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PRESSURE BONDING ZIRCALOY-2 CLAD FUEL ELEMENTS

By

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Fuels Fabrication Development

Reactor and Fuels Research and Development Operation

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ABSTRACT**DECLASSIFIED**

A metallurgical bond can be effected between a Zircaloy-2 jacket and a thin walled uranium tube by treatment in a high temperature, high pressure gas autoclave. Bonding is independent of core history, provided that all surfaces are free from contamination. Gas pressure bonding causes the fuel element jacket to conform to the core, which promotes bonding on all surfaces including the ends. Grain growth occurred in some instances between the jacket and end cap interface. A three phase system (alpha, delta and epsilon) was identified across the interface at the bonding conditions of 845 C (1500 F), 10,000 psi and a time of four hours. Four structures were observed; these were epsilon, epsilon plus delta, delta, and alpha plus delta. Microhardness tests were used to identify the various phases. Also, thickness measurements were made of each component in the interface. The normal pressure bonded interface consists mainly of epsilon and delta phases. A cast bonded sample, subjected to the pressure bonding treatment, consists predominantly of alpha plus delta material while an interface bonded during casting is primarily alpha plus delta phases and epsilon phase.

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PRESSURE BONDING ZIRCALOY-2 CLAD
URANIUM FUEL ELEMENTS

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INTRODUCTION

Solid state diffusion has been widely used in joining dissimilar metals at a temperature below the melting point of either constituent. The first recorded use of solid state diffusion to join two metals occurred in 1820 when Faraday welded steel and platinum wires by tightly clamping them together and sintering at a temperature below the melting point of either. Roberts-Austin showed that steel could be prepared by carburizing iron in contact with diamond in a vacuum without melting the iron. In 1946 Smigelskas and Kirkendall observed diffusion in a copper plated alpha brass block containing molybdenum wire markers. Fick's law, which is based on Fourier's heat flow equations, was used by Smigelskas and Kirkendall to predict the diffusive flow of mass. Examples of the use of diffusion in industry are numerous, especially in the powder metallurgical, electronic and nuclear fields. Fuel elements, required to fuel nuclear reactors, have created a special need for diffusion bonding the fuel element core to the jacket. This union is necessary to insure an uninterrupted heat flow from the core to the coolant. This bonding then minimizes "hot-spot failures" of the jacket or transformation of the core to a less desirable crystalline form.

To obtain an efficient diffusion bond, intimate contact must exist between clean metal surfaces. High pressures enhance such contact and are often used. These pressures may be obtained through the use of a punch and die assembly mounted in a hydraulic press or from compressed fluids within a closed system. Increasing the temperature will increase the diffusivity, and, since diffusion is a rate process, an increase in time will also increase the diffusion.

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Pressure bonding, more specifically known as thermopneumatic cladding, has been used successfully at several other sites to bond the fuel element core to the jacket. Pocalyko and Ransom,⁽¹⁾ of the duPont Engineering Research Laboratory, give the following advantages of using fluid pressure as a bonding technique:

1. Fluid pressure acts normal to all surfaces at all points, thus enabling any configuration to be bonded.
2. Pressure is uniform over the entire working surface including the edges and ends of the fuel assembly.
3. Core dimensions remain unchanged in that there is no plastic deformation. This is due to uniform pressure in all directions, thus no shear stresses exist within the core. Jacket deformation, however, does occur. The amount of deformation is a function of the clearance between the core and jacket as well as the surface roughness of the mating parts.
4. Pressure bonding is self testing for small leaks. If the jacket enclosing the fuel element is not tight before fluid pressurizing, the pressurizing fluid will leak into the jacket. The necessary pressure differential between the outside and inside of the element will not exist, therefore no bonding will occur. If the leak is sufficiently small and the pressure is quickly released from the element, the leak will be shown as a billowing of the jacket.

Pocalyko and Ransom used a pressure as low as 5000 psi to satisfactorily bond aluminum clad plate type fuel elements; excellent results were obtained at pressures as high as 14,000 psi. Fair results were obtained at 2500 psi, but the higher pressures resulted in more intimate contact between the jacket and the core. The average bonding temperature was 525 C with moderate success obtained at temperatures as low as 450 C. The lower limit for bonding 1100 series aluminum to nickel plated uranium was 500 C, 5000 psi and a 30 minute bonding cycle.

1. Pocalyko, A. and J. T. Ransom. Fluid Pressure Bonding - II, DP-148. October 1957 (SECRET).

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The French have used both hot gases and cold oil to cause mechanical bonding between a uranium core and a magnesium or aluminum jacket. Gauthron⁽²⁾ states that cold cladding is difficult to achieve if close tolerances are not held between the clad and core.

Wheeler and Kaulitz,⁽³⁾ of General Electric's Hanford Laboratories, have successfully bonded aluminum clad nickel plated uranium rods and tubes in the BMI high pressure gas autoclave facility. Cores were successfully bonded in both the as-cast and extruded condition. Bonding conditions were 500 C (950 F) for one hour at 10,000 psi pressure.

Another pressure bonding process used in fuel element fabrication is that of hot pressing.⁽⁴⁾ In this process the preassembled aluminum clad nickel plated uranium core is inserted into a preheated die, then pressed at 24,000 psi in a hydraulic press at a temperature of 600 C for five minutes. The resulting bond is metallurgically sound.

Paprocki, Hodge and Carmichael⁽⁵⁾ of Battelle Memorial Institute, have used gas pressure at elevated temperatures to produce Zircaloy-clad flat-plate uranium dioxide fuel elements. Compartmentalized Zircaloy picture frames, uranium dioxide fuel plates and the Zircaloy cladding plates were assembled, placed into a container, evacuated and then welded. This sealed unit was processed at 10,000 psi pressure and a temperature of 843 C (1500 F) for four hours. This treatment welded the

-
2. Gauthron, M. "Thermopneumatic Cladding", Fuel Elements Conference, Paris. TID-7546, Book 1, November 18-23, 1957.
 3. Wheeler, R. G. and D. C. Kaulitz, Aluminum Clad Rod and Tube Element, HW-55498. March 26, 1958 (CONFIDENTIAL).
 4. Tverberg, J. C. Improvements in the Hot Press Process, HW-59129. April 1, 1959 (SECRET).
 5. Paprocki, S. J., E. S. Hodge and D. C. Carmichael. "Pressure Bonding of Zircaloy-Clad Flat-Plate Uranium Dioxide Fuel Elements", Nuclear Metallurgy, Volume 7. New York: American Institute of Mining, Metallurgical, and Petroleum Engineers, October 29, 1959.

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Zircaloy sections together while a graphite coating prevented reaction between the core and clad. This Zircaloy bond had been examined by Young and Schwartz⁽⁶⁾ with the aid of an electron microscope. Their general conclusions were:

1. Belt abraded Zircaloy surfaces exhibited a consistent fine scale roughness. Chemically pickled surfaces were smooth regardless of prior treatment.
2. Chemically pickled samples and specimens with the bond line coated with zirconia, which were pressure bonded at 1500 F and 10,000 psi had pitting along the bond line. This was due to voids or contamination along the bond line. This was probably due to voids or contamination along the interface which were removed during etching. Bond porosity was essentially eliminated by pressing for one hour at 260 C (500 F) at a calculated pressure of 350,000 psi. This indicated that the bond line pitting was due to interfacial voids.
3. Voids formed in alpha phase (below 860 C) pressure bonded Zircaloy after a short time beta anneal.
4. Vapor deposited layers of carbon, chromium, iron, nickel, niobium, tin and titanium on belt abraded samples inhibited grain growth across the bond interface of alpha phase pressure bonded material. A contamination layer without interfacial voids was present in the samples coated with carbon, chromium, iron, nickel and tin. There was no positive indication of either voids or contamination in either the niobium or titanium coated samples.
5. Grain growth across the chemically pickled interface may have been inhibited by a thin contamination film originally present on the Zircaloy surfaces or by the surfaces being too smooth.

The purpose of this investigation was to obtain data on the nature of the solid state diffusion bond between uranium and Zircaloy-2. And to obtain an indication of the conditions required for bonding. These conditions would include a general time temperature and pressure range, the effect of

6. Young, A. P. and C. M. Schwartz, Electron Microscopical Examination of Bonds in Zircaloy-2. BMI-1364. July 29, 1959.

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surface energy due to cleanliness or the presence of a pre-existing diffusion bond, and the effect of a variation of core crystalline structures.

SUMMARY

The following observations were made:

1. A four hour treatment at 845 C and 10,000 psi caused excessive diffusion across the Zircaloy-uranium interface. Either the time or temperature could be reduced.

2. Cores in the mechanically worked, heat-treated, or as-cast condition had similar diffusion bonds. In any case the core had to be free of surface contamination to insure uniform diffusion.

3. Bond formation appeared to begin by uranium diffusing across the interface into the Zircaloy, forming a Widmanstatten structure of epsilon phase material. This diffusion appeared to reach a limiting thickness on the Zircaloy side of the interface at which time the continued increase in uranium concentration caused a gradual transformation of the epsilon phase material into a mixture of epsilon plus delta phase. As this transformation began the sharp line associated with the interface was replaced by a diffused region in the uranium. Simultaneously, two additional regions became evident, namely delta phase and a mixture of alpha plus delta phases. Longer diffusion times increased the amount of alpha plus delta phase material along the uranium side of the interface. Termination of the diffused area was characterized by another Widmanstatten structure of alpha uranium and delta phase material which extended into the uranium.

4. Subjecting a cast bonded specimen to the pressure bonding treatment resulted in a three fold growth of the uranium rich interfacial compound; namely, the alpha plus delta constituent.

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5. The following microhardness values were measured across the interface by diamond-pyramid (DPH) and Knoop hardness tests:

a. Uranium	270 DPH	230 Knoop
b. Alpha plus Delta	270 DPH	295 Knoop
c. Delta Phase	400 DPH	385 Knoop
d. Delta plus Epsilon and Epsilon Phase	230 DPH	215 Knoop
e. Annealed Zircaloy-2	160 DPH	165 Knoop
f. Beta Transformed Zircaloy-2	200 DPH	200 Knoop

6. The interfaces were composed of the following approximate compositions:

a. Pressure Bonded:

22% Alpha plus Delta
28% Delta
15% Epsilon plus Delta
35% Epsilon

b. Cast Bonded:

42% Alpha plus Delta
10% Delta
6% Epsilon plus Delta
42% Epsilon

c. Cast Bonded, Pressure Bond treated:

72% Alpha plus Delta
6% Delta
6% Epsilon plus Delta
16% Epsilon

7. The pressure bonding treatment bonded the jacket end cap to the core as well as promoting grain growth across the Zircaloy-to-Zircaloy

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interface of the jacket and end cap. When the fuel element core was in close contact with the jacket end cap, a limited extrusion of uranium into the unbonded interface between the end cap and jacket resulted. If a slight gap existed between the core and end cap prior to the high temperature-high pressure treatment, the jacket would collapse at that point, extruding the uranium until the void was filled. Even under these conditions bonding occurred between the Zircaloy end cap and the uranium core. Any voids or defects present on the surface of the uranium core prior to pressure bonding were bonded to the jacket at the completion of the treatment.

EXPERIMENTAL PROCEDURE

Core Fabrication: Extruded cores were formed by gamma extruding a uranium billet into a tubular shape. They were beta heat treated prior to machining to final size.

Cast cores of dingot uranium were prepared by vacuum induction melting in graphite crucibles coated with flame sprayed zirconia. This procedure is explained in detail elsewhere⁽⁷⁾.

Several of the cast uranium cores were beta heat treated to refine the grain size. This heat treatment consisted of heating in a chloride salt at 730 C, holding for ten minutes, then quenching in water. The cores were then annealed in chloride salt for thirty minutes at 640 C and allowed to air cool.

Machining of the cores consisted of cutting to 8.870 inches in length, then machining and grinding to 1.800 inch OD and 1.513 inch ID.

7. Tverberg, J. C. Dingot Quality Vacuum Remelted Uranium Metal From Ceramic Coated Graphite Crucibles, HW-61749. September 18, 1959.

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Can Fabrication: Two Zircaloy Tubes were used for the fabrication. The tubes were welded and cold drawn; the larger was 1.870 inch OD and 1.810 inch ID and the smaller tube was 1.500 inch OD and 1.440 inch ID. Jacket end caps, in the shape of circular disks, were machined from 0.060 inch Zircaloy-2 sheet. Each can was assembled on a jig, then welded in a vacuum by the electron beam process.

Fuel Element Assembly: Cans and end caps were etched in a standard beta etch consisting of 50 per cent water, 45 per cent nitric acid and five per cent hydrofluoric acid. After etching, the components were rinsed in tap water, then placed in a special rinse solution consisting of 100 grams per liter of aluminum nitrate, one normal nitric acid and water. This rinse solution removed the precipitated zirconium oxyfluoride⁽⁸⁾ from the Zircaloy surface. Another water rinse followed the rinse solution, then there was a final rinse in hot deionized water followed by acetone drying.

The cores were etched in 80 C, 50 per cent nitric acid, rinsed in tap water, then rinsed in hot deionized water and finally dried with acetone. The core was inserted into the can and the end cap placed in position. Closure was made within five minutes after etching to prevent excessive oxidation. The welded closure was made with an electron beam welding unit operating at a pressure of 4×10^{-6} mm of mercury.

Cast Bonded Elements: An alternate method of bonding the uranium core to the Zircaloy-2 jacket is to pour molten uranium directly into a preheated Zircaloy can. Such a prebonded specimen, subjected to the pressure bonding treatment, should indicate the nature of the diffusion mechanism along the uranium-zirconium interface.

8. Shannon, D. W. and B. Griggs. Preparing Zircaloy-2 for Autoclave Testing, HW-60433. July 1, 1959.

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A Zircaloy-2 can was cleaned as described above, then assembled into a graphite mold which had been coated with a zirconia-butyl alcohol slurry, then vacuum outgassed. The assembled mold was placed in a preheat furnace located within the vacuum melting chamber. The melting chamber pressure was reduced to 5×10^{-4} mm of mercury and the mold and can were preheated to 1000 C. Dingo uranium was melted in a graphite crucible heated to 1500 C and was allowed to outgas for ten minutes or until the pressure dropped below 1×10^{-3} mm of mercury. Following the casting operation, the elements were allowed to vacuum cool at a rate of 3 C/minute. Any spilled uranium was etched from the Zircaloy surface with concentrated hydrochloric acid and the open end was chemically milled to a depth of 1/8 inch. Final cleaning was in the beta etch solution followed by immersion in an aluminum nitrate-nitric acid rinse solution. The jacket end cap was then secured in position by electron beam welding.

Pressure Bonding: The solid state diffusion bonding was done in the Battelle Memorial Institute high temperature-high pressure gas autoclaves. These autoclaves are cold wall units with the water cooled walls at room temperature. An internal resistance furnace provided the heat required for bonding. High internal gas pressure was obtained with purified helium compressed to 10,000 psi. Helium tends to produce extreme vertical temperature gradients due to convective heat transfer, so all components within the pressure vessel were packed in Microquartz insulation. Long, massive copper bars were used to equalize the vertical gradients.

The elements were placed in a stainless steel loading can such as that shown in Figure 1. Zirconium foil lined the can interior and zirconium chips were placed inside and above the elements. These chips acted as a "gettering agent", removing the reactive gases from the helium. Loading

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FIGURE 1

Loading Can for Pressure Bonding Zircaloy-2 Clad
Uranium Tubular Fuel Elements

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and operating procedures are given in flowsheet form in Table I. The samples were loaded, the autoclave sealed, then checked for leakage. Pressurization and heating were begun simultaneously so that the temperature and pressure increased at approximately the same rate of time. Temperature was stabilized at 845 C and the pressure at 10,000 psi. A typical autoclave operation curve is shown in Figure 2. After holding the elements four hours at temperature, the heating was stopped and the unit allowed to cool under pressure to room temperature. The vertical temperature gradient along the 24-inch long loading can was within ± 5 C during autoclaving.

DISCUSSION OF RESULTS

Effect of Core Preparation: Each type of bonded element was examined metallographically. No difference was found in the bond of the extruded, cast, or heat-treated core. Figure 3 represents a typical interface formed by pressure bonding. An unbonded specimen is shown for comparison in Figure 4. The diffusion layer in the bonded specimen was excessively wide, which indicated that the treatment was either too long or else performed at too high a temperature. Similar tests should be run to determine the optimum conditions of time and temperature. Unbonded areas, as in Figure 4, probably resulted from surface contamination on either the Zircaloy or uranium.

Cast Bonded Specimens: A cast bonded interface is illustrated in Figure 5. After the pressure bonding treatment the interface appears as in Figure 6. Using the oxide-carbide inclusion line along the interface (see Figure 5) as a marker, excessive diffusion was found to occur into the uranium. Here the uranium-rich constituent, alpha plus delta, increased three fold, diffusing past the oxide-carbide marker line. Also, the zirconium-rich epsilon phase appeared to reach a uniform limiting thickness in the Zircaloy

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TABLE I

PRESSURE BONDING FLOWSHEET

Place Elements in Zirconium Lined Stainless Steel Loading Can

Pack Zirconium Chips into Element ID, Between the Elements and Over the Top of the Elements

Place Stainless Steel Disk Over Loading Can Top with Approximately Three Inches of Zirconium Chips Followed by Another Stainless Steel Disk

Place Loading Can in Autoclave Furnace

Place Copper Bars in Autoclave Furnace

Pack Silica Sand Over and Around the Loading Can and Copper Bars

Pack Micro-Quartz Over the Sample, Connect Thermocouples, and Secure Autoclave Head in Position

Evacuate to -1000 Microns of Mercury Pressure and Maintain Vacuum for Ten Hours

Fill to 300 psi of Helium and Flush System. Backfill to 400 psi of Helium and Check for Leakage

Pressurize to 9,800 psi of Helium While Simultaneously Applying Heat. Stabilize at 840C and 10,000 psi

Run for Four Hours

Shut Off Power and Cool to Room Temperature

Reclaim Helium Where Possible and Reduce Autoclave Pressure to Atmospheric

Remove Sand and Micro Quartz with Vacuum Cleaner

Remove Samples

Under Argon Blanket

FIGURE 2
Pressure Bonding Cycle for Zircaloy-2 Clad
Uranium Tubular Fuel Elements

FIGURE 3

Typical Diffusion Area in a Pressure Bonded Element.
Note how the diffusion begins in the Zircaloy then moves into the uranium.
Electrolytically Etched in a Solution of 5 Parts H_3PO_4 , 5 Parts
Ethylene Glycol and 8 Parts Ethyl Alcohol for 4 Seconds at 4 Volts.
Bright Field Illumination. 100X

FIGURE 4

Unbonded Interface along a Jacket Weld Zone.
There is intimate contact between the surfaces but failure to bond.
Electrolytically Etched, 4 Seconds at 4 Volts.
Bright Field Illumination. 100X

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FIGURE 5

Typical Diffusion Layer of a Cast Bonded Element. Notice the transformed Zircaloy structure and the numerous oxide and carbide particles along the diffusion interface. Electrolytically Etched, 4 Seconds at 4 Volts. Bright Field Illumination. 250X

FIGURE 6

Interface of a Cast Bonded Element Subjected to a Pressure Bonding Treatment. The alpha plus delta component has diffused past the oxide-carbide particle line. Electrolytically Etched, 4 Seconds at 4 Volts. Bright Field Illumination. 250X

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before diffusing back into the uranium. It is interesting to note that unbonded areas still existed in the samples in the same regions as the heavy diffusion. This is unusual in that the surface contamination of the cast bonded samples should be at a minimum due to the method of fabrication.

Interface Phase Identification: The photomicrograph shown in Figure 7 illustrates the method of compound formation along the interface. The various compounds can be identified by using the Zirconium-Uranium phase diagram of Rough and Bauer⁽⁹⁾ which is reproduced in Figure 8. Reaction appeared to begin by uranium diffusing across the interface forming an epsilon phase with the zirconium. The interface acted as a barrier to the less mobile zirconium, preventing diffusion into the uranium. Thus, uranium-rich compounds were not formed in the first stage of diffusion. Longer high temperature exposure resulted in a gradual consumption of the epsilon phase material to form a higher uranium constituent of epsilon plus delta phases. Diffusion then progressed into the uranium forming delta phase material and the eutectoid formation of alpha plus delta phases. Slow cooling allowed the delta phase to form instead of retaining the metastable gamma plus delta phase mixture which is characteristic of rapid cooling.

A cast bonded interface, Figure 5, is composed primarily of epsilon phase and a mixture of alpha plus delta phases. A pressure bonding treatment caused an increase in the delta plus epsilon and a threefold increase in the alpha plus delta phases.

9. Rough, F. A. and A. A. Bauer. Constitution of Uranium and Thorium Alloys, BMI-1300. June 2, 1958.

FIGURE 7

Photomicrograph illustrating the nature of diffusion bonding.

The uranium first diffuses across the interface as in the center of the picture forming epsilon phase material. Continued diffusion causes a breakdown of epsilon to epsilon plus delta, the dark gray compound. Simultaneously, the zirconium begins to diffuse into the uranium forming delta phase. Also, alpha plus delta, the black compound, grows into the uranium.

Electrolytically Etched, 4 Seconds at 4 Volts.

Bright Field Illumination. 100X

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FIGURE 8
 Uranium-Zirconium Phase Diagram
 (From Rough and Bauer. BMI-1300)

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Diffusion Layer Thicknesses: A Filar eyepiece mounted on a 50X microscope was used to measure the width of each compound in the interface. Similar samples prepared under these conditions should have the same widths as those presented in Table II, within a ten per cent range. Note that in those samples in which diffusion bonding existed, i.e. cast bonded samples, the epsilon thickness increased very little even with longer diffusion times. However, the other constituents, namely the delta plus epsilon and delta, actually decreased at the expense of a three-fold growth of the alpha plus delta.

Micro-Hardness Determination: Micro-hardness values were obtained from the interface compounds using both the Knoop and the 136° diamond indenters. A load of 50 grams was used to make the indentation. An average hardness of two compounds was obtained with those compounds which were too thin to accept the indenter. These data indicated that the combined phases of epsilon plus delta has essentially the same hardness as the uranium, namely 240 DPH. Hardness of the combined delta and alpha plus delta phases was considerably greater than either the uranium or the Zircaloy. These data are presented in Table III. The transformed Zircaloy Widmanstätten structure of the weld zones or on the jacket of the cast bonded elements presented a higher hardness value than the annealed Zircaloy. These values were 200 DPH and 200 Knoop for the transformed material as compared to 160 DPH and 165 Knoop for Zircaloy in the annealed state. Uranium hardness by comparison averaged 270 DPH and 230 Knoop.

[REDACTED]

TABLE II

WIDTH OF URANIUM-ZIRCONIUM DIFFUSION COMPOUNDS

Core Description	Alpha + Delta		Delta		Delta + Epsilon		Epsilon		Total mm
	mm	% Total	mm	% Total	mm	% Total	mm	% Total	
Extruded	0.017	27.0	0.014	22.2	0.009	14.3	0.023	36.5	0.063
Cast	0.013	20.5	0.019	30.2	0.010	15.9	0.021	33.4	0.063
Cast-Heat Treated	0.012	19.7	0.011	18.0	0.010	16.4	0.028	45.9	0.061
Cast Bonded	0.020	41.7	0.005	10.3	0.003	6.3	0.020	41.7	0.048
Cast Bonded, Pressure Bonded	0.089	71.8	0.007	5.6	0.008	6.5	0.020	16.1	0.124

TABLE III

MICROHARDNESS VALUES FOR URANIUM-ZIRCONIUM DIFFUSION COMPOUNDS

Core Description	Uranium		Alpha + Delta & Delta		Delta + Epsilon & Epsilon		Zircaloy-2	
	DPH	Knoop	DPH	Knoop	DPH	Knoop	DPH	Knoop
Extruded	290	246	276	234	207	176	155	124
Cast	243	230	290	358	247	240	160	161
Cast-Heat Treated	280	212	376	358	233	228	160	207
Cast Bonded	214	385	406	322	370	212	139	244
Cast Bonded, Pressure Bonded*	223	370	400*	384*	285	299	202	202

* Alpha + Delta = 272 DPH 295 Knoop
Delta = 400 DPH 384 Knoop

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DECLASSIFIEDJacket Deformation

The high pressure treatment deformed the ends of the jacket to the extent illustrated in Figure 9. Any voids or flaws on the uranium surface were clearly seen after the treatment as the jacket had conformed and bonded exactly to the core surface. Figure 10 indicates how the uranium had extruded into the small opening between the cap and jacket. Both Figures 9 and 10 show the extent of bonding along the uranium-Zircaloy interface. A Recrystallized interface was observed along the cap and jacket junction, Figure 11, indicating that diffusion welding had occurred along the interface. This type of interface was similar to that observed by Paprocki, Hodge and Carmichael⁽¹⁰⁾ when the Zircaloy had been subjected to a beta etch prior to pressure bonding.

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FIGURE 9

An example showing how pressure bonding deforms the end section of an element in which a gap existed between the cap and jacket. The white zone between the Zircaloy wall and the uranium is the diffused area. Etched in Nitric Acid. 20X

FIGURE 10

A view of an end section of a fuel element in which the end cap was in contact with the uranium prior to bonding. A small amount of uranium, on the right, was extruded into the gap between the cap and jacket. Etched in Nitric Acid. 20X

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FIGURE 11

Recrystallized Interface along the End Cap of a Pressure Bonded Fuel Element. Grain growth has occurred across the interface. Etched in 45% HNO_3 , 45% H_2O and 10% HF . Polarized Light 250X

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