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DEVELOPMENT OF A PROCESS FOR SODIUM BONDING
OF EBR-II FUEL AND BLANKET ELEMENTS

by

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DEVELOPMENT OF A PROCESS FOR SODIUM BONDING OF EBR-II FUEL AND BLANKET ELEMENTS

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I. INTRODUCTION

The EBR-II fuel element was designed as a high-performance unit to be used in a sodium-cooled reactor core. As a consequence of the severe demand placed upon such an element during its anticipated exposure in the reactor, it is understandable that the elements produced must exhibit a high degree of perfection. This is particularly true of the annular sodium bond which serves as a path by which heat is conducted from the uranium rod to the stainless steel cladding, which in turn transmits the heat energy to the flowing coolant. Table I summarizes the characteristics of the EBR-II fuel element.

Table I⁽¹⁾

SPECIFICATIONS FOR THE EBR-II FUEL ELEMENT

Fuel type	rod
Alloy	5% cast "fissium"
Rod diameter	0.144 in.
Rod length	14.22 in.
Bond	Sodium
Annular width	0.006 in.
Cladding	Type 304 Stainless Steel
Cladding thickness	0.009 in.
Maximum central metal temperature	715°C (1320°F) at full power
Burnup	2% of total atoms

The level of the sodium extends to 0.600 in. above the top of the uranium rod, and a small volume of gas is situated above this level. The element is completely sealed by a weld made at the top cap.

Irradiation tests have shown⁽²⁾ that, at the temperature and burnup considered for the EBR-II element, diametral expansion of the fuel will result in displacement of the sodium from the annulus into the gas volume.

Obviously, since the heat flux conducted across the annulus is high and the tolerances quite restrictive, the quality of the bond must be very high to prevent the generation of excessive temperatures in the uranium.

As a consequence, the acceptance requirement for an element is the absence of any void equal to or greater than $\frac{3}{16}$ in. long by $\frac{1}{16}$ in. wide. This is the minimum void that will cause excessive fuel temperature, according to calculations.

Basically, the achievement of satisfactory bonding requires the accomplishment of two conditions: the first is to fill the annulus sufficiently with sodium to a specific level, and the second is to "wet" the contact surfaces with the liquid metal. In the actual process, the second step can be easily attained by heat treatment of the element for several hours in the range from 450°C to 550°C.⁽³⁾ However, in the processes actually tried, frequently the two steps were carried out coincidentally.

II. PROCESS REQUIREMENTS

The operations required in the process for assembling and bonding the EBR-II fuel element are listed as follows:

a) Measure the required quantity of sodium and insert into tubing used as the cladding. For the EBR-II fuel element this step was carried out by the extrusion of sodium in cylindrical form to some diameter smaller than the tube ID. The extrusion is then cut to the desired length and weighed to assure that the proper quantity is present. The sodium cylinder finally is inserted into the cladding tube which has had its bottom fitting welded in position to effect a bottom closure. Figure 1 is a photograph of the type of extruder used in this operation.

Fig. 1. Sodium Extrusion Apparatus

b) Meltdown of the extrusion is conducted within the fuel tube. This operation is generally carried out on a cluster of tubes simultaneously. The tubes are placed in a cylindrical vacuum furnace (shown in Fig. 2) under an atmosphere of argon. The pressure in the furnace is lowered to approximately one-third of an atmosphere and the tubes are heated to 150°C . Under these conditions, the sodium melts and flows into contact with the tubing wall. The lowered pressure encourages the release of gross quantities of gas which may be entrapped by the sodium. After ten minutes the argon pressure in the furnace is raised to one atmosphere and the furnace temperature to 550°C . A ten-minute exposure to this temperature insures a sodium-wetted region for a few inches upward from the bottom of the tube.

Fig. 2
Sodium Meltdown Furnace

c) The tubes are removed from the furnace, cooled to room temperature, placed in a bonding fixture, and the uranium fuel rods inserted into the magazine fixture (see Fig. 3). At this time, the fuel projects a short distance above the lip of the tube as it sits with its lower end in contact with the frozen sodium. The magazine containing a number of these loaded tubes is placed upon the settling furnace shown in Fig. 11. In this furnace, the internal heater projecting into the interior of the heating fixture raises the temperature of the fuel and container above the melting point of sodium. During this heating process, the entire fixture and the fuel elements are subjected to a 60-cycle vibration imparted by an electromechanical vibrator situated below the furnace pedestal. This procedure results in the settling of the uranium to the bottom of the fuel can with consequent displacement of the sodium upward into the annulus. However, innumerable tests have shown that the upward

annular flow of sodium is not uniform, but tends to flow in preferred channels, leaving pockets of entrapped gas and large unbonded areas. This may be partially due to nonuniform wetting or to nonuniform pressure drop because of nonconcentricity, producing an eccentric annular section⁽⁴⁾ or a combination of the above factors.

Fig. 3. Fuel Element Magazine with Uranium Loading Magazine in Position.

d) After the settling process is completed, the top cap of the element is inserted in position and welded closed.

e) With the tube closure effected, the leak integrity of the sealed unit is determined with the leak-detection equipment, and the element is then subjected to the bonding operation. The present process consists of holding the element at 550°C for 4 hr with simultaneous application of vertical 60-cycle electromechanical vibration. This process will be described in greater detail later in this paper. Following the heat treatment, the elements are cooled to room temperature by an air blast which is deliberately tailored to freeze the annular sodium progressively from bottom to top. This procedure is necessary to eliminate freezing voids which appear as non-bonded sections in subsequent nondestructive examination.

f) The completed elements are subjected to an eddy current nondestructive test to determine acceptability. In this test, the element is slowly drawn through a high-frequency annular coil which is part of an electronic oscillator circuit. The interaction of the fuel element components with the electromagnetic field of the coil affects the output of the oscillator. The amplified output, in turn, controls the reading of a rapid-response recorder on which the signal variations are traced. The recorder speed and the element traverse are stepped in some ratio to allow correspondence of position with signal variation. Upon comparison of the trace produced by the element in question with the traces produced by prepared standards, it is possible to determine the acceptability of the fuel element bond.

g) The accepted fuel elements are loaded into an EBR-II sub-assembly in a hexagonal cluster of 91 elements contained in a hexagonal can, as shown in Fig. 4. In the fuel-cycle facility, this operation will be carried out remotely with apparatus similar to the Prototype shown in Fig. 5.

Fig. 4. EBR-II Fuel Subassembly

Fig. 5

Remote Assembly Machine for
the EBR-II Subassembly

III. EXPERIMENTAL PROGRAM

A few years ago the program for developing the reassembly process was undertaken at ANL. The aims of the program were to consider various approaches to the problem and to determine the effectiveness of each of these approaches with respect to application to the demands of remote assembly at the EBR-II fuel-cycle facility. The initial steps of the process were relatively simple from the mechanical-handling approach. Such steps as the extrusion of sodium and its insertion into the empty tubes could be carried out in an unshielded area, since radioactive materials were not involved. It was decided that these initial loadings would be conducted in a glovebox under a purified argon atmosphere to protect the sodium from contact with air.

A. Meltdown Experiments

During initial exploratory experiments on bonding, the appearance of troublesome and large unbonded areas at the base of the fuel pin suggested that large pockets of argon were being entrapped at the bottom of the fuel can during the initial meltdown of the sodium extrusion. When the cylinder melted and the uranium settled, the sodium flowing upward in the annulus would entrap the gas, forming the large void. The obvious solution considered was to perform the meltdown operation under a high vacuum. This was tried, but did not solve the problem for two reasons. First, any gas trapped under or in the sodium expanded so rapidly in the small annular volume that its linear velocity was very high. This would invariably result in the deposition of sodium upon the upper lip of the tube. Once deposited, this sodium would disastrously impede the subsequent welding operation and force rejection of the element. The second reason was that invariably a large void would form during the settling process and would extend in a continuous channel from the bottom to the top, along the uranium. As a result, when the gas was readmitted, the void would again fill with the gas.

As a consequence of these observations, the use of vacuum was dropped and attention was directed toward a study of the meltdown of the extrusion in the tube. Several tests were conducted in which extrusions were melted in tubes, in vacuo, and under one atmosphere of argon. Radiographs made upon these tubes disclosed that, whenever the entrapped gas expanded under a bridge of sodium, a dome was formed which pushed slugs of the liquid metal upward along the tube interior. If permitted to freeze in this position, the sodium would remain in random positions, depending upon the quantity of gas entrapped. Actually, it was found that this quantity of gas was very small, so that the slugs could be driven back down to the bottom by raising the gas pressure back to one atmosphere.

These studies led to the adoption of the following sequence in the meltdown. First, the extrusion-containing tube is evacuated to approximately one-third atmosphere and the sodium melted. Following this, the inert gas pressure is raised to one atmosphere to drive the sodium to the bottom, and the temperature is then raised to 550°C for 10 min. The latter step insures wetting of the tube wall area in contact with the sodium.

B. Uranium-settling Experiments

With the meltdown procedure established, the next step was directed toward understanding the behavior of the sodium during the process of settling the uranium to the bottom of the tube. A number of experiments were devised to permit such a study. The first of these consisted of observing the settling, visually, by placing the sodium and uranium in a Vycor tube. This assemblage was simply placed in a furnace equipped with an observation port through which the progression of events could be viewed.

The second experiment was arranged so that the uranium could be lowered slowly and in a controlled fashion to the bottom of the stainless steel tube. In this latter instance, the settling could be conducted at temperatures as high as 550°C with all components adequately preheated.

Inspection of the bond was made after cooling to room temperature and stripping of the stainless steel cladding by peeling.

These experiments yielded information of fundamental importance to the process. The fact was that the sodium instead of rising uniformly in the annulus, preferred to rise along channels to the top of the tube. As a result, large unbonded areas were left along the element, and a very significant proportion of the sodium bond would be found residing atop the uranium pin after it had settled to the bottom. This information indicated that bonding would not be accomplished concurrently with the settling of the uranium unless rather complicated techniques and equipment were utilized. Consequently, the approach adopted required correction of the imperfect, unbonded element after settling and possibly weld closure were completed.

C. Bonding Experiments

With the method of attack established, the question remaining was: what process should be used to accomplish the objectives? The processes considered and tried are listed as follows:

1. furnace bonding;
2. submerged canning;
3. ultrasonic bonding;
4. centrifuging;
5. pressure pulsing; and
6. vibratory bonding.

All of these methods offered some promise on testing. Although they are not presented in chronological order, each will be discussed in the order listed.

1. Furnace Tests

Initially, it was hoped that the sodium could be induced to flow into the void space by holding the system at high temperature for a nonexcessive period of time. The time interval considered ranged from 2 to 48 hr at temperatures from 400 to 550°C. The furnace tests conducted did show improvement in bonding upon heat treatment, particularly at the higher temperatures. Typical results are shown in Fig. 6, which is a trace made with the nondestructive eddy current device after each step in the test. The upper curve was made after the element was heated in the furnace for

48 hr at 375°C. This curve shows a considerable improvement over the condition just before heat treatment, for at that time the curve was entirely out of the range of the instrument. The lower curve shows the same element after an additional 3 hr at 525°C, and we see further improvement. However, still further heating did not result in improvement of the element or removal of the void observed in the trace. These results were observed in many tests of the same type and demonstrated that the yield of suitable elements by furnace treatment would be too low for adoption as a process. The spectacular initial improvement when the element is subjected to the first heat treatment period is merely caused by the wetting of the wall by the sodium in contact. The yields for the tests of this sort were random and ranged from a high of 80% for a rare case down to 20%. The heating periods exceeded 3 hr in duration at temperatures above 375°C but below 550°C.

FIG. 6
EFFECT OF HEAT TREATMENT ON EBR-II ELEMENT

2. Submerged Canning

Another approach was to fill and preheat the stainless steel can and the uranium pin before assembly. An apparatus was constructed in which the stainless steel can, suspended vertically, could be submerged

under molten sodium while a vacuum was maintained over the sodium surface. Simultaneously, a uranium pin was submerged under the same surface. After this was completed, argon was admitted into the vacuum space above the sodium and the entire system raised to 550°C for 30 min. The fuel element was then raised from the liquid and permitted to cool to room temperature. Unfortunately, this bonding technique was not any more successful than the furnace method. The reason was that a channel void could form in this system and gas would still have access to the annular region. Further, the disadvantages of cleaning the excess sodium from the element and the difficulties of metering the proper quantity led to early rejection of this technique.

3. Ultrasonics

The effectiveness of ultrasonic energy in promoting physical effects in liquids in contact with surfaces led to a consideration of this form of energy as a bonding agent. The application of this method to the bonding of EBR-II elements, however, was beset with a number of difficulties. These difficulties resulted from the coupling of a transducer requiring relatively low temperatures to a fuel element which had to be maintained at a temperature near 500°C.

Several methods were tried. The most successful consisted of coupling the nickel core of a magnetostrictive transducer to the fuel element side via an exponential brass coupling. The broad end of the coupling was fastened, by brazing, to the top end of the nickel core. The entire assembly is shown in Fig. 7. The fuel element was heated electrically by passing a direct, low-voltage current longitudinally through the element. Bus connections were made at the top and bottom of the element via flexible cable connectors. The element was exposed to the ultrasonic energy by drawing it vertically across the narrow face of the exponential probe. In this manner, the ultrasonic energy was concentrated locally at the point of contact.

The ultrasonic generator used was a 2-kw, 20,000-cycle unit manufactured by Acoustica Associates. The transducer was capable of generating 400 acoustical watts per unit and had a laminated magnetostrictive nickel core which was water cooled. Teflon gaskets were used to contain the water in the cooling region, and the exponential horn protruded through this gasket as shown in Fig. 7.

The treatment of the fuel element consisted of raising the temperature by passing the current through its length and then drawing the element downward across the face of the probe. The drive which moved the element could be varied and permitted a very low linear speed. It required 15 to 25 min. to travel the entire length of the element. The pressure for contact was maintained upon the face of the probe by a spring-loaded backup wheel riding against the opposite side of the element.

The experimental results showed that yields from 60% to 80% could be expected. However, despite good yields, only one element at a time could be handled and the treatment time was relatively long. In addition, complexity of equipment and its susceptibility to radiation damage precluded its incorporation into the fuel-cycle facility. Consequently, this approach was dropped in favor of other methods.

4. Centrifuge Bonding

During some of the initial exploratory observations of behavior of the molten annular sodium in the Vycor tube mockups, it was seen that centrifugal forces produced a desirable effect. To further study this effect a special centrifuge was constructed. The laboratory model is shown in Fig. 8. The model was equipped with slip rings which permitted the application of power to heaters located in the two opposing buckets. The power could be applied simultaneously with rotation so that the elements could be heated to 550°C during rotation. Two fuel elements loaded in each basket were held in an insulated cavity with heaters wound about the outer periphery of the insulation. The procedure consisted of placing the fuel elements within the cavity, preheating them to 550°C for approximately 5 min, then initiating the rotation. The model used rotated at 1700 rpm and the extended baskets covered a diameter of approximately

3 ft. The heat was applied concurrently with rotation for 10 min then turned off. Rotation continued for about 10 min more. During the final rotation period, the elements would cool to room temperature and could be removed immediately when the centrifuge was stopped. The total time for a cycle amounted to a 5-min preheat, a 10-min spinning with applied heat, and a 10-min spinning with heating power off.

Fig. 8. Top End of Fuel Element Centrifuge

The results of many tests with the centrifuge disclosed that this method was the most spectacularly successful. Not only was it possible to bond freshly loaded elements with 100% yields, but also elements not adequately bonded in other processes could be reclaimed. An example of this is shown in Fig. 9. There the upper curve shows a trace of an improperly bonded element; the lower trace shows the same element after centrifuge treatment.

FIG. 9
CENTRIFUGAL VOID REMOVAL

When the cladding was stripped from the element it was seen to be free of voids. In a test run where 20 elements were bonded by another process with a yield of 80%, the 20% rejects were reclaimed with the centrifuge to yield 20 acceptable elements.

The centrifuge process was not selected for use in the fuel-cycle facility, however, since several disadvantages exist. The first involves the relative complexity and power requirement in such a device. Since remote operation and the possibility of contamination require a machine which is completely reliable, a simpler device would be preferred. Also, the high ambient gamma radiation poses many problems in the operation of a high-capacity, rotating electrical system. The second disadvantage is that repairs made upon the equipment would possibly have to be done remotely with considerable difficulty. Thirdly, the process does not lend itself to the treatment of elements having lengths substantially greater than the ~17.5-in. EBR-II element. Finally, the handling is limited to a relatively few elements at one time. These factors limit the use of the centrifuge to laboratory or out-of-cell processes.

5. Gas Pulsing

Early experiments demonstrated that voids tended to be reduced when the interior of the fuel element was subjected to an alternating gas-pressure pulsation. The theory supporting this effect is that the sodium above the wetting temperature is forced to greater coverage of the uranium and cladding surfaces bordering the void when the void is compressed. When the expansion part of the cycle occurs, the sodium does not retreat from the wetted areas, with the result that the void is deformed from its original configuration. The combined deformation and agitation imposed upon the system by the rapidly pulsing gas pressure eventually results in the detachment of the void from the walls. When this detachment is effected, normal hydrogravitational forces tend to move the gas pocket upward and out of the annulus.

The equipment for performing the tests is shown in Fig. 10. The apparatus consisted of a piston moving in a cylindrical chamber propelled by a rod connected to a rotating flywheel. This supplied the reciprocating motion to the piston. The motor was a dc unit powered by a control which permitted a wide variation in rotational speed. The pressure line entered the top of the fuel element chamber which, in turn, was heated with electrical heaters surrounding its periphery. A preset pressure could be introduced into the chamber before the run and the pressure modulated about this level as a nodal point. The parameters studied were pressure, pulsation amplitude, and pulsation frequency. Obviously, the fuel elements did not have the top plugs in position during the treatment. In all tests, the element

chamber was maintained at 550°C. The base-pressure settings used during the tests ranged from 5 psig to 23 psig. It was found to be undesirable to use a base pressure under one atmosphere, since the resultant bubble expansion would eject sodium from the element. The imposed pulse amplitudes investigated ranged from ± 1 psi to ± 18 psi, and the frequency from a low of 200 to a high of 1000 cycles per min.

Fig. 10
Gas-pulsing Apparatus

The best results were achieved with an initial pressure setting of 5 psig pulsed at 350 cycles per minute with an imposed pressure variation of ± 1 psi. Under these conditions, the process yield for the tests was in the vicinity of 80%.

The objections to using this method were directed to the high possibility of splashing small quantities of sodium onto the lip of the tube. Such a condition would always result in a faulty closure weld which would force rejection of the element. In addition, the difficulty associated with remote processing still had to be considered. Because of these considerations this method was abandoned.

6. Vibratory Bonding

The final process which was given serious consideration was one in which the elements would be subjected to a vertical vibration coincidentally

Fig. 11. "Syntron" Vibrator Furnace

with furnace heat treatment at 500°C to 550°C. The laboratory furnace which was constructed for this purpose is shown in Fig. 11. The elements were held in a vertical support basket which, in turn, was suspended by vertical hanger rod from the vibrating member of a "Syntron" vibrator. Although the frequency of the vibrator was 60 cps, the elements, which were unrestrained, and therefore free to vibrate in a random manner, did not have any consistent frequency. The experiments showed that best results were obtained when the maximum amplitude of the element lay between $\frac{1}{32}$ in. and $\frac{3}{32}$ in. If the amplitude exceeded $\frac{3}{32}$ in., sodium would be driven upward by the uranium and would be suspended at the upper end of the tube. This would result in a deficiency of sodium in the bond region, producing voids at the top of the uranium. Below $\frac{1}{32}$ in., the forces were not great enough to provide the desired bonding. It is believed that the bonding action is produced by the abrupt deceleration of the fuel element as it falls and contacts the vibrating platform and by the slight relative movement of the uranium with respect to the stainless steel cladding. This latter motion produces a wiping action which tends to move sodium into the nonwetted areas. The exposure time required to produce effective bonding must be at least 2 hr. Table II is an example of one run which gave a yield of 94%.

suspended at the upper end of the

Table II

TYPICAL VIBRATORY PROCESS YIELD

<u>Condition</u>	<u>Number of Elements</u>	<u>Percentage</u>
Good	37	56
Acceptable	25	38
Rejected	4	6
TOTAL	66	100

The advantage of this type of process is that it involves relatively simple equipment and permits the simultaneous processing of a large quantity of elements. As an example, the prototype furnace used in the bonding of the first core for EBR-II utilizes a fixture holding fifty elements.

IV. DISCUSSION

The list of processes described in this report reflects the magnitude of the effort expended upon this project. The reasons for the final selection of the vibratory bonding for the production of the first EBR-II core and its introduction into the process line of the fuel-cycle facility have been stated. Up to the time of writing, approximately the entire set of elements for the EBR-II, Mark-I core has been bonded by means of the prototype equipment. The yield for this production line was in the vicinity of 93%, with respect to the bonding process alone. Understandably, the yield is lower when all causes for rejection (leaks, improper level, etc.) are considered.

During the course of the experimental program two methods were used to examine the condition of the bond following the bonding procedure. The first was to pass the element through an eddy current nondestructive testing device which drew a trace upon a recorder chart. This trace reflected a signal magnitude which was a function of the condition of the portion of the element passing through the coil. Figure 12 is a photograph of the equipment used in the laboratory.

The second method of examination was to strip back the cladding by peeling it away from the element for visual examination. An example of the cyclograph trace with a corresponding nonbonded area can be seen in Fig. 13.

These steps were followed since it was desired to correlate the nature of the curve produced with the type and size of void in the bond. This was necessary since the elements ultimately produced for the use in the reactor would have to be screened by nondestructive technique. During these investigations, a problem arose because of the appearance of void signals in random areas along the element which, after stripping, were found to be wetted with sodium. It was suspected that these were voids formed by the shrinkage of the sodium when it froze. To prove this assumption, several tests were tried in which the element was suspended vertically in a cylindrical furnace which held the element at a uniform temperature from top to bottom. The element was lowered directly from this furnace into the testing coil. Several traverses made with the element just below and just above the melting point of sodium showed the appearance of a large void after freezing at the top of the element. This void disappeared when the melting point was exceeded.

Fig. 12. Bond Inspection Cyclograph

The detection of the shrinkage voids dictated that some method would have to be devised to prevent their formation since they could not be distinguished from other voids with the nondestructive equipment. The method chosen was progressive freezing of the bond sodium starting at the bottom of the element and rising to the top. The method selected could be performed simultaneously upon a large group of elements. The hot elements are placed vertically in a circle within the confinement of a vertical, cylindrical chimney. A blast of cooling air is directed transversely from several jets across the base of the elements. When a temperature differential of 120°C is established from top to bottom, the jet blast is discontinued and cooling is continued by an axial stream of cooling air. A typical set of cooling curves is shown in Fig. 14.

FIG. 13
CYCLOGRAPH TRACE SHOWING NON-BONDED AREA AND THE CORRESPONDING DEFECT

FIG. 14
QUENCH COOLING CURVE, EBR-II BONDING PROCESS

In this manner the bond sodium is frozen progressively from bottom to top to provide a continuous bond. The appearance of a well-bonded fuel element can be seen from the trace in Fig. 15. It is interesting to note that void indications could be introduced into perfectly bonded fuel elements

by the simple expedient of reheating the element above the melting point of sodium, and quenching with an aluminum chill ring clamped about some position along the element. When the element was cooled, the eddy current test would show a large void in the preferentially chilled area. Subsequent stripping would show a shrinkage void at this position. The conclusion of this program is now being followed by development of equipment to be used in the fuel-cycle facility currently being constructed as part of the EBR-II complex.

FIG. 15
TYPICAL TRACE OF A WELL-BONDED ELEMENT

V. REFERENCES

1. L. J. Koch et al., Hazard Summary Report Experimental Breeder Reactor II (EBR-II), ANL-5719 (May 1957).
2. J. H. Monaweck and E. S. Sowa, Summary Report on Irradiation of Prototype EBR-II Fuel Elements, ANL-6010 (Sept 1960).
3. Greenwood and Sharpe, AERE M/R 1568.
4. C. H. Bachman and H. G. Hottenrott, Flow through Capillary Tubing with Eccentric Annular Sections, Rev. Sci. Instr. 30, 126 (1959).

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