE 59. Perspective Drawing of Press-Welder Used for Closing Seams in Cladding Billet.

The welding equipment consisted of four Heliarc torches, one for each side and one for each end, each mounted on positioning and traversing mechanisms. The two torches for welding the longitudinal seams in the billet sides were mounted on a mechanism adjustable linearly both horizontally and vertically by means of rack and pinion and angularly in both vertical and horizontal planes. These torches were traversed by a standard cutting and welding machine carriage riding on rails mounted on each side of the press. The speed of these buggies was adjustable from 4"/min to 32"/min. The two torches for welding the seams in the ends of the billet were positioned and traversed both vertically and horizontally by an especially designed mechanism. The clamp holding the angle torch was driven vertically and horizontally in a plane normal to the billet axis by screw and nut drives. Power was furnished for these movements by two small 27 v DC motors through spur gear reduction. The speed of these units was adjustable from 3"/min. to 20"/min.

All four welding torches used were designed for operation at 500 amp. The two torches used for welding the billet ends were designed for hand welding, and the two used for welding the billet sides were designed for machine welding. The electrodes used were of thoriated tungsten, 1/8" diameter; a 5/8" dia metal nozzle was used to provide gas shielding. Welding power was supplied by a 600-amp DC welding motor generator set. Initiation of the arc was accomplished by means of a high frequency starter.

The purging equipment for introduction of argon into the assembled billet is shown in Figure 59. This equipment consists of a Zircaloy-2 fitting, tapered to match the purge opening in the billets, connected by means of plastic tubing to the argon gas supply. The flow of the purge gas was controlled by means of a flowmeter, 0 to 15 liters/min.

Evacuation-Seal Welding Equipment

The second operation in the billet assembly process, removal of purge gas and back-diffused air and the sealing of the purge opening, was performed in the evacuation-seal welding equipment shown in Figure 60. This equipment consists of a chamber, roughing and high-vacuum pumping systems, rack, electrodes, power distribution system, and power supply. The chamber was simply a tube, 30" dia x 19" long, closed at the bottom and flanged at the top for acceptance and sealing of the rack shown in Figure 61. A cutaway perspective of the evacuation-seal welding equipment is given in Figure 62.

The roughing system was provided so that the high-vacuum diffusion pump system could be operated continuously even during loading and unloading of the chamber (being closed by a valve). The function of the roughing system was to reduce the chamber pressure to below 100 microns at which pressure the high-vacuum system could be opened to the chamber.

FIGURE 60. Billet Evacuation-Seal Welding Equipment

FIGURE 61. Billet Rack for Support of Billets during Evacuation and Sealing.

FIGURE 62. Cutaway Perspective of Evacuation-Seal Welding Equipment

The rough pumping system consisted of a two-stage rotary, mechanical vacuum pump, a 1-1/2" vacuum valve, a stainless steel-wool filter and appropriate 1-1/2" steel pipe and neoprene tubing. The mechanical pump had a free air capacity of 5 liters/sec and was designed for an ultimate vacuum of 0.01 micron. The vacuum valve was a globe type with a bellows-sealed stem operated pneumatically by a double-acting cylinder controlled by a solenoid valve. The stainless steel-wool filter was provided to exclude weld splatter from the pumping system. This pumping system was capable of reducing the chamber pressure from atmospheric to 100 microns in 4 min.

The high-vacuum system was composed of a vacuum valve, a fractionating oil diffusion pump, a booster oil diffusion pump, a rotary mechanical pump and appropriate connecting piping. The vacuum valve, flanged for 6" dia piping, was of the low-impedance gate type. This valve was located between the chamber and fractionating pump. The 6" fractionating oil diffusion pump had a speed of 650 liters/sec at 0.5 micron and was capable of producing an ultimate vacuum of the order of 10^{-7} mm Hg with Octoil-S. The limiting forepressure of this pump was 140 microns. The backup pump for the fractionation pump was a 3-7/8" dia booster. The peak pumping speed of this pump was 110 liters/sec at approximately 7 microns, with a limiting forepressure of 400 microns. The mechanical pump of this system was identical to that described for the roughing system. The fractionating pump was connected to the 6" valve, which was in turn connected to the chamber by 6" stainless steel fittings. This pumping system was capable of reducing the chamber pressure to the 10^{-6} mm pressure range without a cold trap.

The chamber pressure was measured in three pressure ranges by means of a Bourdon vacuum gage, a thermocouple gage, and a cold cathode (Miller) gage. With these gages the chamber pressure could be measured from atmospheric to 10^{-7} mm Hg.

The rack used for supporting billets in groups of twelve for evacuation and seal welding is pictured in Figures 61 and 62. The billets were supported on a stainless steel base plate, circular in shape, and were positioned by spacers at the bottom and a clamp plate at the top. The electrical connection for welding was made to the billet by the water-cooled copper clamp plate which was, in turn, connected to the top cover by means of a copper post, as shown. The clamp plate and base plate were suspended from the top cover by means of four stainless steel tie rods.

The brass cover plate, which sealed to the chamber top flange by an "O" ring, also carried the welding electrodes. The electrode assemblies, positioned directly above the billet purge openings, were insulated from the top cover and sealed by Micarta fittings. A compression type of seal using neoprene rings of square cross section permitted the electrodes to be moved vertically.

FIGURE 63. Electrode Used for Seal Welding Billet Purge Openings by a Vacuum-Arc Process.

FIGURE 64. Line Diagram of Electrical Circuit for Welding Time Control.

BILL OF MATERIALS

SYMBOL	DESCRIPTION	FUNCTION
KS-1	DISCONNECT SWITCH	CONTROL POWER SOURCE
A	MAGNETIC RELAY	EXCITE GENERATOR SHUNT FIELD
TD	VARIABLE TIME DELAY RELAY	CONTROL DURATION OF WELDING CYCLE
OV	OVER VOLTAGE RELAY	STARTS TIMER CYCLE UPON RASE IN VOLTAGE UPON INITIATION OF ARC
CC	RESISTOR	GENERATOR AMPERAGE CONTROL
VC	RESISTOR	GENERATOR VOLTAGE CONTROL
PRS	POLARITY REVERSING SWITCH	CONTROL POLARITY OF GENERATOR OUTPUT
TC	TIMER CLUTCH	ENERGIZES TIMER

The electrode assembly is shown in Figure 63. The electrodes of Zircaloy-2, carrying the seal pins, were screwed into the water-cooled, copper alloy barrels to make electrical and thermal contact. A fitting which introduced water into the bottom of the barrel and exhausted it at the top screwed into the other end of the barrel. Each billet, of course, required a new seal pin; but the electrodes, since only a small portion was consumed per billet, were reused after remachining of the tips. The electrodes were used until they were about 50% consumed, then discarded.

Electrical Arrangement

The electrical connection to the welding power source was made with $1/4" \times 4"$ cross-sectional copper bus bars. The negative bus bar was connected directly to the rack cover. The current path from cover to billet top was through a copper post secured to both the cover and billet clamp plate. This arrangement completed the negative circuit. The positive bus bar was fastened to a circular copper bus bar, of $1/2" \times 2"$ cross section, which was positioned on top of the chamber concentric with the billet rack when in loaded position. The circular bus bar was fastened to, but insulated from, the chamber. The connection from the circular bus bar to the electrodes was accomplished by a power connector, as shown in Figure 62. Since welding was done on a single billet at a time, only one power connector was used. The power connector was moved from one electrode to another. This arrangement completed the positive circuit.

The power required for preheating and welding was supplied by two, 700-amp DC welding generators connected in parallel. The generators were controlled at the control cabinet shown in Figure 60. Located on this control cabinet were the start and stop buttons for the motors, generator open-circuit voltage control, current control and rheostat position indicator, welding cycle reset button, generator polarity switch, and generator volt and ampere meters.

In addition to the open-circuit voltage control and current control normally found on a welding generator, electrical equipment for automatic control of the duration of the welding cycle was added to the exciter circuit of the generators. This equipment consisted of a contactor, time delay relay and an overvoltage relay, shown schematically in Figure 64. The timer motor and exciter main line contactor were energized manually by a start button. The time-delay relay was energized by an overvoltage relay connected between the output poles of the welding generator. The overvoltage relay was energized by the voltage increase accompanying initiation of the arc (to be discussed later). Closing of the overvoltage relay, contact (OV) energized the time delay relay (TD) which opened contact (TD) after the relay had timed out. Opening (TD) in turn opened the exciter main line contactor (A) extinguishing the arc.

Billet Assembly and Welding

The manipulations necessary in transforming components into an unevacuated cladding billet were: (1) placing the components in their respective positions, (2) transferring these components in place to the double-acting hydraulic press, (3) purging air from within the billet, and finally (4) closing the seams in the cladding by welding. Of primary concern in these operations was the reduction of contamination, particularly of the bonding surfaces. The sources of contamination were twofold: handling and welding.

Contamination resulting from handling was minimized through the exclusion of contact with the bonding surface by either hand or glove. Movement of all components from the place of storage to the assembly rack was done with stainless steel tongs cleaned by degreasing. After placing the components in position all bonding surfaces were unexposed, and the movement from assembly rack to press was done with lint-resistant gloves. Contamination potentially possible during welding was minimized by the restriction of the heat-affected zones through the use of chill plates and removal of contaminating elements, oxygen and nitrogen, from within the billet by argon purging.

The cladding billet components were removed from their places of storage (vacuum chamber for the uranium alloy cores and cabinet for the Zircaloy-2 cladding components) and placed in positions in the rack shown in Figure 65. Prior to assembly, however, the cover plate thicknesses were measured at several points and variations noted. When assembled, the cover plates were positioned so that thickness variations cancelled instead of being cumulative. This was done in an attempt to minimize camber developed during rolling resulting from thickness variations from one side of the billet to another. Thickness variation across the width of the cover plate resulted from crown developed in rolling the multiple width cover plate strip.

The billet cores were handled by means of special, stainless steel grips. Contact was made with the tapered ends of the billet for movement from the vacuum storage chamber to its position on the bottom cover plate. The cladding billet components were picked up and positioned by means of standard laboratory stainless steel tongs.

Having assembled the components in their respective positions, the loose billet was moved from the assembly rack to the press-welder (Figure 66) by hand. Lint-resistant gloves were used. The billet components were placed on the bottom chill plate of the press and moved into contact with the stationary side chill plate. After final alignment, the components were pressed together by the vertical and horizontal cylinders. Full pressure of 4 tons, 5540 lb/sq in. for thin and 3500 lb/sq in. for thick billets, was applied to the billet side plates; but reduced pressure, approximately

FIGURE 65. Rack for Assembly of Cladding Billet Components. Welded Billets at Right.

106-2748

FIGURE 66. Press-Welding Machine for Sealing Seams in Cladding Billets.

one ton, 157 lb/sq in. for thin and 144 lb/sq in. for thick billets, was applied to the cover plates by the vertical ram. The purge fitting was then seated in the tapered purge opening in one end plug, and the tank argon purge gas was introduced into the billet at a gage pressure of approximately one pound and a flow rate of 10 liters/min. The reduced pressure was used on the cover plates to provide channels between cover and side plates for escape of air and argon. Purging was continued for 10 min, a time previously found sufficient for prevention of contamination during welding. Following the purge cycle, full pressure of the vertical ram, 50 tons, 7866 lb/sq in. for thin and 7200 lb/sq in. for thick billets, was applied to the cover plate, which in most cases stopped the flow of argon.

Having purged the billet, all seams formed by the mating Zircaloy-2 components were closed by welding using the conventional inert gas-shielded, tungsten-arc welding process. The welds on the billet sides and ends were made by the appropriate mechanized torches (see Figure 66) using 150 amp of current at a speed of 16 in./min. The weld penetration with this current and speed was between 0.030" and 0.040", as shown in Figure 67. No difficulty was experienced during welding, except in a very few cases where the escape of purge gas extinguished the arc. In those cases gas pressure was reduced sufficiently so that the weld could be completed. The high-frequency arc starter minimized tungsten contamination; the torch gas shield was adequate for restricting external contamination sufficiently so as not to cause difficulty in the subsequent roll bonding. This shield, however, was inadequate for restricting weld contamination sufficiently to retain resistance to corrosion by water. Shielding for corrosion resistance of the clad was not a requirement because the prerolling weld metal was removed in machining the resulting fuel plate to length and width.

The welds produced by this processing are illustrated in Figure 67. Because of the chills used, the fusion zone was restricted to the vicinity of the seam, and very little sag of the weld resulted. Surface contamination was normally restricted to a slight bluing or straw coloring.

Within the limitations discussed above, this method of processing the cladding billet was considered equivalent to the more costly and cumbersome practice of dry box welding. Setup time was reduced; welding was unincumbered by a closure; and cost of equipment was less.

The assembly and welding cycle was completed in approximately 30 min. Two operators were engaged in these operations. One, a technician, assembled the billets and loaded the press, and the other, a welder, performed the welding.

FIGURE 67. Sections Through Cladding Component Seal Welds.

(These photographs have been reduced 37% for reproduction.)

Billet Evacuation and Sealing

When twelve (12) billets had accumulated from the assembly-welding operation, they were loaded into the evacuation-sealing rack shown in Figure 61. Before loading the billets, the Zircaloy-2 electrodes carrying the Zircaloy-2 seal pins were screwed into the copper alloy electrode barrels. The loaded rack was then positioned in the chamber where it was sealed with an "O" ring. In this equipment, pictured in Figure 60, the billets were evacuated through the purge opening; upon completion of evacuation, the purge openings were plugged by seal pins which were in turn made leak tight by a vacuum-arc welding process.

The evacuation-seal welding cycle is shown in Figure 68. For the evacuation portion of the cycle, the seal pins and electrodes were suspended above the billets to permit gas escape out of the purge openings. The first operation in the removal of purge gas was an evacuation-back fill with air, a procedure repeated three times (3X) for the dilution of the entrapped argon purge gas. This was done as a precautionary measure against sealing argon in the billet. Inert gas, even in small amounts, produced blisters in the finish-rolled fuel plate. Following this evacuation-back filling procedure the billets were evacuated two (2) hours in the chamber maintained in the 10^{-5} - 10^{-6} mm pressure range. Typical evacuation rates of the gas within the billet are plotted in Figure 69. The pressure within the billets was reduced into the 10^{-5} mm range by the end of the evacuation period.

FIGURE 68. Evacuation-Seal Welding Cycle Shown Schematically

Figure 69. Pressure-Time Curves for EBWR Billet Evacuation.

Upon completion of the evacuation, the electrodes were lowered, seating the seal pins in the purge openings. Then, one at a time, the electrode barrels were connected to the circular bus bar and the seal pins were welded in vacuum. First the seal pin and weld area in the end plug were preheated 15 sec by a flow of 900 amp at about 3 v. This was done to increase the depth of fusion of the weld. Following the preheat cycle the current was raised to approximately 1300 amp, which melted the section of the seal pin between billet end plug and Zircaloy-2 electrode, thus establishing the arc. Upon initiation of the arc, the voltage increased from the 3 v during preheat to 30 v. This voltage increase energized an overvoltage relay which in turn energized a time delay relay which controlled the duration of the arc. This time delay relay was set for three (3) sec. During this three (3)-sec interval the seal pin was fused to the end plug and depth was given to the weld by consumption of a portion of the Zircaloy-2 electrode.

During the welding, the system pressure rose to approximately 40 microns but returned immediately to the prewelding pressure after

extinguishment of the arc. Because of this very rapid recovery of high vacuum, a major fraction of the pressure increase was believed to be due to metallic vapors generated in the arc.

In order to maintain the arc in a vacuum range of 0.1 to 1 micron a high open-circuit generator voltage was essential. To stabilize the arc, the open-circuit voltage of the two 700-amp welding generators used in parallel was set at their maximum of approximately 90 v. The high amperage resulting from the high voltage necessary for stabilization of the arc made manual manipulation of the more conventional tungsten arc-welding process extremely difficult.

The welds resulting from this process in general had good depth for maintaining integrity of the seal during the roll bonding which followed. Satisfactory welds are pictured in Figure 70. A longitudinal section of a good weld is shown in Figure 71.

Each seal pin weld was examined visually for completeness. The billets which exhibited welds appearing to have sealed the pin but insufficient in depth were rewelded, using an electrode without a seal pin. In these cases the electrode was lowered into contact with the original weld. Power required to melt the electrode tip for initiation of the arc was somewhat higher than discussed above. Seal pin welds which were incomplete as shown in Figure 70 required the removal of the seal pins and complete resealing. The seal pins were extracted after removal of the weld metal by milling.

Successful seal pin welds were obtained in 98.7% of the billets. Based on the high rate of defective seal pins and cladding bonds in finished fuel plates rolled from billets which had rewelded seal pins, this rewelding practice proved to be an unsatisfactory salvage practice. Of the 35 rolled fuel plates (3.1% of the production) which had defective seal pin or cladding bonds, 11.4% came from billets which had been rewelded. Table XVIII contains a listing of rewelded billets and resulting fuel plate evaluation.

FIGURE 70. Vacuum-Arc Seal Pin Welds, Satisfactory and Unsatisfactory.

106-2797
Satisfactory Weld

106-2796
Unsatisfactory Weld
Incomplete Penetration

106-2794
Unsatisfactory Weld
Incomplete Sealing

FIGURE 71. Longitudinal Sections through Vacuum-Arc Seal Pin Welds.

18159
Satisfactory Seal Pin Weld. Weld penetration
approximately 0.10".

18158
Unsatisfactory Seal Pin Weld. Weld penetration
approximately 0.015".

Table XVIII

BILLETS HAVING SEAL PIN REWELDED AND
RESULTING FUEL PLATE EVALUATION

Rewelded Billet No.	Finished Plate Evaluation
447	Acceptable for reactor use.
478	Acceptable for reactor use.
603	Acceptable for reactor use.
607	Acceptable for reactor use.
609	Seal pin not bonded - rejected.
E361	Crack in seal pin - rejected.
E376	Acceptable for reactor use.
E483	Acceptable for reactor use.
E484	Acceptable for reactor use.
E486	Acceptable for reactor use.
E607	Poor bond at side clad to end plug one end - rejected.
E649	Poor bond at all cladding interfaces - rejected.
E684	Acceptable for reactor use.
E708	Acceptable for reactor use.
E778	Acceptable for reactor use.

JACKETING CLADDING BILLET

The cladding billets subsequent to the manufacturing operations discussed above were placed in prefabricated steel jacketing components which were, in turn, closed by welding. The function of the steel jacket was two-fold. First, it provided the necessary protection of the Zircaloy-2 cladding components against atmospheric contamination, which became increasingly more important as the cladding was reduced in thickness. The surface contamination causing loss of corrosion resistance, although undesirable, could be subsequently removed; but the reduction of ductility of the surface resulting from contamination, which could initiate fracture of the cladding, could not be tolerated. Secondly, the restraining influence of the jacket upon the shifting of the billet components was of major importance in maintaining the proper relationship of core and clad components during the initial stages of rolling before bonding occurred. The steel jacket and its design had a great influence upon the spread during rolling, and the restraint imposed in the rolling direction kept the cladding billet end plug in its proper location instead of being pushed from the billet.

Jacket Preparation

The four-piece channel-type steel jackets, as shown in Figure 72, were machined from 1-1/4" x 8", 1-1/8" x 2", and 1-1/2" x 2" hot rolled, SAE 1020 steel bars. The 1-1/4" x 8" bars were cut into 16" lengths and ground on both faces to a thickness uniform to ± 0.002 ". A groove, whose width was 10 mils greater than the width and whose depth was 2 mils greater than one-half the thickness of the cladding billet, was milled in one face of each plate. The two halves, when placed together, formed a cavity into which the billet fitted. End plugs for the thin billet jackets were machined from the 1-1/8" x 2" bar, and for the thick billet jackets from the 1-1/2" x 2" bar. For weld closure of the steel jacket, the outboard edges of all mating surfaces were chamfered 1/2" at 30°.

Great care was taken to identify the various lots of steel so that a jacket half from one lot was not mated with a half from another lot. A difference in carbon content of 15 points from one jacket half to another caused the development of severe bowing during the rolling of the billet, so much, in fact, that rolling without intermediate flattening operations became impossible.(6)

Assembly of Rolling Billets

The rolling billets were produced by the combination of cladding billets and steel jackets sealed by welding. No attempt was made to evacuate the steel jacket, since the cladding billet bonding surfaces were sealed against contamination resulting from gas entrapped within the jacket or outgassing therefrom. The quantity of air entrapped within the jacket was small

FIGURE 72. Design and Dimensions of Steel Jackets.

and inconsequential to the surface quality of the finished plate since, even if the steel jacket were evacuated, a pickling operation was necessary to develop a corrosion-resistant surface.

The cladding billets coming from the welding, evacuation, and sealing processes contained obstructions which interfered with their insertion into the steel jackets. These obstructions, in the form of weld metal sag along the cladding seams, seal weld buildup, and weld spatter, were removed by milling sufficiently to permit entry into the bottom of the steel jacket. The steel jackets were vapor degreased prior to use.

Welding of Steel Jackets

Sealing of the steel jacket around the cladding billet was accomplished by a two-stage welding operation. The first operation was the sealing of the root of the "V's" formed by jacketing components by a deposit of uncoated steel filler rod by means of conventional inert gas-shielded tungsten arc welding. The second stage consisted of the complete filling of the "V's" by standard consumable electrode welding using a coated, powdered steel rod.

For the initial welding, the assembled rolling billet was placed between heavy steel platens of the press shown in Figure 73 and pressed tightly together with a pressure of 15 tons, which was maintained throughout welding to prevent separation and nonuniform billet thicknesses. The deposit of uncoated filler rod by the Heliarc process excluded flux from inside the billet during the final filling of the "V's." Flux contained within the jacket was considered detrimental to the quality of the finish-rolled fuel plate. The final welding stage was performed on the billet after removal from the press. Three passes with the 5/16" diameter rod were required to completely fill the "V." A turntable, pictured in Figure 74, was employed for manipulation of the billet during this welding. Following these welding operations the billets were ready for roll bonding. Cladding billets and rolling billets at various stages of preparation are shown in Figure 75.

FIGURE 73. Press for Holding Rolling Billet for Heliarc Seal Root Weld.

210-130

FIGURE 74. Turntable for Consumable Electrode Arc Welding of Rolling Billets.

FIGURE 75. Cladding and Rolling Billets at Various Stages of Preparation.

FUEL PLATE FABRICATION

Establishment of continuity within the cladding components and of the integrity of core and clad was done by rolling at elevated temperature. The development of unity among the seven components which make up the original cladding was, of course, of paramount importance. This skin had to be free of channels through which water could pass to the core and must act as a permanent barrier to high temperature water and steam for the life of the fuel plate. In addition, the cladding had to be married to the uranium core alloy so as to offer the least resistance to the flow of heat from the core to the coolant; further, the interface between core and clad had to be free of passages through which water could flow as a control of the rate of core corrosion in event water reached the core in some local area.

Maintenance of dimensions of the finished fuel plate was of critical importance. The control of these dimensions, length, width, and thickness, coupled with the straightness of plate, could best be controlled by the use of the rolling process as opposed to other methods of fabrication such as extrusion.

The roll bonding of the billets was done on the 17" x 24", two-high rolling mill shown in Figure 76. The housings of this mill were of close top design and made of cast steel. Each housing post had a cross-sectional area of 146 sq in. The mill was equipped with 5" dia, 1/4" pitch, Acme thread screws driven by means of a single 5-hp, shunt wound DC motor through suitable gear reduction and worm and pinion. The roll neck bearings were Timken 4-row, tapered roller type, 11-1/4" I.D. x 14.994" O.D. x 9-5/8" long, which mounted in cast steel chocks. The capacity of these bearings at 500 rpm were radial - 110,640 lb., and thrust 23,450 lb. The top roll and chocks were balanced by means of four hydraulic oil cylinders, mounted two in each bottom chock. The rolls were chill cast alloy, cast iron ground, without crown and matched in diameter to $\pm 0.001"$.

The rolls were driven by a 150/200-hp, shunt wound, DC, mill-type motor through a combination drive and pinion stand, 15.56 to 1 reduction. All gearing was double helical (herringbone), mounted on roller bearings. Spring-balanced spindles equipped with universal couplings transmitted torque from pinions to rolls.

The speed of the 17" dia rolls was 114 ft/min at the base motor speed of 400 rpm and 342 ft/min at the top motor speed of 1200 rpm. In this speed range the motor was controlled by field weakening and operated in the increasing horsepower portion of the speed-horsepower curve. For speed reduction from base speed of 400 rpm to 50 rpm (100 to 13 ft/min roll speed), control was accomplished by reducing the generated voltage to

FIGURE 76. Perspective Drawing of 17" x 24" Rolling Mill and Auxiliary Equipment.

the armature. In this range the motor was operating in the constant torque portion of the torque-speed curve. These speed control functions were performed by means of an electronic control unit.

In addition, the mill was made reversing by provision of definite time acceleration and deceleration functions in the same electronic control unit used for speed control. The resistor-capacitor time delay principle was employed for controlling the rate of acceleration and deceleration. With this equipment, the voltage applied to the armature was built up as rapidly as the motor was able to build up its counter emf in a stepless fashion, using the maximum current for which the equipment was designed. Likewise, deceleration was accomplished by control of the regenerative currents at the maximum allowable with the motor, switchgear, and generator. With this electronic control equipment, the mill running at 125 ft/min could be reversed in 10 sec.

The mill was equipped with a semi-automatic program control for presetting of the roll schedule. This equipment, as shown in Figure 77 consisted of a $1/8$ " pitch screw 87" long, a follower nut and trip arm, and microswitches. The screw was coupled to the shaft of the driven gear of the screwdown gear reducer. With this arrangement 1" travel of the nut carried on the screw was equivalent to 0.036" vertical travel of the mill rolls. By proper arrangement of the position of the microswitches the roll setting could be adjusted to conform with any schedule. The sensitivity of this equipment was less than one-mil roll change. The minimum change in roll opening was 0.048", being limited by the width of the microswitch mounting brackets. The wiring diagram for the screwdown program controller is contained in Figure 78.

Operation of this equipment was semiautomatic. The starting of the screwdown motor was accomplished manually by an operator depressing the appropriate "Up" or "Down" push button. Once energized, the motor continued to operate until the appropriate up or down limit switch, acting as a stop button, was tripped. The time delay relays shown in Figure 78 were for purposes of overriding the limit switch during restarting of the screwdown motor. The time delay was set to time out just after the trip arm cleared the limit switch. This eliminated the inconvenience of the operator having to hold down the starting button until the limit switch was cleared. If necessary, however, the screwdown functions could be converted to completely manual operation by means of a selector switch. In addition, the pass number and direction of travel was indicated on the operator's panel (Figure 79) by means of two Selsyn motors, one coupled to the end of the program screw and the other mounted in the operator console. The Selsyn mounted on the program screw was connected through a 900 to 1 gear reducer so as to obtain one revolution of the motor in 3" of top roll travel. The motor mounted in the cabinet was fitted with an indicator and pass numbers which could be adjusted to the proper location.

FIGURE 77. Perspective Drawing of 17" x 24" Mill Screwdown Program Controller.

106-3055

FIGURE 78. Line Diagram of Electrical Circuit for Screwdown Program Controller.

* LIMIT SWITCHES MOUNTED ON SCREWDOWN PROGRAM CONTROLLER. ONE LIMIT SWITCH REQUIRED FOR EACH "UP" AND "DOWN" ROLL CHANGE.

BILL OF MATERIAL		
SYMBOL	DESCRIPTION	FUNCTION
BR	MAGNETIC RELAY	SCREWDOWN MOTOR BRAKE RELAY
2F	STARTING CONTACTOR	SCREWDOWN MOTOR "DOWN" STARTER
2R	STARTING CONTACTOR	SCREWDOWN MOTOR "UP" STARTER
1GR	MAGNETIC RELAY	CONTROL INTERLOCK
2GR	MAGNETIC RELAY	CONTROL INTERLOCK
2AP	MAGNETIC RELAY	ANTI-PLUG INTERLOCK
2FA	MAGNETIC RELAY	CONTROL INTERLOCK
2RA	MAGNETIC RELAY	CONTROL INTERLOCK
21A	TIME DELAY RELAY	MOTOR ACCELERATION CONTROL
22A	TIME DELAY RELAY	MOTOR ACCELERATION
20L	OVERLOAD HEATER	MOTOR PROTECTION
R1	RESISTOR	MOTOR ACCELERATION
R2	RESISTOR	MOTOR ACCELERATION
DB	RESISTOR	MOTOR DECELERATION
4KS	KNIFE SWITCH	POWER DISCONNECT
5KS	KNIFE SWITCH	POWER DISCONNECT
6KS	FUSE SWITCH	POWER DISCONNECT
TRS-I	440V-100V TRANSFORMER	POWER SUPPLY
SS-I	SELECTOR SWITCH	TRANSFER OF SCREWDOWN CONTROL FROM MANUAL TO AUTOMATIC
FH	MAGNETIC RELAY	CONTROL INTERLOCK
RH	MAGNETIC RELAY	CONTROL INTERLOCK
TD-1	VARIABLE TIME DELAY RELAY	OVER RIDE "DOWN" LIMIT SWITCHES DURING STARTING OF SCREWDOWN MOTOR
TD-2	VARIABLE TIME DELAY RELAY	OVER RIDE "UP" LIMIT SWITCHES DURING STARTING OF SCREWDOWN MOTOR
LS	LIMIT SWITCH	LIMIT MILL SCREW "UP" TRAVEL
PL-1	PILOT LIGHT	INDICATE SCREW TRAVEL DIRECTION
PL-2	PILOT LIGHT	INDICATE SCREW TRAVEL DIRECTION

EH

FIGURE 79. Rolling Mill and Feed Table Control Console with Preheat and Reheat Cycle Timers and Pass Indicator.

The program controller greatly simplified the operation of the mill; furthermore, the probability of errors being made in roll settings was greatly reduced. Because of the number of functions the mill operator had to perform in controlling the rolling operation (see Figure 79), counting screw revolutions and reading dial indicator positions were very difficult operations. The reduction in the number of errors assumed major proportions when the value of the plates which were rolled was considered.

As a means of transport of billets and plates from furnace to mill and return, and as an aid in the control of plate quality, the mill was equipped with power-driven roller tables. Because of the weight of the billets (approx. 100 lb each) and the number of passes and reheats necessary during plate rolling, the use of these tables permitted a reduction of the number of operators and helpers from six men to two. Even more importantly, by means of the tables the quality of the rolled product was improved because of reproducibility of such influencing factors as time between furnace and mill, and entry position of the work into the mill. With this equipment, production was performed by two men, one operating mill and table controls and the other entering and discharging the work from the furnaces. The tables were of rugged mill-type construction.

This equipment was designed so that a single roll could withstand a pressure of 44,000 lb without damage. This design criterion was established by measurement of the total force necessary to straighten a bowed plate approximately $2\text{-}1/2$ " thick. The necessary pressure as measured on a hydraulic press was found to be 20,000 lb. A table of this type had to be constructed to carry this heavy load in the event a billet or plate should bow downward during rolling.

A drawing of the general arrangement of the mill tables, which were located on each side of the mill, is given in Figure 80. The rolls were carried in staggered roller bearings, each rated at 23,850-lb radial capacity at 100 rpm. The bearings were fitted into steel chocks which were carried on 6" I-beam rails. To restrict horizontal thrust on the rolls, a pad was provided between the mill roll and first table roll and between each table roll to pick up the work in case of downward bowing. Wedge-type leveling pads were provided for adjustment of table height, and slotted holddown screw openings were provided for horizontal adjustment of the table.

For driving, double sprockets were mounted on one end of each roll, and torque was transmitted from one roll to another by means of a roller chain, as shown in Figure 80. Power from the drive motor was transmitted by roller chain to two adjacent rolls located roughly in the center of the table. Each table was driven by a 3-hp, shunt wound, DC gear motor, controlled principally by armature voltage, with a 10% speed variation possible by field control. The motors were wired to break dynamically by means of regenerative current as an aid to the operator in manipulation of billets and plates during rolling. Practically all coasting of the rolls was eliminated.

FIGURE 80. General Arrangement Drawing of Mill Feed Table.

The mill tables were equipped with air-operated cylinders for the horizontal positioning of the work on the center line of the mill. These cylinders, with roller-type pusher heads, were selected over straight bar-type pushers because of the fish tail developed on the plates during rolling. This increase in width at the ends of the plates was much greater than the more or less uniform spread of the plate between these fish tails. In addition to the spread being large at the plate ends it was asymmetrical. Although the high spread at the plate ends could be compensated by alignment of the work going into the mill, the asymmetry could not be compensated without exceptionally complicated mechanism for measuring and adjusting the positioning equipment.

The cylinders were located opposite each other on each side of the table. Four sets were used and were spaced at increasing distances for positioning as plate length increased. The two pairs of cylinders closest to the rolls had the minimum spacing to position the 16" long billet. The operation of the cylinders was controlled by means of solenoid-operated, pilot-operated, 4-way valves, and flow control valves, one for the cylinders on each side of the table. The work had to be positioned by the cylinders, and then the cylinders had to be retracted in a manner such that the plate position was not disturbed. The cylinders on each side of the table operated in unison, their rate of movement being controlled by means of flow control valves. The position of the work was established by the cylinders along one side of the table whose extended position was adjusted to the desired alignment of one side of the plate. The cylinders on this reference side of the table were operated at higher pressure than the cylinders on the opposite side to assure reproducibility of position each time. If all the cylinders were operated at the same pressure, the final position of the plate would be dependent upon such variables as friction and rate of pressure rise in the cylinders, which were difficult to control.

The operating sequence of the cylinders was so controlled by time delay relays that the reference cylinders moved inward before the opposite set of cylinders moved inward to push the work against the reference cylinders. Upon retracting, the low-pressure cylinders were withdrawn first and the reference cylinders last. In this way, the position of the work was reproduced with each operation, and the work was not kicked out of alignment by minor variations in cylinder operation. The wiring diagram for the cylinder control system is given in Figure 81.

The heating of the billets for rolling and reheating during rolling was done in two electric furnaces, preheating in one and reheating in another, located one on each side of the mill as shown in Figure 76. The preheating furnace, which was positioned perpendicular to the mill center line, was rated at 36 kw. The dimensions of the hearth were 18" wide x 72" long. Heating elements were located beneath the alloy steel hearth

FIGURE 81. Line Diagram of Electrical Circuits for Mill Table Plate Positioning
Cylinder Controls and Furnace Table Pusher Cylinder Controls.

BILL OF MATERIAL		
SYMBOL	DESCRIPTION	FUNCTION
KS-3	FUSE DISCONNECT	POWER DISCONNECT
GR	GROUND	115 V POWER SOURCE
AB, C, D, E, F	MAGNETIC RELAY	CONTROL RELAY
LS-1	LIMIT SWITCH	EXTREME FORWARD STOP NORTH CYLINDERS
LS-2	LIMIT SWITCH	INTERMEDIATE FORWARD STOP NORTH CYLINDERS
LS-3	LIMIT SWITCH	EXTREME REVERSE STOP NORTH CYLINDERS
LS-4	LIMIT SWITCH	EXTREME FORWARD STOP SOUTH CYLINDERS
LS-5	LIMIT SWITCH	INTERMEDIATE FORWARD STOP SOUTH CYLINDERS
LS-6	LIMIT SWITCH	EXTREME REVERSE STOP SOUTH CYLINDERS
SV-1	SOLENOID PILOT VALVE	CONTROL NORTH CYLINDERS FORWARD MOVEMENT
SV-2	SOLENOID PILOT VALVE	CONTROL NORTH CYLINDERS REVERSE MOVEMENT
SV-3	SOLENOID PILOT VALVE	CONTROL SOUTH CYLINDERS FORWARD MOVEMENT
SV-4	SOLENOID PILOT VALVE	CONTROL SOUTH CYLINDERS REVERSE MOVEMENT
PL-1, 2, 3, 4	PILOT LIGHT	INDICATE MOVEMENT DIRECTION OF CYLINDERS
SV-5	SOLENOID PILOT VALVE	CONTROL MOVEMENT OF NORTH PLATE POSITIONING CYL.
SV-6	SOLENOID PILOT VALVE	CONTROL MOVEMENT OF SOUTH PLATE POSITIONING CYL.
TDC	VARIABLE TIME DELAY RELAY	DELAYS DE-ENERGIZING SOLENOID SV-5 WHICH IN TURN DELAYS RETRACTION OF NORTH CYLINDERS
TDO	VARIABLE TIME DELAY RELAY	DELAYS ENERGIZING SOLENOID SV-6 WHICH IN TURN DELAYS FORWARD MOTION (CLOSING) OF SOUTH CYL.

- NOTE:
- SOLENOID PILOT VALVE SV-1 AND SV-2 ARE MOUNTED ON AND CONTROL A SINGLE FOUR WAY, THREE POSITION (CENTER POSITION OFF) AIR CONTROL VALVE WHICH CONTROLS MOTION OF NORTH FURNACE TABLE CYLINDERS.
  - SOLENOID PILOT VALVE SV-3 AND SV-4 ARE MOUNTED ON AND CONTROL A SINGLE FOUR WAY, THREE POSITION (CENTER POSITION OFF) AIR CONTROL VALVE WHICH CONTROLS MOTION OF SOUTH FURNACE TABLE CYLINDERS.
  - SOLENOID PILOT VALVE SV-5 CONTROLS A SINGLE FOUR WAY, TWO POSITION AIR CONTROL VALVE. SOLENOID OPENS ONE PAIR OF PORTS AND A SPRING RETURN OPENS OTHER PAIR OF PORTS WHEN SOLENOID IS DE-ENERGIZED. AIR VALVE CONTROLS MOVEMENT OF NORTH MILL TABLE CYLINDERS.
  - SOLENOID PILOT VALVE SV-6 CONTROLS A SINGLE FOUR WAY, TWO POSITION AIR CONTROL VALVE SAME AS 3. AIR VALVE CONTROLS MOVEMENT OF SOUTH MILL TABLE CYLINDERS.

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plates and exposed on top and both sides. Temperature of the four (4) feet of the furnace was held uniform to $\pm 10^{\circ}\text{C}$ by the use of two separately controlled zones. A pneumatically operated door was located on one end only.

The loading and unloading of this furnace was aided through the use of hot buggy trays, rolling in channels which extended from the rear of the furnace to a point beyond the mill table. The buggies carrying the billets after preheating were pulled from the furnace and positioned at the end of the mill table. The furnace operator, as shown in Figure 82, manually pushed the billets onto the mill table. Three billets were preheated at a time in the rear 4 ft of the furnace.

The reheat furnace, which was located on the opposite side of the mill from the preheat furnace, was positioned so that its center line superimposed upon the mill center line. This furnace, rated at 150 kw, had elements in three zones arranged beneath the Inconel hearth plate and exposed on the sides and arched roof. The hearth dimensions of the furnace were 38" wide x 109-1/4" long. The height of the chamber was 21-1/4" at the side wall and 25-9/16" at the peak of the arch. The furnace was equipped with a pneumatically operated door at each end.

The heating elements were divided longitudinally into three zones. The center zone, 48" long, was rated at 70 kw and the two end zones, 30" long, were rated at 40 kw each. With this arrangement the center 7 ft of the furnace was uniform in temperature to $\pm 3^{\circ}\text{C}$.

As an aid in the loading and unloading of the furnace a roller hearth was provided. The hearth consisted of 144 individual rollers, 4" dia x 1" face cast integrally with 1" dia shaft. Rollers and support frame were castings of 35-15 nickel-chrome stainless steel. The rollers were arranged in sixteen (16) transverse rows spaced 7-1/2" on centers and in nine (9) longitudinal rows spaced 4" on centers. Perforated alloy steel plates bolted inside the side elements protect the element from damage and the furnace operator from shock. Entry and discharge was done by means of a combination push and pull rod. The temperature of each zone of the furnace was controlled by means of an L & N Micromax recorder-controller and an electronic proportioning device.

Reheating in this furnace was done three plates abreast, so that each could be discharged and re-entered into the furnace without disturbing the other two. In so doing, only the center plate laid on the center line of the mill and needed no lateral movement for entry onto the mill table. The other two plates laying on either side of the center, however, had to be shifted to the mill line for rolling and back to their furnace positions for re-entry following rolling. These manipulations were performed on a motor-driven roller table equipped with pneumatically operated pusher bars. This furnace table was located between the reheat furnace and one of the mill tables (see Figure 76).

FIGURE 82 . Furnace Operator Pushing Billet from Hot Buggy Tray onto Mill Feed Table.

The rollers were driven by a 2-hp, DC shunt wound, gear motor through the sprocket and roller chain arrangement described previously. The speed of this table was matched to that of the mill table by adjustment of motor field strength.

Lateral movement of the work was done by means of two pusher bars located one on each side of the table. Each pusher was driven back and forth by means of two double-acting air cylinders coupled together by two racks and pinions on a common shaft to maintain alignment of the pusher irrespective of where the load was applied to the pusher. Operation of each pusher was controlled by means of a solenoid-controlled, pilot-operated, 4-way valve. The pushers were semiautomatic in operation in that movement was initiated by the operator but stopped by means of microswitches located in the proper stop position. The wiring diagram for the pusher control is shown in Figure 81.

The entire operation of the mill and auxiliary equipment, except for speed control of the mill and table motors, was performed at the control console shown in Figure 79. The panel on this console contained push buttons for the control of the following functions:

- a. Mill motor forward, reverse and stop.
- b. Table motors forward, reverse and stop.
- c. Table motor jog forward and reverse.
- d. Screwdown motor up, down and emergency stop.
- e. Furnace table pushers forward, reverse and stop.
- f. Mill table positioning cylinders, forward and reverse.
- g. Furnace doors up.
- h. Horn signal.

In addition, a selector switch for selection of manual or automatic operation of the screw down motor, and two timers, one for measuring duration of the preheat cycle and the other for the reheat cycle, were located on the panel. Indicator lights and lighted arrows were provided for indication of direction of travel where appropriate.

With a modest amount of training an operator could develop sufficient dexterity for the efficient operation of the mill and equipment. The problem of securing uniformity in handling and rolling plates from pass to pass and plate to plate was greatly simplified.

Rolling of Cladding Billets

The bonding of the components which make up the cladding billet and the development of desired dimensions in the fuel plate were accomplished by rolling at an elevated temperature. Bonding was accomplished by diffusion, brought to effective rates by elevated temperature, during intimate contact

established by the pressure of the mill rolls. In addition, attenuation of residual contamination on the mating surfaces by deformation greatly aided in the establishment of the metallic intimacy necessary for initiation of diffusion.

In the production of the subject plate-type elements with end closures, the development of certain dimensions and the maintenance of the desired proportion and location of the components was more easily accomplished by the rolling process than other methods available.

The bonding and establishment of the plate dimensions necessary for the finishing operations were accomplished by a total reduction of 80%, 5:1, in the billet thickness at a nominal rolling temperature of 850°C. This reduction was made in a total of 12 passes on a cycle of two passes followed by a reheat, with the exception of the first and last passes which were single. All rolling was done at a linear roll speed of 125 ft/min.

The bonding of the EBWR fuel plates was done on a 17" x 24", two-high mill serviced by the auxiliary equipment and heating furnaces sketched in Figure 76, and described in detail in the previous section of this report. In preparation for rolling, the billets, in groups of three, were placed on hot buggy trays and entered into the 36-kw electric furnace, the rear four feet of which were maintained at 850°C ± 10°C. The billets were permitted to heat for two hours, which was 30 min in excess of the time required to bring the central temperature of the core to rolling temperature. Following the preheating period, the billets, carried on the buggies, were withdrawn one at a time from the furnace and manually pushed from the buggy onto the power-driven mill table by the furnace operator, as shown in Figure 82. After positioning the billet on the roll center line by means of the air-actuated cylinders mounted on the mill table, it was reduced 3.15% in a single pass at a rolling speed of 125 ft/min. Following this pass, the billet was driven to the furnace table, where it was positioned by a pusher bar, then pulled manually into the 150-kw reheating furnace. The remaining two billets comprising a preheat furnace load were rolled in succession and entered abreast in the reheat furnace, being positioned by pneumatic cylinder-driven push bars on the furnace table. A plate being moved to the furnace for entry and the three plate positions in the furnace are shown in Figure 83. The center 7' of this furnace was maintained at 850°C ± 3°C at times other than when the doors were opened.

Immediately following discharge from the preheat furnace, three more billets were loaded on the buggies and pushed into the furnace. These billets were then at rolling temperature when rolling was completed on the previous three billets. The complete rolling cycle was identical in duration to the two-hour preheating period.

FIGURE 83. Steel Jacketed Fuel Plate being Entered into Reheat Furnace after Rolling.

The billets were reheated 18 min which, by optical measurement of surface temperature, was sufficient to return the billet to the rolling temperature. The reheated plates were then, one at a time, pushed manually from the furnace, as shown in Figure 84, onto the furnace table. The billet or plate was then positioned, while moving, on the mill center line by the table pushers and driven onto the mill table where the plate was positioned by the table cylinders. After positioning, the plate was driven into the rolls by the mill table and given the second pass (10.00% reduction). The plate was stopped on the opposite table in proper location for realignment by the cylinders, the mill was reversed automatically by the electronic reversing controller after actuation by the mill operator, and the top roll was automatically brought to the next pass setting by the program controller after manual starting. During the resetting of the mill, the operator centered the billet and upon completion of the mill changes the plate was rolled through the third pass (8.45% reduction) and re-entered in the furnace. The remaining two plates in the furnace load were rolled in succession in a like manner. Between each plate-rolling cycle the mill had to be reversed in direction and the roll setting brought back to the appropriate pass.

Rolling proceeded on this double pass followed by a reheat cycle in accordance with the appropriate roll schedule for the thin and thick billets. This single last pass was required because of the close temperature control necessary in developing a uniform final thickness. The rolling procedure was identical for the thin and thick billets except for minor variations in the final pass setting. The rolling schedules for both the thin and thick billets are contained in Table XIX.

After rolling, the plates were carried from the mill table to a 50-ton hydraulic press (Figure 85), where they were placed between sheets of asbestos and cooled to below red heat under restraint of the platens.

The production rate, excluding the initial two-hour preheat, was 12 billets/8 hr. Normal operation of the mill required two men, one mill operator (roller) and one furnace man. The complete operation of the mill, mill and furnace tables and opening of the reheat furnace door were performed from the control console shown in Figures 79 and 83. The furnace man was charged with loading and unloading of the preheat furnace and pulling the plates into and pushing them out of the reheat furnace during the rolling operation. The labor burden for the rolling operation performed in producing the fuel plates amounted to 1-1/3 man-hours per plate, excluding preheating time. This figure was increased by 0.006 man-hour if the labor required to load the first three billets at the start of a shift was included. This small increase is a realistic figure since, during the first two-hour preheat, plates from the previous days rolling were heat treated. The cost of the heat-treating operations will be discussed in a following section.

FIGURE 84. Fuel Plate being Discharged from Reheat Furnace for Rolling.

FIGURE 85. 50-Ton Hydraulic Straightening Press Used to Cool Plates Under Pressure after Rolling.

106-2348

Table XIX

ROLL SCHEDULE FOR ROLL BONDING EBWR FUEL PLATES
BOTH THICK, 0.273", AND THIN, 0.210"

STOCK: EBWR Rolling Billets, 2-3/8" x 8" x 16". REHEAT: 18 min at 850°C. ROLLING MILL: 17" x 24" 2-high. ROLLING SPEED: 150 ft/min. PREHEAT: 2 hr at 850°C.							
Pass No.	Roll Parting (in.)	Draft (in.)	Reduction (%)	Plate Thickness (in.)	Average Power Consumption		Remarks
					(kw)	(hp)	
1	2.300	0.075	3.15		118	143	
2	2.070	0.230	10.00		148	179	Reheat(3)
3	1.895	0.175	8.45		170	206	
4	1.700	0.195	10.29		148	179	Reheat
5	1.500	0.200	11.76		174	210	
6	1.300	0.200	13.33		171	207	Reheat
7	1.120	0.180	13.85		169	204	
8	0.960	0.160	14.28		149	180	Reheat
9	0.830	0.130	13.54		143	172	
10	0.690	0.140	16.87		144	173	Reheat
11	0.570	0.120	17.39		141	171	
12A Thick Fuel Plate(1)	0.469	0.101	17.72	0.469(2)	130	157	Reheat
12B Thin Fuel Plate(1)	0.480	0.090	15.79	0.480(2)	124	150	Reheat

- (1) Pass 12A was used for thick fuel plates only, and pass 12B was used for thin fuel plates only. All other passes were used for both thick and thin plates since the over-all thickness of all billets was the same.
- (2) Plate thickness measured hot.
- (3) The remark "Reheat" indicates reheating before pass shown.

The precision necessary in the hot rolling of the fuel plates was established by the tolerances affixed to the various dimensions of the plate. For example, the length and tolerance of the core of the fuel were set at $51" \pm 1/2"$. This 1" variation in length of the core was exceeded if the thickness of the thin (0.210") plates varied more than 3.2 mils and the thick (0.273") plates varied more than 5.2 mils. A width variation greater than 40 mils also caused the length of the plate to fall outside this tolerance. It was obvious when considering that the finished length of the fuel plate was developed in a hot rolling operation while in the steel jacket that high precision was necessary in both equipment and adjustments. For this reason, the original bronze roll neck bearings were replaced with four-row, tapered roller bearings. The changes in roll opening caused by increase in roll and housing temperature required compensation. For every degree centigrade rise in roll temperature, the roll opening closed approximately 0.4 mil. Of course, temperature rise in the mill housing effected an opposite change in the roll opening, but the temperature changes were much less than in the rolls which were heated predominantly by conduction. Compensation in the final pass setting had to be made to offset the effect of temperature rise. This was done by rolling uniform thickness gage blocks of steel or aluminum

from which changes in roll opening could be measured before the final pass on each group of three billets. These blocks could not be used to determine the absolute thickness to which a fuel plate would be rolled at a given roll setting because of the difference in rolling characteristics; but the change in rolled thickness from block to block accurately reflected the change in roll opening at fixed settings of the screws.

Temperature of the work entering the mill was also a factor in the final rolled thickness of a fuel plate. The furnaces used for heating were designed and controlled to a temperature variation of 10°C over a zone sufficient in length to accommodate a plate at its maximum length. The temperature drop in movement of work from furnace to mill was a function of the time required. This interval had to be fixed and was so done within close limits by control of the roll speed of the furnace and mill tables. Manipulation of the work from furnace position to mill line on the furnace table was done while the plate moved toward the mill, being stopped only momentarily at the mill for positioning.

The length of fuel plate, in addition to being influenced by variations in plate thickness, changed with deviations of the width from the nominal. Since edging equipment for control of the width by deformation was not available, the steel jacket was relied upon to provide restraint against free spread of the plate. The design of the steel jacket was found to have marked influence in the restraint effected.⁽⁶⁾ For example, a steel jacket made up of side plates, end plugs, and cover plates joined by welding, as shown in Figure 86, provided approximately $1/3$ the resistance to spread as the design adopted. The channel type of jacket used for EBWR billets is shown in Figure 86. In comparing these two designs it is obvious why the channel type was stronger in the transverse direction than was the picture frame type. The restraint of spread of the cladding billet contained in the steel jacket is a function of the product of stress and friction between rolls and work and the strength of the steel jacket side plate. The stress and friction between rolls and work are constant for both and can be eliminated when comparing these two jacket designs. The resistance to transverse movement of the jacket is not only a function of the strength of the side plate in the picture frame jacket and its counterpart in the channel type of can, but also the additional restraint offered by the transfer of stress through shear to the cover plates. Because of the lesser width of the shear plane in the picture frame billet (weld only $1/4$ of the side plate width) its ability to transfer stress to the cover plates is lower than in the channel billet where the side and cover plates are integral. Of course the strength of the side plate in the picture frame jacket could be made equal to the side plate channel jacket by increasing its width. This solution, however, is wasteful of both mill and furnace capacity. The additional capacity of both mill and furnace required for wider jackets is directly proportional to the increase in jacket width.

FIGURE 86. Modified Picture Frame and Channel-Type Steel Jackets.

The other factors which affect spread during rolling, such as temperature, reduction schedule, and rolling speed, were held essentially constant for all plates. Temperature control has been discussed. The roll schedule was fixed by the screwdown program controller. Rolling speed was maintained at 125 ft/min by the electronic controller.

In addition to the careful control exercised in maintaining length of plate by reproduction of thickness and width from plate to plate, equally careful control was exercised over the straightness of the fuel plates. The precision necessary in mill setup and operation is made apparent by the calculation which is given in the Appendix.

This calculation shows that one (1) mil difference in thickness of the fuel plate from one side to the other would produce 0.435 mil of camber. This amount of camber produced by a one-mil transverse taper in a plate appears excessive, but measurement thickness differential and camber of rolled plates have proved it to be essentially correct. The width of the core and its tolerance had been set to allow enough excess in the 1/4" wide side plate for machining to accommodate a camber up to 1/32". Considering camber of this magnitude is caused by 0.07-mil difference in the thickness of the plate from side to side, the need for an exceptionally stable mill, very careful setup, and reproduction of operation becomes apparent.

Before rolling, parallelism of the rolls was roughly set by rolling and measuring steel gage blocks rolled simultaneously at each side of the roll body. Final setting was made after a steel plate 1" thick x 8" wide x 16" long, ground to uniform thickness within a few tenths of a mil, had been hot rolled 75% reduction. Final settings were made after measurement of both camber and difference in thickness at opposite sides of the test plate. Considering that changes in the order of tenths of mils are being corrected for, it appears impossible to make them on a mill screw dial graduated to a mil with any accuracy. It must be remembered, however, that changes in the screw setting, which are 36" apart, are nine times the change required in a 4" width, the base-height relationship in similar triangles.

In addition to accurate setup, great care had to be exercised in superimposing the major axis of the work on the center line of the rolls so that the deflection of the rolls would be equal to both sides of the plate. If the plate be positioned off center, the side of the plate closest to one of the screws would be rolled thinner than the other because of the lesser deflection of the roll at the position closest to the bearing.

The finish-rolled, steel-jacketed plates are pictured in Figure 87. These rolled plates were approximately 1/2" x 8-1/2" x 78" for both the thick and thin fuel plates, all rolling billets being the same initial thickness. After the last pass the plates in general were flat; however, all plates were cooled under pressure, as discussed previously. Evaluation of the fuel plates is contained in a later section of this report.

FIGURE 87. Stack of Finished-Rolled Steel-Jacketed Fuel Plates.

106-2740

Approx. 1/10X

Heat Treatment

The heat treatment of the fuel plates was designed to develop a structure in the uranium alloy of the core which would be dimensionally stable under irradiation. This heat treatment as based on irradiation studies⁽⁴⁾ consisted of a gamma solution treatment followed by an isothermal quench into the high alpha plus gamma temperature range, holding at this temperature, and then air cooling. The major variable in the heat treatment appeared to be the temperature at which transformation took place and not the quenching rate,^{(4),(18)} since cooling in a furnace developed a structure which was nearly as stable. For this reason the steel jacket was allowed to remain on the fuel plate during the heat-treating operations. This jacket served as protection against mechanical damage during handling, atmospheric contamination during the gamma solution treatment, and lead contamination during the quenching.

The specific heat treatment of the plates consisted of heating to $825^{\circ}\text{C} \pm 5^{\circ}\text{C}$, followed by an isothermal quench, and a 22 to 23-hour hold in lead at $640^{\circ}\text{C} \pm 5^{\circ}\text{C}$. The plates were air cooled after removal from the quench bath. The gamma solution treatment was performed in the 150-kw furnace used for reheating during rolling. In order for the steel-jacketed plates to fit into the lead tank furnaces used for quenching, some of the steel along the sides and ends was removed. The plates were sheared to 6" wide x 66" long by removing equal amounts from the sides and from the ends. This shearing operation is pictured in Figure 88. The plates were loaded in groups of seven or fourteen into a rack. This rack was placed in the furnace the previous night so as to be at furnace temperature when the plates were loaded. The plates were permitted to remain in the furnace at $825^{\circ}\text{C} \pm 5^{\circ}\text{C}$ for one hour to assure complete and uniform heating. After the solution treatment the plates, one at a time, were pushed from the furnace, picked up with tongs and submerged horizontally in the lead quench bath at 640°C , as shown in Figure 89. Plates were spaced and supported by means of combs submerged in the lead and held down by weights. Each tank furnace accommodated seven plates. With three of these furnaces, the heat treatment production rate was 21 per day. The plates were permitted to remain in the lead at the quenching temperature for between 22 and 23 hours, being removed the following morning.

This heat treatment developed the structure shown metallographically in Figure 90. The phases present were alpha uranium and zirconium-niobium-rich gamma.⁽¹¹⁾ Some diffusion took place between the core and clad during the heat treatment. The increase in the diffusion zone as shown in Figure 90 was from approximately 0.4 mil in the as-rolled plate to 0.7 mil in the heat-treated plate.

The selection of lead as the quenching medium instead of salt was based on studies of the effect of salt heating upon the bond strength of clad plate.⁽⁶⁾ It was found that specimens of unjacketed clad plate heated in salt

FIGURE 88. Trimming Steel Jacket for Heat Treatment of Fuel Plates.

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FIGURE 89. Heat Treating Steel Jacketed Fuel Plates.

106-2803 Removing Fuel Plate after 825°C Gamma Solution Treatment.

106-2767 Quenching Fuel Plates in Lead at 640°C.

FIGURE 90. Metallographic Structures of Uranium Core Alloy As Rolled and after Heat Treatment and Growth of Diffusion Zone upon Heat Treatment.

21026 Bright Field 250X
Transverse Section As Rolled⁽¹⁾ of Bond between
Core and Face Clad. Diffusion Zone - 13 to 15 μ

21190 Bright Field 250X
Transverse Section As Heat Treated⁽²⁾ of Bond
between Core and Face Clad. Diffusion Zone -
17 to 23 μ

21025 250X
Transverse Section As Rolled of Bond between
Core and Side Clad. Diffusion Zone - 15 to 33 μ

21191 Bright Field 250X
Transverse Section As Heat Treated of Bond between
Core and Side Clad. Diffusion Zone - 25 to 51 μ

(1) As rolled structure of core alloy developed by air cooling after final roll pass of 17.7% reduction at 850°C.

(2) Heat treatment - 1 hour to 850°C ---- Isothermal quench and 23 hour soak in lead at 640°C ---- Air cool.

(These photographs have been reduced 32% for reproduction.)

and water quenched had bond strengths less by a factor of 10 than the original rolled plate. Analyses of the specimens showed their hydrogen contents to be high; 15 ppm. Subsequent heat treatment at 475°C in air restored most of the bond strength. Analyses of these outgassed specimens showed hydrogen content to be 0.3 ppm, essentially that of the original rolled plate.

Similar heat treatment performed without introduction of hydrogen produced bond strengths which varied only slightly from the plate in the as-rolled condition.

Stripping Steel Jacket

After completion of the heat treatment, the steel jackets were removed from the fuel plates. Two methods were used for the stripping of steel. One consisted of shearing all steel from the ends of the jacketed plate to locate the fuel plate within, and then shearing longitudinally along a line approximately $1/16$ " out from the fuel plate. This procedure broke the steel away from the fuel plate permitting the remaining steel on the faces to be peeled from the fuel plate. This longitudinal shearing operation, however, was difficult to control. If this cut was made too far out from the fuel plate side, the cover steel was extremely difficult to remove, since the steel was bonded to itself along the plate sides. If the cut was made within the fuel plate part of the cladding at the side of the fuel plate, material was removed which not only produced camber in the plate from relief of stress but also removed the fiducial side used for setup in milling plate to final width.

Because of these difficulties encountered with shear stripping of the steel jacket and the concern overstress imposed on the fuel plate by shearing, an alternate method which eliminated the longitudinal shearing was also employed. The ends of the fuel plate were exposed by shearing the jacketed plate approximately $1/2$ " in from the ends of the fuel plate. Using the fuel plate ends as references, the plates were clamped to the table of a planer in proper alignment with the double cutters as shown in Figure 91. Two grooves were then machined simultaneously in the steel just inside the edges of the fuel plate within. The depth of cut was in most cases slightly less than the thickness of the steel jacket, so that the fuel plate was not cut. The plate was then turned over and the opposite side was grooved similarly. The steel on each side of the fuel plate was then broken off by holding one side of the plate in a "T" slot of the planer bed and bending the opposite side until fracturing along the root of the cut, as shown in Figure 91. The cover steel was easily removed by peeling.

The sides of the fuel plates were not touched in this operation; even if the faces of the plates were accidentally cut during the grooving operation, no damage was done because the cut came in the excess side clad of the fuel plate, which was removed in machining the plates to width. Fuel plates after removal of the steel jacket are illustrated in Figure 92.

FIGURE 91. Planing and Stripping of Steel Jacket from Fuel Plate.

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Planing Grooves in Steel Jacket

106-2798

Stripping Steel Jacket from Fuel Plate

FIGURE 92. Fuel Plates after Removal of Steel Jackets.

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Machining of Fuel Plates

After removal of the steel jacket, and degreasing if the jacket was removed by machining, each plate was measured for thickness, length and camber. The location of the ends of the core with respect to the ends of the plate was determined by the use of X-ray radiography, being recorded on film(19) as shown in Figure 93.

The plates were then given a low-temperature stress relief. One day's production, 21 to 24 plates, were loaded into an electric furnace and heated two hours with the furnace at 400° C, after which the power was cut off and plates permitted to cool with the furnace for six hours.

After removal from the furnace, the plates were laid out for machining. By the use of the radiograph the position of the ends of the core were marked on the plate with bluing. The core length was then measured and subtracted from 54", the over-all length of the finished plate. Using this value the full length of the plate was marked, centering the core within.

The fuel plates were cut 1" oversize in length on an abrasive wheel, as shown in Figure 94. Excess length was allowed for machining a projection 1/2" long and 1/4" x 3/16" cross section at each end of the plate. The projections were located 1" from one side of the plate, and were provided as a means of hanging in a fixture during pickling.

Next, the plates were machined to width, either by straddle milling shown in Figure 95 or straddle planing similar to that shown in Figure 91. Of prime importance in both these methods of machining to width was the positioning of the plate with respect to the cutters so that an equal amount of metal be removed from both side plates. Misalignment of plates would cause one finished side plate to be narrower than the other. Unequal removal from side to side caused an unequal relief of stress which caused camber to develop in the plate during the machining. Even more serious, however, was the machining of the side plates under the nominal 1/8" minimum width.

For positioning, the plate widths were measured at two places, 6" from one end of the core and 6" from the opposite end. Positions of measurement were marked for use as references in the setup of the plates for machining. Using these measurements, the center line of the plate at the reference positions was calculated, and the plate was positioned with respect to the milling cutters so that equal amounts be removed from each side. In addition, the measured value of, and indicated direction of, camber were used in the calculation of the plate position. The plates were offset one-half the value of its camber toward the concave side. In this way equal amounts were removed from both side plates. Of course, symmetry across the plate major axis could not be developed.

FIGURE 93. Radiographing Ends of Fuel Plates for Core End Location.

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FIGURE 94. Cutting Fuel Plate to Rough Length on Abrasive Wheel Saw.

FIGURE 95. Straddle Milling Fuel Plate to Width.

The straddle milling was done on a machine equipped with an extension table. Cutting was done with carbide side milling cutters at a speed of 116 rpm and a feed of $4\text{--}1\frac{1}{4}''/\text{min}$. A single cut by both cutters was used in machining the plates to width. Approximately twenty (20) plates were machined between regrindings of the milling cutters. Sharp cutters were essential to a satisfactory cut; if dull cutters were used, the top or trailing edge was fractured during machining. The width of the plates was held to ± 2 mils. Some camber developed in the plates during the machining operation. This camber ranged from 0 to 27 mils, with the average being 7.7 mils.

An alternate method was used for machining the fuel plates to width. This method was planing with two carbide tools spaced the width of the finished plate. The plates were positioned by the same procedure discussed above. Cutting was done on both sides of the plate simultaneously, using a feed of $0.005''/\text{cut}$ at a speed of $24''/\text{sec}$.

The final machining of the fuel plate produced the hanger projection and the final over-all length of 54". This machining was done using a standard high-speed, four-lipped end mill, $1\frac{1}{2}''$ diameter at 130 rpm, as pictured in Figure 96. During machining to length, the hanger projection discussed above was also formed. The projection was undercut slightly at its base by cutting approximately $1/16''$ deep by means of a hand hacksaw. This undercut was provided to facilitate removal of the projection by fracturing after all pickling operations had been completed.

After machining, deburring, and degreasing with acetone, the dimensions of the plates were determined. Over-all width, length and camber were measured and recorded.

Testing

The machined fuel plates were subjected to a nondestructive bond test to determine the completeness of bonding between the face cladding and the core. A through-transmission ultrasonic technique was used.⁽¹⁴⁾ In this method, the sending and receiving crystals were mounted on a yoke such that the sending crystal was on one side of the plate and the receiving crystal on the opposite side. By a suitable drive mechanism the crystals were caused both to move up and down across the width and travel along the length of the plate. The plate was supported vertically along one side, and both plate and crystals are submerged in water treated with a wetting agent. With this equipment, shown in Figure 97, a two-dimensional plot was made of the intensity of the transmitted ultrasonic beam, using an electrosensitive paper. The sensitivity of the equipment could be varied and the cutoff level below which no record was printed was adjustable. The reproduction of the trace of an acceptable plate is shown in Figure 98. A uniform density of this trace indicated uniform transmission of the ultrasonic beam and consequently no

FIGURE 96. End Milling Fuel Plate to Length.

FIGURE 97. Ultrasonic Testing Equipment for Nondestructive Inspection of Fuel Plate Bonds. Same Equipment Used for Soundness Inspection of Billet Cores.

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FIGURE 98. Ultrasonic Traces of Acceptable and Rejected Fuel Plates. Plate E-718 on Right Acceptable. Plates E-250 and E-724 on Left Rejected.

measurable defects in the plate. The trace of a defective plate is also reproduced in Figure 98. The light area indicates a defect through which the passage of the ultrasonic beam was impeded.

The sensitivity of this equipment was claimed to be sufficient to locate a defect (unbonded area or crack) of $1/32$ " diameter.⁽¹⁴⁾

The amount of clad on the finished machined plate sides and ends and the thickness of clad on the plate faces had to be determined before a plate could be accepted for reactor use. The cladding specifications were 0.115" on each side, 1-1/4" on each end and 0.017" to 0.022" on each face. The side and end clads were measured from a film record of the total plate made by X-ray radiography.⁽¹⁹⁾ The plates were laid three abreast on film and were separated by steel strips of $3/16$ " x $1/2$ " cross section, with a steel strip on the outside of two extreme plates. An exposure of 33 sec at 200 kv, 10 ma was made with a 250-kv X-ray machine using type A film. Tube to plate distance was 41" as measured normal to the center plate. The radiation covered the 14" x 17" film in a single exposure. Four exposures were necessary to cover the full length of the plates.

After development, washing, and drying of the film, the radiographic record was available for measurements. The minimum width of the side cladding was measured by means of an optical comparator graduated down to 5 mils. The length of the end clad was measured with a steel scale graduated to $1/64$ ". Plates having less than the minimum 0.110" side clad width were re-radiographed singly to minimize parallax, which will be discussed later, and remeasured. Of the 1120 plates produced, 30 were rejected because of narrow side clad width. No fuel plate was rejected for short end clad alone.

The radiograph did not very faithfully reproduce the actual width of the side plate. Because of parallax, and perhaps scatter, errors resulted. Almost without exception, actual side plate widths measured on sectioned plates were equal to or greater than the corresponding widths measured from the radiograph of the plate. Table XX contains a comparison of actual side plate widths with indicated widths measured from radiographs. On this basis, it was felt that some plates were rejected for narrow side plates which actually did not have narrow sides; however, as a measure of insurance, all plates with the radiograph-indicated side plate widths below specification were rejected.

The face-cladding thickness was measured using an autoradiograph technique⁽¹⁹⁾ on the equipment pictured in Figure 99. The soft beta radiation from the core alloy was counted by a scintillation counter employing a $3/4$ " diameter crystal area which was oscillated back and forth across the width of the plate being measured while the plate was moved longitudinally beneath the counter. In this way a two-dimensional trace was plotted of the counting rate over one face of the plate. The equipment was calibrated with the use of standard plates.

FIGURE 99. Equipment for Measurement of Face Cladding Thickness by Autoradiography.

106-2793

Table XX

SIDE CLAD WIDTH MEASUREMENTS: ACTUAL VS. RADIOGRAPH

Plate No.	Actual		Radiograph	
	Left (in.)	Right (in.)	Left (in.)	Right (in.)
292	0.195	0.100	0.195	0.100
348	0.140	0.180	0.140	0.175
	0.155	0.175	0.155	0.165
316	0.165	0.175	0.145	0.155
	0.165	0.170	0.160	0.160
E210	0.140	0.190	0.120	0.145
	0.150	0.175	0.130	0.165
E259	0.175	0.165	0.170	0.160
	0.180	0.180	0.160	0.175
E395	0.175	0.165	0.160	0.150
	0.175	0.170	0.165	0.150
E458	0.130	0.125	0.125	0.120
	0.160	0.175	0.150	0.170
E514	0.165	0.165	0.165	0.165
	0.140	0.135	0.130	0.135
E568	0.180	0.200	0.175	0.195
	0.145	0.155	0.145	0.150
E599	0.135	0.150	0.135	0.145
	0.125	0.130	0.085	0.125

Final Cleaning of Plates

The final operation in the manufacture of the fuel plates was the development of a surface finish which was resistant to corrosion by water at 550° F. A procedure was developed whereby surface contamination resulting from rolling, heat treatment, stress relieving, and machining was readily removed to assure uniform attack by the pickling bath which developed the corrosion resistant surface. The cleaning procedure employed was as follows:

1. Wet abrasive blast both faces.
2. Pickle one minute.
3. Scrape.
4. Reblast.
5. Repickle two minutes.

The initial wet abrasive blasting operation was employed to remove the minor amount of contamination from the faces of the plates so that the rate of attack by the pickling bath would be uniform over the entire plate. The blasting was done in the automatic equipment discussed previously. The plates were blasted in groups of three plates abreast on the carriage. Blasting was done at the rate of 5"/min using 400 mesh alumina abrasive. Abrasive was removed by washing in tap water.

The second operation, pickling, was performed to delineate minor surface defects such as stringers and specks resulting from alloying of the clad with the steel jacket. These small defects were not easily recognized on the surface of the rolled fuel plate after removal of the steel jacket and the mat surface produced by wet abrasive blasting hid all but gross defects. The pickling operation removed the mat finish and produced a bright surface. In addition, the rate of attack on the alloy specks by the pickle bath was much lower than on the Zircaloy-2; therefore the alloy specks were raised from the surface and easily identified.

The pickling was performed in an aqueous bath containing 35% concentrated nitric acid and 5% concentrated hydrofluoric acid by volume contained in a Koroseal-lined tank. The critical temperature control (35°C to 38°C) of the acid bath was maintained by the Type 347 stainless steel tubing heat exchanger located on the bottom of the tank. Either heating or cooling could be controlled with a mixing valve connected to both hot- and cold-water lines.

For pickling, a single plate was suspended horizontally and edgewise from the end projections, discussed previously, in a fixture shown in Figure 100. This type of suspension was found necessary since a fixture which touched the plate proper left stains which formed a white corrosion product. The plate suspended in the fixture was lowered into the acid bath by means of an electric hoist carried on a monorail. The fixture was supported by the hoist above the tank bottom during the pickling so that the plate could be swung back and forth to prevent a pitting type of attack along the bottom side of the plate and to promote uniform removal of metal. This initial pickling operation was one minute in duration and removed approximately 1 mil from the thickness of the plate, 1/2 mil on each side. Following pickling, the plate was rinsed in three separate tap water baths and two tanks containing distilled water. The final distilled water rinse used nearly boiling water to facilitate the air drying of the plate.

The surfaces of the plates were normally smooth and highly reflective; the steel jacket alloy defects were easily recognizable, as may be observed by examining Figure 101.

The third operation performed in the plate-cleaning procedure was scraping minor defects from the plate surfaces. The primary purpose, however, was the removal of the alloy specks resulting from diffusion between clad and steel jacket.

FIGURE 100. Pickling of EBWR Fuel Plate.

106-3058

FIGURE 101. Surface Defects Caused by Alloying of
Zircaloy-2 Cladding and Steel Jacket.

20626

5.62X

Initially it was felt that, since the rate of pickling attack was lower in these areas than on the remainder of the plate, the water corrosion rate would be lower. This, however, was not the case, for white corrosion product developed on the alloy speck surfaces during testing in 550° F water. Upon examination of transverse sections through many of these specks, it became apparent that their removal could quite easily be accomplished by scraping. As shown in Figure 102, the alloy projects principally above the surface of the pickled plate with very little (less than a mil) penetrating below the general surface of the plate.

Scraping of the plates was done by hand using a scraper made by brazing a carbide tool bit, $1/8" \times 1/4" \times 1/2"$, on the end of a $1/2"$ dia high-carbon steel rod, 6" long, and providing a handle. The end of the carbide tip was ground square with the face at a small radius. The reduction in cladding thickness produced by scraping in general lay between $1/2$ to 1 mil.

This scraping was followed by a second wet abrasive blasting operation. Blasting at this stage was done at a carriage speed of 7"/min using 400 mesh alumina. Again this cleaning operation was performed on three plates simultaneously.

After the second blasting operation, the plates were again pickled for a period of two minutes in the manner discussed above. This operation removed approximately 2 mils from the plate thickness. This pickling operation was done in two steps. The first step was pickling for 1 min 45 sec, after which the plate thickness was measured by means of a micrometer. The second step was a 15-sec pickle for purposes of removing contamination caused by the small amount of abrasion produced by the micrometer screw. If the thickness was measured after the completion of pickling, white corrosion product developed over the area touched by the micrometer screw.

After the pickling, washing, and drying operations, the plates were stacked individually, being separated by Kraft paper. Any abrasion caused by sliding one plate over another was subject to a high local corrosion rate as evidenced by formation of white corrosion product.

A visual examination of the plate surfaces and a microscopic examination of the excess end coupon retained after cutting plates to length normally completed the plate manufacturing procedure.

Defects such as mechanically produced dents, inclusions, deep pits, excessive stringers, etc. caused a plate to be rejected on visual examination. If the examination at 90 diameters of a transverse section of the end coupons prepared metallographically revealed unbonding or bond line inclusion in any of the side plate-end plug, cover plate-end plug, cover plate-side plate or seal pin bonds, the plate was rejected.

FIGURE 102. Section Through Zircaloy-2 Clad-
Steel Jacket Alloy Defect.

19472

Polarized Light

250X

The finding of jacket alloy defects during the first inspection did not, however, cause rejection of the plate. Plates with this type of defect alone were rescraped to remove the defects and repickled as many as two times. This pickling for a period of 30 sec was sufficient to produce a corrosion-resistant surface, whereas white corrosion product was formed on scraped area which had not been pickled.

Excessive scraping which caused thin areas in the clad was a basis for rejection of a plate. Depth of scraping was measured with a depth micrometer. Very few plates were rejected for this reason because the manufacturing procedure was adjusted to produce plates with face cladding close to the upper thickness limit of 22 mils. The lower limit was 17 mils.

Plates surviving the inspection were individually wrapped in Kraft paper for protection and transferred to the Reactor Engineering Corrosion Test Facility.

Corrosion Testing

All plates were given an acceptance corrosion test of two weeks in water at 550° F.⁽¹⁾ Testing was done in four autoclaves, three of which would accept 40 plates each and one which would accommodate 120 plates. Testing and evaluation of the tested plates was done by the Corrosion Testing Group of the Reactor Engineering Division.

The plates were placed in square stainless steel fixtures for loading as shown in Figure 103. The plates were spaced by means of stainless sheets corrugated along both sides.

Following testing, the plates were removed from the boxes and inspected visually for evidence of white corrosion product. Plates with minor amounts of white corrosion product, principally found at steel jacket alloy defects, were returned for rescraping. Plates were rescraped and repickled for 30 sec to develop corrosion resistance in the scraped area. No attempt was made to remove all black corrosion product from the plate surface. The HNO₃-HF pickle did not attack or disturb the black corrosion product produced in the two-week test. The contamination introduced by scraping was adequately removed by this 30-sec pickling operation. Plates were then recorrosion tested for two weeks. Following the final testing and acceptance of the fuel plates, the projections on each end of the plates were removed. The projections were simply hit with a hammer, which caused fracture of their notched bases. The fractured surfaces were found to be corrosion resistant.

FIGURE 103. Equipment Used for Corrosion Testing of Fuel Plates.

111-3870

Large Autoclave Being Loaded with Fuel Plates

111-3871

Stainless Steel Fixture for Loading Fuel Plates in Autoclave

EVALUATION OF FUEL PLATES

A total of 1120 fuel plates was fabricated during this manufacturing program. Of this total, 930 plates were acceptable for reactor use, a recovery of 83.0%. The number of plates, acceptable and rejected, of each type are shown in Table XXI. A summary of rejected plates is given in Table XXII in which the cause for rejection and the number of defective plates in each category are given.

Narrow side clad was the cause of the highest number of rejected plates. If the width of the side clad, as illustrated in the reproduction of a radiograph in Figure 104, was less than 0.110" the plate was rejected. Narrow side clad in the finish-machined fuel plate was caused by one or a combination of reasons: excessive spread of the plate during rolling, excessive camber, or errors in setup for machining. Machining errors were not listed as such since they could have been caused by the removal of the fiducial side or sides during removal of the steel jacket by shearing as well as by straightforward errors. Some of the plates in this category undoubtedly could have been accepted had a more accurate method for determination of side plate width been available. In all the plates sectioned, the side plate measured wider than indicated on the radiograph. Even so, all plates of questionable side plate width were rejected. A good fraction of these rejects could have been eliminated had equipment been available for control of plate width by deformation during rolling.

Surface defects such as pits, inclusions, stringers, ripples, and dents on the rolled plates caused rejection. These types of defects caused the rejection of twenty (20) plates, 1.78% of the production. Examples of these defects are shown in Figure 105. The pits, inclusions, and stringers were presumed to have existed in the initial stock or to have been produced during rolling. Rippled surface was clearly a rolling defect, and dents in the plate surface were assumed to be a result of roll in of foreign material falling onto the steel jacket or caused by hard spots in the jacket itself. The cause of surface ripples is not known, but this type of defect was more prevalent in the thick plates than in the thin.

A number of plates were rejected on the basis of questionable bonds as determined by ultrasonic testing. Defects of this classification accounted for the rejection of twenty (20) plates. These plates were rejected as assurance for the rejection of all plates with bond defects. The sensitivity of the test equipment was set so high that some plates without bond line defects, as evaluated metallographically, were also rejected.

Eighteen (18) fuel plates were rejected as being definitely unbonded as determined by ultrasonic testing. A great deal of reliance was placed in the evaluation of these plates since ten (10) were judged unsatisfactory by other means. Among these ten (10) plates some showed blisters, some

Table XXI

EBWR FUEL-PLATE PRODUCTION SUMMARY

Plate Size and Type	Total No. Rolled ⁽¹⁾	Total No. Acceptable	Total No. Rejected ⁽²⁾	Yield %
Thin - Normal	147	125	22	85.0
Thin - Enriched	419	353	66	84.2
Thick - Normal	134	119	15	88.8
Thick - Enriched	420	333	87	79.3
TOTAL	1120	930	190	83.0

¹Excluding six (6) plates used for a practice weld assembly.

²Does not include plates damaged in handling after inspection by producer or one plate damaged during assembly welding.

Table XXII

SUMMARY OF FUEL PLATE DEFECTS

Type of Defect	No. of Plates Rejected	Loss %
Side Clad Undersize	30	2.68
Surface Inclusions or Depressions from Rolling	20	1.78
Questionable Bond on Ultrasonic Test	20	1.78
Nonbond on Ultrasonic Test	18	1.61
Seal Pin Not Bonded	18	1.61
Clad Damaged Mechanically	16	1.43
Plate Sectioned for Process Evaluation	11	0.98
Tungsten Inclusions in Cladding	10	0.89
Thin Face Clad	10	0.89
Side Plate to End Plug Not Bonded	9	0.80
Cover Plate to End Plug Not Bonded	8	0.71
Errors in Machining	6	0.54
Crack in Seal Pin	5	0.45
Face Damaged by Wet Abrasive Blasting	4	0.36
Failed in Corrosion Test	3	0.27
Tungsten Contamination in Assembly Weld	2	0.18
TOTAL	190	17.0

FIGURE 104. Photo of Radiograph of Fuel Plate with Narrow Side Clad.

21163

Left Side Cladding - 0.065".
Right Side Cladding - 0.130".

1X

FIGURE 105. Surface Defects in Zircaloy-2 Cladding which Caused Rejection of Fuel Plates.

21112 Stringer 1X

20322 Depression and Ridge 1X

20328 Deep Pits 1X

20331 Circular Depressions 1X

20314 Elongated Depression 1X

20922 Severe Ripples 1X

(These photographs have been reduced 23% for reproduction.)

cracks in the end plugs, one had a lamination within the cover plate, as pictured in Figure 106, and others had inclusions in the bonds as evaluated metallographically.

The seal pin not bonded or inclusions in the seal pin bond was the cause of rejection of 1.61% of the plate production, eighteen (18) plates. This defect was easily identified by microscopic examination of the end coupons taken during the cutting of the fuel plates to length. Polishing and heavy etching of a transverse section made defects in the seal pin bond as well as the end plug-cover plate and end plug side plate bonds clearly visible at 90X magnification. Examples of an unbonded seal pin and bond line inclusions are shown in Figure 107. If the seal pins were clearly unbonded, ultrasonic testing revealed the defect.

Mechanical damage during machining and handling caused sixteen plates, 1.43%, to be rejected. Gouges, scrapes, and dents which could have fractured or materially thinned the face clad were taken as reason for plate rejection. Examples of these types of defects are shown in Figure 108.

During the course of manufacture a certain number of plates were sectioned for evaluation. These plates were intentionally destroyed for verification of some test result such as radiography or ultrasonic inspection of process evaluation. Eleven (11) plates were sectioned for examination.

Fuel plates containing tungsten inclusions which were missed during the radiographic inspection of the cladding stock were rejected no matter how innocuous in appearance. Some tungsten inclusions caused defects which were observable on the surfaces of the plates, as shown in Figure 109; some inclusions imbedded in the end or side clad did not produce visible defects but were found in the radiograph of the finished plate, as shown in Figure 109.

Face cladding thickness below 17 mils, as evaluated by the autoradiographic technique, was the basis for rejection of ten (10) fuel plates. Thin face cladding was caused principally by overpickling.

Nine fuel plates were rejected because of nonbonding or inclusions between the end plug and side plate. Inspection for this type of defect was done by metallographic examination of transverse sections of thin bonds at each end of the fuel plates. Inspection was made at 90X after polishing and etching the excess end coupons. An example of this type of defect is given in Figure 110.

Inclusions in the bond between end plug and cover plate or an unbond between these members caused the rejection of eight (8) fuel plates, 0.7%. Inspection for this type of defect was made on the end plug at the same time the seal pin and end plug side plate bonds were inspected. This type of defect is pictured in Figure 110.

FIGURE 106. Defects in Fuel Plates Found by Ultrasonic Testing and Visual Examination.

20321 1X
Lamination in Cover Plate

20330 1-1/4X
Cracks in End Plug

20317 3/4X
Blister in Face Cladding

20920 1-1/2X
Plate Section Through Blister at Left.

(These photographs have been reduced 27% for reproduction.)

FIGURE 107. Defective Seal Pin Bonds. Pitted surface caused by heavy etching to magnify defects.

21107

16X

Partially Unbonded Seal Pin

21099

16X

Inclusions in Seal Pin Bond

FIGURE 108. Mechanical Damage to Zircaloy-2 Cladding Causing Rejection of Fuel Plates

20924

Dent

1X

21156

Dents

1X

20933

Gouge

1X

20316

Machining Holddown Screw Depression

1X

FIGURE 109. Tungsten Inclusions in Zircaloy-2 Cladding of Fuel Plates.

21165
Tungsten Inclusions in End Clad Found in Radiograph.

1X

21166
Tungsten Inclusion in Side Clad Found in Radiograph.

1X

20315
Tungsten Inclusion in Surface of Fuel Plate.

3/4X

FIGURE 110. Zircaloy-2 to Zircaloy-2 Bond Line Defects. Pitted Surface Caused by Heavy Etching to Magnify Defects.

21104 16X
Nonbonding between end plug and side plate. Inclusions in bonds between cover plates and end plugs and side plates.

21101 16X
Nonbonding between end plug and cover plate.

21103 16X
Nonbonding between end plug and side plate.

21105 16X
Inclusions in bond between end plug and side plate.

(These photographs have been reduced 32% for reproduction.)

Errors in layout for machining or in setup for machining which produced unequal cladding at the ends of the plates, as shown in Figure 111, or at the sides made six (6) plates unacceptable for reactor use.

Cracks in the seal pins accounted for the rejection of five (5) fuel plates. This defect, in all probability, existed in the rod stock from which seal pins were made, and its presence in the finished fuel plates could be charged to inadequate inspection. A seal pin crack is shown in Figure 112.

Malfunctioning of the wet abrasive blasting equipment during the cleaning of the fuel plates caused four (4) plates to be rejected. Stalling of the plate drive mechanism resulted in the cutting of transverse grooves by the three reciprocating guns, as shown in Figure 113. Prolonged blasting on the stationary plate thinned the cladding appreciably. Stalling of both the carriage drive and the gun drive produced the spot type defect as may be seen in Figure 113. Here a hole was blasted completely through the cladding to the core by one of the guns. These types of defects could be eliminated by interlocking the gun and carriage drives with the air-supply solenoid valve so that if either drive stopped the gun air supply would be cut off.

Failure of plates in corrosion test caused rejection of only three (3) plates, 0.18% of the production. As shown in Figure 114, no need arose concerning a decision as to whether a plate should be rejected or not. Water entry to the core produced a large change of volume, causing the cladding to swell to outlandish proportions. Each of these three plates failed very shortly after the start of the corrosion testing, which indicated the existence of a water channel completely through the clad at the start of test. Complete metallographic examination of at least one section of all bond interfaces of the three failed plates did not reveal defects through which water could penetrate the cladding at the bond lines.

The presence of hard inclusions along portions of the sides of two fuel plates was reason for rejection of two (2) plates. These inclusions, as shown in Figure 115, were the result of tungsten contamination to the pre-rolling welds.

The 930 fuel plates accepted for reactor use appeared essentially as shown in Figure 116. The surfaces were reasonably smooth, as pictured in Figure 117. The surfaces of the thin (0.210") plates in general were less rippled than the thick (0.273") plates. It is recalled that both sizes of plates were rolled in steel jackets of the same over-all thickness. This practice left a greater thickness of steel over the major faces of the thin billets than over the thick billets (see Figure 72). Since the thickness of the steel jacket was the only design change which could be made, the last sixteen (16) thick fuel plates were rolled in steel jackets 3" thick instead of 2-3/8" thick. This change completely eliminated the rippled surface found on the plates rolled in the thinner jackets.

FIGURE 111. Photo of Radiograph of Rejected Fuel Plate with Unequal End Clad Resulting from Machining Error.

21164

Top End Clad 2-1/8"

21164

Bottom End Clad 1-3/16"

1X

FIGURE 112. Cracks in Seal Pins.

21100

16X

Crack in Center of Seal Pin

21102

16X

Crack in Left Side of Seal Pin

FIGURE 113. Defects Produced by Malfunctioning of Wet Abrasive Blasting Machine.

20329

Grooves Resulting from Stalled Carriage

20325

Hole through cladding caused by stalled carriage and gun drive.

FIGURE 114. EBWR Fuel Plate Which Failed During Corrosion Testing in Water at 550°F.

111-4360

Fuel Plate No. E-535 after 1 week in Autoclave

Approx. 0.2X

111-4444

Fuel Plate No. 475 after 2 weeks in Autoclave

Approx. 0.15X

111-4445

Side view of Plate No. 475 above

Approx. 0.15X

111-3848

Fuel Plate No. 290 after 2 days in Autoclave

Approx. 1.5X

111-3851

Side view of Plate No. 290

Approx. 1.5X

FIGURE 115. Tungsten Contamination of Billet Assembly Weld.

20326

0.6x

FIGURE 116. Finished EBWR Fuel Plates.

106-2474

FIGURE 117. Surface of Fuel Plates after Wet Abrasive
Blasting with 400 Mesh Al_2O_3 .

21160

Thin (0.210") Fuel Plate

1X

21161

Thick (0.273") Fuel Plate

1X

The minimum cladding specifications were equaled or exceeded. The face cladding on the accepted plates averaged 0.0203" thickness with the high and low values being 0.016" and 0.024". The thickness of the fuel plates over the center line of the core were as follows:

Type of Plate	Center Thickness (in.)		
	Avg.	High	Low
Thin	0.212	0.222	0.205
Thick	0.278	0.287	0.272

The thickness along the sides of the plate over the side clad and over the end clad averaged 0.006" greater than at the center of the plates. The cladding, as shown in Figure 118, did not thin over the transition from core to side plate and the roundness at the sides of the core was not considered objectionable. The cladding over the core-end plug transition thinned very little, and the core end tapers were considered to be uniform, as shown in Figure 119.

The acceptable fuel plates were judged by the ultrasonic test to be completely bonded, all surfaces of the core bonded to the clad, and all cladding components bonded to each other. Metallographic examination of transverse sections of 2240 end coupons revealed clad-to-clad bond line defects in a low percentage (3.1%) of all the plates rolled.

Except for the three plates which failed in corrosion test, none of the plates produced were judged to be unsatisfactory for reactor use on the basis of areas of high corrosion rate alone. A small number of plates⁽¹⁾ selected for extended corrosion testing have survived 3600 hours of testing in 550° F water with no evidence of failure. Development plates essentially the same size and produced by the same procedure as the production plates have survived 6500 hours of corrosion testing without failure.⁽⁶⁾

A test plate, smaller in dimensions (0.200" x 2" x 17") with identical cladding thicknesses and produced by identical procedure as the reactor plates, has survived 0.35 total a/o burnup at 485° F without serious effect. Dimensional changes were very small, 0.004" increase in width and length, and no warp or twist was observable.⁽¹⁾ The growth rate of this plate has indeed been very low, 0.57 and 0.067 microin./in./ppm burnup width and length, respectively. This plate after testing is shown in Figure 120.

FIGURE 118. Transverse Sections of Fuel Plates at Six Equally Spaced Intervals along Length of Plates.

21157

Thin (0.210") Fuel Plate

1X

21158

Thick (0.273") Fuel Plate

1X

FIGURE 119. Longitudinal Sections at Core Ends of Fuel Plates.

21159

1X

Thin (0.210") Fuel Plate at Top.
Thick (0.273") Fuel Plate at Bottom.

FIGURE 120. EBWR Prototype Fuel Plate after Irradiation to 0.35 Total a/o Burnup at 485°F.

111-4499

One Side of Plate

111-4500

Opposite Side of Plate

RECLAMATION OF CORE ALLOY FROM FUEL PLATES

Because of the high value of the materials in the fuel plates, a procedure for reclamation of the components would be desirable. Two alternatives immediately present themselves. First, separation of the clad and core by a melting process would salvage the core alloy. Of course contamination of the Zircaloy-2 cladding with fissionable material not easily removed would make this fuel-plate component unsuitable for direct conversion to ingot form. Second, combination of the core and clad of the fuel plate would be possible since one of the alloying additions which produce Zircaloy-2 (Sn, Fe, Cr, and Ni), however, would contaminate the core alloy.

First attempts were made toward the salvaging of the uranium core alloy by a melting process. Because of the wide difference in melting temperature ranges of the core and clad alloy, it was possible to put the uranium alloy core in the molten state while maintaining the Zircaloy-2 cladding in the solid state; if the core alloy could be quickly drained from within the cladding, contamination of the core alloy could be kept low,

Test heats were designed to accomplish the above objective. Complete fuel plates were separated into 6" to 7" sections by sawing normal to the major axis, thereby exposing the core alloy. These sections were supported vertically on their Zircaloy side plates in a special graphite crucible, sketched in Figure 121. The crucible, charge, and 2" x 4" mold were loaded into the 20" vacuum induction furnace. The charge was quickly heated to 1400° C, approximately 125° above the melting range, which caused the uranium core alloy to drain from the Zircaloy-2 cladding and collect in the bottom section of the crucible. Upon completion of the separation, the uranium alloy was poured by means of a stopper rod into the mold below.

Separation of the uranium core alloy from the Zircaloy-2 cladding was quite efficient. For the three separations made, the average recovery of the core alloy was 94.9%. Within the accuracy of the calculation of the composition of the core alloy no increase in the zirconium content resulted from the separation. Contamination of the core alloy by the alloying elements of the cladding, Sn, Fe, Cr, and Ni, were slight, with the exception of tin which increased from less than 5 ppm to approximately 100 ppm. The Zircaloy-2 cladding after melt out of the uranium alloy core is shown in Figure 122.

Second attempts were made toward salvaging both the core and clad components. The procedure used was the combination of core and clad by melting. This practice would increase the zirconium content of the uranium alloy and dilution to the desired Zr level by additions of uranium and niobium would be required.

FIGURE 121

Cutaway Perspective of Crucible and Charge for Reclamation
of Core Alloy from Fuel Plates

FIGURE 122. Fuel Plate Cladding after Melt Out of Core Alloy as Viewed from Bottom.

19600

Approx. 1/2X

In this method the fuel plates were cut into short sections and loaded into a coated graphite crucible. The crucible and a mold were placed in one of the 20" quartz-tube furnaces, and the charge was heated to approximately 1600° C and held for one-half hour in an attempt to dissolve the cladding in the uranium melt. The melt was poured into a graphite mold.

The recovery by this method could not be compared directly with the recovery in the separation method; but on the basis of uranium recovery calculated using analytical data, recoveries were poorer. In the method where clad and core were combined, 85.7% of the uranium in the charge was recovered in the casting, as opposed to 94.8% recovery in the separation method. Only 75.6% of the zirconium in the cladding dissolved in the melt, which raised the Zr content from 5.4% to 17.3%. Contamination of the melt with Sn from the cladding was considerably higher in the complete melting as opposed to the separation process, 1000 ppm vs. 100 ppm. The Cr and Ni levels were raised somewhat, but the Fe content remained about the same. The over-all recovery from charge to casting was 84.8%.

FUEL ASSEMBLY MANUFACTURE

The fuel plate manufacture, testing, and evaluation having been completed, acceptable plates were transferred to the Jacketing and Coating Group of the Metallurgy Division for incorporation into fuel assemblies. The development of the manufacturing procedure and the manufacturing of the fuel assemblies are reported elsewhere. (20,21)

The fuel assembly, as pictured in Figure 123, consisted of six fuel plates, two Zircaloy-2 side plates, and stainless steel locating bottom and top fittings. The fuel plates were arranged in parallel, nominally spaced $3/8$ " apart, and welded to two perforated Zircaloy-2 side plates. Welding of the side plates to the fuel plates was done using a technique termed tungsten-arc spot welding. In this process heat generated by arcing between a tungsten electrode and the work produced a molten pool through the side plate into the side clad of the fuel plate. The nugget upon freezing bonded the side plate to the fuel plate. Welding was done in a dry box containing an argon-helium atmosphere. All welding was done automatically in the equipment shown in Figure 123. A total of 264 welds were made on each assembly. The welds were spaced at 3" intervals along the length of the fuel plate, except for the three welds at each end which were spaced $1/2$ " apart.

The fuel assemblies after welding were corrosion tested for one (1) week at 550° F. Testing was done in the as-welded condition without pickling or other preparation. None of the assemblies produced failed in the corrosion test, and only one assembly showed evidence of excessive corrosion in the weld areas.

After corrosion testing and acceptance, the top and bottom fittings were attached to the Zircaloy-2 assembly side plates projecting beyond the ends of the fuel plates. Attachment of these fittings was done by riveting, employing stainless steel rivets.

FIGURE 123. Equipment for Welding EBWR Fuel Assemblies.

Front View of Welding Chamber

Rear View of Welding Chamber

Carriage & Positioning Fixture

DISCUSSION

Evaluation and testing of the EBWR fuel plates have shown that the manufacturing practice used was essentially sound. Even though all operations could not be referred to as simple, all procedures were straightforward. With the exception of a few operations, the skill of the operators was not depended upon unduly for the success of the operation. Only in the visual and microscopic inspection of the cladding components were personal judgement depended upon for the quality of the finished product. In all other operations, pre-established procedures based on measurable quantities, such as time, temperature, concentration, power, reduction, etc., were used, thus eliminating errors in human judgement. In addition, equipment, where possible, was made automatic to assure reproducible results.

Even though many of the operations required special equipment, none of these was so complicated as to make it impractical for use in commercial fuel-plate manufacturing. Operation of the equipment did not require highly skilled personnel nor long training periods.

Many aspects of the manufacturing procedure which could be improved or simplified came to attention during the project. Of these, one raised itself well above all others because of the difficulties associated with it. This was the quality of the Zircaloy-2 ingots allotted. Much could be done to improve this product which would greatly simplify the production of cladding stock suitable for use and reduce the very expensive scrap losses.

Improvement of ingot quality is possible because ingot of higher quality has been received. During the development of the EBWR fuel plates, high-quality ingot was obtained which presented little difficulty in fabrication into cladding stock. Little or no spot grinding was necessary for the removal of surface defects before finish rolling, and no difficulty was experienced in the wet abrasive blasting cleaning due to the absence of surface defects containing contamination.

The preparation of cladding component stock for the EBWR production plates was plagued with the necessity of removal of a great number of surface defects such as laps, seams, stringers and porosity before the finish rolling operation to obtain any kind of yield at all from a large fraction of the material. Because of this vast amount of severe spot grinding, the finish rolling procedure had to be changed from cold rolling to warm (600°C) rolling, since the 10% reduction possible by cold rolling was not sufficient to roll out grinding depressions. The warm-rolled strip required more extensive blast cleaning than the cold-rolled product for the removal of contamination; in addition, much closer inspection was required to cull out defective areas in the finish material.

Tungsten inclusions also marred the quality of the Zircaloy-2. This required the tedious procedure of radiographing all rolled cladding stock to inspect for their presence, and an even more tedious procedure of transferring the location of inclusions from the film used to the stock. Even with this inspection, some inclusions were missed, and their presence caused rejection of some fuel plates, which was costly. Modification of the welding method used in the preparation of the primary consumable electrode from pressed sponge, so as to eliminate tungsten at its source, would be a great improvement.

The next phase of the manufacturing procedure which could be modified to good advantage is the control of the width of the fuel plate during rolling. Even with the massive steel jacket used and the close control of variables, such as temperature, reduction, position and rolling speed, more variation developed in the width of the plates than was desirable. To date the cause of this width variation between billets of one design has not been found. Equipment in which the width dimension could be controlled would be very desirable. With an edge-rolling mill, much of the excess side plate width provided for spread variation could be eliminated and the length dimension could be controlled to much closer limits by rolling to a width tolerance comparable with the thickness tolerance obtained.

In addition, equipment of this type could have been used in the rolling of the Zircaloy-2 cladding stock. The saving in Zircaloy-2 scrap alone would have been high by reduction in the amount of side scrap.

Performance of the wet abrasive blasting equipment, so vital to the production of cladding stock, could be improved. Equipment which would blast both sides of the strip simultaneously is possible, and a feed mechanism which would function continuously would be more desirable than the batch type feed used. Both of these modifications would increase efficiency and improve the operation.

During the vacuum welding of the seal pins, control of the preheating and welding power was done manually by changing the setting of a rheostat. Since this change required time, melting of the seal pin which established the arc at times occurred before the desired power setting was reached. The bulk of the faulty welds was caused by this premature arcing. Operation could be improved by providing switchgear and controls for automatic change from preheat to welding cycle.

The design of tests which duplicate reactor conditions is very difficult, and the reactor test facilities which are available will accommodate only small versions of the full-scale fuel element. This, coupled with the problem of accelerating the test condition, make complete evaluation of a fuel element nearly impossible. The performance of EBWR fuel elements to the tests performed have been good. The test which was closest to reactor conditions was the corrosion test. During this testing only three (3)

plates of the 1120, 0.27%, failed. Considering that approximately 3,500 sq ft of surface was tested, the presence of three defects in the Zircaloy-2 cladding through which water could enter appears remarkable. A great deal of confidence was placed in this test, since all failures occurred almost immediately and test periods up to nine (9) months did not cause failure in development plates. The fuel plates have now been loaded into the reactor and only time will tell how well or how poorly the plates will function in the production of electrical power.

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APPENDIX

During the rolling of a rectangular billet, a straight plate will be produced providing the faces remain parallel during rolling. If, however, because of errors in mill screw settings or entry position, the plate is rolled to a lesser thickness on one side than on the opposite side, a curvature will develop in the plane of the plate face. The plate will curve such that the concave side is on the thick side of the plate.

Assuming that the curvature is an arc of the circle as shown below, the following equations may be written:

The lengths at each side of the plate rolled from a rectangular billet are inversely proportional to the thicknesses at each side of the plate (a).

$$\frac{a_1}{a_2} : \frac{t_2}{t_1}$$

a_1 = length of concave side of plate.

a_2 = length of convex side of plate.

$$a_2 = a_1 \frac{t_1}{t_2} \quad (a)$$

t_1 = thickness of side a_1 .

t_2 = thickness of side a_2 .

Assuming the curvature developed in the plate rolled to a uniform taper from one side to the other is an arc of a circle, two equations for the plate curvature may be written, (b) and (c).

$$r \theta = a_1$$

r = radius of curvature of side a_1 .

$$\theta = \frac{a_1}{r} \quad (b)$$

w = width of plate.

$$a_2 = \theta (r + w) \quad (c)$$

θ = angle subtended by plate in radians.

Substituting the value of θ in (b) for θ in (c), r may be calculated (d)

$$a_2 = \frac{a_1}{r} (r + w)$$

$$ra_2 = a_1 (r + w)$$

$$r = \frac{a_1 w}{a_2 - a_1} \quad (d)$$

Having found the radius of curvature, θ may be found (b) and then h (e).

$$\frac{n}{r} = \cos \frac{\theta}{2}$$

$$h = r \cos \frac{\theta}{2} \quad (e)$$

The camber then may be found (f).

$$r = C + h$$

C = Camber

$$C = r - h$$

To demonstrate the camber produced by a small change in thickness from one side of the plate to the other, a value for C , camber, for a change in thickness of one (1) mil is given below:

The following values which are in the ranges for plates produced are assumed to be

$$a_1 = 54.000''$$

$$t_1 = 0.210''$$

$$t_2 = 0.209''$$

$$w = 4.000''$$

Substituting in equation (a) the length of side a_2 may be determined.

$$a_2 = 54'' \times \frac{0.210''}{0.209''} = 54.2484.$$

The radius of curvature and the angle θ can then be found by substituting into equations (d) and (e):

$$r = \frac{54'' \times 4''}{54.2583'' - 54.0000''}$$

$$= 836.237''$$

$$\theta = \frac{54.000''}{836.237}$$

$$= 0.06457 \text{ radians}$$

$$= 3.70^\circ$$

$$= 3^\circ 42'$$

The value of h and the camber C can be found from (e) and (f).

$$h = r \cos 1^\circ - 51'$$

$$= 836.237 \times 0.99948$$

$$= 835.802$$

$$C = 0.435''$$