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COEXTRUSION OF ZIRCALOY-CLAD U - 2 W/o Zr ROD FOR THE EBR-I MARK III CORE LOADING

By
H. F. Sawyer

April 30, 1958

Nuclear Metals, Inc.
Cambridge, Massachusetts

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Nuclear Metals, Inc.
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A. R. Kaufmann
Technical Director

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ABSTRACT

Technical data is given concerning the fabrication of Zircaloy-clad U - 2 $^{w}/_{o}$ Zr alloy rod from extrusion billets prepared at Argonne National Laboratory and coextruded at Nuclear Metals. The development of high yield extrusion billets for fabricating the enriched core and blanket rod is described.

I. INTRODUCTION

Several factors were of prime importance in the development of an extrusion clad rod for the Mark-III core loading of the EBR-1. The extrusion process was chosen because it could effect a metallurgical bond between the Zircaloy cladding and U - 2 $^{w}/_{o}$ Zr core. In addition, at the time, it was considered possible to extrusion bond Zircaloy ribs to the cladding. Initial development work proceeded along these lines in a twofold effort to put ribs on the coextruded rod. One method developed was termed the "ribbed die" technique, in which the ribs were formed on the rod as it passed through the extrusion die. The second method, the "ribbed billet" technique, consisted of placing strips of Zircaloy against a cylinder of Zircaloy cladding which was in turn placed over a slug of the core alloy. The Zircaloy "rib" strips were held in position against the clad by copper spacers; the entire assembly was canned in copper and extruded through a round die. The desired ribs were exposed after pickling away the copper extrusion jacket and spacer material. Details of this development work are described in a separate report.

The urgency of the core loading program coupled with several technical problems associated with the coextruded ribbed element led to discontinuing this phase of the work. It was decided to extrude a conventional round rod with emphasis on maximum yield per billet, particularly with respect to the enriched metal. Ribs would be welded on at a later date by ANL during the assembly of the core.

Two extrusion billet sizes were developed. One size for fabricating the enriched rod and one for the blanket (natural) rod. The maximum billet size for the enriched extrusions was limited principally by criticality considerations and secondly by extrusion tools. The billet developed was 2 inches in diameter and 9-3/4 inches over-all length. Since there were no criticality limitations on the blanket billet the object became simply to develop the largest billet that could be extruded into a rod that would still meet clad thickness and uniformity specifications. Obviously, with a larger billet, the billets required to complete the core loading would be fewer. The final billet developed was 2-3/4 inches in diameter and 9 inches over-all length.

Some additional 2-inch diameter natural billets were prepared and extruded exactly as the enriched to provide stock with the same fabrication history for ANL to use for the blanket ends which were welded directly to the enriched sections.

The finished rod specifications were: diameter, 0.406 - 0.408; core, 0.362 - 0.364.

II. CORE ROD

A. Prototype Billets (Natural Uranium)

The basic billet size for the enriched extrusions was determined from a combination of criticality limitations, extrusion tools and time. The allowable mass was set at approximately 5 kg Oy fully enriched per billet. Of the available extrusion tools, a 2 inch and a 2-3/4 inch liner, the former was chosen since this would make a long billet with a 20:1 reduction. The larger liner would have resulted in a shorter billet and a higher reduction ratio (40:1), with longer extrusion "defects" at the ends; the net effect would be a smaller yield of uniform clad rod per extrusion. The longest billet that could be fitted into the existing 2-inch extrusion liner contained 4.42 kg of U_{235}.

The next objective was to minimize the length of the end taper or non-uniform cross section at the front and rear of the extrusion. A total of nine extrusion billets were prepared and extruded; six of these were canned and extruded by different techniques and, after selecting the most promising one, three more extrusions were made to confirm the data. Details of the procedures are given below.

1. Preparation of Components

a. Zircaloy

Cladding components were machined from pre-extruded Zircaloy tube stock described in Section IV. All Zircaloy came from the large forged ingot supplied by ANL, except for extrusions No. 14685, 14686 and 14687, for which graphite melted stock was used. Cladding components were finished machined to $1.860 \begin{smallmatrix}+0.000 \\ -0.003\end{smallmatrix}$ inch OD, $1.658 \begin{smallmatrix}+0.003 \\ -0.000\end{smallmatrix}$ inch ID x $8 \pm 1/64$ inches long. The maximum variation in wall thickness was 0.003 inch. Discs for end seals were machined to $1.653 \begin{smallmatrix}+0.000 \\ -0.003\end{smallmatrix}$ inch diameter x $1/4 \pm 1/64$ inch long from pre-extruded rod stock from mixed sources.

b. Uranium Alloy

All U - 2 $^{w}/_{o}$ Zr alloy was prepared at ANL and shipped to NMI with either an as-cast or rough machined surface, and/or an as-cast or heat-treated structure. The billets were finished machined at NMI to $1.653 \begin{smallmatrix}+0.000 \\ -0.003\end{smallmatrix}$ inches diameter x $7\text{-}1/2 \pm 1/64$ inches in length.

c. Accessories

Copper-nickel alloy for nose plugs and cut-offs was cast in large diameter molds, extruded into rod stock, and finished machined to the component specifications. Copper extrusion cans, end plugs and evacuation tubes were prepared by conventional techniques.

2. Assembly and Evacuation

Before assembly, all billet components were degreased and, except for the cores, chemically cleaned. Zircaloy parts were bright etched in a 50% water - 48% nitric - 2% hydrofluoric acid solution. Copper and copper-nickel accessories were etched in a 50% water - 50% nitric acid solution. The U - 2 $^{w}/_{o}$ Zr alloy cores were rotated in a lathe and sanded with 320 wet paper. This was followed by (1) degreasing in carbon tetrachloride, (2) rinsing in acetone and (3) air drying. Chemical etching of the cores was avoided because of the explosion hazard.

The billets were assembled immediately following air drying of the core, then connected to a vacuum system by means of the copper evacuation tube at the back end of the billet.

3. Degassing and Seal Off

After obtaining a vacuum of 5×10^{-5} mm of Hg or less the billets were brought from room temperature to 800°F in 1/2 hour and held at this temperature for an additional hour to outgas. The billets were sealed off hot by pinching the evacuation tube closed close to the billet, then removing the remainder by torch-cutting.

4. Preheating and Extrusion

After preheating for one to 1-1/2 hours in a 1225°F furnace the billets were inserted into the 2-inch diameter liner and extruded through a 0.453-inch diameter die, into a catch tube, for an area reduction of 20.2:1. The press ram speed was 30 in./min. All extrusion tools were preheated to 900°F and were lubricated with a colloidal suspension of graphite in oil. Various billet and extrusion data is listed in Table I.

5. Cold Finishing

Subsequent to pickling away the copper extrusion jacket in a 50% nitric - 50% water solution, the rods were swaged to finished size (0.406-0.408) on a Torrington No. 3 swager and, in some cases, a Fenn No. 3-F. Details of the cold working schedule are described below. The average amount of cold work was 6.2%.

6. Evaluation

a. Yield

The long length of the extrusion billet was the most significant factor in producing a high yield extrusion. The length of the end tapers at the front and rear of an extruded rod remains essentially constant for a given reduction, regardless of the length of the billet, if all other extrusion conditions remain unchanged; therefore the percent of uniform cross section rod obtainable per extrusion increases as the billet is made longer. The initial design called for the longest permissible billet.

A secondary effort to further increase the yield was made by changing the canning and extrusion techniques in order to reduce the actual amount of end taper. One variation known to cause a marked reduction in "defect" length is a decrease in the included cone angle. This could not be done in this case, however, since the increase in cone length (as a result of the smaller angle) would have necessitated shortening the billet with a net loss in efficiency. Using a conventional 90^{o} extrusion cone, a number of combinations of nose plug, and cut off shapes, materials, and temperatures were tried. Of all the combinations, the yield was observed to vary only from 88 to 94%. In terms of uniform core and cladding per extrusion the acceptable lengths varied from 137 inches to 146 inches. The lengths of the uniform cores and front and rear tapers have been tabulated in Table II.

In general, the rear U - 2 $^{w}/o$ Zr tapers were not affected by the cut off material because of the Zircaloy end seal.* An internal copper-nickel cut-off was chosen because it avoided the handling of an external cut-off and, since it was heated within the billet assembly it would always be at the same temperature as the billet.

The lengths of the front tapers were more sensitive to the nose plug material than the rear. Relatively long tapers resulted with an external copper nose plug (89% yield) and without any nose plug at all (88% yield). When internal copper-nickel nose plugs were used, yields varied from 91 to 94%. Two types were tried. One with a machined taper on the front to fit a 90^{o} (included angle) nose can; the other with a square face to fit in a flat end can. Since there was no significant difference between the two,

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*The Zircaloy end seals were not included to make an element with integral end seals as is normally the case, but rather to prevent acid attack of the U - 2 $^{w}/o$ Zr at the ends of the rod when the copper jacket was pickled off, partly to void the explosion hazard but mostly to minimize accountability procedures on the enriched metal that was to follow.

the latter was chosen because of its ease in machining and the elimination of a spun nose extrusion can.

b. Bond Strength

Qualitative bond strength data was obtained by cutting longitudinally through 1/4-inch long sections of rod until approximately equal thicknesses of clad and core remained and then bending the remaining material to fracture. In all cases, excellent bonds were observed as evidenced by a clean fracture through the U - 2 $^{w}/o$ Zr alloy and Zircaloy-2. By this method, if a weak or poor bond exists the clad will peel from the core rather than fracture.

c. Cross Section Dimensions

Micrometer measurements were taken every foot along the length of the rods first in the as-extruded condition, then after removal of the copper jacket, and finally, after swaging. These values are reported in Table II. Neglecting the end effects, the as-extruded and after-pickling diameters varied on the average of approximately 0.002 inch. The difference between the two measurements varied from 0.028 inch to 0.032 inch, corresponding to an average copper thickness of 0.015 $\pm$ 0.001 inch.

Some difficulty in obtaining the desired diameter in the cold finishing operation was experienced, although in all cases the surface was satisfactory. Part of the dimensional problem resulted from the lack of the proper size swaging dies and the balance of the difficulty was felt to lie in some peculiarity of the cold working properties of the U - 2 $^{w}/o$ Zr alloy itself coupled with the structure resulting from extrusion. At NMI, time did not permit an investigation along these lines.

Extrusions No. 14685, 14686, and 14687 were swaged through a 0.406-inch die and did not come down to tolerance. This was followed by a pass through a 0.400-inch die, the only die available at the time. Considerable variation in the finished diameters was observed. On rods 14685 and 14586, the central section of the extrusion reached a low of 0.403 to 0.404 inch;

toward the rear of both rods a high of 0.410 inch resulted. Extrusion No. 14687 was satisfactory throughout its length, except toward the rear where a maximum diameter of 0.411 inch was measured.

Since part of the dimensional difficulty arose out of the inability of the Torrington machine to size the rod on the first pass with the 0.406-inch die, the next series of rods was swaged in one pass on a Fenn No. 3-F swager with the same dies held in adapters to accommodate them in the heavier machine. The as-swaged dimensions did not vary more than 0.002 inch along the length of any rod. Maximum and minimum values are listed in column 9 of Table II.

d. Clad Thickness

Measurement of the clad thickness was complicated in some cases by variations in the regularity of the interface between the core and the clad. Average values were determined from measurements taken from a sample cut from the front and the rear of each rod after the end tapers were removed. Readings were made on a toolmaker's microscope by translating the polished cross section on a micrometer driven stage. The rods were trimmed back until a clad thickness of 0.022 $\pm$ 0.001 inch was obtained. A brief discussion of the character of the interfaces resulting from the various treatments performed on the starting metal is given in Section IIIA 6.

B. Production Billets (Natural and Enriched)

1. Preparation

A total of 32 normal billets and 19 enriched billets were machined, assembled, canned and evacuated at ANL according to the specifications shown in Fig. 1. The billets were sealed by torch heating, hammering flat, and bending over the copper evacuation tube. This seal was made at a minimum distance of 10 inches from the end plug to allow the tube to be reopened at NMI for final evacuation and outgassing. The initial evacuation was to prevent oxidization of the billet components during shipment to NMI.

2. Evacuation and Outgassing

Upon receipt at NMI, the sealed end of the evacuation tube was removed with a tubing cutter and the billet immediately attached by means of a rubber hose to a high vacuum system. Heating and outgassing procedures were the same as described above in Section A3. Total evacuation time and time at the outgassing temperature for all the 2-inch billets are listed in Table III. All billets were leak tested after attaching to the vacuum system and again at 800°F immediately before sealing off. No leaks were detected in any of the 32 natural billets and only one in the 19 enriched billets. This one was returned to ANL for recanning and subsequently returned to NMI and extruded.

3. Preheating

Natural billets were preheated to groups of from one to four in a steel temperature equalizing box inside a resistance furnace. A thermocouple survey within this box indicated no left to right variation in temperature (billets were placed side by side in the box) and a maximum of 10°F difference from the front to rear. The front of the billet in the furnace became, in all cases, the front of the extruded rod. The preheat temperature reported in column 6 of Table III is the temperature of the halfway point along the length of the billet immediately before each extrusion.

Enriched billets were preheated as described above except that a smaller temperature equalzing box was used and, due to criticality limitations, only one billet was heated and extruded at a time. The temperature of each billet was continuously monitored during preheating to prevent temperature excursions due to faulty equipment, etc.

4. Extrusion

All 2-inch diameter billets were extruded on a 300-ton capacity Watson-Stillman extrusion press. The loading time (i.e., the elapsed time from the opening of the preheat furnace door until the extrusion started) was approximately 20 seconds for all extrusions. To minimize variables in handling, loading time, etc., the same press crew was used throughout the work.

Extrusion constants, based on the relation $K = \frac{P}{\ln R}$ where P is the extrusion pressure (tons/in.^{2}) and R is the extrusion area reduction, have been tabulated in columns 7 and 8 of Table III. The starting constants exhibited a variation of from 19 tsi to 33 tsi with a preponderance of values between 22 and 31 tsi. Part of this spread is attributed to variation in composition (stiffness at the extrusion temperature) of the copper-nickel alloy used for nose plugs. A number of typical copper-nickel analyses are listed in Table XI. The running constants, calculated from the pressures recorded at the halfway point of the extrusions, were all between 20 to 24 tsi with the exception of one (extrusion No. 15253) which was close to 26 tsi.

The same liner, ram, and set of six dies were used for all extrusions. No tool failures occurred during any of the 51 extrusions, and all billets extruded satisfactorily, as noted in the remarks column of Table III. Occasional slight pickup of copper on the extrusion cone and in the land of the die was noted, but in no case was it severe enough to have a measurable effect on the as-extruded surface and dimensions.

III. BLANKET ROD

A. Prototype Billets

The development of an extrusion billet from which the blanket rod could be successfully extruded was not limited by criticality considerations as was the case of the core rod. The object was to extrude as long a rod as could be handled that would meet the required dimensions and specifications. Since the 2-inch billet designed for the core rod could not be made longer without special extrusion tools, a billet was designed to fit an available 2-3/4 inch extrusion liner. With this billet it was possible to almost double the amount of rod per extrusion. Details of the development of this billet are described below.

1. Preparation of Components

a. Zircaloy

Pre-extruded Zircaloy tube stock was machined into cladding components of the following dimensions; OD 2.610 $^{+0.000}_{-0.003}$ inch; ID 2.327 $^{+0.003}_{-0.000}$ inch; length 7 inches; concentric to 0.003-inch total indicator reading. This metal came from the large forging supplied by ANL.

The original billet design called for Zircaloy discs to seal the ends of the coextruded rod and stock was pre-extruded for this purpose. However, since no accountability problem was present, the pickling hazard was the only justification for the end seals. It was felt that this could be adequately taken care of and the space in the billet normally occupied by the end seals was replaced with core alloy to give more rod per extrusion.

b. Uranium Alloy

U - 2 $^{w}/o$ Zr alloy was prepared at Argonne and shipped to Nuclear with an as-cast or heat-treated structure. The cores were finish machined to 2.322 $^{+0.000}_{-0.003}$ inches diameter x 7 inches long.

c. Accessories

Two and three quarter inch OD x No. 16 Stubs' gage copper tubing for canning the billets was not available commercially. Cans were prepared from 3-inch OD x 0.065-inch wall tubing by drawing down (sinking) over a mandrel. Nose plugs, cut off, and end plugs were prepared by conventional techniques.

2. Assembly and Evacuation

The procedures used here were the same as those described for the 2-inch diameter billets.

3. Degassing and Seal-Off

The billets were held for an average time of 2 hours at 800^{o}F, one hour more than the smaller billets, to allow for complete outgassing.

4. Preheating and Extrusion

After preheating for a minimum of 2 hours at 1225°F the billets were inserted into the 2-3/4 inch diameter liner and extruded through a 0.437-inch die into a catch tube for an area reduction of 42.5:1. The press ram speed was 30 in./min. The extrusion die, cone, dummy block and liner were heated to 900°F and lubricated with a colloidal suspension of graphite in oil.

5. Pickling and Swaging

The copper extrusion jackets were removed in a 50% nitric acid - 50% water solution. Care was taken not to move the rods in the acid and to drain the tank before inspection to minimize the explosion hazard. Adequate safety equipment was worn during this operation. The exposed uranium-zirconium alloy at the front of the rods was carefully washed down and wiped to remove loose pyrophoric material; no difficulties were encountered.

Swaging was carried out on a Fenn No. 3-F swager. The rods were sized in one pass for an average area reduction of 3.4%.

6. Evaluation

a. Yield

Although the yield was not as important as in the case of the enriched billets, some attention was given to the billet design to keep the yield as high as possible. The value of using a copper-nickel alloy of the same stiffness as the U - 2 $^{w}/o$ Zr in reducing the front end taper had already been established on the 2-inch billets. However, it was not certain whether the internal nose plug-flat end billet combination would work as successfully at the higher reduction.

To determine this, one billet (extrusion No. 14915) was prepared with an external nose plug of copper-nickel machined to fit the cone. A second billet (extrusion No. 14916) had an internal nose plug of copper-nickel and a flat end. In the first case the yield was 82%, vs 85% for the latter.

This amounted to 10 inches more of uniform rod or a total of 244 inches per extrusion. Data for these extrusions plus four additional prototype billets is listed in Table IV and V.

b. Bond Strength

Bond tests were made in the same manner as those described above and all bonds were found to be acceptable.

c. Cross Section Dimensions

The as-extruded diameter varied a maximum of 0.004 inch throughout the length of any extrusion, with an average diameter of 0.435 inch. A similar variation was recorded after removal of the copper. The average diameter was 0.415 inch. By difference the copper jacket was 0.010 ± 0.0005-inch thick for all extrusions.

No difficulty was experienced in cold finishing the rod by swaging. In all cases, the as-swaged dimensions throughout the 20 feet of acceptable rod per extrusion were not observed to vary more than 0.002 inch. This data was compiled from micrometer readings read to the nearest thousandth of an inch every foot along the length of the rods; its primary purpose was to prototype the process not to represent an exhaustive survey.

d. Core to Clad Interface

All U - 2 $^{w}/o$ Zr alloy used in the prototype and production extrusions was prepared at ANL. No attempt is made here to correlate in detail the character of the core-to-clad interface with the many variations in melting, casting, and heat treating. Rather it is intended to present quantitative data concerning the regularity of the interface together with any pertinent conclusions which would aid in comparing the data obtained from the two laboratories.

Two illustrations of each core-to-clad interface have been included. One is a photomicrograph at 100X to show interface detail; the other, a macrograph at 7.5X, was intended to present a more over-all picture of the cross section. The reason for this was the duplex nature of the interfaces. For example, at high magnification a rod might appear to have a relatively smooth interface with a short period ripple, but on a macro scale, it would be observed to have a long period ripple two or three times the magnitude of the first.

In the past no difficulties had been experienced in extrusion cladding the U - 2 $^{w}/o$ Zr alloy with Zircaloy. Even in the cast condition, zirconium refined the uranium grain size sufficiently to produce an acceptably smooth interface.

The first group of 1-7/8 inch diameter x 9 inches long castings for 2-inch billets received from ANL, however, yielded an extremely irregular interface when coextruded. These castings were made in an eight cavity mold. Sections from the front and rear of three of the first rods are shown in Fig. 3. Variations in the clad thickness as high as 7 mils were observed as a result of this irregularity; the average clad thickness was within the 0.022 $\pm$ 0.001 tolerance. In addition, there was a decided difference between the front and rear of the extrusions. The possibility of this being an extrusion effect was ruled out since in two of the extrusions the interface became more irregular toward the rear and in one of them, toward the front. Macrophotographs are shown in Fig. 4.

The next group of 2-inch billets from metal cast in 1-11/16 inch diameter x 9 inches long single cavity molds, produced the smoothest interfaces of any of the extrusions, as shown in Fig. 5 and 6. Measurements indicate a roughness of only 1/2 mil,

By contrast, the second most undesirable interface resulted from metal cast in a large eight cavity 2-3/8 inch diameter x 15-1/2 inches long mold. Two billets were prepared and extruded from one of the eight simultaneously cast sections. The interface irregularities in the clad rod averaged 4 to 5 mils. No significant difference in the interface was observed in sections of rod corresponding to the top, center, and bottom of the casting. This is shown in Figs. 7 and 8.

Two heat treatments were performed in an attempt to refine the cast structures which gave irregular interfaces. Considerable improvement in the interface was observed when one of the 2-3/8 diameter eight cavity mold castings was heat treated at 780°C for 30 minutes and air cooled. The core-to-clad interfaces resulting from this treatment are shown in Figs. 9 and 10. Interface irregularities averaged 3 mils. Further interface improvement resulted from a combination heat treatment: 30 minutes at 780°C quenched in lead at 500°C; held for 30 minutes and air cooled. The regularity of the interface compared favorably with that resulting from the small single cavity castings used for the 2-inch billets. Measurements indicated a roughness of approximately 1 mil. Illustriations are shown in Figs. 11 and 12. This treatment was adopted for the 2-3/4 inch production billets.

Heat treatment of the smaller diameter (1-7/8 inch) simultaneously cast billets also resulted in an improved interface in the coextruded rod. Thirty minutes at 780°C followed by air cool or water quench resulted in an average variation of 1 mil. Three repetitions of the air cool treatment resulted in a slight improvement of the interface. Three repetitions of the water quench showed no improvement over the single quench. Photomicrographs of rod cross sections from the single and multiple air cooled treatments are shown in Figs. 13 and 14. Figures 15 and 16 illustrate the difference between a single and multiple water quench. Since none of the treatments produced are interface equally as smooth as that resulting from the small single cavity molds, multiple casting of this section size was discontinued. All 2-inch diameter production billets had as-cast structures from single cavity 1-11/16 inch diameter molds.

The above data on the character of the interface was compiled from one specimen only taken from the front and rear of each extrusion. Irregularity values, given in mils, are the variations in clad thickness due to the interface. Total clad thickness variations would be somewhat higher and would include eccentricity plus any other conditions which cause additional variations.

It is interesting to note that the greatest interface irregularities resulted from multiple cast 1-7/8 inch billets, whereas one would expect more irregularity from the multiple cast 2-3/8 inch billets since these would, presumably, have a slower cooling rate. The smaller diameter castings, however, underwent a 20:1 extrusion area reduction whereas the larger castings were reduced over 40 times in area. It is presumed that the greater reduction in area reduced the magnitude of the irregularities.

B. Production Billets

1. Preparation

Sixty-four billets were prepared, assembled, and pre-evacuated at ANL according to the specifications shown in Fig. 2. The evacuation tube was sealed at a minimum distance of 10 inches from the billet to allow it to be re-opened for final evacuation and outgassing immediately before extrusion at NMI.

2. Evacuation and Outgassing

The 2-3/4 inch billets were evacuated and outgassed in the same way as the 2-inch billets. Considerable variation in the total evacuation time as well as in the time at the outgassing temperature (800^{o}F) occurred for various reasons. In some instances, billets were attached to a vacuum system on a Friday evening and evacuated over the weekend, accumulating as much as 71 hours total evacuation time. The minimum time was 2 hours. Outgassing hours (elapsed time while a billet was in an 800^{o}F furnace) were much more regular, with the minimum time being 1 hour and the maximum 3 hours. Actual times for each extrusion are tabulated in Table VI.

3. Pre-heating

Extrusion billets were loaded, in groups of from 1 to 6, into a steel temperature equalizing box inside a resistance furnace. The furnace was at temperature when the billets were loaded and a minimum preheat time of 2 hours was allowed. In many cases the preheat time was considerably longer than this. Either the furnace required adjusting to achieve the desired extrusion temperature or difficulties with the press delayed extrusion.

Temperature variations were greater for the 2-3/4 inch billets than for the 2-inch billets, particularly when a full charge of 6 billets was made in the furnace. Thermocouple surveys under these conditions indicated a maximum of 20°F variation over the area occupied by the billets. The thermocouple was placed in the middle zone; the final equilibrium temperature just before extrusion started is reported in the tables. Since part of the temperature variation was from left to right in the furnace, the gradient in individual billets was less than 20°.

4. Extrusion

A 1000-ton capacity Watson-Stillman press was used for the blanket rod extrusions. The strength of the extrusion tools in conjunction with the pumps on the press limited the maximum available force to 560 tons.

No difficulties were experienced during the prototype extrusions and the first group of production billets extruded without incident. However, in the second group the first billet stalled and the liner cracked. No single condition would explain the occurrence, but a combination of several variables could; the billet was preheated for 1 hour and 50 minutes and the furnace had a full charge in it. In addition, if the copper-nickel nose plug was from a rod having high nickel content the increased stiffness would add to the pressure. The remaining billets in the series were extruded in the cracked liner.

The liner was replaced and a new ram installed; subsequent extrusions were satisfactory. In some cases preheat times were increased because it became necessary to re-align the ram between extrusions due to incipient bending. Eventually the ram bent too severely for use and was replaced. The replacement ram failed in the same manner. Hardness readings made on the cross sections cut from the bent rams were as low as 30 Rockwell C, indicating improper heat treatment. A third ram, properly heat treated, was used on the last 22 extrusions without any bending.

All of the various incidents which occurred have been included in the remarks column of Table VI which correlates them with the extrusion.

This detail may be of value in correlating physical differences, if any, between extrusions.

IV. PRIMARY EXTRUSION

A. Zircaloy

A total of 16 tube extrusions and 2 rod extrusions were made to supply stock for machining the Zircaloy billet components. Technical data concerning these extrusions is listed in Tables VII and VIII. All of this metal originated from the two pieces of forged Zircaloy bar, 7-3/8 inches OD by approximately 48 inches long. The bars were forged at Allegheney Ludlum Steel and identified with the No. 5YPD44. Chemical analyses supplied by ALS are reported in Table X.

B. Copper-Nickel

Ten castings totalling 700 pounds were fabricated into rod stock for nose plugs and cut-offs for the 2 inch and 2-3/4 inch extrusion billets. The nickel content varied from 7-1/4 to 10-3/4%. Chemical analysis are reported in Table XI. No exact specifications for nickel content were required since relatively little changes in extrusion constant vs composition occurs in this range. This small difference would have negligible effect on the tapers in the subsequent coextrusions.

Data on the primary extrusions is tabulated in Table IX.

Table I

Prototype 2-Inch Diameter Billets

Extrusion area reduction, 20.2:1; liner, 2.030 inch; die, 0.453 inch; ram speed, 30 in./min; lubrication, Oil Dag

Extrusion No.	Billet Code Letter	Core: ANL No.*	Core: Machined Wt. (gms)	Core: ANL Heat Treatment	Extrusion Preheat (°F)	Extrusion Constants (tsi): Start	Extrusion Constants (tsi): Run	Billet Assembly Details
14685	--	H-462	10.50 lb	as cast	1222	26.7	22.6	External Cu nose peened to cone at 900°F. External Cu cut-off at 900°F.
14686	--	H-462	10.50 lb	as cast	1222	23.7	20.6	No nose plug (flat end billet). External Cu cut-off at 900°F.
14687	--	H-462	10.50 lb	as cast	1222	20.6	22.6	Internal Cu-Ni nose in spun nose can. Internal Cu-Ni cut-off.
14832	A	SNC52	--	as cast	1232	22.6	20.6	Internal 1/2-inch long Cu-Ni nose plug. Internal 3/4-inch long Cu-Ni cut-off. Flat end can.
14833	B	SNC62	--	as cast	1232	22.6	21.6	Internal 1/4-inch long Cu-Ni nose plug. Internal 1-inch long Cu-Ni cut-off. Flat end can.
14834	C	H474-5	--	30 min at 780°C water quenched one time	1232	22.6	19.5	Internal Cu-Ni nose in spun nose can. Internal 1-inch long Cu-Ni cut-off.
15050	I	H-473-4 B ⟶ A	4825.	30 min at 780°C air cooled repeated 3 times	1218	23.7	20.6	Same as No. 14833
15051	J	H-473-5 B ⟶ A	4786.	30 min at 780°C water quenched repeated 3 times	1218	21.6	19.5	Same as No. 14833
15052	K	H-474-2 B ⟶ A	4829.	30 min at 780°C air cooled one time	1218	21.6	20.6	Same as No. 14833

*Where shown, arrow indicates extrusion direction.

Table II

Rod Fabricated from Prototype 2-Inch Billets

Extru-sion No.	Billet Code Letter	Length of U - 2% Zr (in.)			% Yield (based on max theoreti-cal core length	Dimensions (in.)		
						Diameter		
		At front taper	At rear taper	Uniform core		As extruded (w/Cu)	As extruded, after re-moval of Cu	After swaging
14685	--	11-1/2	10	139	89.4	0.446 0.447	0.418 0.419	0.404 0.410
14686	--	14	10	137	88.1	0.447 0.448	0.419 0.420	0.403 0.410
14687	--	5	10	143	92.0	0.447 0.448	0.419 0.421	0.408 0.411
14832	A	4	11	142	91.4	0.450 0.451	0.419 0.420	0.408 0.410
14833	B	4	9	146	94.0	0.449 0.450	0.419 0.421	0.407 0.408
14834	C	3	11	143	92.0	0.453 0.454	0.424 0.426	0.408 0.409
15050	I	--	--	144	92.6	0.449 0.450	0.417 0.418	0.403 0.405
15051	J	--	--	141	90.7	0.453 0.454	0.421 0.423	0.403 0.405
15052	K	--	--	146	94.0	0.447 0.448	0.415 0.417	0.403 0.405

Table III

Preheating and Extrusion of 2-Inch Production Billets

Lubrication, Oil Dag; Liner, 2.030 inch; Die, 0.453 inch; Reduction, 20.1; Ram Speed, 30 in./min

Identification		Time (min)			Temp. (^oF)	Extrusion Constant (tsi)		Extrusion Group No.
		Evacuation		Pre-heating				
ANL No.	NMI Extrusion No.(1)	Total	Outgassing at 800^oF			Start	Run	
N-1	15029	105	70	75	1215	18.5	21.6	1
N-2	15030	100	70	75	1215	22.6	22.6	1
N-3	15031	100	65	80	1215	22.6	23.2	2
N-4	15032	105	70	80	1215	24.7	24.2	2
N-5	15033	100	65	80	1215	22.6	23.7	2
N-6	15245	200	75	130	1225	23.7	21.6	3
N-7	15246	205	80	130	1225	22.6	21.6	3
N-8	15247	210	75	130	1225	23.7	23.7	3
N-9	15248	210	80	145	1225	22.6	22.6	3
N-10	15249	140	80	90	1218	28.8	22.6	4
N-11	15250	140	80	90	1218	29.8	22.6	4
N-12	15251	140	80	90	1218	25.7	21.6	4
N-13	15252	140	80	90	1218	21.6	22.6	4
N-14	15253	145	80	120	1225	29.8	25.7	5
N-15	15254	145	80	120	1225	28.3	20.6	5
N-16	15255	145	80	120	1225	23.2	20.6	5
N-17	15256	145	80	120	1225	23.2	23.7	5
N-18	15275	155	75	105	1225	24.7	22.1	6
N-19	15276	155	75	105	1225	23.7	23.2	6
N-20	15277	155	75	105	1225	22.6	22.6	6
N-21	15308	175	110	105	1222	23.2	22.1	7
N-22	15309	1150	85	165	1227	22.1	21.1	8
N-23	15310	1150	85	165	1227	22.6	22.1	8

(Cont'd on next page)

Table III (Cont'd)

Identification		Time (min)			Temp. (°F)	Extrusion Constant (tsi)		Extrusion Group No.
		Evacuation		Pre-heating				
ANL No.	NMI Extrusion No.[1]	Total	Outgassing at 800°F			Start	Run	
N-24	15311	1150	85	165	1227	20.6	21.6	8
N-25	15312	1150	85	165	1227	22.1	22.1	8
N-26	15787	150	75	110	1220	22.6	21.1	9
N-27	15788	145	75	110	1220	23.2	22.6	9
N-28	15789	140	75	115	1220	22.6	22.6	9
N-29	15952	1085	75	100	1228	23.7	22.6	10
N-30	15953	1085	75	105	1228	23.7	22.1	10
N-31	15954	1085	75	120	1225	23.7	23.1	10
N-32	15955	1085	75	120	1225	23.7	23.2	10
E-1	15532	95	65	90	1227	27.8	21.6	1
E-2	15533	110	65	90	1227	30.9	22.6	2
E-3	15534	95	70	95	1227	26.8	21.6	3
E-4	15535	100	70	90	1227	30.9	21.6	4
E-5	15600	100	65	90	1228	23.7	21.6	5
E-6	15601[2]	100	80	90	1228	27.8	23.7	6
E-7	15602[2]	100	70	90	1228	26.8	21.6	7
E-8	15603[3]	105	75	90	1228	32.9	23.7	8
E-9	15636	90	65	90	1235	22.6	21.1	9
E-10	15637	95	65	90	1235	22.6	20.6	10
E-11	15638	95	70	90	1240	24.7	20.1	11
E-12	15639	90	65	90	1228	22.6	20.6	12
E-13	15641	95	65	95	1235	24.2	21.1	13
E-14	15642	90	65	95	1235	22.6	20.6	14
E-15	15643	100	70	95	1235	23.7	20.6	15
E-16	15768	85	65	90	1225	24.2	22.1	16
E-17	15769	90	70	90	1225	23.7	21.1	17
E-18	15770[4]	100	70	90	1227	24.2	21.6	18
E-19	15771	90	65	85	1225	24.7	20.6	19

(1)All extrusions satisfactory
(2)Cu scored on rod; pickup on cone and die
(3)Cu scored on rod; pickup on cone and die; high staring pressure
(4)Billet leaked. Returned to ANL for recanning. Recanned billet extruded satisfactorily.

Table IV

Prototype 2-3/4 Inch Billets

Extrusion area reduction, 42.5:1; liner, 2.800 inch; die, 0.437 inch; ram speed, 30 in./min; lubrication, Oil Dag

Extrusion No.	Billet Code Letter	Core			Extrusion Preheat Temp. (°F)	Extrusion Constant (tsi)		Billet Assembly Details
		ANL No.*	Machined Weight (gms)	ANL Heat Treatment		Start	Run	
14915	D	H-476-1 C→T	8895	30 min at 780°C 30 min at 500°C air cool	1230	21.4	17.3	External Cu-Ni nose peened to cone at 900°F. Internal Cu-Ni cut-off.
14916	E	H-476-1 B→C	8890	30 min at 780°C 30 min at 500°C air cool	1230	18.6	17.1	Internal Cu-Ni nose 1/2-inch long. Internal Cu-Ni cut-off 1-inch long.
14988	F	H-476-2 C→T	8922	as cast	1225	18.6	17.6	Same as No. 14916
14989	G	H-476-4 B→C	8919	as cast	1225	18.9	18.0	Same as No. 14916
14990	H	H-476-5 C→T	8756	30 min at 780°C air cool	1225	19.3	18.2	Same as No. 14916
15331	L	H-476-5 B→C	8897	30 min at 780°C air cool	1225	21.5	19.5	Same as No. 14916

*Arrow indicates extrusion direction.

Table V

Rod Fabricated from Prototype 2-3/4 Inch Billets

Extrusion No.	Billet Code Letter	Length of U - 2 w/o Zr in inches			% Yield (based on maximum theoretical core length)	Dimensions in inches		
		At front taper	At rear taper	Uniform core		As extruded, (w/Cu)	As extruded, after removal of Cu	After swaging
14915	D	28	34	234	81.8	0.432 0.436	0.413 0.417	0.407 0.409
14916	E	28	29	244	85.4	0.431 0.433	0.410 0.414	0.407 0.409
14988	F	28	32	244	85.4	0.434 0.436	0.413 0.417	0.407 0.409
14989	G	28	31	244	85.4	0.434 0.436	0.415 0.417	0.407 0.408
14990	H	28	29	241	84.3	0.434 0.436	0.414 0.416	0.407 0.409
15331	L	28	--	243	84.9	0.434 0.436	0.413 0.415	0.406 0.408

Table VI

Preheating and Extrusion of 2-3/4 Inch Production Billets

Identification		Extrusion Group No.	Time (min)			Temp. (°F)	Extrusion Constant (tsi)		Remarks
			Evacuation		Preheating				
ANL No.	NMI Extrusion No.*		Total	Outgassing at 800°F			Start	Run	
B-51	15193	1	4245	130	120	1220	23.4	19.0	
B-52	15194	1	4245	130	125	1220	21.6	19.5	
B-53	15195	1	4245	135	130	1220	23.8	20.4	
B-54	15196	1	4245	135	135	1220	23.4	20.4	Billet overheated to 1225°F during outgassing
B-55	15197	1	4245	140	145	1220	23.4	20.4	
B-56	15224	2	135	60	110	1230	24.2+	--	Billet stalled; returned to ANL; die cracked, liner cracked
B-57	15225	2	135	60	145	1230	21.6	18.6	
B-58	15226	2	135	60	145	1230	22.1	18.6	
B-59	15227	2	135	60	160	1230	21.6	18.6	Die cracked
B-60	15228	2	135	65	175	1230	21.2	19.5	
B-61	15229	2	135	65	190	1230	22.1	19.5	Die cracked
B-62	15230	3	255	175	145	1235	22.5	19.0	
B-63	15231	3	255	175	150	1235	22.1	19.0	
B-64	15232	3	255	175	160	1235	22.5	19.5	
B-65	15233	3	255	175	175	1235	22.1	19.5	
B-66	15280	4	120	70	175	1222	21.2	18.6	
B-67	15281	5	225	105	135	1225	21.2	18.2	Realigned ram
B-68	15282	5	225	105	220	1225	20.8	19.0	
B-69	15283	5	225	105	225	1225	20.4	19.0	
B-70	15284	5	225	105	230	1225	21.6	19.0	
B-71	15285	5	225	105	234	1225	20.8	19.0	

(Cont'd. on next page)

Table VI (Cont'd.)

Identification		Extrusion Group No.	Time (min)			Temp. (^{o}F)	Extrusion Constant (tsi)		Remarks
			Evacuation		Preheating				
ANL No.	NMI Extrusion No.*		Total	Outgassing at 800^{o}F			Start	Run	
B-72	15286	6	220	175	135	1222	22.9	19.9	
B-73	15287	6	220	175	140	1222	23.8	19.9	
B-74	15288	6	220	175	150	1222	22.5	19.9	
B-75	15289	6	220	175	165	1222	22.5	19.9	
B-76	15290	6	220	175	170	1222	22.1	19.9	
B-77	15291	7	740	130	130	1220	21.6	19.5	
B-78	15292	7	740	130	135	1220	21.2	19.0	
B-79	15293	7	740	130	145	1220	21.4	19.5	Die cracked
B-80	15294	7	740	130	150	1220	21.2	20.6	Die cracked; small rib on rod (Cu)
B-81	15295	7	740	130	160	1220	20.8	19.5	
B-82	15332	8	190	110	165	1227	23.8	19.9	Slight scoring on rod
B-83	15333	10	210	120	135	1240	22.9	19.9	Evacuation tube leaked--billet recanned at NMI
B-84	15334	8	195	110	180	1227	23.1	19.5	
B-85	15335	8	195	115	210	1227	23.4	19.9	
B-86	15336	8	205	125	225	1227	23.1	20.4	Ram bent
B-87	15337	9	205	120	430	1235	22.1	19.7	Previously preheated 4-1/2 hr and cooled; reheated and extruded with new ram
B-88	15338	9	140	95	160	1235	22.1	19.9	
B-89	15339	9	140	90	165	1235	20.4	19.5	
B-90	15340	9	145	105	170	1235	20.8	19.7	
B-91	15341	9	145	110	175	1235	21.6	19.9	
B-92	15406	10	385	125	150	1240	23.4	20.4	Ram bent

(Cont'd. on next page)

Table VI (Cont'd.)

Identification		Extrusion Group No.	Time (min)			Temp. (°F)	Extrusion Constant (tsi)		Remarks
			Evacuation		Preheating				
ANL No.	NMI Extrusion No.*		Total	Outgassing at 800°F			Start	Run	
B-93	15407	10	380	125	215	1240	19.5	18.2	Installed new ram
B-94	15408	10	380	125	225	1240	20.4	18.6	
B-95	15409	10	375	125	230	1240	20.6	19.5	Slight scoring on rod
B-96	15410	11	1010	120	135	1240	23.1	19.9	
B-97	15411	11	1015	120	140	1240	22.5	18.6	
B-98	15412	11	1015	125	145	1240	22.9	20.4	
B-99	15413	11	1020	130	150	1240	23.4	19.2	
B-100	15414	11	1020	130	155	1240	22.5	18.6	
B-101	15415	12	170	120	135	1240	24.2	19.9	Billet leaked--recanned at NMI; die cracked, liner cracked
B-102	15416	11	1020	130	165	1240	22.5	19.0	Note: Cracked liner used for remaining extrusions;
B-103	15417	12	260	150	135	1240	23.8	18.6	
B-104	15418	12	260	150	140	1240	23.8	18.8	
B-105	15419	12	265	155	140	1240	22.5	18.6	
B-106	15420	12	265	155	145	1240	23.8	19.0	Rod scored
B-107	15421	12	270	155	145	1240	24.2+	--	Billet stalled. Returned to ANL
B-108	15422	13	170	120	135	1240	24.2	19.5	
B-109	15423	13	170	120	140	1240	23.8	19.2	
B-110	15424	13	170	125	145	1240	22.1	18.6	
B-111	15425	13	175	130	150	1240	22.5	20.1	Rod scored
B-112	15658	14	220	150	135	1235	21.6	18.6	
B-113	15659	14	220	150	140	1235	22.9	18.6	
B-114	15660	14	225	155	145	1235	22.7	18.6	

*All extrusions satisfactory, unless otherwise noted.

Table VII

Primary Extrusion of Zircaloy Tube

	Extrusion No.	Diameter (in.)		Extrusion			Ram Speed (in./min)	Billet		Length of Tube (in.)	Preheat Temp. (°F)	Material Source and History
		Die	Mandrel	Area Reduction	Constant (tsi)			Wt. (lb)	Length (in.)			
					Start	Run						
SMZ-541 A*	14643	2.770	2.170	16.4	20.8	16.0	60	112	14	181	1480	Extruded at Revere 2-3/4 inch billets
	14644	2.000	1.500	25.1	--	--	--	70	10	--	1450	Stalled at Revere
	14725	4.470	1.620	2.5	22.9	21.3	15	67	9	24	1440	Recanned from 14644; 1st primary
	14726	2.010	1.500	10.7	18.9	18.3	15	32	10-5/8	102	1440	Formerly 14725; 2nd primary
	14727	2.010	1.500	10.7	19.7	19.4	15	32	10-3/8	102	1440	Formerly 14725; 2nd primary
	14914	4.470	1.620	2.5	21.9	21.2	15	48	6-1/2	16	1420	
	14991	2.010	1.500	10.7	19.7	21.3	15	47	15-7/8	153	1420	Formerly 14914
SMZ-541 B*	15141	2.770	2.170	16.4	21.5	17.2	34	88	11	174	1450	Extruded at Revere 2-3/4 inch billets
	15142	2.770	2.170	16.4	19.1	16.3	37	88	11	174	1450	Extruded at Revere 2-3/4 inch billets
	15143	2.770	2.170	16.4	19.1	15.8	40	88	11	174	1450	Extruded at Revere 2-3/4 inch billets
	15176	4.450	1.620	2.5	22.0	21.4	15	30	4	11	1460	1st primary
	15177	2.010	1.500	10.7	23.7	23.1	15	29	10	94	1450	Formerly 15176; 2nd primary
	15366	4.470	1.620	2.5	22.9	20.8	15	40	5-1/2	14	1450	1st primary
	15367	2.010	1.500	10.7	25.3	23.6	15	39	13	127	1450	Formerly 15366; 2nd primary
	15877	4.470	1.620	2.5	21.6	19.7	15	33	4-1/2	12	1450	1st primary
	15878	2.010	1.500	10.7	21.1	19.5	15	32.5	11-1/2	109	1450	Formerly 15877; 2nd primary

*SMZ A and B were the designations assigned by NMI to the 2 sections of forged bar received from ANL

**All tubing was extruded for use as clad stock in subsequent coextrusions, for 2-inch billets, unless otherwise noted.

Table VIII

Primary Extrusion of Zircaloy Rod

Extrusion No.	Die Dia. (in.)	Extrusion			Ram Speed (in./min)	Billet		Length of tube (in.)	Preheat Temp. (^{o}F)	Material Source and History	Intended Use
		Area Reduction	Constant (tsi)			Wt. (lb)	Length (in.)				
			Start	Run							
14641	1.800	16.5	14.1	11.8	16	45	5	88	1480	SMZ-541A extruded at Revere	End seals 2-inch billets
14642	2.480	8.6	16.7	14.1	88	90	10	88	1480	SMZ-541A extruded at Revere	End seals 2-3/4 inch billets.

Table IX

Primary Extrusion of Copper-Nickel Rod for Nose Plugs and Cut-Offs

Extrusion No.	Die Dia. (in.)	Extrusion			Billet		Rod Length (in.)	Preheat Temp. °F	Casting No.	For Use With ___ Diameter Billets
		Area Reduction	Constant (tsi)							
			Start	Run	Wt Lb	Length (in.)				
14366	3.000	2.6	19.6	18.6	64	11-1/2	29	1500	3	2-3/4 inch
14714	2.010	7.8	14.7	13.5	88	10	64	1500	MX-120	2 inch
15004	2.010	7.8	13.6	13.1	59	7-1/2	--	1500	MX-128	2 inch
15061	2.875	3.8	15.9	15.6	40	------	19-1/2	1500	MX-130	2-3/4 inch
15062	2.875	3.8	14.7	14.2	36	------	17-1/2	1500	MX-131	2-3/4 inch
15165	2.010	7.8	20.3	19.5	60	7-1/2	59	1260	MX-132	2 inch
15166	2.750	4.2	21.0	20.0	82	10-3/4	44	1260	MX-133	2-3/4 inch
15170	2.750	4.2	23.1	20.2	82	10-5/8	43	1260	MX-134	2-3/4 inch
15171	2.750	4.2	21.2	19.3	82	10-5/8	43	1260	MX-135	2-3/4 inch
15172	2.750	4.2	21.4	20.0	82	10-11/16	43	1260	MX-136	2-3/4 inch
15181	2.750	4.2	19.5	19.0	82	10-3/4	43	1250	MX-137	2-3/4 inch

Table X

Chemical and Spectrographic Analysis of Zircaloy Ingot*

Alloy Analysis by Percent			
Sn	Fe	Cr	Ni
1.42	0.13	0.115	0.060

Impurities by ppm							
N	C	Si	Al	Hf	Cu	Ti	V
13	22	<50	48	<100	<25	<25	<25
18	70	<50	44	<100	37	<25	<25
Mn	Mg	Pb	Mo	Co	W	B	Cd
39	<10	80	<20	<10	69	<0.3	<0.2
34	<10	74	<20	<10	36	<0.3	<0.2

Brinnell Hardness 182 Av
Sponge Blend WC-13
Specification No. PDS 11537-F

*Analysis supplied by Allegheny Ludlum Steel.

Table XI

Chemical Analysis of the Copper-Nickel Alloy

Extrusion No.	Casting No.	Analysis % Nickel
14366 Front 14366 Rear	3	9.58 8.96
15004 Front 15004 Rear	MX-128	10.68 10.71
15061 Front 15061 Rear	MX-130	9.19 9.17
15062 Front 15062 Rear	MX-131	7.25 7.66
14714	MX-120 Top MX-120 Bottom	8.33 8.66
15165 Front 15165 Rear	MX-132	8.73 8.90
15166 Front 15166 Rear	MX-133	8.80 9.21
15170 Front 15170 Rear	MX-134	9.12 9.02
15171 Front 15171 Rear	MX-135	7.24 7.36
15172 Front 15172 Rear	MX-136	9.01 8.76
15421 (B-107)*		9.48

*Machined from nose of stalled billet.

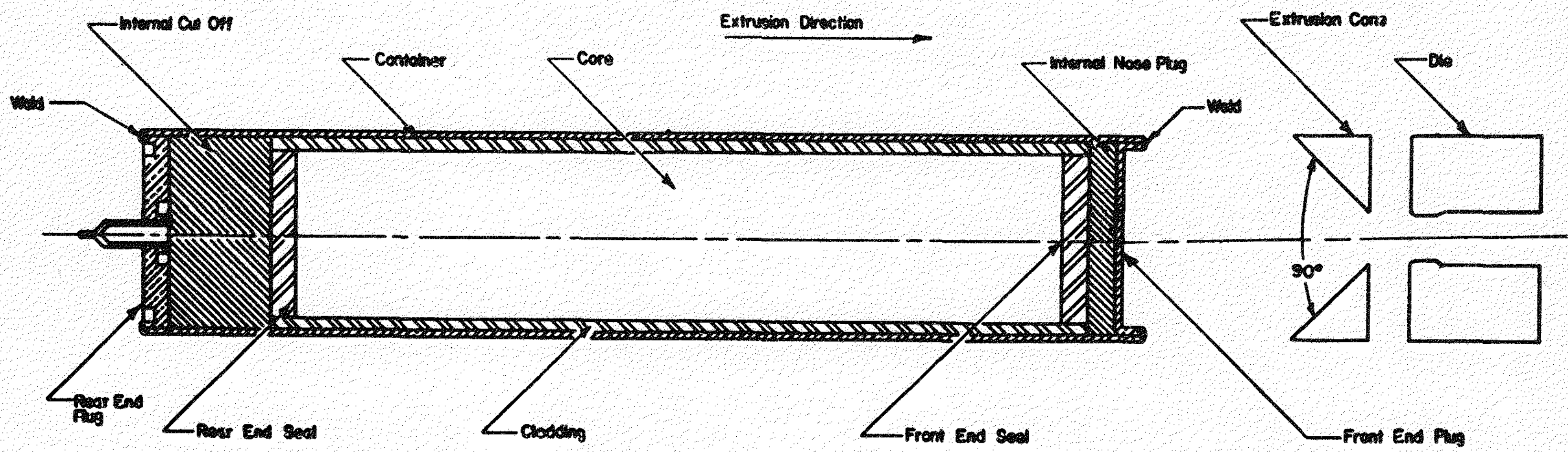


Fig. 1

Composite Billet for Coextrusion of EBR-I Mark III Core Rod

Specifications				
Component	Material	Dimensions in inches		
		OD	ID	Length
Core	U - 2 ^{w}/o Zr	1.653+0.000-0.003	--	7-1/2
Cladding	Zircaloy-2	1.860+0.000-0.003	1.658+0.003-0.000	8
End Seals	Zircaloy-2	1.653+0.000-0.003	--	1/4
Internal Nose Plug	Cu - 10 ^{w}/o Ni	1.860+0.000-0.005	--	1/4
Internal Cutoff	Cu - 10 ^{w}/o Ni	1.860+0.000-0.005	--	1
Container	Seamless hard drawn Cu tube	2.000	1.870	Cut to fit assembled billet
Front End Plug	No.16 gage Cu sheet punched and cupped	1.870	--	1/4
Rear End Plug	Deoxidized Cu plate	1.865+0.000-0.005	1/4 drill	1/4
Evacuation Tube	Seamless hard drawn Cu tube	1/4	1/8	
Extrusion Cone	Mild steel	2.020±0.002	0.515+0.025-0.000	0.752 Ref.
Extrusion Die	18-4-1 steel	2.025+0.000-0.003	0.453	1-1/4

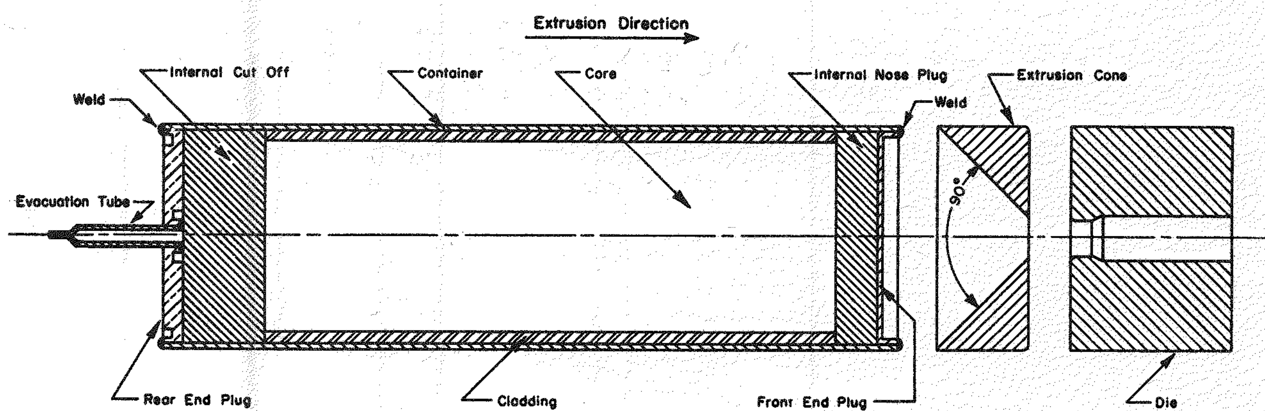
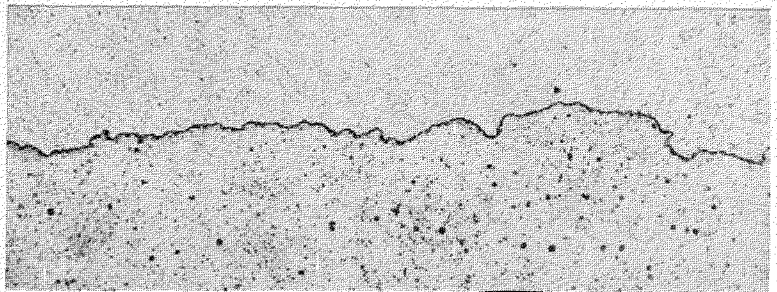


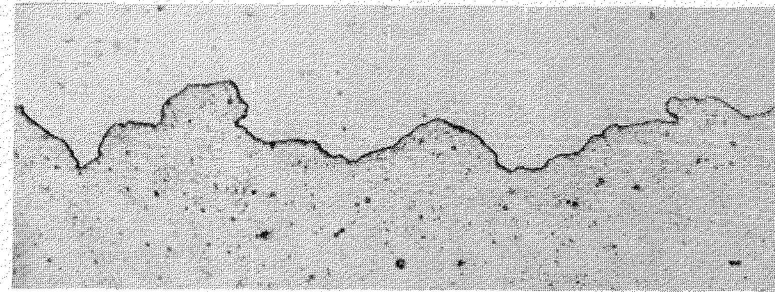
Fig. 2

Composite Billet for Coextrusion of EBRI Mark III Blanket Rod

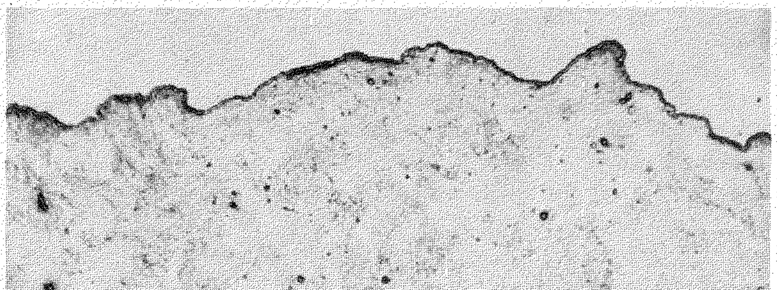
Specifications				
Component	Material	Dimensions in inches		
		OD	ID	Length
Core	U - 2 $^{w}/_{o}$ Zr	$2.322^{+0.000}_{-0.003}$	--	7
Cladding	Zircaloy-2	$2.610^{+0.000}_{-0.003}$	$2.327^{+0.003}_{-0.000}$	7
Internal nose plug	Cu - 10 $^{w}/_{o}$ Ni	$2.610^{+0.000}_{-0.005}$	--	1/2
Internal cut-off	Cu - 10 $^{w}/_{o}$ Ni	$2.610^{+0.000}_{-0.005}$	--	1
Container	Seamless hard drawn Cu tube	2.750 $\pm$0.003	$2.620^{+0.003}_{-0.000}$	Cut to fit assembled billet
Front end plug	16 gage Cu sheet punched and cupped	2.620	--	1/4
Rear end plug	Deoxidized Cu plate	$2.615^{+0.000}_{-0.005}$	1/4 Drill	1/4
Evacuation tube	Seamless hard drawn Cu tube	1/4	1/8	10 min.
Extrusion cone	Mild steel	$2.785^{+0.000}_{-0.005}$	$0.520^{+0.020}_{-0.000}$	1.132 Ref.
Extrusion die	18-4-1 steel	2.785 $\pm$0.002	0.437	2



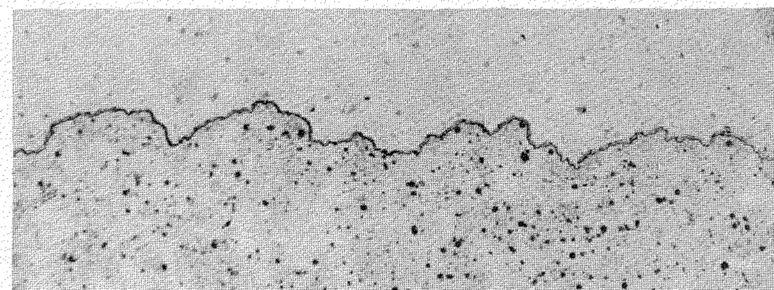
100X Bt.Lt. A-2112-11
Extrusion 14685 Front Core H-462



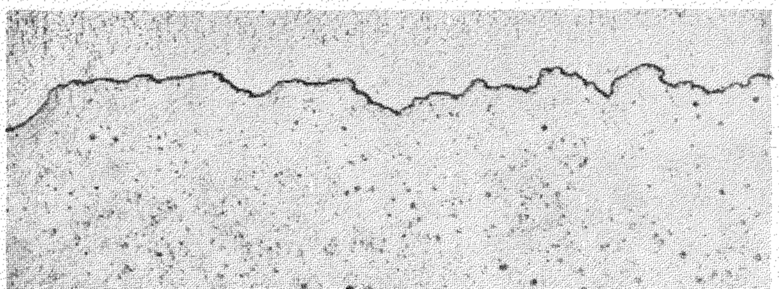
100X Bt.Lt. A-2112-10
Extrusion 14685 Rear



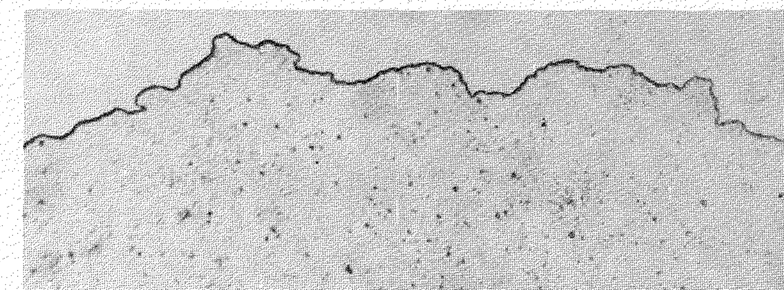
100X Bt.Lt. A-2112-7
Extrusion 14686 Front Core H-462



100X Bt.Lt. A-2112-3
Extrusion 14686 Rear

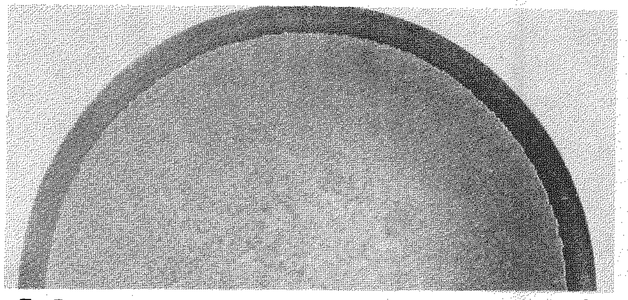


100X Bt.Lt. A-2112-12
Extrusion 14687 Core H-462

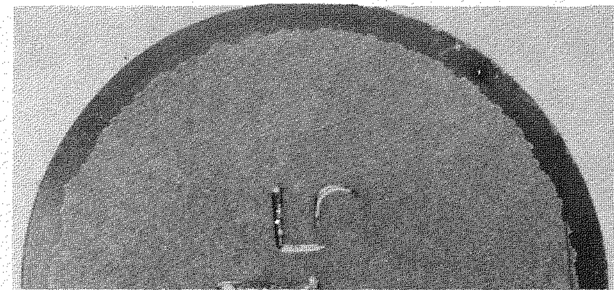


100X Bt.Lt. A-2112-4
Extrusion 14687

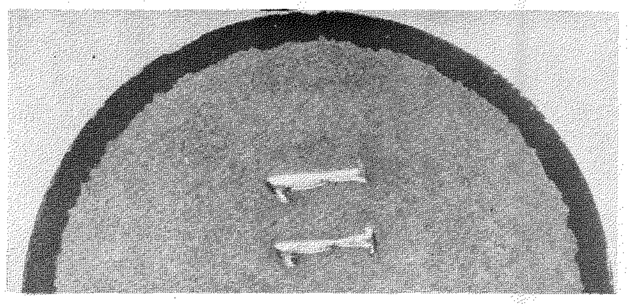
Fig. 3 - Irregular core-to-clad interface in the coextruded rod. Extrusion billet cores were machined from as-cast metal produced in an eight-cavity, 1-7/8 inch diameter mold. Note varying irregularity between front and rear of extrusions.



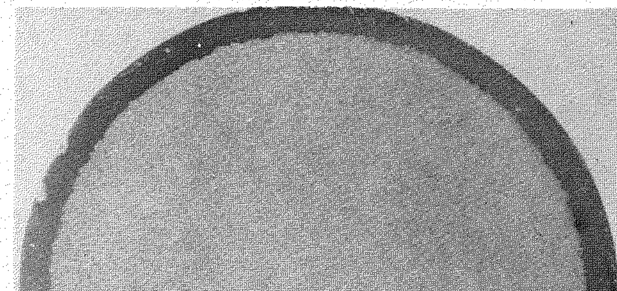
7.5X RF 5605
Extrusion 14685 Front Core H-462



7.5X RF 5606
Extrusion 14685 Rear

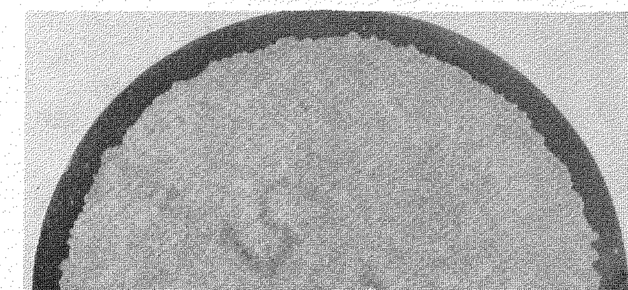


7.5X RF 5607
Extrusion 14686 Front Core H-462



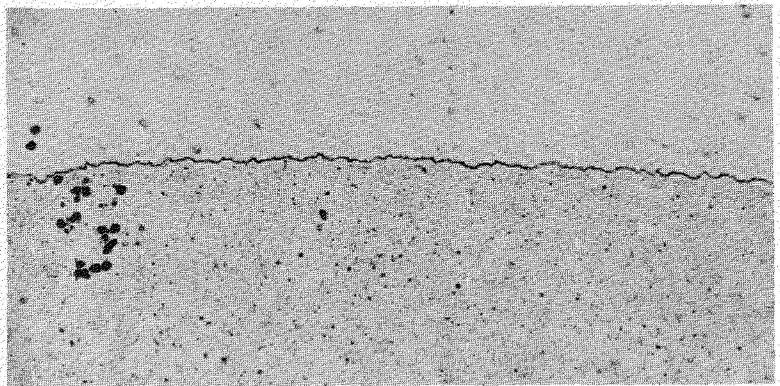
7.5X RF 5617
Extrusion 14686 Rear

7.5X RF 5604
Extrusion 14687 Front Core H-462

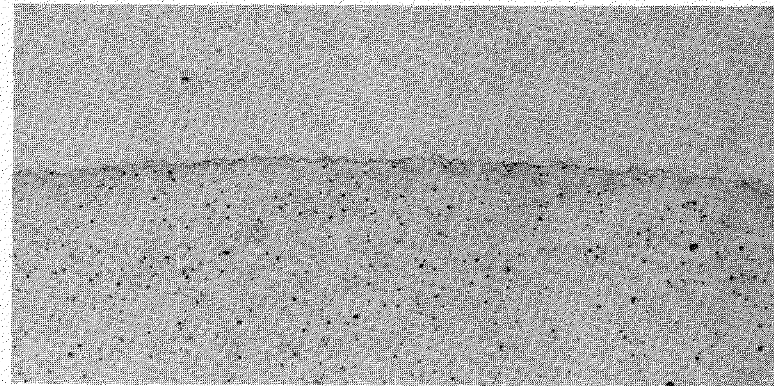


7.5X RF 5611
Extrusion 14687 Rear

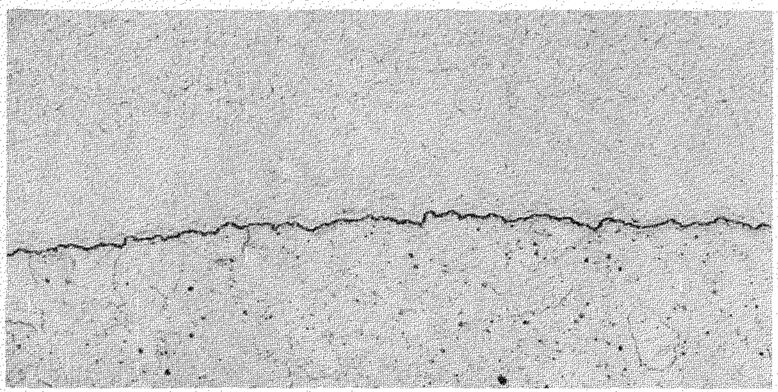
Fig. 4 - Macrographs of core-to-clad interface. Extrusion billet cores were machined from as-cast metal produced in an eight-cavity, 1-7/8 inch diameter mold. This group had the most unsatisfactory interfaces of all.



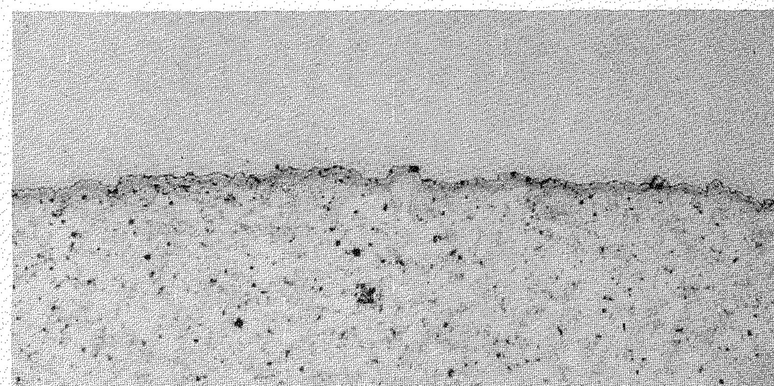
100X Bt.Lt. A-1048-1
Extrusion 14832 Front Core SNC 52



100X Bt.Lt. A-1048-2
Extrusion 14832 Rear

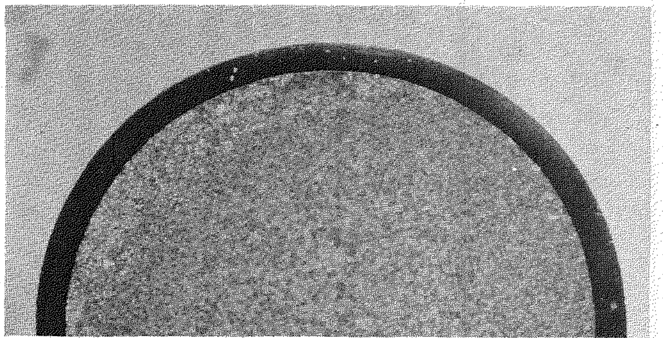


100X Bt.Lt. A-1048-3
Extrusion 14833 Front Core SNC 62

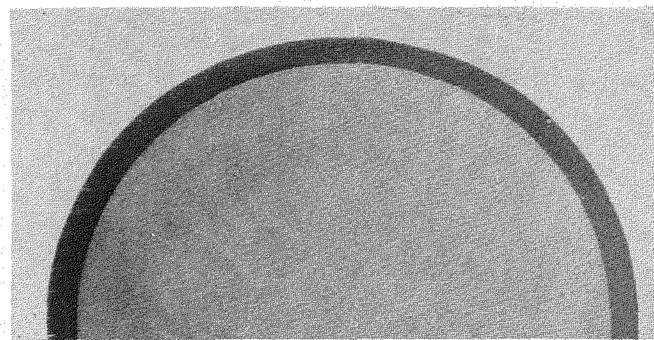


100X Bt.Lt. A-1048-4
Extrusion 14833 Rear

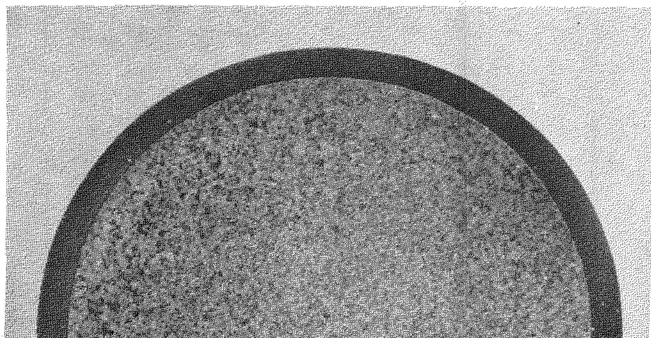
Fig. 5 - Photomicrographs of the core-to-clad interface in the coextruded rod. Upper portion of picture is clad; lower portion, core. Extrusion billet cores were as-cast from single-cavity molds.



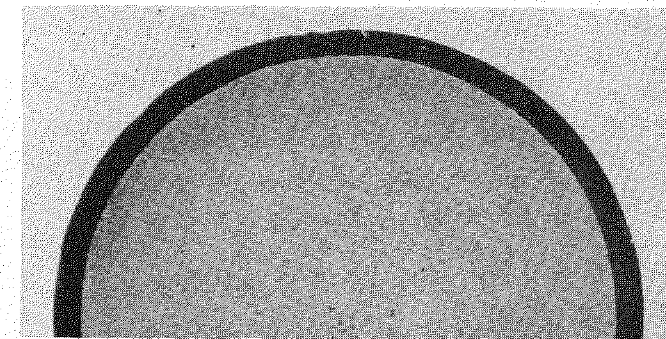
7.5X RF 4840
Extrusion 14832 Front Core SNC 52



7.5X RF 4841
Extrusion 14832 Rear

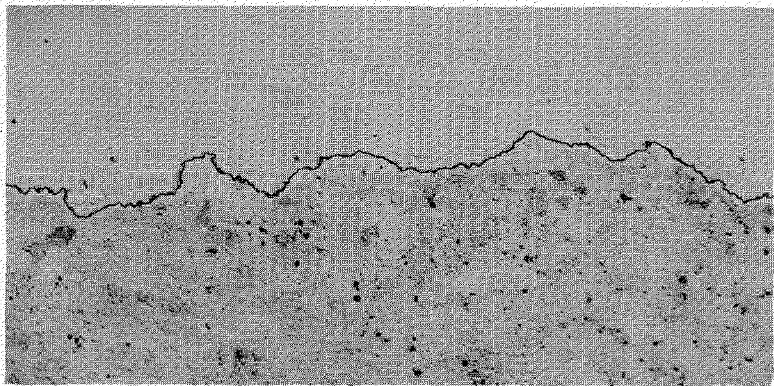


7.5X RF 4842
Extrusion 14833 Front Core SNC 62

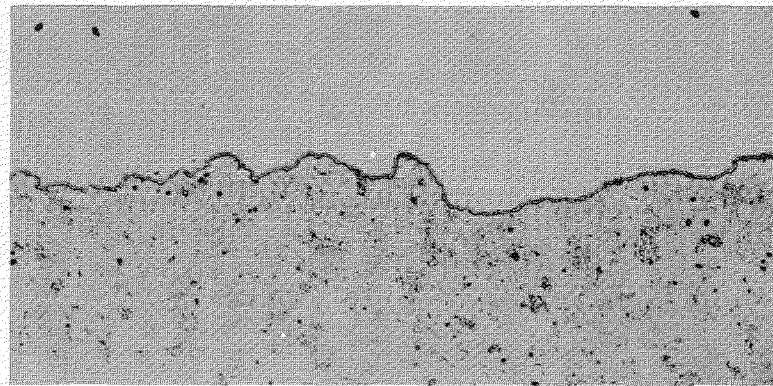


7.5X RF 4843
Extrusion 14833 Rear

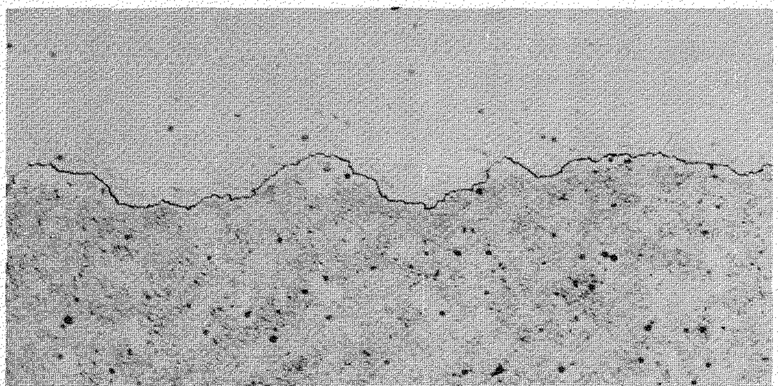
Fig. 6 - Macrographs of cross sections taken from the front and rear of coextruded rods, showing the smooth interface between cladding and core. Extrusion billet cores were in the as-cast condition from small, single-cavity molds.



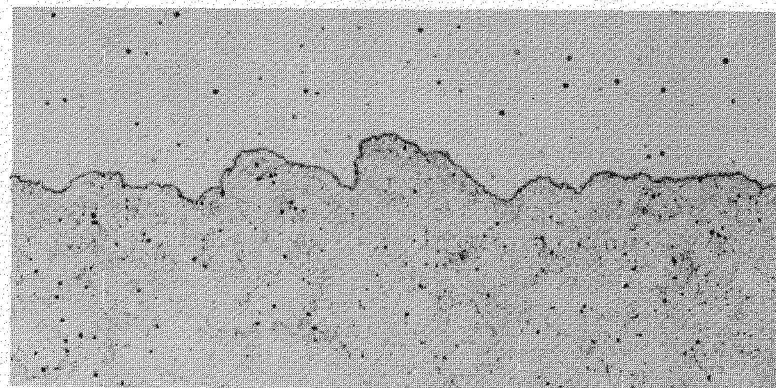
100X Bt.Lt. A-1048-11
Extrusion 14988 Front Core H-476-2 Top



100X Bt.Lt. A-1048-12
Extrusion 14988 Rear Core H-476-2 Center

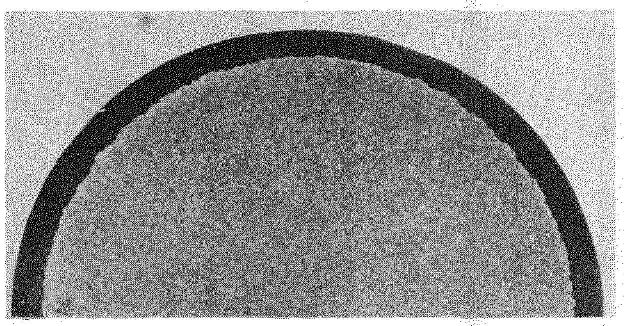


100X Bt.Lt. A-1048-13
Extrusion 14989 Front Core H-476-4 Center



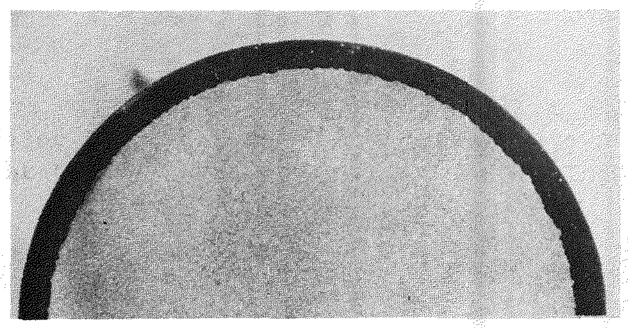
100X Bt.Lt. A-1048-14
Extrusion 14989 Rear Core H-476-4 Bottom

Fig. 7 - Photomicrographs of the core-to-clad interface in the coextruded rod. Cladding appears light; core, dark. Extrusion billet cores were in the as-cast condition from a 2-3/8 inch diameter, eight-cavity mold.



7.5X RF 4850
Extrusion 14988 Front Core H-476-2 Top

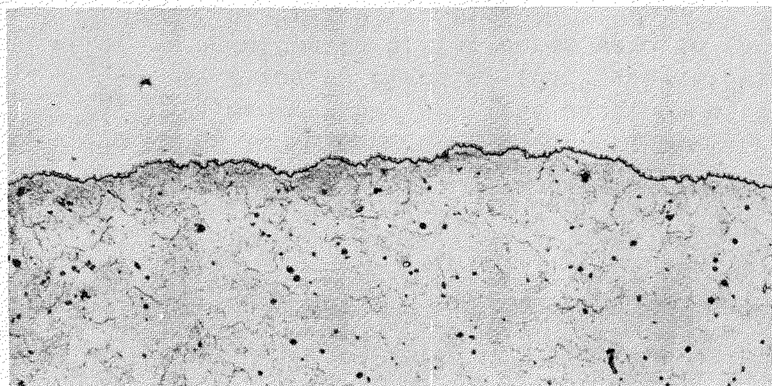
7.5X RF 4851
Extrusion 14988 Rear Core H-476-2 Center



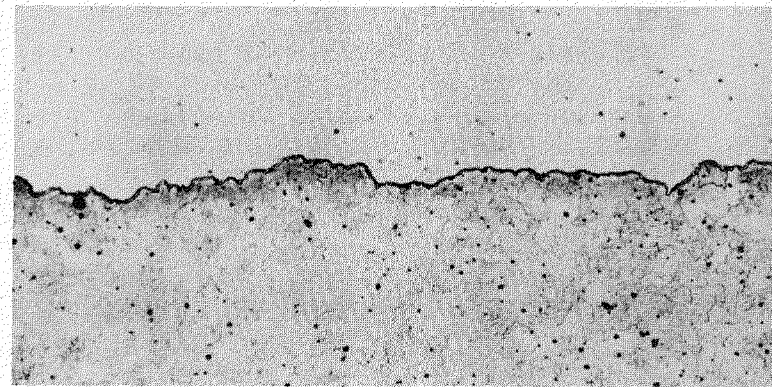
7.5X RF 4852
Extrusion 14989 Front Core H-476-4 Center

7.5X RF 4853
Extrusion 14989 Rear Core H-476-4 Bottom

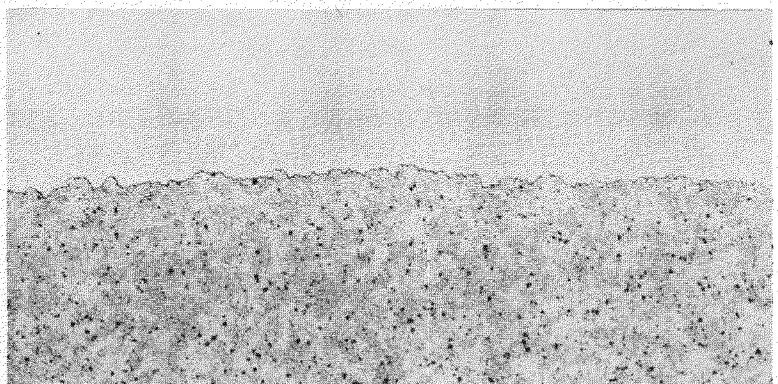
Fig. 8 - Macrographs of cross sections of coextruded rod showing rough interface between Zircaloy cladding (dark appearing) and U - 2 $^{w}/_{o}$ Zr core (light appearing). Extrusion billet cores were in the as-cast condition from a 2-3/8 inch diameter, eight-cavity mold.



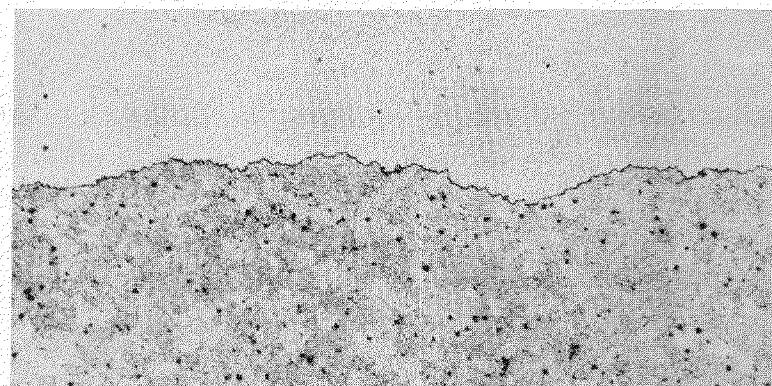
100X Bt.Lt. A-1048-15
Extrusion 14990 Front Core H-476-5 Top



100X Bt.Lt. A-1048-16
Extrusion 14990 Rear Core H-476-5 Center

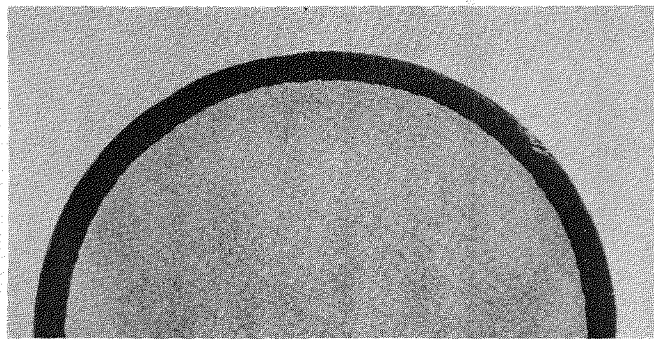


100X Bt.Lt. A-1097-1
Extrusion 15331 Front Core H-476-5 Center

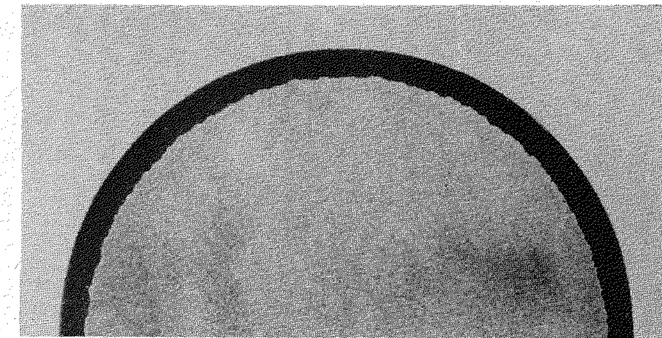


100X Bt.Lt. A-1097-2
Extrusion 15331 Rear Core H-476-5 Bottom

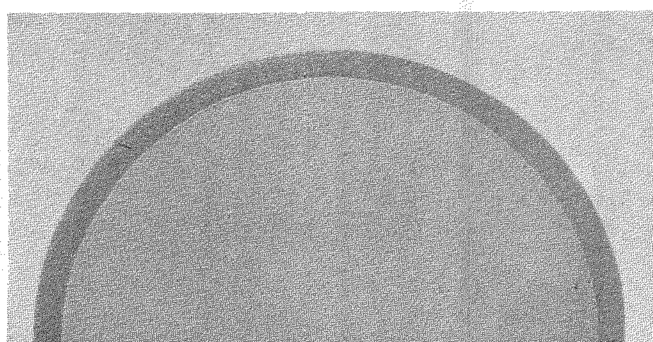
<u>Fig. 9</u> - Core-to-clad interface in the coextruded rod. Extrusion billet cores from a 2-3/8 inch diameter casting made in an eight-cavity mold; heat treated for 30 minutes at 780°C and air cooled.



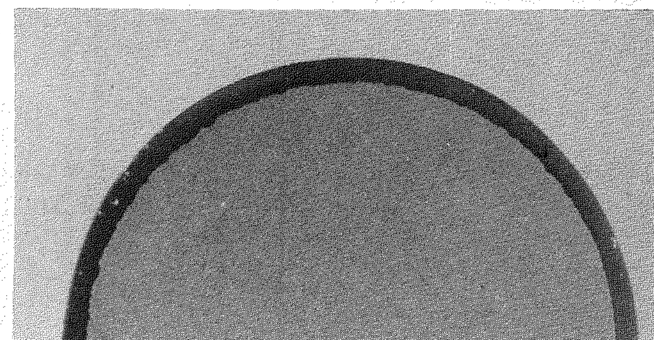
7.5X RF 4854
Extrusion 14990 Front Core H-476-5 Top



7.5X RF 4855
Extrusion 14990 Rear Core H-476-5 Center

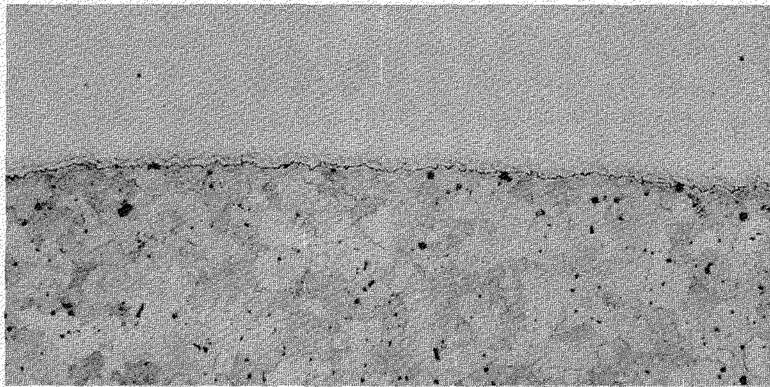


7.5X RF 5610
Extrusion 15331 Front Core H-476-5 Center

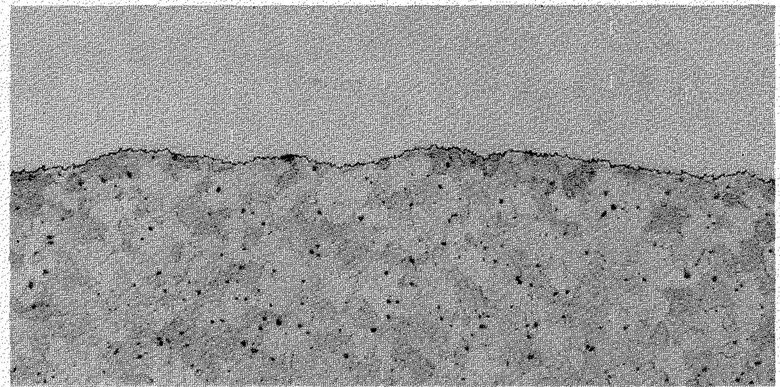


7.5X RF 5618
Extrusion 15331 Rear Core H-476-5 Bottom

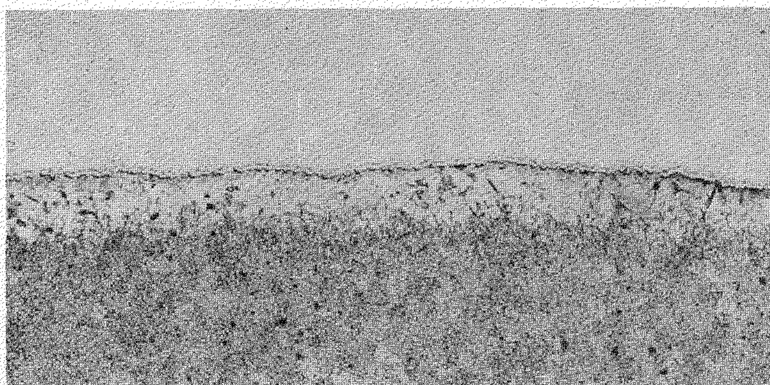
Fig. 10 - Cross sections of the coextruded rod. Extrusion billet cores from a 2-3/8 inch diameter casting made in an eight-cavity mold; heat treated for 30 minutes at 780°C and air cooled.



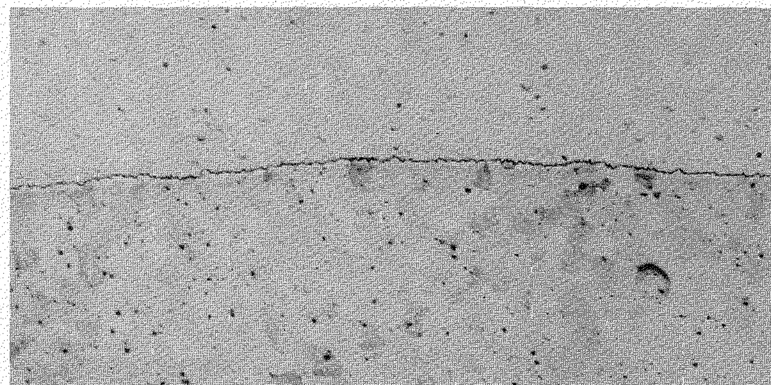
100X Bt.Lt. A-1048-7
Extrusion 14915 Front Core H-476-1 Top



100X Bt.Lt. A-1048-8
Extrusion 14915 Rear Core H-476-1 Center

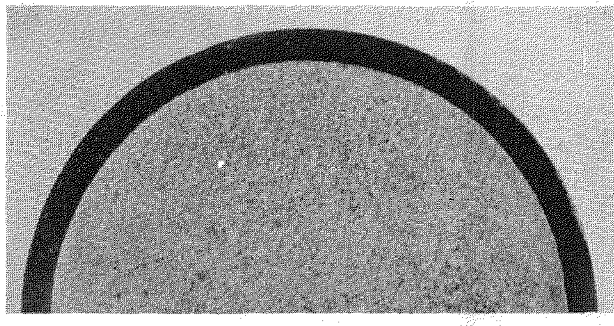


100X Bt.Lt. A-1048-9
Extrusion 14916 Front Core H-476-1 Center

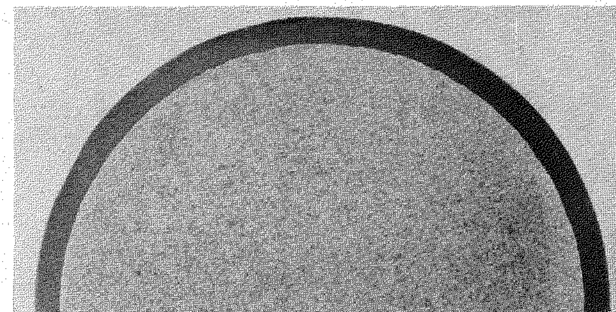


100X Bt.Lt. A-1048-10
Extrusion 14916 Rear Core H-476-1 Bottom

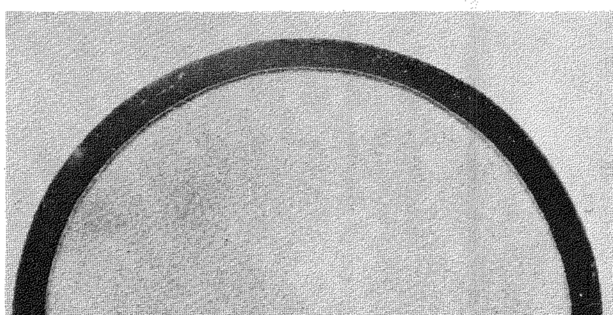
Fig. 11 - Core-to-clad interfaces in the coextruded rod. Cladding appears light; core, dark. Extrusion billet core was from a 2-3/8 inch diameter, eight-cavity mold casting, heat treated for 30 minutes at 780°C followed by 30 minutes at 500°C and air cooled.



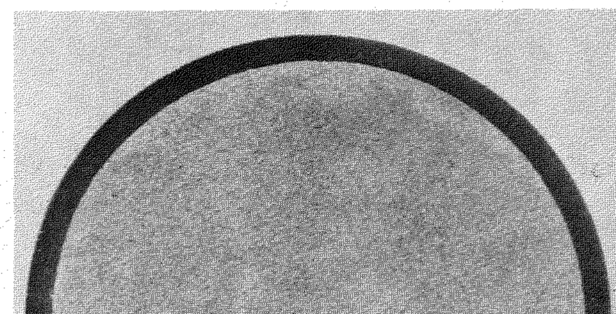
7.5X RF 4846
Extrusion 14915 Front Core H-476-1 Top



7.5X RF 4847
Extrusion 14915 Rear Core H-476-1 Center

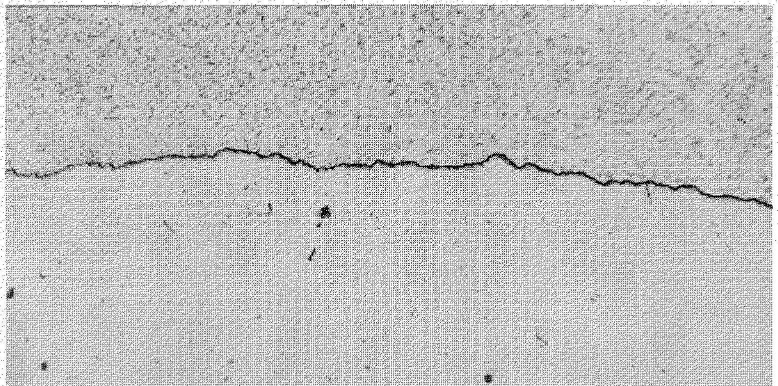


7.5X RF 4848
Extrusion 14916 Front Core H-476-1 Center

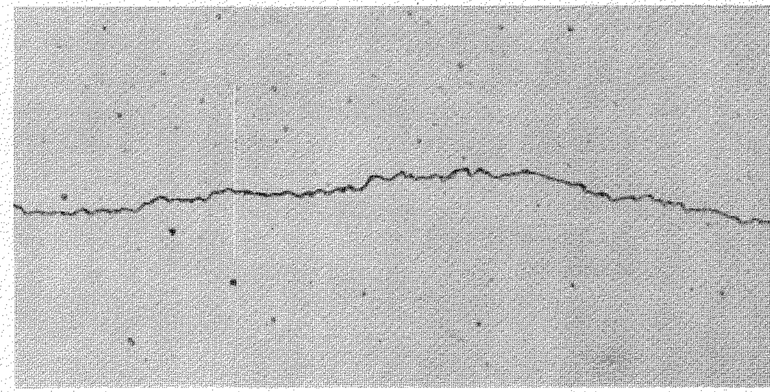


7.5X RF 4849
Extrusion 14916 Rear Core H-476-1 Bottom

<u>Fig. 12</u> - Cross sections of coextruded rod. Extrusion billet core was from a 2-3/8 inch diameter, eight-cavity mold casting, heat treated for 30 minutes at 780°C, followed by 30 minutes at 500°C and air cooled.

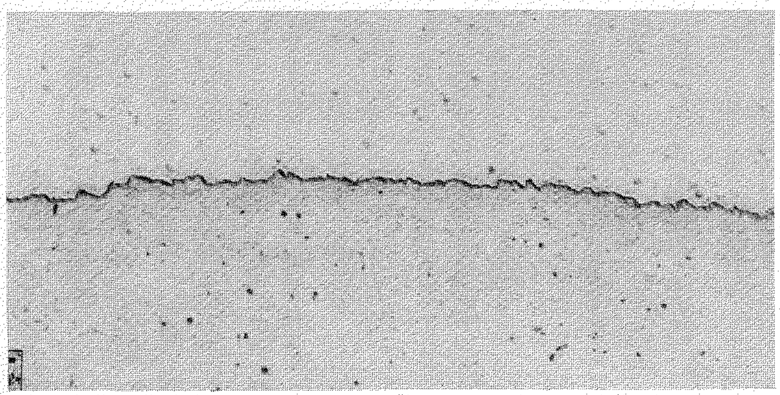


100X Bt.Lt. A-2112-1
Extrusion 15052 Front Core H-474-2 A

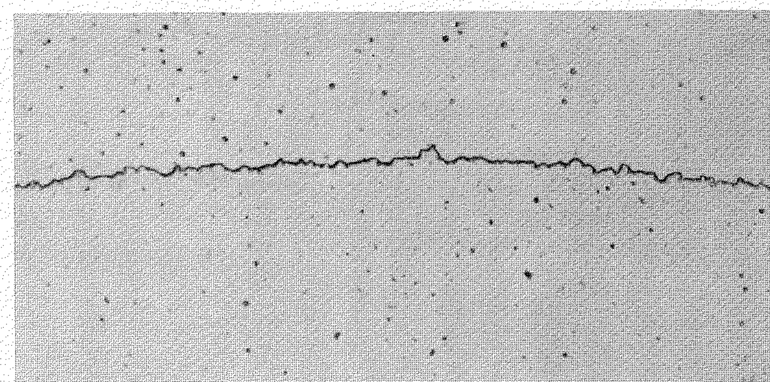


100X Bt.Lt. A-2112-2
Extrusion 15052 Rear Core H-474-2 B

Single Heat Treatment



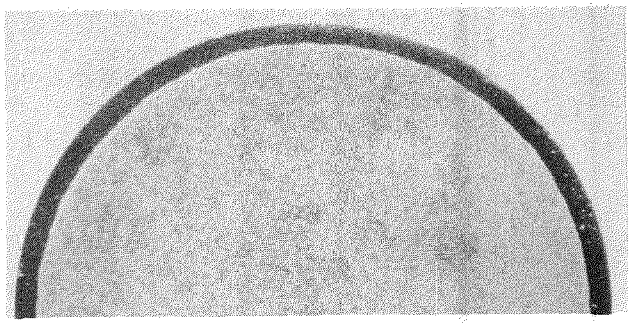
100X Bt.Lt. A-2112-5
Extrusion 15050 Front Core H-473-4 A



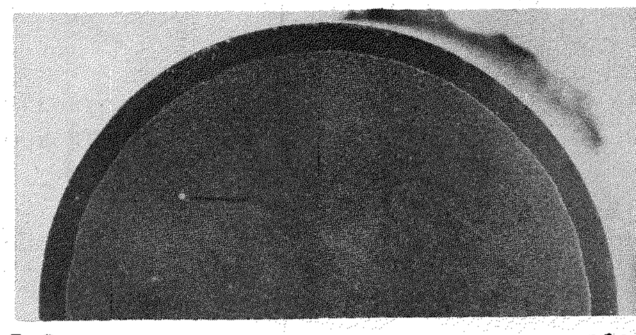
100X Bt.Lt. A-2112-6
Extrusion 15050 Rear Core H-473-4 B

Triple Heat Treatment

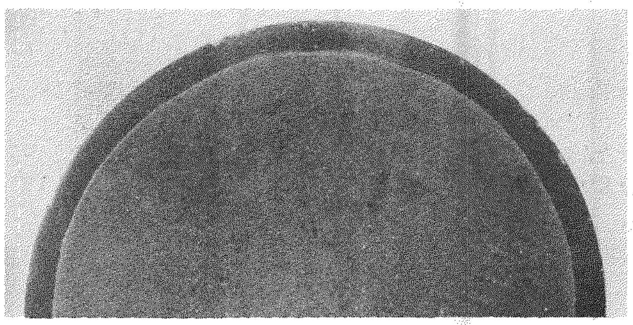
Fig. 13 - Core-to-clad interface in the coextruded rod. Zircaloy-2 at top of picture; U - 2 $^{w}/o$ Zr core at bottom. Extrusion billet cores were from small, eight-cavity molds and were heat treated for 30 minutes at 780°C and air cooled. Number of repetitions is listed under illustrations.



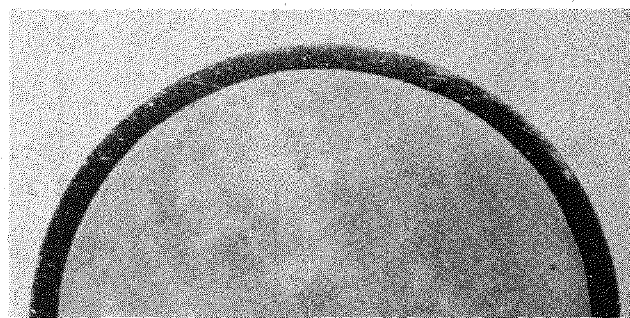
7.5X RF 5620
Extrusion 15052 Front Core H-474-2 A
Single Heat Treatment



7.5X RF 5609
Extrusion 15052 Rear Core H-474-2 B

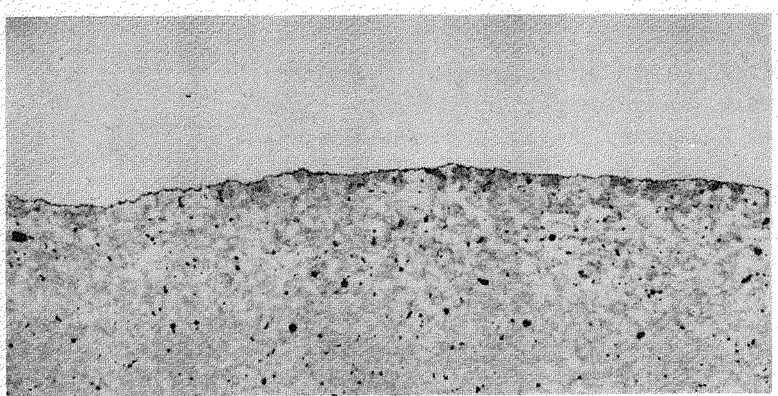


7.5X RF 5619
Extrusion 15050 Front Core H-473-4 A
Triple Heat Treatment

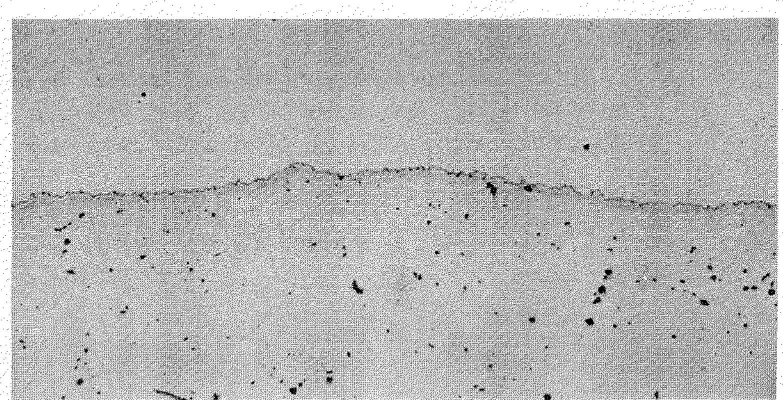


7.5X RF 5621
Extrusion 14050 Rear Core H-473-4 B

<u>Fig. 14</u> - Macrographs of cross sections taken from the front and rear of the coextruded rod. Extrusion billet core was heat treated for 30 minutes at 780°C and air cooled. Number of repetitions is listed under the illustrations.

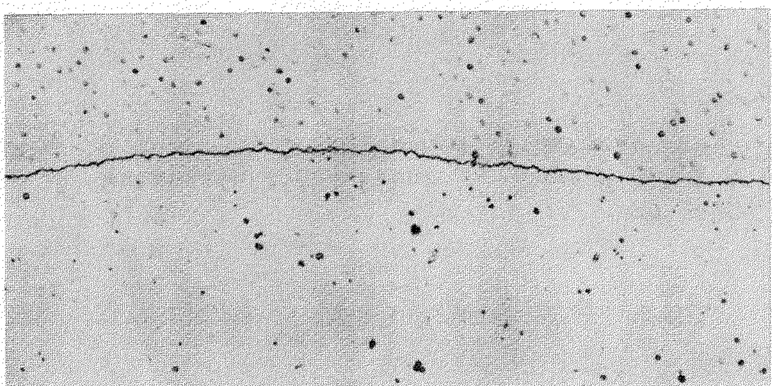


100X Bt.Lt. A-1048-5
Extrusion 14834 Front Core H-474-5

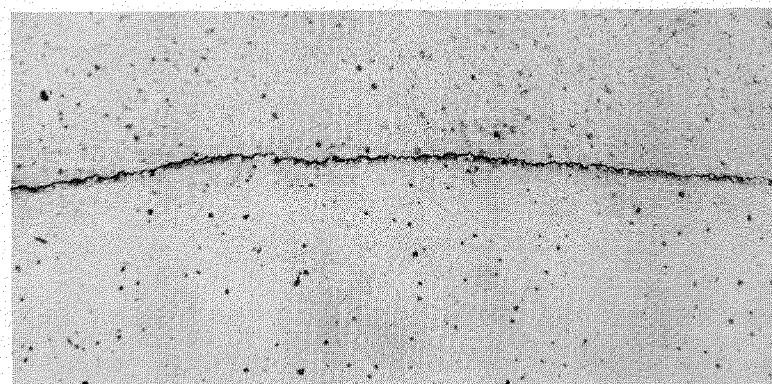


100X Bt.Lt. A-1048-6
Extrusion 14834 Rear

Single Heat Treatment



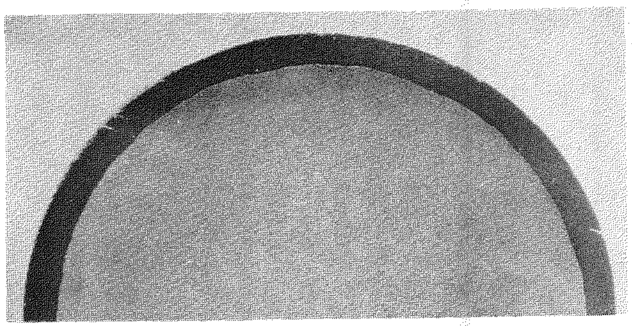
100X Bt.Lt. A-2112-8
Extrusion 15051 Front Core H-473-5 A



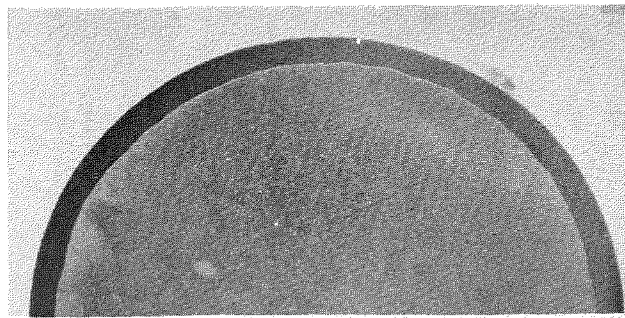
100X Bt.Lt. A-2112-9
Extrusion 15051 Rear Core H-473-5 B

Triple Heat Treatment

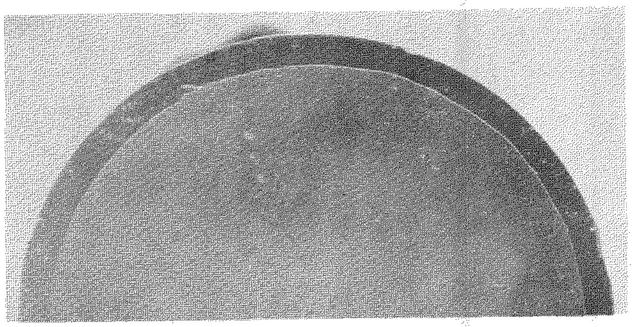
Fig. 15 - Core-to-clad interface in the coextruded rod. Zircaloy is at top of picture; U - 2 $^{w}/o$ Zr at bottom. Extrusion billet cores were from small, eight-cavity molds and were heat treated for 30 minutes at 780°C and water quenched. Number of repetitions is listed under illustrations.



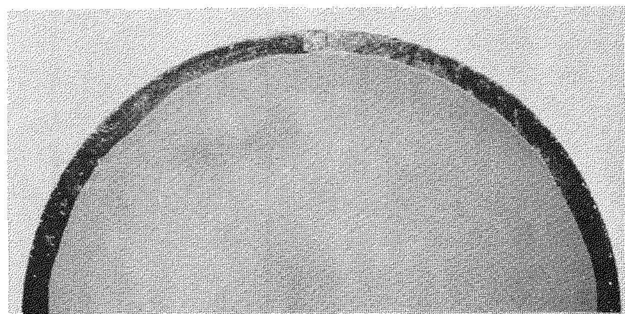
7.5X RF 4844
Extrusion 14834 Front Core H-474-5
Single Heat Treatment



7.5X RF 4845
Extrusion 14834 Rear



7.5X RF 5608
Extrusion 15051 Front Core H-473-5 A
Triple Heat Treatment



7.5X RF 5622
Extrusion 15051 Rear Core H-473-5 B

Fig. 16 - Macrographs of cross sections taken from the front and rear of the coextruded rod. Extrusion billet core was heat treated for 30 minutes at 780°C and water quenched. Number of repetitions is listed under the illustrations.