Second United Nations International Conference on the Peaceful Uses of Atomic Energy

A/CONF.15/P/791
USA
23 June 1958

ORIGINAL: ENGLISH

Confidential until official release during Conference

THE MANUFACTURE OF EBR-I, MARK III FUEL AND BLANKET RODS

Robert A. Noland, N. J. Carson, C. C. Stone, F. D. McCuaig, and R. E. Macherey*

FOREWORD

The purpose of this paper is to describe the manufacture of the fuel elements and blanket elements used in the Mark III core of the Experimental Breeder Reactor (EBR-I). It is the intention of the authors to present this work in a general manner which includes the salient details. Comprehensive reports on the various phases of this program are or will be available elsewhere for those who, for reasons of their own, may require information more detailed than that to be presented here.

INTRODUCTION

The EBR-I reactor is a liquid-metal (NaK) cooled reactor utilizing fast neutrons. It was designed for experimental purposes directed toward the promotion of further understanding of the principles of the fast breeder reactor system and to investigate the feasibility of certain ideas.(1) Among these were 1) the generation of useful electrical power, and 2) the breeding of fissionable material with a breeding ratio of unity or greater. Useful electricity was first produced in EBR-I in 1951; in the next four years 4000 megawatt hours of heat were produced, much of which was used to generate electrical energy consumed in plant operation. Experiments performed during this period showed that a breeding ratio of one is achieved with this design.

Two slightly different cores, namely Mark I and Mark II were used in this 4-year period. Both employed fuel elements which were essentially thin-wall (0.022 in.) stainless steel (AISI type 347) tubes each of which contained as fuel two 0.384 in. diameter, $4\frac{1}{4}$ in. long cylinders of highly enriched (93.5%) uranium.

*Argonne National Laboratory, Lemont, Illinois, U.S.A.

These were flanked top and bottom with natural uranium (blanket) cylinders of the same diameter so that the total length of blanket and fuel material was of the order of 20 in. Each rod was sealed at its bottom end by a suitably machined locating tip; at the top end by a by-pass section to which was fastened an appropriate handle. An annular clearance of 0.010 in. (per side) existed between the inner diameter of the stainless steel tubes and the uranium. Spacers centered and held the fuel in the tubes, thus guaranteeing an approximately uniform annulus. This annulus was filled with static NaK alloy to a point slightly above the top blanket slug in each rod. The NaK bonded the uranium to the jacket, permitting easier removal of heat by the dynamic NaK reactor coolant. In the Mark I core, two longitudinal ribs 120 degrees apart were located on the outer surface of each fuel tube adjacent to the fuel. When the rods were in position in the reactor the ribs were in contact or in near-contact with the outer surfaces of adjacent rods; thus each element was held firmly in place by its neighbors. No ribs were used on the fuel in the Mark II loading.

The reactor was found to be quite stable and essentially self-regulating when operated normally.(2) However, it was observed that although the overall temperature coefficient was negative, a prompt positive coefficient which was overcome by a slower negative coefficient was noted when the reactor was operated under certain conditions. A series of experiments to investigate these effects were planned as a last use of the Mark II (ribless fuel) core loading. A transient test run as a part of this group of experiments resulted in the melting of many of the fuel elements in the core, preventing completion of the test program.(2,3) In the investigation of the core meltdown it was postulated that melting was the result of a prompt positive temperature coefficient probably caused by simultaneous bowing of the rib-less fuel elements toward the core center.

To demonstrate and to investigate the stability of EBR-I, a third core loading, namely Mark III was designed.(2) In this design lateral bowing of the fuel and/or blanket elements, either in groups or singly is essentially eliminated by means such as clamps which encircle the core at the sides, spacing ribs on the rods, and expanders which tighten rod clusters (assemblies). To prevent bowing of the individual fuel slugs within their jackets the NaK-filled uranium-to-jacket annulus present in the Marks I and II designs was eliminated. The NaK bond was replaced by a solid phase metallurgical bond, necessitating the substitution of Zircaloy-2 for the stainless steel formerly used as cladding.

<u>Fuel Rods</u>

The fuel rods (Fig. 1) each consist of three uranium-2 w/o zirconium alloy cylinders, 0.364 in. in diameter, arranged in line on a common longitudinal center. They are clad with and metallurgically bonded to Zircaloy-2

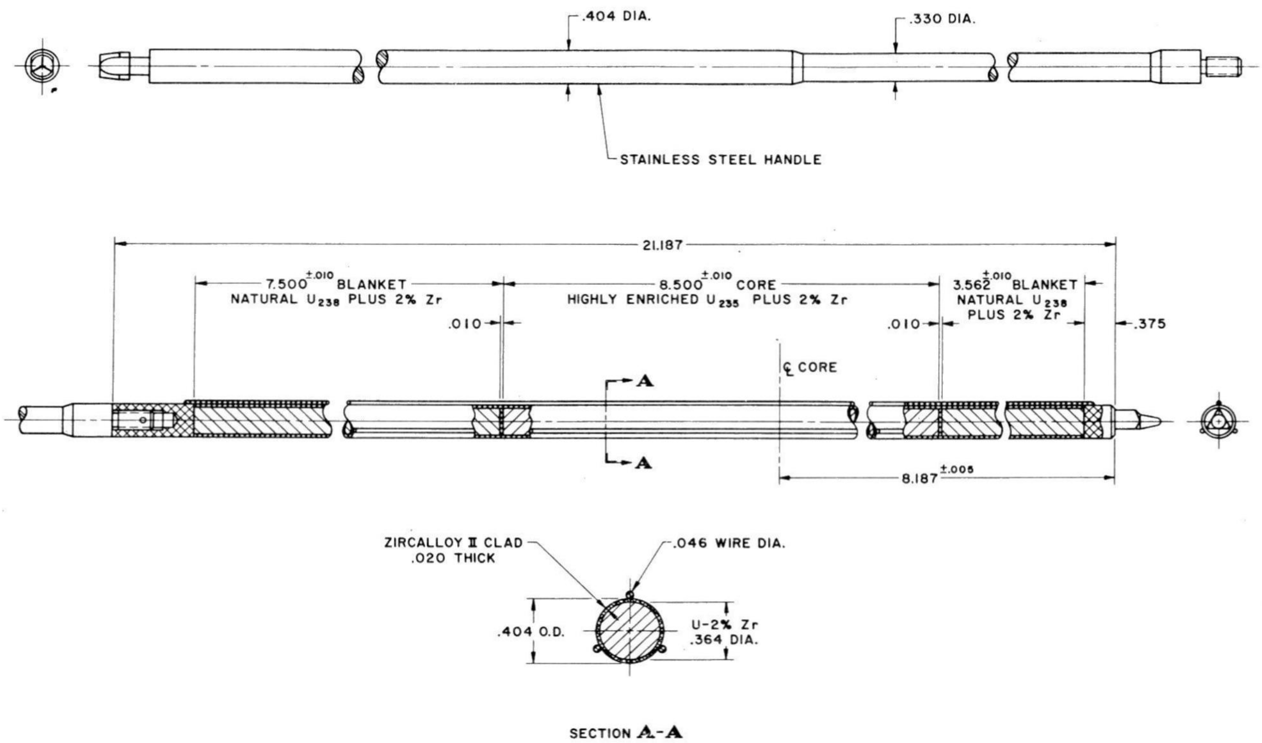

Fig. 1. Fuel Rod EBR-I, Mark III

cladding 0.020 in. in thickness. The top and bottom sections respectively, 7.750 and 3.562 in. long, contain natural uranium only. These act as blanket material above and below the 8.500 in. long, highly-enriched uranium containing fuel section. A 0.010 in. thick zircaloy spacer at each end of the fuel separates the fuel from the blanket sections. At the bottom end, the uranium is sealed by a Zircaloy-2 tip having a machined triangularly-shaped section which locates and orients the rod when in the reactor. The uranium is sealed at the top end by a short section of Zircaloy-2 which is drilled and tipped to receive a type 304 (AISI) stainless steel handle which also serves as part of the upper shield. This handle, after being screwed in place, is locked by pinning. Three zirconium-wire spacing ribs, 0.046 in. high, spaced 120 degrees apart are fixed to the rod perimeter by spot welding at 1/4 in. intervals along the length of each rib. To provide maximum mechanical strength the uranium-bearing and zircaloy components are metallurgically bonded throughout a minimum of 80% of the adjoining area at each joint interface. Note (Fig.1) that all dimensions are stated in decimals, an indication of the micrometric precision required in the manufacture of fast reactor hardware.

Maximum capacity of the reactor core is 252 fuel rods comprising a total of 60 kg of enriched uranium.(2)

Blanket Rods

The design of the uranium-bearing section of the blanket rods is identical to that of the fuel rods except that no fuel section is required. Thus each rod is made up of one 19.852 in. long section of Zircaloy-2 clad normal uranium - 2 wt. % zirconium alloy. Stainless steel handles of two different lengths were made; rods with short handles are used in the blanket assemblies; handles of the same length as those on the fuel rods are used on blanket rods placed in the fuel zone in positions not occupied by fuel rods. Capacity of the blanket zone in the reactor is 432 rods. A total of 561 rods were made to provide a suitable number of spare rods if needed.

Fuel and Blanket Assemblies

To provide rigidity as part of the Mark III core concept, the fuel and blanket rods in groups of 36 are contained in 0.040 in. thick stainless steel hexagonal tubes (Fig. 2) to form assemblies.

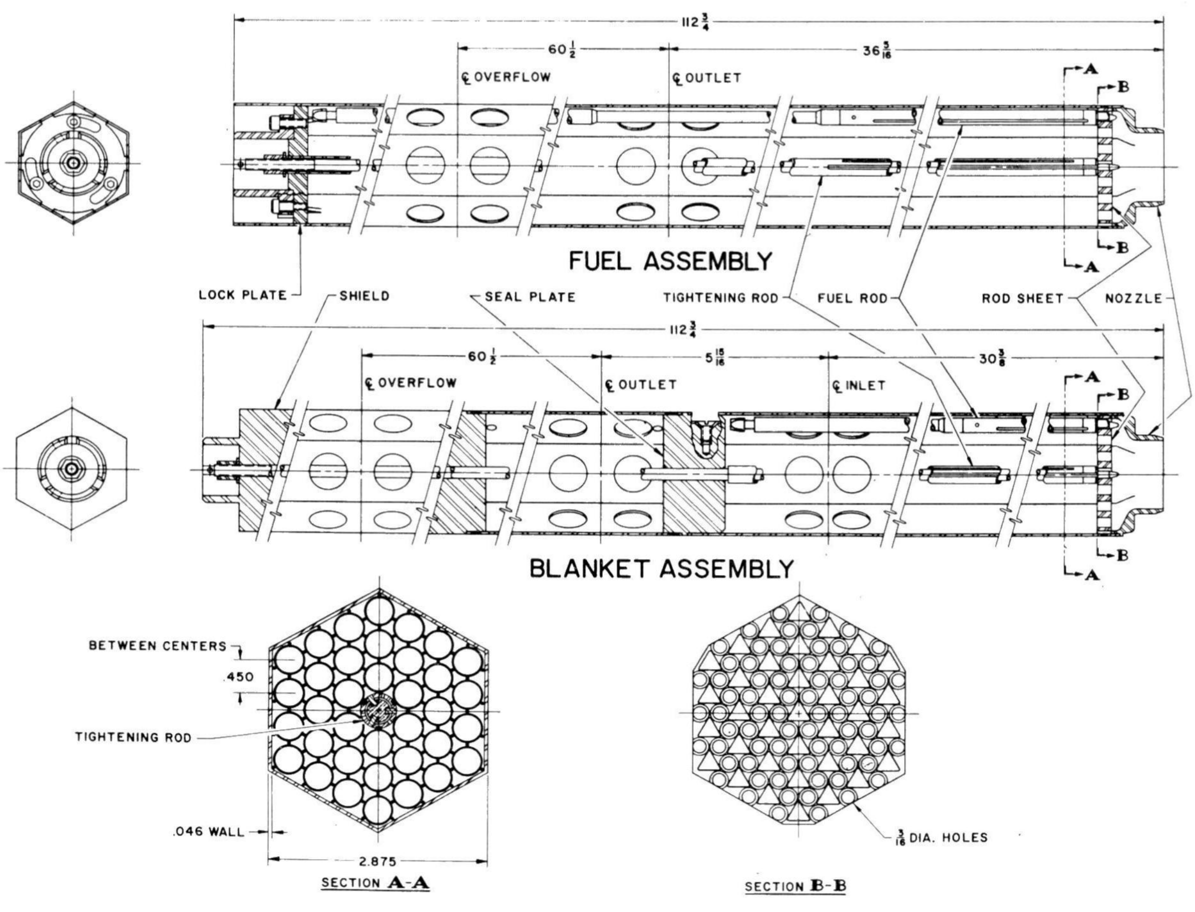

Fig. 2

A tightening rod is located in the center of each of these assemblies. This rod is fitted with a series of movable wedges which are made to move out against the neighboring rods thus tightening the entire group. It is obvious that very close control of all radial dimensions and straightness is necessary if mechanical tightness is to be achieved. For example, it was noted that if the rod diameters in a single cluster exceeded specified tolerances by 0.001 in., the accumulated error made impossible the assembly of the last rod. It is believed that this description of the fuel and blanket assemblies is sufficient for purposes of orientation. A fuller description, if desired, may be found elsewhere.(2)

MANUFACTURING PROCEDURE

General Description

In general, manufacture of the subject rods involves first the making of Zircaloy-2 clad, uranium-2 wt.% zirconium alloy rod by co-extrusion. To circumvent the end effects common to co-extrusion, the clad rod is extruded in long lengths. These contain uranium alloy in which the uranium is either normal (blanket) or highly enriched in U^{235} (fuel). The long lengths are next cut into the appropriate shorter lengths for incorporation into fuel rods or blanket rods by assembly with the required zircaloy components. Integration of these into rods is achieved by first welding to seal each joint at the rod perimeter (jacket) followed by high frequency electric induction heating to bond the uranium alloy to the Zircaloy-2 by fusion. This produces a rod of high mechanical strength capable of supporting a tensile load of 8500 to 11,000 lb.

The bonded rods are next heat treated and straightened, the end fittings machined, and are centerless ground to size. Spacing ribs are then spot welded in place semi-automatically, followed by a few machining operations to size the ribs and finish the locating tip. To complete the rods, an appropriate handle is fastened to each at its top end, all dimensions are re-checked, and the rod is ready for use in an assembly.

Production of U-2 wt.% Zr Alloy Billet Cores

Two sizes of extrusion billets are used for the extrusion of these rods. The weight limitations imposed by criticality considerations and the capacity of the available furnaces fixed the size of the enriched billet core at 5 kg. This is an appropriate core weight for a 2 in. diameter billet. The size of the natural uranium billets, limited only by the size of the extrusion press available, is $2\frac{3}{4}$ in. in diameter. This is close enough to the 2 in. diameter billet in size to allow extrapolation of known procedures and yet large enough to reduce appreciably the number of natural uranium billets required.

Extrusion billet cores are machined from vacuum induction melted, alloyed, and cast material. Two sizes of cores are desired, 1.653 in. diameter x $7\frac{1}{2}$ in. for the 2 in. diameter billets and 2.322 in. diameter x 7 in. for the $2\frac{3}{4}$ in. billets. In addition the 1.653 in. diameter cores are made of two enrichments, uranium enriched to 93.5 wt. % U^{235} and normal uranium. The smaller cores furnish material for the fabrication of fuel elements whereas the larger cores furnish material for blanket elements. The smaller normal cores provide fuel blanket material; i.e., the blanket slugs to be welded to either end of the fuel slugs. This gives a historical similarity to the three slugs comprising a fuel element and also allows the enriched material to be piloted on the normal.

To avoid the accidental accumulation of a critical mass the enriched core castings are made individually in a 5 in. I.D. Vycor tube vacuum induction furnace. The charge, which consists of broken pieces of uranium reduction buttons and zirconium wire, is limited to 5 kg by the capacity of the crucible used. Wire is preferred because it can be attached to the stopper rod and held submerged until thoroughly wetted by the molten uranium. Improved wetting results in faster dissolution.and increased recovery of alloy.

A conventional bottom pouring technique is used wherein the crucible rests above the mold and the melt is poured by lifting a central stopper rod. A $3\frac{1}{4}$ in. I.D. x $3\frac{3}{4}$ in. O.D. x $8\frac{1}{2}$ in. tapered bottom crucible, a 1/2 in. thick crucible cover, and a 1/2 in. diameter stopper rod are used, all made of high purity magnesia. A split-type graphite mold held together by graphite compression rings at top and bottom is used. The body of the mold is a $3\frac{3}{4}$ in. O.D. x 11 in. cylinder containing a $1\frac{3}{4}$ in. diameter x $8\frac{3}{4}$ in. cylindrical cavity. Its top and bottom are tapered to accommodate the compression rings. The 1 in. diameter sprue hole is counterbored to a depth of 3/4 in. creating a shoulder to support a 0.005 in. thick uranium foil disc. This disc prevents magnesium vapors liberated by the reduction of magnesia by molten uranium from condensing inside the mold but offers little resistance to the passage of molten metal. All molds are coated with a mixture of 98 wt. % thoria and 2 wt. % zirconia powders suspended in water and dried 4 hours at 175° C before using. This wash prevents mold attack and aids casting removal.

Core castings for the 2.322 in. diameter cores are also made by vacuum induction melting and casting; however, they are poured in multiples from heats in the 185 kg size. Melting is done in a $14\frac{1}{2}$ in. O.D. x $12\frac{1}{2}$ in. I.D. x $13\frac{1}{2}$ in. deep graphite crucible coated in turn with magnesium zirconate and thoria. The charge consists of uranium biscuit and zirconium sponge with the sponge placed below the uranium to achieve maximum wetting. Melts are bottom poured by means of a graphite stopper rod into an eight-cavity solid graphite mold coated with magnesium zirconate. Each casting is of sufficient length to yield two 7 in. long billet cores.

A typical melt cycle consists of taking the melt to 1525° C in a period of $2\frac{1}{2}$ hours and holding for 1 hour while the alloy dissolves. The melt is cooled to 1125° C, solidifying it in the crucible, and then heated to between 1400° C and 1425° C for pouring.

The core castings made individually in the 5 in. diameter tube furnace, because of their smaller mass and cross section, cool relatively fast and have uniform structures conducive to the formation of a smooth core-clad interface on extrusion. The larger castings made in multicavity molds have a range of structures including a very large grained top. On extrusion a core-clad interface is generated which is very rough and leads to large variations in cladding thickness and core diameter. To alleviate this situation it is necessary to heat treat the large castings. An isothermal quench from the gamma phase is effective. Castings are heated to 790° C in salt and quenched in lead at 500° C. Quenching into baths at temperatures below 400° C produces cracking; however, quenching into lead at 500° C does not affect the soundness of the casting and produces a structure ultimately yielding a satisfactory core-clad interface. All cores are finished by turning.

Production of Zircaloy-2 Cladding and Jacket Components

Each 2 in. diameter billet requires a Zircaloy-2 cladding sleeve 1.860 in. O.D. x 1.658 in. I.D. x 8 in., two Zircaloy-2 end seals 1.653 in. diameter x 1/4 in., a Cu-10 wt. % Ni internal nose plug 1.860 in. diameter x 1/4 in., and a Cu-10 wt. % Ni internal cut-off plug 1.860 in. diameter x 1 in. Each $2\frac{3}{4}$ in. diameter billet requires a Zircaloy-2 cladding sleeve 2.610 in. O.D. x 2.327 in. I.D. x 7 in., a Cu-10 wt. % Ni internal nose plug 2.610 in. diameter x 1/2 in., and a Cu-10 wt. % Ni internal cut-off plug 2.610 in. diameter x 1 in. All are made from extruded bar stock or tubing and finished by turning. Jackets for the 2 in. diameter billets are made from 2 in. O.D. x 16 gage seamless deoxidized copper tubing while jackets for the $2\frac{3}{4}$ in. diameter billets are made from 2.750 in. O.D. x 2.620 in. I.D. tubing drawn from 3 in. O.D. x 16 gage seamless copper tubing. Front end plugs for both types of billets are drawn from 16 gage copper discs and rear end plugs machined from 1/4 in. thick deoxidized copper plate. Each rear end plug is fitted with a 1/4 in. O.D. seamless copper tube for evacuation of billets. Prior to billet assembly all Zircaloy-2 components are pickled in boiling nitric acid containing 1/2 to 1% HF and all copper containing components in nitric acid.

Assembly and Evacuation of Extrusion Billets

After the billet components are prepared the extrusion billets are assembled and the end plugs sealed by welding. The billets are then connected to an evacuation chamber, operated at an absolute pressure in the 10^{-5} mm range, and evacuated overnight. While connected to the manifold the billets are heated to 100° C for outgassing and then sealed. Sealed billets are shipped to Nuclear Metals, Inc. for extrusion.

Extrusion of Billets into Clad Rods

When the billets are received by Nuclear Metals the evacuation tubes are reopened, the billets re-evacuated, outgassed, and resealed. The billets are heated to 650° C for extrusion thru plane circular dies to 0.453 in. diameter rods. The reduction in area for the 2 in. diameter billets is approximately 20:1 and for the $2\frac{3}{4}$ in. diameter billets 40:1. The rods are extruded 0.010 in. oversize in diameter to provide stock for swaging to diameter. The cladding is extruded 0.002 in. over the nominal 0.020 in. finish thickness to provide stock for clean up of the finish assembled fuel and blanket rods.

Processing of Rod for Fuel and Blanket Assemblies

After extrusion the rods are returned to ANL for final processing. The initial operation is the removal of the copper jacket by immersion in 50 % nitric acid. The rods extruded from 2 in. diameter billets are stripped directly. This is possible since the uranium alloy core is completely enclosed in Zircaloy-2. Rods extruded from $2\frac{3}{4}$ in. diameter billets are not stripped directly because the core alloy is not completely enclosed in Zircaloy-2. Therefore, the unclad ends are removed and Zircaloy-2 end caps are heliarc welded to each end of the rod. After sealing, these rods are stripped of copper by immersion with minimum danger of explosion from contact between nitric acid and the 2 wt. % zirconium alloy core.

The stripped rods are then swaged to a diameter which results in a core diameter of 0.364 in. $\pm$ 0.004 in. It is necessary to submit all completed elements to a heat treatment designed to increase their dimensional stability under irradiation. To minimize dimensional changes of the elements during the final heat treatment, it is necessary to produce an equi-axed core structure after swaging. Therefore the swaged rods are given a transformation heat treatment to remove the oriented structure resulting from extrusion and swaging. The heat treatment consists of heating the rods to 800° C in an evacuated bomb and cooling the bomb in air. Significant dimensional changes do occur during this treatment and in most cases swaging and heat treatment need to be repeated.

The amount of scrap cut from the lead end of a rod is determined by measuring the cladding with an Eddy-Current Cladding Thickness tester. The length of the extrusion defect is measured by Co^{60} radiography. After the undesirable material is removed from both ends, rods are cut and machined to appropriate lengths for fuel, fuel blanket, and blanket slugs. The individual slugs are straightened and their ends polished in preparation for assembly into fuel and blanket elements.

Clad Welding

The various lengths of rod sections necessary to form a fuel or blanket element are initially welded at the Zircaloy-2 jacket by specialized inert gas tungsten arc equipment specifically conceived and built for that purpose. The various rod components, including solid Zircaloy-2 end caps, clad uranium stock and Zircaloy-2 disk separators are shown in Fig. 3. Prior to welding all butting interfaces are electrolytically etched in a perchloric-acetic acid electropolishing solution which preferentially removes the uranium alloy core to an approximate depth of 5 ten-thousandths of an inch, thereby providing for intimate contact between jacket portions during subsequent joining operations.

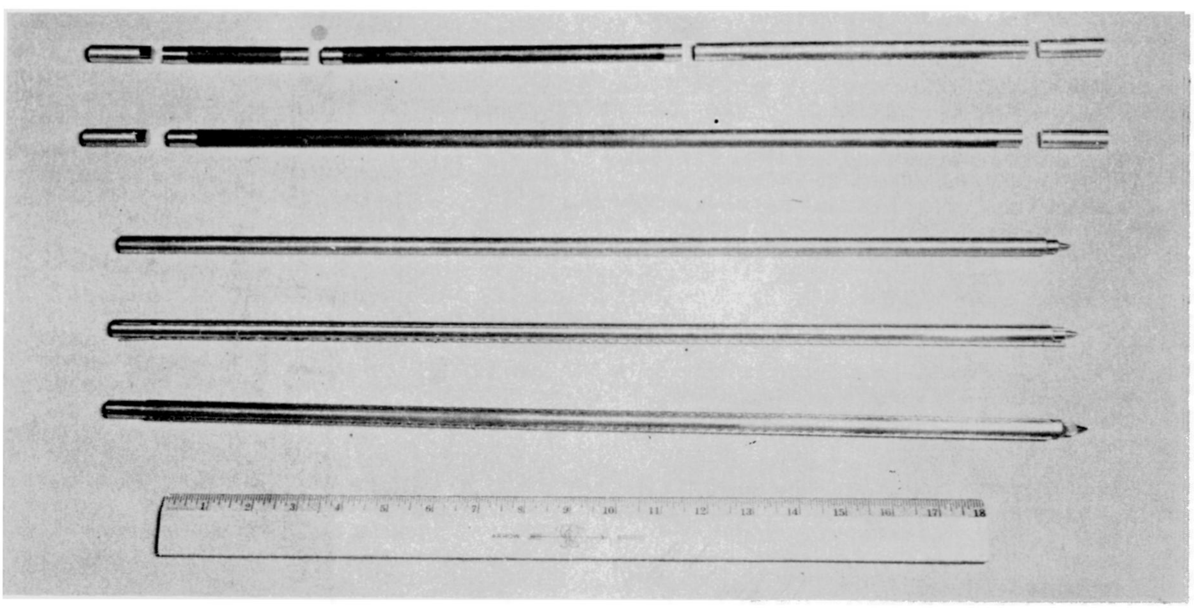

Fig. 3. EBR-I, MARK III, Rods in Various Stages of Manufacture

A minimum clad penetration of 70% was arbitrarily chosen to assure adequate restraining forces and leak tightness to retain the molten uranium which is produced during the subsequent core bonding process. This penetration could not be reliably attained in a single pass weld but was achieved by a double pass procedure, where a first pass with a relatively high welding current was immediately followed by a second pass at a reduced welding current. The second pass did not fuse as deeply as the first, but supplied sufficient additional heat to the already preheated rod, to raise the temperature of the internal portions of the rod sufficiently to produce solid diffusion between the unfused portions of the Zircaloy-2 clad.

The inert gas tungsten arc equipment developed for the clad welding process is shown in Fig. 4. Basically the equipment consists of a lathe type, rotating mechanism coupled to a direct current welding current power supply with adequate electronic control circuits to provide the following automatically controlled sequences.

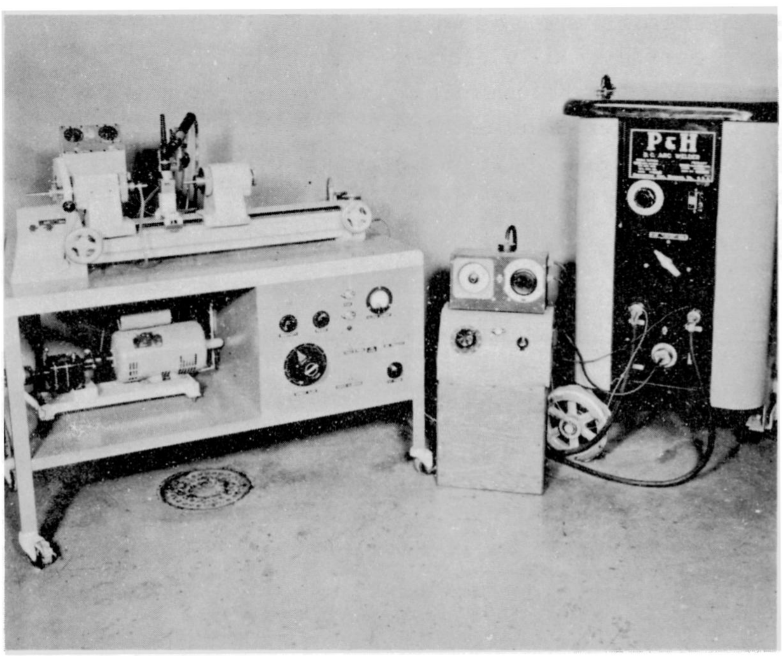

Fig. 4

Inert Gas Tungsten Arc Welding Equipment.

1. An inert gas purge cycle initiation, which purges the joint interfaces prior to mechanical abutment, and purges the dynamic flow type shield for a pre-set time prior to arc initiation.

2. Arc initiation by means of a superimposed high frequency, high voltage power supply. During arc starting interval, rotational sequences are interlocked "out" until the arc has become fully stabilized.

3. A preheat cycle, with no spindle rotation, may be incorporated to assure that mating interfaces are bridged with molten metal prior to rotating. Preheat current may be pre-selected to differ from welding current.

4. Rotation of the rod under the electrode is commenced automatically. The rotational speed is electronically varied to compensate for increasing residual heat within the rod as the rod revolves under the electrode. Rotational speeds are variable as much as 4 to 1 in 360° rotation of the spindle.

5. After 450° of arc rotation, a current decay cycle is initiated for crater elimination. Current decay time and degree is controlled by the time constant associated with the discharge of an inductive saturable reactor across a variable resistance.

6. A post weld gas purge cycle is incorporated to provide protection to weld area during "cool down" time.

The shielding gas used was helium with sufficient argon (~ 20 v/o) added to assure reliable arc stability. A 2% thoriated tungsten electrode was used in preference to straight tungsten to give better arc stability and starting characteristics.

All joints are maintained under mechanical pressure during welding to allow slight clad upset to occur, providing intimately contacted surfaces desirable for solid diffusion. Filler metal is not required since accurate joint fits and mechanical upset are sufficient to maintain dimensions within required tolerances.

The complexity of the clad welding process is realized when the melting point of the low heat capacity uranium alloy core (~1200°C) is compared to the higher melting point and higher heat capacity of the 0.020 in. thick Zircaloy-2 clad (~1700° C). Very little, if any, core melting may be tolerated during the clad welding operation since dilution occurs rapidly, rendering the rod unsuitable for subsequent operations.

<u>Cross-section Bonding</u>

After the rod sections and end plugs are welded at the Zircaloy-2 clad, the elements are subjected to a bonding process at the joints to increase the mechanical strength of the elements. The equipment used for core bonding is shown in Fig. 5.

The core bonding process consists of inserting the element through a single turn induction coil where each joint is heated to melt the uranium alloy core, producing a bond between the core and Zircaloy-2 end fittings or disc separators. Melting of the Zircaloy-2 does not occur during the bonding process. Bond strengths (tensile) higher than the ultimate tensile strength are consistently obtained. Protection from atmospheric contamination is accomplished by containing the elements within a Vycor tube, through which a continuous flow of helium is maintained. The induction heating power supply is a 20 KVA, 450 KC unit operated at maximum output. The skin heating effect obtained by the use of a relatively high frequency power supply produced the desirable effect of preferentially heating the Zircaloy-2 clad to a temperature somewhat higher than what would be produced in the core, thereby further improving the solid diffusion bond at the Zircaloy-2 interfaces.

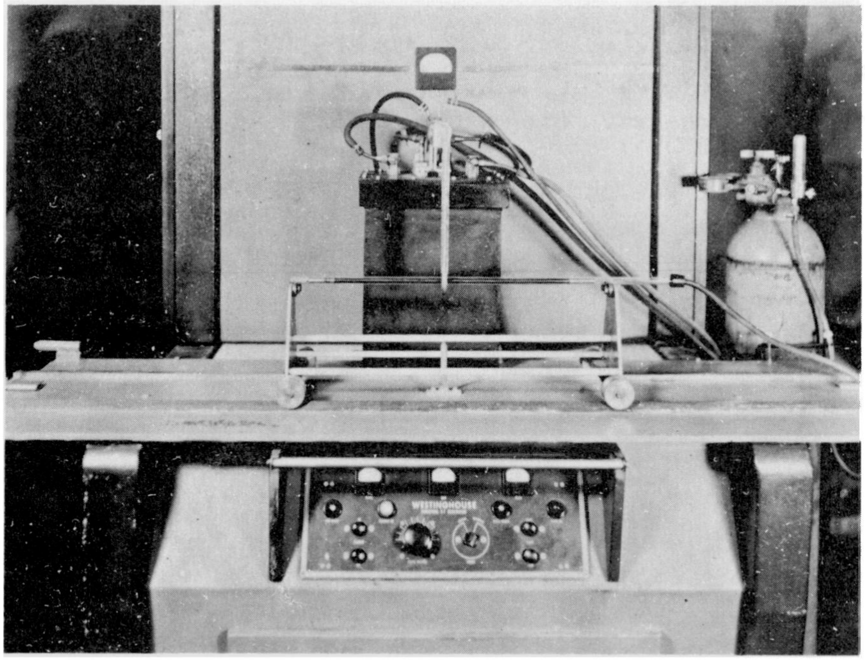

Fig. 5. Core Bonding Equipment

Sufficient pressure to minimize voids at the bonding surfaces was produced by the relatively positive coefficient of thermal expansion of the uranium alloy as compared to that of the Zircaloy-2 cladding.

Maximum power output accompanied by a short time heating interval and the use of a single turn coil served to reduce the width at the heated zone to a minimum.

Heat Treatment

Upon completion of the bonding process the integrally joined rod elements are subjected to a number of operations including ultrasonic bond testing, heat treatment., straightening, machining and grinding, and a final testing prior to having spacing ribs attached.

The initial test given at the completion of the bonding sequence consists of visual inspection for uranium leakage at the joint areas, followed by a non-destructive bond quality test on an ultrasonic tester utilizing the reflection principle. Rods which failed to pass inspection were recovered by recycling to the appropriate stage of the fabrication sequence.

After testing the elements were heat treated by a procedure intended to impart maximum resistance to irradiation damage to the rods. The heat treatment consisted of a 15 minute soak in lead at 800° C followed by a 1 hour isothermal quench in 690° C lead after which the rods were air cooled, de-leaded and straightened.

A rather rigid overall diameter tolerance was maintained by centerless grinding, the elements after the straightening operation. After grinding the end caps are machined to the required shape but the triangular section is not machined on the locating tips.

The final tests after machining are a bond continuity recheck followed by eddy-current measurement of the cladding thickness after centerless grinding.

Spacing Rib Attachment

Each completed rod is provided with three longitudinal spacing ribs, placed at 120° intervals around the periphery of the jacket. The ribs, in the form of 0.056 in. diameter zirconium wire, are automatically spot welded at 1/4 in. spacing. All three ribs are fastened in a single set-up. The necessary equipment for spot welding the ribs is shown in Figs. 6 & 7.

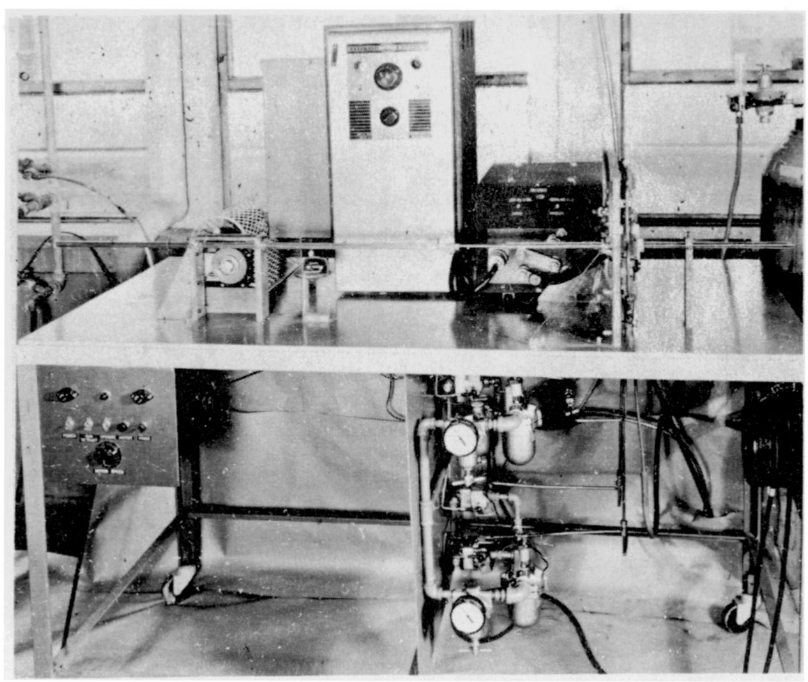

Fig. 6. Rib Spot Welding Equipment

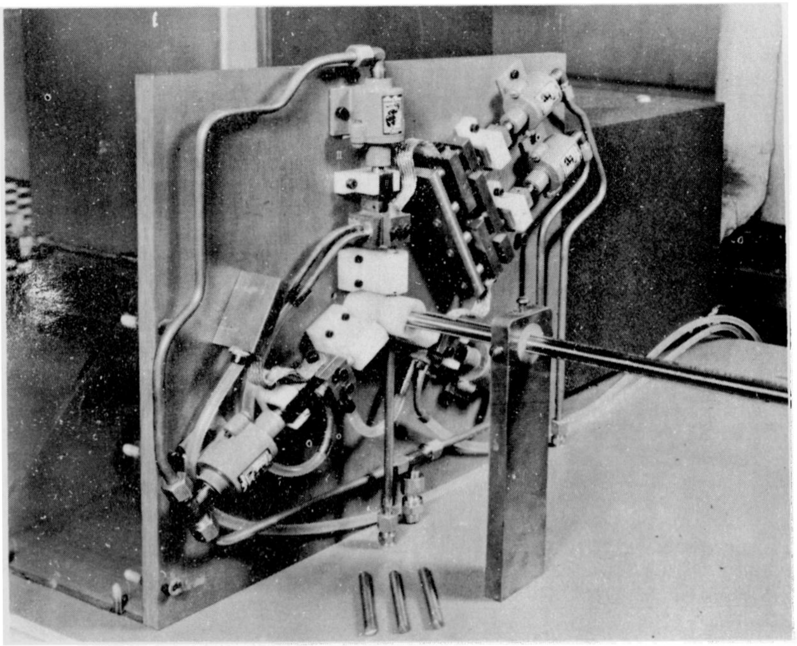

Fig. 7

Spot Welding Electrode Arrangement.

Welding current is supplied by the discharge of high voltage capacitors across the primary of a step-down welding transformer. Approximately 400 watt-seconds of energy may be introduced into a weld in less than 10 milliseconds. The charging voltage of the capacitor is variable with a maximum of 1500 volts.

Three air operated, water-cooled, copper electrodes are utilized. The electrodes are positioned radially about the rod at 120° rotational spacing (Fig. 7). Individual spot welds are made with one electrode active while the remaining two act as a ground. Polarity changes of electrodes is accomplished by air operated switches.

Rib spacing is maintained by the linear movement at rod and ribs through a nylon guide. The nylon guide is also counter-bored and supplied with helium gas to serve as an atmospheric shield around the weld area.

The mechanism supplying an intermittent linear motion to the rod is also coupled to a series of rotating electrical switches such that electrode position, polarity, and firing sequence occur in relationship to rod position.

Manual operations consisted of the insertion and initial positioning of rod and ribs in nylon guide, correction of liner drive, actuation of automatic sequence and the final removal of the completely welded rod. Final machining of the ribs to assure accurate diametral spacing was done on a shaper.

Final Operations

After welding, the ribs are first clipped to length and then machined to a height of 0.046 in. by machining, one at a time, on a shaper. Following this, the triangular section on the locating tip is milled while being held in a fixture which is located on the spacing ribs, thus guaranteeing the desired precise relationship required for correct rod orientation when loaded. The last operations are those wherein the handles are screwed in place and pinned so that accidental loosening is impossible.

ACKNOWLEDGEMENTS

The authors would like to acknowledge their gratitude to all of the members of the ANL staff and Central Shops organization for their help and cooperation in this work. We are especially grateful to Messrs S. Matras, D. E. Walker, R. Salley, W. R. Burt, N. J. Beck, W. J. McGonnagle, and L. C. Hymes of the ANL Metallurgy Division. We are also indebted to the personnel of Nuclear Metals, Inc., Cambridge, Massachusetts for their help in designing the extrusion billets and for the excellence of their extrusions.

REFERENCES

1. Lichtenberger, H. V., et al., Operating Experience and Experimental Results Obtained from a NaK-Cooled Fast Reactor, Geneva Report - A/Conf. 8/P/813 Rev. 1, July 18, 1955.

2. Rice, R. E., Curran, R. N., et al., EBR-I, Mark III - Design Report, ANL-5836, March 1958.

3. Kittel, J. H., Novick, M., Buchanan, R. F., EBR-I Meltdown, - Physical and Metallurgical Changes in the Core, ANL-5731; November 1957.

- - - - -