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ROLL CLADDING URANIUM-ZIRCONIUM AND
URANIUM-ZIRCONIUM-NIOBIUM ALLOYS WITH
ZIRCALOY-2 FOR PLATE-TYPE FUEL ELEMENTS

by

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ROLL CLADDING URANIUM-ZIRCONIUM AND URANIUM-ZIRCONIUM-NIOBIUM ALLOYS WITH ZIRCALOY-2 FOR PLATE-TYPE FUEL ELEMENTS

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ABSTRACT

Clad plate-type fuel elements containing uranium-5 w/o zirconium-1.5 w/o niobium alloy cores integrally clad on all surfaces with Zircaloy-2 were developed for the Experimental Boiling Water Reactor (EBWR). These plates were prepared by roll bonding assembled components inside steel jackets at 850°C with 80% reduction in thickness to effect sound diffusion bonds at all component surfaces. To obtain reproducible sound bonds, uranium alloy core and cladding components were clean and free from surface contamination, such as inclusions, oxides, or other foreign material; contamination of mating surfaces was avoided during welding operations; all bonding surfaces were sealed to prevent contamination from outgassing of the steel jacket during heating and rolling; billets were designed with a differential thermal expansion allowance for the core relative to the cladding; and all assembled billet components were evacuated and sealed by welding in vacuum. Integrally roll-bonded end closures were obtained by orienting billet end plugs so that the prior hot-working anisotropy of Zircaloy-2 would increase their lateral spread and facilitate the Zircaloy-2 end to Zircaloy-2 side bonds during rolling.

Investigations were made of alternate methods of bonding fuel shapes and the use of alternate core alloys in flat plates. Roll bonding in shaped pass rolls, cast bonding the core alloy into Zircaloy-2 molds, and bonding by coextrusion were all found to be feasible, although no integrally clad specimens were prepared for in-pile testing. Substitution of U-Zr binary alloys for the ternary reference alloy in roll-clad plates did not appear promising from corrosion test data, and further development with core alloy substitutions was abandoned.

Alterations and additions were made to development facilities needed to fabricate roll-clad plates for the EBWR core. Pilot production of EBWR-type plates proved that the plate cladding process could be adapted to production facilities.

SUMMARY

Roll-clad plate-type fuel elements were developed for use in the Experimental Boiling Water Reactor at ANL. These plates consisted of an uranium-5 w/o zirconium-1.5 w/o niobium alloy core clad with Zircaloy-2. The fundamental process consisted of assembling components of Zircaloy-2

cladding material in the form of cover plates, side strips, and end plugs around the uranium alloy core, welding the seams of all cladding components with a protective atmosphere at component mating interfaces, evacuating all gas from the clad-to-core interface, and sealing the assembly in vacuum. This assembled cladding billet was then jacketed in steel, heated, and hot rolled at a suitable temperature, then reduced to effect a bond at all core and cladding interfaces. The developed process was capable of being adapted to the production of EBWR-type plates approximately $1/4$ " thick, $3\frac{5}{8}$ " wide, and 54" long with 0.020" of face cladding, 0.125" of side cladding, and $1\frac{1}{2}$ " of end cladding on the uranium alloy core. Plates made by this process had an integral roll bond between the core and cladding on all faces, sides, and ends, an integral roll bond at all cladding interfaces surrounding the core, were dimensionally stable under irradiation testing, and were corrosion resistant in 290°C water for test periods up to 13,000 hours. The cladding was adequate to contain fuel fission products and provide structural support for subassembly welding.

The uranium-5 w/o zirconium-1.5 w/o niobium alloy was originally selected as the reference alloy for EBWR fuel plates because of its good water corrosion resistance in the supersaturated alpha phase, a property which could not be retained coexistent with dimensional stability during irradiation. Since this alloy was particularly amenable to roll cladding with Zircaloy-2 and could be heat treated for dimensional stability, plus the fact that there were no satisfactory uranium-rich alloy substitutes which were known to be both water corrosion resistant and dimensionally stable, its continued use for development of EBWR fuel plates was justified.

Alloy core material used for the development of clad plates was prepared from both hot-rolled slabs and individual core castings. Cast slab material could be readily forged or rolled to special shapes and finish machined to size. For roll cladding billets which required core material $3/4$ " thick or greater, the material yield from individual castings was significantly better than from hot-rolled stock. The established procedure for obtaining cores satisfactorily clean for roll bonding consisted of degreasing, wet abrasive blasting with 400 mesh alumina grit, air-water blast rinsing, rinsing in distilled water, rinsing in absolute alcohol, and drying and storing in vacuum until used in billet assemblies.

All Zircaloy-2 cladding material was prepared from consumable electrode arc-melted ingots which were forged to slab at 980°C, hot rolled at 850°C, cleaned, and finish rolled either by warm rolling at 600°C or by cold rolling. The surface finish of cleaned 600°C rolled Zircaloy was comparable to cold-rolled material. Because of the greater reductions per pass on rolling and reduced crown on 6" to 9" wide 600°C rolled sheet as compared with cold rolling, this method of finish rolling was preferred. Oxide scale which formed on hot and warm rolled plate and sheet was found to be tightly adherent and penetrated into microfissures and pits in the surface, making the

scale difficult to remove. Coarse abrasive particles were easily imbedded in the surface, thereby introducing additional contamination without penetrating and cleaning surface microfissures. Thoroughly clean hot or warm-rolled surfaces could be acquired by over-all surface machining, removing 0.005" to 0.010" of metal, or by wet abrasive blasting with alumina grit followed by an acid pickle in HNO_3 -HF acid. Roll-bond studies were made of Zircaloy-2 bonded to compare the effects of material surface preparation on bond quality. Results showed that the only roll bonds completely free from defects were obtained from surfaces which were prepared either by machining or by wet abrasive blasting with 400 mesh alumina followed by an acid pickle in boiling concentrated HNO_3 containing 1.0 v/o HF.

Roll cladding billets were rolled in a steel sheath or jacket to protect the external surfaces from surface contamination during heating and rolling and to provide some restraint along the side to effect greater uniformity in rolled-plate width. Uniform hot-working properties of the steel used for the protective jackets were found to be necessary to secure reproducible plate dimensions. The plain low carbon hot or cold rolled SAE 1018 or SAE 1020 steels and titanium-killed (Ti-Namel*) steel were all satisfactory for jacketing material.

Although most of the facilities used in the preparation of materials for development of EBWR fuel plates were of a conventional type, such as vacuum melting equipment, welding, heating, rolling, and shearing equipment, and machine shop facilities, some specialized equipment was designed and built to effectively clean and assemble roll-cladding billets. Automatic wet abrasive blasting equipment was used to ensure uniform cleaning of both core and cladding stock. Similar air-water blast equipment was used to effectively rinse the abrasive blasted cores. A billet assembly press was modified to include semiautomatic welding with combined vertical and horizontal application of pressure to the assembled cladding billet components. A vacuum welding chamber was developed for sealing the evacuated billet assemblies. Alterations and additions were also made to the existing cleaning, heating, rolling, and heat treating facilities to expedite fabrication and handling of full-scale EBWR-type plates.

Clad fuel elements for EBWR other than flat plates, and methods of roll bonding plate-type elements were investigated. Sound clad-to-core bonds were obtained on round rods by rolling in hand-round shaped pass rolls, and in smaller diameter rods by coextrusion. Further work would be required to perfect an end closure and uniform distribution of cladding for either process. Several cylindrical cladding billets were rolled in oval-edge-oval shaped passes and open-square shaped passes followed by flat rolling, primarily to obtain sound clad-to-core bonds along the sides of flat plates. Even though satisfactory clad-to-core bonds were produced

*Manufactured by Inland Steel Co.

in this way, the problems of cladding thickness variation and end closure remained unsolved. Regular flat rolling of assembled components was found to effect a good side bond at the clad-to-core interface and further work with shaped pass rolling was discontinued.

One other approach to the problem of clad-to-core side bonds was to prebond the core to the cladding side strips by casting the core alloy into a mold with Zircaloy side strips comprising the mold side walls. Castings prepared in this way were machined and assembled into billets with the addition of Zircaloy cover plates and end plugs. Billets of this type could be readily roll bonded. On several billets the uranium core alloy was cast directly into welded or fabricated and welded Zircaloy-2 cans to obtain prebonds at the bottom and on all four sides. This was intended to simplify core machining and billet assembly operations. The added cost of preparing components for prebonding plus the added contamination from welding and heating of the Zircaloy during casting, which was detrimental to its corrosion resistance in water, did not justify further investigations.

Billets prepared with cladding components assembled and pressed together to secure an intimate contact of cladding mating surfaces around the core and then welded to seal the components were referred to as modified picture frame-type billets. Sufficient billets of this type were prepared to determine effects of rolling variables on the physical, mechanical and metallurgical properties of rolled plates. Clad plates rolled 80% reduction in thickness at 850°C with reductions of 17% to 20% per pass were uniform in thickness and width, had a uniform distribution of cladding, and sound clad-to-core bonds. The transition from core to end cladding was extremely irregular in the first development plates which were rolled. This undesirable end effect was overcome by shaping the core ends to a 90° included angle taper and using matching shaped Zircaloy and plugs.

The continued presence of inclusions in the Zircaloy cladding bonds of rolled plates, even though the components had been thoroughly cleaned before assembly into cladding billets, indicated that they were being contaminated at some stage in the billet assembly, heating, or rolling operation. Measurements of the thermal expansion coefficients of Zircaloy-2 and the core alloy showed sufficient positive differential expansion for the core relative to the cladding on heating to the roll-bonding temperature to rupture the billet assembly welds. Components assembled loosely in previously outgassed SAE 1020 steel jackets or in Ti-Namel steel jackets were found to be contaminated from outgassing of the steel after evacuating and heating to 850°C with the billet evacuation continued during heating. To effectively eliminate contamination from the steel jacket, billet components had to be completely sealed by welding before being inserted in the steel jacket. Comparison of a group of Zircaloy-cladding billet assembly welds showed that pressed contact between mating surfaces and the use of

water-cooled copper chills on the face and sides of assembled components would eliminate most contamination from the billet internal surfaces. To completely eliminate weld contamination, particularly at Zircaloy mating surfaces around the end plugs, an inert purge gas was required. Unless all traces of the inert gas were removed from the billet assembly it would remain at the component interfaces of rolled plates to prevent bonding. Billet contamination during assembly, heating, and roll bonding was eliminated by the following steps:

1. Allowing 0.020"/inch differential thermal expansion for the core relative to the cladding in design of billet components.
2. Purging the assembled components for 10 to 15 minutes with argon gas prior to welding. Purge gas entered the billet through a 1/4" hole in one Zircaloy end plug.
3. Evacuating all remaining purge gas from the welded billet, evacuating through the 1/4" purge gas opening.
4. Sealing the evacuated billet by inserting and welding a Zircaloy pin into the hole in the end plug, both operations performed in vacuum.
5. Jacketing assembled billet in plain low carbon steel to prevent excessive external contamination of cladding material during roll bonding.

Restraint from the steel jacket was insufficient to facilitate satisfactory bonds at the vertical interface between Zircaloy-2 end plugs and Zircaloy-2 side strips for integral roll-bonded plate end closures. Without the use of edge-rolling equipment, some additional technique was needed to develop side pressure at this interface. The anisotropy present in hot-worked Zircaloy affected its resistance to deformation during subsequent hot working. By proper orientation of the hot-rolled slab stock as used for end plug material in cladding billets, there was a greater tendency for end plugs to spread laterally during rolling, which increased pressure at the end plug to side strip interface. Sound integral end closure roll bonds were obtained in this way.

A number of experimental binary alloy clad plates with uranium-zirconium alloy cores roll clad with Zircaloy-2 were prepared, duplicating the procedures developed for cladding the uranium-zirconium-niobium ternary alloy. Satisfactory plates of this type could effect a saving in fuel material costs and reduce the amount of neutron-absorbing material in the reactor core. The cladding distribution on the face and ends of plates with uranium-5 w/o zirconium in the core was very irregular, increasing the probability of thin spots. These defects could not be eliminated by changing any of the roll-cladding variables. A few sound clad plates with uranium-7.5 w/o zirconium and 10 w/o zirconium alloy cores appeared to be satisfactory on physical, mechanical, and metallurgical examination, but unexplained failures during corrosion testing in 290°C water discouraged further development of binary alloy plates as substitutes for the proven reference alloy.

Roll-clad plates with reference alloy cores were fabricated for irradiation testing in MTR. Plate sections with various heat treatments and cladding thicknesses were irradiated to observe the effects of these variables on the dimensional stability of plates during irradiation. The final specified isothermal transformation heat treatment for EBWR plates was based on the results of these tests. Roll-bonded cladding material was reported as having a beneficial effect in retarding growth during irradiation of otherwise unstable core material, an effect which was proportional to the thickness of the cladding. One integrally roll-clad plate fabricated and heat treated by procedures developed for EBWR production plates was irradiated to approximately 0.35 a/o burnup in the MTR water loop with less than 0.005" dimensional change in the 17" plate length.

Development plates which were scaled to the dimensions of EBWR-type plates indicated that the available development facilities at ANL were inadequate to properly prepare components and handle billets for roll bonding on the scale which would be required for the production of EBWR fuel plates. In order to meet this requirement, additions were made to the facilities for cleaning components, welding of assembled billet components including pop-welding the end closure in vacuum, billet preheating and handling during roll bonding, and for final heat treatment of rolled plates. Alterations were also made to all existing cleaning, assembly, heating, roll bonding, and handling equipment. Upon the completion of these changes a pilot run of EBWR type plates was made to show that sound clad plates could be fabricated at a rate of 9 to 12 per eight-hour day, the minimum required to meet the EBWR fuel plate production schedule.

INTRODUCTION

For central station water reactors analogous to the Experimental Boiling Water Reactor constructed at Argonne, the selection of a fuel element is dependent on economic factors if the reactor is to be competitive. The successful operation of this type of water-cooled and water-moderated reactor also depends on the many facets of the selection, design, and fabrication of fuel element materials.

Optimum economic advantage for the reactor fuel requires that it have a long survival in the reactor (up to 10 years for 1% atom burnup), with a maximum of trouble-free service. To obtain this service without additional enrichment with U^{235} and a corresponding loss in conversion ratio, the amount of neutron-absorbing materials used for structural support, fuel jacketing, and as alloy in the fuel must be kept to a minimum. A direct saving in initial fuel cost could be expected if little or no enrichment were needed and if a method of fabrication were developed which required a minimum of specialized equipment and services. Early specifications and recommendations for the EBWR fuel elements were

based on available physical, mechanical, and nuclear properties of fuel and structural materials, as well as the economic factors influencing the design and intended operation of the reactor. It was then necessary to develop a fabrication procedure for an element which would meet these requirements.

Primary consideration was given to irradiation stability of the fuel, corrosion resistance of the fuel to water and corrosion resistance of the cladding to water. The jacketing or cladding material was intended to retain fuel fission products but could not be relied on for 100% integrity throughout the life of the fuel. Previous data of Kittel and Paine^{(1)*} showed that stability under irradiation could be obtained by small alloy additions, such as 2 w/o zirconium, to uranium. Several promising corrosion-resistant uranium alloys had been developed at ANL⁽²⁾ and at Nuclear Metals.⁽³⁾ However, there was still some doubt whether corrosion-resistant alloys would be dimensionally stable or would retain their corrosion resistance after irradiation. The amount of corrosion product from core alloy irradiated to 1% total atom burnup which could safely be tolerated in the EBWR was specified at no more than 1 kg, which represents 1 sq ft of fuel alloy corroding at the rate of 500 mg/cm²/mo, if the reactor were allowed to operate for at least two weeks from the time of cladding failure to permit a scheduled shutdown. It was further desired that the fuel alloy have sufficient strength and rigidity to be as nearly self-supporting as possible within the heterogeneous core, in order to effect greater neutron economy in structural materials.

Available uranium-rich fuel alloys which showed the most promising corrosion resistance to water were of three types: metastable gamma alloys, supersaturated alpha alloys, and a stable epsilon-phase alloy. Alloys in the first group included 9 w/o niobium or 12 w/o molybdenum in uranium. The second group included alloys of uranium with 6 w/o niobium, 3 w/o niobium, 5 w/o zirconium-1.5 w/o niobium, and 3 w/o niobium-0.75 w/o tin. The stable epsilon-phase alloy consisted of 3.8 w/o silicon in uranium. With the exception of the metastable gamma alloys, the effects of irradiation were not known or were inconclusive at the time these fuel alloys were under consideration.

Zircaloy-2 was conceded to be the most satisfactory material available for the core structure and for jacketing the fuel alloy because of good corrosion resistance to water and low neutron-absorbing properties. Because there are no intermetallic compounds in the zirconium-uranium system it was surmised that a strong diffusion bond could be expected between the Zircaloy cladding and an uranium-rich core without the formation of a brittle interface. Considerable information was available on the physical and mechanical properties of Zircaloy-2.⁽⁴⁾⁽⁵⁾⁽⁶⁾ Consequently all fabrication work and clad fuel development evolved around the use of Zircaloy-2.

*The figures appearing in parentheses pertain to references at the end of this report.

Preliminary design of EBWR called for the following operating temperatures:

Water	252°C
Maximum fuel plate surface	275°C
Maximum core surface	295°C
Maximum core interior	364°C

Fuel alloys whose physical properties are dependent on specific heat treatments must be stable upon prolonged heating at the maximum core temperature. The reactor fuel was to be operated to 1.0 total atom percent burnup, the equivalent of 10,000 megawatt days per ton of fuel over a 10-year period. The water to uranium ratio was figured at 2.5:1. For this water-uranium ratio, a reactivity of 1.10, and 10 v/o zirconium in the core structure, the metastable gamma alloys with 9 w/o niobium or 12 w/o molybdenum were unacceptable because of their parasitic neutron-absorption characteristics. Similar parameters with other corrosion-resistant alloys showed the 3.8 w/o silicon and 5 w/o zirconium-1.5 w/o niobium alloys to have the greatest nuclear advantage.

Some difficulty was experienced in casting the uranium-3.8 w/o silicon alloy within the narrow limits of silicon content required to obtain a satisfactorily epsilonized structure for corrosion resistance. The most satisfactory epsilonized structures were obtained by heating for one week at 850°C. The cast alloy was hard and brittle from room temperature to 900°C. Though epsilonizing reportedly made it softer, it was still a difficult alloy to fabricate or jacket for fuel elements.

By comparison with the stable epsilon-phase alloy, the uranium-5 w/o zirconium-1.5 w/o niobium alloy could be readily cast, fabricated by hot rolling or extrusion, and heat treated to form a reproducible corrosion-resistant, alpha-supersaturated structure. Because of these apparent advantages, the 5 w/o zirconium-1.5 w/o niobium alloy was selected as the reference alloy for EBWR.

Fuel elements fabricated for EBWR were specified to be integrally clad on all surfaces with a good metallurgical or diffusion bond at all surfaces for lowest possible number of fuel element failures and maximum heat transfer. A number of feasible fuel shapes were considered, including tubes, rods, twisted ribbons, and flat plates. All could be fabricated by extrusion or rolling or a combination of both. Some of these shapes might also be fabricated by casting the core alloy into a Zircaloy jacket followed by extrusion or rolling. Facilities were available at Argonne for developing flat plates by several methods of sandwich roll bonding or combinations of casting and roll bonding. Previous clad plates rolled from a modified type of picture frame billet suggested a technique which might be applied to develop Zircaloy-2-clad fuel elements with the reference alloy core.

Some of the difficulties encountered in roll-bonding plates of uranium or uranium-rich alloys with zirconium and zirconium alloys were with cladding thickness variations, irregular end configurations, and lack of an integral bond, particularly along the sides and at the ends. Zirconium-clad normal uranium plates rolled at ORNL⁽⁷⁾ were fabricated with the core in a machined zirconium frame sandwiched between zirconium cover plates and rolled in a protective steel jacket. This type of assembly, known as a picture frame assembly, is shown in Figure 1. Zirconium-clad, normal uranium plates rolled at ANL⁽⁸⁾ were fabricated with the core surrounded by loose components of side strips, end blocks, and cover plates which were pressed together, welded, and then rolled in a protective steel jacket. This cladding billet assembly, as shown in Figure 2, is referred to as a modified picture frame assembly. Clad-to-core bonds in the plane normal to the applied force on rolling were generally satisfactory by both methods, but zirconium to zirconium bonds were often interrupted by uranium extruded into the clad-to-clad interface during rolling, as may be seen in Figure 3. Due to surface irregularities and cladding thickness variations, the plate ends required cropping and sealing by welding. As a means of increasing contact and bonding between the cladding and core along the sides of plates, a few exploratory billets were rolled in shaped passes as indicated by Figure 4. This procedure was considered worthy of further investigation for roll cladding the reference alloy.

Several of the corrosion-resistant, supersaturated alpha-type alloys were roll clad with Zircaloy-2 at ANL.⁽⁹⁾ Using the modified picture frame assembly welded around alloy cores of both 3 w/o niobium and 6 w/o niobium, a number of Zircaloy-2-clad test plates were prepared for irradiation testing in the high-temperature circulating water loop in MTR. There was practically no bond between the core and cladding along the sides or ends of these plates. The ends were sealed with welded strips. Plates were heated 1/2 hour in lead at 850°C, followed by a water quench to obtain the desired corrosion-resistant, supersaturated alpha structure. Finished plates were difficult to clean after heat treating, and pre-irradiation corrosion testing indicated that over-all machining followed by acid pickling produced the most corrosion-resistant surface on the cladding. Considerable encouragement for roll bonding the reference alloy resulted from the discovery of roll-bonding temperatures for which the resistance to deformation of the binary alloy core, Zircaloy-2 cladding, and protective steel jacket were nearly alike. Hot-working properties for the reference alloy closely resembled those of the 3 w/o and 6 w/o niobium binary alloys.

Necessary research and development work in support of the reference alloy for EBWR fuel plates was undertaken by the Reactor Engineering Division and various groups of the Metallurgy Division at Argonne concurrent with work being done on fuel element fabrication. As a result of data collected on material properties and tests on fabricated plates, changes and improvements could be made which were not anticipated at the onset of the fabrication development program.

FIGURE 1. Picture Frame Cladding Billet Assembly

FIGURE 2. Modified Picture Frame Cladding Billet Assembly

FIGURE 3. Uranium Core Extruded into Zirconium to Zirconium Interface by Roll Cladding

FIGURE 4. Cylindrical Billets Reduced to Flat Plate after Rolling in Hand-Round, Open-Square, and Oval-Edge-Oval Shaped Roll Passes

The Physical Metallurgy Group prepared constitution diagrams for the U-Nb and U-Nb-Zr systems⁽¹⁰⁾ and studied the kinetic transformations for these alloys.⁽¹¹⁾ This information was beneficial in establishing the effects of alloy variations and properties of the reference alloy. Specific dilatometer measurements and metallographic techniques were also beneficial.

Corrosion tests were continued with the reference alloy, other supersaturated alpha alloys, and the stable epsilon alloy by Draley and Greenberg,⁽¹²⁾⁽¹³⁾ both before irradiation and after irradiation. Tests on irradiated specimens of the reference alloy disclosed no appreciable change in corrosion resistance after 0.036 a/o burnup. However, considerable loss of corrosion resistance in 290°C degassed distilled water was noted between 0.046 and 0.074 a/o burnup. Other supersaturated alpha alloys showed a similar loss of corrosion resistance when tested after irradiation. Aside from extensive cracking and breaking up during corrosion testing, the irradiated epsilon alloy appeared to be the most corrosion resistant.

Autoclave corrosion testing of clad plate specimens was conducted by the Corrosion and Irradiation Group of the Reactor Engineering Division. Plates which were subjected to long-time testing in distilled, demineralized water at 290°C included binary U-Nb alloys, binary U-Zr alloys, and the ternary U-Nb-Zr alloy, all clad with Zircaloy-2.⁽¹⁴⁾ Corrosion results from representative plates, some with alloy cores heat treated for corrosion resistance and others not heat treated, were used to evaluate different Zircaloy cleaning procedures as well as integrity of the cladding. Complete data on all tested plates are included in the evaluation of various experimental plates discussed in this report.

The effects of irradiation were studied by Kittel on both bare and clad reference alloy specimens⁽¹⁵⁾ and bare specimens of other uranium rich alloys.⁽¹⁶⁾ Measurements of plate stability as a function of heat treatment, clad thickness, and amount of burnup were instrumental in establishing the ultimate specifications for EBWR fuel plates. Specimens which had been heat treated for corrosion resistance with a rapid quench from 800°C were dimensionally unstable with a high growth rate of 200 microin./in. per fission/ 10^6 total atoms during irradiation. On the other hand, an isothermal heat treatment consisting of heating for 15 minutes at 800°C, followed by cooling to and holding at 650°C for 24 hours, then water quenching from 650°C, resulted in a growth rate of only 5.4 microin./in. per fission/ 10^6 total atoms. A number of specimens which were given a duplex heat treatment in which the alloy was first heat treated for dimensional stability, and then given a gamma quench for corrosion resistance, were all found to be highly unstable upon irradiation, with no improvement over material which had been gamma quenched alone. The poor dimensional stability after heat treating for corrosion resistance, coupled with loss of corrosion resistance after 0.046 a/o burnup, invalidated the desired

corrosion-resistant property of the reference U-Zr-Nb alloy for EBWR fuel elements. Unless a suitable replacement could be found for the reference alloy, the only alternative was to heat treat fuel plates for dimensional stability and stress the development of an infallible integral cladding. Extent of the development program by this time indicated that the latter course was the most promising.

The only assurance that complete bonds and uniform cladding existed in rolled plates was to make a 100% inspection of the entire plate. Such an inspection by metallographic techniques on sectioned development plates was impossible. Methods were developed by the Nondestructive Testing Group of the Metallurgy Division for nondestructive test of roll-clad bonds and measurement of plate cladding thickness.⁽¹⁷⁾⁽¹⁸⁾ An ultrasonic through-transmission test, using a scanner with an electro-sensitive paper recorder, indicated both unbonded areas and degree of bonding. Unbonded areas as small as $1/32$ " in diameter could be detected over all core-to-clad and clad-to-clad interfaces. The thickness of the cladding over a $1\frac{1}{2}$ " dia area was found to be proportional to the natural radiation coming from the core and could be measured at the surface with a photomultiplier tube. This emission, when amplified, recorded, and compared with standard plate sections of known cladding thickness, gave a reliable measurement of cladding thickness within 0.001" over the range from 0.015" to 0.025". Possible isolated spots of thin cladding caused by inclusions, mechanical damage to the plate surface, or defective material could not be detected by this method. Conventional radiographic procedures were used to locate the plate core relative to the side and end cladding.

A supporting program of casting the uranium-5 w/o zirconium-1.5 w/o niobium alloy into zirconium and Zircaloy-2 containers to obtain prebonded billets for subsequent rolling was carried on in conjunction with roll-cladding developments.⁽¹⁹⁾ It was anticipated that this procedure would lead to satisfactory bonds at the sides and possibly at the ends of rolled plates. Investigations were made of shapes which could be used as molds for casting the core alloy, methods of preheating the mold, and problems of porosity at the cast core to mold interface and contamination of the mold with oxygen and nitrogen. Successfully bonded castings which could be rolled into plates and rounds were made by pouring the core alloy at 1400-1425°C into preheated Zircaloy-2 molds after first outgassing Zircaloy at 1500°C in a vacuum of 8×10^{-5} mm of Hg. Although this procedure was promising, the disadvantages of high cost of preparing Zircaloy molds and equipment limitations did not justify its use for production of EBWR plates, especially since later developments led to satisfactory bonds at the sides and ends of plates rolled from the modified picture frame-type of billet.

The melting and casting of reference alloy billets and cores continued throughout the development program.(20) Original castings were made in the form of billets or slabs to be rolled into shapes which could be machined into cladding billet cores. As the final size and shape for the EBWR fuel plates evolved, it appeared advantageous to produce castings which could be machined directly to size for assembly into roll-cladding billets. Individual castings were favored over larger slab-type castings, due to improved homogeneity and a minimum of internal defects.

The scope of fabrication work as covered by this report was limited by a number of elements. The principal limiting elements were selection of materials, availability of materials, equipment, and time. Since the ternary reference alloy could not be justified for its corrosion resistance, the use of other uranium-rich alloys having a greater neutron economy and less expensive alloy additions than niobium could be considered. Attempts to substitute uranium-zirconium binary alloys were not successful. No uranium-rich alloys were investigated which matched the hot-rolling characteristics of Zircaloy-2 as well as the reference alloy. A softer cladding material, such as Zircaloy-3, had it been available, might have resulted in more latitude in selection of the core alloy.

Some of the difficulties encountered in the fabrication of Zircaloy-2 for cladding components were due to lack of uniform physical properties. Considering such variables as source of supply, primary working of ingot, hot rolling, cleaning, and cold finishing, it was difficult to trace the effect of any one variable to finish material with the limited amount of material available for development work. Reports of work done later at WAPD were helpful in the control of Zircaloy-2 properties.(21)(22)(23) Plain carbon steel of the SAE types proved to be a satisfactory substitute for Ti-Namel steel as a protective jacket for cladding billets during rolling; however, neither was available for some of the first billets which were scaled to a full-size EBWR-type fuel element. Substitution of ASTM A7-52T hot-rolled plate for jacketing billets gave considerable trouble because of a wide spread in carbon analysis and higher phosphorus and sulfur contents than the SAE 1020 steel, making it difficult to determine the effects of introduced variables in rolling practice.

Had it been possible to restrain the sides of cladding billets by edge rolling it is probable that initial bonding along the sides of fuel plates could have been effected with less total reduction, a saving in amount of side cladding required, and greater control over the width and length of finished plates with a corresponding saving in finish machining. The optimum reductions per pass for roll bonding as established with some of the early development plates proved to be in excess of the capacity of the 16" x 24" mill used for rolling larger size EBWR-type fuel plates. These plates were approximately 1/4" thick, 4" wide, and 60" long as rolled. This size of fuel element probably represents the maximum which could

be handled with available rolling mill capacity. The use of mechanized equipment for cleaning materials, billet assembly, transporting billets from furnace to mill, and positioning and guiding during rolling was introduced too late in the development work to avoid the unpredictable variances of manual operation. Further refinements in the fabrication of clad flat plates were postponed in order to fulfill the requirements for the EBWR core to meet the scheduled completion date for the reactor.

Valuable information for evaluating the roll-cladding process was later obtained from the production of EBWR fuel plates. Data were collected on material yields, manpower requirements, uniformity of product, corrosion and nondestructive test results for over 1,000 rolled plates.⁽²⁴⁾ Performance as a reactor fuel will be obtained under operating conditions in the EBWR prototype central station power reactor.

MATERIAL PREPARATION AND EQUIPMENT

Preparation of Core Alloy

All uranium-rich alloy core material used for fabrication development was induction melted, alloyed, and cast in vacuum at ANL.^(19,20) Variables introduced during melting and casting included type of alloy material used in virgin melts, crucible material and wash, mold design, mold material and wash, melting practice, and final pouring temperature. A summary of casting practice and average alloy composition for core castings used in development work is covered in Tables I to V, inclusive. The castings listed in these tables were separated into five groups as follows:

Table I. Castings which were hot rolled before machining to the desired core size.

Table II. Reference alloy prebonded to Zircaloy-2 by casting.

Table III. All uranium-zirconium binary alloy castings.

Table IV. Single castings which were machined directly to a single core.

Table V. Single or multiple castings which were machined directly to seven or more cores.

Table I
CASTINGS FOR WROUGHT ALLOY CORES

Casting No.	Type of Alloy Addition		Crucible	Crucible Wash	Mold	Mold Wash	Pouring Temp. (°C)	Chemical Analysis, w/o	
	Zirconium	Niobium						Zirconium	Niobium
L-24	Sponge	Pressed Powder	Magnorite*	None	Copper	None	1400	5.26	1.58
L-68	Sponge	Pressed Powder	Magnorite*	None	Graphite	CaO	1400	4.62	1.68
L-111	Grade A Sponge	Sinter Bar	Magnorite*	None	Graphite	CaO	1570	4.81	1.70
L-118	Grade A Sponge	Sinter Bar	Magnorite*	None	Graphite	CaO	1500	5.30	1.74
L-121		Remelt	Magnorite*	None	Graphite	CaO	1360	5.26	1.78
L-123	Grade A Sponge	Sinter Bar	Magnorite*	CaO	Graphite	CaO	1570	5.36	1.75
L-124	Grade A Sponge	Sinter Bar	Magnorite*	CaO	Graphite	CaO	1550	5.16	1.19
L-125	Grade A Sponge	Sinter Bar	Magnorite*	CaO	Graphite	CaO	1450	5.08	1.77
L-126	Grade A Sponge	Sinter Bar	Magnorite*	CaO	Graphite	CaO	1475	5.59	1.74
L-127	Grade A Sponge	Sinter Bar	Magnorite*	MgZrO ₃	Graphite	CaO	1550	5.21	1.63
L-136	Grade A Sponge	Sinter Bar	Magnorite*	CaO	Graphite	CaO	1560	6.58	1.68
L-159		Remelt	Magnorite*	None	Graphite	CaO	1465	5.91	1.96
L-161		Remelt	Magnorite*	None	Graphite	CaO	1510	4.47	1.69
L-162	Grade A Sponge	Sinter Bar	Magnesia	None	Graphite	CaO	1540	4.89	1.41
L-163		Remelt	Magnorite*	None	Graphite	CaO	1450	4.91	1.51
L-168	Grade A Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1520	5.95	1.72
L-170	Grade A Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1475	5.52	1.79

*Magnesia crucible manufactured by Norton Company.

Table II

URANIUM-5 W/O ZIRCONIUM-1.5 W/O NIOBIUM ALLOY CAST BONDED
TO ZIRCALOY-2 (ALL CORE MATERIAL REMELTED CASTINGS)

Casting No.	Crucible	Crucible Wash	Mold	Mold Wash	Pouring Temp. (°C)	Chemical Analysis	
						Zr (w/o)	Nb (w/o)
L-84	Magnorite*	None	Zircaloy-2 & Graphite	MgO	1365	--	--
L-86	Magnorite*	None	Zircaloy-2 & Graphite	None	1420	--	--
L-128	Magnorite*	None	Zircaloy-2 & Graphite	CaO	1470	5.11	1.67
L-129	Magnorite*	None	Zircaloy-2 & Graphite	CaO	1500	4.76	1.50
L-130	Magnorite*	None	Zircaloy-2 & Graphite	CaO	1495	5.31	1.58
L-131	Magnorite*	CaO	Zircaloy-2 & Graphite	CaO	1490	5.03	1.57
L-132	Magnorite*	CaO	Zircaloy-2 & Graphite	CaO	1500	5.03	1.58
L-134	Magnorite*	None	Zircaloy-2 & Graphite	CaO	1485	5.04	1.59
L-139	Magnorite*	CaO	Zircaloy-2 & Graphite	CaO	1530	6.00	2.15
L-140	Magnorite*	CaO	Zircaloy-2 & Graphite	CaO	1530	6.05	2.20
L-141	Magnorite*	CaO	Zircaloy-2 & Graphite	CaO	1525	4.80	1.85
L-148	Magnorite*	None	Zircaloy-2 & Graphite	CaO	1505	4.85	1.83
L-149	Magnesia	None	Zircaloy-2 & Graphite	CaO	1510	5.93	1.72
L-151	Magnesia	None	Zircaloy-2 & Graphite	None	1445	5.48	1.68
L-152	Magnesia	None	Zircaloy-2 & Graphite	None	1440	5.51	1.67
L-153	Magnesia	None	Zircaloy-2 & Graphite	None	1430	5.81	1.64
L-154	Magnesia	None	Zircaloy-2 & Graphite	None	1440	5.62	1.68

* Magnesia crucible manufactured by Norton Company.

Table III

URANIUM-ZIRCONIUM BINARY ALLOY CORE CASTINGS

Casting No.	Type of Zr Charge	Crucible	Crucible Wash	Mold	Mold Wash	Pouring Temp (°C)	Chemical Analysis
							Zr (w/o)
L-228	Grade C Sponge	Magnorite*	ThO ₂	Graphite	CaO	1500	5.53
L-231	Grade C Sponge	Magnorite*	ThO ₂	Graphite	CaO	1500	4.98
L-233	Grade C Sponge	Magnorite*	ThO ₂	Graphite	CaO	1480	5.41
L-235	Remelt	Magnorite*	ThO ₂	Graphite	CaO	1450	5.02
L-236	Remelt	Graphite	ThO ₂	Graphite	CaO	1500	5.15
L-251	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1425	5.35
L-252	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1440	5.52
L-254	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1435	5.07
L-255	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1550	5.55
L-258	Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgO	1500	5.40
L-261	Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	4.89
L-262	Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1550	5.64
L-283	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	8.00
L-284	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	10.35
L-285	Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	7.21
L-286	Grade C Sponge	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	11.27

* Magnesia crucible manufactured by Norton Company.

Table IV
INDIVIDUAL CORE CASTINGS

Casting No.	Type of Alloy Addition		Crucible	Crucible Wash	Mold	Mold Wash	Pouring Temp. (°C)	Chemical Analysis w/o	
	Zr	Nb						Zr	Nb
L-184	Grade A Sponge	Sinter Bar	Magnorite*	ThO ₂	Graphite	CaO	1495	5.62	1.70
L-202		Remelt	Magnorite*	ThO ₂	Graphite	ThO ₂	1450	5.10	1.75
L-204		Remelt	Magnorite*	ThO ₂	Graphite	CaO	1450	5.46	1.72
L-205		Remelt	Magnorite*	ThO ₂	Graphite	CaO	1425	5.37	1.70
L-207		Remelt	Magnorite*	ThO ₂	Graphite	CaO	1450	5.16	1.62
L-209		Remelt	Magnorite*	ThO ₂	Graphite	CaO	1450	5.61	1.71
L-213	Grade A Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1435	5.41	1.66
L-214	Grade A Sponge	Pressed Powder	Graphite	ThO ₂	Graphite	CaO	1425	5.62	1.73
L-215	Grade A Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1430	5.30	1.67
L-216	Grade A Sponge	Pressed Powder	Graphite	ThO ₂	Graphite	CaO	1420	5.37	1.53
L-217	Grade C Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1455	5.60	1.66
L-218	Grade C Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1410	5.43	1.70
L-221	Grade C Sponge	Pressed Powder	Graphite	ThO ₂	Graphite	CaO	1480	5.16	1.50
L-222		Remelt	Magnorite*	ThO ₂	Graphite	CaO	1505	4.96	1.63
L-224	Grade C Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1450	5.43	1.53
L-225	Grade C Sponge	Pressed Powder	Graphite	ThO ₂	Graphite	MgZrO ₃	1460	5.50	1.26
L-226	Grade C Sponge	Pressed Powder	Magnorite*	ThO ₂	Graphite	CaO	1450	5.36	1.37
L-229	Grade C Sponge	Pressed Powder	Graphite	ThO ₂	Graphite	CaO	1410	5.47	1.50
L-244		Remelt	Magnorite*	ThO ₂	Graphite	ThO ₂	1455	5.28	1.78
L-247		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	ThO ₂ over MgZrO ₃	1435	5.01	1.58
L-248		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1435	5.55	1.64
L-249		Remelt	Graphite	CaO over MgZrO ₃	Graphite	MgZrO ₃	1425	4.97	1.61
L-257		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1510	5.03	1.64
L-259		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgO	1490	5.24	2.07
L-260		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	6.70	2.36
L-263		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1430	5.41	1.63
L-264		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1435	5.31	1.65
L-265		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1440	5.05	1.67
L-267		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	5.80	1.75
L-268	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	5.05	1.53
L-269		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1450	5.15	1.59
L-270		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1455	5.22	1.66
L-271		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1445	5.80	1.78
L-272		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1510	5.73	1.66
L-273		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1510	5.27	1.73
L-274		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1515	4.77	1.61
L-276		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1530	5.12	1.51
L-278		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	5.02	1.54
L-279		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	5.10	1.66
L-289	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1505	5.37	1.54
L-291	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1545	4.80	1.55
L-296	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1495	5.47	1.43
L-298	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1495	5.73	1.64

*Magnesia crucible manufactured by Norton Co.

Table V
MULTIPLE CORE CASTINGS

Casting No.	Type of Alloy Addition		Crucible	Crucible Wash	Mold	Mold Wash	Pouring Temp. (°C)	Type of Ingot	Chemical Analysis w/o	
	Zr	Nb							Zr	Nb
K-5	Grade A Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1452	Slab	5.18	1.47
K-6	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1550	Slab	5.74	1.62
K-7	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1540	Slab	5.16	1.78
K-9	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1560	Slab	5.31	1.69
K-10	Grade A Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1500	Slab	5.38	1.31
K-17	Grades A and C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1610	Slab	5.25	1.45
K-18	Grade 2 Crystal Bar	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1550	Slab	5.64	1.46
K-19		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1565	Slab	4.46	1.13
K-20		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1550	Slab	4.84	1.32
K-43		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1400	Slab	4.23	1.27
K-51		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	1 1/2 MgZrO ₃ 1 1/2 Bare	1460	Slab	3.96	1.22
K-53	Grade A Sponge	Sinter Bar	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1460	Slab	6.32	2.25
K-68	Grade A Sponge	Sinter Bar	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1540	Slab	5.30	1.60
K-77		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1445	Slab	5.77	1.69
K-82		Remelt	Graphite	ThO ₂ over MgZrO ₃	Graphite	MgZrO ₃	1495	10 Core	4.11	1.37
K-95	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	ThO ₂ over MgZrO ₃	1515	10 Core	4.77	1.55
K-96	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	ThO ₂ over MgZrO ₃	1470	10 Core	5.07	1.64
K-97	Grade C Sponge	Pressed Powder	Graphite	ThO ₂ over MgZrO ₃	Graphite	ThO ₂ over MgZrO ₃	1500	12 Core	4.98	1.44

Wrought core material of U-5 w/o Zr-1.5 w/o Nb was fabricated from castings having either a round or rectangular cross section. Castings from the 3" diameter round and 2" x 4" rectangular cross-section molds had smooth surfaces which were free from porosity, laps, or seams. These castings required no surface preparation such as grinding or machining before rolling. The amount of pipe removed from the top of the castings before rolling varied from 1" to 5" in depth. All castings were heated and rolled out of a carbonate salt bath (K₂CO₃-39%, Na₂CO₃-33%, Li₂CO₃-28%) at 850°C. Rolling details and final dimensions of all wrought material are given in Table VI. Reductions up to 15% per pass did not cause excessive checking or cracking along the edges, and there was no evidence of damage to the cast structure as a result of a large initial breakdown on rolling. The surface finish as rolled was very smooth and free from defects unless it was exposed to air on cooling. Surface oxidation on cooling produced a rough granular finish from 1/16" to 1/8" deep, a surface which had to be removed by machining. An increase in hardness from 27-32 Rockwell C for cast material to 41-46 Rockwell C for hot-rolled material was believed to be related to the cooling rate after rolling. It is possible that slow cooling or reheating and controlled cooling would have lowered the hardness and improved the machinability after rolling. Wrought material was machined by abrasive cutting and grinding to size. Since the final machined cores were of various sizes, the material yields varied from 51.1% to 76.7%, with an average of 64.2%. There was no noticeable difference in the quality of finished material from either a round or rectangular casting.

Sound castings approximately the shape of a cladding billet core with a minimum of excess material for machining appeared to offer a saving in both material recovery and fabrication costs. Chips and grindings

Table VI
FABRICATION OF WROUGHT CORE ALLOY HEATED IN CARBONATE SALT AT 850°C

Casting No. (1)	Size Before Rolling, Inches	Preheat Time, Minutes	Reheat Time	Total No. of Passes	Roll Speed, ft/min	Percent Red./Pass	Type of Rolling	Final Size, Inches
L-24	2-15/16 dia x 6-7/8	30	5 min./2 passes	14	75	10-12	Open square passes (2)	1-1/2 dia x 27-1/2
L-68	1.945 x 3-7/8 x 10-7/8	90	5 min/pass	16	75	7	Flat	0.627 x 4-3/4 x 27
L-111	2-15/16 dia x 4-5/8	30	5 min/pass	14	75	8-12	Open square and flat	1.240 x 2-1/8 x 12-1/4
L-118	1.95 x 3-7/8 x 8	45	5 min/pass	4	25	12-15	Flat	1.250 x 4-5/8 x 10-3/4
L-121	1.95 x 3-7/8 x 13-7/8	45	5 min/pass	4	25	12-15	Flat	1.248 x 4-5/8 x 18
L-123	2-3/8 dia x 11-1/8	30	5 min/pass	14	75	8-12	Open square and flat	1.235 x 2-1/8 x 18-7/8
L-124	2-3/8 dia x 9-1/4	30	5 min/pass	14	75	8-12	Open square and flat	1.250 x 2-1/8 x 17-15/16
L-125	2-5/8 dia x 9	30	5 min/pass	14	75	8-12	Open square and flat	1.250 x 2-1/4 x 17-5/8
L-126	2-5/8 dia x 9-1/4	30	5 min/pass	14	75	8-12	Open square and flat	1.250 x 2-5/16 x 18
L-127	2-3/8 dia x 11	30	5 min/pass	14	75	8-12	Open square and flat	1.235 x 2-1/8 x 19
L-136	1.95 x 3-7/8 x 9-3/8	45	5 min/pass	4	75	12-15	Flat	1.249 x 5-1/4 x 11
L-159	1.95 x 3-7/8 x 10	30	5 min/pass	4	75	12-15	Flat	1.250 x 5-1/16 x 12-3/8
L-161	1.95 x 3-7/8 x 9-1/2	30	5 min/pass	4	75	12-15	Flat	1.250 x 4-1/8 x 13-7/8
L-162	1.95 x 3-7/8 x 5	30	5 min/pass	4	75	12-15	Flat	1.250 x 5-3/16 x 6-1/8
L-163	1.95 x 3-7/8 x 4-7/8	30	5 min/pass	4	75	12-15	Flat	1.250 x 5-3/16 x 6
L-168	1.95 x 3-7/8 x 11-5/16	30	5 min/pass	4	75	12-15	Flat	1.250 x 4-1/8 x 16-1/2
L-170	1.95 x 3-7/8 x 9-13/16	30	5 min/pass	4	75	12-15	Flat	1.250 x 4-1/8 x 13-7/8

(1) See Table I for casting summary.

(2) Final pass 1-1/2" round.

Note: L-136, L-159, L-162, and L-163 were cross rolled first 2 passes.

L-111, L-123, L-124, L-125, L-126, and L-127 rolled to 2" square and then flat rolled to finish size.

from machining wrought material could be reclaimed by melting, but processing would be hazardous and recoveries low. Castings from individual 15-kg melts were cropped and machined to finished cores by removing 1/16" of metal from each face, 1/16" from each side, and tapering the ends. Cast material could be machined by sawing, abrasive cutting, grinding, shaping or milling. The material yield from machined castings was from 78% to 80%. Larger single slab-type castings, as shown in Figure 5, were sectioned and machined into finished cores. Multiple core castings were made in segmented molds, as shown in Figure 6. Yields from slab and multiple core castings were 85% or better.

Smooth surfaces of the reference core alloy which were free from contamination exhibited a silvery gray appearance. This surface developed a light straw-colored or golden interference film if heated slightly as in machining or after prolonged exposure to air. Presence of this film or any other surface contamination was considered detrimental to clad bonding. Several procedures for cleaning the machined core surface prior to assembly into cladding billets were investigated. These included electropolishing, sandblasting, sandblasting and rinsing, wet abrasive blasting, and wet abrasive blasting followed by water blasting or rinsing and drying. These various cleaning methods were evaluated by comparing surface appearances and quality of the Zircaloy to core bond in roll clad plates.

Small core specimens, 1/4" x 1" x 1", were degreased in trichloroethylene and electropolished to remove surface contamination and interference films. The electropolishing solution consisted of 46 v/o H₂SO₄, 9 v/o glycerine, and the balance water. Two ml of concentrated HCl were added

FIGURE 5. Single Slab-Type Casting of Uranium-5 w/o Zirconium-1.5 w/o Niobium to be Sectioned and Machined into Individual Cores. Slab casting shown on left, graphite mold on right.

FIGURE 6. Mold for Multiple Core Castings Partially Disassembled at Left, Assembled at Right.

Front segments and top compression ring removed. Mold coated with $\text{MgZrO}_3\text{-ThO}_2$ Wash.

Assembled Mold.

106-3060

1/4X

106-3065

1/4X

per 100 ml of solution. Making the work the anode, using a current density of 10 amp/sq in. at 10 volts, and alternate withdrawal from the solution to break the current and washing to remove loosened oxide from the surface, a clean lustrous finish was obtained. With larger pieces, $1\frac{1}{2}$ " x $1\frac{1}{2}$ " x 3", approaching the size of core used for the first 16 experimental cladding billets, only 90% of the exposed surface could be cleaned with a current density of 9 amp/sq in. This current represented the maximum rectifier output of 125 amp. Still larger specimens were not cleaned at all but only became more tarnished in the solution. Due to the high current density required and the limited available power, no further attempts were made to electropolish the reference alloy.

Sandblasting machined cores with 40 mesh alumina or silica grit produced a light gray mat finish. Cores with this finish were readily roll bonded to Zircaloy-2. Unfortunately, fine particles of grit became imbedded in the surface of the core and appeared as small inclusions and discontinuities in the bond line, as may be seen in Figure 7a. Rinsing in water or scrubbing in alcohol after sandblasting did not remove the imbedded particles. Since these foreign particles could weaken the bond line, interfere with heat transfer, or act as localized points of stress in the bond, their presence was undesirable.

Cores cleaned with a 400 mesh alumina grit in water suspension which was air driven, or blasted, against the surface of the core were microscopically clean. A thorough water rinse or air-water blast was necessary to remove traces of loose wet abrasive grit. Cores were then dipped in absolute alcohol and placed in a vacuum de-alcoholer for drying and storage until needed for billet assembly. A typical clad-to-core bond from a plate with the core cleaned by wet abrasive blasting is shown in Figure 7b.

Preparation of Zircaloy-2 Cladding Material

Zircaloy-2 used for the development of clad fuel plates was procured from the Bureau of Mines and Allegheny Ludlum. Except for 900 lb of rolled slab, 5Y663, and one 943-lb conditioned ingot, 5Y525, all material was received as 9" to 12" diameter, conditioned ingots, weighing approximately 500 lb each. The surface of conditioned ingots was smooth, bright, and generally free from porosity and cold shuts, except for the bottom $1\frac{1}{2}$ " of some ingots, which showed partially fused metal which had been placed in the bottom of the mold at the start of arc melting. The ingot shown in Figure 8 is representative of the material that was received. Although reflectoscope results were reported which indicated heavy porosity through the center of some ingots, no correlation could be found between this ingot porosity and quality of finished material. No attempt was made at ANL to study or identify ingot porosity. Ingot numbers and compositions based on average chemical and spectroscopic analyses are given in Table VII. The hardness of the cast ingots ranged from 154 and 185 Brinell. Metallographic structures of several cast ingots may be seen in Figure 9.

FIGURE 7. Zircaloy-2 Clad U-5 w/o Zr-1.5 w/o Nb Bonds
Showing Effects of Core Cleaning Process.

- 7a. Inclusions and discontinuities in bond between uranium alloy core and Zircaloy-2 cladding due to fine particles of grit imbedded in the surface of the core by sandblasting prior to billet assembly.

Zircaloy-2
Cladding

Cladding to
Core Bond

Uranium Alloy
Core

Micro 18722

Bright Field

250X

- 7b. Typical diffusion bond between uranium alloy core and Zircaloy-2 cladding rolled from a billet with the core cleaned by wet abrasive blasting before assembly.

Zircaloy-2
Cladding

Cladding to
Core Bond

Uranium Alloy
Core

Micro 21026

Bright Field

250X

FIGURE 8. Cast Zircaloy-2 Conditioned Ingot No. 710D443.

106-1166

1/6x

Table VII

CHEMICAL ANALYSES OF ZIRCALOY-2 INGOTS⁽¹⁾

Ingot No.	Tin	Iron	Chromium	Nickel	Nitrogen	Carbon
710D443	1.54	0.141	0.090	0.043	0.0068	-
710D528	1.48	0.114	0.092	0.047	0.0038	-
710D530	1.49	0.102	0.093	0.046	0.0038	-
710D960	1.50	0.124	0.107	0.057	0.0031	-
1X081	1.47	0.089	0.109	0.048	0.0070	0.012
1X082	1.55	0.122	0.114	0.050	0.0056	0.034
5Y345	1.43	0.108	0.105	0.048	0.0032	-
5Y525	1.47	0.115	0.109	0.049	0.0036	0.023
5Y663	1.39	0.142	0.117	0.050	0.0051	0.037

⁽¹⁾All analyses reported as weight percent.Forging Cast Ingots

Ingots were fabricated by hammer forging to a size which could subsequently be rolled to finished plate, bar, rod, or sheet. Forging was done at Anderson Shumaker Company in Chicago. All ingots were pre-heated $1\frac{1}{2}$ hours at 980°C (1800°F) and forged to the finished size. Heating

FIGURE 9. Metallographic Structure of Cast Zircaloy-2
Ingots Used for Cladding Billet Development.

9a. Ingot No. 710D443

Micro 16800 Bright Field 250X

9b. Ingot No. 710D960

Micro 20756 Bright Field 250X

9c. Ingot No. 1X081

Micro 16803 Bright Field 250X

9d. Ingot No. 1X082

Micro 16804 Bright Field 250X

9e. Ingot No. 5Y345

Micro 16798 Bright Field 250X

was done in a gas-fired furnace equipped with recording controllers. A slight reducing atmosphere was maintained and refractory baffles or convection walls along the sides of the hearth prevented direct flame impingement on the ingot. The forging was done on a 4,000-lb steam hammer with a reduction of 1" or greater per blow. Ingot No. 5Y525 required an additional one hour of reheating at 980°C during forging because of its greater size and weight. None of the other ingots forged at 980°C required reheating. Half of ingot 710D443 was forged to a slab 2" x 6" in cross section, the remaining half was forged to 3 $\frac{1}{4}$ " and 1 $\frac{1}{2}$ " diameter rod stock. All other material was forged to slabs ranging from 2" x 6" to 3" x 10" by developed length. Several steps in the forging of an ingot are shown in Figures 10, 11, and 12.

The metallographic structure of forged Zircaloy revealed the presence of dark parallel stringer in a matrix of fine-grained material. These stringers were oriented parallel to the direction of forging, as may be seen in the photomicrographs of transverse and longitudinal sections taken from forged slabs (Figure 13).

Forged Zircaloy-2 slabs were cut into suitable lengths and the surfaces prepared for rolling. All oxide scale, superficial laps, and surface checks were removed from the rolling faces of each slab by machining from 0.060" to 0.100" of metal from each wide face. This machining or scalping was done on a shaper or planer; in most cases all defects could be removed with a single cut. The sides and ends of all slab stock were sound and free from cracks. An inspection for cracks was made after scalping by using a penetrating dye, Turco Dye-Chek, manufactured by Turco Products, Inc. The surface was coated with the dye, which penetrated into all crevices and surface irregularities. Excess dye was removed and the surface coated with a developer which intensified the outline of flaws or cracks revealed by the colored dye. Forged rods, 1 $\frac{1}{2}$ " diameter, were not conditioned by machining before being hot rolled to 1" diameter and 3/8" diameter rod stock.

Fabricating Bar, Plate, Strip, and Sheet Stock by Rolling

The finished Zircaloy sheet to be used for development of clad plates required a fabrication process which would not lessen its corrosion resistance in water, strength, or ductility. The surface had to be smooth and free from contaminants which might prevent self-diffusion on roll bonding. This necessitated heating, rolling, and cleaning with a minimum of nitrogen, oxygen, or hydrogen pickup to produce a finished surface that would not require over-all machining. Variations in rolling practice which were investigated included hot rolling alone, a combination of hot and cold rolling, and a combination of hot and warm rolling. For purposes of this development work, warm rolling may be defined as the temperature range in which Zircaloy-2 may be plastically deformed in air without the formation of the

FIGURE 10. Initial Breakdown of Zircaloy-2 Ingot by Forging on 4000 lb. Hammer.

106-2221

FIGURE 11. Zircaloy-2 Ingot Ready for Finish Forging Reheated End.

106-2222

FIGURE 12. Final Sizing of Slab Forged from Zircaloy-2 Ingot.

106-2218

FIGURE 13. Transverse and Longitudinal Sections from Zircaloy-2 Slab Forged at 980°C.

13a. Longitudinal section from forged Ingot 710D443.

Micro 19311 Bright Field 250X

13b. Transverse section from forged Ingot 5Y345.

Micro 20772 Bright Field 250X

13c. Longitudinal section from forged Ingot 710D960.

Micro 18807 Bright Field 250X

13d. Transverse section from forged Ingot 710D960.

Micro 18803 Bright Field 250X

white oxide, ZrO_2 . Cold rolling alone was not considered practical because of the large reduction needed to convert scalped slab to plate, strip, or sheet stock without frequent annealing. Facilities were not available to intermediate vacuum anneal the amount of material required.

Several attempts were made to control or limit contamination during heating and hot rolling. Slabs of Zircaloy were heated in an argon-purged muffle which was not sealed or evacuated. The muffle was heated to 850°C in an electric resistance-type furnace. After heating for 15 minutes, the slabs appeared to be coated with as much oxide as those heated in air. Considerable protection was obtained by heating and rolling Zircaloy in a sealed Ti-Namel steel sheath or jacket. Sheath-rolled material still required cleaning to remove iron contamination from the surface. Sheath rolling had the disadvantages of additional cost for preparation of the steel sheath and difficulty in maintaining close dimensional tolerances on rolling.

Material hot rolled in air from a $2\frac{13}{16}$ " thick slab to sheet or strip had a rough oxidized surface which was not corrosion resistant in 550°F water without machining 0.005" to 0.010" of metal from all surfaces. The hot-rolling practice which was followed is summarized in Table VIII.

Table VIII

ROLLING PRACTICE USED FOR HOT ROLLING
AND WARM ROLLING ZIRCALOY-2

Operation	Hot Rolling at 850°C	Warm Rolling at 600°C
Preheat Temperature ($^\circ\text{C}$)	850	600
Preheat Time (min)	30/in. of Thickness	10
Reduction/pass (%)	8-22	7-15
Passes/reheat	2	2
Reheat Time (min)	20	10
Total Reduction (%)	46-92	50
Roll Speed (ft/min)	175	125

The typical metallographic structure of 850°C rolled Zircaloy-2 after 90% reduction in thickness is shown in Figure 14. A comparison between longitudinal and transverse sections photographed with bright field illumination (Figures 14a and 14b) shows that Zircaloy-2 contains numerous "stringers"

FIGURE 14. Transverse and Longitudinal Sections from 850°C Rolled, 1/8" Thick Zircaloy-2 Strip from Ingot 710D443.

14a. Longitudinal section.

Micro 19301 Bright Field 250X

14b. Transverse section.

Micro 19302 Bright Field 250X

14c. Longitudinal section.

Micro 20828 Polarized Light 250X

14d. Transverse section.

Micro 20827 Polarized Light 250X

which are elongated parallel to the direction of working. Whether these stringers are inclusions, alloy precipitate, or micro-fissures was not established. The same sections viewed with polarized light (Figures 14c and 14d) show that the metal has recrystallized at the rolling temperature with many of the grains aligned parallel to the long axis of the stringers, which appear to be unaffected by the recrystallization.

To fabricate strip with maximum reductions and obtain an improved surface finish it appeared feasible to combine hot and cold rolling. By removing surface contamination after hot rolling, plate surface asperities would be attenuated by cold rolling to produce a smooth clean surface on finished material. Hot-rolled strip from 1/8" to 1/4" thick could be cold rolled 10% to 20% reduction in thickness. Cold reduction was limited by the capacity of the 9" x 16" mill used to finish material of this size. Rolling with this mill necessitated taking four to five passes for a 10% reduction, which resulted in excessive cold working of the strip. Total reductions in excess of 20% resulted in edge cracking, 0.005" crown on an 8" wide strip, and scalloped edges. Greater reductions, up to 30% or 40%, were permissible on thinner strip, 0.100" or under, before edge cracking would appear. Thoroughly cleaned material fabricated by this combination of rolling procedures was satisfactory for cladding stock as determined by Zircaloy bond studies. Figure 15 shows the metallographic structure of Zircaloy-2 after a combined reduction of 80% at 850°C and 20% at room temperature. Bright field illumination in Figures 15a and 15b shows typical Zircaloy stringer formations parallel to the rolling direction. This material also has a characteristic wrought structure with severe deformation and elongation of the grains parallel to the rolling direction, as shown by polarized light in Figures 15c and 15d.

Since little contamination in the form of an oxide film was noted on clean Zircaloy after heating for 15 or 20 minutes at 600°C, and hot hardness values for Zircaloy-2 were shown by Muehlenkamp and Schwoppe⁽⁴⁾ to drop rapidly between 450°C and 750°C, it seemed probable that hot rolling combined with rolling at 600°C would offer the same advantages as combined hot and cold rolling. The warm-rolling procedure is summarized in Table VIII. Material finished 50% reduction in thickness by warm rolling was more uniform than cold-finished strip, had less than 0.002" crown in an 8" width, and was free from edge cracking or tearing. Zircaloy bond studies showed that thoroughly cleaned material finished by warm rolling was equivalent to cold-finished material. It can be seen from Figure 16 that there is little difference in the structure of Zircaloy-2 rolled at 600°C from that rolled at 850°C (Figure 14). Material rolled at either 850°C or 600°C showed stringers and complete recrystallization at the rolling temperature.

A large variation existed in both the size and number of stringers present in different pieces of rolled sheet. Similar variations were often noted at different locations within the same piece of material. To what

FIGURE 15. Metallographic Structure of Zircaloy-2 from Ingot 5Y345 after Hot Rolling at 850°C Followed by 20% Reduction in Thickness by Cold Rolling.

15a. Longitudinal section.

Micro 20877 Bright Field 250X

15c. Longitudinal section.

Micro 16929 Polarized Light 250X

15b. Transverse section.

Micro 20876 Bright Field 250X

15d. Transverse section.

Micro 16928 Polarized Light 250X

FIGURE 16. Metallographic Structure of Zircaloy-2 Rolled by Combination of 850°C and 600°C Rolling.

16a. Longitudinal section.

Micro 19266 Bright Field 250X

16c. Longitudinal section.

Micro 20830 Polarized Light 250X

16b. Transverse section.

Micro 19258 Bright Field 250X

16d. Transverse section.

Micro 20829 Polarized Light 250X

extent their presence would affect the corrosion resistance of Zircaloy-2 to water was not known, but it was conceivable that a large concentration of stringers in a thin section, such as the face cladding of a fuel plate, might result in catastrophic failure. Attempts to remove or dissipate these stringers by beta heat treatment, cold working, recrystallization, or combinations of these operations proved unsuccessful. The series of photomicrographs in Figure 17 shows that stringers formed during hot rolling are not altered by a beta treatment at 1010°C followed by a water quench, nor by subsequent cold work and recrystallization at 850°C . In all cases stringers extended across primary beta grain boundaries or through recrystallized alpha grains.

Cleaning Rolled Sheet, Strip, and Cladding Component Stock

All fabricated Zircaloy exhibited varying degrees of surface contamination. This ranged from black or white oxide to dissolved gases in the metal. Although cleaning procedures which would produce corrosion-resistant Zircaloy-2 bonds were known,⁽⁹⁾ and the development of clad reference alloy plates using these procedures had begun, microscopic examination disclosed many Zircaloy bonds containing inclusions believed to result from inadequate surface cleaning. Consequently a thorough investigation was made to establish microscopically clean, corrosion-resistant surfaces for 850°C rolled, 600°C rolled and cold-rolled strip and plate, as well as the final preparation of material used for cladding billet components.

Cleaning methods which were considered included acid pickling, machining, sandblasting, shot blasting, wet blasting with fine particles, vacuum high-temperature diffusion treatment (by which high concentrations of oxide and nitride at the surface would be diluted in the zirconium), and combinations of these methods. All were tried with the exception of shot blasting, for which facilities were not available. Speed of cleaning and metal recovery were emphasized in addition to surface cleanliness.

Oxide coatings were strongly adherent and direct acid pickling with various concentrations of HNO_3 plus HF had almost no effect on them. The principal value of acid for cleaning proved to be in conjunction with mechanical removal of surface oxides. Over-all surface machining could be depended upon to remove all contamination. Attempts to limit the amount of metal removed to less than 10 mils by milling, shaping, or grinding were unsatisfactory, due to normal variations in flatness. Cold-rolled sheet was particularly difficult to machine, due to differential cold-working stresses across the thickness, which caused warping as stresses at the surface were relieved by machining. Except where close dimensional tolerances or irregular shapes were required, surface machining as a means of cleaning Zircaloy was not considered practical.

FIGURE 17. Effects of Beta Anneal, Cold Work, and Recrystallization on Stringers in 850°C Rolled Zircaloy-2 Sheet.

17a. Structure as hot rolled at 850°C.

17b. Structure as hot rolled at 850°C, beta annealed 15 minutes at 1010°C, water quenched, and cold rolled 10% reduction in thickness.

17c. Structure as hot rolled at 850°C, beta annealed 15 minutes at 1010°C, water quenched, cold rolled 10% reduction in thickness, and annealed 15 minutes at 850°C.

17d. Structure as hot rolled at 850°C, beta annealed 15 minutes at 1010°C, water quenched, cold rolled 10% reduction in thickness, and annealed 30 minutes at 850°C.

The surface of all Zircaloy-2 after sandblasting with either silica or alumina abrasives was mottled with incompletely removed oxides. A considerable amount of abrasive particles were imbedded in the surface. A longer exposure time to remove the oxide resulted in a greater amount of imbedded abrasive fragments. The rough contaminated surface of sandblasted hot-rolled sheet is shown in Figure 18. Acid pickling in 35 v/o HNO_3 plus 5 v/o HF* did not remove trapped abrasive particles from sandblasted material without removing 3 to 5 mils of metal from each face.

FIGURE 18. Surface of 850°C Rolled Zircaloy-2 Sheet after Sandblasting with 46 Mesh Alumina Grit.

Macro 17006

50X

* All HNO_3 -HF baths referred to throughout the balance of this paper were composed of nitric acid with 1.42 specific gravity and hydrofluoric acid of 49.2 w/o HF.

Cleaning with a fine abrasive grit suspended in water and ejected against the work by a stream of air from a blast gun produced clean surfaces on all rolled Zircaloy-2 without introducing further contamination provided the proper relation of operating variables and selection of grit were obtained. A series of 850°C hot-rolled plates and cold-finished plates were abraded with different materials to an optimum degree of surface cleanliness. All tests were made with a single gun of 1/2" nozzle diameter and 7/32" diameter air jet. The air pressure was held at 100 psi and abrasive pressure at 5 psi. The gun was operated manually at an angle of 90° to the work. Complete data on introduced cleaning variables and cleaning results are shown in Table IX. Cleaning rates are for visibly clean specimens without resorting to microscopic examination. In nearly every case examination at 90X showed some adherent oxide particles at the bottom of pits or depressions.

Table IX

RESULTS OF CLEANING VARIABLES IN WET BLASTING
ZIRCALOY WITH FINE PARTICLES

Sample Number	Surface Condition	Type of Abrasive	Mesh Size	Cleaning Rate (in. ² /min)	Gun Distance (in.)	Microscopic Examination of Cleaned Surfaces
A1	Cold Rolled	Novaculite	325	18	1	Oxide in bottom of isolated pits. Some grit imbedded.
A2	Cold Rolled	Novaculite	625	15	1	Same as A1 above, perhaps slightly cleaner.
A3	Cold Rolled	Novaculite	1250	13	1	Oxide in all pits. Surface quite smooth.
A4	Cold Rolled	Brite Shot*	1900	15	1	Surface "peened." Insufficient metal removed to "expose" oxide in pits.
B1	Rolled at 850°C	Crushed Quartz	80	20	1-1/2	Quartz particles imbedded throughout. Oxide not all removed.
B2	Rolled at 850°C	Alumina	80	19	1-1/2	Alumina particles imbedded. Oxide not all removed.
B3	Rolled at 850°C	Crushed Quartz	140	14-1/2	1	Oxide imbedded in pits. All high spots clean.
B4	Rolled at 850°C	Alumina	220	8	1	Very few isolated spots of oxide in pits.
B5	Rolled at 850°C	Novaculite	200	6	1	Oxide in all pits.
B6	Rolled at 850°C	Novaculite	325	4-1/2	1	Oxide in bottom of isolated pits. Some grit imbedded.
B7	Rolled at 850°C	Silica Sand	50	8	1-1/2	Grit heavily imbedded.
B8	Rolled at 850°C	Brite Shot	1900	7	1	Clean surface.
B9	Rolled at 850°C	Brite Shot	1160	8-1/2	1	Fairly clean, but not quite as good as B8 above.

*Manufactured fused silica abrasive, spherical in shape, supplied by Vapor Blast Manufacturing Company.

From these tests it was concluded that a grit coarser than 100 mesh was unsatisfactory for cleaning Zircaloy-2, as too many foreign particles were imbedded in the surface, much the same as in sandblasting. For 850°C hot-rolled material, 220 mesh alumina and Brite Shot* produced the cleanest surfaces without becoming imbedded. The cleaning rate with these materials was faster than with novaculite. Neither the novaculite nor the Brite Shot, at cleaning rates tested, produced clean surfaces on cold-rolled material. Since alumina was the most economical abrasive, had a fast cleaning rate, and did not become imbedded in the surface, additional investigations were made using alumina to clean 850°C rolled and 600°C rolled strip stock with semiautomatic blast-cleaning equipment.

A wide variation, 1.9 mils to 6.9 mils, was noted in the thickness of the total oxide layer on 850°C rolled strip at various sections within the same piece of material. This variation is illustrated in the photomicrographs of Figure 19. Less variation, 0.4 to 0.7 mil, existed in oxide formed on 600°C rolling, as can be seen in Figure 20. Figure 20b also shows a crevice or fissure in the surface, which penetrated to a depth of 2.5 mils. Although coarser abrasives, 100 to 200 mesh, have a higher apparent cleaning rate than 400 mesh and finer, the smaller particle size of finer grits would be better able to penetrate the pits and crevice shown in Figure 20b. Cleaning tests for rolled strip combined initial cleaning with 100 mesh or 400 mesh grit with a second cleaning using 400 mesh grit, both with and without intermediate pickling. All cleaning was done on a modified B-20 Vapor Blast machine equipped for automatic cleaning of rolled sheet or strip. Three blasting nozzles, or guns, were attached to an hydraulically driven reciprocating arm to give a uniform cleaning pattern across the work. Material being cleaned traveled under the nozzles, which were mounted 2" above and at an angle of 60° to the work, on a variable speed, power-driven carriage. The gun travel was set at 2 sec/cycle with a $12\frac{1}{8}$ " long stroke. The grit concentration was maintained at 35 v/o in the water-abrasive slurry.

For 850°C rolled material a single cleaning with 100 mesh grit at rates as low as $31\frac{1}{2}$ sq in./min or with 400 mesh grit at 18 sq in./min failed to produce clean surfaces. The specimens blasted with 100 mesh grit at $31\frac{1}{2}$ sq in./min and reblasted with 400 mesh grit at 27 sq in./min with or without intermediate pickling in 35 v/o HNO₃-5 v/o HF were free from surface contamination, with the exception of a very few small black oxide particles in the deepest pits which were visible at 90X. With the intermediate pickle, double blasting with 400 mesh grit resulted in a microscopically clean surface. The optimum cleaning procedure for producing microscopically clean surfaces on 600°C rolled Zircaloy consisted of blasting with 400 mesh grit at 18 sq in./min, pickling in 35-5 acid, and reblasting with 400 mesh grit at 18 sq in./min. Samples of 850°C rolled material blasted more rapidly with 100 mesh grit at $67\frac{1}{2}$ sq in./min,

* Brite Shot is a manufactured 1900 mesh fused silica abrasive supplied by Vapor Blast Mfg. Co.

FIGURE 19. Transverse and Longitudinal Sections from 850°C Rolled Zircaloy-2 Showing Surface Oxide before Cleaning.

19a. Longitudinal section. Oxide layer 1.9 mils thick.

Oxide

Zircaloy-2

Micro 20424

Bright Field

100X

19c. Longitudinal section. Oxide layer 3.0 mils thick.

Oxide

Zircaloy-2

Micro 20427

Bright Field

100X

19b. Transverse section. Oxide layer 6.9 mils thick.

Oxide

Zircaloy-2

Micro 20425

Bright Field

100X

19d. Transverse section. Oxide layer 3.0 mils thick.

Oxide

Zircaloy-2

Micro 20426

Bright Field

100X

FIGURE 20. Longitudinal and Transverse Sections from 600°C Rolled Zircaloy-2 Showing Surface Oxide before Cleaning.

20a. Longitudinal section showing oxide surface 0.4 to 0.7 mils thick.

Oxide

Zircaloy-2

Micro 20688

Bright Field

200X

20b. Transverse section showing crevice type oxide penetration 2.5 mils thick.

Oxide

Zircaloy-2

Micro 20686

Bright Field

200X

pickled, reblasted with 400 mesh grit at $67\frac{1}{2}$ sq in./min, and rolled 50% reduction at 600°C were thoroughly cleaned by the above procedure for cleaning 600°C rolled strip. Strip which was cold finished from previously cleaned 850°C rolled strip was satisfactorily cleaned by degreasing and acid pickling.

Zircaloy-2 components from rolled and mechanically cleaned strip were degreased or acid dipped before being used for bond studies, cladding billets, or corrosion testing. Degreasing alone with acetone, trichloroethylene, or carbon tetrachloride did not provide sufficiently clean surfaces. Solutions of HNO₃ plus HF in three different concentrations were tried. Reaction and dissolution of Zircaloy-2 in a cold solution of 10 v/o HNO₃-2 v/o HF was very slow and produced a dull mat finish, mottled with a white fluoride deposit. A solution of 35 v/o HNO₃-5 v/o HF maintained between 35°C and 40°C effected a mild uniform attack desirable for controlling the rate of metal removed. This cleaning imparted high-temperature water corrosion-resistant surfaces. Zircaloy immersed for 15 to 20 seconds in a boiling solution of concentrated HNO₃ containing 1 v/o HF had a bright lustrous finish which proved to be most desirable for the preparation of bonding and cladding components. All acid cleaning was followed by a thorough rinsing in running tap water followed by a distilled water rinse.

A number of plate specimens used for Zircaloy-2 bond studies were diffusion treated in an attempt to dilute surface contaminants in the zirconium. Heating for 5 hours in a vacuum of 2×10^{-3} mm Hg at a temperature of 1400°C for five hours in a vacuum of 7×10^{-6} mm Hg at a temperature of 1100°C was not an acceptable substitute for surface machining or acid pickling to obtain sound Zircaloy to Zircaloy bonds. A higher diffusion temperature, better vacuum, or both, might have resulted in better diffusion of surface contaminants. The probable disadvantage of this treatment as reported by Rauch⁽²⁵⁾ would be loss of Zircaloy alloy additions due to vaporization.

In order to conserve material and minimize machining, rolled Zircaloy strip and plate from 1/8" to 1/4" thick was cut into component parts by shearing. Dimensional tolerances of ± 0.005 " in width or length could not be maintained unless the sheared edge was smooth and free from shatter cracks or tearing, a condition which seemed to prevail on both cold and warm-finished material. The induced diagonal shearing stresses, which are at a maximum in the plane inclined at an angle of 45° with the shearing plane, exceeded the elastic limit in compression. Consequently, cracks such as those shown in Figure 21a developed in 1/8" thick strip sheared across the rolling direction. Severe cracking and tearing appeared in 1/4" thick plate sheared parallel to the rolling direction, as shown in Figure 21b. On cold-finished plate, shatter cracks often extended from 1/4" to 3/4" from the sheared edge. A series of 1/4" thick plates rolled at 600°C

FIGURE 21. Shearing Defects in Zircaloy-2 Caused by Induced Diagonal Shearing Stresses.

21a. Crack along side of 1/8" thick 600°C rolled strip after shearing across the rolling direction.

Maximum induced stress developed 45° to the applied shearing stress.

Macro 19305

25X

21b. Tearing along side of 1/4" thick 600°C rolled plate sheared parallel to the rolling direction.

Macro 21377

1/2X

were heated in air for 5 minutes at 200°C, 300°C, 400°C, and 500°C, then sheared parallel to the rolling direction immediately after being removed from the furnace. At 400°C or above, the sheared edges were smooth and free from defects, as illustrated in Figure 22. Zircaloy with a lustrous finish, such as was obtained by acid pickling, could be heated in air for 10 minutes at 450°C without surface contamination or discoloration. Components sheared in this way were used either without machining or with a minimum of machining as needed to maintain desired length and width tolerances.

FIGURE 22. Edges of 600°C Rolled 1/4" Thick Zircaloy-2 Plate Heated 5 Minutes at 450°C and Sheared Parallel to the Rolling Direction. Sheared edges smooth and free from cracks, checks, or tears.

Macro 21376

1/2X

In addition to the previously discussed stringer-type inclusions noted in Zircaloy-2, several other structural defects contributed to the difficulties of securing sound metal for clad-plate development. Some rolled plates contained microcracks or fissures which could be identified independently of stringer inclusions. No correlation could be found between these defects and methods of fabrication. It is possible that defects developed from original ingot porosity or entrained gas which was not closed by subsequent hot working. Shallow surface cracks were removed by grinding after rolling at 850°C. Finished components which showed defects were rejected. Hard metallic inclusions, some of which were as large as 1/8" in diameter (Figure 23), were found in the face clad of several roll-clad plates. These inclusions were identified as tungsten by spectrographic analysis and were not deformed by rolling at 850°C as long as they were completely embedded in the Zircaloy. Tungsten

inclusions are believed to have originated from tungsten electrodes used for heli-arc welding the primary sponge consumable electrode for Zircaloy ingots. Inclusions as small as 0.005" diameter could be located in rolled material by radiograph inspection.

FIGURE 23. Tungsten Inclusion in 850°C Rolled Zircaloy-2 Slab.

Macro 20415

5X

Preparation of Protective Steel Jackets for Cladding Billets

A sealed protective jacket was placed around all cladding billets to minimize contamination of the component surfaces during heating and rolling. Ideally, this jacket should perform the following functions:

1. Seal out oxygen and nitrogen from the atmosphere.
2. Deform uniformly with the cladding components at roll-bonding temperatures.
3. Avoid contaminating Zircaloy-2 by diffusion or alloying.

4. Provide a minimum of outgassing at roll-bonding temperatures.
5. Restrain the sides of billet components during rolling.
6. Have the same coefficient of expansion as Zircaloy-2.
7. Be economical and easy to fabricate.

Although no material was available which would fulfill all of these requirements, the plain low carbon steels satisfied most of them. Practically all of these steels could be expected to outgas some at 850°C. Some alloying of iron with zirconium might also be expected at this temperature. The coefficient of expansion for low carbon steel is more than twice that for Zircaloy-2 ($16.0 \times 10^{-6}/^{\circ}\text{C}$ for steel as compared with $6.6 \times 10^{-6}/^{\circ}\text{C}$ for Zircaloy-2 from room temperature to 800°C). Superficial surface contamination from steel outgassing or alloying might be tolerated if the rolled fuel plates could be adequately cleaned for water corrosion resistance. Proper design of the protective jacket and cladding components could compensate for differential expansion of the jacket on heating and for width spread on rolling. Steels used for jackets on development plates were hot-rolled Ti-Namel, a low carbon titanium-killed steel; hot rolled ASTM A7-52T structural steel for bridges and buildings; and hot and cold-rolled SAE 1018 and SAE 1020, low carbon steels.

The modified picture frame billets prepared for zirconium-clad uranium plates⁽⁸⁾ were rolled in a built-up jacket made by welding side rails and one end plug between flat plates. These billet components before assembly are illustrated in Figure 24a and as welded in Figure 24b. The strength of the welds between the cover plates and the side rails plus friction between the side rails and covers during rolling offered insufficient lateral restraint to the cladding billet during rolling to provide adequate control over the finish-rolled plate width or to facilitate bonding between the core and cladding along the side. By machining a rectangular slot on one side of both flat plates, the sides of the jackets could be made an integral part of the cover, as in Figure 25, minimizing lateral spread. For cylindrical billets rolled in shaped passes, seamless steel tubing provided a protective jacket of uniform wall thickness. The ends of all jackets were sealed with preshaped plugs welded in place.

The surfaces of most machined steel jackets were used either as machined or as cleaned by degreasing in trichloroethylene. Some jackets were outgassed after degreasing by heating two hours at 900°C in a vacuum of 1 to 2 microns.

Equipment Used for Development of Clad Fuel Plates

Beginning with raw materials for the uranium alloy core castings, forged Zircaloy-2 slabs, and rolled steel bars for jacket material, all fabrication of components and development of plates was done with facilities

FIGURE 24. Protective Cladding Billet Jacket with
Welded between Flat Plates

24a. Billet components before assembly

24b. Welded cladding billet jacket

FIGURE 25. Protective Cladding Billet Jacket with
Sides Integral with the Covers

available at ANL. Operations included melting and casting, heating for rolling, rolling, shearing, cleaning, billet assembly, heat treating, testing and evaluation, and inspection. All machining and most welding was done with standard shop equipment. Modified arc welding equipment was developed for cladding billet end closures.

Detailed descriptions of melting and casting facilities⁽²⁰⁾ and mill fabrication facilities⁽⁸⁾ are available in other publications. Equipment alterations and additions to permit increased production and mechanized handling for EBWR fuel plate production were tested with experimental plates scaled to the size of EBWR fuel plates. This equipment for cleaning, billet assembly, welding, handling and rolling, and heat treating, is described in another report.⁽²⁴⁾

Clad-plate evaluations were based on conventional metallographic and mechanical testing procedures in addition to special facilities for non-destructive testing,^(17,18) irradiation testing,⁽¹⁵⁾ and high-temperature water and steam corrosion testing. Corrosion testing was performed by the Reactor Engineering Division in sealed autoclaves equipped with self-contained heating elements.

ZIRCALOY-2 TO ZIRCALOY-2 ROLL-BOND DEVELOPMENT

Preparation of Test Specimens, Roll Bonding, and Evaluation Procedure

One requisite of the modified picture frame process for clad-bonding fuel plates is a sound metallurgical or diffusion bond at all Zircaloy-to-Zircaloy interfaces. For water-cooled fuel plates containing a core alloy which is not corrosion resistant, it is imperative that no discontinuity or corrodible substance remain in the bond line. For plates prepared with an integral end closure, the same requirement obtains for the Zircaloy end plug bond interfaces. A group of Zircaloy-to-Zircaloy bond tests were undertaken to learn more about the effects of Zircaloy preparation on bonding and the possibility of implementing a bond with other metals in the interface under fabricating conditions which might be expected for roll-cladding fuel plates.

The Zircaloy used for 27 bond tests was hot rolled at 850°C to 0.275" thick from forged ingot No. 5Y345, cleaned by wet blasting with 325 mesh Al_2O_3 grit to remove visible oxide contamination, and cold finished to 0.250" thick. Roll-bonding specimens were cold sheared 1/4" oversize on width and length and finish machined to $1.225" \pm 0.005"$ wide x $2.750" \pm 0.005"$ long. Bonding surfaces were cleaned by several mechanical and chemical methods, including machining, sandblasting, wet abrasive grit blasting, degreasing, acid pickling, and caustic dipping. A previously discussed surface treatment for diluting surface contamination by diffusion in zirconium at temperatures of 1100°C and 1400°C in vacuum was applied to five of these test specimens. Two others were heated for two hours from 850°C to 1000°C in a vacuum of 4×10^{-6} mm Hg to remove possible hydrogen contamination. Details of surface preparation for each test are summarized in Table X.

Because of the high activation energy generally required to promote self-diffusion in metals, six test plates were prepared with metallic coatings or foils in the interface, which were expected to have a higher diffusion rate with Zircaloy than the self-diffusion rate for Zircaloy. Mating surfaces were prepared by tinning, copper plating, and nickel plating for three test specimens; 0.001" thick niobium foil was introduced in one specimen, and 0.001" thick copper foil was introduced in the remaining two.

The Zircaloy surfaces for bond test No. 16 were tinned by heating in air to a temperature of 300°C, coating with SnCl_2 , and holding at temperature until the surface was uniformly coated with molten tin. Excess SnCl_2 volatilized along with the ZrCl_2 formed, leaving a bright metallic coating. Light wire brushing while still hot improved the contact and distribution of the tin on the surface. Material for test plate 17 was electroplated with copper in a copper sulfate-sulfuric acid plating bath containing 219 grams/liter of $\text{CuSO}_4 \cdot 5 \text{H}_2\text{O}$ and 52 grams/liter of H_2SO_4 at a temperature of 40°C

TABLE X
ROLL BOND TESTS - ZIRCALOY-2 BONDED TO ZIRCALOY-2

Test No.	Zircaloy-2 Preparation			Rolling Variables		Microexamination
	Mechanical Cleaning	Chemical Cleaning (1)	Other Treatment	Temp. (°C)	Reduct. (%)	
1	As cold rolled.	Degreased with acetone	5 hr at 1400°C in vacuum 1×10^{-3} mm Hg.	800	80	Complete lack of bond.
2	0.010" removed by machining.	Degreased with acetone	5 hr at 1400°C in vacuum 1×10^{-3} mm Hg.	800	80	Small continuous inclusions throughout interface.
3	One piece as cold rolled, other machined.	Degreased with acetone	Machined piece only same as 1 & 2 above.	800	80	Segmented inclusions throughout interface.
4	Same as 3 above, both sandblasted with 46 mesh Al_2O_3 .	None	Machined piece only same as 1 & 2 above.	800	80	Profuse semicontinuous line of inclusions.
5	As cold rolled, sandblasted with Al_2O_3 .	None	None	800	80	Profuse semicontinuous line of large inclusions.
6	As cold rolled, sandblasted with Al_2O_3 .	10-sec dip in boiling conc. HNO_3 + 1 v/o HF.	None	800	80	Profuse semicontinuous line of small inclusions.
7	As cold rolled, sandblasted with Al_2O_3 .	5-min dip in cold 10 v/o HNO_3 + 2 v/o HF.	None	800	80	Profuse segmented inclusions throughout interface.
8	As cold rolled, sandblasted with Al_2O_3 .	5-min dip in cold 10 v/o HNO_3 + 2 v/o HF.	None	800	90	Similar but thinner inclusions than in 7 above.
9	0.018" removed by machining.	Degreased with carbon tetrachloride.	None	850	80	Excellent bond. No inclusions visible.
10	0.018" removed by machining.	Degreased with carbon tetrachloride.	5 hr at 1100°C in vacuum 7×10^{-6} mm Hg.	800	90	Good bond. A few thin segmented inclusions in interface.
11	0.025" removed by machining. Wet blasted 400 mesh Al_2O_3 .	None	None	850	80	Continuous band of fine dispersed inclusions.
12	0.025" removed by machining. Wet blasted 400 mesh Al_2O_3 .	30-min dip in cold 10 v/o HNO_3 + 2 v/o HF.	None	850	80	Intermittent segmented inclusions throughout interface.
13	0.025" removed by machining. Wet blasted 400 mesh Al_2O_3 .	30-sec dip in 35 v/o HNO_3 + 5 v/o HF at 40°C.	None	800	80	Semicontinuous line of inclusions in one area only.
14	0.025" removed by machining. Wet blasted 400 mesh Al_2O_3 .	30-sec dip in 35 v/o HNO_3 + 5 v/o HF at 40°C.	None	850	80	Good bond. A few short segmented inclusions in bond.
15	0.025" removed by machining. Wet blasted 400 mesh Al_2O_3 .	15-min dip in 1/2 normal NaOH at 80°C.	None	850	80	Semicontinuous line of inclusions throughout interface.
16	0.019" removed by machining.	10-sec dip in boiling conc. HNO_3 + 1 v/o HF.	Surface tinned by deposition from $SnCl_2$.	800	80	Large voids and semicontinuous line of inclusions at interface.
17	0.025" removed by machining.	45-sec dip in NH_4F + HF at 100°F.	Copper plated.	850	80	Large semicontinuous inclusions of Cu at interface.
18	0.025" removed by machining.	45-sec dip in NH_4F + HF at 100°F.	Nickel plated.	850	80	Cracks and large inclusions at interface.
19	0.025" removed by machining.	45-sec dip in NH_4F + HF at 100°F.	0.001" Cu foil in interface.	800	80	Inclusions of Cu at interface similar to 17 above.
20	0.025" removed by machining.	45-sec dip in NH_4F + HF at 100°F.	0.001" Cu foil in interface.	800	90	Inclusions of Cu at interface similar to 17 above.
21	0.025" removed by machining.	45-sec dip in NH_4F + HF at 100°F.	0.001" Nb foil in interface.	850	80	Uniformly distributed layer of Nb. A few inclusions at Zr to Nb interface.
22	As cold rolled. Wet blasted 400 mesh Al_2O_3 .	10-sec dip in boiling conc. HNO_3 + 1 v/o HF.	None	850 ⁽²⁾	80	Fine segmented inclusions in some areas.
23	As cold rolled.	30-sec dip in boiling conc. HNO_3 + 1 v/o HF.	None	850	80	Excellent bond. No inclusions visible.
24	As cold rolled.	30-sec dip in boiling conc. HNO_3 + 1 v/o HF.	5 hr at 1100°C in vacuum 7×10^{-6} mm Hg.	800	80	Semicontinuous line of small inclusions at interface.
25	As cold rolled.	30-sec dip in boiling conc. HNO_3 + 1 v/o HF.	5 hr at 1100°C in vacuum 7×10^{-6} mm Hg.	800	90	Same as No. 24 above.
26	As cold rolled.	30-sec dip in boiling conc. HNO_3 + 1 v/o HF.	2 hr from 850°C-1000 °C vacuum 4×10^{-6} mm Hg.	800	80	Excellent bond. No inclusions visible.
27	As cold rolled. Wet blasted 140 mesh Al_2O_3 .	30-sec dip in boiling conc. HNO_3 + 1 v/o HF.	2 hr from 850°C-1000 °C vacuum 4×10^{-6} mm Hg.	850	80	Excellent bond. No inclusions visible.

(1) All acid and caustic-treated specimens were rinsed in running tap water followed by a rinse in distilled water and air dried.

(2) Reheat time between passes increased from 5 minutes to 30 minutes for Test No. 22.

and a current density of 35 amp/ft². Zircaloy for test plate 18 was electroplated with nickel in a nickel sulfate-nickel chloride-boric acid bath containing 330 grams/liter of NiSO₄ · 7H₂O, 46 grams/liter of NiCl₂ · 6H₂O, and 36 grams/liter of H₃BO₄ at a temperature of 60°C and a current density of 40 amp/ft².

The strips of Zircaloy prepared for roll bonding were pressed together with an applied load of 18 tons/in.² between water-cooled copper platens. The edges on all four sides were then sealed by inert-gas tungsten-arc welding. Welded specimens were sheathed in machined Ti-Namel steel jackets to minimize surface contamination during rolling. Details of the Ti-Namel jacket are shown in Figure 26.

FIGURE 26. Ti-Namel Jacket Used for Sheath Rolling Zircaloy-2 Roll Bond Specimens.

Jacketed Zircaloy specimens were heated one hour prior to rolling. Except for test specimen No. 22, all were reheated five minutes between passes. No. 22 was reheated 30 minutes between passes. Rolling temperatures of 800°C and 850°C and total reductions of 80% and 90% were used, as shown in Table X. Uniform reductions of 17% per pass were made at a roll speed of 125 ft/min. Reductions on rolling and rolling temperatures selected were those which gave best results on concurrent roll-clad core alloy investigations.

Rolled plates were air cooled and the bond specimens were extracted from the steel jacket by shearing excess steel from the sides and ends. Metallographic examinations and representative photomicrographs were made from polished and etched sections of the bond interfaces. Plate No. 15, rolled from components whose bonding surfaces were cleaned by wet blasting followed by a 15-minute soak in 1/2 normal NaOH at 80°C and water rinsed, was sectioned for corrosion testing in water at 315°C. Measurements of ultimate bond strength in tension were made on various bonds representing gradations of poor to good quality bonds as determined by metallographic examination. Tensile test specimens were prepared by percussion welding two 1/4" diameter Zircaloy-2 studs to the plate in a fixture which positioned the studs normal to the plate surface and directly opposite and parallel to each other on both sides of the clad plate. The welded studs and bond specimen were machined to 0.200" diameter to eliminate possible shearing stress due to misalignment of the studs in tension.

Discussion of Results

Data compiled from the examination of Zircaloy-to-Zircaloy roll bonds, Table X, indicated that absolute cleanliness of the mating surfaces was the most important single factor in obtaining satisfactory diffusion bonds. Contamination generally shows in bonds as microscopic inclusions but may occur as gross inclusions.

Of the various surface preparations tried, over-all machining accompanied by degreasing with CCl_4 , or thorough acid pickling of either clean cold-finished or wet abrasive-blasted plate produced the only completely sound roll bonds. Photomicrographs of sections from rolled plates 9, 23, and 27 in Figures 27a, 27b, and 27c show sound Zircaloy bonds. Final cleaning by sandblasting cold-rolled plate or wet abrasive-blasting machined plate, test plates 5 and 11, introduced contaminants in the form of abrasive grit, which appeared as bond line inclusions (Figures 28a and 28b). Sandblasted and wet abrasive-blasted material which was acid dipped in either 35 v/o HNO_3 -5 v/o HF or 10 v/o HNO_3 -2 v/o HF showed considerable improvement in the bond as sections from test plates 12 and 14 (Figures 29a and 29b) show. The 35-5 acid apparently did a more thorough cleaning job than did the 10-2 acid.

FIGURE 27. Sound Zircaloy-2 to Zircaloy-2 Diffusion Bonds in Test Specimens Rolled 80% Reduction in Thickness at 850°C.

27a. Section from plate No. 9. Components prepared by machining all over and degreasing in CCl_4 .

Micro 17486

Bright Field

250X

27b. Section from plate No. 23. Components cold rolled and cleaned by 30-sec dip in boiling concentrated HNO_3 containing 1 v/o HF acid, water rinsed.

Micro 20767

Bright Field

250X

27c. Section from plate No. 27. Components cold rolled and cleaned by wet abrasive blasting with 140 mesh alumina followed by 30-sec. dip in boiling concentrated HNO_3 containing 1 v/o HF acid and water rinsed.

Micro 20768

Bright Field

250X

74
FIGURE 28. Zircaloy-2 Bond Line Inclusions.

28a. Section from test plate No. 5 showing large inclusions. Components cold rolled and sand blasted with 46 mesh alumina.

Micro 16756

Bright Field

250X

28b. Section from test plate No. 11 showing a continuous band of fine dispersed inclusions. Components machined all over and wet abrasive blasted with 400 mesh alumina.

Micro 17488

Bright Field

250X

FIGURE 29. Zircaloy-2 Bond Line Inclusions.

29a. Section from test plate No. 12 showing string of inclusions in the bond line. Components machined all over, wet abrasive blasted with 400 mesh alumina, acid pickled 5 minutes in cold 10 v/o HNO_3 -2 v/o HF acid.

Plate
Bond →

Micro 17496

Bright Field

250X

29b. Section from test plate No. 14 showing segmented inclusions in the bond line. Components machined all over, wet abrasive blasted with 400 mesh alumina, acid dip 30 sec in 35 v/o HNO_3 -5 v/o HF acid at 35°C.

Plate
Bond →

Micro 17491

Bright Field

250X

Bond surfaces dipped in 1/2 normal NaOH to remove surface contamination without dissolving metal also showed contamination in the form of semicontinuous inclusions in the interface after roll bonding (Figure 30). Cracks developed along the bond interface of this plate, No. 15, after three days of corrosion testing in water at 315°C.

FIGURE 30. Zircaloy-2 Bond Line Inclusions.

Section from test plate No. 15 showing semicontinuous inclusions in the bond line. Components machined all over, wet abrasive blasted with 400 mesh alumina, immersed 15 min in 1/2 normal NaOH at 80°C, and water rinsed.

Vacuum heating bond specimens at 1100°C and 1400°C to dissolve surface contaminants did not improve the roll bonds as all showed varying amounts of segmented inclusions. Heating at 850°C to 1000°C to remove hydrogen had no measurable effect on the roll bond. Comparison between the bonds of plate Nos. 23 and 26, rolled with unheat-treated and heat-treated components, respectively, indicated that this treatment did not improve or facilitate bonding.

All bond tests with introduced metallic films showed varying degrees of contamination at the interface. With the exception of plate 21, rolled with 0.001" thick niobium foil in the interface, the introduced metals

segregated with no metallographic evidence of having diffused into the Zircaloy. The bond interface from specimens prepared with 0.001" thick copper foil contained the same type of copper inclusions as the specimen prepared with copper-plated surfaces. Niobium was uniformly distributed throughout the interface and, except for a few inclusions in the Zircaloy to niobium bond, a good diffusion bond was obtained. Representative bond sections from these plates are illustrated in Figure 31.

No significant improvement in roll bonds could be noted as a result of rolling at temperatures of 850°C instead of 800°C or in reductions of 90% instead of 80%. Bond line inclusions were thinner after 90% reduction but were still dispersed over the same total area of the interface. Increasing the reheat time between passes from 5 minutes to 30 minutes for test plate No. 22 did not improve the quality of the bond.

Results of bond tensile measurements, Table XI, showed good correlation between metallographically observed bond line defects and bond strength. The defects observed in most bonds have been generally referred to as inclusions. Since they do not contribute measurably to bond strength, they are probably nonmetallic contaminants or voids. The ultimate tensile strength of sound bonds free from contamination was in excess of 70,000 psi, comparable to the strength of hot rolled Zircaloy-2 used for roll bonding stock.

Table XI

ZIRCALOY-2 ROLL BOND TENSILE TEST DATA

Test No.	Metallographic Examination of Bond Interface	Ultimate Strength in Tension (psi)
18	Cracks and large inclusions of nickel at interface	770
4	Profuse semicontinuous line of inclusions	16,700
7	Profuse segmented inclusions	17,250
8	Slightly thinner line of profuse segmented inclusions than in 7 above	18,100
17	Semicontinuous inclusions of copper	19,800
20	Inclusions of copper at interface	20,980
6	Profuse semicontinuous line of small inclusions	42,000
16	Voids and semicontinuous line of inclusions at interface	44,100
24	Semicontinuous line of small inclusions	51,750
10	Good bond - Few thin segmented inclusions	71,000
26	Excellent bond - No inclusions visible	79,200

FIGURE 31. Zircaloy-2 Bonds in Test Plates Prepared with a Metallic Coating or Foil at the Interface.

31a. Mating surfaces of test specimens prepared by tinning. Large voids and semi-continuous inclusions in bond.

Micro 16821 Bright Field 250X

31b. Mating surfaces nickel plated. Cracks and large inclusions in bond.

Micro 17489 Bright Field 250X

31c. Copper foil placed between the mating surfaces. Inclusions of copper in bond.

Micro 20770 Bright Field 250X

31d. Niobium foil placed between the mating surfaces. Uniform distribution of niobium throughout the bond.

Micro 17493 Bright Field 250X

DEVELOPMENT OF BOND BETWEEN ZIRCALOY-2 AND URANIUM-5 w/o ZIRCONIUM-1.5 w/o NIOBIUM ALLOY

Bonds Established by Rolling in Shaped Roll Passes

Roll bonding in shaped passes offers several advantages over rolling a flat cladding billet with built-up components. The principal advantages may be summarized as follows:

1. Greater variety in cross section of finish rolled shapes, such as rounds, squares, ovals, or flats.
2. Simplified billet assembly in which the core may be cast or fitted to an extruded or drawn cylindrical cladding jacket.
3. Possibility of obtaining a cast bond between the core and jacket.
4. More uniform working of all surfaces on rolling due to increased roll surface area in contact with the billet.
5. Greater probability of ensuring a side bond on shapes finished to flat plates.

Billets Rolled in Hand-Round Shaped Roll Passes

Two groups of cylindrical billets, one prebonded by casting and the other assembled from machined components, were prepared for roll bonding in the hand round roll passes illustrated in Figure 32. The prebonded billets were prepared by casting uranium-5 w/o zirconium-1.5 w/o niobium alloy core material into $1/8$ " wall, $1\frac{1}{4}$ " O.D. x $6\frac{1}{4}$ " long Zircaloy-2 cans.⁽¹⁹⁾ One end of each billet was sealed during casting with the $3/8$ " thick Zircaloy-2 can bottom. The other end was open with the core alloy exposed. Billets were rolled out of carbonate salt (Houghton 235, manufactured by E. F. Houghton & Co.) without protective steel jackets around the Zircaloy. Rolling data are given in Table XII. In rolling, the closed end of the billet entered the rolls first, with the result that some of the core alloy mushroomed out of the tail end of the billet. This effect was pronounced at the higher rolling temperatures but was barely noticeable at 750°C , indicating a closer match between the workability of the two materials at this temperature. Sections taken from these rolled billets had a fairly uniform reduction and thickness of the cladding material. A cross section of rolled billet 1005, Figure 33a, shows the distribution of the core and cladding after rolling 93.5% reduction in cross-sectional area at 850°C . Rolled rods from cast prebonded billets were completely diffusion bonded. A typical cladding to core interface is shown in the photomicrograph of 1005 in Figure 33b.

FIGURE 32. Hand Round Roll Set for 9 x 16 Mill.

FIGURE 33. Zircaloy-2 Bonded to Uranium-5 w/o Zirconium-1.5 w/o Niobium by Rolling in Hand-Round Roll Passes.

33a. Cross section of roll clad rod showing configuration of core and distribution of clad.

Macro 20913

10X

33b. Bond between clad and core in roll clad rod. Dark band at the interface is part of the diffusion layer, not a void.

Zircaloy-2
Clad

Diffusion Layer

Uranium Alloy
Core

Micro 20912

Bright Field

250X

Table XII

ROLLING DATA FOR CYLINDRICAL BILLETS ROLLED
IN HAND ROUND PASSES

Billet No.	Rolling Temperature (°C)	Final Diameter (in.)	Reduction (%)
1005	850	0.320	93.5
1006-A	750	0.849	54.0
1006-B	750	0.539	81.5
1007-A	775	0.849	54.0
1007-B	775	0.539	81.5
1009-A	800	0.849	54.0
1009-B	800	0.539	81.5

Rolled rods, 0.849" dia. and 0.539" dia. from billets 1006, 1007 and 1009, were flat rolled out of carbonate salt at 750°C, 775°C, and 800°C, respectively. The larger diameter rods were reduced 63% in cross-sectional area, the smaller rods 42.5%, with reductions of 20% per pass. All specimens showed complete bonding between the cladding and core on the flat surfaces as well as along the sides. Thicknesses of the diffusion layer on the flat surfaces varied from 0.3 mil to 0.7 mil and at the sides from 0.4 mil to 0.9 mil. The rolled strips were uniform in width and thickness, with the least amount of lateral spread occurring at the lowest rolling temperature, as may be seen from the dimensions given in Table XIII. Cladding thickness measurements were taken on both sides of the rolled strips at 0.100" intervals across the width from sections taken at three equally spaced intervals along the length. Cladding analyses based on these measurements are summarized in Table XIV.

Table XIII

FINISHED DIMENSIONS OF COMBINATION HAND
ROUND AND FLAT ROLL CLAD STRIP

Billet No.	Rolling Temp. (°C)	Finished Width (in.)		Ave. Width Spread (%)	Finished Thickness (in.)	
		Max.	Min.		Max.	Min.
1006-A	750	1.405	1.375	63.8	0.153	0.149
1006-B	750	0.893	0.878	64.3	0.149	0.146
1007-A	775	1.427	1.420	68.0	0.147	0.146
1007-B	775	0.902	0.888	66.1	0.149	0.143
1009-A	800	1.418	1.404	66.1	0.152	0.146
1009-B	800	0.920	0.908	69.7	0.151	0.146

Table XIV

CLADDING THICKNESS ANALYSIS ON COMBINATION
HAND ROUND AND FLAT ROLL CLAD STRIP

Cladding Billet No.	Cladding Measurements (mils)				Min. Clad Thickness
	Avg.(1) Thickness	Avg.(2) Deviation	Range of Deviation(3)	Avg.(4) Variation	
1006-A	25.0	2.5	+5.1 to -7.4	3.1	17.6
1006-B	22.8	3.0	+4.8 to -11.8	4.0	11.0
1007-A	25.9	2.6	+5.2 to -5.7	3.1	20.2
1007-B	22.2	3.3	+4.4 to -7.6	4.8	14.6
1009-A	25.1	3.0	+4.3 to -7.6	2.9	17.5
1009-B	22.1	4.2	+5.6 to -8.5	4.7	13.6

- (1) Determined by averaging thickness measurements taken at 0.100" intervals across both sides of three sections, equally spaced along the length of bar.
- (2) Determined by summing the differences between average clad thickness and each measurement, and dividing by the total number of measurements.
- (3) Greatest positive and negative deviation observed.
- (4) Sum of differences between each pair of measurements divided by number of individual variations determined.

Four cylindrical billets were assembled from machined components and rolled in hand-round passes. Dimensions of the billet components are given in Table XV. The cans and top plugs were machined from Zircaloy forged from Ingot 710D443 and the cores were machined from rolled casting No. L-24. All components were degreased in trichloroethylene before being assembled. The top plug was sealed by inert-gas shielded-arc welding and the billets rolled to 0.322" diameter out of carbonate salt at 775°C. No bonds were obtained on any of these billets due to contamination of the clad-to-core interface which resulted from air entering the billet through cracks in the end plug welds.

Billets Rolled in Oval-Edge-Oval and Open-Square Shaped Roll
Passes

Six $1\frac{1}{4}$ " O.D. cylindrical cladding billets were rolled in the oval-edge-oval passes illustrated in Figure 34, one 3" O.D. cylindrical billet was rolled in the oval-edge-oval passes illustrated in Figure 35, and another was rolled in the open-square passes illustrated in Figure 36. After shaped pass rolling to obtain complete bonding on all sides, all billets were flat rolled to strip or plate.

FIGURE 34. Oval-Edge-Oval Roll Set for 9 x 16 Mill.

ROLLING SCHEDULE					
ENTER 1 1/2" @ 17671"					
PASS	AREA	RED	PASS	AREA	RED.
A	1.27"	28%	A	1.27"	28%
B	1.04"	18%	B	1.04"	18%
C	.76"	25%	C	.76"	25%
D	.61"	21.6%	D	.61"	21.6%
E	.51"	16.5%	E	.51"	16.5%
F	.41"	13.2%	F	.41"	13.2%
G	.31"	10.0%	G	.31"	10.0%
H	.21"	7.7%	H	.21"	7.7%
I	.11"	4.4%	I	.11"	4.4%
J	.01"	0.0%	J	.01"	0.0%

FIGURE 35. Oval-Edge-Oval Roll Set for 16 x 24 Mill.

FIGURE 36. Open-Square Roll Set for 16 x 24 Mill.

Table XV

DIMENSIONS OF COMPONENTS FOR CYLINDRICAL BILLETS
ROLLED IN HAND ROUND PASSES

Component	Billet No. R-1	Billet No. R-2	Billet No. R-3	Billet No. R-4
Zircaloy Can Length (in.)	4.0	4.0	4.0	4.0
Zircaloy Can Outside Dia. (in.)	0.751	0.750	0.750	0.750
Zircaloy Can Inside Dia. (in.)	0.494	0.485	0.480	0.485
Zircaloy Can Bottom Thickness (in.)	0.500	0.500	0.500	0.500
Zircaloy Can Top Plug Thickness (in.)	0.500	0.500	0.500	0.500
Zircaloy Can Top Plug Dia. (in.)	0.489	0.482	0.477	0.482
Alloy Core Diameter (in.)	0.464	0.471	0.477	0.482
Alloy Core Length (in.)	3.0	3.0	3.0	3.0
Foil at Interface	0.012" Thick Niobium	0.005" Thick Crystal Bar Zr	None	None

Core alloys for the first six billets were machined to 1" diameter bars, assembled in machined 1/8" wall Zircaloy-2 tubes, 6" long, and sealed with 1/2" thick welded end plugs of Zircaloy-2. Fabrication data for both shaped pass rolling and flat rolling are given in Table XVI. Three billets were rolled without protective steel jackets for the Zircaloy and the remaining three were rolled in machined 1/8" thick wall Ti-Namel steel sheaths. Bars with protective Ti-Namel sheaths could not be finish rolled due to thinning and separation of the steel from the Zircaloy on flat rolling. Sections of billet Nos. 1 and 4 after oval-edge-oval rolling are shown in Figure 37.

Table XVI

ROLLING SCHEDULE FOR CYLINDRICAL BILLETS ROLLED
IN OVAL-EDGE-OVAL PASSES FOLLOWED BY FLAT ROLLING

Cladding Billet No.	Alloy Core Composition (w/o)	Alloy Core Casting No.	Jacket	Rolling Temp. (°C)	Dimensions After O.E.O. Rolling (in.)		Red. in Area on O.E.O. Rolling (%)	Dimensions After Flat Rolling (in.)		Red in Area on Flat Rolling (%)
					Major Dia.	Minor Dia.		Thickness	Width	
1	U-5 w/o Zr-1.5 w/o Nb	L-24	None	850	1.155	0.652	43.7	0.132	1.498	71.5
2	U-6 w/o Nb	L-34	None	850	Cladding Ruptured During Rolling					
3	U-3 w/o Nb	L-36	None	850	1.175	0.652	42.3	0.130	1.539	71.8
4	U-5 w/o Zr-1.5 w/o Nb	L-24	Ti-Namel	850	1.060	0.550	54.5	0.128	1.502	65.5
5	U-6 w/o Nb	L-34	Ti-Namel	850	1.040	0.535	56.4	0.136	1.399	64.6
6	U-3 w/o Nb	L-36	Ti-Namel	850	1.050	0.545	55.3	0.131	1.531	63.7

A sound metallurgical bond was obtained after oval-edge-oval rolling on all clad uranium-3 w/o niobium and uranium-6 w/o niobium alloy core material. The clad uranium-5 w/o zirconium-1.5 w/o niobium rolled without a protective steel jacket was not completely bonded after oval-edge-oval rolling, and the same clad alloy rolled in a Ti-Namel jacket had a brittle bond which could easily be broken. A wide range existed in

FIGURE 37. Sectioned Bars Rolled in Oval-Edge-Oval Passes Showing Distribution of Alloy Core, Clad, and Steel Jacket. Top bar rolled in Ti-Namel steel jacket, bottom bar rolled bare.

106-1447

FIGURE 38. Zircaloy-2 Bonded to Uranium-5 w/o Zirconium-1.5 w/o Niobium by Combination Rolling in Oval-Edge-Oval Shaped Pass Rolls Followed by Flat Rolling.

Zircaloy-2
Cladding

Diffusion
Layer

Uranium Alloy
Core

Micro 20914

Bright Field

250X

the cladding thickness of rolled bars, although those rolled without protective steel jackets were more uniform. Cladding thickness measurements from three sections along the length of bar No. 1, with measurements taken at $1/8$ " intervals around the periphery of each section, varied from 0.070" to 0.090" with an average of 0.079", compared with a range of 0.057" to 0.105" and an average of 0.069" for bar No. 4. The average thickness variation between each $1/8$ " interval on bar No. 1 was 4.9 mils and on bar No. 4 it was 10.2 mils. The finished dimensions for flat rolled bars without protective jackets are included in Table XVI. All bonds were sound after final flat rolling. A section of clad-to-core bond from finish rolled billet No. 1 is shown in Figure 38.

Two 3" diameter cylindrical billets, Nos. 61 and 62, were assembled for oval-edge-oval and open-square pass rolling. The billets were designed to be finish rolled to plates 2.77" wide x 0.375" thick with 0.020" of Zircaloy-2 clad on the sides and faces. Components were machined and assembled as detailed in Figure 39. The cores were machined from uranium alloy casting No. L-88, which contained 4.20 w/o zirconium and 1.40 w/o niobium by analysis. Machined cores were sandblasted with alumina grit just prior to assembly in the Zircaloy jacket. All Zircaloy-2 was prepared from forged and hot-rolled slab from Ingot 710D443. Zircaloy end caps were machined from hot-rolled plate, and the Zircaloy sleeves were formed from 0.100" thick cold-rolled sheet. The formed sheet was cleaned by wet abrasive blasting with 325 mesh alumina, followed by pickling in boiling nitric acid containing 1 v/o hydrofluoric acid. The alloy core and Zircaloy end caps were assembled in the Zircaloy sleeve, and the assembly was placed in an argon-flooded box for welding. The welding detail with Zircaloy filler strip is also shown in Figure 39. Commercial 3" seamless mechanical tubing of low carbon steel with a $1/8$ " wall was used for protective steel jackets during heating and rolling. A 15° tapered nose plug machined from SAE 1020 steel was welded into one end of the billet to facilitate entry into the desired roll pass on rolling. Steel jackets and plugs were degreased in trichloroethylene before assembly and final welding.

Both billets were preheated in air one hour at 775°C for shaped pass rolling with intermediate reheating of 10 minutes between passes. The billets were reheated in carbonate salt an additional hour prior to flat rolling. Reduction on shaped pass and flat rolling, and rolled dimensions are given in Table XVII. Since there were no bonding of the steel to the Zircaloy during rolling, the steel end plugs drifted away from the billet after 50% reduction on shaped pass rolling. The thinner steel jackets later ruptured and were removed before the billets were flat rolled.

FIGURE 39. Component and Assembly Details for 3" Diameter Cylindrical Billets Rolled in Shaped Passes.

Table XVII

REDUCTIONS ON ROLLING AND FINISHED DIMENSIONS OF ROLL CLAD PLATES
ROLLED IN SHAPED PASS ROLLS FOLLOWED BY FLAT ROLLING

Rolling Procedure	Billet Number 61 Oval-Edge-Oval	Billet Number 62 Open-Square-Passes
Total reduction on shaped pass rolling (%)	65.88	55.56
Reduction/pass on shaped pass rolling (%)	7-20	6-12.6
Cross section as rolled in shaped pass (inches)	2.060 x 1.152	1.843 x 1.843
Total reduction on flat rolling (%)	66.9	81
Reduction/pass on flat rolling (%)	17	17-19
Cross section as flat rolled (inches)	0.370 x 2.360	0.323 x 2.379

No sections were taken from partially rolled billets to compare the effects of deformation on cladding and core. Large variations in cladding thickness, from 0 to 40 mils for both rolled plates, indicated that some portions of the billets were worked more than others. The surfaces of roll clad plates were very uneven, with total thickness variations of as much as 50% in the area of the Zircaloy sleeve welds. All areas of plate which were clad were completely bonded. Typical clad-to-core bonds are shown in Figure 40.

From prefatory rolling of cylindrical billets in shaped passes it may be concluded that special finished shapes for clad fuel elements may be rolled. Precasting the fuel alloy into a cylindrical cladding jacket can simplify assembly. The amount of working which all surfaces of a cylindrical billet receive on rolling will effect a bond between the cladding and core on all sides; however, a more uniform finished product is desired. Improvements might be expected from better control of rolling temperature variables, use of a thicker protective steel can, and substitution of extruded seamless Zircaloy tubing for a welded cladding jacket. No further development of shaped pass rolling was undertaken, since it could not be readily adapted to rolled integral end closures, large diameter Zircaloy-2 seamless tubing was not available, and the rolling mill equipment at ANL was not adequate to permit the use of heavier steel cans with the development of plates of the desired size for EBWR fuel elements.

Bonds Established by Coextrusion

Extrusion is a more rapid method of fabricating round sections than rolling in hand round passes. It appeared probable that round sections with a composite of uranium alloy core in a Zircaloy jacket could be metallurgically bonded by coextrusion. Three types of composite cylindrical billets were designed for the purpose of attaining a coextruded bond on small diameter rod.

FIGURE 40. Zircaloy-2 Bonded to Uranium-5 w/o Zirconium-1.5 w/o Niobium by Combination Shaped Pass and Flat Rolling.

40a. Section from rolled Plate No. 61

Zircaloy-2
Cladding

Diffusion
Layer

Uranium Alloy
Core

Micro 16422

Bright Field

250X

40b. Section from rolled Plate No. 62.

Zircaloy-2
Cladding

Diffusion
Layer

Uranium Alloy
Core

Micro 16423

Bright Field

250X

Billets were prepared for Zircaloy-2 cladding, zirconium crystal bar cladding, and for Zircaloy-2 cladding with a thin niobium layer between the cladding and core to act as a water-corrosion barrier should any defects occur in the cladding. The core was uranium-5 w/o zirconium-1.5 w/o niobium alloy. Components used for each type of billet are listed in Table XVIII. Dimensions for components are shown in Figure 41. Three billets of Type I, two of Type II, and one of Type III were prepared.

Table XVIII

COMPONENTS USED FOR ZIRCONIUM AND ZIRCALOY-2 EXTRUSION BILLETS

Component	Type I Billet	Type II Billet	Type III Billet
Core	U-5 w/o Zr-1.5 w/o Nb Casting No. H-377 ⁽¹⁾	Same as Type I	Same as Type I
Cladding	Zircaloy-2. 710D528.	Zirconium Crystal Bar Grade I. Billet AM34.	Same as Type I
Barrier at Interface	None	None	0.006" thick Nb
Can	1020 Steel	1020 Steel	1020 Steel

(1) Composition of casting H-377 was 5.17 w/o Zr, 1.51 w/o Nb, balance uranium.

The alloy core for each billet was machined and ground to size. Cores were cleaned by dry sandblasting with alumina grit immediately before assembly. All cladding material was machined. One jacket each for Type I and Type II was cleaned by degreasing in CCl_4 , rinsed in absolute ethyl alcohol, and vacuum dried. All other jackets were pickled in a solution of 10 v/o HNO_3 and 2 v/o HF followed by a thorough water rinse, alcohol rinse and dried in vacuum. The niobium barrier in the form of welded tubing was swaged onto the uranium alloy core and cleaned with abrasive paper. Machined steel cans and end caps were degreased in trichloroethylene. The billets were then assembled and welded as illustrated in Figure 41.

The extruding was done on a 100-ton capacity Verson hydraulic press through a 0.200" diameter 120° conical die. A copper lead nib and graphite cut-off plug were heated to the billet temperature for each billet. The press container, die, and ram were preheated to temperatures shown in Table XIX. All billet heating and extrusion data are included in Table XIX.

From the extrusion rates and pressures required, it may be seen that zirconium crystal bar cladding billets were much more readily extruded than Zircaloy-2 cladding billets. The steel can served as a satisfactory lubricant for the zirconium or Zircaloy at extrusion temperatures above 750°C. This steel was easily removed from the extruded rod by

FIGURE 41. Dimensions of Components Used for Extrusion Cladding Billets.

E.H.S.

mechanical stripping or acid pickling. Except for the higher heat transfer rate, there did not appear to be any advantage in heating billets in the carbonate salt. All extruded rods showed some eccentricity of core which resulted in a variation in thickness of the cladding from 5 to 10 mils. The niobium foil in billet III-A was extruded between the cladding and core in an uninterrupted layer varying from 0.6 to 1.4 mils in thickness.

Table XIX

DATA FOR COEXTRUSION OF ZIRCONIUM AND ZIRCALOY-2 CLAD
URANIUM ALLOY BILLETS⁽¹⁾

Billet Type	Billet Heating		Temperature (°C)		Extrusion Pressure (tons)		Extrusion Speed (Ram Speed-in./sec)
	Heating Medium	Time (min)	Billet	Container, Die & Ram	Start	Finish	
I-A	Air	10	820	270	50	50	None ⁽²⁾
I-B	Air	15	850	270	35	75	Not Measured
I-C	Carbonate Salt	6	800	270	40	75	0.8
II-A	Carbonate Salt	7	800	205	30	75	3.6
II-B	Carbonate Salt	6	750	270	30	75	1.5
III-A	Air	20	850	270	35	75	1.3

⁽¹⁾ Billets 0.950" diameter extruded 22.5 : 1 reduction through a 0.200" diameter die.

⁽²⁾ Billet cooled too rapidly in die before sufficient pressure was applied to start the extrusion.

Extruded rods had thin clad-to-core diffusion layers 0.4 to 0.6 mil thick. The photomicrograph of a section from extruded rod II-A in Figure 42a shows a representative zirconium clad-to-core interface. Much thinner diffusion layers were noted at the niobium-to-Zircaloy and niobium-to-uranium alloy interfaces from a section of III-A, as shown in Figure 42b.

The number of cylindrical billets coextruded with zirconium or Zircaloy clad over the EBWR reference ternary alloy was sufficient to demonstrate the feasibility of obtaining a metallurgical bond by this technique. Rod-type fuel elements could be fabricated in this manner with conventional extrusion press equipment. Additional development work could be expected to minimize core eccentricity and lead to a suitable coextruded integral end closure.

Roll Bonds Established in Flat Plates

Some of the intrinsic advantages of flat plate-type elements for reactor fuel justified a greater effort in establishing sound roll bonds between flat plates of Zircaloy-2 and the reference core alloy. In addition to

FIGURE 42. Bonds in Coextruded Zircaloy-2 Clad Uranium-5 w/o Zirconium-1.5 w/o Niobium Alloy Rods.

42a. Interface of cladding and core showing diffusion layer 0.3 to 0.4 mils thick.

Zircaloy-2
Cladding

Diffusion Layer

Uranium Alloy
Core

Micro 20957

Bright Field

250X

42b. Interface of cladding and core coextruded with niobium foil barrier. Uniform distribution of niobium 0.002" thick.

Zircaloy-2
Cladding

Diffusion Layer

Niobium Barrier

Diffusion Layer

Uranium Alloy
Core

Micro 20958

Bright Field

250X

having large surface areas exposed to coolant for heat transfer, flat plates could be readily assembled into a geometric pattern with uniform coolant channels and moderator distribution. This assembly made it easier to obtain the proper water to fuel ratio with the light water moderator and with the needed heat transfer surfaces than would have been possible with cylindrical rod or tube elements. To ensure maximum heat transfer and prevent the formation of localized hot spots, the core must be integrally bonded to the cladding. The strength and ductility of the bond should be comparable to the strength and ductility of the cladding to withstand stresses created by thermal cycling during starting up and shutting down the reactor, and effects of irradiation damage to the fuel.

Problems associated with the clad-to-core bonds for an integrally clad flat plate may be divided into three categories: face cladding, side cladding, and end cladding. The face cladding bonds, which are developed in the plane surfaces normal to the direction of applied force during rolling, should be most amenable to roll bonding since the maximum pressure and increased surface area of bond interface occurs in this plane. The bond between the core and cladding along the side of a flat plate occurs in a plane which is parallel to the applied force on rolling. Although this bond interface is deformed and attenuated on rolling, the total surface area of the interface remains unchanged. Consequently any contaminants present in the initial interface will simply be redistributed. Without added restraint from edge rolling, this side bond should be more difficult to obtain than a face bond. Cast bonding the core alloy into a mold containing cladding side strips to effect a bond before rolling was considered possible. The interface between the core and cladding at the end of the plate was also believed to be difficult to bond. This surface is also parallel to the applied force on rolling and no deformation occurs at the two faces relative to each other. Prebonding by casting was again considered as a possible means of achieving an integral end bond.

Investigation of Roll Cladding Variables

A survey was made of the effects of variables which could be expected to have the greatest influence on the face cladding to core bond, namely, the roll bonding temperature and amount of total reduction on rolling. Other variables which might affect the quality of bond, such as the type of steel and design of the steel jacket used to protect the cladding from contamination during rolling and the use of an introduced niobium barrier at the bond interface, were also investigated. In addition to forming a desirable corrosion-resistant barrier between the core and cladding, niobium could be readily bonded to Zircaloy and might be used to facilitate bonds between the Zircaloy components. The number of test specimens prepared included four for temperature variables, four for reduction variables, two with niobium barriers at the interface, and one with a change in the steel jacket material.

The test specimens prepared for roll bonding were referred to as cladding billets. These preliminary cladding billets were designed to yield plates 0.125" thick, 2.00" wide, and 17" long over-all with 0.017" of cladding on each face, 1/8" on each side, and 3/8" at each end after a reduction in thickness of 80% by rolling. The dimensions of the individual components for the modified picture frame assemblies are given in Table XX.

Table XX

DIMENSIONS OF COMPONENTS IN CLADDING BILLETS
PREPARED TO STUDY ROLL BOND VARIABLES

Billet Components	Width (in.)		Thickness (in.)		Length (in.)	
	Billets 40, 41, 43, 44, 50, 54-57, 59	Billet 49	Billets 40, 41, 43, 44, 50, 54-57, 59	Billet 49	Billets 40, 41, 43, 44, 50, 54-57, 59	Billet 49
Core	1.410	1.550	0.450	0.375	3.375	1.512
Cover Plates	1.800	1.800	0.087	0.125	3.525	1.762
Side Plates	0.450	0.375	0.195	0.125	3.525	1.762
End Plates	0.450	0.375	0.075	0.125	1.410	1.550

Components for all eleven cladding billets were selected from the same wrought core casting, No. L-68, and Zircaloy-2 cladding stock from forged and rolled ingot, No. 710D443. Cores were machined to size and cleaned just before being assembled into billets by dry sandblasting in coarse (46 mesh) alumina grit. All cladding stock was sheared to size from cold-finished strip, cleaned in boiling concentrated nitric acid containing 1 v/o hydrofluoric acid, and double rinsed in running tap water followed with hot distilled water. The Zircaloy-2 components for billet No. 49 were preclad with 0.002" thick niobium on the face which was in contact with the core when the billet was assembled. The preclad components were cleaned in acid the same as all other Zircaloy components before billet assembly.

The niobium-clad Zircaloy component material was prepared by direct roll bonding in a Ti-Namel steel sheath. Both the niobium and Zircaloy were cleaned in boiling concentrated HNO₃-HF before assembly for roll cladding. Niobium foil, 0.012" thick, 1.800" wide, and 3.525" long, was placed on a 0.613" thick, 1.800" wide, and 3.525" long Zircaloy-2 block. The two were then pressed together between water-cooled copper platens at a pressure of 9½ tons/sq in., and the edges of the niobium foil sealed to the Zircaloy by inert-gas tungsten-arc welding. This compact was jacketed in a welded Ti-Namel steel sheath and rolled 80% reduction

in thickness at 775°C. The rolled plate was easily removed from the steel can with no evidence of bonding to the steel. Niobium was uniformly distributed and completely bonded to the Zircaloy throughout. A cross section of the niobium-clad Zircaloy interface may be seen in Figure 43. The diffusion layer at the interface was between 0.1 and 0.2 mil thick.

FIGURE 43. Niobium Foil Roll Bonded to Zircaloy-2
by 80% Reduction in Thickness at 775°C.
Diffusion layer at niobium-Zircaloy
interface 0.1 to 0.2 mil thick.

Clean cladding and core components were assembled and welded for cladding billets. The 60-ton, vertical, air-hydraulic billet assembly press is illustrated in Figure 44 with a typical cladding billet assembled for welding. The bottom Zircaloy cover plate was placed on a 1.800" wide by 3.525" long water-cooled copper block which served as the lower platen for the press. The alloy core was then centered on this bottom plate and the remaining Zircaloy side, end, and top components were assembled around the core. All components were handled with clean laboratory tongs or clean cellulose tissues to minimize contamination at the mating and subsequent bonding surfaces. Another water-cooled copper block of the same size as the lower platen was placed on top of the assembly and acted as a top platen in the press. Sufficient pressure, 500 psi, was applied to the top of the assembly to hold the components together while C-clamps were applied to the sides and ends of the assembly to ensure a closer contact between the uranium alloy core and the surrounding components. A maximum pressure of $9\frac{1}{2}$ tons/sq in. was applied to the cover plates and maintained during welding. The seams formed along the sides and at the ends of the assembly by the junction of the various Zircaloy components were sealed with an inert-gas tungsten-arc weld. The water-cooled copper chill conducted much of the heat from the weld area, resulting in a

FIGURE 44. Cladding Billet Assembly Press with Components of Modified Picture Frame-Type Billet Assembled for Welding.

minimum amount of oxide and nitride contamination of the welds and adjoining surfaces. No attempt was made to provide a protective atmosphere for the assembled billet, all welding being done in air. This method of sealing billet assemblies was referred to as press-welding.

In assembling the cladding components for billet No. 59, strips of 0.005" thick niobium foil, the same width and length as the Zircaloy components, were inserted between the core and the Zircaloy. This assembly was compressed and welded as discussed above.

Welded cladding billet assemblies were jacketed in steel sheaths or cans which were machined from flat plates in which the sides formed an integral part of the cover. Jacket design details are given in Figure 45.

FIGURE 45. Design Details for Steel Jackets Used with Small Preliminary Cladding Billets.

The inside dimensions of the jacket used for billet No. 59 were increased 0.010" in width and depth to accommodate the increase in cladding billet dimensions due to the addition of the niobium foil barrier. Titanium-killed low-carbon steel, Ti-Namel, was used for jacketing all billets except No. 50, which was jacketed in SAE 1020 steel. The top and bottom jacket plates and two end plugs were placed around the cladding billet and clamped rigidly in a vise. This provided optimum contact and reduced distortion of the jacket while a fillet weld with coated consumable electrodes was deposited around the sides and ends. The steel jacket was neither evacuated nor welded in a protective atmosphere. The previous sealing welds in the Zircaloy components of the cladding billets were intended to protect the core and roll-bonding interfaces from contamination. Contamination on external cladding surfaces of rolled plates could be removed by cleaning.

The jacketed cladding billets were preheated in air in an electric resistance-type furnace for 30 minutes at the roll-bonding temperature. Billets were all rolled with a uniform reduction of 17% per pass and reheated 5 minutes after every pass. Rolling speed was maintained at 75 ft/min. Data for rolling temperatures, total reductions, and significant billet variables are given in Table XXI. Steel jackets were removed from the rolled plates by shearing the steel from the sides and ends to within 1/8" of the Zircaloy cladding and chiseling the steel down to the cladding on one side so as not to damage the roll-clad plate.

Table XXI

ROLLING DATA FOR PRELIMINARY CLADDING BILLETS

Cladding Billet No.	Preheat and Rolling Temp. (°C)	Total Reduction (%)	Significant Variable
40	850	80	Roll bonding temperature 850°C.
41	775	80	Roll bonding temperature 775°C.
43	750	80	Roll bonding temperature 750°C.
44	800	80	Roll bonding temperature 800°C.
49	775	80	Zircaloy-2 preclad with 0.002" niobium for cladding billet with niobium barrier.
50	775	80	1020 steel used for jacket.
54	775	50	Billet thickness reduction of 2:1 on rolling.
55	775	67	Billet thickness reduction of 3:1 on rolling.
56	775	75	Billet thickness reduction of 4:1 on rolling.
57	775	90	Billet thickness reduction of 10:1 on rolling.
59	775	80	Niobium foil 0.005" thick between core and clad on assembled billet for cladding billet with niobium barrier.

The effects of billet assembly and rolling variables were evaluated from the physical appearance and physical dimensions of rolled plates, mechanical properties of rolled plates, and metallographic examination of clad-to-core bonds. None of these preliminary plates were subjected to corrosion or irradiation testing.

Measurements of plate width and thickness were taken at six equally spaced intervals along the length of the plate. Thickness measurements were made at each of these intervals at both the edge and center of the plate. Sections 1/2" long cut from the plate at six equally spaced intervals along the length were ground to 600 grit on wet metallographic grinding paper for cladding thickness measurements. A light electrolytic etch in eight parts H_3PO_4 , five parts ethanol, and five parts ethylene glycol served to delineate the clad-to-core interface. Cladding thickness measurements were made with a monocular microscope with an eyepiece calibrated to read 0.0002". Measurements of cladding thickness were taken at 0.10" intervals on both sides of each section of plate. The results of all physical measurements and statistical analysis of the cladding thickness are given in Table XXII.

Table XXII

PHYSICAL MEASUREMENTS OF PLATES ROLLED FROM PRELIMINARY CLADDING BILLETS

Cladding Billet No.	Avg. Thickness as Rolled (in.)	Avg. Width as Rolled (in.)	Length as Rolled (in.)	Avg. Width Increase on Rolling (%)	Cladding Dimensions (mils)			
					Avg. Thickness(1)	Avg. Deviation(2)	Range of Deviation(3)	Min. Clad. Thickness
40	0.138	1.979	15-1/8	9.7	18.1	0.58	+2.6 to -1.8	16.3
41	0.135	1.978	15-1/2	9.8	18.1	0.73	+2.4 to -2.2	15.9
43	0.139	1.991	14-3/4	10.6	18.3	0.92	+3.1 to -4.8	13.5
44	0.141	1.973	14-3/4	9.5	19.0	0.70	+3.2 to -2.4	16.6
49	0.130	2.006	7-3/4	11.1	22.6	1.76	+5.4 to -4.7	17.9
50	0.128	1.988	16-1/8	10.2	17.0	0.57	+2.8 to -1.8	15.4
54	0.325	1.920	6-5/8	6.6	42.8	2.00	+2.2 to -2.8	40.0
55	0.206	1.961	10-3/16	8.9	27.8	0.76	+3.4 to -2.6	25.2
56	0.158	1.975	13-1/8	9.6	20.5	0.77	+2.7 to -3.4	17.1
57	0.065	1.994	32-1/2	10.5	8.6	0.54	+1.7 to -1.8	6.8
59	0.127	1.939	16-1/4	7.7	18.2	0.79	+3.4 to -3.2	15.0

(1) Determined by averaging thickness measurements taken at 0.100" intervals across both sides of six sections, equally spaced along the length of plate.

(2) Determined by summing the differences between average cladding thickness and each measurement, and dividing by the total number of measurements.

(3) Greatest positive and negative deviation observed.

Sections from each rolled plate were heat treated to produce a corrosion-resistant, supersaturated alpha structure. This heat treatment for rolled plate was considered desirable before the results of irradiation testing and corrosion testing of irradiated specimens were available, as previously discussed. The heat treatment consisted of heating in a carbonate salt bath for 15 minutes at 850°C, water quenching, and aging for 45 minutes in air at 425°C followed by air cooling. Mechanical properties were measured on plate as rolled, as quenched, and as quenched and aged.

A reliable bond tensile test for clad-plate bonds had been used with Zircaloy-2-clad uranium-niobium alloy plates.⁽⁹⁾ Little change was needed to adapt this test to the clad reference alloy plates. A 1/4" diameter Zircaloy-2 stud was percussion welded to the cladding on one side of a clad plate. The cladding around the base of the stud was then machined down to the core as shown in Figure 46. With the plate supported in a holding jig with a universal joint suspension, the cladding adhering to the stud could be pulled from the core in a tensile testing machine. Weld penetration at the stud-to-clad interface was limited to a narrow band from 5 to 7 mils thick. The weld heat affected zone in the cladding did not penetrate more than 15 mils. The metallographic structure of the core alloy and cladding adjacent to the bond line were unaffected by the weld. Results of bond tensile testing are included with other mechanical testing data in Table XXIII.

Table XXIII
MECHANICAL PROPERTIES OF PLATE ROLLED FROM PRELIMINARY CLADDING BILLETS

Cladding Billet No.	Uranium Alloy Core Hardness (Rockwell "C")			Face Cladding to Core Bond Tensile Strength ⁽³⁾ (psi)			Guided Bend Test ⁽⁴⁾ (Degrees)		
	As Rolled	Heat Treated ⁽¹⁾	Heat Treated and Aged ⁽²⁾	As Rolled	Heat Treated ⁽¹⁾	Heat Treated and Aged ⁽²⁾	As Rolled	Heat Treated ⁽¹⁾	Heat Treated and Aged ⁽²⁾
40	46	42	52	47,200	11,800	25,550	22	29	5
41	48	38	52	34,980	20,260	20,960	30	39	5
43	47	43	50	45,780	19,400	31,200	12	34	6
44	46	37	50	33,290	19,160	22,800	26	48	2
49	50	44	52	43,670	19,840	19,000	20	41	13
50	49	36	51	44,580	20,860	Not Measured	16	41	3
54	46	42	Not Measured	27,100	15,880	Not Measured	3	19	1
55	44	37	52	47,675	16,418	35,000	19	20	5
56	47	38	51	45,390	16,560	22,500	25	31	6
57	47	41	52	Not Measured ⁽⁵⁾	-	-	19	45	3
59	49	38	50	29,990	20,020	19,750	25	39	8

(1) Heated 15 min in carbonate salt at 850°C, water quenched.

(2) Heated 15 min in carbonate salt at 850°C, water quenched, aged 45 min at 425°C.

(3) Average of 3 or more measurements.

(4) Angle to rupture around a 1/8" radius.

(5) Cladding too thin after 90% reduction in thickness (0.0086") to prepare tensile test specimen.

Bend test data gave some measure of plate ductility and formability. Test strips, 1/2" wide and taken 90° to the direction of rolling, were subjected to a guided bend test around a mandrel with a 1/8" radius. Measurement of the angle through which strips could be bent before rupturing furnished a quantitative evaluation of plate formability. Bend test results are also included in Table XXIII.

The surface finish of rolled plates was smooth and free from bumps and ripples except at the ends. Total plate thickness variations of 30% to 50% for the nominal 0.125" thick plates were observed at the junction between the core and Zircaloy end cladding. This irregularity was

FIGURE 46. Detail of Specimens for Bond Tensile Tests in Clad Plates.

46a. Welded assembly and machining detail for cladding cover plate to uranium alloy core bond tensile test specimen.

46b. Welded assembly and machining detail for cladding side strip to cladding end plug bond tensile test specimen

accompanied by a thinning of the cladding on one side of the plate or the other. In some instances the cladding thickness measured 0.001" or less in this area. Thickness of the side cladding was greater than the thickness at the center of rolled plates, with the difference being between 0.003" and 0.009". Although variations in rolling temperature and reduction had little effect on plate and irregularity, the differences in thickness between the side and center of rolled plates were least for plates rolled at 775°C and became progressively greater with increasing rolling temperatures. These irregularities in rolled plate geometry were believed due to the differential hot hardness of the core and cladding at the roll-bonding temperatures. Plate uniformity in terms of thickness and width variations at intervals along the plate length was better for plates rolled at 800°C or 850°C than for plates rolled at 775°C or 750°C. A similar improvement in uniformity of rolled plate dimensions was noted with increasing total reduction and with the plate rolled in a SAE 1020 carbon steel can. Plates rolled at the higher temperatures, greater reductions, or in the SAE 1020 steel jacket also had the most uniform face cladding, as shown by a comparison of statistical thickness deviations.

Mechanical properties of the clad plates did not show any significant variance with rolling temperature or as a result of rolling in different steel jackets. Bond-strength data indicated that a total reduction of only 50% yielded ineffectual or incomplete bonds between the core and cladding, whereas reductions of 67% or greater at a rolling temperature of 775°C produced sound clad-to-core bonds. The effects of heat treatment were most pronounced on all mechanical properties. Quenching from 850°C out of salt resulted in decreased core hardness, bond strength, and resistance to deformation on bending. A marked increase in all of these properties followed the 45-minute aging at 425°C. Although the properties of the quenched core alloy differed from the properties of as-rolled material due to the supersaturated alpha phase present, results of tests which will be discussed later in this report showed the bond tensile strength was influenced more by hydrogen absorption from the heating medium, carbonate salt, than by alloy phase changes within the cladding interface.

Metallographic examination of clad-to-core bonds from billets rolled only 50% reduction in thickness at 775°C, or 80% at 750°C, showed the presence of voids at the clad-to-core interface. There was no side bond between the core and cladding and no bond at Zircaloy-to-Zircaloy interfaces on these plates. Billets rolled at 775°C or higher with reductions of 3:1 or greater had complete bonds between the cladding and core and mechanically sound bonds at Zircaloy cover to side plate, although some discontinuous inclusions existed in the bond line. Zircaloy bonds at the plate ends were not satisfactory. Measurements of the total diffusion layer in the face cladding to core interface after 80% reduction in thickness revealed a sharp increase in diffusion rate at the highest roll-bonding temperature, 850°C, compared with lower roll-bonding temperatures, as shown in Table XXIV.

Table XXIV

EFFECT OF ROLL BONDING TEMPERATURE ON
CLAD-TO-CORE DIFFUSION AFTER
80% REDUCTION IN THICKNESS

Rolled Plate No.	Rolling Temp. (°C)	Thickness of Diffusion Layer (mils)
43	750	0.08 to 0.12
41	775	0.12 to 0.20
44	800	0.12 to 0.24
40	850	0.32 to 0.52

The two billets prepared with niobium foil barriers had an uniformly distributed cladding and niobium barrier after roll bonding. Plate from billet No. 49, which had preclad Zircaloy components, was completely bonded at all interfaces. Thickness of this barrier at the face cladding varied from 0.32 mil to 0.54 mil and along the side cladding from 1.34 mils to 2.02 mils, as shown in the photomicrograph of Figure 47a. Figure 47b, a photomicrograph of a section of plate from billet No. 59 prepared with 0.005" of niobium foil between the core and cladding, shows only incomplete and intermittent bonding between the niobium and alloy core, even though good bonds were obtained between the niobium and Zircaloy. The presence of niobium in the interface between cladding components promoted sound cladding bonds.

Although heating and rolling variables such as preheat time, reheat time, roll speed, reduction per pass, and number of passes made between reheating could all be expected to influence the quality of roll-clad plates, results from preliminary cladding billets comparing only the variables of temperature and total reduction indicated that satisfactory roll bonds between the cladding and core in flat plates could be expected at a temperature of 800°C or higher and with reductions of 80% to 90% in thickness. The use of 1020 steel as a jacketing material in place of Ti-Namel steel did not appear detrimental to bonding and might contribute to rolled plate uniformity and better surface finish. The feasibility of introducing a niobium barrier for added corrosion resistance or to facilitate roll bonding by precladding niobium to one side of rolled Zircaloy-2 components was demonstrated in one of the preliminary billets. The parasitic neutron absorption from added niobium in roll bonds would make its use in the fabrication of fuel elements unacceptable except as a last resort.

FIGURE 47. Sections from Plates Roll Clad with Niobium Barrier between Uranium Alloy Core and Zircaloy-2 Cladding.

47a. Section of plate rolled from Billet No. 49 showing interface of core, side cladding, and face cladding. Billet prepared with Nb-clad Zircaloy-2 components.

47b. Section of plate rolled from Billet No. 59 showing interface of core, side cladding, and face cladding. Billet prepared with 0.005" Nb foil between Uranium alloy core and Zircaloy-2 cladding.

Cast Bonds Established before Rolling

To simplify the preparation of material and assembly of billets and also effect an initial bond between the cladding and core, one group of experimental cladding billets was designed with the core material cast between cladding side plates and into rectangular cans. Development of the mold, casting technique, and evaluation of the castings for core alloy cast between cladding side strips and into rectangular cans was done on a concomitant program with roll bonding and the results were reported separately.⁽¹⁹⁾

The dimensions used for the design of cladding components used for the cast-bonded billets are given in Table XXV. Billets were designed to give 0.025" of face cladding as rolled. A slight adjustment was made in the width of some billets to permit the use of different thicknesses of side cladding. Some billets with cast side plates were also used to study the effects of specially designed cladding end plugs. Design of these end plugs and their effect on rolled plate ends will be discussed later. Seven billets of Type A, six of Type B, two of Type C, and one of Type D, were cast, assembled, and roll clad into plates. Core casting numbers and preparation of the materials used in these 16 cast bonded billets are given in Table XXVI.

The Zircaloy-2 used for side strip castings was held in place in a split graphite mold with tapered graphite retainer rings, as shown in Figure 48. A typical side strip casting of Type B is shown in Figure 49 after being stripped from the mold and cropped to length. The side strips at the bottom end of this casting were extended $1\frac{1}{2}$ " beyond the end of the core for subsequent fitting of a specially shaped end plug. Most castings contained solid Zircaloy bottom end plugs which were also cast bonded to the core. The Zircaloy-2 jackets used for billets of Type C were made from hot-rolled and hot-formed, 0.100" thick Zircaloy channels, pictured in Figure 50. Zircaloy-2 stock for these channels was heated to 850°C in carbonate salt, press-formed in a preheated closed die, and cleaned by wet abrasive blasting with 325 mesh alumina. The edges of the channels were machined to size, a $1/4$ " thick machined Zircaloy plug fitted into the bottom end, and the components welded as shown in Figure 51. A finished fabricated jacket is shown in Figure 52. The protective steel sheath used with Type C billet Nos. 60 and 111, with a cast-bonded billet ready for assembly, is shown in Figure 53. Zircaloy-2 components used for the built-up welded can for the Type D cladding billet No. 52 were machined to width and length and the edges bevelled for welding as detailed in Figure 54. The welded can prepared for cast bonding the core alloy for billet No. 52 is shown in Figure 55. The protective steel sheath used with Type D billet No. 52 and the cast-bonded billet ready for assembly are shown in Figure 56.

Table XXV

DESIGN DIMENSIONS⁽¹⁾ FOR CLADDING COMPONENTS USED WITH CAST BONDED BILLETS

Billet Component	Type A ⁽²⁾			Type B ⁽³⁾			Type C ⁽⁴⁾			Type D ⁽⁵⁾		
	Width	Thick.	Length	Width	Thick.	Length	Width	Thick.	Length	Width	Thick.	Length
Core	2.345	1.700	5.250	2.382	1.360	6.500	2.450	1.360	6.500	3.500	0.840	13.625
Cladding Side Strip	2.250	0.195	9.000	2.250	0.195	9.000	(Fabricated with cover plate - see below.)			0.840	0.250	14.000
Cladding End Plate	1.700	0.250	2.345	1.360	0.250	2.382	1.360	0.250	2.450	0.840	0.375	3.500
Cladding Cover Plate	2.595	0.125	5.750	2.632	0.100	7.000	Fabricated jacket assembled from formed and welded sheet (2 pcs. 3.81" x 9" x 0.100").			4.000	0.100	14.000
Assembled Billet	2.595	1.950	5.750	2.632	1.560	7.000	2.650	1.560	7.000	4.000	1.040	14.000
SAE 1020 Steel Jacket	5-1/2	3	10	5-1/2	2-1/2	11	5-1/2	2-1/2	11	7	2	15
Finish Rolled Plate	2.770	0.375	26.0	2.770	0.375	26.0	2.770	0.375	26.0	4.000	0.250	48.0

(1) All dimensions given in inches.

(2) Side strips cast in place - 80% reduction on rolling.

(3) Side strips cast in place - 75% reduction on rolling.

(4) Uranium alloy core cast into fabricated Zircaloy-2 jacket - 75% reduction on rolling.

(5) Uranium alloy core cast into welded Zircaloy-2 can - 75% reduction on rolling.

Table XXVI

MATERIALS USED FOR CAST-BONDED CLADDING BILLETS

Cladding Billet No.	Core Casting No.	Surface Preparation of Cast Core Material	Zircaloy-2 Cladding	Surface Preparation of Zircaloy Cladding
(Type A Castings - Side Strips Cast in Place for 80% Reduction on Rolling)				
51	L-84	Machined and degreased in trichloroethylene.	710D443	Machined all over. Degreased in absolute alcohol.
53	L-86	Machined and degreased in trichloroethylene.	710D443	Same as 51 above.
74	L-129	Machined and sandblasted	710D528	Sheared to size. Pickled in boiling concentrate HNO ₃ + 1 v/o HF acid.
75	L-131	Machined and sandblasted	710D528	Same as 74 above.
76	L-134	Machined and sandblasted	710D528	Same as 74 above.
80	L-148	Hand polished and degreased in absolute alcohol.	710D528	Sheared to size. Pickled in cold 10 v/o HNO ₃ + 2 v/o HF acid.
81	L-149	Same as 80 above.	710D528	Same as 80 above.
(Type B Castings - Side Strips Cast in Place for 75% Reduction on Rolling)				
77	L-132	Machined and sandblasted.	710D528	Same as 74 above.
78	L-128	Machined and sandblasted.	710D528	Same as 74 above.
79	L-130	Machined and sandblasted.	710D528	Same as 74 above.
89	L-141	Machined and degreased in trichloroethylene.	1X081	Same as 74 above.
90	L-139	Machined and degreased in trichloroethylene.	1X081	Same as 74 above.
91	L-140	Machined and degreased in trichloroethylene.	1X081	Same as 74 above.
(Type C Castings - Core Cast into Fabricated Zircaloy-2 Jacket for 75% Reduction on Rolling)				
60	1033	Exposed end milled and sandblasted.	1X081	Wet abrasive blasted with 325 mesh Al ₂ O ₃ grit. Water rinsed.
111	1053	Exposed end milled and sandblasted.	710D528	Wet abrasive blasted with 400 mesh Al ₂ O ₃ grit. Water rinsed.
(Type D Casting - Core Cast into Welded Zircaloy-2 Can for 75% Reduction on Rolling)				
52	1013	Exposed end milled and sandblasted.	710D443	Same as 60 above.

FIGURE 48. Split Graphite Mold used for Cast Bonding Uranium - 5 w/o Zirconium - 1.5 w/o Niobium to Zircaloy-2 Side Strips.

FIGURE 49. Side Strip Casting Showing Uranium-5 w/o Zirconium-1.5 w/o Niobium Cast Bonded to Zircaloy-2 Side Strips.

FIGURE 50. Hot-Formed Zircaloy-2 Channels used in Fabricating Molds for Cast-Bonded Cladding Billets.

106-1471

FIGURE 51. Welding Detail for Zircaloy-2 Jacket Used for Type-C Cast Bonded Cladding Billets.

FIGURE 52. Welded Zircaloy-2 Jacket used for Type-C Cast -
Bonded Cladding Billets.

106-1432

FIGURE 53. Protective Steel Sheath Used with Type-C Billets and Cast-Bonded Billet Ready for Assembly.

FIGURE 54. Component Details for Welded Zircaloy-2 Can Used for Type-D Cast-Bonded Cladding Billets.

FIGURE 55. Welded Zircaloy-2 Can Prepared for Cast-Bonding Type-D Cladding Billet.

106-1431

FIGURE 56. Protective Steel Sheath Used with Type-D Billet and Cast Bonded Billet Ready for Assembly.

106-1435

After the castings with bonded side strips were machined to size and cleaned for billet assembly, cladding cover plates and end plugs were pressed together and welded in position using the procedure described for the assembly of preliminary cladding billets. All of the cast-bonded billets were assembled into machined SAE 1020 protective steel jackets of the same basic design as shown in Figure 26, and the jackets were sealed by welding.

The assembled billets were preheated in an electric resistance-type furnace at the roll-bonding temperature. Due to the greater initial thickness of some of these cladding billets, 2.5" and 3.0" as compared with 1.0" on previously rolled billets, uniform reductions as great as 17% could not be taken on the first couple of roll passes without exceeding the capacity of the 16" x 24" rolling mill. This mill operated with constant torque and increasing horsepower at roll speeds up to 100 ft/min. At 100 ft/min the rated horsepower is 150, increasing to 200 at a roll speed of 300 ft/min. Since the maximum horsepower to speed ratio occurs at 100 ft/min, by increasing the rolling speed from 75 ft/min to 125 ft/min, the increase in power made it possible to roll thicker billets with a maximum reduction of 7% to 10% on the first pass. The length of preheat and reheat time was also increased with increased billet size. Billets were reheated after each pass through the mill. Changes were made in rolling temperature and total reduction as a check on the influence of these variables on the cast bonded cladding billets. Rolling data for each billet are contained in Table XXVII.

Table XXVII

ROLLING DATA FOR CAST-BONDED CLADDING BILLETS

Cladding Billet No.	Rolling Temp. (°C)	Preheat Time (min)	Reduction Per Pass (%)	Reheat Time (min)	Total No. of Passes	Rolling Speed (ft/min)	Total Reduction (%)
51	800	120	7-17	10	12	75	80
52	775	90	12-17	5	9	75	75
53	775	120	7-17	10	12	125	80
60	775	60	10-17	10	10	125	75
74	800	60	10-17	10	12	125	80
75	800	60	10-17	10	12	125	80
76	800	60	10-17	10	12	125	80
77	800	60	10-17	10	10	125	75
78	800	60	10-17	10	10	125	75
79	800	60	10-17	10	10	125	75
80	800	60	10-17	10	12	125	80
81	800	60	10-17	10	12	125	80
89	900	90	12-23	10	9	75	90
90	850	75	15-20	10	7	75	80
91	900	90	12-33	10	7	75	80
111	800	90	9-18	10	13	125	81

Table XXVIII

PHYSICAL MEASUREMENTS OF PLATES ROLLED FROM
CAST-BONDED CLADDING BILLETS.⁽¹⁾

Cladding Billet No.	Billet Type ⁽²⁾	Average Thickness as Rolled (in.)	Average Width as Rolled (in.)	Length as Rolled (in.)	Average Width Increase on Rolling (%)
51	A	0.370	2.957	27	14.0
53	A	0.358	3.005	27	15.8
74	A	0.240	2.589	37-1/2	10.8
75	A	0.243	2.665	36-1/8	12.0
76	A	0.241	2.701	31	10.8
80	A	0.238	2.767	34-1/4	8.7
81	A	0.237	2.803	34-3/8	10.1
77	B	0.262	2.557	32-3/8	11.0
78	B	0.261	2.562	30-1/8	11.1
79	B	0.261	2.667	26-7/8	9.8
60	C	0.367	3.010	19-3/4	13.6
111	C	0.298	2.890	33-3/4	9.1
52	D	0.225	4.150	52	3.75

(1) Plates 89-91, inclusive, were sectioned for bond line examination before plate measurements were obtained.

(2) See Table XXV for description of billet types.

Table XXIX

CLADDING THICKNESS ANALYSIS FOR PLATES ROLLED FROM
CAST-BONDED CLADDING BILLETS

Cladding Billet No.	Billet Type ⁽¹⁾	Cladding Dimensions (mils)			
		Average Thickness ⁽²⁾	Average Deviation ⁽³⁾	Range of Deviation ⁽⁴⁾	Min. Cladding Thickness
51	A	26.7	0.88	+2.9 to -2.9	23.8
53	A	26.0	1.74	+5.5 to -3.0	23.0
60	C	26.4	2.96	+10.8 to -10.6	15.8
52	D	23.5	2.25	+14.9 to -8.1	15.4

(1) See Table XXV for description of billet types.

(2) Determined by averaging thickness measurements taken at 0.100" intervals across both sides of six sections, equally spaced along the length of plate.

(3) Determined by summing the differences between average cladding thickness and each measurement, and dividing by the total number of measurements.

(4) Greatest positive and negative deviation observed.

After the plates which were rolled from cast-bonded billets had been removed from their steel jackets, they were physically inspected for defects. With the exception of plate Nos. 89, 90 and 91, all plates were measured for thickness, width, and length. These dimensions are recorded in Table XXVIII. The rolled plates were all sectioned for further evaluation.

Sections from the first four plates rolled, Nos. 51, 52, 53, and 60, were analyzed for clad thickness, using the procedure described for the preliminary cladding billets. Cladding measurements are summarized in Table XXIX. A longitudinal section of one end of plate No. 51 and transverse sections from both 51 and 111 were polished, etched, and photographed to show distribution of the core and cladding (Figure 57).

Thorough metallographic examination of all bonds in plate sections proved to be the most reliable means of evaluating clad plates. Consequently very little mechanical testing was justified except as a further check on bond quality. Previous measurements had shown that diffusion bonds between the core and cladding had an ultimate strength in tension comparable to the strength of the rolled Zircaloy-2 cladding material. Bond tensile measurements were made on sections of clad plate rolled from billets 51, 53, and 60 to show comparative strength of the face and side bonds. These three plates were the only ones which had sufficient total thickness to permit the percussion welding of 1/4" diameter Zircaloy-2 studs to the side cladding by the procedure illustrated in Figure 46. Results of these tests along with core hardness measurements of rolled plates are given in Table XXX. Two longitudinal strips, 3/4" wide and approximately 20" long, were cut from rolled plate No. 76 and subjected to a torsion test. For this test one end of the strip was gripped in a vise and the other end twisted with a wrench to produce a permanent twist of 360° per foot of length, as shown in Figure 58.

Table XXX

MECHANICAL PROPERTIES OF THREE PLATES ROLLED
FROM CAST-BONDED CLADDING BILLETS

Cladding Billet No.	Core Hardness (Rockwell "C")	Bond Tensile Strength (psi) ⁽¹⁾	
		Face Clad to Core Bond	Side Clad to Core Bond
51	45	62,500	66,600
53	48	64,400	63,600
60	44	63,000	54,000

(1) Average of 3 or more measurements.

FIGURE 57. Sections Showing Distribution of Core and Cladding in Clad Plate Rolled from Cast Bonded Billets.

57a. Longitudinal section from end of rolled plate No. 51, side strips cast in place.

Macro 15782

1X

57b. Transverse sections from 6 equally spaced intervals along length of plate No. 51, side strips cast in place.

Macro 15783

1X

57c. Transverse section from center of plate No. 111, cast bonded in fabricated Zircaloy-2 jacket.

Macro 20529

2X

FIGURE 58. Torsion Test Specimens from Roll-Clad Plate No. 76 after Twisting 360° per Foot of Length.

Macro 16924

Both cut faces of 1/2" wide plate sections cut transverse to the rolling direction from a minimum of six equally spaced intervals along the length of each rolled plate were examined microscopically. Specimens were polished to 600 grit on a wet abrasive wheel, etched with 35-5 HNO₃-HF, and examined at 90X and 250X under oblique and bright field illumination. Photomicrographs were taken of representative structures and plate defects.

Cast-bonded billets with the core cast between Zircaloy side strips or into a Zircaloy mold all showed good diffusion bonds between the core and cladding. Although good cast bonds were obtained, the following inherent casting defects often affected these bonds:

1. Contamination of the Zircaloy due to prolonged heating in the furnace prior to casting.
2. Entrained inclusions at the bond line.
3. Cracks at the bond line from differential cooling stresses between the core alloy and clad during solidification and cooling of the core.
4. Trapped gas in the core alloy at the bond interface.

Two sections of Zircaloy-2 from cast-bonded billets, one from side strip casting No. L-141 used for cladding billet No. 89, and the other from a Type-C billet (Table XXV), casting No. 1045, which was not jacketed and rolled,⁽¹⁹⁾ were examined metallographically and analyzed for carbon, nitrogen, and oxygen content. Material in the side strip casting had been heated for 15 minutes at 1525°C in a vacuum of 20 μ . The Zircaloy mold for casting No. 1045 was heated overnight at 1000°C in a vacuum of 10 μ . The chemical analyses for these two specimens are given in Table XXXI.

Table XXXI.

CHEMICAL ANALYSES OF ZIRCALOY-2 HEATED
FOR CAST-BONDED CLADDING BILLETS

Zircaloy-2 Ingot No.	Casting No.	C (ppm)	N (ppm)	O (w/o)
710D443 1X081	L-141 1045	74 120	69 315	0.78 - 0.92 0.19

A comparison of the metallographic structure of these two specimens under polarized light, Figure 59, shows a large grain structure with considerable inclusions in the grain boundaries. These inclusions are in almost direct

59a. Zircaloy-2 heated 15 min at 1525°C in a vacuum of $20\ \mu$;
oxygen analysis 0.19%.

Micro 16471

Polarized Light

100X

59b. Zircaloy-2 heated overnight at $1,000^{\circ}\text{C}$ in a vacuum of $10\ \mu$;
oxygen analysis 0.85%.

Micro 16473

Polarized Light

100X

proportion to the amount of oxygen present and are presumed to be an oxygen-rich phase of zirconium. Unless contamination from the furnace atmosphere is kept to a minimum, the oxygen and nitrogen pickup by Zircaloy used in cast-bonded billets will be detrimental to its water corrosion resistance.

Sections were taken from the top and bottom of castings L-129 and L-130 for metallographic study. These castings were prepared with side strips cast in place for roll bonding billet Nos. 74 and 79. Figure 60 shows photomicrographs of the cast core to side strip bonds in these sections. A very heavy diffusion layer, 2 to 3 mils thick, is apparent at all bonds. Although sound bonds may be seen in sections from the top of casting L-129 and bottom of L-130, a crack extends across the sample from the bottom of L-129 between the uranium alloy core and the diffusion layer, and considerable porosity may be seen in the uranium alloy adjacent to the Zircaloy at the top of L-130. To remove the porosity near the surface, side strip castings for billets 74 to 81 and 89 to 91, inclusive, were machined under-size on thickness, and finish rolled to 0.250" thick plate to retain the scheduled total reduction for billets of Type A and B (Table XXV).

The surface finish of all plates rolled from cast-bonded cladding billets, except Nos. 52 and 60, was smooth and free from cracks, checks, and scale. The surfaces of plates 52 and 60 showed checking along the sides and edges corresponding to the original welded areas of the assembled can and fabricated jacket. Irregularities in the surface of plate No. 52 may be seen in Figure 61. Attempts to improve the surface finish of a section from plate No. 52 by grinding followed by hot rolling 10% reduction in thickness at 850°C out of carbonate salt resulted in further checking of the surface.

All of the billets prepared with core alloy cast between side strips and which were preheated one hour and rolled at 800°C exhibited nearly the same width increase or spread on rolling. This spread of approximately 9% to 11% was of the same order of magnitude as on preliminary clad plates and was not affected by changes in roll speed from 75 to 125 ft/min or total reduction from 75% to 80%. The greater spread for billets 51 and 53, 14% to 16%, was believed due to the increase in total preheating time to 120 minutes, resulting in less temperature gradient throughout the billet. The actual rate of temperature rise during billet preheating was established later. There was significantly less spread, 3.75%, on rolled billet No. 52. This reduction in spread was attributed to restraint of the Zircaloy-2 jacket. This jacket had thicker side strip components and increased hardness of the Zircaloy resulting from contamination during welding and heating for casting.

FIGURE 60. Cast Core to Side Strip Bonds in Cast-Bonded Cladding Billets.

60a. Bottom of casting L-129 showing crack at cast bond.

Zircaloy-2
Side Strip

Diffusion
Layer
Crack

Cast Uranium
Alloy

Micro 16548 Bright Field 250X

60c. Bottom of casting L-130 showing sound bond.

Zircaloy-2
Side Strip

Diffusion
Layer

Cast Uranium
Alloy

Micro 16550 Bright Field 250X

60b. Top of casting L-129 showing sound bond. White and black lines in the bond are preferential etch lines.

Zircaloy-2
Side Strip

Diffusion
Layer

Cast Uranium
Alloy

Micro 16549 Bright Field 250X

60d. Top of casting L-130 showing porosity in core adjacent to cast bond.

Zircaloy-2
Side Strip

Diffusion
Layer

Cast Uranium
Alloy

Micro 16551 Bright Field 250X

FIGURE 61. Plate Rolled from Cladding Billet No. 52 with the Core Alloy Cast into a Welded Zircaloy-2 Can.

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The distribution of face cladding on plates rolled from billets with side strips cast bonded in place was comparable to plates rolled from modified picture frame assemblies. Of the two billets of this type for which the cladding thickness was analyzed, it was again noted that the one rolled at the higher temperature, 800°C, had a lower cladding thickness deviation. Plates rolled from billets with the core cast bonded into either a welded or fabricated Zircaloy-2 jacket had very irregular face cladding with an average deviation of 2 to 3 mils across the plate at 0.10" intervals and with total thickness variations of 35% to 60%.

The bond tensile strength of side strip to core bonds on rolled plate from billets 51 and 53 with cast-bonded side strips, was equal to the strength of the roll bond between the cover plate and core on these same plates. The strength of side and cover bonds on the plate rolled from billet No. 60 with the core cast bonded to a fabricated Zircaloy jacket was equivalent to the strength of other cast or roll-clad bonds. Although the torsion specimens from plate No. 76 were not twisted to ultimate failure, the test showed that the bond interface in strips of the geometry had sufficient ductility to permit cold forming of twisted ribbons as proposed for ribbon-type fuel elements.

Complete metallurgical bonds between cladding and core were obtained at the sides and on the top and bottom faces of all plates rolled from cast-bonded billets. The thick diffusion layers formed along the sides of billets by casting were not attenuated by rolling and appeared in rolled plate as heavy jagged layers, 2 to 4 mils thick, as may be seen in Figure 62. Typical sound roll bonds were obtained between cover plate and core on billets prepared with cast-bonded side strips, as shown in Figure 63a. Contamination of the cover plate to core interface in billets cast bonded into Zircaloy-2 jackets resulted in voids or inclusions in the bonds of rolled plates, as shown in Figure 63b.

Careful metallographic examination of Zircaloy-2 cover plate to Zircaloy-2 side strip roll bonds on all plates from billets with cast-bonded side strips disclosed varying degrees of bond line imperfections. These ranged from voids, as shown in Figure 64a, to discontinuous bands of inclusions, as in Figure 64b, and a nearly perfect bond except for a few scattered inclusions, as in Figure 64c. The best bond was obtained in plate No. 89 after rolling 90% reduction in thickness at 900°C. Incomplete Zircaloy bonds in these plates could only result from the presence of a contaminant at the interface. Interference from inadequately cleaned cover plate stock was a possibility. It is also quite probable that contaminants in the form of oil, dirt, or solvent could have penetrated into porosity at the cast core to side strip interface ultimately affecting the cover to side strip bond.

FIGURE 62. Side Strip to Core Bond in Plates Rolled from Billets with Cast-Bonded Side Strips.

62a. Side strip to core bond from plate No. 51 rolled 80% reduction in thickness at 800°C.

62b. Side strip to core bond from plate No. 75 rolled 80% reduction in thickness at 800°C.

FIGURE 63. Cover Plate to Core Bonds in Clad Plate Rolled from Billets Prepared with Cast-Bonded Cladding Components.

63a. Cover plate roll bonded to core from billet No. 51 with cast bonded side strips.

Zircaloy-2
Cover Plate

Diffusion Layer

Uranium
Alloy
Core

Micro 16387

Bright Field

250X

63b. Cover plate to core bond on plate rolled from billet No. 60 with core cast into fabricated Zircaloy-2 jacket.

Zircaloy-2
Cover Plate

Diffusion Layer

Uranium
Alloy
Core

Micro 16414

Bright Field

250X

FIGURE 64. Zircaloy-2 Cover Plate to Zircaloy-2 Side Strip Bond Defects in Plate Rolled from Billets with Cast-Bonded Side Strips.

64a. Voids in cover plate to side strip bond in plate No. 75 rolled 80% reduction in thickness at 800°C.

Zircaloy-2
Cover
Plate

Bond
Zircaloy-2
Side Strip

Micro 16630 Bright Field 250X

64b. Discontinuous band of inclusions in cover plate to side strip bond in plate No. 80 rolled 80% reduction in thickness at 800°C.

Zircaloy-2
Side
Strip

Zircaloy-2
Cover
Plate

Micro 16810 Bright Field 250X

64c. Scattered inclusions in cover plate to side strip bond in plate No. 89 rolled 90% reduction in thickness at 900°C.

Zircaloy-2
Side
Strip

Zircaloy-2
Cover
Plate

Micro 16813 Bright Field 250X

Casting the core alloy into fabricated Zircaloy-2 jackets obviates the need for a roll bond between cover plate and side strip. Unfortunately, fabricating these jackets by welding resulted in some contamination at the weld which was augmented by heating for casting.

Cast bonding core alloy to Zircaloy-2 side strips or prepared Zircaloy-2 jackets did effect a side strip bond. These cast billets could be fabricated into flat plates by rolling without rupturing the initial bond. Further development of this technique to control dimensional variables and contamination of the cladding would be justified in the event that integral clad bonds could not be obtained by the modified picture frame technique. For either process satisfactory integrally bonded end closures were sought. Variables in billet and design which would minimize or eliminate the irregular end effect at the core to end plug transition during rolling were investigated in both modified picture frame-type billets and the above cast-bonded billets.

Elimination of End Effects at the Cladding End Plug to Core Transition in Rolled Plates

The severe end irregularities with thin face cladding and total plate thickness variations of 50% or more which occurred at the clad-to-core junction at both ends of rolled 1/8" thick flat plates could not be tolerated in a finished fuel plate. Although this type of defect may be due to differential hot-working properties of the core and cladding, variations in the roll bonding temperature from 750°C to 850°C did not alleviate the condition. Changing other variables, such as reduction on rolling and type of protective steel jacket used with the cladding billet, did not improve the plate ends.

Previous practice⁽⁹⁾ for closing plate ends consisted of rolling plates oversize on length, cutting them to the desired length by removing uneven or unbonded end sections, and then sealing the exposed core. Sealing was done by etching the exposed core material from the ends to a depth of 3/16", inserting Zircaloy-2 filler strips, and then fusing the insert to the cladding with inert-gas tungsten-arc welding. The weld penetration between the Zircaloy-2 side cladding and insert was generally poor, as may be seen in the radiograph of Figure 65. Because of the poor weld seal and lack of bond between core and cladding at the plate end, it was imperative that a satisfactory rolled end be developed for clad plates.

In addition to the differential rolling characteristics of the core and cladding affecting rolled plate ends, particularly in the case of a softer core material becoming extruded into cladding interfaces, some of the mechanics of rolling might contribute to end defects. Possibilities which were suggested included horizontal shear of the entire billet on the longitudinal axis, localized shear at the clad-to-core interface due to shifting of the

Figure 65. Print of Radiograph of Roll-Clad Fuel Plates with Ends Sealed by Welding.

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components in the steel jacket, or localized shear at this interface in the event that the forces applied by the top and bottom rolls were not parallel to the interface. Combinations of these shearing stresses could be expected to occur in billets which bowed or rippled during rolling or failed to enter the roll pass on the true centerline of the rolls. On the assumption that the vertical interface between the core and cladding was not upset uniformly during rolling because of either general or localized shearing stresses, a number of cladding billets were designed with the object of either eliminating the vertical interface or distributing the roll stresses over a longer transition area.

Three basic variations in billet design were studied for improved roll-bonded plate ends. The first included billets with preshaped core ends and matching end plugs to eliminate the vertical core-to-clad interface. The second variation included billets with increased length of Zircaloy-2 end plugs or with zirconium inserts between the core and Zircaloy-2. The length of the end plug was increased in an attempt to reduce the amount of shear along the length of the plug during rolling. The softer zirconium insert was introduced in an attempt to match the rolling characteristics of the core alloy. For the final variation, billets were prepared with the core cast bonded to a true picture frame with shaped ends both to eliminate the vertical core-to-clad interface and preclude the possibility of components shifting in the billet during rolling.

Billets with Preshaped Core Ends and Matching End Plugs

A total of 22 cladding billets were prepared with preshaped core ends and matching end plugs. These included 14 billets of the modified picture frame type designed specifically to study preshaped core ends, and 8 of the previously discussed billets with cast-bonded side strips which were machined with shaped core ends to supplement data on core end design. Core ends were prepared with chamfered edges, radii on the edges, concave and convex end faces, and ends tapered with included angles ranging from 60° to 120° . A chart of the detailed core end dimensions for these 22 billets is shown in Figure 66. Machined core and end plug components for the first four billets, Nos. 45-48 inclusive, may be seen in Figure 67.

Six of the modified picture frame type of billets, 45, 46, 47, 48, 58, and 63, were patterned after the eleven preliminary billets used to study roll-bonding variables. Core and cladding materials were obtained from the same core casting and Zircaloy ingot stock as was used for the previous billets. Except for the end plugs, the over-all dimensions of components and protective steel jackets were also the same. The remaining eight modified picture frame-type billets were designed to yield plates 0.250" thick with 0.025" of cladding on each face and either 0.125" or 0.250" of cladding on the sides. These plates would be comparable in

FIGURE 66. Core End Dimensions for Cladding Billets with Pre-Shaped Cores and Matching End Plugs.

thickness and cladding to plates proposed for EBWR but somewhat smaller in width and length. The dimensions of the billet cladding components and source of cladding and core materials used for these eight billets are summarized in Table XXXII.

Table XXXII

DIMENSIONS OF COMPONENTS AND SOURCE OF MATERIALS USED FOR CLADDING
BILLETS PREPARED WITH SHAPED CORE ENDS AND MATCHING END PLUGS

Cladding Billet No.	Alloy Core				Zircaloy-2 Cladding									
	Casting No.	Core Dimensions (in.)			Ingot No.	Cover Plate Dimensions (in.)			Side Plate Dimensions (in.)			End Plug Dimensions (in.)		
		Thick.	Width	Length		Thick.	Width	Length	Thick.	Width	Length	Thick.	Width	Length
70	L-121	1.085	1.965	5.738	710D528	0.125	2.215	6.676	0.125	1.085	6.676	1.085	1.965	0.938
71	L-121	1.085	1.965	5.885	710D528	0.125	2.215	6.970	0.125	1.085	6.970	1.085	1.965	1.085
72	L-121	1.085	1.965	6.676	710D528	0.125	2.215	8.552	0.125	1.085	8.552	1.085	1.965	1.876
73	L-121	1.085	1.965	6.676	710D528	0.125	2.215	8.552	0.125	1.085	8.552	1.085	1.965	1.876
82	L-136	1.085	2.078	5.400	710D528	0.125	2.578	7.000	0.250	1.085	5.400	1.085	2.578	1.342
83	L-136	1.085	2.078	5.400	710D528	0.125	2.578	7.000	0.250	1.085	5.400	1.085	2.578	1.342
84	L-136	1.085	2.078	5.400	710D528	0.125	2.578	7.000	0.250	1.085	5.400	1.085	2.578	1.342
85	L-136	1.085	2.078	5.400	710D528	0.125	2.578	7.000	0.250	1.085	5.400	1.085	2.578	1.342

FIGURE 67. Uranium-5 w/o Zirconium-1.5 w/o Niobium Alloy Cores with Shaped Ends and Matching Zircaloy-2 End Plug Components for Cladding Billets.

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Details of material preparation and rolling data for the billets with cast-bonded side strips are included in the section on cast-bonded cladding billets and in Table XXVII. For all other billets with preshaped core ends, the cores were machined to size and cleaned by sandblasting immediately before assembly. The cladding components were pickled in boiling concentrated HNO_3 containing 1 v/o HF. The components were assembled, welded and jacketed in steel cans for rolling by the procedure described for preliminary cladding billets. The smaller billets were jacketed in Ti-Namel cans, as detailed in Figure 45, and the larger ones in SAE 1020 cold-rolled steel cans, as detailed in Figure 68.

FIGURE 68. Design Details for Steel Jackets Used with Cladding Billets Prepared with Pre-Shaped Core Ends.

A temperature gradient between the cladding and core from inadequate preheating of the billet components could be expected to affect the relative hot hardness of components during rolling. Since more accurate data was required on the heating rate for thick billets, $2\frac{1}{2}$ " to 3" thick, which were preheated in a 36-kw Hevi Duty resistance-type furnace, temperature measurements during heating were made on billet No. 85. This billet was modified by inserting a $1\frac{1}{4}$ " deep Zircaloy-2 thermocouple well in the center of one face, as shown in Figure 69. A chromel-alumel thermocouple in a $1/8$ " O.D. Type 302 stainless steel sheath, insulated with magnesia, was inserted in the Zircaloy thermocouple well and seal welded in place. The furnace was brought up to a temperature of

FIGURE 69. Zircaloy-2 Insert for Thermocouple Well in Center of Cladding Billet No. 85.

800°C $\pm$ 2°C and the billet inserted with the sheathed thermocouple leads extended through a 1/2" IPS opening at the rear of the furnace to a temperature-compensated galvanometer potentiometer. A plot of billet temperature vs. elapsed time is shown in Figure 70. Temperature rise at the center of the billet was rapid for the first hour and decreased to a rate of 2°C per minute for the next 30 minutes. The billet required an additional 30 minutes for the temperature to increase the last 10°C to reach equilibrium with the furnace temperature. From these data it was concluded that jacketed billets 2 1/2" thick should be preheated a minimum of 90 minutes, and preferably 120 minutes, to assure uniform heating of all components.

FIGURE 70. Temperature vs. Elapsed Time for Cladding Billet No. 85 Heated in Air at 800°C. (Billet Dimensions - 2.5 x 6" x 11.5")

The assembled cladding billets were all preheated in air in a 36-kw Hevi Duty electric resistance-type furnace. Reduction of the 2½" thick billets was limited to 10% or 12% for the first couple of passes without exceeding the capacity of the 16" x 24" rolling mill. Reductions on subsequent passes were increased to the desired maximum rate. Billets were reheated after every pass through the mill. Data on preheat temperature, preheat time, and the rolling variables for these billets are included in Table XXXIII.

Table XXXIII

ROLLING DATA FOR CLADDING BILLETS WITH PRE-
SHAPED CORE ENDS AND MATCHING END PLUGS

Cladding Billet No.	Preheat and Rolling Temp. (°C)	Preheat Time (min)	Reduction Per Pass (%)	Number of Passes	Reheat Time (min)	Rolling Speed (ft/min)	Total Reduction (%)
45	775	30	17	9	5	75	80
46	775	30	17	9	5	75	80
47	775	30	17	9	5	75	80
48	775	30	17	9	5	75	80
58	775	30	17	9	5	75	80
63	775	30	17	9	5	75	80
70	800	60	10-17	12	10	125	80
71	800	60	10-17	12	10	125	80
72	800	60	10-17	12	10	125	80
73	800	60	10-17	12	10	125	80
82	800	150	10-20	10	10	75	80
83	800	150	10-20	10	10	75	80
84	800	120	10-24	12	8	75	90

In addition to the primary evaluation of rolled-plate ends, physical measurements and metallographic examination were made on plates rolled from billets with shaped-core ends. These additional data were obtained as a further check on roll-cladding variables. A cladding thickness analysis was made on plates rolled from billet Nos. 45-48 inclusive, 58, 63, and 71-73 inclusive. The plates were sectioned longitudinally down the centerline normal to the rolling plane. The sections were polished, etched, and cladding thickness measurements taken on both sides at 0.10" intervals along the length by the same procedure described for preliminary clad plates. Data obtained from this analysis are given in Table XXXIV. Measurements of the rolled-plate dimensions and effect of rolling variables on width changes are summarized in Table XXXV.

Table XXXIV

CLADDING THICKNESS ANALYSIS OF ROLL-CLAD PLATES WITH SHAPED CORE ENDS

Cladding Billet No.	Cladding Dimensions (mils)				Min. Cladding Thickness at Tapered Ends
	Avg.(1) Thickness	Avg.(2) Deviation	Range of Deviation(3)	Min. Cladding Thickness Between Tapered Ends	
45	15.3	1.02	+3.7 to -2.1	13.2	10.1
46	16.1	0.57	+2.1 to -2.1	14.0	9.4
47	15.9	0.53	+2.3 to -3.5	12.4	11.1
48	16.3	0.96	+2.9 to -2.0	14.3	8.1
58	16.4	0.95	+3.2 to -2.8	13.6	1.5
63	16.4	0.95	+3.0 to -2.5	13.9	1.3
70	20.7	0.88	+3.8 to -2.6	18.1	13.1
71	21.1	0.92	+3.4 to -4.0	17.1	14.5
72	19.8	1.97	+3.3 to -5.0	14.8	15.0
73	19.4	1.69	+4.2 to -6.0	13.4	14.0

(1) Determined by averaging thickness measurements taken at 0.100" intervals on both sides of a longitudinal cross section of the plate.

(2) Determined by summing the differences between average cladding thickness and each measurement, and dividing by the total number of measurements.

(3) Greatest positive and negative deviation observed.

Table XXXV

PHYSICAL MEASUREMENTS OF ROLL-CLAD PLATES WITH SHAPED-CORE ENDS

Cladding Billet No.	Rolled Plate Dimensions (in.)			Width Increase (%)
	Thickness	Width	Length	
45	0.130	1.983	15-7/8	10.2
46	0.130	1.981	15-7/8	10.0
47	0.129	1.963	16-1/8	9.0
48	0.128	1.994	15-5/8	10.8
58	0.133	1.970	16-5/8	9.5
63	0.135	1.991	16	10.6
70	0.243	2.442	34-3/4	10.3
71	0.244	2.440	36-5/16	10.2
72	0.241	2.431	44-1/8	9.8
73	0.239	2.438	44-1/16	10.1
82	0.257	2.849	35-1/8	10.5
83	0.259	2.857	34-3/4	10.8
84	0.132	2.869	65-3/4	11.3

Evaluation of plate ends for all plates with preshaped core ends, including those rolled from billets with cast-bonded side strips, was made by examining the plate surface at the core to end cladding transition. The length of core which was distributed or tapered along this transition area in a transverse section of the plate end was also measured. Results of this evaluation are given in Table XXXVI. Metallographic examinations were made of the clad-to-core bonds at the face, sides, and ends, and Zircaloy cover plate to side cladding bonds of all plates rolled from the modified picture frame-type billets, Nos. 70-73 and 82-84, inclusive.

Table XXXVI

PLATE END EVALUATION OF ROLL CLAD PLATES WITH SHAPED CORE ENDS

Cladding Billet No.	Type of Shaped Core Ends ⁽¹⁾	Length of Affected Core End as Rolled (in.)	Appearance of Plate at Core Ends
45	1/4" convex radius at ends.	0.975	Plate surface smooth but thicker at ends. Core 0.020" thicker at ends.
46	1/8" radii at top and bottom edges both ends.	0.610	Surface depressions and bumps at plate ends. Considerable cladding variations. Core 0.018" thicker at ends.
47	60° included angle taper at ends. Core 0.450" thick.	1.940	Plate surface smooth. No irregularity at ends. Uniformly tapered core end.
48	120° included angle taper at ends.	0.760	Plate ends 0.025" thicker than center of plate. Cladding variations similar to 46 above.
58	1/4" concave radius at ends.	0.420	Severe surface irregularities at core ends. Cladding only 0.0015" thick at core ends.
63	Same as 58 above.	0.420	Same as 58 above.
70	0.469" long x 30° chamfer at ends.	2.375	Slight bump on surface at core end. Fairly uniform transition from core to end plug.
71	90° included angle taper at ends. Core 1.085" thick.	2.687	No visible irregularity in transition from core to end plug.
72	60° included angle taper at ends. Core 1.085" thick.	4.687	No irregularity in transition from core to end plug. Objectionably long core taper.
73	Same as 72 above.	4.687	Same as 72 above.
74	Same as 71 above.	2.687	Same as 71 above.
75	Same as 70 above.	2.375	Same as 70 above.
78	90° included angle taper at ends. Core 0.863" thick.	1.750	Slight irregularity on surface at core end. Uniform taper of core end.
79	0.373" long x 30° chamfer at ends.	1.500	Bump & depression on surface at core end. Fairly uniform transition through tapered core end.
80	Same as 71 above.	2.687	Same as 71 above.
81	Same as 71 above.	2.687	Same as 71 above.
82	Same as 71 above.	2.687	Same as 71 above.
83	Same as 71 above.	2.687	Same as 71 above.
84	Same as 71 above.	5.375	No irregularity in transition from core to end plug. Objectionably long core taper.
89	90° included angle taper at core. 60° taper at Zircaloy to steel can end plugs.	5.375	No irregularity in transition from core to end plug. No advantage from end plug to can taper.
90	100° included angle taper at ends.	1.812	Some surface irregularity in transition from core to end plug with 10% thickness variation.

⁽¹⁾ See Figure 66 for Core End Details.

Physical measurements of rolled plates show that all plates were rolled to within 5% of the desired finished thickness with less than 0.002" variation in thickness for plates rolled according to the same rolling schedule. The width increase on rolling was fairly uniform for all plates and did not appear to be affected by a difference of 25°C in the rolling temperature or by the initial billet thickness. This width increase, 9% to 11%, was of the same magnitude as noted in Tables XXII and XXVIII on other roll-clad plates. Considerable range in rolled-plate length resulted from length variations in the initial billet and variations in the total reduction on rolling. Cladding thickness analyses for the six small plates rolled at 775°C indicated little difference between plates except for the ends. The cladding variation of ± 2 to 4 mils was comparable to that of other plates rolled at temperatures of 775°C or less, and not as uniform as on plates rolled at higher temperatures. A plot of the cladding thickness measurements for plate No. 47 is shown in Figure 71.

It was apparent from the first six plates rolled from billets with preshaped core ends that a proper design of cladding billet would eliminate all irregularities at the core to end cladding transition in rolled plates. The photomacrograph of the cross section of rolled plate ends in Figure 72a illustrates the effects of five different core end shapes on the surface irregularities and core distribution at the ends of these rolled plates. The rolled ends of plate No. 63 with severe irregularities and a minimum cladding thickness of only 1.3 mils at the core end were identical in appearance to the ends of plate No. 58. Of these six plates, plate No. 47 was the only one which had a smooth surface finish at the ends, showed no visible transition from core-to-clad at the plate ends, and a uniformly tapered core throughout the end section. The core for cladding billet No. 47 was preshaped with 60° included angle tapered ends. Plate end sections from plate Nos. 70-73, inclusive, are shown in Figure 72b. The most uniform plate thickness and core taper were again observed from billets with preshaped cores with 60° included angle tapered ends. Although the core was not as well centered at the end of plate No. 75, which had been rolled from a billet with 90° included angle preshaped core ends, the surface finish at the plate ends and thickness uniformity of this plate were good. Considerable irregularity occurred at the end of the core in plate No. 70 rolled from a billet with a 30° x 0.469" long chamfered core end. The same effect from a chamfered core end on plate No. 75 may be seen more clearly in Figure 72c. The length of tapered core developed in 0.250" thick plate after rolling 80% reduction in thickness exceeded $4\frac{1}{2}$ " from billets with 60° included angle preshaped core ends. This type of end was exceptionally uniform but constituted too much of the plate length for practical use in fuel plates designed with 4-ft long cores. Even though the surface was not uniform, good transition between core and cladding with only $2\frac{11}{16}$ " of core end taper in 0.250" thick plate was obtained at the ends of plates rolled from billet cores preshaped with a 90° included angle. The same results were obtained with shaped core ends on billets with cast bonded side strips as with the modified picture frame billets.

FIGURE 71. PLOT OF CLADDING THICKNESS MEASUREMENTS ALONG THE LENGTH OF ROLLED PLATE NO. 47.

FIGURE 72. Sections Through Ends of Plates Rolled from Billets With Shaped Core Ends. Light area is Zircaloy-2 cladding; dark area surrounded by Zircaloy is alloy core.

72a. Longitudinal section through one end of plate Nos. 45, 46, 47, 48, and 58.

72b. Longitudinal section through one end of plate Nos. 70, 71, 72, and 73.

72c. Longitudinal section through both ends of plate No. 75.

Complete clad-to-core bonds were noted on metallographic examination of sections from all clad plates. The presence of uniform diffusion layers and the absence of voids or inclusions in bonds between the cladding and the core at the sides, covers, and tapered end sections on all plates indicated that satisfactory diffusion bonds had been obtained. As long as reproducible clad-to-core bonds could be obtained along the sides and at the ends of rolled plate from billets with modified picture frame component assemblies, integrally clad plates could be developed without cast bonding the side strips or welding the core end closure.

The bonds between Zircaloy-2 cover plate and Zircaloy-2 side strip components in this group of plates all showed varying amounts of segmented, discontinuous, or pin-point type of inclusions. Separate Zircaloy bond studies, Table X, had shown that these inclusions were probably the result of contamination.

Billets with Increased Length of End Plugs and Zirconium
Inserts between Core and End Plug

Possible improvements in the end effect on rolled-clad plates were expected by either increasing the length of the cladding end plug to reduce shear along the length of the plug during rolling or by inserting a softer zirconium plug between the core and end plug to more nearly match the rolling characteristics of the core. If successful, this type of end plug could effect a saving in both machining time and material loss compared with a shaped core end and matching end plug. Seven billets were prepared with end plug variations of this type, four of which were modified picture frame billets, and the remaining three were cast-bonded side strip billets. Descriptions of the billet and plugs are included in Table XXXVII.

Table XXXVII

CLADDING BILLETS WITH INCREASED LENGTH OF
ZIRCALOY-2 END PLUGS AND ZIRCONIUM INSERTS

Cladding Billet No.	Core Casting No.	Zircaloy-2 Cladding	Type of Core Ends
66	L-118	710D528	Squared ends with 1" long Zircaloy-2 end plugs.
67	L-118	710D528	Squared ends with 1" long Zircaloy-2 end plugs with 1" long sponge zirconium plugs between core and Zircaloy-2.
68	L-118	710D528	Squared ends with 0.938" long 60° included angle sponge zirconium inserts between core and Zircaloy-2 end plugs.
69	L-118	710D528	Same as 68 above.
76 *	L-134	710D528	Squared ends with 1" long Zircaloy-2 end plugs.
77 *	L-132	710D528	Squared ends with 2" long Zircaloy-2 end plugs.
91 *	L-140	1X081	Squared ends with 1.746" long Zircaloy-2 end plugs having 60° included angle at Zircaloy-2 end plug to steel can end.

* Cast-bonded side strip billet (see Table XXVI).

The preparation of materials and assembly of components for the billets followed the same procedure used with preceding billets of the same type. Details of the fabrication and rolling of the cast-bonded billets has been described. The assembled billets were roll clad in SAE 1020 welded steel cans of the size shown in Figure 68. All four cladding billets were preheated 60 minutes at 800°C, reheated 10 minutes between passes, and rolled 10% to 17% per pass at 125 ft/min to a total reduction of 80% in thickness. These billets were rolled before the 90-minute minimum heating rate had been established with billet No. 85. Decanned plates were physically inspected, measured, and then sectioned for examination of the core to end plug transition at the plate ends and metallographic examination of all bonds. Plate measurements and end evaluation for plates rolled from billets 66-69, inclusive, are given in Table XXXVIII.

Table XXXVIII

PHYSICAL MEASUREMENTS AND PLATE END EVALUATION FOR
PLATES ROLLED FROM BILLETS WITH INCREASED LENGTH OF
ZIRCALOY-2 END PLUGS AND ZIRCONIUM INSERTS

Cladding Billet No.	Rolled Plate Dimensions (in.)			Width Increase (%)	Plate End Evaluation ⁽¹⁾
	Thickness	Width	Length		
66	0.228	2.431	36-1/8	9.8	Severe irregularities in core and cladding thickness at core to end plug transition at both ends.
67	0.227	2.433	44-9/16	9.8	Same as 66 above.
68	0.238	2.419	44-5/16	9.2	Same as 66 above.
69	0.240	2.422	44-1/8	9.4	Same as 66 above.

⁽¹⁾Plates rolled from cast bonded side strip billets 76, 77, and 91, all exhibited end defects similar to 66-69 inclusive.

None of the plates rolled from billets prepared with additional length of Zircaloy-2 end plug or with a zirconium insert between the Zircaloy end plug and the alloy core showed any improvement as a result of this change in end plug design. Irregularities at the core to end plug transition in rolled plates were as bad as in all previous plates rolled from billets with a vertical interface between the core and end plug. Longer end plugs or change in material did not prevent longitudinal displacement or shearing of components and evidently would not eliminate rolling defects at the plate end. Acceptable rolled end closures would have to be made from billets with tapered core ends and matching end plugs.

The clad-to-core bonds at the sides and faces of plates from billets 66-69, inclusive, were all sound. The core was not completely bonded at the plate ends with intermittent cracks at the interface. As in previous plates, the cover plate to side strip bonds were found to contain segmented inclusions in the bond line.

Billets with Core Alloy Cast into a True Picture Frame Type of Mold

A true picture frame type of Zircaloy mold was designed with shaped ends, as shown in Figure 73, in which the core alloy could be cast bonded to the Zircaloy comprising the sides and ends of a cladding billet. It was expected that this type of billet would eliminate shifting of the components relative to one another during the early stages of rolling, assuring more uniform rolled-plate ends. This design would provide an integral seal of the cladding components at the ends of rolled plates eliminating the need for a diffusion bond at the end plug to side strip interface which is normal to the rolling plane and not subject to forces which would effect a Zircaloy-to-Zircaloy roll bond. Unfortunately, the extensive machining required to make this mold and the amount of scrap Zircaloy which would be generated by the machining would detract from its use for quantity production of fuel elements. Photographs of machined molds prior to casting are illustrated in Figure 74. To simplify the machining operations at the ends of the mold, separate shaped end plug inserts were made for two of the molds as shown in Figure 75.

FIGURE 73. Zircaloy-2 Picture Frame Mold.

FIGURE 74. Machined Zircaloy-2 Picture Frame Mold with Shaped Ends Integral with Sides.

106-1592

FIGURE 75. Machined Zircaloy-2 Picture Frame Mold with Shaped End Inserts.

106-1591

Preparation of the mold, preheating, and melting and casting of the core alloy are described in other reports.⁽¹⁹⁾⁽²⁰⁾ The top and bottom views of a finished casting before machining, No. L-151, are shown in Figure 76. Figure 77 shows a longitudinal section through the center and a transverse section at one end of casting No. L-151 after machining. This casting completely filled the mold with core alloy with no porosity at the Zircaloy to uranium alloy interface. Adherent bonds developed between the core and sides of the mold but the ends were not completely bonded as a result of core shrinkage during solidification.

Three cast cladding billets were prepared to be rolled into $1/4$ " thick plates with 0.025" of cladding on each face, $1/8$ " on the sides, and approximately $4\frac{3}{8}$ " at the ends. The Zircaloy molds were machined from forged and rolled Ingot No. 710D528 and cleaned by degreasing in carbon tetrachloride and absolute alcohol before casting. Excess core alloy was machined from the top and bottom faces of the three castings, L-152, L-153, and L-154, and machined core and cladding were degreased in carbon tetrachloride, rinsed in absolute alcohol, and dried in vacuum. Top and bottom cover plates were machined to width, length, and thickness. Cold rolled Zircaloy plate, 0.135" thick, was finished to the desired 0.125" thickness by machining 0.005" from each face on a vertical milling machine using a fly cutter. Cover plates were degreased in the same manner as for the machined casting and dried in vacuum.

The cover plates and cast-bonded components were assembled and press-welded to seal the edges by the previously described procedure used for modified picture frame billets. A pressure of 4 tons/in.² was applied to the sandwiched components during welding. Welded assemblies were sealed in machined SAE 1020 cold-rolled steel cans, as detailed in Figure 68, for subsequent roll cladding.

All three cladding billets, Nos. 86, 87, and 88, were preheated and rolled at 800°C. Billet No. 86 was preheated 120 minutes; the other two were preheated 60 minutes. Reductions of 10% to 18% per pass were made by rolling at 75 ft/min, followed by a 10-minute reheat after each pass. Total reduction on all billets was 80%.

Physical measurements were made of rolled plates and the plate ends evaluated at core to end cladding transition. Plate Nos. 86 and 88 were sectioned for examination of core-to-clad bonds and Zircaloy-to-Zircaloy bonds between the cover and the sides and ends of the plate. Plate No. 87 was heat treated after being decanned. The heat treatment consisted of heating in carbonate salt at 850°C for $1/2$ hour followed by a water quench. Although this heat treatment might not be desirable for ultimate stability of fuel plates, it could be expected to simulate the most severe thermal stresses encountered by other possible heat treatments. After quenching, the plate was overaged in air for two hours at 500°C to

FIGURE 76. Uranium-5 w/o Zirconium-1.5 w/o Niobium Cast into
A Machined Zircaloy-2 Picture Frame Mold.

76a. Top view of casting No. L-151.

Macro 16531

3/4X

76b. Bottom view of casting No. L-151.

Macro 16532

3/4X

destroy the corrosion resistance of the supersaturated alpha phase in the core alloy. The plate was then cleaned by wet abrasive blasting with 325 mesh Al_2O_3 , followed by an acid pickle for 10 seconds in cold 35-5 HNO_3 -HF, and rinsed in running tap water. The cleaned plate was submitted to the Corrosion and Irradiation Testing Group of the Reactor Engineering Division for corrosion testing in static water at 290°C (550°F).

FIGURE 77. Sections Through Center and End of Casting L-151 Showing Distribution of Cast Core Alloy in Zircaloy-2 Picture Frame Mold.

Macro 16600

3/4 X

Data from physical measurements and examination of the rolled plates are given in Table XXXIX. Billet No. 86, which was preheated for 120 minutes, evinced a greater spread on rolling than billets preheated only 60 minutes. Similar effects had been noted previously (see Tables XXVII and XXVIII). The surface finish and core to end cladding transition on all three of the plates rolled from cast picture frame billets were excellent.

Plate No. 87 exhibited an adherent gray to black coating over the entire surface after testing in water at 290°C for 1,865 hours. Continued testing for a total of 9,794 hours showed selective attack over an area $1/4'' \times 1/8''$ along one edge from prerolling weld contamination. No additional change was noted after 12,770 hours of testing. There was no selective bond line attack at the sides or ends of the plate after corrosion testing.

Table XXXIX

PHYSICAL MEASUREMENTS AND PLATE END EVALUATION FOR PLATES
ROLLED FROM BILLETS WITH THE CORE CAST BONDED TO A ZIRCALOY-2
PICTURE FRAME-TYPE MOLD

Cladding Billet No.	Rolled Plate Dimensions (in.)			Width Increase (%)	Plate End Evaluation
	Thickness	Width	Length		
86	0.259	2.504	34-7/8	13.0	Core end tapered 2-11/16" with no visible irregularity in transition from core to end cladding.
87	0.252	2.466	35-7/16	11.3	Same as 86 above.
88	0.258	2.469	35-3/4	11.5	Same as 86 above.

All clad-to-core interfaces of the sectioned plates showed sound metallurgical bonds. The Zircaloy cover plate to Zircaloy side and end cladding bonds contained segmented inclusions throughout approximately 50% of the bond interface. There was no apparent difference in the quality of Zircaloy bonds between plates 86 and 88 as a result of preheat variables. Nor was there any noticeable improvement in the quality of Zircaloy bonds as a result of changes in the preparation and cleaning of the Zircaloy components as compared with Zircaloy bonds from previously rolled cladding billets.

Conditions which contributed most to rolled-plate end defects were extrusion of core alloy between cladding components, particularly at the trailing end of the billets during rolling, and slipping of the core end faces relative to the end plugs. Core extrusion could be overcome by reversing the rolling direction of the billet after each pass and by eliminating sharp corners at core ends which were adjacent to the cladding cover plate and end plug interface, as noted on plates rolled from all billets prepared with chamfered, rounded, or tapered cores. Slipping at the core to end plug interface occurred with uneven deformation of the top and bottom half of billet components, such as bowing during rolling or shearing along a longitudinal plane during rolling. This slipping resulted in uneven deformation of the face cladding with a large cladding thickness variation at the ends of rolled plates. By tapering the core ends and providing a matching taper for the end plugs, the amount of slip which occurred at the core to end plug during rolling was reduced with a corresponding improvement in the surface of rolled plate ends. Consequently all plates which were rolled from billets with core ends tapered to an included angle of 90° or less exhibited the least dislocation relative to the end plugs during rolling with a corresponding improvement in plate end irregularities.

DEVELOPMENT OF INTEGRAL ZIRCALOY-TO-ZIRCALOY BONDS IN ROLL-BONDED FLAT PLATES

Elimination of Introduced Contamination Leading to Zircaloy-to-Zircaloy Bond Defects in Roll-Clad Plates

There seemed to be no question but that sound bonds could be obtained between the uranium-5 w/o zirconium-1.5 w/o niobium alloy core and Zircaloy-2 cladding material. Plates with integral clad-to-core bonds at the sides, faces, and ends were acquired with considerable latitude in rolling variables and from billets prepared from various assembled components or by cast bonding. Yet none of these processes yielded satisfactory Zircaloy-to-Zircaloy bonds completely free from intermittent voids or inclusions. Plates rolled from billets with components prepared by procedures developed expressly to effect sound cladding bonds, as shown in Table X, invariably had defective Zircaloy bonds as though additional contamination had been introduced with the assembly or roll-cladding process.

The extent of contamination in cladding bonds was not observed on the first 20 experimental billets rolled. The etchant first used on metallographic specimens, $\text{AgNO}_3\text{-HF}$, did not delineate bond line inclusions as clearly as $\text{HNO}_3\text{-HF}$, which was used later. This is illustrated by a comparison of the two etchants on a bond line in the photomicrographs of Figure 78. The use of nitric-hydrofluoric acid etchant led to the development of a metallographic technique which made it possible to observe bond line inclusions with oblique lighting on a low-power binocular microscope after a comparatively rapid preparation of the specimen. Samples cut from clad plate with an abrasive cut-off wheel were polished by grinding to 600 grit on wet abrasive paper and etched in the boiling concentrated $\text{HNO}_3 + 1 \text{ v/o HF}$ solution used to clean cladding billet components. In this way a liberal number of clad sections from a rolled plate could be analyzed for bond quality in just a few hours.

The large number of inclusions which persisted at the Zircaloy bond lines were assumed to have originated from entrained gases (oxygen or nitrogen) during billet assembly, preheating for rolling, or roll cladding. Optimum roll fabrication and cleaning processes were found which resulted in a microscopically clean Zircaloy-2 sheet and plate as discussed in the section on preparation of cladding material. Assuming that cleaned components were maintained in a clean, dust-free atmosphere until they were assembled into cladding billets, the possibility of foreign particles on the surface of the Zircaloy causing inclusions was negligible. A number of tests were made to establish the extent of contamination from gases during assembly, heating, and rolling of billets, and to find ways of minimizing such contamination.

FIGURE 78. Zircaloy-2 Cover Plate to Zircaloy-2 Side Strip Bond in Plate No. 70 Rolled 80% Reduction in Thickness at 800°C.

78a. Specimen etched with 3 gm AgNO_3 -5 cc HF- 92cc H_2O . Inclusions in bond which extends from upper left to lower right in photomicrograph are obscure.

Direction
of Bond

Zircaloy-2
Side Strip

Zircaloy-2
Cover Plate

Alloy Core

Micro 16760

Bright Field

250X

78b. Same specimen used for 78a above repolished and etched with 10 v/o HNO_3 -2 v/o HF. Bond in same location of specimen as in 78a shows line of segmented inclusions from upper left to lower right.

Direction
of Bond

Zircaloy-2
Side Strip

Zircaloy-2
Cover Plate

Alloy Core

Micro 16738

Bright Field

250X

Contamination Related to Billet Assembly Press-Welding Operations

During the press-welding operation in which the cladding components were fused together at all seams to completely jacket and seal the uranium alloy core for subsequent roll bonding, a considerable amount of heat was dissipated into the Zircaloy adjacent to the weld area. Formation of dark blue or even black oxide films on the exterior surfaces of billet components and on the weld metal surfaces were not objectionable provided they did not influence the interior bonds. External contamination could be removed from the surface of rolled plates to provide a corrosion-resistant surface. Water-cooled copper chills in contact with the top and bottom faces of the billet components were designed to prevent the interior surfaces from overheating and from oxidizing. The amount of gas or air which was trapped in the billet between components was kept to a minimum by maintaining a close fit between machined components, clamping side strips and end plugs to the core, and applying several tons/in.² of pressure to the cover plates. The small amount of residual air trapped in the billet, being mainly nitrogen and oxygen, should theoretically be absorbed and diffused into the core or cladding during roll bonding without sufficient compounds being formed at the component interfaces to affect the bond. As a measure of the effectiveness of the press-welding in minimizing internal contamination, several test plates were welded around a core and then opened for examination.

Test welds were made with sections of Zircaloy-2 cover plates and side strips assembled around a machined uranium alloy core. End plugs were eliminated in order to simplify removal of the core from the welded components. Width and thickness of the machined core were 1.953" and 1.084", respectively. The weld components consisted of cover plates, 1/8" thick x 2.353" wide, and side strips, 1/4" thick, of different predetermined widths. Sets of side strips were machined to widths of 1.074", 1.079", 1.084", 1.086", 1.087", and 1.089" to produce intentional gaps between cladding side strip and cover plate at the weld on two assemblies, and between the core and cover plate at the top of three other assemblies. The cladding components were cleaned by wet abrasive blasting in 325 mesh alumina, thoroughly pickled in the boiling HNO₃-HF, rinsed in running tap water, hot distilled water, and absolute alcohol. Components were assembled around the core, the side strips clamped in place, and the cover plates and core sandwiched between water-cooled copper chills at a pressure of 6 1/2 tons/in.². The side strip to cover plate joints were arc welded with a 1/16" diameter tungsten electrode shielded with helium. After welding, the top cover was broken loose from the side welds, the core removed, and the internal surfaces of the Zircaloy examined for oxide contamination.

Photomacrographs of representative components after welding are shown in Figure 79. Components with 1.074" and 1.079" wide side strips (0.010" and 0.005" wide gaps between top cover plate and side strip) showed severe discoloration, with black and dark blue oxide at the side strip to cover plate interface and at the side strip to core interface. Contamination at the side strip to core interface was largely due to heating required to fuse metal across the gap which existed at the interface and the greater access of air to exposed surfaces in the interface. Components with side strips which were 1.084" wide, the same width as the alloy core thickness, exhibited practically no discoloration of the cover plate and only a faint straw-colored coating at the side strip to cover plate interfaces. Considerable dark oxide could be seen at the side strip to core interface. The three sets of components having side strips wider than the alloy core, 1.086", 1.087" and 1.089" wide, all of which had gaps between the alloy core and the top cover plate, showed little or no discoloration at the cladding side strip to cover plate interface, and very little straw-colored contamination on the cover plate itself. It was noted that the side strip to core interface was again badly contaminated.

Since all side strips which were adjacent to the core but not chilled during welding were badly contaminated, and all cover plates which were not actually in contact with the core but were cooled during welding exhibited almost no contamination, it was concluded that adequate cooling of the components during welding would do more to reduce internal contamination than close contact between core and cladding. Close contact between Zircaloy cladding surfaces was essential to reduce contamination during welding. To provide suitable chills for the wide side strips in cladding billets to be rolled to 1/4" thick plate by 80% reduction in thickness, and hydraulic side pressure to improve contact of mating Zircaloy components, a horizontal press attachment, as illustrated in Figure 80, was designed for use in the existing vertical press.

Two billets were prepared with the objective of avoiding contamination from surface impurities in the Zircaloy, trapped gases in the press-welded billet, and gases absorbed during welding, by completely machining all Zircaloy surfaces, assembling the components loosely in welded steel cans, and evacuating and sealing the cans for rolling. Zircaloy for these two billets, Nos. 92 and 93, from forged and rolled ingot No. 710D530, was machined to size, degreased in trichloroethylene, rinsed in absolute alcohol, and dried in vacuum before assembly. The uranium alloy cores from castings L-127 and L-126 for billets 92 and 93, respectively, were machined, sandblasted, rinsed in alcohol, and dried in vacuum. Dimensions of these components are shown in Table XL. The jackets used for these billets were machined from cold-rolled SAE 1020 steel, the same as those detailed in Figure 68. The steel jacket sides and bottom end plug were welded, the core and cladding components inserted, and the top end plug welded in place. The top end plug contained a seal-welded evacuation tube made of 1/2" O. D. x 1/4" I. D. x 18" long seamless mechanical tubing.

FIGURE 79. Zircaloy-2 Cover Plate and Side Strip Components after Press-Welding in Air Around an Uranium Alloy Core. Contamination is shown on internal surfaces of Zircaloy components.

79a. Gap 0.010" wide between top cover plate and side strips as assembled for welding.

Macro 16681

3/4 X

Macro 16683

3/4 X

79b. Side strips same width as core thickness as assembled for welding.

3/4 X

Macro 16686

79c. Gap 0.006" wide between top cover plate and core as assembled for welding.

FIGURE 80. Horizontal Press Attachment with Water Cooled Copper Chills for Press-Welding Cladding Billets

VIEW A A
(Typical For Four Posts)

Table XL

DIMENSIONS OF COMPONENTS FOR CLADDING BILLETS
PREPARED TO STUDY CONTAMINATION DURING
ASSEMBLY, HEATING, AND ROLLING

Component	Thickness (in.)	Width (in.)	Length (in.)
Core ⁽¹⁾	1.080	1.953	5.400 ⁽²⁾
Cover Plate	0.125	2.453	7.000
Side Strip	0.250	1.080	7.000
End Plug	1.080	1.953	1.340 ⁽²⁾

(1) Core designed with 90° included angle shaped ends.

(2) Over-all length including tapered portion.

The jacket welds on billet No. 92 were helium leak tested, the billet evacuated overnight to an absolute pressure of 5×10^{-6} mm of Hg, and the evacuation tube sealed by heating with an acetylene torch and forge welding. Billet No. 93 was also leak tested and evacuated to 5×10^{-6} mm of Hg at which time it was heated for six hours at 850°C while still connected to the vacuum system in order to outgas the steel and cladding billet components. The billet was then sealed in the same way as was done for No. 92. Both billets were preheated two hours at 850°C and rolled at 850°C at a speed of 125 ft/min with reductions of 11% to 18% per pass. The billets were reheated 10 minutes after every pass. Total reduction in thickness on rolling was 80%. The roll-clad plates were decanned and sectioned for metallographic examination.

Satisfactory core to cladding bonds were obtained on both rolled plates. All Zircaloy-to-Zircaloy bonds were no better than on plates rolled from press-welded cladding billets. The cover plate to side strip bonds in plate No. 92 were very poor, with continuous lines of inclusions. All cover plate to side strip bonds in plate No. 93 were much better than in plate No. 92, but with thin, semicontinuous lines of dotted inclusions which were visible at a magnification of 200X. It was evident that outgassing billet No. 93 before rolling had helped reduce contamination, but that this outgassing was either inadequate or contamination from some other source was introduced during heating and rolling.

A further check was made of contamination from gases trapped during press-welding of billets and the feasibility of diffusing this contamination into the cladding at an elevated temperature. Components having the same dimensions as those shown in Table XL were prepared

from core casting No. L-125 and Zircaloy forged and rolled from ingot No. 710D530. The cores were cleaned by sandblasting, followed by an alcohol rinse and drying in vacuum. All Zircaloy was acid bright dipped in boiling concentrated HNO_3 with 1.0 v/o of HF, and rinsed in tap water and hot distilled water. Two billets, Nos. 102 and 113, were assembled and press-welded by the procedure described for previous roll-bonding tests. Billet No. 113 was opened immediately after welding for examination of the internal surfaces of cladding components. Billet No. 102 was heated three hours in a minimum vacuum of 1.5×10^{-5} mm of Hg at a temperature of 1100°C and allowed to furnace cool overnight in vacuum. Charts showing billet temperature and absolute pressure during the time the billet was heated are given in Figures 81 and 82. The furnace was evacuated to a pressure of 1×10^{-6} mm of Hg before power was turned on to heat the billet. Except for a brief interruption in the rate of billet heating at 800°C with a corresponding drop in the rate of outgassing, the increase in absolute pressure to a maximum of 4×10^{-5} mm of Hg within the furnace continued steadily until the billet reached a temperature of 1050°C . The furnace pressure dropped to 2×10^{-6} mm of Hg during the next three hours, with the billet temperature maintained at 1100°C .

The core and internal surfaces of the cladding components from billet No. 113 after welding are shown in Figure 83. Except for the impression left by the core in contact with the cover plate, there was little discoloration of the cover plate surfaces from oxide contamination. Excessive amounts of dark blue to black oxide were present on the internal surfaces of both side strips and end plugs adjacent to the weld areas and at Zircaloy mating surfaces. These results from an assembled press-welded billet checked closely with results from preceding weld tests.

All external surfaces including the weld surfaces of billet No. 102 were bright and free from oxide after heating in vacuum. The internal surfaces of all Zircaloy components, as well as the core surface, were also bright and completely free from contamination. The Zircaloy-2 exhibited a large coarse-grained structure which was metallographically clean and free from inclusions, as may be seen in the photomicrograph in Figure 84. The alloy composition of this metal after heating was not determined. Heavy diffusion bonds were obtained at some of the clad-to-core interfaces. A diffusion layer 0.007" thick was measured at one location between core and cladding, as illustrated in Figure 85a. Some self-diffusion was noted at Zircaloy-2 interfaces, but this was probably retarded by the presence of a dark band in the metallographic structure of some areas, as shown in Figure 85b. Approximately 50% of the initial billet welds were cracked or ruptured. Cracking was the result of a positive differential expansion of the core relative to the cladding on heating from room temperature to 1100°C .

FIGURE 81. CHART OF TEMPERATURE VS ELAPSED TIME FOR
CLADDING BILLET NO.102 HEATED IN VACUUM.
(BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 83. Uranium Alloy Core and Internal Surfaces of the Cladding Components from Billet No. 113 after Press-Welding. Note contamination on side strip and around end plug. Dark areas on cover plate were due to contact with core and are not surface contamination from welding.

Macro 16888

1/2 X

FIGURE 84. Zircaloy-2 from Cladding Billet No. 102 Heated 3 Hours
at 1100°C in Vacuum.

Micro 16799

Bright Field

250X

FIGURE 85. Zircaloy Cladding to Core Interface and Zircaloy to Zircaloy Interface from Cladding Billet No. 102 Heated 3 Hours at 1100°C. in Vacuum.

85a. Diffusion layer 0.007" thick at cladding to core interface.

Micro 16819

Bright Field

250X

85b. Zircaloy to Zircaloy interface shows partial self diffusion of Zircaloy-2 components.

Micro 16820

Bright Field

250X

Examination of welded billets 102 and 113 proved that considerable contamination of Zircaloy mating surfaces occurred during the regular press-welding assembly of modified picture frame billets. This contamination could be diffused or dissolved in the Zircaloy at elevated temperatures in vacuum. The temperature and time required to effect complete outgassing of billet No. 102 indicated that billet No. 93 had not been completely outgassed before sealing for rolling. It was unlikely that sealed billets assembled from tightly fitting components would remain sealed during heating for rolling because expansion of the core alloy on heating could rupture the Zircaloy welds. If this happened, outgassing of the steel jacket or entrained gas in the steel jacket would contaminate the exposed internal surfaces and Zircaloy-2 component mating surfaces of the cladding billet.

Contamination Related to Differential Thermal Expansion between the Core and Cladding

Data on the differential expansion of the core and cladding were obtained from an examination of welded cladding billet No. 85 which had been heated in a steel can to 800°C to establish a preheating rate (see Figure 70). Expansion of the alloy core during heating had pushed out the Zircaloy components, causing them to separate at the interfaces which has been pressed into close contact during billet assembly. On subsequent cooling, the Zircaloy components did not contract as much as the core, leaving a gap between core and cladding components. These various gaps were measured, establishing an empirical differential thermal expansion of approximately $1/64$ "/in. between room temperature and 800°C for the core relative to the cladding. To insure adequate space for core expansion, an allowance of 0.020 "/in. was made in the design of billets to be heated to 850°C. This figure proved ample on the basis of dilatometric measurements of thermal expansion coefficients for the reference core alloy from 0-850°C and for Zircaloy-2 from 0-800°C. Results of these measurements are included in Table XLI. An original dilation curve for the U-5 w/o Zr-1.5 w/o Nb alloy recorded with the aid of a Precision Quartz Differential Dilatometer⁽²⁶⁾ using a heating and cooling rate of approximately 5°C/minute is shown in Figure 86.

Providing an expansion allowance of 0.020 "/in. for the core in cladding billets would trap an excessive amount of air in billets assembled by the established practice of direct welding in air. Two alternate methods of assembling billets with core expansion allowances and with a minimum of air in the interface were investigated. The first method consisted of assembling components in a steel can, followed by evacuation and sealing with as little contamination from outgassing of the steel as possible. The second consisted of purging the gap between the cladding components and core of the assembled billet with an inert gas, and press-welding with the inert gas in the gap, followed by evacuation to remove the residual gas and then sealing the components.

1/3 INCH OF CHART SCALE EQUALS 5.136×10^{-4} INCHES EXPANSION.

Table XLI

THERMAL EXPANSION COEFFICIENTS FOR
U-5 w/o Zr-1.5 w/o Nb AND ZIRCALOY-2

Specimen Axis	Mean Thermal Expansion Coefficient Per Degree C	
	U-5 w/o Zr-1.5 w/o Nb ⁽¹⁾ (0°C-850°C)	Zircaloy-2 ⁽²⁾ (25°C-800°C)
X	25.00 x 10 ⁻⁶	6.16 x 10 ⁻⁶
Y	25.88	7.63
Z	25.17	5.90

(1) Cast specimens machined with mutually perpendicular axes (Casting No. K-20).

X axis parallel to original casting length.

Y axis parallel to original casting width.

Z axis parallel to original casting thickness.

(2) Specimens machined with mutually perpendicular axes from 850°C rolled 1-1/8" thick plate (Ingot No. 710D960).

X axis in rolling plane parallel to rolling direction.

Y axis normal to rolling plane.

Z axis in rolling plane perpendicular to rolling direction.

Contamination from Protective Steel Sheath during
Billet Preheating

Components assembled in a steel sheath or can are susceptible to contamination during outgassing of the steel while it is being heated for roll bonding. This contamination might be decreased by evacuating the billet while it was being heated to remove gas from the steel; outgassing the steel can at a temperature above the rolling temperature, in vacuum, before inserting the components; or by substituting a titanium-killed low carbon steel, Ti-Namel, for the SAE 1020 steel.

The effects on cladding components of outgassing from the steel sheath used to protect billets while heating to 850°C were established with seven billets in which the billet components were assembled loosely in a welded evacuated can. Zircaloy-2 components and alloy cores of dimensions given in Table XLII were machined all over, degreased, and vacuum dried before being assembled in the steel cans. An allowance of 0.020"/in. was made for positive differential thermal expansion of the core relative to the cladding during heating. The steel cans were of the same design

Table XLII

DIMENSIONS OF BILLET COMPONENTS ASSEMBLED
LOOSELY IN WELDED AND EVACUATED STEEL CANS

Component	Thickness (in.)	Width (in.)	Length (in.)
Core ⁽¹⁾	1.080	1.953	5.400 ⁽²⁾
Cover Plate	0.115	2.580	6.845
Side Strip	0.250	1.094	6.845
End Plug	1.094	2.080	1.162 ⁽²⁾

(1) Core designed with 90° included angle shaped ends.

(2) Over-all length including tapered portion.

as those in Figure 68 except that steel tubes were fitted to the end plugs for evacuation connections and pressure measurements, the same as on billet Nos. 92 and 93. All welds on the steel were made with uncoated rod (Oxweld No. 32) by heliarc welding to avoid weld flux deposits at the steel mating surfaces.

Test procedures for each of these canned billets were as follows:

- Billet No. 95 - Evacuated in SAE 1020 plain carbon steel can, continuously evacuated while being heated at 850°C for two hours, billet sealed, furnace cooled, and opened for examination.
- Billet No. 96 - Evacuated in SAE 1020 plain carbon steel can, sealed before heating, heated at 850°C for two hours, furnace cooled, and opened for examination.
- Billet No. 97 - Evacuated in SAE 1020 plain carbon steel can, continuously evacuated while being heated at 850°C for two hours, billet sealed, rolled 80% reduction in thickness at 850°C.
- Billet No. 99 - Evacuated in SAE 1020 plain carbon steel can which had been previously outgassed for one hour at 1100°C in vacuum, continuously evacuated while being heated at 850°C for two hours, furnace cooled, and opened for examination.

Billet No. 99a - Evacuated in SAE 1020 plain carbon steel can which had been previously outgassed for one hour at 1100°C in vacuum, sealed before heating, heated at 850°C for two hours, furnace cooled, and opened for examination.

Billet No. 100 - Evacuated in Ti-Namel steel can, continuously evacuated while being heated at 850°C for two hours, furnace cooled, and opened for examination.

Billet No. 100a - Evacuated in Ti-Namel steel can, sealed before heating, heated at 850°C for two hours, furnace cooled, and opened for examination.

A summary of materials used for loosely assembled and jacketed billets and a comparison of testing procedures is given in Table XLIII.

Table XLIII

MATERIALS AND TESTING PROCEDURE FOR BILLETS WITH COMPONENTS
ASSEMBLED LOOSELY IN WELDED AND EVACUATED STEEL CANS

Cladding Billet No.	Core Casting No.	Steel Can Material	Steel Outgassed Before Assembly	Billet Evacuated Before Heating	Billet Evacuated During Heating	Final Disposition of Billet
95	L-123	SAE 1020	No	Yes	Yes	Opened for examination.
96	L-111	SAE 1020	No	Yes	No	Opened for examination.
97	L-123	SAE 1020	No	Yes	Yes	Billet sealed and rolled 80% reduction in thick- ness at 850°C.
99	L-111	SAE 1020	Yes	Yes	Yes	Opened for examination.
99a	L-111	SAE 1020	Yes	Yes	No	Opened for examination.
100	L-123	Ti-Namel	No	Yes	Yes	Opened for examination.
100a	L-123	Ti-Namel	No	Yes	No	Opened for examination.

Records were made of the billet temperatures and internal pressures during heating. Pressure measurements on Billet No. 95 were made with a thermocouple gage (General Electric Thermocouple Vacuum Gage) which had a range scale from 0 to 500 microns. The pressure in billet No. 95 increased to more than 500 μ due to outgassing during heating above 700°C. On all other billets except No. 97, vacuum measurements were made with an Alphanon Vacuum Gage (manufactured by National Research Corp.) which had six scales covering a vacuum range from 0.001 to 1000 mm of Hg. The billets were evacuated with a MCF-700 fractionating diffusion pump backed up with a MB-100 booster pump and a mechanical pump. Measurements of billet temperature and pressure versus time are plotted in Figures 87 to 95, inclusive.

FIGURE 87. TEMPERATURE AND ABSOLUTE PRESSURE VS ELAPSED TIME
 FOR CLADDING BILLET NO. 95.
 (BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 88. TEMPERATURE VS ELAPSED TIME FOR CLADDING BILLET NO. 96.
(BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 90. TEMPERATURE AND ABSOLUTE PRESSURE VS ELAPSED TIME
FOR CLADDING BILLET NO. 99.

FIGURE 91. TEMPERATURE VS ELAPSED TIME FOR CLADDING BILLET NO. 99-A.
(BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 92. ABSOLUTE PRESSURE VS. ELAPSED TIME FOR CLADDING BILLET NO. 99-A
(BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 95 ABSOLUTE PRESSURE VS. ELAPSED
TIME FOR GLADDING BILLET NO. 100-A
(BILLET DIMENSIONS--2.5"X6"X11.5")

FIGURE 94. TEMPERATURE VS ELAPSED TIME FOR CLADDING BILLET NO. 100-A
(BILLET DIMENSIONS - 2.5" X 6" X 11.5")

FIGURE 95. ABSOLUTE PRESSURE vs. ELAPSED TIME FOR CLADDING BILLET NO. 100-A.
(BILLET DIMENSIONS - 2.5" X 6" X 1.5")

Measurements during the heating of these billets indicated that pressure changes reflected changes of billet temperature very closely. Fluctuations in temperature as seen on the curves were due to changes in the rate of power applied to the electric resistance-type elements used to heat the billet. This power was adjusted manually with a variable voltage transformer. A sharp pressure increase with temperatures up to approximately 500°C was noted on all billets. This was followed by a pressure drop between 500°C and 600°C, indicating that the cladding components were probably absorbing more gas than was being evolved by the steel can. Another pressure rise between 700°C and 800°C accompanied the evolution of gas at a rate greater than could be absorbed by the components. It is possible that the outgassing of hydrogen, which begins evolution at an appreciable rate in this temperature range, contributed to the increase in pressure. In the billets which were evacuated and sealed before heating, Nos. 96, 99a, and 100a, practically all gas was absorbed or was being absorbed as fast as it was liberated after heating one hour at 850°C. The amount of outgassing from SAE 1020 steel which has been previously outgassed at 1100°C was appreciably less than from cold-rolled SAE 1020 steel. Ti-Namel steel was found to be superior to the outgassed SAE 1020 steel in this respect. This difference was apparent in billet Nos. 95, 99, and 100, which were evacuated during heating, as well as in those billets which were sealed before heating.

All components which were removed from the steel cans for examination after heating showed considerable contamination, as may be seen in Figure 96. Billet No. 96, which was not evacuated while heating, was most severely contaminated. The other two billets not evacuated while heating, Nos. 99a and 100a, were also contaminated. The least contamination was noted on billets which were evacuated while being heated, and even billet No. 100, Figure 96d, heated in a Ti-Namel steel can, showed discoloration of the core and some of the Zircaloy-to-Zircaloy mating surfaces. Metallographic examination of sections cut from the plate rolled from billet No. 97 showed profuse inclusions at all Zircaloy-to-Zircaloy bonds.

The results from billets with components assembled loosely in steel cans indicated that billet cladding components would have to be sealed by welding before assembling in the steel can for rolling to prevent contamination of the mating surfaces. Use of an outgassed steel or Ti-Namel steel, while minimizing surface contamination, could not be expected to prevent the bonding interfaces of loosely assembled billet components from becoming contaminated by outgassing from the steel during heating for roll bonding. Sufficient contamination from this source would lead to impurities or inclusions in the Zircaloy-2 cladding bonds.

FIGURE 96. Contamination from Outgassing on Cladding Components Assembled Loosely in Steel Cans.

96a. Cladding Components from Billet No. 95 after Heating 2 Hours at 850°C. in SAE 1020 Steel Can Evacuated Continuously.

Macro 16935

1/2 X

96c. Cladding Components from Billet No. 99 after Heating 2 Hours at 850°C in a Previously Outgassed SAE 1020 Steel Can Evacuated Continuously.

Macro 17007

1/2 X

96b. Cladding Components from Billet No. 96 after Heating 2 Hours at 850°C. in an Evacuated and Sealed SAE 1020 Steel Can.

Macro 16971

1/2 X

96d. Cladding Components from Billet No. 100 after Heating 2 Hours at 850°C in a Ti-Namel Steel Can Evacuated Continuously.

Macro 17017

1/2 X

Billets Assembled by Inert Gas Purge-Welding, Evacuated, and Sealed in Vacuum to Minimize Contamination of Zircaloy Mating Surfaces

Cladding billet No. 107 was prepared to test the effectiveness of an inert atmosphere to prevent contamination inside an assembled billet while welding the Zircaloy components by the press-welding procedure. This billet, as detailed in Figure No. 97, had a thermal expansion allowance of 0.020"/in. between the alloy core and cladding jacket and a 1/2" O.D. x 1/4" I.D. Zircaloy-2 tube seal welded through one end plug. With the components clamped at the sides only, argon gas entering through the Zircaloy tube purge connection could travel along the gaps between core and cladding components, escaping around the edges of the top cover plate. The assembled components for billet No. 107 were purged in this manner with welding argon gas for a period of 15 minutes at a pressure of 10 psi. Vertical pressure of $6\frac{1}{2}$ tons/in.² was then applied to the top cover plate and the Zircaloy seams were sealed by welding. This billet was opened for examination.

FIGURE 97. Purge-Welded Cladding Billet No. 107.

All internal component surfaces in billet No. 107 were bright and free from contamination except for a narrow straw-colored band of oxide in the heat-affected zones $1/4$ " from the welds. Billet components surfaces are illustrated in Figure 98a. Microscopic examination of a Zircaloy cover plate to side plate interface adjacent to the weld, Figure 98b, showed no evidence of trapped inclusions or contaminants. It was apparent that this method of billet assembly, to be referred to as purge-welding, would result in a minimal amount of contamination.

Two additional problems which were introduced with the purge-welding billet assembly process were removal of gas from inside the welded components and sealing of the hole in the end plug through which purge gas was administered during welding. The presence of oxygen or nitrogen between core and cladding in the gap left for core expansion would contaminate the components during heating and rolling. If any inert purge gas remained in the billet it could not be expected to either diffuse or combine with the billet components and would doubtless collect at component interfaces in the rolled plate. Such areas would not be bonded. Ideally, the interior of cladding billets would have to be evacuated and then sealed to prevent re-entry of any gas. The existing opening used to introduce purge gas could also be adapted to billet evacuation. This hole then had to be sealed in vacuum with a leak-tight corrosion-resistant Zircaloy-2 insert or plug. A number of experimental cladding billets were prepared to test billet evacuation and sealing processes. Processes included evacuation of individual cladding billets, multiple billet evacuation in a vacuum chamber, mechanical screw-type end plug seals, and vacuum welded end plug seals. Billets sealed by these processes were used to obtain additional data on the effects of other assembly variables, roll-cladding variables, and contamination introduced during rolling.

Four cladding billets, Nos. 103-106, inclusive, were prepared to test the effectiveness of purge-welding followed by evacuation and sealing to prevent contamination of roll-bonded Zircaloy interfaces. To verify the predicted need for a positive differential core expansion allowance in the design of billets, two of these billets, Nos. 103 and 104, were prepared with an allowance of 0.020 "/in. for the core; the remaining two were prepared without allowance for core expansion. Dimensions of the cladding components for these billets are given in Table XLIV.

Wrought uranium alloy cores from casting No. L-124 were used for billet Nos. 103 and 104 and from casting No. L-125 for billet Nos. 105 and 106. The cores were machined to size, sandblasted, rinsed in alcohol, and dried in vacuum. All Zircaloy components were rolled from forged ingot No. 710D530. Cover plates and side strips were machined to width and length from rolled sheet, end plugs were machined from rolled slab, and all were cleaned by an acid bright dip in boiling concentrated HNO_3 with 1.0 v/o HF, and rinsed in running tap water and hot distilled water.

- 98a. Internal surfaces of billet components after purging 10 minutes with argon and sealing by inert-gas tungsten-arc welding. All internal surfaces were clean except for light straw-colored oxide adjacent to welds on Zircaloy end plugs.

Macro 16768

1/2 X

- 98b. Zircaloy cover plate to side strip interface adjacent to weld shows no evidence of contamination at the interface. Black spots at left center are from porosity in the weld.

Weld
Area

Zircaloy-2
Cover
Plate

Component
Interface

Zircaloy-2
Side
Strip

Micro 16809

Bright Field

250X

Table XLIV

DIMENSIONS OF BILLET COMPONENTS FOR PURGE WELDED,
EVACUATED, AND SEALED CLADDING BILLET
NOS. 103-106, INCLUSIVE

Component	Thickness (in.)	Width (in.)	Length (in.)
Core ⁽¹⁾ - Billet Nos. 103 and 104	1.059	2.040	5.292(2)
Core ⁽¹⁾ - Billet Nos. 105 and 106	1.080	2.080	5.400(2)
Cover Plate	0.125	2.581	6.875
Side Strip	0.250	1.080	6.875
End Plug	1.080	2.080	1.292(2)

(1) Core designed with 90° included angle shaped ends.

(2) Over-all length including tapered portion.

One end plug for each billet was drilled, tapped, and fitted with a Zircaloy tube for purging during welding and evacuation of the welded cladding billet, as shown in Figure 99.

The cladding components were assembled around the core, purged for 15 minutes with commercial argon, and sealed at the side and end seams by welding, using the same procedure for purging and welding as was used for billet No. 107. All welded billets were leak tested, evacuated to a pressure of 1×10^{-6} mm of Hg through the vacuum connection of the adapter shown in Figure 99, and mechanically sealed in vacuum with machined Zircaloy-2 plugs. The Zircaloy screw-type plugs were seated on the sharp edges at the bottom of the holes drilled in the end plugs by the sealed screw-driver extension. The Zircaloy tube welded to the end plug was then removed and the end of the screwed plug sealed to the end plug with a helium-shielded arc weld. This weld served as a second seal in the event that the mechanical seal should fail during subsequent handling, heating, or rolling. Machined SAE 1020 steel cans, as shown in Figure 68, were welded around the sealed cladding billets for protection during rolling.

All four billets were preheated 90 minutes at 850°C and rolled at 850°C to a total reduction in thickness of 80% with reductions of 12% to 17% per pass at a speed of 125 ft/min with 10-minute reheats after every pass. The rolled plates were decanned and sectioned for metallographic examination.

Plates rolled from billet Nos. 103 and 104 with an allowance for core expansion had perfect bonds at all examined clad-to-clad and clad-to-core interfaces, including the rolled end seal. A section through the cladding cover plate to end plug bond is shown in Figure 100.

FIGURE 99. Zircaloy-2 End Plug with Billet Evacuation Adapter and Screw-Type Seal Pin for Evacuating and Sealing a Welded Cladding Billet

FIGURE 100. Section Through Zircaloy-2 to Zircaloy-2 Bond from Plate Rolled from Billet Designed with a Core Expansion Allowance and Assembled by Purge Welding, Evacuating, and Sealing.

Micro 19310

Bright Field

250X

The two plates rolled from billet Nos. 105 and 106, designed without allowance for core expansion, had numerous segmented or continuous inclusions in the Zircaloy-2 to Zircaloy-2 bonds, although the clad-to-core bonds were sound.

By comparing the results from these plates it was concluded that an expansion allowance would have to be made for billet cores to prevent the possible rupture of sealed billets and contamination during heating and rolling. The combination of purge-welding, evacuating, and sealing had eliminated cladding bond line inclusions. Further test billets were needed to establish the reliability of this process and to simplify the evacuation and sealing of the cladding billet.

A change was made in the design of the screwed seal pin to secure a more effective mechanical seal between the pin and the seat in the end plug. A soft zirconium tip was percussion welded to the end of a 1/4" diameter, 8" long Zircaloy-2 rod and machined as shown in Figure 101. This softer zirconium tip would seat better in the end plug than Zircaloy. Zircaloy-2 backing up the zirconium tip would provide the needed corrosion resistance to water for the end seal. The longer rod was substituted for the screw-driver in the adapter shown in Figure 99 and the end screwed into the

Figure 101. Zircaloy-2 End Plug and Screw-Type Seal Pin with Extension
for Sealing a Welded and Evacuated Cladding Billet

evacuated billets. Sufficient torque was applied to the rod after the tip of the pin was seated to shear the rod at the root of the threads extending beyond the end plug. After removing the welded Zircaloy-2 tube from the end plug, the screwed seal pins were seal welded as on billet Nos. 103-106. This type of closure was used with cladding billet Nos. 114-117, inclusive, and No. 121.

Detailed dimensions for these cladding billet components are presented in Table XLV. Information on the materials used, rolling data, significant variables in assembly or rolling, and results of metallographic examination of Zircaloy bonds are included in Table XLVI. The uranium alloy cores for billet Nos. 114-117, inclusive, and No. 121 were cleaned by sandblasting. Cladding materials were cleaned with 400 mesh alumina by wet abrasive blasting followed by dipping for 2 minutes in cold 10 v/o HNO_3 -2 v/o HF and a distilled water rinse. Purging time before welding was reduced to 5 minutes for this group of billets. All billets were preheated 90 minutes at the rolling temperature and rolled a total of 80% reduction in thickness at a speed of 125 ft/min with a 10-minute reheat after each pass.

Table XLV

DIMENSIONS OF BILLET COMPONENTS FOR
CLADDING BILLET NOS. 114-121, INCLUSIVE

Component	Thickness (in.)	Width (in.)	Length (in.)
Core ⁽¹⁾	1.071	2.100	5.600 ⁽²⁾
Cover Plate	0.125	2.642	7.312
Side Strip	0.250	1.092	7.312
End Plug	1.092	2.142	1.346 ⁽²⁾

(1) Prepared with 90° included angle shaped ends.

(2) Over-all length including tapered portion.

Plates rolled from billet Nos. 114 and 116 were machined by removing 2" of Zircaloy from each end and 1/8" from each side to remove all pre-rolling weld metal from the plates. These plates were then heat treated in carbonate salt at 850°C for 20 minutes, water quenched, and overaged in an air furnace for two hours at 500°C. As with plate No. 87, this heat treatment was intended to introduce thermal stresses equivalent to or greater than would be expected in the ultimate heat treatment for fuel plates and at the same time remove any of the corrosion-resistant supersaturated alpha phase in the core alloy to increase sensitivity in a corrosion test. The heat-treated plates were cleaned by wet abrasive blasting with 325 mesh alumina, pickled in 35 v/o HNO_3 -5 v/o HF for 1 minute, and rinsed in running tap water. After corrosion testing for 11,823 hours in water at 290°C

Table XLVI

MATERIALS, ROLLING DATA, SIGNIFICANT VARIABLE, AND RESULTS OF METALLOGRAPHIC EXAMINATION
FOR CLADDING BILLET NOS. 114-117, INCLUSIVE, AND NO. 121

Cladding Billet No.	Core Casting No.	Zircaloy-2 Ingot No.	Billet Rolling Data			Significant Billet Assembly or Rolling Variable	Results of Metallographic Examination of Zircaloy-2 to Zircaloy-2 Roll Bonds
			Preheat & Rolling Temp. (°C)	Reduct. Per Pass (%)	No. Passes		
114	L-159	710D530	775	13-17	10	Purged 5 min before assembly welding. Rolled at 775°C.	Bonds not examined, plate submitted for corrosion testing.
115	L-159	710D530	775	12-17	10	Same as No. 114 above.	All Zircaloy cover plate to end plug and side strip bonds free from inclusions. Some segmented inclusions between side strip and end plug.
116	L-159	710D530	850	13-20	10	Purged 5 min before assembly welding. Rolled at 850°C.	Same as No. 114 above.
117	L-159	710D530	850	12-17	11	Purged 5 min before assembly welding. Evacuated, sealed at atmos. pressure	A few thin segmented inclusions throughout all Zircaloy bonds.
121	L-163	5Y345	850	12-17	10	Not purged before or during assembly welding. Evacuated and sealed	Fine line of continuous inclusions at end plug to side strip interface. Occasional segmented inclusions at all other bonds.

(550°F) by the Corrosion and Irradiation Testing Group of the Reactor Engineering Division, these plates showed a uniform black coating on all surfaces. Although not all Zircaloy bonds were perfect, as noted by metallographic examination of plate end coupons, plates rolled from purge-welded, evacuated and sealed billets were satisfactorily corrosion resistant.

From the results of assembly and rolling variables on Zircaloy-2 bonds, as shown in Table XLVI, it may be concluded that the cold acid dip, which does not produce microscopically clean surfaces on Zircaloy cladding components, coupled with purging for only 5 minutes, does not remove all sources of contamination from the billet assembly. Since billets rolled at 775°C had no more bond line defects than those rolled at 850°C, the integrity of Zircaloy bonds appeared to be influenced more by cleaning and assembly methods than by rolling temperature. Plates rolled from billet Nos. 117 and 121 indicated that inert-gas purging of the welded assembly followed by evacuation and vacuum sealing are essential to optimum cladding bonds. In comparing these two steps, the vacuum sealing apparently had more influence on the quality of Zircaloy bonds than purge-welding.

Improved Vacuum Weld Sealing Techniques

The possibility of undetected leaks in a screwed mechanical seal motivated the investigation for welding the seal pin to the billet end plug in a vacuum. The objective was to evacuate the billet to 10^{-4} or 10^{-5} mm Hg, insert the seal pin with part of the pin projecting above the end plug, resistance heat the pin with electric current from a d.c. welder until the

projection melted, and fuse the melted portion of the pin to the end plug with the electric arc which was established as the seal pin projection melted. This procedure is shown schematically in Figure 102. Since the initial intensity of the arc at 1500 to 2500 amp had an almost explosive effect on molten metal, which was confined to a small area $1/2"$ to $3/4"$ in diameter, this process was called pop-welding.

Figure 102

Schematic Diagram
Illustrating Method of
Vacuum Welding Billet
End Seals

Three cladding billets, Nos. 118, 119, and 120, were prepared with pop-weld seals. Dimensions of cladding billet components for these three billets are also given in Table XLV. The end plugs were designed with a recess around the central hole as shown in Figure 103. In this way the preheating for pop-welding could be concentrated in a smaller volume of metal adjacent to the seal pin. A threaded Zircaloy tube was screwed into the end plugs for purging, and the billets were sealed in a vacuum chamber, eliminating the need for the welded Zircaloy tubes on the end plugs. The $1/4"$ diameter threaded pin extension rods were notched to provide a $3/16"$ projection above the end plug after the pin was screwed into the end plug, and the rods were sheared as on billet Nos. 114 to 117, inclusive. Uranium alloy cores from casting L-162 were used for billet Nos. 118 and 119 and from casting L-163 for billet No. 120. Core and cladding components were prepared and assembled by the same procedure used for billet Nos. 114 to 117, inclusive. The purge-welded billets were clamped in an upright position in the vacuum chamber, evacuated to 5×10^{-6} mm of Hg, and the screwed pin inserted. The $3/16"$ long projection from the sheared pin was then preheated, melted, and the seal pin welded to the end plug with a Zircaloy electrode in an offset water-cooled copper electrode holder as illustrated in Figure 104. An empirical procedure was used for pop-welding based on preliminary weld tests which combined preheating the seal pin at a relatively low amperage, 750 to 1000 amp, followed by welding at a higher amperage, 2000 to 2500 amp. Power was supplied by three Lincoln Model S-7080, 900-amp, d.c. welders in parallel.

Figure 103. Zircaloy-2 End Plug and Seal Pin for Vacuum Pop-Welded Billet End Closure

FIGURE 104. EQUIPMENT FOR VACUUM POP-WELDING BILLET END CLOSURES.

The depth of weld penetration on experimental welds proved to be erratic due to welding variables which affected the stability of the arc, causing premature cutoff, welding off center, and corona discharge. Although complete fusion of the seal pin was obtained on billets 118, 119, and 120, there was some question as to whether such a seal would remain intact during roll bonding.

These billets were jacketed in machined SAE 1020 steel cans, of the type shown in Figure 68, for roll bonding. Billet Nos. 118 and 119 were rolled to 80% reduction in thickness at 850°C and No. 120 was rolled to 83½% reduction at 800°C. Billet No. 118 was reheated 10 minutes after every other pass; the other two billets were reheated 10 minutes after every pass.

Plate uniformity, surface quality, and rolled end closures for plate No. 118, reheated after every other pass during rolling, were equally as

good as for plates from billets reheated after every pass. It was estimated that the amount of furnace capacity, billet handling, and rolling time could be reduced almost 50% on production rolling of fuel plates with this change in schedule.

Metallographic examination of Zircaloy-2 cladding bonds on plates from billet Nos. 118 and 119 showed very few inclusions; these were restricted to the vertical bond interface between end plug and side strips, similar to plate No. 115. A longitudinal section through the end seal pins showed periodic inclusions corresponding to gaps between seal pin and end plug at the root of each thread. Scattered inclusions were present in all Zircaloy bonds in billet No. 120. This examination indicated that a vacuum pop-welded seal could be obtained which was comparable to a mechanical seal for cladding billet end closures. This method of sealing required further development before it could be considered reliable.

Numerous tests were made to find the optimum conditions for sealing the ends of cladding billets in vacuum by welding the Zircaloy-2 seal pin to the end plug after the billets were evacuated. Variables which influence uniformly tight seals which will not be ruptured during rolling of the cladding billet include electrode polarity, preheat current, preheat time, no-load voltage, current required to initiate the arc, current maintained during arc welding, length of seal pin projection, and length of time the arc is maintained.

Preliminary tests had shown that the most satisfactory length of seal pin projection for arc stability and weld penetration was from $3/16$ " to $1/4$ ". To center the deposit of weld metal from the electrode to the seal pin, the electrode was tapered to within $1/8$ " of the diameter of the seal pin, with an included angle of 60° . Greater area of contact was obtained between the Zircaloy seal pin and billet end plug mating surfaces by substituting a tapered seal pin and matching hole in the end plug for the threaded seal pin and tapped hole. Pins with 15° included angle tapers eliminated voids at the root of threads. If these voids were not sealed during roll bonding they might provide a helical path through the end plug by which water or steam could penetrate to the core. The presence of some of these voids is illustrated by Figure 105 which shows the cross section of a screwed seal pin in one end of a cladding billet after a partial reduction by rolling at 850°C . The end plug, seal pin, and electrode designed for pop-welding tests are shown in Figure 106. A billet end plug with seal pin and electrode ready to be inserted for welding is shown in Figure 107.

The dual controls furnished with the welding generators for open-circuit voltage control and welding current control were supplemented with a contactor, time-delay relay, and an overvoltage relay in the exciter circuit to automatically regulate the pop-welding arc time. An electrical circuit diagram for this equipment is shown in Figure 108. The timer

FIGURE 105. Cross Section Through Cladding Billet Screw-Type Seal Pin and End Plug after Partial Reduction at 850°C Showing Voids at the Root of Threads.

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 voltage increase which accompanied the starting of the arc energized the overvoltage relay. After the overvoltage relay contact (OV) closed, the time-delay relay (TD) timed out, opening the time-delay contact (TD), which opened the exciter main line contactor (A) to extinguish the arc.

The weld seal conceivably could be made in three ways, either by melting the electrode and depositing a sufficient amount of metal from the electrode over the seal pin, by melting the top of the seal pin and a portion of the surrounding end plug thereby fusing them together, or by a combination of these two methods. All attempts to melt both the seal pin and surrounding end plug and maintain a pool of molten metal for satisfactory weld penetration were unsuccessful. The high current required to start and maintain an arc in vacuum had a blasting effect on molten weld metal which resulted in little or no weld penetration. With the electrode negative this blasting effect was more severe and resulted in undesirable cratering.

FIGURE 106. BILLET END PLUG SEAL PIN, & ELECTRODE
DESIGNED FOR POP-WELDING TESTS.

BILLET END PLUG
(TAPERED HOLE 15° INCLUDED ANGLE)

ELECTRODE AND SEAL PIN
(ELECTRODE TAPER 60° INCLUDED ANGLE)
(SEAL PIN TAPER 15° INCLUDED ANGLE)

FIGURE 107. End of Purge-Welded Cladding Billet with
Tapered Zircaloy Seal Pin in Zircaloy
Electrode Ready to be Inserted for Pop-
Welding.

Figure 108. Electrical Circuit Diagram for Pop-Welding Generator and Controls

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 RAISE 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

This method was abandoned in favor of melting the seal pin projection and depositing additional weld metal over the seal pin and end plug from the Zircaloy electrode. All welds made by initiating the arc as rapidly as possible without preheating showed poor penetration and inconsistent seals. A two-step operation was established for all weld tests; it consisted of preheating the seal pin for 15 seconds at a fixed current setting between 500 and 1000 amp, followed by arcing for a measured time interval. The current settings for each weld were adjusted manually. Table XLVII lists all data for variables in the pop-welding tests and the results obtained from each individual test.

The optimum welding procedure established by these tests consisted of preheating the seal pin for 15 seconds by applying a current of 900 to 950 amp, followed by arcing started at 1400 amp with the electrode positive, and continuing for two seconds at approximately 1100 amp and 30 volts. Consistently good welds could be made in this way with adequate penetration and without unnecessary consumption of the electrode. Figures 109a and 109b show cross sections of seal pin to end plug weld test specimens illustrating adequate and inadequate penetration after sealing. Prolonged arc time resulted in unnecessary electrode consumption and an excessive amount of weld deposit on the end of the billet, as shown in Figure 109c.

Since more power is required to initiate an electric arc in high vacuum than in a gas atmosphere, by setting the generator open-circuit voltage at the maximum, 90 volts, more power was available at the start of the arc welding. This also resulted in a more stable arc during melting of the seal pin and electrode than was possible at lower open-circuit voltages. The optimum current for arcing was determined to be the minimum required to start an arc, but not less than 1100 amp. High starting currents caused excessive spattering of weld metal and cratering. Low starting currents following prolonged preheating of the seal pin were inadequate to sustain the arc for the required length of time.

Electrode polarity had a marked effect on the amount of electrode consumption, amount of weld deposit, and extent of penetration. With the electrode negative, little of the heat energy was generated in the electrode. This resulted in low electrode consumption and very little metal deposited on the end plug. Unless a high current was used with the electrode negative, not enough heat was concentrated at the end plug to melt the seal pin into the end plug except at the surface; but the higher current caused cratering and very little weld metal was deposited over the seal pin. When the electrode was made positive, more of the heat energy was given off at the electrode and a larger amount of the electrode was consumed and deposited on the seal pin which gave a sound weld with good penetration.

TABLE XLVII
VARIABLES INVESTIGATED AND RESULTS OF VACUUM POP-WELDING TESTS FOR SEALING CLADDING BILLETS

Test Weld No.	Electrode Polarity	Preheating Current (amps)	No-Load Voltage	Arc Starting Current (amps)	Arc Welding Current (amps)	Arc Time Relay Setting (sec)	Arc Voltage	Weld Chamber Vacuum (μ)	Electrode Consumption	Weld Penetration	Appearance of Sealing Weld
1	Negative	550	70	2500	2000	2	30	6×10^{-5}	Low	Poor	Weld cratered with weld metal splattered away from billet end. Little metal deposited on seal pin. Arc on No. 4 broke in less than 1 sec; billet not completely sealed when leak tested.
2	Negative	750	70	2500	2000	2	30	6×10^{-5}	Low	Poor	
3	Negative	750	70	2350	1600	2	30	6×10^{-5}	Low	Poor	
4	Negative	750	70	2350	1650	2	30	6×10^{-5}	Low	Poor	
5	Negative	750	70	2000	1500	2	30	6×10^{-5}	Low	Poor	
6	Negative	550	70	1350	-	3-1/2	30	6×10^{-5}	Low	Poor	Arc broke in less than 1 sec on all of these welds. No. 11 not completely sealed. All other welds sealed, but little weld metal deposited on seal pin.
7	Negative	1000	70	1350	1150	3-1/2	30	Not Recorded	Low	Poor	
8	Negative	700	70	1150	-	3-1/2	30	Not Recorded	Low	Poor	
9	Negative	550	70	2000	1150	3-1/2	30	Not Recorded	Low	Fair	
10	Negative	900	70	1300	-	3-1/2	30	Not Recorded	Low	Fair	
11	Negative	700	70	1500	-	3-1/2	30	Not Recorded	Low	Poor	
12	Positive	950	90	1500	1100	3-1/2	30	Not Recorded	High	Good	Weld displaced to one side. Groove not filled on one side.
13	Positive	950	90	1700	1300	3-1/2	30	Not Recorded	High	Good	Excellent seal with grooves around seal pin completely filled with weld metal.
14	Positive	950	90	1300	1100	3-1/2	30	Not Recorded	High	Good	
15	Positive	900	90	1450	1000	6	30	Not Recorded	Very High	Excellent	Excellent seal. Excessive amount of weld metal deposited on top of billet end plug.
16	Positive	900	90	1450	1000	6	30	Not Recorded	Very High	Excellent	
17	Positive	900	90	1550	1100	2	30	Not Recorded	Moderate	Good	Good seal. Groove filled with weld metal.
18	Positive	900	90	1500	1200	2	30	4.5×10^{-5}	Moderate	Good	End sealed, but weld metal displaced to side of seal pin.
19	Positive	900	90	1450	1150	2	30	4.5×10^{-5}	Moderate	Good	Good seal. Groove filled with weld metal.
20	Positive	900	90	1300	1100	2	30	4.5×10^{-5}	Moderate	Good	End sealed, but weld metal displaced to one side of seal pin.
21	Positive	900	90	1300	1000	2	30	4.5×10^{-5}	Moderate	Good	Good seal. Groove around seal pin filled with weld metal.
22	Positive	900	90	1550	1100	2	30	4.5×10^{-5}	Moderate	Good	
23	Positive	900	90	1400	1200	2	30	3×10^{-5}	Moderate	Good	
24	Positive	900	90	1400	1200	2	30	3×10^{-5}	Moderate	Good	
25	Positive	900	90	1340	1000	2	30	3×10^{-5}	Moderate	Good	
26	Positive	900	90	1200	950	2	30	3×10^{-5}	Moderate	Good	
27	Positive	900	90	1500	1150	3	30	5×10^{-5}	Moderate	Good	
28	Positive	900	90	1700	1250	3	30	5×10^{-5}	Moderate	Poor	End sealed, but weld cratered.
29	Positive	900	90	1550	1200	3	30	5×10^{-5}	Moderate	Good	
30	Positive	900	90	1500	1150	3	30	5×10^{-5}	Moderate	Good	Good seal. Groove around seal pin filled with weld metal.
31	Positive	900	70	1500	1100	2	26	4.5×10^{-5}	Moderate	Good	
32	Positive	900	70	1550	1100	2	27	4.5×10^{-5}	Moderate	Good	
33	Positive	900	70	1650	1200	2	30	4.5×10^{-5}	Low	Poor	Arc broke in fraction of a second. Not sealed when leak tested.
34	Positive	900	70	1700	1250	2	30	4.5×10^{-5}	Moderate	Fair	Good seal. Groove partially filled with welded metal.
35	Positive	900	90	1650	1200	6	30	4.5×10^{-5}	Excessive	Excellent	Excellent seals. Large amount of weld metal deposited on top of billet end plug. Electrode consumed completely and part of copper electrode holder melted.
36	Positive	900	90	1850	1300	6	30	4.5×10^{-5}	Excessive	Excellent	
37	Positive	900	90	1300	1100	6	30	4.5×10^{-5}	Excessive	Excellent	
38	Positive	900	90	1600	1000-1300	6	30	4.5×10^{-5}	Excessive	Excellent	
39	Positive	900	90	1600	1000-1100	6	30	4.5×10^{-5}	Excessive	Excellent	
40	Positive	900	90	1550	1000-1100	6	30	4.5×10^{-5}	Excessive	Excellent	

FIGURE 109. Cross Sections of Seal Pin to End Plug Weld Test Specimens.

109a. Weld test No. 23. Good seal with good penetration.

Macro 18159

2X

109b. Weld test No. 7. End sealed but penetration poor.

Macro 18158

2X

109c. Weld test No. 37. Good seal with good penetration.
Excessive weld deposit on billet end.

Macro 18398

1X

Effects of Other Types of Contamination Introduced during Billet Assembly and Rolling

A group of 14 billets, Nos. 147 to 152, inclusive, and Nos. 160 to 167, inclusive, was prepared to assay the effects of weld penetration and contamination during billet assembly, external contamination of cladding billets during roll bonding, and further variations in the rolling schedule. Component dimensions for these billets are given in Table XLVIII. A differential thermal expansion allowance of 0.020"/in. was made for the alloy cores. All cladding components were rolled from forged Zircaloy-2 ingots 5Y345 and 5Y525. The alloy core castings used for these billets are included in Table XLIX. Cores were cleaned by wet abrasive blasting with 325 mesh alumina, followed by an air-water blast to forcefully remove any trace of abrasive grit, rinsed in alcohol, and dried in vacuum. The cladding components were prepared from sheared Zircaloy plate and strip and machined Zircaloy slabs. These were cleaned by dipping 30 seconds in boiling concentrated HNO₃ containing 1 v/o HF, rinsed in tap water, distilled water, and air dried. Components were assembled for purge-welding in the same manner as cladding billets 114 to 120, inclusive, and purged 10 minutes with argon prior to welding.

Table XLVIII

DIMENSIONS OF COMPONENTS FOR BILLETS 147 TO 152,
INCLUSIVE, AND 160-172, INCLUSIVE

Component	Thickness (in.)	Width (in.)	Length (in.)
Core ⁽¹⁾	1.071	2.100	5.600 ⁽²⁾
Cover Plate	0.125	2.642	6.712
Side Strip	0.250	1.092	6.712
End Plug	1.092	2.142	1.046 ⁽²⁾

(1) Core designed with 90° included angle shaped ends.

(2) Over-all length including tapered ends.

BILLETS 147 to 152, inclusive, and 160 and 161 were purge-welded with the maximum weld penetration which would not result in burning through the cover plate to side strip interface or sagging of the weld metal. These welds were made manually at 240 amp with a 1/8" diameter, thoriated tungsten electrode. Welding speed was maintained between 10" and 12" per minute. The average weld penetration was approximately 3/16" deep. Four billets, 147, 148, 160, and 161, had no introduced defects on assembly. The Zircaloy cover plates and side strips used with billet

TABLE XLIX

CORE CASTING NUMBER, SIGNIFICANT VARIABLE, ANALYSES, AND EVALUATION OF CLADDING BILLETS 147 TO 152, INCLUSIVE,
AND 160 TO 167, INCLUSIVE

Cladding Billet No.	Core Casting No.	Weld Penetration of Assembled Cladding Components	Significant Variable	Tests and Analyses	Evaluation of Cladding Billet or Rolled Plate
147	L-126	Maximum ⁽¹⁾	Maximum weld penetration.	Metallographic examination of representative bond interfaces. Tensile test of side strip to end plug bond.	Clad-to-core bonds excellent. Cladding bonds excellent except for inclusions at side strip to end plug. Side strip failed at 47,100 psi in tension; no rupture at bond to end plug.
148	L-123	Maximum ⁽¹⁾	Same as 147 above.	Metallographic examination of representative bond interfaces.	Clad-to-core bonds excellent. Cladding bonds excellent except for continuous inclusions at side strip to end plug.
149	L-123	Maximum ⁽¹⁾	White zirconium fluoride deposited on mating surfaces of cladding components during acid cleaning.	Same as 148 above.	Clad-to-core bonds excellent. All cladding bonds excellent. Fluoride contamination did not interfere with bonding.
150	L-136	Maximum ⁽¹⁾	Same as 149 above.	Same as 148 above.	Clad-to-core bonds excellent. Cladding bonds excellent except for a very few inclusions at side strip to end plug. Fluoride contamination did not interfere with bonding.
151	L-111	Maximum ⁽¹⁾	1/2" long unwelded gap between cover plate and end plug at one end of billet.	Same as 148 above.	All clad-to-core and cover plate to side strip bonds excellent. Intermittent inclusions in cover plate to end plug bonds at unsealed end and continuous inclusions at all side strip to end plug bonds.
152	L-124	Maximum ⁽¹⁾	Same as 151 above.	Same as 147 above.	Metallographic examination same as 151 above. Side strip failed at 58,900 psi in tension; no rupture at bond between side strip and end plug.
160	L-184T	Maximum ⁽¹⁾	1/2" long unwelded gap along side of protective steel can.	Machined to 2-5/8" wide x 30" long. Wet abrasive blasted, pickled 3 min in 35-5 HNO ₃ -HF, corrosion tested in water at 290°C for 10,572 hr.	Adherent lustrous black coating on all plate surfaces except for 2 small white streaks along edges from prerolling weld deposit after 715 hr test time. No change after 10,572 hr.
161	L-184B	Maximum ⁽¹⁾	Same as 160 above.	Same as 160 above.	Same as 160 above except no white streaks developed along edges.
162	L-222T	Minimum ⁽²⁾	Minimum weld penetration	Same as 148 above.	All clad-to-core and clad-to-clad bonds excellent.
163	L-222B	Minimum ⁽²⁾	Same as 162 above.	Same as 148 above.	Same as 162 above.
164	L-257T	Minimum ⁽²⁾	Heated 90 min at 850°C, but not roll bonded.	Cladding billet opened for examination.	Core and cladding components were all clean, bright and free from contamination.
165	L-257C	Minimum ⁽²⁾	Same as 164 above.	Same as 164 above.	Same as 164 above.
166	L-257B	Minimum ⁽²⁾	Rolled only one pass (13-1/2% reduction in thickness), at 850°C.	Billet de-canned and all assembly welds examined for possible defects or rupture.	No cracks or other defects noted in any of the billet assembly welds. Cladding partially bonded to core.
167	L-259T	Minimum ⁽²⁾	Same as 166 above.	Same as 166 above.	Same as 166 above.

⁽¹⁾Welded by inert-gas shielded-arc with 1/8" dia. tungsten electrode at 240 amp. Average penetration 3/16".

⁽²⁾Welded by inert-gas shielded-arc with 1/16" dia. tungsten electrode at 120 amp. Average penetration 1/16".

Nos. 149 and 150 had light white fluoride deposits on the mating surfaces as the components were delayed in being transferred from the acid bright dip to the first rinsing operation, a deposit which could not be removed by rinsing. These two billets were assembled with the contaminated components to establish their effect on roll bonding. A $1/2$ " long unwelded gap was left between the cover plate and end plug at one end of cladding billets 151 and 152, simulating a defective or incomplete assembly weld. Billets 162 to 167, inclusive, were purge-welded with the minimum penetration which would assure an adequate seal at the component seams. These welds were made at 120 amp with a $1/16$ " diameter, thoriated tungsten electrode. The speed of welding was also maintained at 10" to 12" per minute, which effected an average penetration of $1/16$ ". No defects were introduced in the assembly of these six billets.

Purge-welded billets were evacuated and mechanically sealed in a vacuum chamber with zirconium tipped Zircaloy screws of the type shown in Figure 101. These seals were not pop-welded in vacuum as facilities for pop-welding were not available at the time these billets were assembled. The ends of the seal pins were seal welded to the end plug manually after the billets were removed from the vacuum chamber.

All 14 billets were jacketed in machined SAE 1020 steel cans, as detailed in Figure 68. The steel jackets for billets 160 and 161 were not completely sealed, but had $1/2$ " long gaps in the weld along one side to simulate possible contamination from defective jacket welds during heating and rolling.

These jacketed billets, with the exception of 164 to 167, inclusive, were preheated 120 minutes and roll bonded to 80% reduction in thickness at 850°C, and were reheated 10 minutes after every pass, with the exception of billet Nos. 149 and 150 which were reheated 20 minutes after every two passes. To check the possibility of weld failures on subsequent heating and rolling for billets assembled with a minimum weld penetration, billets 164 and 165 were heated 90 minutes at 850°C and examined without rolling, and billets 166 and 167 were rolled only to $13\frac{1}{2}$ % reduction in thickness at 850°C.

Plates rolled from cladding billet Nos. 160 and 161 were machined to $2\frac{5}{8}$ " wide and 30" long by removing 0.080" of cladding material from each side and 1" from each end. This did not remove all of the metal from the sides which had been fused during the initial weld assembly of the components. Machined plates were cleaned by wet abrasive blasting with 325 mesh alumina, pickled 3 minutes in 35 v/o HNO₃-5 v/o HF at a temperature of 32°C, and rinsed in running tap water. A total of 0.005" of metal was removed from all surfaces by this cleaning procedure. These plates were then corrosion tested in 290°C water to check the effect of introduced external contamination during heating and rolling on the water corrosion resistance of clad plates. All other rolled plates and billets were sectioned and

examined metallographically at all component interfaces. Attempts to test the strength in tension of the vertical Zircaloy end plug to side strip interface by percussion welding a Zircaloy-2 stud to the side strip (see Figure 46) were inconclusive, since the test specimens failed in the side strip material instead of at the bond line. Billet variables, tests, and the evaluation of cladding billets 147 to 152, inclusive, and 160 to 167, inclusive, are summarized in Table XLIX.

Billets assembled with either a maximum or minimum of weld penetration during purge-welding could be roll clad with equally good bonds at all component interfaces. The welds on billets prepared with a minimum of penetration were not ruptured during heating for rolling nor on the initial roll pass. These billets were prepared with an allowance for differential expansion of the core, thereby eliminating the probability of internal pressure rupturing the welds. Seeing that the Zircaloy-to-Zircaloy bonds were defective on plates rolled from cladding billets 151 and 152, which were not completely sealed by welding, it was imperative that all billet seams be completely welded.

From the results of corrosion tests on plates rolled from billet Nos. 160 and 161 it was concluded that external contamination of the Zircaloy cladding during heating and rolling, such as would result from the use of an unsealed protective steel jacket, was not detrimental to the water corrosion resistance of a Zircaloy-clad plate provided the plate was thoroughly cleaned before testing. The presence of a white corrosion product at some of the plate edges corresponding to the billet assembly weld metal disclosed the necessity for removing all of the initial weld from rolled plates. This would be practical only if the initial weld penetration were kept to a minimum consistent with obtaining a satisfactory seal, approximately $1/16$ ", as on billet Nos. 162 to 167, inclusive.

The light fluoride deposit on the cleaned components used for billets 149 and 150 probably decomposed on heating for roll bonding and did not affect the quality of Zircaloy bonds, indicating that the surfaces were otherwise clean. Changing the roll schedule to two passes per reheat for these two billets confirmed results from previous billet No. 118 which indicated that the heat lost between the passes during rolling was not detrimental to bonding.

The persistent continuous and semicontinuous inclusions along the vertical Zircaloy end plug to side strip interface in most rolled plates were not unexpected, as normal roll pressure without edge rolling was not conducive to the formation of a bond at this interface. The fact that very few or no inclusions could be found in this bond in some plates, as in plates 103, 104, 115, 118, 119 and 149, indicated that these bonds were possible. A detailed study of the factors which could contribute to or detract from reproducible Zircaloy-2 bonds at the ends of rolled plate was indicated.

Elimination of Bond Defects at Zircaloy Interfaces of Rolled-Plate End Closures

In assembling the components of a cladding billet, certain mating surfaces lie in a plane which is normal to the applied stress during roll bonding. Other mating surfaces are parallel to this stress, as may be seen in the sketch of assembled components shown in Figure 110. On subsequent rolling, reproducible bonds were readily obtained at all clad-to-core interfaces irrespective of their orientation. Sound Zircaloy-2 cover plate to side strip and cover plate to end plug bonds, which are in planes normal to the applied stress, could also be reproduced. However, the frequent occurrence in rolled plate of voids or inclusions at the end plug to side strip interface, which is parallel to the roll bonding force, precluded integrally bonded end closures. The metallographic structure of typical transverse and longitudinal sections through roll bonded side strip to end plug interfaces showing bond line inclusions in rolled plate is shown in Figure 111.

FIGURE 110. RELATIONSHIP BETWEEN BILLET COMPONENT MATING SURFACES AND DIRECTION OF APPLIED FORCE DURING ROLL BONDING.

COMPONENTS IN PARTIALLY ASSEMBLED CLADDING BILLET SHOWING POSITION OF BOTTOM COVER PLATE, LEFT SIDE STRIP, AND BOTH END PLUGS. RIGHT SIDE STRIP, TOP COVER PLATE, AND CORE NOT SHOWN.

DIRECTION IN WHICH ROLL PRESSURE IS APPLIED TO ASSEMBLED CLADDING BILLET DURING ROLL BONDING.

FIGURE 111. Transverse and Longitudinal Sections from the End of a Rolled Plate Showing Inclusions at the Side Strip to End Plug Interface.

111a. Transverse section showing discontinuous segmented inclusions.

Micro 17552

Bright Field

250X

111b. Longitudinal section showing semi-continuous inclusions.

Micro 18649

Bright Field

250X

The two factors considered most essential to effect a roll bond between thoroughly cleaned mating surfaces were temperature and proximity of the surfaces to be bonded. An optimum rolling temperature of 850°C had been established as a requisite to total plate and cladding uniformity. The only possible improvement in proximity of components along the sides of billets during heating and rolling was by side restraint of the billet and protective steel jacket or by pressure developed at the interface from within the billet itself. Edge-rolling equipment was not available; therefore direct restraint along the sides during rolling was not possible. By comparing the mean thermal expansion coefficients for low carbon steel and Zircaloy-2 from room temperature to 800°C ($16 \times 10^{-6}/^{\circ}\text{C}$ for steel compared with $6.6 \times 10^{-6}/^{\circ}\text{C}$ for Zircaloy-2), it was evident that the steel jacket around the cladding billet would expand more on heating than the Zircaloy. For a 3" wide cladding billet heated to 850°C in a steel jacket, a gap at least 0.010" wide would be formed between the steel and Zircaloy on each side of the cladding billet. Since the steel jacket also increases some in width during rolling due to lateral spread, little restraint would be provided along the sides. Subsequently special attention was given to the anisotropy in Zircaloy which might improve contact between the end plugs and side strips as billets were being heated and rolled.

Some anisotropy exists in the thermal expansion of Zircaloy-2 (see Table XLI), which gives a total differential expansion between two of the axes of 3.5 mils along a $2\frac{1}{2}$ " length on heating to the roll-bonding temperature. By proper orientation of these axes the billet end plugs could theoretically be made to expand more across the width of the billet than the adjacent cover plates, thereby moving into closer contact with the side strips. Unfortunately since the end plugs are also welded to the side strips during billet assembly, and the steel jacket provides no side restraint during heating, the side strips would have a tendency to move along with the end plugs. For this reason it appeared unlikely that thermal expansion anisotropy would be beneficial in improving contact between the end plug and side strip.

The mechanical properties of hot and cold-rolled Zircaloy-2 sheet as reported by Mudge and Forscher⁽⁶⁾⁽²¹⁾ showed anisotropy in tensile and hardness measurements. Since rolling tends to rotate the slip plane of most hexagonal close-packed metals into the rolling plane,⁽²⁷⁾ a similar texture in rolled Zircaloy-2 would be expected to show some variation in properties along axes in the rolling plane compared with the axis normal to the rolling plane. Also since hexagonal metals often retain their rolling texture upon recrystallization,⁽²⁷⁾ it was possible that the hot-working properties of Zircaloy-2 would be influenced by its prior fabrication.

Investigation of Anisotropy in Hot-Rolled Zircaloy-2

X-ray diffraction studies of Zircaloy-2 specimens from $1\frac{1}{4}$ " thick slab rolled at 850°C from forged ingot 5Y345 showed that the basal (002)

plane, which is the slip plane, was predominantly in the rolling plane. The 850°C rolled material used for X-ray diffraction measurements had a fine-grained recrystallized structure. From this information it seemed probable that the hot-working properties of Zircaloy-2 would be influenced by its prior rolling history.

Room-temperature diamond pyramid hardness measurements with a 10-kg load were made on the faces of Zircaloy-2 cubes machined from forged, rolled and beta-annealed plates from ingot 5Y345. Ingot 5Y345 was forged to a 3" thick, 8" wide, 7' long slab at 950°C. Sections from the forged slab were hot rolled to 50% reduction in thickness at 850°C with the rolling direction parallel to the long axis as forged. Hardness data, Table L, revealed that indentations made parallel to the direction of previously applied stress during forging or rolling were from 30 to 50 DPH hardness points greater than those observed in either of the other two principal directions. This amount of anisotropy decreased, but was not eliminated, after a beta anneal for one hour at 1000°C in a vacuum of 4×10^{-6} mm of Hg.

Table L

HARDNESS DATA FOR FORGED, HOT-ROLLED
AND BETA-ANNEALED ZIRCALOY-2

Condition	Hardness ⁽⁴⁾ (DPH-10-kg load)		
	Rolling or Forging Plane	Longitudinal Cross Section	Transverse Cross Section
Forged ⁽¹⁾	220	170	171
Hot Rolled ⁽²⁾	203	170	170
Beta Annealed ⁽³⁾	189	168	164

(1) Ingot 5Y345 forged at 950°C.

(2) Forged ingot 5Y345 rolled to 50% reduction in thickness at 850°C.

(3) Hot-rolled plate from ingot 5Y345 annealed for one hour at 1000°C in a vacuum of 4×10^{-6} mm of Hg.

(4) Average values for three or more different specimens.

To study the directional hot-working properties of both forged and hot-rolled Zircaloy-2, six 1.000" cubes were machined from forged slab from ingot 5Y345, and eighteen 1.125" cubes were machined from plate hot rolled from forged ingot 5Y345. Three of the cubes cut from hot-rolled plate were beta annealed one hour at 1000°C in a vacuum of 4×10^{-6} mm of Hg. The three principal forging or rolling axes were marked on the faces

of the cubes normal to the axes. The X axis was designated as the principal forging direction or direction of rolling, Z the axis at right angles to the forging or rolling direction in the forging or rolling plane, and Y the axis perpendicular to the forging or rolling plane.

Of the six cubes prepared from forged slab, three were hot pressed at 850°C between preheated stainless steel platens to approximately 1/2 their original thicknesses with pressure applied parallel to a different forging axis for each cube. The remaining three cubes were hot rolled to 80% reduction in thickness at 850°C, each with a different forging axis parallel to the rolling direction. For the hot-pressed cubes, the spread in the X and Z directions was from 70% to 90% greater than in the Y direction, as shown in Table LI. Similar results were noted in lateral spread of the three rolled cubes.

Table LI

ANISOTROPY IN FORGED, HOT-ROLLED,
AND BETA ANNEALED ZIRCALOY-2
DURING HOT PRESSING

Condition Before Hot Pressing	Axis Parallel to Applied Stress ⁽⁴⁾	Dimensions of Hot Pressed Specimens (in.)		
		X-Axis	Y-Axis	Z-Axis
Forged ⁽¹⁾	X	0.565	1.350	1.608
Forged ⁽¹⁾	Y	1.451	0.578	1.436
Forged ⁽¹⁾	Z	1.591	1.305	0.575
Hot Rolled ⁽²⁾	X	0.635	1.448	1.721
Hot Rolled ⁽²⁾	Y	1.624	0.636	1.584
Hot Rolled ⁽²⁾	Z	1.736	1.479	0.633
Beta Annealed ⁽³⁾	X	0.637	1.564	1.657
Beta Annealed ⁽³⁾	Y	1.627	0.634	1.607
Beta Annealed ⁽³⁾	Z	1.647	1.562	0.629

(1) Ingot 5Y345 forged at 950°C. Specimens machined to 1.000" cubes.

(2) Forged ingot 5Y345 rolled to 50% reduction in thickness at 850°C. Specimens machined to 1.125" cubes.

(3) Hot-rolled plate from ingot 5Y345 annealed for one hour at 1000°C in a vacuum of 4×10^{-6} mm of Hg. Specimens machined to 1.125" cubes.

(4) The X axis was designated as the principal forging direction or direction of rolling, Y the axis perpendicular to the forging or rolling plane, and Z the axis at right angles to the forging or rolling direction in the forging or rolling plane.

Twelve of the cubes from 850°C rolled plate were hot pressed at 850°C to half their original thicknesses. Four cubes were compressed parallel to the X axis, four parallel to the Y axis, and four parallel to the Z axis. In every case the spread in the X and Z directions, as shown in Table LI, was from 70% to 85% greater than in the Y direction. Photographs of representative pressed cubes are shown in Figure 112. Three other cubes from hot-rolled plate were further hot rolled at 850°C to 80% reduction in thickness with different rolling orientations. The first cube was rolled with the X axis in the direction of rolling and the Z axis perpendicular to the rolling plane. The second cube was rolled with the Y axis in the direction of rolling and the X axis perpendicular to the rolling plane. The third was rolled with the Z axis in the rolling direction and the Y axis perpendicular to the rolling plane. The second and third cubes both spread approximately 40% more in width than the first, as shown in Figure 113. These results show the extent to which the hot working of Zircaloy-2 is influenced by its prior hot-working history and that this anisotropy is just as significant in hot rolling as it is in hot pressing.

The three remaining beta-annealed cubes were also hot pressed at 850°C, each with a different axis parallel to the applied stress. After 50% reduction, the spread was only 20% greater in the X and Z directions than in the Y direction, Table LI, indicating that most of the hot-working anisotropy was removed by this heat treatment.

In hot working forged or previously hot-rolled Zircaloy-2, the resistance to deformation along the axis parallel to the applied stress during initial forging or prior hot rolling was found to be significantly greater than along the other two axes. It was not speculative, therefore, to assume that the anisotropy in hot-rolled Zircaloy-2 could be advantageous in enhancing a Zircaloy end plug to Zircaloy side strip bond in the roll cladding of fuel plates if the orientation of the previous hot-rolling or forging axes were properly selected in the preparation of end plugs for cladding billets. To facilitate a side bond during rolling, the orientation of the end plug should be selected which would result in the maximum side spread and the maximum resistance to deformation in the rolling direction. The orientation which would provide the maximum resistance to deformation in the rolling direction of the cladding billet, which is the direction along which the length of the end plug is measured, would correspond to the Y axis, which is parallel to the original applied forging or rolling stress as indicated in Figure 114. The choice of X or Z axis for the thickness or width of the end plug would not be important, since the spread in each is approximately the same.

FIGURE 112. Zircaloy-2 Cubes Machined from Hot-Rolled Slab and Hot Pressed at 850°C to Half Their Original Thickness. Each cube was pressed along a different hot-rolling axis. The hot-rolling direction was designated as the X axis, the direction normal to the rolling plane as the Y axis, and the direction at right angles to the rolling direction in the rolling plane as the Z axis. The principal rolling axes were marked on the faces of the cubes normal to the axis.

FIGURE 113. Zircaloy-2 Cubes Machined from Hot-Rolled Slab and Rolled to 80% Reduction in Thickness at 850°C. Each cube was rolled with the prior hot-rolling axes in different directions. The prior hot-rolling direction was designated as the X axis, the direction normal to the rolling plane as the Y axis, and the direction at right angles to the rolling direction in the rolling plane as the Z axis.

- 113a. Cube rolled with the X axis in the rolling direction and the Z axis normal to the rolling plane. Very little spread occurred along the Y axis.

- 113b. Cube rolled with the Y axis in the direction of rolling and the X axis normal to the rolling plane. Width spread along the Z axis was approximately 40% greater than along the Y axis in Figure 113a.

- 113c. Cube rolled with the Z axis in the rolling direction and the Y axis normal to the rolling plane. Width spread along the X axis was approximately 40% greater than along the Y axis in Figure 113a.

FIGURE 114

Desired Orientations of Cladding Billet End Plugs to Obtain Maximum Side Spread in Producing a Side Strip to End Plug Roll Bond

- X = Direction of rolling or forging in hot-worked slab.
- Y = Axis of hot-worked slab normal to forging or rolling plane.
- Z = Axis at right angles to forging or rolling direction in forging or rolling plane.
- L = Length dimension in machined end plug which will be parallel to rolling direction of the cladding billet.
- W = Width dimension in machined end plug which will be parallel to width dimension of the cladding billet.
- T = Thickness dimension in machined end plug which will be parallel to thickness dimension of the cladding billet.

Anisotropy of Hot-Rolled Zircaloy-2 Applied to Cladding Billet Component Selection to Promote Sound Bonds at Integral End Closures

The effects of hot-rolled Zircaloy-2 anisotropy on roll-bonded plate end closures was studied in three cladding billets, Nos. 168, 169, and 170, prepared with end plugs having different orientations. Two additional billets, Nos. 171 and 172, were prepared with end plugs beta annealed for one hour at 1000°C in vacuum. The dimensions of these billet components were the same as on previous billets as shown in Table XLVIII. The orientation of end plugs in billet 168 was with the perpendicular or Y axis of the previously hot-rolled slab in the billet rolling direction, as suggested in Figure 114. For billets 169 and 170, end plug orientations in the billet rolling direction were from the X and Z axes, respectively, in hot-rolled plate, as shown in Figures 115a and 115b.

Cores for cladding billets 168 to 172 were machined from castings L-259C, L-259B, L-260T, L-260C, and L-260B, respectively. Machined cores were cleaned with a 400 mesh alumina wet abrasive blast followed by a water blast rinse. All cladding components were selected from slab

FIGURE 115. Directions from which Zircaloy-2 End Plugs Were Machined from Hot Rolled Plate.

115a) Rolling direction of end plugs for Billet No. 169 machined from the X axis of hot rolled plate.

115b) Rolling direction of end plugs for Billet No. 170 machined from the Z axis of hot rolled plate.

or strip rolled from forged ingot 5Y345, machined to size, and cleaned with an acid bright dip in boiling concentrated HNO_3 containing 1.0 v/o HF, water rinsed, and air dried. Billets were assembled, purge welded, evacuated, and mechanically sealed in a vacuum chamber with zirconium-tipped Zircaloy-2 screws, as illustrated in Figure 101. The ends of the seal pins were manually seal welded to the end plug after the billets were removed from the vacuum chamber. Sealed billets were placed in machined SAE 1020 steel jackets, of the type shown in Figure 68, for protection during heating and rolling. All billets were preheated two hours at 850°C and rolled to 80% reduction in thickness at 125 ft per minute with reductions of 10% to 17% per pass. Each billet was reheated 10 minutes after each individual pass. The rolled plates were sectioned for metallographic examinations of Zircaloy bonds.

Figure 116 shown three photomicrographs of the Zircaloy-2 end plug to Zircaloy-2 side strip bonds from plates rolled from billet Nos. 168, 169, and 170. With the proper orientation of the end plugs, as in billet No. 168, no defects or inclusions were present in this bond. For the billets with end plugs machined with their axes other than as shown in Figure 114, numerous segmented or continuous defects could be noted in the bond. The end plug to side strip bonds in plates rolled from billets 171 and 172 showed little or no improvement over the bonds in plates 169 and 170 as a result of beta annealing the end plugs.

Evidence obtained from the examination of Zircaloy bonds in plates 168 to 172, inclusive, demonstrated the need for proper orientation of the Zircaloy end plug with respect to the previous hot-working directions of the material being used if sound metallurgical bonds were to be obtained in the rolled end closure of clad fuel plates.

FIGURE 116. Zircaloy-2 End Plug to Zircaloy-2 Side Strip Bonds from Billets Prepared with End Plugs Having Different Orientations of the Previously Hot-Rolled Slab in the Rolling Direction of the Cladding Billet.

116a. Section from end of plate No. 168. There is no evidence of inclusions in the side strip to end plug bond. The axis which was normal to the prior hot-rolling plane was oriented parallel to the rolling direction of the cladding billet.

116b. Section from end of plate No. 169. A large number of inclusions or discontinuities may be noted at the side strip to end plug interface. The axis which was parallel to the prior hot-rolling direction was oriented parallel to the rolling direction of the cladding billet.

116c. Section from end of plate No. 170. A large number of inclusions or discontinuities may be noted at the side strip to end plug interface. The axis which was at right angles to the rolling direction in the prior hot-rolling plane was oriented parallel to the rolling direction of the cladding billet.

ROLL-CLAD URANIUM-ZIRCONIUM BINARY ALLOYS

Introduction

Unless a satisfactory heat treatment could be found which would impart both corrosion resistance and dimensional stability under irradiation to the EBWR ternary reference alloy, the ternary alloy becomes wholly dependent upon an integral clad for water corrosion resistance. A dimensionally stable uranium-zirconium binary alloy would be equally dependent upon the cladding for water corrosion resistance.⁽¹²⁾ Although the feasibility of cladding the uranium-5 w/o zirconium-1.5 w/o niobium ternary alloy had been established, it was proposed that a substitution of an uranium-zirconium binary alloy for the reference alloy in EBWR fuel plates would effect a saving in both alloy cost and neutron economy by eliminating the niobium. A similar cladding procedure might be used for the binary alloy provided the rolling properties of the alloy core approximated those of the cladding material at temperatures which would promote diffusion between the core and cladding and self-diffusion of the cladding components to assure satisfactory heat transfer and corrosion resistance in the finished plate. Previous experience⁽⁸⁾ indicated that an uranium-2 w/o zirconium alloy would have insufficient hot hardness to be roll clad with Zircaloy-2. Inexpensive alloy additions of low neutron absorbers, such as silicon, chromium, or molybdenum, or increased zirconium additions could be expected to improve the hot-rolling properties of the uranium-2 w/o zirconium alloy. For this reason uranium alloys with 5 w/o, 7.5 w/o, and 10 w/o zirconium, which were immediately available, were selected for cladding investigation. No attempt was made to prepare additional alloys for roll cladding due to lack of time.

In an effort to conserve time and materials, a limited number of uranium-zirconium binary cladding billets were prepared for roll bonding. Billets of the modified picture frame design, which incorporated the best proven practices of material preparation, billet assembly, and rolling procedures developed for reference alloy clad plates, were used. The billets were scaled to produce plates the size of proposed EBWR fuel plates (0.250" thick x 3.875" wide x 54" long) for better evaluation of physical properties and corrosion test data.

Preparation and Assembly of Cladding Billets

Sixteen cladding billets (Nos. 135-139, inclusive, Nos. 153-159, inclusive and Nos. 187-190, inclusive) were assembled with cast uranium-zirconium binary alloy cores welded in Zircaloy-2 jackets. Assembled billets were sealed in plain carbon steel cans for roll cladding.

The uranium alloys were vacuum-induction melted and cast into heated rectangular graphite molds. Details of melting, casting, and ingot

analyses are given in Table III. Cast ingots were cropped to $10\frac{1}{2}$ " long and machined to final core size by removing from 0.020" to 0.090" of metal from each face. Cores were finished with 100° included angle tapered ends for billets 135 to 139, inclusive, and 90° included angle tapered ends for all other billets. Final cleaning of the machined cores immediately before assembling them into billets consisted of wet abrasive blasting with 400 mesh alumina grit followed by an air-water blast rinse. The finished cores were uniformly smooth, free from foreign particles on the surface, and with a minimum of surface oxide contamination.

All Zircaloy-2 used for cladding billet components was prepared from ingots 5Y345, 5Y525, and 710D530 (see Table VII). Component stock was hot rolled at 850°C in air to within 10% of the desired finished size, cleaned by wet abrasive blasting with 100 mesh alumina grit, pickled in 35 v/o HNO₃-5 v/o HF, and cold finished to size. Cladding billet cover plate stock was sheared to size from cold-finished sheet; side plates were machined to width and length from sheared plate; and end plugs were machined to size from hot-rolled slabs. The orientation of machined end plugs relative to the direction in which the slab was rolled for billets 187 to 190, inclusive, was as illustrated in Figure 114. For all other billets the orientation of machined end plugs was as illustrated in Figure 115b. The dimensions of all cladding components are given in Table LII.

Table LII

DIMENSIONS OF CLADDING COMPONENTS FOR BILLETS
WITH URANIUM-ZIRCONIUM BINARY ALLOY CORES⁽¹⁾

Billet Component	Billets 135-139, Incl.			Billets 153-159, Incl.			Billets 187-190, Incl.		
	Thick.	Width	Length	Thick.	Width	Length	Thick.	Width	Length
Alloy Core	1.070	3.205	10.720	1.061	3.205	10.400	1.061	3.205	10.400
Cover Plates	0.100	3.519	11.734	0.125	3.769	11.408	0.125	3.769	12.250
Side Plates	0.125	1.091	11.734	0.250	1.082	11.408	0.250	1.082	12.250
End Plugs	1.091	3.269	0.859	1.082	3.269	0.941	1.082	3.269	1.350
Steel Can	1.962	7.000	13.875	2.450	8.000	16.000	2.450	8.000	16.000

⁽¹⁾All dimensions given in inches.

Since thorough cleaning of the Zircaloy-2 components was found to be a vital requisite to obtaining Zircaloy bonds on clad ternary alloy plates, final cleaning was done according to the following established practice:

1. Wet abrasive blast with 400 mesh Al_2O_3 .
2. Rinse in hot running tap water.
3. Acid dip for 20 seconds in boiling concentrated HNO_3 containing 1.0 v/o HF.
4. Rinse in cold running tap water.
5. Rinse in cold distilled water.
6. Rinse in hot distilled water.
7. Air dry in clean warm air.

All subsequent handling during billet assembly was done with clean metal tongs.

Steel jackets, or cans, were machined from SAE 1020 and ASTM A7-52T hot-rolled steel to the dimensions shown in Figure 117. All machined cans were degreased in trichloroethylene.

FIGURE 117. Dimensions of Protective Steel Cans for Uranium-Zirconium Binary Cladding Billets.

BILLET NOS.	JACKET DIMENSIONS									JACKET MATERIAL
	A	B	C	D	E	F	G	H	I	
135-139	$14 \pm \frac{1}{8}$	$7 \pm \frac{1}{8}$	$1 \pm \frac{1}{32}$	$3.519 \pm \frac{.005}{.000}$	$1 \frac{3}{4}$	$.646 \pm .002$	$3.519 \pm \frac{.000}{.005}$	$1 \frac{1}{8} \pm \frac{1}{8}$	$1.292 \pm \frac{.000}{.005}$	SAE 1020
153-159	$16 \pm \frac{1}{8}$	$8 \pm \frac{1}{8}$	$1 \frac{1}{4} \pm \frac{1}{32}$	$3.769 \pm \frac{.005}{.000}$	$2 \frac{1}{8}$	$.666 \pm .002$	$3.769 \pm \frac{.000}{.005}$	$2 \frac{5}{16} \pm \frac{1}{16}$	$1.332 \pm \frac{.000}{.005}$	ASTM A7-52 T
187-190	$16 \pm \frac{1}{8}$	$8 \pm \frac{1}{8}$	$1.200 \pm .010$	$3.769 \pm \frac{.005}{.000}$	$2 \frac{1}{8}$	$.666 \pm .002$	$3.769 \pm \frac{.000}{.005}$	$1 \frac{7}{8} \pm \frac{1}{32}$	$1.332 \pm \frac{.000}{.005}$	ASTM A7-52 T

The uranium alloy cores were assembled in the cladding components with the cover plates and side plates between pressurized vertical and horizontal water-cooled copper platens. A positive differential thermal expansion allowance of 0.020"/in. was left in each billet for the core with respect to the cladding. This expansion allowance for the temperature range from room temperature to 850°C was arbitrarily selected on the basis of previous measurements with uranium-5 w/o zirconium-1.5 w/o niobium alloy cores. No thermal expansion data were obtained on the uranium-zirconium binary alloys. The gap between the core and cladding was purged with commercial argon gas at a rate of 15 cfm for 15 minutes to displace all entrained air prior to welding the cladding jacket. Zircaloy-2 component mating surfaces were pressed together with a pressure of 4 to 7 tsi while welding. All welding was done manually with an inert-gas shielded-arc at 380 amp with a 1/8" diameter thoriated tungsten electrode. The inert purging gas was removed from the welded billet by evacuating two hours through the purge gas inlet hole at one end of the billet. The billet was then sealed in a vacuum chamber with a zirconium-tipped Zircaloy-2 screw plug.

Welded billets were sealed in steel cans to minimize surface contamination of the cladding during heating and rolling. The root pass used to seal the cans was made with an inert gas-shielded metal arc weld to avoid contamination from volatile flux compounds on coated weld rod. Subsequent can welds and weld reinforcement were made with coated metal electrodes.

Billet Rolling and Plate Heat Treating

Assembled billets were preheated and rolled with variations in temperature and reduction as shown in Table LIII. Uniform billet temperatures were obtained by preheating two hours at the rolling temperature. Billets were rolled at 125 fpm with the rolls preheated 30 minutes with a gas burner before rolling. Roll temperature after preheating was between 150°C and 200°C.

Billet Nos. 135 to 139, inclusive, which were contained in SAE 1020 steel jackets, presented no difficulty during rolling, using reductions established for other billets of corresponding thickness and width. Some of the billets rolled in ASTM A7-52T steel jackets bowed either up or down on each pass during rolling. Although bowing from 2" to 4" did not interfere with the rolling schedule, more power was required of the mill than on equal reductions with plates which did not bow. Billet No. 157 developed such a severe bow in one direction, Figure 118, that rolling had to be discontinued after the fourth pass. Examination of the two halves of the billet jacket disclosed that they had been machined from two different hot-rolled plates, presumably of different heats, as chemical analyses showed a variation from 0.08% carbon in one, to 0.23% carbon in the other. There were

FIGURE 118. Severe Bow in Cladding Billet No. 157 after a Total of 31% Reduction in Thickness at 850°C. Variations in carbon analysis from 0.08% in one half of the steel jacket to 0.23% in the other half affected the hot-working properties. The half with lower carbon content deformed and elongated more during rolling, which forced the other half to follow along the curvature of the roll.

Table LIII

ROLLING DATA FOR URANIUM-ZIRCONIUM
BINARY ALLOY CLAD WITH ZIRCALOY-2

Cladding Billet No.	Core Casting No.	Nominal Zr Comp. of Core (%)	Core Wt. (kg)	Rolling Temp. (° C)	No. of Passes per Reheat	Reheat Time (min)	Reduction in Thick. per Pass (%)	Total Reduction (%)
135	L-235	5	9.94	850	1	10	7-20	80
136	L-236	5	9.91	800	1	10	7-20	80
137	L-231	5	9.96	800	1	10	7-20	80
138	L-228	5	9.94	900	1	10	7-20	80
139	L-233	5	9.92	900	1	10	7-20	80
153	L-251	5	9.54	850	1	10	4-17-1/2	80
154	L-252	5	9.50	850	1	10	4-17-1/2	80
155	L-254	5	9.48	850	1	10	4-17-1/2	80
156	L-255	5	9.57	850	1	10	4-1/2-17-1/2	80
157	L-258	5	9.50	850	1	10	4-1/2-11	31
158	L-261	5	9.59	850	1	10	4-17-1/2	80
159	L-262	5	9.52	850	1	10	2-1/2-17-1/2	80
187	L-283	7-1/2	9.01	850	2	15	10-17	80
188	L-285	7-1/2	9.11	850	2	15	10-17	80
189	L-284	10	8.61	850	2	15	10-17	80
190	L-286	10	8.55	850	2	15	10-17	80

no significant differences in the manganese, sulphur, or phosphorus analyses on these steels. The difference in carbon content between the two halves of the jacket affected their hot-working properties. As a result, the half with lower carbon content deformed more readily, elongated more during rolling, and forced the other half of the steel jacket to describe a concave course along the curvature of the roll. This distortion of the steel can caused a similar distortion of the cladding billet within. A longitudinal cross section through one end of the billet core and end plug, as shown in Figure 119, indicates the extent to which the tapered core end and end plug were deformed. Care in matching the jacket components from each individual steel plate was required to eliminate this rolling defect. Variations in carbon content within individual heats probably accounted for some bowing irregularities which occurred while rolling billets with matched jacket components.

Hot-rolled plates 135 to 139, inclusive, developed varying amounts of camber from 0.001"/ft to a maximum of 0.024"/ft on hot rolling. The most severe camber, in plates 135, 136, and 193, was removed by cold rolling with reductions of 0.005" to 0.010" before removing the steel can from the plate. Although the steel mating surfaces of the protective cans were bonded during rolling, the can was easily removed from the clad plate by shearing across the ends and along the sides.

FIGURE 119. Longitudinal Section from End of Cladding Billet No. 157 after 31% Reduction at 850°C. Distortion of core end taper and end plug resulted from severe bow in steel jacket having different carbon content in top and bottom half.

Macro 17537

1X

Eight of the rolled plates were given an isothermal heat treatment to improve dimensional stability of the alloy core under irradiation. Although these plates were not to be used for irradiation testing, the heat treatment was intended to introduce stresses comparable to those which would be expected of plates heat treated for reactor service and to observe their effects during water corrosion testing. These plates were heat treated before being removed from their protective steel jackets as follows:

Plate Nos. 153, 154, 155 and 158

1. Heat for 20 minutes in carbonate salt at 800°C.
2. Isothermal quench into carbonate salt at 650°C.
3. Hold for 24 hours at 650°C.
4. Air cool.

Plate Nos. 187, 188, 189, and 190

1. Heat for one hour in carbonate salt at 800°C.
2. Isothermal quench into carbonate salt at 640°C.
3. Hold for 24 hours at 640°C.
4. Air cool.

The uranium-5 w/o zirconium binary alloy cores in hot-rolled plates were sufficiently ductile to permit cold reductions of 20% to 25% in thickness without rupture of the cladding or clad-to-core bonds along the faces or sides. However, the bond at the end clad-to-core transition of rolled end closures was completely separated by cold reductions of 5% or less.

Clad-Plate Evaluation

Roll-clad plates were examined by physical and mechanical testing, metallographic examination, and corrosion testing. Sufficient results were obtained to evaluate the clad uranium-zirconium binary alloys for comparison with the clad reference alloy.

The dimensions of all rolled plates are presented in Table LIV.

Table LIV

PHYSICAL MEASUREMENTS OF ROLL-CLAD URANIUM-ZIRCONIUM BINARY ALLOY-CLAD PLATES

Plate No.	Length (in.)	Width (in.)	Avg. Thick. at Side (in.)	Avg. Thick. at Center (in.)	Length of Core End Taper (in.)	Nominal Clad Thick. (in.)
135	52-5/8	3.760	0.267	0.259	2-1/4	0.020
136	53.5/16	3.700	0.263	0.259	2-1/4	0.020
137	52-1/2	3.707	0.260	0.261	2-1/4	0.020
138	54-9/16	3.734	0.250	0.259	2-1/4	0.020
139	54-3/4	3.718	0.251	0.259	2-1/4	0.020
153	55-7/16	3.882	0.275	0.257	2-5/8	0.025
154	52-11/16	3.982	0.273	0.264	2-5/8	0.025
155	54-3/4	3.902	0.275	0.258	2-5/8	0.025
156	54-1/16	3.895	0.277	0.264	2-5/8	0.025
157	16-5/16	3.827	0.914	0.919	3/4	0.039
158	53-1/4	3.945	0.268	0.265	2-5/8	0.025
159	52-1/4	3.937	0.276	0.272	2-5/8	0.025
187	56	3.932	0.276	0.268	2-5/8	0.025
188	56-15/16	3.887	0.272	0.265	2-5/8	0.025
189	55-3/4	3.869	0.273	0.266	2-5/8	0.025
190	55-7/8	3.906	0.276	0.266	2-5/8	0.025

Complete cladding thickness variations and analyses were not obtained. Severe clad surface irregularities, as shown in the photomicrographs of Figure 120, were generally coupled with equally severe cladding thickness variations. In Figure 120, sections of the uranium-5 w/o zirconium binary alloy plates with 0.020" thick nominal cladding rolled at 800°C, 850°C, and 900°C

FIGURE 120. Clad Surface Irregularities of Uranium-5 w/o Zirconium Alloy Plates Clad with Zircaloy-2 at 800°C, 850°C, and 900°C. Surface of an Uranium-5 w/o Zirconium-1.5 w/o Niobium plate roll clad at 850°C shown for comparison.

120a. Uranium-5 w/o Zirconium-1.5 w/o Niobium roll clad at 850°C.

Macro 17279

3/4X

120b. Uranium-5 w/o Zirconium roll clad at 850°C.

Macro 17285

3/4X

120c. Uranium-5 w/o Zirconium roll clad at 800°C.

Macro 17289

3/4X

120d. Uranium-5 w/o Zirconium roll clad at 900°C.

Macro 17294

3/4X

are contrasted with a section of the reference alloy with 0.020" cladding rolled at 850°C. The most uniform cladding distribution for all plates with 5 w/o zirconium in the core alloy was obtained by rolling at 850°C. Sections cut at six equally spaced intervals along the length of plate No. 135 are shown in Figure 121. Tapered core sections at the ends of plate Nos. 135, 136, and 137 were badly distorted, with less than 0.005" of cladding in some places.

FIGURE 121. Sections Cut at Six Equally Spaced Intervals along the Length of Clad Plate No. 135 Showing Distribution of Core and Cladding.

Macro 17244

1X

The end taper was considerably better on plates rolled at a higher temperature (900°C), as may be seen in Figure 122. Increasing the length of the core end taper on subsequent uranium-5 w/o zirconium clad plates rolled at 850°C (Nos. 153-159, inclusive) resulted in a more uniformly tapered distribution of the core in rolled plates. Clad plate Nos. 187-190, inclusive, showed no surface or tapered core end irregularities. Radiographs of full length plates showed uniform distribution of cladding along the sides and equal amounts of Zircaloy-2 at the ends of rolled plates.

FIGURE 122. Longitudinal Section at End of Clad Plate Nos. 137 and 139 Showing End Effects with 100° Included Angle Core End Tapers on Uranium-5 w/o Zirconium Alloy Cores.

122a. Plate No. 137 rolled 80% reduction in thickness at 800°C.

Macro 17245

Zircaloy-2 Cladding

Uranium Alloy Core

Zircaloy-2 Cladding

3-1/2X

122b. Plate No. 139 rolled 80% reduction in thickness at 900°C.

Macro 17245

Zircaloy-2 Cladding

Uranium Alloy Core

Zircaloy-2 Cladding

3-1/2X

Data obtained from representative bond tensile strength tests revealed clad-to-core bond strengths between 56,000 psi and 60,000 psi on all plates as hot rolled to 80% reduction in thickness at rolling temperatures between 800°C and 900°C. The cold formability of roll-clad uranium-5 w/o zirconium was appreciably better than for the clad reference alloy. Strips 1" x 6" x 0.250" cut parallel to the direction of rolling from plate Nos. 156 and 159 were twisted 225° over $4\frac{3}{8}$ " gage length without rupturing the cladding, core, or clad-to-core bond in a torsion test at room temperature. Torsion test specimens are shown in Figure 123.

Complete bonding was obtained at all clad-to-core interfaces of all rolled plates. All Zircaloy bonds were sound except at the side strip to end plug interfaces of plate Nos. 135 to 139, inclusive, 153, 156, 157, and 159, and along all screwed seal pins which showed numerous segmented or continuous inclusions in the bond line. Diffusion bands observed on metallographic examination of clad-to-core interfaces were uniform throughout each plate but varied with rolling temperature. This variation can be seen in the photomicrographs of plates rolled at 800°C, 850°C, and 900°C in Figure 124.

Coupons were cut from the solid Zircaloy-2 end of all rolled plates, except No. 157, for corrosion testing in 400°C steam. The eight plates which had been heat treated were prepared for static corrosion testing in distilled water at 290°C by machining to $3\frac{3}{4}$ " wide x 53" long. Whenever possible, equal amounts of metal were removed from the sides and ends by machining. Initial roll camber in plates 154 and 158 necessitated removing more metal from one side of the plate than from the other. Uneven removal of metal from the sides of these plates relieved some of the differential stresses between the cladding and core which resulted in camber of 0.011" to 0.012" along the plate length. After machining, the plates were cleaned to remove all contamination from the plate surfaces. Plates were cleaned by wet abrasive blasting with 400 mesh Al_2O_3 ; plate Nos. 153, 154, 155, and 158 were acid pickled three minutes in 35 v/o HNO_3 -5 v/o HF at 38°C; and Nos. 187 to 190, inclusive, were pickled 10 minutes in 35 v/o HNO_3 -5 v/o HF at 43°C.

Clad plates 187 to 190, inclusive, were given an ultrasonic through transmission test⁽¹⁷⁾ for bond quality. This test indicated plate No. 189 had probable weak or discontinuous bonds in some areas, particularly between the side cladding and the core. No bond line defects were detected in the other plates.

The plate end coupon containing the seal pin from clad plate No. 153 showed some white corrosion product throughout the seal pin after testing for 1,314 hours in 400°C steam. All other coupons exhibited a uniform black adherent oxide coating on all surfaces, with no preferential bond line attack after 900 to 1,500 hours of testing.

FIGURE 123. Torsion Test Specimens of Uranium-5 w/o Zirconium Alloy Clad with 0.025" of Zircaloy-2. Specimens twisted 225° over a 4-3/8" gage length at 20°C.

123a. Section from clad plate No. 156.

Macro 17565

3/4 X

123b. Section from clad plate No. 159.

Macro 17564

3/4 X

FIGURE 124. Cladding to Core Interface of Roll Bonded Uranium-5 w/o Zirconium Alloy Core and Zircaloy-2 Cladding.

124a. Cladding to core interface of plate No. 137 rolled at 800°C. The distribution of cladding on this plate was very irregular. Width of diffusion band 0.24 mil.

Zircaloy-2
Cladding

Uranium
Alloy
Core

← Cladding
to Core Bond

Micro 17383 Bright Field

250X

124c.

Cladding to core interface of plate No. 139 rolled at 900°C. Width of diffusion band 0.90 mil.

Zircaloy-2
Cladding

Cladding to
Core Bond

Uranium
Alloy
Core

Micro 17386

Bright Field

250X

124b. Cladding to core interface of plate No. 135 rolled at 850°C. Width of diffusion band 0.48 mil.

Zircaloy-2
Cladding

Cladding to
Core Bond

Uranium Alloy
Core

Micro 17382 Bright Field

250X

Detailed corrosion test data on the clad plates are given in Table LV.

Table LV

CORROSION TEST DATA ON ZIRCALOY-2-CLAD URANIUM-
ZIRCONIUM BINARY ALLOY PLATES, STATIC TEST ON
ALL PLATES IN 290°C DISTILLED WATER

Plate No.	Core Alloy Composition	Test Time (hr)	Comments
153	U-5 w/o Zr	70	Adherent iridescent tarnish on surface. Blister 2-3/4" x 2" between cover plate and end plug at seal pin end of plate. Plate bowed during test.
154	U-5 w/o Zr	70	Adherent iridescent tarnish on surface. Plate bowed during test
155	U-5 w/o Zr	70	Same as 154 above.
158	U-5 w/o Zr	70	Plate ruptured followed by complete oxidation of all core alloy.
187	U-7.5 w/o Zr	42	Plate ruptured after 20 hr in test which was followed by complete oxidation of all core alloy.
188	U-7.5 w/o Zr	1714	Adherent black coating with several white areas on sides from pre-rolling weld contamination. Small blisters on both side 6" from one end. Slight bow.
189	U-10 w/o Zr	1714	Adherent black coating on surface with white mottled areas on sides where plate was supported during acid pickle. Slight bow.
190	U-10 w/o Zr	1714	Same as 189 above.

A blister which developed at the end of plate No. 153 (see Figure 125) showed a poor bond between the Zircaloy cover plate and end plug with a defective seal pin bond in the end plug. Selective attack of the seal pin in the end coupon corrosion tested in 400°C steam indicated that failures could be expected through the end seal of this plate. The catastrophic failure of plate No. 158, as shown in Figure 126, caused extensive damage

FIGURE 125. Clad Uranium-5 w/o Zirconium Alloy Plates after Corrosion Testing for 70 hr in 290°C Water. Plate No. 153 developed a blister between the cover plate and end plug at one end. No defects noted in the other two plates.

Scale 1:7

111-3111

FIGURE 126. Catastrophic Failure of Uranium-5 w/o Zirconium Alloy Clad with Zircaloy-2 after 70 Hours in 290°C Water. Clad plate No. 158.

Scale 1:5

111-3112

to the face cladding, making it impossible to determine the location or type of defect which initiated the failure. Subsequent metallographic examination of Zircaloy bonds at the ends and sides of plate No. 158 revealed no bond line defects. A similar catastrophic type of failure was noted in plate No. 187, which is illustrated in Figure 127a. The fact that the corrosion had not progressed as far in this plate as in plate No. 158 is probably due more to the shorter exposure time (42 hours instead of 70 hours) than to increased zirconium content of the core alloy. A close-up of this failure, Figure 127b, shows that corrosion had progressed in ever-increasing bands from a point along one side which may have been the location of the initial defect. Since the cladding to side strip bond was intact at this point, the failure may have been due to defects in the face cladding or cracking of the face cladding due to localized triaxial stresses at the face cladding, side cladding, and core interface. Blisters which developed in plate No. 188 were attributed to lack of bond between the core and cladding.

Discussion of Results

The preparation of alloy core material, cladding components, protective steel can; and the billet assembly procedure of purge-welding and vacuum sealing which were developed for cladding the ternary reference alloy, were all readily adapted to cladding investigations of the uranium-zirconium binary alloys. Increasing the zirconium content of uranium-zirconium binary alloys from 5 w/o zirconium to 7.5 w/o and 10 w/o zirconium improved the hot-working properties, surface finish, and dimensional uniformity of rolled plates. None of the billets presented any difficulty during rolling at the temperatures and reductions which were investigated.

Some differences in width and length of plates rolled at various temperatures were anticipated even though reductions and speed of rolling were constant. However, uniformity of plate size, surface finish, cladding thickness, and end effects in the roll-clad uranium-5 w/o zirconium alloy plates were all greatly affected by rolling-temperature variations. The surfaces of plates rolled at 850°C with 0.020" nominal cladding were quite rough with regular depressions of 0.010" to 0.020" at 1/4" intervals throughout the plate surface. Increasing the cladding thickness to 0.025" improved the surfaces of plates rolled at 850°C, although some slight depressions were still evident. Surface irregularities were due to differences in the hot-working properties of the core and cladding. In roll-clad uranium-niobium binary alloy plates,⁽⁹⁾ this condition was corrected by adjustments in the rolling temperature. Roll-cladding temperatures of 800°C and 900°C for uranium-5 w/o zirconium alloy plates intensified the surface irregularities. At 800°C the core did not deform as readily as the cladding and the reverse was true at 900°C. This was confirmed by cladding thickness variations which were most severe in plates rolled at 800°C and still present to some extent in plates rolled at 850°C. From these

FIGURE 127. Catastrophic Failure of Uranium-7.5 w/o Zirconium Alloy Clad with Zircaloy-2 after 42 hr in 290°C Water. Clad plate No. 187.

127a. Clad plate showing area of failure.

Scale 1:5

111-3371

127b. Close-up of area of plate failure shown in 127a.

Scale 1:2

111-3371

results it seemed probable that the optimum roll-cladding temperature for the uranium-5 w/o zirconium core alloy was close to 850°C, with very little latitude for furnace control and heat losses during rolling. End effects were bad at the core to end cladding transition in plates rolled below 900°C. This end effect was improved by increasing the length of preshaped core end taper in the cores for billet Nos. 153-159, inclusive.

On comparison of roll-clad uranium-zirconium binary alloys with roll-clad uranium-5 w/o zirconium-1.5 w/o niobium, it may be noted that preparation of cladding components and billet assembly were effected with equal ease. The mechanical strength of clad-to-core bonds as determined by mechanical testing were also equally good. Hot-rolled plates of the binary alloy containing 7.5 w/o or 10 w/o zirconium were as uniform in width and length when rolled at 850°C as the ternary reference alloy plates. Results from corrosion tests, with a high incidence of plate failures, indicated that the integrity of the cladding was not comparable to the clad ternary plates. Cladding thickness variations in rolled binary alloy plates with localized thin spots in the face cladding could account for catastrophic failures of the type noted, particularly if these thin areas were mechanically damaged or further reduced by cleaning and pickling. The cladding thickness variations and poor corrosion test results did not justify a substitution of uranium-zirconium binary core alloy for the proven uranium-zirconium-niobium reference alloy for EBWR fuel plates.

Any advantages from additional increases in zirconium content would be offset by neutron losses in the fuel. Other alloy additions such as silicon, chromium, or molybdenum, either as binary alloys or ternary alloys with zirconium or one another, might be suitable for roll cladding and prove to be more economical than the reference alloy.

ROLL-CLAD PLATES AND PLATE SPECIMENS PREPARED FOR IRRADIATION TESTING

The ultimate acceptability of uranium-5 w/o zirconium-1.5 w/o niobium for EBWR fuel plates depended upon the results of nuclear irradiation of the clad core alloy under conditions which would approach the operating conditions proposed for EBWR. Clad-plate specimens were needed which could be used to measure the effects of irradiation on corrosion resistance and dimensional stability, effects of cladding and heat treatment on dimensional stability, and high-temperature water dynamic loop testing of integrally clad specimens to simulate EBWR operations. The only available testing facilities with adequate neutron flux to effect the desired burn-up in the fuel specimens within the time available were in the Materials Testing Reactor (MTR). For this reason the sizes of specimens were limited and no full-size EBWR-type plates could be irradiated. Various sizes of clad-plate specimens were designed and fabricated to meet the needs of irradiation testing groups in the Reactor Engineering Division and Metallurgy Division.

Fabrication of Test Plates and Preparation of Specimens

A total of eight clad plates were fabricated for irradiation specimens and for control specimens to be corrosion tested. Two plates, Nos. 64 and 65, were designed to yield clad specimens for irradiation in NaK capsules for which the integrity of the cladding was not significant. Plate No. 98 was roll clad with a heavy face cladding for preparation of specimens with various face cladding thicknesses. Specimens from plate No. 98 were also prepared for irradiation in NaK capsules to show effects of cladding thickness in restraining dimensional changes, or growth, during irradiation. The remaining five plates, Nos. 253 to 257, inclusive, were designed and fabricated by the best practice established for EBWR fuel plates, as these plates were intended for corrosion and irradiation testing in the 250°C circulating water loop in MTR. Plate Nos. 256 and 257 had alloy cores enriched to 1.44% U^{235} . Dimensions of the cladding components for these eight billets are given in Table LVI.

As these eight cladding billets were fabricated at different stages in the plate development program, considerable variation occurred in the preparation of components, billet assembly, and roll cladding. All components were machined to size and cleaned according to the procedures given in Table LVII. No allowance was made in billet Nos. 64 and 65 for differential thermal expansion of the alloy core. A thermal expansion allowance of 0.020"/in. was made for the cores in all other billets. End plugs for billet Nos. 253 to 257, inclusive, were machined from hot-rolled slab so that the length dimension of the end plugs was oriented along the axis normal to the original hot-rolling plane of the rolled slabs. No attention was given to the orientation of axes in end plugs for the other billets.

Table LVI

DIMENSIONS OF CLADDING COMPONENTS FOR BILLETS
FABRICATED INTO IRRADIATION TEST PLATES

Cladding Billet No.	Dimensions for Billet Nos. 64 & 65 ⁽¹⁾ (in.)			Dimensions for Billet No. 98 ⁽²⁾ (in.)			Dimensions for Billet Nos. 253 to 257, incl. ⁽²⁾ (in.)		
	Width	Thickness	Length	Width	Thickness	Length	Width	Thickness	Length
Core ⁽³⁾	0.475	0.850	5.900	1.935	1.082	5.400	1.630	0.803	3.134
Cover Plates	0.675	0.075	7.600	2.473	0.310	6.741	2.162	0.125	4.395
Side Strips	0.850	0.100	7.600	1.100	0.250	6.741	0.819	0.250	4.395
End Plug ⁽³⁾	0.475	0.850	1.700	1.973	1.100	1.160	1.662	0.819	1.000
Steel Can	3.625	1.935	11.625	6.000	2.375	11.000	8.000	2.400	10.000

(1) Cores designed with 60° included angle shaped ends.

(2) Cores designed with 90° included angle shaped ends.

(3) Length dimension for cores and end plugs is over-all length including tapered ends.

Table LVII

PREPARATION OF COMPONENTS FOR CLADDING BILLETS
FABRICATED INTO IRRADIATION TEST PLATES

Cladding Billet No.	Core Material		Zircaloy-2 Cladding Material		Steel Can Material
	Casting No.	Surface Preparation	Ingot No.	Surface Preparation	
64	L-24	Dry sandblasted with 40 mesh Al ₂ O ₃ .	710D528	Acid bright dip 30 sec in boiling conc. HNO ₃ containing 0.5 v/o HF. Rinsed in running tap water.	Ti-Namel
65	L-24				Hot Rolled
98	L-125	Dry sandblasted with 40 mesh Al ₂ O ₃ .	710D530	Acid dip 1 min in 35 v/o HNO ₃ -5 v/o HF at 40°C. Rinsed in running tap water.	SAE-1020 Cold Rolled
253	K-68-5	Wet abrasive blasted with 400 mesh Al ₂ O ₃ , air-water blast rinse, rinsed in distilled water, rinsed in absolute alcohol, dried in vacuum.	5Y663	Acid bright dip 30 sec in boiling conc. HNO ₃ containing 1.0 v/o HF. Rinsed in running tap water, cold distilled water, hot distilled water, dried in clean dry circulating warm air.	Ti-Namel Hot Rolled
254	K-68-5				
255	K-68-5				
256	156-B				
257	156-B				

The cladding components for billet Nos. 64 and 65 were simply assembled around the core, clamped in position, the top and bottom covers pressed against the core and other cladding components with water-cooled copper chills at a pressure of $11\frac{1}{2}$ tsi, and all seams sealed by manual welding with an inert-gas tungsten arc. The remaining six billets were assembled and purged for 10 minutes with argon at 15 psi before being welded. These purged billets were all evacuated and sealed in a vacuum chamber. Billet No. 98 was sealed in vacuum with a zirconium-tipped Zircaloy-2 screw seal pin. Billets 253 to 257, inclusive, were sealed in vacuum with tapered seal pins followed by vacuum pop-welding. All billets were welded into steel jackets of the type illustrated in Figure 25 for protection during heating and roll cladding. Details of billet heating and rolling are included in Table LVIII.

Table LVIII

ROLLING DATA FOR BILLETS FABRICATED INTO IRRADIATION TEST PLATES

Cladding Billet No.	Rolling Temp. (°C)	Preheat Time (min)	Reduction Per Pass (%)	Reheat Time (min)	Passes Per Reheat	Rolling Speed (ft/min)	Total Reduction (%)
64 and 65	775	60	12 to 17	5	1	125	80
98	850	90	10 to 18.5	10	1	125	80
253 to 257, inclusive.	850	150	10 to 17	20	2	125	80

Rolled plate Nos. 254 to 257, inclusive, were heat treated for dimensional stability of the core alloy before being removed from their steel jackets. The following heat-treating procedure was used:

1. Heat for 30 minutes in air at 800°C.
2. Quench into lead at 640°C.
3. Hold 24 hours in lead at 640°C.
4. Air cool.

Plate No. 98 was decanned and heat treated for 15 minutes in a carbonate salt bath at 850°C followed by a water quench. After this heat treatment it was expected that any dimensional stability of specimens cut from plate No. 98 could be attributed to the restraining effect of the cladding.

Test specimens, which were 0.187" thick, 0.775" wide, and $13/16$ " to $1\frac{1}{4}$ " long with 0.015" of cladding on each face, were cut from plate No. 64. Five of these test specimens were finished with welded end closures and four with the core material exposed at the ends.

The welded closures were prepared by machining the core material from the ends to a depth of $1/8$ ", inserting a matching Zircaloy-2 plug, and welding across the ends with an inert-gas tungsten arc. All specimens were heat treated for corrosion resistance by heating 15 minutes in carbonate salt at 850°C , water quenching, and tempering 45 minutes in lead at 425°C . Surface contamination was removed by wet abrasive blasting with 325 mesh Al_2O_3 .

Plate No. 65 was cleaned with a wet abrasive blast, degreased, and pickled two minutes in 35 w/o HNO_3 -5 v/o HF at 40°C . This plate was committed to a long term corrosion test in 290°C water. After 535 hours of testing, the plate was machined across the ends and along the sides to remove all of the original billet component seal weld metal from the rolled plate. The machined plate was then heat treated the same as test specimens from plate No. 64, recleaned, and returned to corrosion testing.

Irradiation test specimens were prepared from sections cut from plate No. 98 by machining equal amounts of metal from each face to give various thicknesses of face cladding (0.060", 0.035", and 0.004"). On several additional specimens the face cladding was completely removed by machining.

Of the five plates designed to fit the cartridge in the MTR test loop (Nos. 253 to 257, inclusive), No. 253 was sectioned for evaluation of cladding bonds, Nos. 254, 255 and 256 were submitted to the Reactor Engineering Division for corrosion and irradiation testing, and No. 257 was rejected because of a defective seal pin weld in the cladding billet which affected the quality of the Zircaloy bonds in the rolled plate.

Sections cut from a clad development plate, No. 78 (see Tables XXVI, XXVII, and XXVIII), were heat treated in an attempt to impart both corrosion resistance and dimensional stability to the alloy core for irradiation specimens. Six samples, $3/4$ " wide and $1\frac{1}{4}$ " long with 0.022" nominal cladding, were cut from the rolled plate with the long axis parallel to the direction of rolling. Samples were heat treated in two groups of three each, according to the following schedules:

Group One

1. Heat for 3 minutes in carbonate salt at 850°C .
2. Quench into salt at 650°C .
3. Hold one hour at 650°C .
4. Air cool.
5. Heat for 3 minutes in salt at 850°C .
6. Water quench.
7. Age two hours in air at 400°C .

Group Two

1. Heat for 3 minutes in carbonate salt at 725°C.
2. Quench into salt at 650°C.
3. Hold one hour at 650°C.
4. Air cool.
5. Heat for 3 minutes in salt at 725°C.
6. Water quench.
7. Age two hours in air at 400°C.

The above treatments were referred to as "duplex" heat treatments. All of these specimens were submitted to the Irradiation Group of the Metallurgy Division for irradiation testing in NaK capsules.

Evaluation of Test Plates and Discussion of Results

Physical measurements were taken on decanned plates, and the location of the core relative to the side cladding and end cladding was determined by radiographic examination. Results of these measurements are included in Table LIX. Plates rolled close to the same final thickness were uniform in all other dimensions, including core length. The excessive amounts of width increase in plate Nos. 64 and 65 were due to the unusual width to thickness ratios (1 to 1.5) of the narrow cladding billets. The width spreads during rolling for the five billets rolled in 8" wide Ti-Namel steel cans were less than had been experienced with wider billets in the same size of can or billets rolled in other types of steel cans. This was a good indication of the degree of dimensional control which could be obtained in rolled plates with added restraint along the sides of cladding billets.

Table LIX

DIMENSIONS OF PLATES ROLLED FOR IRRADIATION TEST SPECIMENS

Clad Plate No.	Ave. Plate Thick. (in.)	Ave. Plate Width (in.)	Width Increase During Rolling (%)	Avg. Plate Length (in.)	Nominal Core Width (in.)	Ave. Core Length (in.)	Nominal Cladding Thick. (mils)
64	0.188	0.776	14.8	36-3/8	0.550	27-3/8	15
65	0.188	0.775	14.8	36-3/8	0.551	27-3/8	15
98	0.336	2.695	9.0	32-1/8	2.195	27-1/8	62
253	0.205	2.189	0.2	22-1/8	1.689	16-3/4	25
254	0.204	2.222	2.8	21-3/8	1.722	16-11/16	25
255	0.219	2.206	2.0	20-3/8	1.706	15-13/16	25
256	0.221	2.203	1.9	20-1/2	1.703	15-11/16	25
257	0.221	2.211	2.3	20-1/2	1.711	15-7/8	25

Metallographic examinations were made on all cut plate sections. Sections from plate No. 64 showed sound uniform bonds between the core and cover plates and at the tapered core ends. No bond was obtained between the core and side cladding or between the side cladding and end plugs on this rolled plate. Good bonds were noted at all cladding and core interfaces in plate No. 98, except for a few inclusions in cladding side strip to end plug interfaces. Figure 128 shows a representative section of clad-to-core bond from plate No. 98 after heat treating for 15 minutes at 850°C followed by a water quench. The average thickness of the diffusion layer after this heat treatment was 0.004". No defects were noted in any of the bonds in sectioned plate No. 253. The defective seal weld in cladding billet No. 257 resulted in poor quality Zircaloy bonds in the rolled plate.

FIGURE 128. Cladding to Core Interface in Plate No. 98. Plate heat treated 15 minutes in carbonate salt at 850°C followed by a water quench. Average thickness of the diffusion layer is 0.0004".

After an initial corrosion test for 535 hours in water at 290°C, plate No. 65 showed a faint white coating at the sides and ends corresponding to the prerolling billet weld metal. On subsequent testing, after removing this contaminated material by machining, a uniform grey coating developed on all Zircaloy surfaces early in the test. There was no change in the plate surface after an additional 12,785 hours of testing. The surfaces of plates

254, 255, and 256 showed adherent dark green and red interference films after testing 90 hours in water at 290°C. Plates 255 and 256 showed little change after an additional test for 170 hours in a stainless steel cartridge in a dynamic water test loop operated at 290°C.

All irradiated specimens were examined by the irradiation groups and complete analyses of all tests are included in other reports.⁽¹⁴⁾⁽¹⁵⁾ Data on specimens from plates 64, 78, and 98 irradiated in NaK capsules showed that the heat treatment for corrosion resistance of the core, or the duplex heat treatment combining an isothermal quench for stability with a water quench for corrosion resistance, did not produce stable structures under irradiation. The clad specimens all showed considerable restraint from the cladding to indicated burnups of 0.085 a/o. This effect of the cladding is partially demonstrated in Figure 129, in which there is shown little dimensional change in the section of plate 64 with sealed ends and considerable mushrooming of the core along the sides of the sections from plate No. 78, which were not sealed. The ability of the cladding to restrain growth in gamma-quenched specimens was found to increase with increasing cladding thickness. With a cladding 0.060" thick a hundred-fold decrease was noted in the growth rate compared with bare samples from plate No. 98, as shown in Figure 130.

Integrally clad plate Nos. 255 and 256 were examined after testing in the MTR water loop. Plate No. 256 with a slightly enriched uranium alloy core was irradiated for 2,700 hours in the in-pile cartridge, while plate No. 255 with a normal uranium alloy core was used as a control plate in the out-of-pile cartridge. Both plates had a shiny grey-black, evenly distributed oxide coating and showed no evidence of warp or distortion. After an estimated burnup of 0.35 a/o, plate No. 256 showed an increase in length and width of 0.004", with no measurable change in thickness. A photograph of the irradiated plate, No. 256, is shown in Figure 131.

The above results demonstrated that integrally clad plates could be fabricated, heat treated for dimensional stability, and irradiated in circulating water under conditions approaching those expected in a boiling water reactor. The final evaluation of the cladding process would now depend on irradiating a large number of full-size EBWR-type plates under actual EBWR operating conditions.

FIGURE 129. Irradiated Sections from Clad Plate Nos. 64 and 78.

129a. Section from clad plate No. 64 with ends sealed by welding. Indicated burnup of 0.021 a/o with G_i^* less than 5.

Macro 17637

2X

129b. Section from clad plate No. 78 heat treated with group No. 2 at 725°C, core exposed at 4 sides. Indicated burnup of 0.048 a/o with G_i of 18.

Macro 17648

2X

129c. End view of section from clad plate No. 78 heat treated with group No. 1 at 850°C, core exposed at 4 sides. Indicated burnup of 0.030 a/o with G_i of 33.

Macro 17657

2X

* G_i = microin./in. per fission/ 10^6 total atoms.

FIGURE 130. Irradiated Sections from Clad Plate No. 98 Showing Restraining Effect of the Cladding on the Irradiation Growth Rate of the Core Alloy.

130a. Section from clad plate No. 98 before irradiation.

Macro 18093

2X

130c. Section from clad plate No. 98 with 0.035" thick clad. Indicated burn-up of 0.12 a/o with G_i of 8.3.

Macro 18131

2X

* G_i = microin./in. per fission/ 10^6 total atoms.

130b. Section from clad plate No. 98 with 0.060" thick clad. Indicated burn-up of 0.12 a/o with G_i of 0.8.

Macro 18125

2X

130d. Section from clad plate No. 98 with all cladding removed. Indicated burnup of 0.087 a/o with G_i of 85.0.

Macro 18141

2X

FIGURE 131. Irradiated Plate No. 256 after 0.35 a/o Burnup. Plate was tested in the in-pile cartridge of the 250°C water loop in MTR. The plate surface was uniformly coated with a grey-black oxide. There was no evidence of distortion or warping.

111-4499

ROLL-CLAD DEVELOPMENT PLATES SCALED TO THE DIMENSIONS OF EBWR FUEL PLATES

Material and Fabrication Facility Restrictions Imposed on the Development of EBWR-Type Clad Plates

The possibility of fabricating fuel plates for EBWR at ANL further complicated the development program because of the size of plates which were proposed and the limitations of doing production work with facilities intended for development work. In order to obtain information on the limitations of existing facilities, effect improvements in billet assembly, roll cladding, heat treatment, and plate-cleaning operations, establish dimensional tolerances in rolled plates of the EBWR size, and fabricate some plates on a pilot plant scale, a total of 122 plates were rolled that were approximately $1\frac{1}{4}$ " thick, $3\frac{1}{2}$ " to 4" wide, and 4' to 5' long. Since detailed descriptions of component preparation, billet assembly, rolling procedures, and methods of evaluating rolled plates were given elsewhere in this report, most of this information for the EBWR-type plates is presented in tabular form. Although many of the rolled plates were sectioned in the course of evaluating changes of procedure, some were submitted to corrosion testing and fuel element subassembly welding tests.

Billets Rolled to Provide Handling Experience and to Supplement Development Data

The first EBWR-type billets which were rolled, up to No. 140, were used to supplement data from smaller development plates and provide experience in handling plates of this size. The components used for these sixteen billets and component preparation data are presented in Table LX. Data on billet assembly and roll cladding are given in Table LXI. Physical measurements and plate evaluations are summarized in Table LXII. Preliminary designs for EBWR fuel plates called for over-all plate dimensions to be 0.250" thick, 3.750" wide, and 52" long with the core uniformly clad with 0.020" of Zircaloy on each face, 0.125" on each side, and 1.000" on each end. Extra cladding material was to be provided to permit cleaning the face and machining the sides and ends to remove all surface defects and contamination. The billets were designed with a differential thermal expansion allowance of 0.020"/in. for the core relative to the cladding and an allowance of 10% for spread during rolling. The plate width was later revised to 3.625" and the allowance for spread during rolling was changed as indicated by data from rolled plates. Several additional revisions which affected billet dimensions were made in the fuel plate dimensions before the final design was approved for production.

Data from the evaluation of the first group of EBWR-type plates which were rolled confirmed results obtained from the development plates. Although several variables were involved in the design and fabrication

TABLE LX
COMPONENTS AND COMPONENT PREPARATION FOR EBWR-TYPE BILLETS USED TO SUPPLEMENT CLADDING DEVELOPMENT DATA

Cladding Billet No.	Core Casting No.	Zircaloy-2 Cladding	Assembled Cladding Billet Dimensions (in.)			Cover Plate Thick. (in.)	Side Strip Thick. (in.)	Core Length (in.)	Core End Taper (°)	Surface Preparation of Core	Surface Preparation of Cladding	Type of Steel in Jacket	Over-all Steel Jacket Dimensions (in.)	
			Thick.	Width	Length								Thick.	Length
108	L-161	710D530	1.321	3.680	11.525	0.125	0.250	10.584	90	Sandblasted followed by alcohol rinse and air dried.	1-min dip in 10 v/o HNO ₃ - 2 v/o HF, rinsed in tap water and distilled water.	ASTM A7-52T	2.50	16
109	L-170	710D530	1.321	3.680	11.525	0.125	0.250	10.584	90	Same as 108 above.	All components machined all over, degreased in trichloroethylene.	ASTM A7-52T	2.50	16
110	L-168	710D530	1.321	3.680	11.525	0.125	0.250	10.584	90	Same as 108 above.	Same as 109 above.	ASTM A7-52T	2.50	16
122	L-202	5Y345	1.342	3.643	12.740	0.125	0.250	10.800	100	Sandblasted only.	Same as 108 above.	ASTM A7-52T	2.50	16
123	L-204	5Y345	1.342	3.643	12.740	0.125	0.250	10.800	100	Same as 122 above.	Same as 108 above.	ASTM A7-52T	2.50	16
124	L-205	5Y345	1.342	3.643	12.740	0.125	0.250	10.800	100	Same as 122 above.	Same as 108 above.	ASTM A7-52T	2.50	16
125	L-213	5Y345	1.342	3.643	12.740	0.125	0.250	10.800	100	Same as 122 above.	Same as 108 above.	ASTM A7-52T	2.50	16
126	L-209	5Y345	1.342	3.743	12.740	0.125	0.250	10.800	100	Same as 122 above.	Same as 108 above.	ASTM A7-52T	2.50	16
127	L-207	5Y345	1.342	3.743	12.740	0.125	0.250	10.800	100	Same as 122 above.	Same as 108 above.	ASTM A7-52T	2.50	16
128	L-217	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	30-sec dip in 35 v/o HNO ₃ - 5 v/o HF, rinsed in tap water and distilled water.	SAE 1020	2.00	14
129	L-214	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14
130	L-226	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14
131	L-215	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14
132	L-218	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14
133	L-221	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14
134	L-224	5Y345	1.291	3.519	11.734	0.100	0.125	10.720	100	Same as 122 above.	Same as 128 above.	SAE 1020	2.00	14

Table LXI

BILLET ASSEMBLY AND ROLL CLADDING DATA FOR EBWR-TYPE
BILLETS USED TO SUPPLEMENT CLADDING DEVELOPMENT DATA

Cladding Billet No.	Billet Assembly Data				Billet Rolling Data							
	Cover Plate Pressure (1) (tsi on mating surfaces)	Inert Gas Purge Time (min)	Billet Evacuated After Welding	Type of Seal Pin End Closure	Preheat & Roll. Temp. (°C)	Preheat Time (min)	Reduct. per Pass (%)	Total No. of Passes	Passes per Reheat	Reheat Time (min)	Roll Speed (fpm)	Total Reduction (%)
108	5	None	No	None	850	120	10-17	11	1	10	75	80
109	5	12	Yes	Screwed and seal welded	850	120	10-17	11	1	10	125	80
110	5	12	Yes	Same as 109	850	120	10-17	11	1	10	125	80
122	4	15	Yes	Same as 109	850	120	10-17	8	1	10	125	67
123	4	15	Yes	Same as 109	850	120	10-17	12	1	10	125	80
124	4	15	Yes	Same as 109	850	120	10-17	12	1	10	125	80
125	4	15	Yes	Same as 109	850	120	10-17	12	1	10	125	80
126	4	15	Yes	Same as 109	800	120	10-17	12	1	10	125	80
127	4	15	Yes	Same as 109	800	120	14-17	10	1	10	125	80
128	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
129	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
130	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
131	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
132	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
133	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80
134	7	1-1/2	Yes	Same as 109	850	120	14-17	10	1	10	125	80

(1) Side strips for all billets held in place with C-clamps.

of these plates, it was concluded that certain changes in billet design, materials, component cleaning, billet assembly, and billet rolling were not desirable in maintaining good quality of plates. Reducing the amount of core end taper in rolled plates by increasing from 90° to 100° the included angle of shaped core ends could not be justified because of the increased surface irregularities at the plate ends. Reducing the thickness of cladding cover plate and side strip components did not allow sufficient stock for cleaning plate surfaces or squaring the rolled sides of plates by machining. Unless improvements, which would reduce the amount of camber in rolled plates, could be made in the rolling operation, the side cladding would have to be increased from the previously established 0.250" minimum. Although most of the Zircaloy bonds in rolled plates were sound, many defects which were noted in the form of inclusions could have resulted from inadequate cleaning of Zircaloy components in either 10:2 HNO₃-HF or 35:5 HNO₃-HF, absence of purge welding in billet No. 108, insufficient purging time of 1½ min instead of 10 to 15 min, use of screwed seal pins, absence of a vacuum pop-weld for seal pins, or reduction of the rolling temperature from 850°C to 800°C in billet Nos. 126 and 127. The substitution of ASTM A7-52T steel for SAE 1020 steel in one group of billet jackets resulted in severe bowing of some billets during rolling and a wide variation in width spread, 2.9% to 8.2%, in rolled plates. A wide range in carbon analysis of the steel jacket material (see Figure 118) was found to affect its hot-working properties with uneven deformation of various billet jackets

Table LXII

PHYSICAL MEASUREMENTS AND EVALUATION OF ROLL BONDS IN PLATES ROLLED FROM
EBWR-TYPE BILLETS USED TO SUPPLEMENT CLADDING DEVELOPMENT DATA

Cladding Billet No.	Rolled Plate Dimensions						Width Increase on Rolling (%)	Metallographic Evaluation of Roll-Clad Plate Bonds
	Ave. Thick. (in.)	Ave. Width (in.)	Total Plate Length (in.)	Total Core Length (in.)	Core End Taper Length (in.)	Camber (in./ft)		
108	0.238	3.832	59-3/8	51-1/4	2.54	0.035	4.1	Cladding not bonded to core in 3 areas 1/2" to 3/4" in dia. on one side of plate. Intermittent segmented inclusions in all Zircaloy-to-Zircaloy bonds.
109	0.238	3.785	57-3/16	49-3/4	2.46	0.020	2.9	All clad-to-core bonds were sound. Segmented inclusions in end plug to seal pin bond; all other Zircaloy bonds were free from inclusions.
110	0.250	3.862	55-3/4	47-1/2	2.36	0.012	4.9	Same as 109 above.
122	0.447	3.941	39-1/4	27-7/8	1.16	Not Meas.	8.2	Faint inclusions at end plug to side strip interface. Segmented inclusions at end plug to seal pin interface. All other cladding bonds were sound and free from inclusions.
123	0.248	3.862	63-5/8	55-3/16	2.29	0.008	5.8	All bonds were good except for a very small line of inclusions as the end plug to side strip interface. Plate not sectioned through core.
124	0.251	3.783	63-1/8	57-1/2	2.39	0.013	3.8	Same as 123 above.
125	0.249	3.804	64-3/8	56-3/4	2.36	0.013	4.4	Same as 123 above.
126	0.253	3.908	63	55-7/16	2.31	0.009	7.3	Fine line of inclusions at end plug to side strip interface and segmented inclusions at all cover plate to side strip and cover plate to end plug interfaces
127	0.263	3.833	60-3/16	52-5/8	2.19	0.013	5.2	Fine continuous line of inclusions at end plug to side strip interface. Inclusions at junction of side strip, end plug, and cover plate on both ends of plate. Plate not sectioned thru core.
128	0.259	3.662	53-7/8	50-3/4	2.13	0.006	4.1	Cladding not bonded to core in one area 1" wide and 1/2" to 1" long on one side of plate. Segmented and semi-continuous inclusions at cover plate to side strip and end plug to side strip bonds.
129	0.262	3.642	54-3/8	50-15/16	2.14	0.012	3.5	Few segmented inclusions at end plug to side strip bonds. All other bonds sound. Plate not sectioned thru core.
130	0.261	3.672	54	50-1/2	2.12	0.010	4.3	Semi-continuous inclusions at end plug to side strip, end plug to seal pin, and cover plate to side strip along plate length.
131	0.260	3.667	54-9/16	51-1/16	2.14	0.015	4.2	Same as 130 above.
132	0.260	3.662	54-5/8	50-13/16	2.14	0.0005	4.1	Inclusions at all Zircaloy interfaces at seal pin end of plate only, bonds at other end satisfactory. Plate not sectioned thru core.
133	0.259	3.666	54-3/4	51-7/16	2.16	0.012	4.2	Same as 132 above.
134	0.260	3.651	54-1/2	50-7/8	2.14	0.009	3.8	Plate not sectioned for metallographic examination.

during rolling. Billet No. 122 was rolled to only 67% reduction in thickness because of difficulty in handling the severely deformed steel jacket. Billets rolled in the thinner and narrower SAE 1020 steel jackets, while uniform in average width and thickness, did not have uniformly smooth surfaces, and individual plates showed width variations of 0.020" to 0.060" from one end of the plate to the other. While the variables introduced during assembly and rolling did not represent optimum conditions for integral clad bonding, they did point out limitations which would have to be imposed in fabricating plates of this size.

With the first group of EBWR-size plates which were produced, existing facilities were found to limit the fabrication of both the components and cladding billets. Restrictions to large plate development were found to include limited capacity for producing and cleaning components, limited size of purge-welding and pop-welding fixtures, shortage of suitable steel for protective billet jackets, limited furnace capacity for preheating and reheating billets, absence of mechanical facilities for handling jacketed billets during rolling, the need to alter roll schedules to comply with power limitations of rolling equipment, and absence of facilities for de-canning, heat treating, and handling plates for final cleaning operations.

Billet Component Limitations

Production of core castings as outlined in Table IV tied up a good deal of the available melting capacity with individual castings from which a large portion of each casting was cropped and recycled. Until multiple castings as outlined in Table V were developed,⁽²⁰⁾ only a limited number of EBWR-size cores were available. Separate wet abrasive blast cleaning facilities were not available for cleaning uranium alloy core and Zircaloy-2 cladding components. To avoid uranium contamination of the wet abrasive grit used on cladding stock, all cores were dry sandblasted, a process which left some fine grit embedded in the surface. Zircaloy components for development billets were most effectively cleaned with a wet abrasive blast with 400 mesh alumina grit followed by acid pickling in boiling concentrated HNO_3 containing 0.5 v/o to 1.0 v/o HF. For smaller components this pickling was done with the acid in a Pyrex beaker or evaporating dish heated on an electric hot plate. This equipment could not be adapted to cleaning the larger components for EBWR-type billets.

The size and type of steel used for protective billet jackets or cans influenced both surface quality and dimensional uniformity of all rolled plates. Ti-Namel steel in bars $1\frac{1}{4}$ " x 8" suitable for jacket stock for EBWR-type cladding billets was not commercially available. A shortage of SAE 1020 steel in either hot or cold-rolled bars of this size resulted in the temporary use of ASTM A7-52T steel cut from hot-rolled plate. Because of the wide range in carbon analysis and related variation in hot-working properties of the steel, rolled plates could not be evaluated for dimensional tolerances.

Billet and Plate Rolling and Handling Limitations

Camber which developed along the length of a 5' long clad plate was not only a function of the accuracy of the mill setting and uniform temperature of the material being rolled, as in conventional rolling practice, but also reflected individual thickness variations of the composite uranium alloy core, Zircaloy cladding, and steel jacket. For a nominal $2\frac{1}{2}$ " x 8" x 16" cladding billet having a 0.004" thickness variation across the width (2.498" to 2.502"), the roll camber after 80% reduction in thickness would be equivalent to 0.0225"/ft of length provided no camber was introduced by the mill setting or billet position in the mill during rolling. Mill settings which would result in a finish-rolled thickness variation of 0.001" across the width of a 0.210" thick, 4.000" wide plate would result in a camber of 0.097"/ft of length⁽²⁴⁾ provided no camber was introduced by initial billet thickness variations. In order to maintain a minimum side cladding of 0.125" and a core width of $3.310" \pm 0.030"$ in a $3.625" \begin{smallmatrix} +.000 \\ -.005 \end{smallmatrix}$ " wide plate after machining for EBWR-type plates, not more than 0.030" of camber in a 5' length (0.006" camber/ft) could be tolerated. Considerable care in selection and inspection of component materials, minimum thickness variation of the jacketed cladding billet, and accurate mill settings were necessary to minimize roll camber.

Jacketed cladding billets of the EBWR type were found to weigh from 80 to 100 lb, depending on the size of jacket which was used. Manipulating individual billets of this size from the furnace to the rolling mill and back manually with tongs was not only physically difficult but also hazardous. It was difficult to position the billet as it entered the roll pass, and manual handling often caused delays which affected billet temperature, reheat time, and total rolling time. Rolling variables under these conditions were seldom reproducible. With available furnace capacity, a maximum of only three billets could be rolled in one 8-hour day.

The increased size and weight of rolled EBWR-type plates introduced additional handling problems in the plate-finishing operations. The heavier steel jacket was more difficult to remove from rolled plates by tearing or shearing as had been done with smaller development plates. Dissolving the steel from around the plate in an acid bath was found to be a slow operation, requiring acid pickling facilities which were not available. Before the results of heat treatment on irradiated plate specimens were known, the optimum temperatures and procedures for heat treating EBWR-type plates were not established, and facilities for handling and heat treating plates of this size were not available. Final cleaning of clad plates to insure corrosion-resistant Zircaloy surfaces was done by pickling in 35 v/o HNO_3 -5 v/o HF followed by a water rinse. Changes in acid concentration and temperature resulted in uneven removal of metal from the plate surfaces. Introduced contaminants from plates, plate supports, or the pickle tank, and inadequate rinsing or drying resulted in surface contamination

which showed up as a white corrosion product in 290°C static autoclave testing. Alterations and additions to existing facilities and continued development of EBWR-type plates all had to be done concurrently.

Equipment and Fabrication Changes Affecting Quality of EBWR-Type Clad Plates

To overcome the equipment limitations which adversely affected the quality of EBWR-type plates and also permit an increase in the number of plates which could be produced in a single day, additional equipment was added and alterations made to existing equipment. In most cases this required specially designed facilities which had to be made specifically to handle EBWR-type plates. Detailed descriptions of this equipment are included in another report covering manufacture of EBWR fuel plates,⁽²⁴⁾ and only a brief summary to show relationship between equipment changes and quality of rolled plates is given below.

Component Cleaning and Billet Assembly Equipment

Two automatic wet abrasive blasting machines, Figure 132, were used to uniformly clean 850°C and 600°C rolled Zircaloy-2 sheet and finish-machined roll-clad fuel plates. The operation of these machines was described in connection with cleaning of Zircaloy components in the Material Preparation and Equipment section of this report.

A smaller wet abrasive blasting machine, shown in Figure 133, for cleaning uranium alloy cores prior to assembly was constructed with a stainless steel cabinet. The nozzle, which was mounted on an air-driven reciprocating arm, was designed to blast a uniform 4" wide pattern across the core. Cores were placed on a stainless steel rack and were totally enclosed inside the cabinet during blasting. An automatic air-water blast machine, as pictured in Figure 134, was built to remove embedded, as well as loose, grit from the surfaces of alloy cores after wet abrasive blasting. Three air-water nozzles on this machine were also attached to an air-driven reciprocating arm which was mounted on a power-driven carriage over an open tank containing the material to be cleaned.

A double wall-type, 347 stainless steel tank with a capacity of 10 gallons of acid was fabricated to contain the concentrated HNO_3 -1.0 v/o HF solution used to clean cladding components. The acid was heated by regulating a flow of 15 psi, 230°F steam between the inner and outer walls of the tank. Components were clamped in stainless steel tongs, as shown in Figure 135, and lowered into the acid-cleaning tank which was contained in a vented outer stainless steel tank, as shown in Figure 136. After acid pickling, the components were rinsed in running tap water, cold distilled water, hot distilled water, and dried in warm circulating air. Billet core and cladding components were then assembled for welding on an open

FIGURE 132. Automatic Wet Abrasive Blasting Machine Used to Clean Rolled Zircaloy-2 Sheet and Strip and Clad Fuel Plates.

FIGURE 133. Wet Abrasive Blasting Machine Used to Clean Uranium Alloy Cores Prior to Assembly.

FIGURE 135. Zircaloy-2 Cover Plate Components for EBWR-Type Cladding Billets Clamped in Stainless Steel Tongs for Immersion in Boiling Concentrated HNO_3 - 1.0 v/o HF for Cleaning.

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FIGURE 136. Zircaloy-2 Cladding Components Immersed in Boiling Concentrated HNO_3 - 1.0 v/o HF for Cleaning Prior to Billet Assembly

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rack, all components being handled with tongs, as shown in Figure 137. Assembled components were then transferred to the purge-welding assembly press pictured in Figure 138.

The purge-welding facility was constructed with water-cooled copper alloy platens mounted on vertical and horizontal rams. Argon gas was bled into the billet clad-to-core interface by means of a locking taper fitting in one end plug of the billet. Components were clamped together loosely during purging to permit the escape of entrained air and excess inert purge gas. Following the purge cycle, a pressure of 4 to 5 tsi was applied to the cladding mating surfaces, which were then sealed by inert-gas tungsten-arc welding. Automatic power-driven welding carriages, mounted on tracks as shown in Figure 139, were used to produce more uniform assembly welds.

The vacuum chamber used to evacuate inert purge gas from welded billets and seal the billets by welding in vacuum is illustrated in Figure 140. This chamber had a removable cover from which was suspended a support plate for mounting 12 of the EBWR-size cladding billets. A copper spacer and guide for the billets also served as a ground connection during welding. Billets were mounted on the supporting plate and electrodes were changed and positioned with the plate removed from the vacuum box, as shown in Figure 141. Individual electrode holders which were insulated from, but extended through, the cover received power from a common bus bar. All welding controls were preset and the welding arc initiated and regulated from a central panel, as pictured in Figure 142.

Billet Rolling Equipment

The most extensive alterations were made to the facilities for heating, handling, and rolling the cladding billets. The existing 6' long, 36-kw Hevi Duty electric resistance element furnace was relocated for use as a billet preheating furnace. Heat-resistant alloy tracks were placed on the furnace hearth and heat-resistant alloy roller buggies were used to charge cladding billets into the furnace. A new 150-kw Hevi Duty electric resistance element furnace with a 7' long uniform temperature zone was installed for reheating billets and plates during rolling. This furnace was placed on the side of the rolling mill opposite the preheat furnace and in tandem with the mill. Doors at each end of the furnace and a heat-resistant alloy roller hearth simplified manipulation of billets and plates to and from the mill. Three 8" wide EBWR billets or jacketed plates could be accommodated across the width of the hearth. Recording temperature controllers, a multipoint monitoring temperature recorder, and temperature limiting controls for both furnaces were located in one central control bank.

Furnace entry tables and mill feed tables were constructed to convey hot billets and plates between the furnaces and the rolling mill. A short extension table with tracks for the roller buggies was used to transfer

FIGURE 137. Cladding Components Being Assembled for Welding on an Open Rack. All components were handled with clean metal tongs. Assembled components were then transferred to press for purge-welding. Three purge-welded billets are shown on rack at right of assembled components.

FIGURE 138. Schematic Drawing of Press Used for Purge-Welding Cladding Billets between Pressurized Water-Cooled Platens Mounted on Vertical and Horizontal Rams.

FIGURE 139. Purge-Welding Press and Automatic Power Driven Inert-Gas Tungsten-Arc Welding Equipment for Sealing EBWR Cladding Billet Components.

FIGURE 140. Schematic Drawing of Vacuum Chamber Used to Evacuate Inert Purge Gas from Welded Billets and Seal the Billets by Welding in Vacuum.

FIGURE 141. Vacuum Chamber Cover with Suspended Billet Support Plate Containing Cladding Billets, Electrodes, and Electrode Holders Prepared for Evacuation and Welding.

FIGURE 142. Evacuation Chamber with Control Panel for Operating Vacuum Arc Weld Cycle to Seal Evacuated EBWR-Type Cladding Billets.

preheated billets from the 36-kw furnace to the mill feed tables. Power-driven, variable speed, reversible roller feed tables were located on each side of the mill. These tables were designed to handle billets or plates up to 12" in width and 8' long. Both tables were equipped with air cylinders to position or center the work before it entered the mill. A 42" wide x 116" long, power-driven, variable speed, reversible roller table was built to transfer material from the 150-kw furnace to the mill feed table. Cylinder-operated push-up guides on each side of the table aligned billets for rolling or re-entry to the 150-kw furnace.

The 16" x 24" United Mill was modified to increase the mill capacity and simplify control of screwdown settings for production rolling. The spring-type balancing mechanism for the top roll was replaced with hydraulic lifters, and the bronze roll neck bearings were replaced with 4-row tapered roller bearings in new steel chocks. A new set of 17" diameter, hot flat rolls were installed. New 17" diameter, cold-finishing rolls were also available to cold finish cladding component stock if needed. The addition of an automatic screwdown control mechanism, by which any desired rolling schedule could be programmed, eliminated operating errors when rolling several billets simultaneously. A centrally located pulpit-type control console was added, which made it possible for a single operator to observe and perform all operations in the rolling of cladding billets from the time they left the preheat or reheat furnace until they were returned to the furnace. This method of operation resulted in more efficient use of manpower, increased safety, and greater control over the uniformity of the finished product. The location of control console, furnaces, conveyor tables, and screwdown program mechanism relative to the rolling mill is illustrated schematically in Figure 143.

A 50-ton capacity Aetna Standard hydraulic straightening press was modified by placing 10" x 84" water-cooled steel platens on the ram and bed of the press. Hot-rolled plates were transferred from the mill delivery table to the press after the last roll pass and then cooled under pressure to maintain flatness, as shown in Figure 144.

Plate Heat Treating and Cleaning Equipment

After the optimum heat treatment for dimensional stability of clad uranium-5 w/o zirconium-1.5 w/o niobium plates had been established from results of irradiation testing,⁽¹⁵⁾ facilities could be set up for proper heat treatment of EBWR-type plates. The recommended treatment consisted of heating the plates for 30 to 60 min at a temperature of 800°C to 825°C, isothermally quenching to 640°C, holding for 24 hours at 640°C, and air cooling. Heating, quenching, and cooling rates for each step were not thought to be critical; as added protection against mechanical damage or surface contamination, all operations were performed while the rolled plates were still contained in their steel jackets.

FIGURE 144. Fifty-Ton Straightening Press with 84" Long Water-Cooled Platens Used to Flatten Rolled BEWR-Type Billets after the Final Roll Pass.

The only measurements of clad-to-core bond tensile strength which showed a comparison between rolled and heat-treated samples were made on rolled development plates from preliminary cladding billets (see Table XXIII). These tests all showed a sharp decrease in bond tensile strength after heating for 15 min in carbonate salt at 850°C and water quenching. The bond strength on these quenched samples was improved by aging for 45 min in air at 425°C. Proposed explanations for these strength variations included change in thickness of diffusion layer, change of alloy phase in the diffusion layer, and hydrogen absorption from the salt bath.

To check the effects on bond strength following the recommended isothermal transformation heat treatment for dimensional stability of EBWR-type plates, a series of test specimens were prepared from rolled plate No. 213 and heat treated for various times in both carbonate salt and lead. Sections 1/2" wide and 3" long were cut from the clad plate. The core alloy was exposed at all four sides of each specimen, and there was 0.025" of cladding on the top and bottom faces. Tensile-test specimens were prepared with welded 1/4" diameter Zircaloy-2 studs before being heat treated to minimize possible effects from stud welding on the heat-treated specimens. Samples from the rolled plate and all samples held for one hour in either salt or lead at the gamma-solution temperature of 800°C, followed by isothermal transformation treatments, were analyzed for hydrogen content by the Corrosion Group of the Metallurgy Division. The hydrogen analysis was determined by heating specimens at 850°C for one hour in vacuum and measuring the amount of hydrogen which was evolved. Practically all the hydrogen was removed from the uranium alloy core in this way. Since a considerably longer time would be required for complete removal of hydrogen from the Zircaloy-2 cladding, the values obtained were not absolute but were adequate for purposes of comparison. Table LXIII includes heat treatment variables and results of bond tensile strength measurements and hydrogen analyses which were obtained on test specimens.

Since all specimens from plate No. 213 had surfaces with the core alloy exposed during heat treatment, the rate of hydrogen diffusion during heat treatment and vacuum analysis could conceivably be different from that of integrally clad specimens heat treated in salt. The influence of integral cladding on hydrogen diffusion was observed in roll-clad plate No. 292, which was decanned, heat treated in its entirety in carbonate salt, and sectioned for hydrogen analysis. The plate was heated for one hour in salt at 800°C followed by isothermal transformation for 16 hours in salt at 640°C. Sections from this plate containing 0.025" of clad on top and bottom faces only were found to contain 3.8 ppm hydrogen. Sections of the alloy core with all cladding removed analyzed 2.9 ppm hydrogen. Even though the Zircaloy cladding did contain considerable hydrogen as might be expected, the total amount of hydrogen which diffused into the

core was apparently reduced as compared with specimen No. 213E (see Table LXIII). This reduction of hydrogen in the core was not comparable to specimens heat treated in air and lead, indicating that the integral cladding was not a satisfactory barrier for hydrogen diffusion into the alloy core.

Table LXIII

EFFECTS OF HEAT TREATMENT ON BOND TENSILE STRENGTH AND
CONTAINED HYDROGEN IN EBWR CLAD PLATE-TYPE SPECIMENS

Test Specimen No.	Heat Treatment Variables				Bond Tensile Strength ⁽¹⁾ (psi)	Contained H ₂ after Heat Treatment (ppm)
	Gamma Solution Treatment (800°C)		Isothermal Trans. Treatment (640°C)			
	Heating Medium	Time at Temp. (min)	Heating Medium	Time at Temp. (hr)		
213	(As Rolled Plate - Not Heat Treated)				80,800	0.3
213-A	Salt	30	Salt	4	53,800	Not Analyzed
213-B	Salt	30	Salt	16	66,300	Not Analyzed
213-C	Salt	30	Salt	32	35,200	Not Analyzed
213-D	Salt	60	Salt	4	59,800	3.3
213-E	Salt	60	Salt	16	41,500	9.4
213-F	Salt	60	Salt	32	50,100	14.9
213-G	Air	30	Lead	4	79,600	Not Analyzed
213-H	Air	30	Lead	16	75,700	Not Analyzed
213-I	Air	30	Lead	32	52,600	Not Analyzed
213-J	Air	60	Lead	4	83,160	0.6
213-K	Air	60	Lead	16	74,600	0.5
213-L	Air	60	Lead	32	82,400	0.3

(1) Average of 2 or more measurements

From the data in Table LXIII it may be seen that there was a sharp decrease in bond strength for all specimens heat treated in the carbonate salt. This decrease in strength was of the same order as that reported in Table XXIII for previous clad plate specimens heat treated in carbonate salt. Attempts to separate the cladding from the core with a sharp chisel indicated that the bonds on all specimens heat treated in the salt, including specimens from integrally clad plate No. 292, were of a brittle nature and less ductile than either the core or cladding and could be readily broken. Hydrogen analyses showed a continued increase in hydrogen content with increase in time in salt at 640°C. This increase in hydrogen was almost directly proportional to time up to 32 hours, as indicated in Figure 145.

For all specimens heat treated for the same time intervals in air and lead, the ultimate bond tensile strength, with but one exception, did not appear to be affected by the heat treatment. The one exception, specimen No. 213-I, had a bond strength approximately 17,000 psi greater than the corresponding specimen heat treated in salt, No. 213-C. There was no appreciable change in hydrogen content in specimens heat treated in air

FIGURE 145. HYDROGEN CONTAINED IN CLAD PLATE
HEAT TREATED IN CARBONATE SALT
VS TIME IN SALT BATH AT 640° C.

and lead compared with the hydrogen content of the as-rolled plate. These tensile test specimens failed with a nonbrittle fracture and many failed in either the core or cladding material instead of at the bond. The cladding could not be separated from the core by chiseling on any of these specimens.

Although the results showed no decrease in strength with increase in hydrogen beyond 9.4 ppm for samples treated in salt, the brittle nature of all bonds from specimens with 3.0 ppm hydrogen or greater caused more erratic values in bond tensile testing, probably due to greater notch sensitivity at the clad-to-core interface.

The decrease in bond strength and increase in hydrogen content with increase in heating time for clad plate specimens heat treated in carbonate salt, as contrasted with no appreciable change in either bond strength or hydrogen content for clad plate specimens heat treated in air and lead, left little doubt as to the detrimental effect of hydrogen absorption from the carbonate salt bath. These results also rule out the possibilities of changes in the thickness of the diffusion layer or alloy phase changes in the diffusion layer being responsible for the observed differences in bond strength as a result of heat treatment. Change in bond strength from either diffusion or change in alloy phase during heat treating should occur independent of heating medium, which was not the case.

The decision to perform both heat-treating steps on EBWR clad plates while the rolled plates were still jacketed in steel suggested the possibility of the steel protecting the clad plate from hydrogen contamination in the salt bath. A specimen cut from clad plate No. 195 which was heat treated in its entirety while still jacketed in steel for one hour in salt at 800°C, quenched into salt at 640°C, held at 640°C for 24 hours and air cooled, was analyzed for hydrogen. The hydrogen content reported for this plate was only 0.6 ppm, indicating that practically no contamination had occurred. After shearing excess steel from the sides and ends of rolled plates, the steel jacket could no longer be relied upon to provide an integral seal to keep salt from coming in contact with the fuel plate, however, and ideal conditions for heat treating EBWR-type fuel plates ruled out the use of carbonate salt baths for a heating medium.

For subsequent heat-treating operations two 70-kw Hevi Duty electric resistance pot-type furnaces were converted from salt to lead operation. A slotted exhaust duct was installed to remove fumes from both pots. Plates were loaded into racks in the 150-kw Hevi Duty furnace, heated for 45 min in air at 825°C, transferred to a lead pot operating at 640°C, and held at 640°C for 24 hours. Racks in these furnaces supported seven plates at a time.

Excess steel along the sides and ends of jacketed rolled plates was removed by shearing to reduce the weight and volume of plate material which would have to be handled during the heat treatments. It was found that

heat-treated plates could be decanned by shearing the remaining steel to within $1/8$ " of the side of the fuel plate provided the total plate camber did not exceed $1/16$ " in 5 ft.

All plates were rolled with 0.005" of excess cladding on each face. This excess was removed by wet abrasive blasting and pickling after machining to insure a corrosion-resistant surface. Previous experience with single plates indicated that pickling for 10 min in a 35 v/o HNO_3 -5 v/o HF solution at 40°C would remove 0.005" of metal uniformly from all exposed surfaces. An exothermic reaction was found to take place while pickling one group of five plates together; the temperature of the bath was raised to 60°C with the result that most of the cladding was removed from the surface of several plates. One of these plates, No. 221, failed during subsequent corrosion testing in water at 288°C . A photograph of the ruptured area at the end of this plate after 336 hours of testing is shown in Figure 146. Measurements of the cladding thickness adjacent to the ruptured area varied from 0.005" to 0.010", and it is probable that the failure initiated at a break in the cladding.

To maintain proper control over this final cleaning operation, the acid bath was contained in a plastic-lined tank provided with a submerged stainless steel coil in which hot or cold water could be circulated to regulate the bath temperature at $38^\circ\text{C} \pm 2^\circ\text{C}$. Additional HF was added as required to maintain the concentration of the pickle solution. Individual plates were suspended in the bath in a rack supported by an electric chain hoist, as illustrated in Figure 147. Supporting lugs or ears were left at each end of the plates as they were machined to length. The plates were supported in the rack by these lugs to avoid contact at any point on the finished plate surface. While supported in this rack the plate was transferred directly from the pickle solution to subsequent water rinses in running tap water, cold distilled water, and hot distilled water. After cleaning, the lugs could be sheared off the plate ends without damaging the finished surface.

Cladding Billets Rolled During Development of Production Facilities

Billet assembly, roll bonding, and evaluation data for 76 EBWR-type clad plates, which were fabricated at various stages during the development and installation of equipment for production of this size plate, are included in Table LXIV. The handling of various groups of billets of the same size having the same assembly and rolling variables was kept as uniform as possible. Some operational difficulties introduced unintentional variables which affected plate quality or rolled-plate dimensions. The main purpose in rolling some billets which were expected to yield inferior quality plates was to help locate and correct defects in the equipment.

FIGURE 146. End of Clad Plate No. 221 which Ruptured During Corrosion Testing After Excessive Pickling of Face Clad.

111-3587

FIGURE 147. Clad EBWR-Type Fuel Plate Suspended in Rack Above Acid Pickle Tank Containing 35 v/o HNO_3 - 5 v/o HF Used for Final Plate Cleaning.

TABLE LXIV
BILLET ASSEMBLY, ROLL BONDING, AND EVALUATION DATA FOR EBWR-TYPE CLAD PLATES FABRICATED
DURING THE DEVELOPMENT AND INSTALLATION OF EQUIPMENT FOR PRODUCTION OF EBWR FUEL PLATES

Cladding Billet No.	Core Casting No.	Zircaloy-2 Cladding	Significant Billet Assembly Variables	Assembled Cladding Billet Dim. (in.)				Significant Roll Bonding Variables	Rolled Plate Dimensions				Camber (in./ft.)	Width Increase on Rolling (%)	Evaluation of Rolled Plate Bonds (1)				
				Thick.	Width	Length	Core Length		Avg. Thick. (in.)	Avg. Width (in.)	Total Plate Length (in.)	Total Core Length (in.)			Clad to Core	Cover Plate to Side Strip	Cover Plate to End Plug	Side Strip to End Plug	Seal Pin
140	L-216	5Y345	Sealed in vacuum with screw pin. Not pop-welded.	1.332	3.769	12.250	10.400	Reheat 10 min every pass. Rolled in 8" wide ASTM A7-52T steel can.	0.272	3.893	55-31/32	49-9/16	0.0052	3.3	I	I	I	I	I
141	L-225	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.271	3.915	56-7/16	49-7/16	0.0016	3.9	I	I	I	III	I
142	L-229	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.268	3.909	57-1/16	50-3/16	0.0100	3.7	I	I	I	III	I
143	L-244	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.264	3.900	57-1/4	50-9/16	0.0090	3.5	I	I	I	I	III
144	L-247	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.263	3.900	57-3/4	50-1/2	0.0129	3.5	I	II	II	I	I
145	L-248	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.265	3.903	57-3/4	50-1/2	0.0068	3.6	I	I	I	I	I
146	L-249	5Y345	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.267	3.875	57-5/8	50-29/32	0.0077	2.8	I	I	I	II	I
175	L-265	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.265	3.931	57-1/8	50-1/8	Not Meas.	4.3	I	I	I	I	IV
176	L-267	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.268	3.887	56-3/8	49-13/16	Not Meas.	3.1	I	I	I	III	III
177	L-268	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.270	3.910	55-3/4	48-7/8	Not Meas.	3.7	I	I	I	III	III
178	L-269	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.268	3.840	56-9/16	49-11/16	Not Meas.	1.9	I	I	I	III	III
179	L-270	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Reheat 20 min every 2 passes. Rolled in 8" wide ASTM A7-52T steel can.	0.265	3.940	56-3/8	49-9/16	Not Meas.	4.5	I	I	I	I	IV
180	L-271	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.266	3.905	57	49-7/8	Not Meas.	3.6	I	V	V	III	III
181	L-272	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.266	3.881	57-3/16	50-1/8	Not Meas.	3.0	I	I	I	I	IV
182	L-273	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.239	3.931	62-1/4	55-1/2	Not Meas.	4.3	I	I	I	I	V
183	L-274	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.267	3.826	57	50-1/8	Not Meas.	1.5	I	I	I	II	IV
184	L-276	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.263	3.932	57-1/8	50-3/8	Not Meas.	4.3	I	I	I	III	III
185	L-278	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.264	3.923	56-3/4	50-7/16	Not Meas.	4.1	I	I	I	I	IV
186	L-279	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 179 above.	0.247	3.915	60-3/8	53-3/8	Not Meas.	3.9	I	I	I	I	IV
191	L-289	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Same as 140 above.	0.272	3.896	55-1/16	49-9/16	Not Meas.	3.4	I	I	I	III	I
192	L-291	5Y525	Same as 140 above.	1.332	3.769	12.250	10.400	Reheat 15 min every 2 passes. Rolled in 8" wide ASTM A7-52T steel can.	0.279	3.875	54-1/2	48-7/16	Not Meas.	2.8	I	III	III	IV	I
193	L-296	5Y525	Side strip dislocated during assembly. Sealed in vacuum with screw pin. Not pop-welded.	1.332	3.769	12.250	10.400	Same as 192 above.	0.271	3.911	55-9/16	48-13/16	Not Meas.	3.7	I	V	V	IV	IV
194	L-298	5Y525	Same as 193 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.276	3.921	53-7/8	46-5/8	Not Meas.	4.0	I	I	I	IV	I
195	K5-1	5Y525	Sealed in vacuum with 3" included angle locking taper pin. Not pop-welded.	1.332	3.769	12.250	10.400	Reheat 15 min every 2 passes. Rolled in 8" wide Ti-Ni steel can.	0.259	3.861	58-1/8	52	Not Meas.	2.4	I	I	I	II	II
196	K5-2	5Y525	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 195 above.	0.261	3.854	58-13/32	51-5/16	Not Meas.	2.3	I	II	II	III	IV
197	K5-3	5Y525	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 195 above.	0.261	3.851	59-3/16	51-11/16	Not Meas.	2.2	I	II	II	III	IV
198	K6-1	5Y525	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 195 above.	0.266	3.853	57-7/16	50-3/4	Not Meas.	2.3	I	II	II	III	IV
199	K6-2	5Y525	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.295	3.871	52-1/8	45-13/16	Not Meas.	2.7	I	II	II	III	IV
200	K6-3	5Y525	Assembly welded with- out purging. Sealed in vacuum with locking taper pin. Not pop-welded.	1.332	3.769	12.250	10.400	Same as 192 above.	0.295	3.853	52-1/4	45-23/32	Not Meas.	2.3	I	III	III	IV	III
201	L6-4	5Y525	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.267	3.970	56-5/8	49-9/32	Not Meas.	5.3	I	IV	IV	I	IV
202	K6-5	5Y525	Sealed in vacuum with 3" included angle locking taper pin. Pin sealed by pop- welding.	1.332	3.769	12.250	10.400	Same as 192 above.	0.270	3.948	55-3/4	48-27/32	Not Meas.	4.8	I	I	IV	I	IV
203	K6-6	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.268	3.974	55-31/32	48-31/32	Not Meas.	5.4	I	III	III	IV	III
204	K6-7	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.271	3.946	56-3/16	49-1/4	Not Meas.	4.7	I	III	I	III	I
205	K7-1	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.279	3.933	54-1/4	44-1/4	Not Meas.	4.4	I	I	III	IV	III
206	K7-2	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.281	3.907	53-7/16	47-5/16	Not Meas.	4.6	I	I	III	IV	III
207	K7-3	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.275	3.944	54-3/4	48-1/32	Not Meas.	4.4	I	III	III	IV	III
208	K7-4	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 192 above.	0.284	3.925	52-1/4	46-7/32	Not Meas.	4.1	I	I	I	IV	II
209	K7-5	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 195 above.	0.266	3.888	58-1/4	51-9/32	Not Meas.	3.2	I	III	III	IV	III
210	K7-6	710D960	Same as 195 above.	1.332	3.769	12.250	10.400	Same as 195 above.	0.265	3.857	58-1/8	51-3/32	Not Meas.	2.3	I	III	III	IV	III
211	K9-2	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Reheat 15 min every 2 passes. Rolled in 6" wide ASTM A7-52T steel can.	0.295	4.255	51-5/8	Not Meas.	Not Meas.	10.3	I	I	I	IV	III
212	K9-3	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 211 above.	0.298	4.253	51-7/8	Not Meas.	Not Meas.	10.2	I	III	III	IV	IV
213	K9-5	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 211 above.	0.301	4.289	51	Not Meas.	Not Meas.	11.2	I	II	II	III	IV
214	K10-1	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 211 above.	0.298	4.264	51-5/8	Not Meas.	Not Meas.	10.6	I	III	III	IV	IV
215	K10-3	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 212 above.	0.304	4.038	54-1/16	49-29/32	Not Meas.	4.7	I	III	III	IV	IV
216	K19-4	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 192 above.	0.299	4.034	53-3/32	49-3/4	Not Meas.	4.6	I	III	III	IV	IV
217	K10-5	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 192 above.	0.300	4.025	54-5/8	50-1/8	Not Meas.	4.4	I	I	II	III	III
218	K17-2	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.296	3.994	54-7/8	50-3/4	Not Meas.	3.6	I	III	III	IV	III
219	K17-3	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.296	4.011	54-3/8	50-3/32	Not Meas.	4.0	I	II	II	IV	III
220	K17-4	710D960	Same as 195 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.297	3.988	55	50-15/16	Not Meas.	3.4	I	III	III	IV	III
221	K17-5	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Reheat 15 min every pass. Rolled in 8" wide ASTM A7-52T steel can.	0.295	3.998	55-1/8	50-15/32	Not Meas.	3.7	I	I	I	III	I
222	K17-7	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Same as 221 above.	0.299	3.997	55-1/2	50-11/32	Not Meas.	3.7	I	I	I	II	I
224	K18-2	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.290	3.988	55-1/2	51-7/16	Not Meas.	3.4	I	I	I	I	I
225	K18-3	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.292	4.008	56-1/4	51-7/16	Not Meas.	3.9	I	V	I	V	I
226	K18-4	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.295	3.963	55-1/2	Not Meas.	Not Meas.	2.8	I	I	I	III	I
227	K18-5	710D960	Same as 202 above.	1.513	3.856	11.600	10.400	Same as 179 above.	0.294	4.014	54-7/8	50-13/16	Not Meas.	4.1	I	I</			

With the exception of the last eleven cladding billets listed in Table LXIV, the billet end plug components were in the process of being fabricated before the effects of Zircaloy anisotropy and end plug orientation were evaluated. Consequently only billets beginning with No. 239 were prepared with end plugs having the preferred prior hot-working orientation shown in Figure 114. All Zircaloy-2 components were cleaned by pickling in boiling concentrated HNO_3 -1.0 v/o HF, followed by thorough rinsing in running tap water and hot distilled water. All cores were cleaned by wet abrasive blasting and a water blast rinse, followed by rinsing in distilled water and alcohol. The regular purge-welding assembly practice preceded the final vacuum end seal operation. Facilities for pop-welding the seal pin were available for only 28 of these billets, the remainder being sealed with either a screwed pin or a 3° included angle locking taper pin both of which were seal welded in air after the billets were removed from the vacuum chamber. Experimental vacuum pop-welds with the electrode negative instead of positive were made on billet Nos. 246, 249, 250, and 251.

A special heat of hot-rolled Ti-Namel steel bars, $1\frac{1}{4}" \times 8"$, was obtained for cladding billet jackets. This steel was used for jackets on 15 of the EBWR-type development plates. The remaining billets were jacketed in ASTM A7-52T steel. All billets were preheated two hours at 850°C prior to rolling and were rolled at 850°C at a speed of 125 ft/min with reductions of 10% to 17% per pass. Power-driven delivery tables on each side of the mill simplified billet handling for all billets, but until the facilities were installed for manipulating and positioning the billets on each pass, only one pass could be made per reheat. A total reduction of 80% in thickness was made on each billet.

The ratings applied to rolled-plate bonds in Table LXIV reflect a range in quality which is demonstrated by the representative bond interfaces shown in the photographs in Figure 148. Improper orientation of rolled end plug stock and poor end seals on evacuated billets accounted for most of the inclusions found in Zircaloy-to-Zircaloy bonds in the rolled plates. Zircaloy bonds in plates sealed by pop-welding were generally superior, although pop-welds made with the electrode negative exhibited poor weld penetration.

For a total of five changes in the EBWR design dimensions for roll-clad plates, corresponding changes were made in the billet dimensions. Consequently it was not possible to roll enough plates of each size to establish accurate rolled-plate tolerances. However, the data in Table LXIV show that the dimensions of plates rolled in the ASTM low carbon steel varied considerably more than those rolled in Ti-Namel steel. With ideal rolling conditions, plates rolled in the ASTM steel cans may be expected to vary by ± 2.5 mils in thickness and $\pm 1/2"$ in length with an increase of $1\frac{1}{2}\%$ to 5% in width. Plates rolled in the Ti-Namel steel cans

FIGURE 148. Representative Rolled-Plate Bonds Illustrating Evaluation Symbols Used with Table Nos. LXIV and LXVI.

- 148a. Cladding to core bond with no evidence of voids or inclusions at the interface. Type I bond.

- 148b. Cladding to cladding bond with no evidence of voids or inclusions at the interface. Type I bond.

- 148c. Cladding to cladding bond with few widely dispersed inclusions. Type II bond.

- 148d. Cladding to cladding bond with segmented inclusions in less than 50% of the bond interface. Type III bond.

- 148e. Cladding to cladding bond with segmented inclusions in more than 50% of the bond interface. Type IV bond.

- 148f. Cladding to cladding bond with voids or unbonded areas in the bond interface. Type V bond.

may be expected to vary by ± 1 mil in thickness and $\pm 1/4$ " in length with an increase of $2\frac{1}{2}\%$ to $3\frac{1}{2}\%$ in width. The four billets rolled in 6" wide ASTM A7-52T steel cans spread from 10% to 11% in width during rolling.

With the improved facilities for preparing and handling components and cladding billets, the quality and uniformity of EBWR-type plates was improved. These added facilities also made it possible to increase the rate of fabrication from 3 plates in an 8-hour day to from 9 to 12 plates with the same manpower.

Corrosion Testing of EBWR-Type Clad Development Plates

Miscellaneous plates rolled for supplementary development data and for evaluation of fabrication facilities were selected for water corrosion testing. Some of these plates were heat treated for dimensional stability before corrosion testing; others were tested in the as-rolled condition. The heat treatment consisted of heating the plates for one hour in carbonate salt at 800°C, quenching into salt at 640°C, and holding at 640°C for 24 hours, followed by air cooling to room temperature. With the exception of four plates which were clad with only $1/8$ " of Zircaloy along the sides (Nos. 129, 132, 133, and 134), all plates were machined along the sides and across the ends to remove excess cladding stock which was presumed to have been contaminated by welding during billet assembly. All plates were cleaned for testing by wet abrasive blasting and pickling for 10 min in 35 v/o HNO_3 -5 v/o HF followed by a water rinse.

Some plates were fabricated from billets which were assembled and rolled by procedures which deviated noticeably from the best-established practice for plate fabrication. Metallographic evaluation of Zircaloy bonds in coupons cut from the ends of some corrosion test plates showed segmented or continuous inclusions in the Zircaloy interface. The fact that plates with such known defects did not fail in corrosion test indicated that either these interfaces were not selectively attacked or that the test did not continue long enough for water to penetrate to the core. All plates were corrosion tested by the Corrosion and Irradiation Group of the Reactor Engineering Division. The testing was done in static water at temperatures up to 290°C. Details of plate preparation, test temperature, test time, results, and comments on the tests are included in Table LXV.

After the initial testing on plate No. 132 as listed in Table LXV, this plate was subjected to catastrophic corrosion testing to observe the extent by which the core would be attacked in the event that water did penetrate through the cladding. A $1/16$ " diameter hole was drilled through the cladding into the reference alloy core prior to testing. The plate was then examined periodically after testing in water at 288°C. Following is the list of test intervals during which the temperature of the water in the autoclave was held at 288°C:

Table LXV

CORROSION TEST DATA FOR EBWR-TYPE CLAD FUEL PLATES

Clad Plate No.	Plate Preparation					Static Corrosion Testing		Total Test Time (hr)	Comments
	Heat Treated	End Machined	Sides Machined	Acid Pickled	Degreased	Water Temp. (°C)	Time at Temp. (hr)		
123		X	X	X		288	1018	4342	Slight warp at plate ends at conclusion of test.
						227	333		
						288	715		
						216	142		
						288	2134		
127		X	X	X		288	1018	4342	Same as 123 above.
						227	333		
						288	715		
						216	142		
						288	2134		
129		X		X		288	691	11,260	White spots on sides result of prerolling billet assembly weld contamination which was not removed from rolled plate.
						227	333		
						288	715		
						216	142		
						288	9379		
132 ⁽¹⁾		X		X	X	288	355	355	Grey on sides from prerolling assembly weld contamination not removed from rolled plate.
133		X		X		288	691	11,260	Same as 129 above.
						227	333		
						288	715		
						216	142		
						288	9379		
134				X		288	691	4015	Slight warp along plate length.
						227	333		
						288	715		
						216	142		
						288	2134		
175	X	X	X	X		288	145	145	
176		X	X	X		288	145	145	
177		X	X	X		288	145	145	
178	X	X	X	X		288	145	145	
179	X	X	X	X		288	145	145	
181		X	X	X		288	145	145	
184		X	X	X		288	145	145	
185		X	X	X		288	145	145	
193	X	X	X	X		288	338	740	Plate not adequately rinsed following acid pickle.
						288	402		
197	X	X	X	X		288	338	740	Plate not adequately rinsed following acid pickle and not all contaminated assembly weld removed by machining.
						288	402		
198	X	X	X	X		288	338		
199		X	X	X	X	288	402	740	Same as 197 above.
						288	336		
202	X	X	X	X	X	288	336	336	
206	X	X	X	X	X	288	336	336	Billet prerolling assembly weld contamination not completely removed by machining.
209		X	X	X	X	288	336	336	
210		X	X	X	X	288	336	336	
215		X	X	X	X	288	336	336	Plate mechanically damaged during handling causing dent on edge.
216		X	X	X		288	338	740	Same as 197 above.
						288	402		
218		X	X	X	X	288	336	336	
220		X	X	X	X	288	336	336	
221		X	X	X	X	288	336	336	
222		X	X	X	X	288	336	336	No evidence of Zr to Zr bond failure. Excessive face cladding removed during pickling.

(1) Plate No. 132 subjected to catastrophic corrosion test by drilling a 1/16" dia. hole through the cladding into the core and continuing to test in 288°C water, see Figure 149.

Period No. 1	-	2 hours
" "	2	8 "
" "	3	25 "
" "	4	24 "
" "	5	24 "
" "	6	24 "
" "	7	24 "
Total		131 hours

For each test period an additional four hours were required to bring the autoclave up to test temperature and 24 hours more were needed to cool it down so that the plate could be removed for examination. Photographs of the plate showing progressive corrosion attack are included in Figure 149. The rate of corrosion appeared to progress uniformly in the core along concentric rings, with no preferential attack along the bond line. Absence of a preferential bond line attack limited the amount of core material which would otherwise have been exposed to water.

EBWR-Type Plates Fabricated on a Pilot Plant Scale

After all the equipment for handling and fabricating EBWR clad fuel plates had been installed and tested, a group of 30 plates were rolled on a pilot plant basis. These plates were fabricated by the best-established procedure for preparation of billet components, billet assembly, and roll bonding. The dimensions of the components for some of these billets were adjusted to ensure plate dimensions within the tolerances established for EBWR fuel plates.

Core castings for these trial fuel plates were machined to size from ultrasonically inspected multiple core castings. The cores were wet abrasive blasted, blast rinsed, rinsed in distilled water and alcohol, and dried in vacuum before assembly. Cladding component stock for end plugs, electrodes, and seal pins was rolled at 850°C and machined to size. Cover plate and side strip stock was finish rolled at 600°C, cleaned by wet abrasive blasting, sheared oversize, and the sides machined to the desired width and length. All Zircaloy-2 components were pickled in boiling concentrated HNO₃ containing 0.5 to 1.0 v/o HF, triple rinsed in running tap water, rinsed in hot distilled water, and dried in filtered, warm circulating air. Billet components were assembled with clean stainless steel tongs, purged 12 min with argon gas at 15 psi, pressed between horizontal and vertical water-cooled copper alloy platens, and the component mating surfaces welded with a semi-automatic inert-gas tungsten arc. A differential thermal expansion allowance of 0.020"/in. was allowed for the core relative to the cladding. The orientation of Zircaloy-2 end plugs machined from hot-rolled slab was selected so that the rolling direction of the end plug was normal to the prior rolling plane of the slab. This selection took advantage of the hot-working

FIGURE 149. Progressive Corrosion Attack of EBWR-Type Plate No. 132 in 290°C. Degassed Water after Addition of Known Defect.

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anisotropy of Zircaloy to effect a satisfactory side bond between the end plugs and Zircaloy-2 side strips. The purge-welded billets were placed in a vacuum chamber and evacuated to 4×10^{-5} mm of Hg through the $1/4$ " diameter hole in one end plug which was used for the purge connection. This hole was sealed under vacuum with a tapered Zircaloy-2 pin pop-welded to the billet end plug.

Assembled cladding billets were fitted into machined SAE 1020 steel jackets which were sealed by welding. Jackets were welded with a heliarc root pass followed by coated consummable electrode welding. The jacketed billets were preheated three at a time in the 36-kw Hevi Duty furnace. All were rolled to 80% reduction in thickness at 125 ft/min with reductions of 10% to 17% per pass and reheated 18 min in the 150-kw Hevi Duty furnace after every two passes. Rolling mill feed and delivery tables were operated at a speed of 150 ft/min. By preheating three billets two hours before the start of the scheduled day shift, a maximum of 12 billets were rolled in an 8-hour shift, all operations being performed by two men.

Cladding component materials, billet dimensions, rolled-plate dimensions, and bond evaluation for these trial plates are given in Table LXVI. Billet Nos. 264 to 288 were designed for thin EBWR fuel plates, as detailed in Figure 150. Of these 24 billets, a change of 0.006" was made in core thickness (Nos. 276 to 288), and 0.008" in core width (Nos. 282 to 288), to bring these rolled plates within the specified dimensional tolerances for thin EBWR fuel plates. Excess cladding was allowed on the faces, sides, and ends of rolled plates for cleaning and machining. Satisfactory cladding bonds were obtained on all but five of the plates, three of which were rolled from billets which were not completely evacuated before being sealed. There were no bond line inclusions or other defects observed in sections cut from 19 of the rolled plates.

The ability to roll integrally clad uranium-5 w/o zirconium-1.5 w/o niobium alloy fuel plates on a production basis was demonstrated on a pilot scale using modified development fabrication facilities. Results from all EBWR-type plates which were rolled showed that fuel plates could be hot rolled within required tolerances of thickness, width, and length, they could be heat treated for dimensional stability under irradiation, and would be corrosion resistant in water at 290°C. Further evaluation of plates could be expected only from operating conditions within a boiling water reactor core.

Table LXVI

CLADDING COMPONENTS AND EVALUATION OF EBWR-TYPE PLATES FABRICATED ON A PILOT PLANT SCALE

Cladding Billet No.	Core Casting No.	Zircaloy-2 Cladding	Assembled Cladding Billet Dim.(in.)				Rolled Plate Dimensions				Camber (in./ft)	Width Increase on Rolling (%)	Evaluation of Rolled Plate Bonds ⁽¹⁾				
			Thick.	Width	Length	Core Length	Avg. Thick. (in.)	Avg. Width (in.)	Total Plate Length (in.)	Total Core Length (in.)			Clad to Core	Cover Plate to Side Strip	Cover Plate to End Plug	Side Strip to End Plug	Seal Pin
258	K82-1	5Y663 710D960	1.112	3.719	12.158	10.683	0.212	3.817	58-31/32	53-15/32	Not Meas.	2.6	I	I	I	I	III
259	K82-2	5Y663 710D960	1.112	3.719	12.158	10.683	0.217	3.873	58-9/16	51-1/2	Not Meas.	4.1	I	I	I	I	I
260 ⁽²⁾	K82-3	5Y663 710D960	1.112	3.719	12.158	10.683	0.212	3.822	59-1/2	54-1/16	0.0042	2.8	I	IV	IV	IV	IV
261 ⁽²⁾	K82-4	5Y663 710D960	1.112	3.719	12.158	10.683	0.210	3.864	59-5/16	53-11/16	0.0021	3.9	I	I	I	I	IV
262 ⁽²⁾	K82-5	5Y663 710D960	1.112	3.719	12.158	10.683	0.214	3.857	58-3/4	52-1/2	0.0026	3.7	V	IV	IV	V	IV
263	K82-6	5Y663 710D960	1.112	3.719	12.158	10.683	0.214	3.820	58-13/16	53	Not Meas.	2.7	I	I	I	I	I
264	K95-8	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.378	0.214	3.880	57-3/32	50-15/16	0.006	3.5	I	I	I	II	I
265	K95-10	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.322	0.215	3.895	56-11/16	50-35/64	0.0003	3.9	I	I	I	I	I
266	K95-6	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.323	0.215	3.913	55-15/16	50-13/32	0.0011	4.4	I	I	I	I	I
267	K95-3	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.216	3.899	55-3/4	50-47/64	0.0024	4.0	I	I	I	I	I
268	K96-6	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.216	3.898	56-29/32	50-21/64	0.0014	4.0	I	I	I	I	I
269	K96-4	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.215	3.874	55-3/4	50-11/16	0.0054	3.3	I	I	I	II	I
270	K96-2	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.215	3.900	55-1/2	50-15/32	0.0006	4.0	I	I	I	I	I
271	K95-2	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.364	0.216	3.872	56-3/16	50-21/32	0.0011	3.3	I	I	I	I	I
272	K95-9	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.341	0.216	3.858	55-29/32	51-1/32	0.0024	2.9	I	I	I	I	I
273	K95-5	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.361	0.216	3.859	56-1/8	50-3/4	0.0003	2.9	I	I	I	I	I
274	K96-10	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.215	3.895	55-5/8	50-5/8	0.0012	3.9	I	I	I	I	I
275	K96-7	5Y525 5Y663 5Y912	1.094	3.749	11.888	10.400	0.210	3.887	56-19/32	51-15/64	0.0052	3.7	I	I	I	I	I
276	K97-2	5Y525 5Y663 5Y912	1.100	3.657	11.928	10.440	0.214	3.792	55-13/16	50-7/16	0.0017	3.7	I	I	I	I	I
277	K97-3	5Y525 5Y663 5Y912	1.100	3.657	11.928	10.440	0.213	3.794	Not Meas.	Not Meas.	Not Meas.	3.8	I	I	I	II	I
279	K97-5	5Y525 5Y663 5Y912	1.100	3.657	11.928	10.440	0.214	3.798	55-29/32	50-11/32	Not Meas.	3.9	I	I	I	II	I
280	K97-8	5Y525 5Y663 5Y912	1.100	3.657	11.928	10.440	0.215	3.781	56-15/32	51-7/32	0.0015	3.4	I	I	I	I	I
281	K97-11	5Y525 5Y663 5Y912	1.100	3.657	11.928	10.440	0.215	3.763	55-31/32	50-19/32	0.0031	2.9	I	I	I	I	I
282	K95-3	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.217	3.778	55-5/8	50-7/16	0.0047	3.1	I	I	I	I	I
283	K96-8	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.217	3.788	56-5/8	51-3/32	0.0015	3.4	I	I	I	I	II
284	K97-1	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.219	3.780	56-1/16	50-7/8	0.0054	3.1	I	I	I	I	III
285	K97-6	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.217	3.808	56-5/32	50-15/16	0.0002	3.9	I	I	I	I	II
286	K97-7	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.217	3.817	56-5/16	50-7/8	0.0006	4.1	I	I	I	I	I
287	K97-10	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.214	3.821	56-5/8	50-59/64	0.0004	4.2	I	I	I	I	I
288	K97-9	5Y914 5Y663 5Y912	1.100	3.665	11.928	10.440	0.215	3.841	56-1/16	50-29/32	0.0030	4.8	I	I	I	I	I

(1) Evaluation of rolled plate bonds based on ultrasonic through transmission testing of complete plate plus metallographic examination of representative plate sections.

Explanation of evaluation symbols as follows:

- I - Bonded with no evidence of voids or inclusions at the interface as shown in Figures 148a and 148b.
- II - Fair bond with few widely dispersed inclusions at the interface as shown in Figure 148c.
- III - Segmented inclusions noted in less than 50% of the bond interface as shown in Figure 148d.
- IV - Continuous inclusions noted in more than 50% of the bond interface as shown in Figure 148e.
- V - Voids or clearly unbonded areas as shown in Figure 148f.

(2) Cladding billets 260, 261 and 262 were not completely evacuated before being sealed.

FIGURE 150. EBWR ZIRCALOY-2 CLAD URANIUM-5% ZIRCONIUM-1.5% NIOBIUM ALLOY FUEL PLATE DIMENSIONS.

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