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SODIUM BOND DEFECT INVESTIGATIONS

by

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ABSTRACT

Sodium bond voids in EBR-II prototypic fuel elements were characterized as a function of thermal and mechanical treatments to establish a simple, efficient fabrication process that could be adapted to remote fuel fabrication operations. Molten sodium was mechanically positioned in the fuel-clad annulus by manual impacting at temperatures less than the sodium wetting temperature. Bond defects were long linear axial voids that existed in 90° to 180° circumferential arcs around the fuel slug. The bond void volume was only 15% of the annular volume and was much less than the circumferential arc would indicate due to the slug eccentricity in the cladding and surface tension of liquid sodium. In laboratory tests at the reactor inlet sodium temperature (370°C), the sodium completely wetted the fuel and clad surfaces after 8 hours. Wetting reduced the linear porosity to discrete voids and reduced the total annular porosity. The defects were destructively evaluated by direct observation of stripped elements. Annular porosities typically ranged from 10 to 20% in the unwetted condition and ranged from 5 to 15% in the wetted condition. Since the relative thermal expansion of sodium from room temperature to 370°C was 5.5%, the bond porosity should range from 0 to 10% at reactor operating conditions. Irradiation of settled elements with annular porosities less than 20% has been proposed to evaluate the performance effects and limitations of bond defects.

I. INTRODUCTION

Heat produced in EBR-II fuel elements is transferred from the fuel slug to the cladding tube by liquid sodium. The sodium forms an annulus around the slug ranging in thickness from zero to 0.03 in. depending on the eccentricity of the slug and the cladding tube. In the typical element fabricated, the sodium wets the fuel and clad surfaces during an impact bonding process consisting of a 500°C thermal cycle that includes 1000 individual axial impacts. The vertical impacts promote the development of a defect free bond by displacing voids with sodium. Multiple displacements of the slug relative to the cladding allow bond defects to migrate upward to the plenum. The impact bonding process has been very successful in producing elements with less than 1% porosity in the annulus.

An important goal of the IFR program is to demonstrate the remote reprocessing of irradiated metallic fuel which includes the remote encapsulation of recycled fuel slugs into fuel elements. Fabrication of these elements will be accomplished in an inert atmosphere hot cell environment that renders normal fuel element inspection processes, such as radiography, unusable. Characteristics of the sodium bonding process are being investigated with the intent of developing a simplified fabrication process capable of producing acceptable sodium bonds.

Heat transfer calculations have been performed that suggest partial bonds are adequate to prevent fuel melting and redistribution. Partial bonds are defined as voids in the annulus between the slug and the cladding around some portion of the full circumference and of unlimited axial length. This report deals with the correlation between fabrication conditions and the resultant sodium bond quality in prototypic production fuel elements. The size and distribution of sodium bond defects were characterized by both destructive and nondestructive techniques. The effectiveness of the nondestructive inspection methods are discussed. The next phase of this bond defect program will be the irradiation of fuel elements with bond defects to establish the effect of these defects on fuel performance.

II. MATERIALS, FABRICATION AND INSPECTION PROCESSES

Processes under investigation in this research included fabrication variables that were typical of normal Fuel Manufacturing Facility (FMF) fuel production, as well as fabrication variables not normally associated with standard production methods and their effect on the interaction between sodium and the metallic surfaces within the fuel element. Experiments were run in two stages, Series A and B.

A. Materials

The cladding material for the Series A elements was HT9 tubing (0.230 in. diameter X 0.015 in. wall thickness) which was thoroughly cleaned prior to processing. Series B elements were fabricated from HT9 tubing (0.230 in. diameter X 0.018 in. wall thickness) in the as-received clean condition from the tubing vendor. No attempt was made to remove loose or adherent particles or surface oxides that may have been present in the thick-wall tubing. The thicker wall thickness reduced the annular clearance between the slug and the cladding and increased the fuel smear density from 74% to 80%.

Fuel slugs were injection cast EBR-II production Mark-III U-10Zr slugs. The surface condition was typical of normal production slugs having a dull gray-black color. As noted, in later sections of this report, some slugs were cleaned to achieve a uniform metallic surface condition to determine whether the smooth metallic surface would enhance the wetting process and/or the bond quality. The U-10Zr alloy had a light gold coloration when polished or fractured.

Sodium was obtained from the EBR-II secondary sodium loop and was taken directly from the production fuel element supply.

B. Fabrication Processes

Fabrication process variables are discussed relative to the fuel production processes currently being used in the FMF for fresh unirradiated feed materials. Process simplification was primarily focused on reducing

specification and inspection requirements for the remote fabrication of fuel elements cast from irradiated feed materials.

1. Jacket Preparation

Jackets consist of a cladding tube with the bottom end plug welded in place and wire wrapped with a spacer wire. Jackets for the cold line are received and loaded with sodium during the slug loading process. Jackets for the recycle or hot fuel fabrication process may be preloaded with sodium prior to entering the remote handling environment.

2. Element Fabrication

The loading and closure welding of a jacket to form a finished fuel element is performed in an inert gas atmosphere glove box. While in the vertical position, each jacket was loaded with a precise quantity of sodium calculated to fill the annulus and 0.25 in. of the plenum above the fuel slug. Since sodium is a very reactive element, impurity levels of gases in the glove box atmosphere were limited to 50 ppm. After liquifying the solid sodium by heating above 100°C, the sodium was settled to the bottom of the jacket by manually dropping the jacket several times on the bottom of the settling furnace. The jacket was then removed from the furnace and cooled to room temperature to solidify the sodium. Fuel slugs previously assigned to every jacket were dropped from the top of the jacket onto the solid sodium.

Settling the fuel slug was accomplished at 200°C by manually dropping the jacket from a height of 2-3 in. several times to force the fuel slug through the molten sodium until it contacted the bottom end plug. Even in the most pure glove box atmosphere, sodium reacts with the residual impurity gases. To restrict this reaction rate, settling was performed under three different conditions, as follows:

- (a) Slug settling with the top of jacket unobstructed (standard FMF process).

- (b) Slug settling with the top end plug inserted into the jacket.
- (c) Sodium and slug settling after the top end plug was welded in place.

The last technique was advantageous from production considerations since it involved only one heating cycle and eliminated the chance of sodium contamination in the weld. Top end closure welding was performed on individual elements using the production capacitance discharge process on all elements.

A total of 45 elements were subjected to a variety of thermal and mechanical conditioning treatments to evaluate their effect on the amount of bond porosity and its distribution along the annulus. These treatments were performed over a range of temperatures, bottom-to-top cooling gradient and optional mechanical agitation.

3. Inspection Techniques

a. Radiography

The settled elements were radiographed to determine the level of sodium in the plenum. The difference between the actual height and the calculated height of the sodium established the total volume of bond defects along the annulus. The porosity was defined as the excess volume of sodium in the plenum divided by the annular volume.

b. Eddy Current

Every production element is eddy current inspected for annular porosity after it has been impact bonded at 500°C. At that temperature, sodium wets the surfaces of the cladding and the fuel slug so that porosity remaining in the annulus is spherical in nature with a minimum surface-to-volume ratio and completely surrounded by sodium. The differential eddy current inspection equipment was sensitive to abrupt changes in the

conductivity of the annulus and recorded bond defects by deflections on a strip chart. Defects observed through the destructive examinations of production elements have correlated very well with the defect indications on the eddy current trace.

c. Direct Observation

The direct observation of bond defects was made possible by scoring the cladding in a spiral pattern and stripping the clad from the fuel slug. The process revealed the quality of the sodium bond without smearing the sodium over defect areas. This technique was used to examine selected elements at various stages of processing and after all testing was completed.

III. EXPERIMENTAL RESULTS

Forty-five elements were fabricated to study bond void characteristics. These 45 elements were fabricated in two groups, Series A and B. The results of the various tests have been summarized for individual elements in Appendices A and B. Series A elements were the first 25 fabricated and they had a smear density of 74%. Smear density is defined as the ratio of the fuel slug cross-sectional area divided by the clad internal cross-sectional area. The 20 Series B elements were the second group fabricated; they had a higher smear density (80%) because the internal diameter of the cladding was 0.006 in. smaller. Discussions of each test condition will reference the corresponding sets of elements in these data summary tables.

A. Series A Elements

All 25 elements were settled at 200°C and manually dropped several times to settle the fuel slug against the bottom end cap. The temperature was sufficient to assure that the sodium was in the liquid phase but was not high enough to achieve a wetted condition between the sodium and either the cladding or the fuel slug. The drops were uncontrolled with respect to height and number, but were typical of the production fabrication process - 3 drops from a height of 3 in. Five classes of element characteristics were prepared

to study the bond behavior during various thermal treatments. The results for each individual element were tabulated in Appendix A. The average bond porosity of the five groups was calculated from the excess sodium in the plenum and is reported in Table I. The porosity was lower for elements containing the as-cast fuel slugs as compared to slugs having a uniformly abraded metallic surface. The results indicated that the degree of sodium exposure to the box atmosphere had no significant effect on the annular porosity after settling. Considering the uncertainty in the slug volume and clad internal diameter, the porosity calculation was accurate to $\pm 3\%$.

Table I. Series A Elements Settled at 200°C

<u>Description</u>	<u>Qty</u>	<u>Serial No.</u>	<u>Calculated Porosity</u>
1. Production components settled open to the glove box atmosphere	5	A1	10.6%
2. Same as 1 with abraded fuel slugs	5	A2	12.7%
3. Same as 1 heated with the top end plug in the clad tube	5	A3	9.5%
4. Same as 3 with abraded fuel slugs	5	A4	13.3%
5. Elements settled after welding end plug with abraded fuel slugs	5	A5	12.9%

Five elements, one from each group, were destructively evaluated to determine the distribution of porosity. The porosity locations are pictorially represented in Fig. 1. Each drawing is a side view of a fuel slug in the horizontal position after the cladding was removed. The visible side of the cylindrical slug was shaded to show the areas covered with sodium and accent the areas of voids in the annulus. Although not shown in the figure, the opposite side of the slugs was completely covered with sodium. Sodium that was displaced to the plenum by the axial voids formed a cylindrical plug at the top of the slug.

A1-2, Settled at 200°C and Cooled

A2-3, Settled at 200°C and Cooled

A3-5, Settled at 200°C and Cooled

A4-4, Settled at 200°C and Cooled

A5-3, Settled at 200°C and Cooled

Series A

Fig. 1. Extent of Bond Defects in Unwetted Elements

The remaining 20 elements in Series A were reheated to 200°C and allowed to slowly cool from the bottom of the slug to the top. In general, the porosity increased or stayed constant during this treatment. Five more elements were stripped and the porosity presented in Fig. 2 was no different than for the first five elements. In addition, five elements were heated to 200°C and vibrated for 1 hour in the production bonder. As before, no reduction in the annular porosity occurred during the vibrating process.

Two photographs, Figs. 3 and 4, of the stripping operation in progress show that the sodium was not bonded to the fuel slug and peels off the slug with the cladding. The sodium HT9 clad and sodium-slug contact angles were clearly greater than 90°, indicating that no wetting occurred at that temperature. The unwrapped cladding strip near the top of the fuel slug had equal lengths of sodium and bare metal. This was a good example of a 180° wide linear void in the annulus. The second picture was taken farther down on the slug. The sodium bond was wider and represented a 145° wide linear void. The slug was usually not concentric with the cladding and the linear defects generally occurred where the slug-to-clad distance was at minimum. These observations strongly support the belief that during settling, the liquid sodium flows along the largest passage until it reaches the plenum without filling the annulus. Given this behavior, it is not possible to promote the uniform encasement of the slug by the liquid sodium during settling. Furthermore, the sodium level in the plenum will be related to the void volume present in the annulus after settling.

The remaining 15 elements in Series A were statically heated to higher temperatures to promote wetting. Pictographs of the defect distribution are presented in Figs. 5, 6 and 7. The sodium was well bonded, indicating wetting, to both the clad and the slug after heating to 435°C for 1 hour or 370°C for more than 8 hours. Wetting reduced the total length of linear defects from 12 in. to 2.5 in. on the average. Since the fabrication variables seemed to have no apparent effect on the annular porosity, the five original groups were combined to determine the average porosity values listed in Table II. Porosities decreased in all cases, but the decrease was not consistent for all elements. This behavior was attributed to the sodium plug elevation in the plenum. When the plug did not contact the liquid sodium in

A1-3, Settled at 200°C and Directionally Cooled

A2-4, Settled at 200°C and Directionally Cooled

A3-4, Settled at 200°C and Directionally Cooled

A4-3, Settled at 200°C and Directionally Cooled

A5-1, Settled at 200°C and Directionally Cooled

A4-1, 200°C Settle and Direct. Cool with Vibration -1 hour

Series A

Fig. 2. Extent of Bond Defects in Directionally Cooled Elements

Series A

Fig. 3. Top End of Fuel Slug Having a Linear 180°C Bond Void

Series A

Fig. 4. Middle Area of Fuel Slug Having a Linear 90°C Bond Void

A1-4, 435°C for 1 hour

A2-1, 435°C for 1 hour

A3-3, 435°C for 1 hour

A5-4, 435°C for 1 hour

Series A

Fig. 5. Extent of Bond Voids in Elements After Wetting at 435°C

A1-5, 435°C for 1 hour

A2-2, 435°C for 1 hour

A3-1, 435°C for 1 hour

A4-2, 435°C for 1 hour

A5-5, 435°C for 1 hour

Series A

Fig. 6. Extent of Bond Voids in Elements After Wetting at 435°C

A1-1, 370°C for 24 hours

A2-5, 370°C for 24 hours

A3-2, 370°C for 24 hours

A4-5, 370°C for 24 hours

A5-2, 370°C for 24 hours

Series A

Fig. 7. Extent of Bond Voids in Elements After Wetting at 370°C

the annulus, it may not feed sodium to the contracting annular sodium column during cooling. This condition would produce very little net change in the calculated porosity.

Table II. Series A Element Porosity

<u>Description</u>	<u>Qty</u>	<u>Initial Settling</u>	<u>Bot-up Settling</u>	<u>After Wetting</u>
Elements heated at 435°C for 1 hour	9	11.6%	13.7%	9.0%
Elements heated at 370°C for 10 hours	5	12.8%	13.9%	8.7%
Elements heated at 370°C for 16 hours	5	12.8%	13.9%	8.0%
Elements heated at 370°C for 24 hours	4	12.9%	13.4%	6.3%

Linear bond voids were converted into discrete circular voids as the wetting process took place. As time and temperature increased, the voids became more spherical. Wetting reduced the contact angle between sodium and the other components which allowed the sodium to flow into the small annular gap produced during settling. Either the porosity moved circumferentially around the slug or the slug was displaced toward the center of the element. This effect transformed long linear 180° wide voids into shorter 90° wide voids of nearly equal volume.

Large 180° voids commonly developed at the top of the fuel slug in wetted elements, but did not occur in unwetted elements. The void always occurred on the side of the slug farthest from the cladding. In order to determine how much of these voids were due to shrinkage, the relative expansion of sodium in the annulus of five fuel elements was evaluated. The five impact-bonded production elements were radiographed to determine the sodium height in the plenum. These elements were then heated to 370°C and quenched to retain the high temperature axial position of the bond sodium. The elements were cooled to room temperature and the sodium height was remeasured. The sodium height was 0.20 in. longer in the plenum which was equivalent to 0.80 in. linear expansion in the annulus. These results mean

that the relative sodium contraction in the fuel element was 5.5% during cooling and solidification. When the porosity values presented in Table II are reduced by the thermal contraction, the annular porosity of the elements at the reactor inlet sodium temperature is below 5% after wetting.

The porosity in the annulus was reduced and concentrated at the top end of the slug by the wetting process. Long linear voids were eliminated during wetting in favor of more spherical defects that were generally in the thickest region of the annulus. In no case did individual voids larger than 180° exist along the lower 11 in. of the fuel slug. The large voids at the top of the fuel slug were usually 180°, but occasionally were 220° in circumference. Sodium plugs in the plenum were hourglass shaped and were often too far above the slug to supply sodium to the shrinking sodium column during cooling. These top end defects formed, as the sodium contracted during cooling, are expected to be significantly reduced when the element is reheated to 370°C.

B. Series B Elements

The second series of elements were fabricated to evaluate the effect of drop height and sodium loading on slug settling and bond void volume. Twenty elements were loaded, welded and settled without any applied forces. Only four of the slugs settled completely to the bottom end plug. The elements were reheated to 200°C and each element was dropped five times from a height ranging between 3 and 6 in. After impacting, all 20 fuel slugs were in contact with the bottom end plug.

Twelve of the elements (groups B1 through B4) were loaded with calculated sodium quantities to provide a nominal sodium level 0.25 in. above the slug. Eight of the elements (groups B5 through B8) were loaded with excess sodium to provide a nominal sodium level 1.25 in. above the slug. These elements were evaluated radiographically after settling at 200°C but none were stripped. After the impact settling, all 20 elements were heated to the EBR-II fuel storage basket temperature (370°C) and held at that temperature for 13 hours. No impacting was performed during this thermal cycle to approximate the reactor environment. The annular porosities of the elements were calculated and the elements were stripped. The individual

porosity data is presented in Appendix B and the average porosities are reported in Table III. The porosities in Table III were based on the calculated sodium height above the fuel slug.

Table III. Calculated Porosities for Series B Elements

<u>Description</u>	<u>Impact Settled</u>	<u>Wetted at 370°C</u>	<u>Adjusted Porosity</u>	<u>Measured Void Vol.</u>
Element groups B1 & B2 dropped 6" & 5" resp.	14.5%	0.3%	2.5%*	4.2%*
Element groups B3 & B4 dropped 4" & 3" resp.	14.1%	5.4%	9.4%	10.1%
Element groups B5 & B6 dropped 6" & 5" resp.	11.8%	4.5%	9.6%	8.1%
Element groups B7 & B8 dropped 4" & 3" resp.	14.1%	7.2%	12.1%	12.0%

* Except misloaded B1-1.

Seven of these elements were impact bonded at 500°C to establish a defect free sodium bond. The average sodium heights for these elements were below the nominal value used in the porosity calculation. The annulus actually contained more porosity than previously reported. The adjusted porosity values were listed in the third column of Table III. Since the adjusted porosity reported in Table III was determined at room temperature, the column 3 values should be reduced by 5.5% to approximate the porosity at 370°C. Impacting at 5 and 6 in. reduced the average porosity in these elements, after wetting, to below 5% at reactor operating temperatures.

The remaining 13 of the 20 elements were stripped to determine the size and distribution of the porosity. The bond defect pictographs are presented in Fig. 8. Void volumes were calculated from the void area assuming that the void existed in an average annulus spacing. The porosity associated with these volumes was included in Table III, column 4. Annular defects in the

wetted elements generally extended 90° around the slug and ranged from 0.2 to 1.5 in. long. Top end voids occurred in 9 of the 13 elements, the largest being 200° by 2.25 in. long.

C. Eddy Current Results

Differential Eddy Current (DEC) traces were run on all elements after each thermal/mechanical treatment. After settling at 200°C, the linear defects did not produce larger deflections than the 180° bond defect standard used for impact bonded production elements. The DEC traces were evaluated to determine the sodium plug height. Consistent results were obtained after a uniform system of trace interpretation was developed. The measurements are listed in Appendix C along with the radiographic length data. In some cases the sodium trap was separated into distinct plugs. The sum of the DEC measured plugs compared closely with the sum of the radiographic plug measurements.

Static thermal treatments above 370°C did not eliminate all linear defect areas in the bond region, as shown in the pictographs of the stripped elements. DEC trace deflections presented in Appendix C corresponded to the defect locations but their amplitude was not proportional to the actual void sizes. None of the trace deflections exceeded the deflections produced by the 180° bond defect standard even though the elements contained 180° defects. The differential eddy current signal apparently was controlled by the defect shape rather than the circumferential magnitude of the defect. The result was that DEC techniques could not be used to quantitatively evaluate defect sizes in elements settled or wetted at reactor operating temperatures. These results show that the DEC technique will not provide a basis for accepting or reworking fuel elements with respect to critical size bond defects.

B1-1, 370°C for 13 hours

B1-2, 370°C for 13 hours

B2-1, 370°C for 13 hours

B2-2, 370°C for 13 hours

B3-1, 370°C for 13 hours

B3-3, 370°C for 13 hours

Series B

Fig. 8. Bond Defects After Impact Settling and Wetting at 370°C

B4-1, 370°C for 13 hours

B4-3, 370°C for 13 hours

B5-1, 370°C for 13 hours

B6-1, 370°C for 13 hours

B6-2, 370°C for 13 hours

B7-2, 370°C for 13 hours

Series B

Fig. 8. Bond Defects After Impact Settling and Wetting at 370°C (cont'd)

IV. DISCUSSION OF RESULTS

A. Fabrication Process Factors

Only four of the 20 Series B fuel slugs displaced liquid sodium and settled completely to the bottom end cap by gravitational forces alone. This problem was typical of production and experimental fuel element manufacturing experience. Settling must be accompanied by the application of some axial force to seat the slugs on the bottom end cap. Fuel slugs are injection cast into quartz molds. After demolding and routine straightening, the slugs are straight to within 0.005 in. The slug-to-clad clearance was 0.030 in. for the Series A elements and 0.024 in. for Series B elements providing ample clearance for slug loading and settling. Radiographs of elements clearly showed that some of the settled fuel slugs bowed and make three point contact with the cladding tube. The frictional force between the slug and the cladding was apparently high enough to oppose the gravitational force on the slug and prevent spontaneous settling.

The fifth set of Series A elements were fabricated by the simplest conceivable process in terms of both time and effort. The jacket was loaded with sodium, the fuel slug, top end welded and then settled. This "one-step" loading process should be considered for the reference fuel fabrication sequence because it minimizes the reaction between the bond sodium and trace impurities in the atmosphere and eliminates multiple settling operations. Additionally, when the fuel slugs are seated mechanically into liquid sodium, the sodium can be displaced with enough velocity to splash sodium to the top of the cladding tube. When sodium contaminates the weld region, a defective weld is produced. The "one-step" loading process precludes the potential for weld contamination that was inherent in the other fabrication sequences. The different settling sequences used for the five groups of Series A elements seemed to have no effect on the bond quality.

Axial forces achieved by vertically dropping the elements were shown to be beneficial in reducing the annular porosity in the Series B elements. The additional 1 in. of sodium in the plenum had no effect on the annular porosity. The maximum drop height in these tests was arbitrarily chosen to be

6 in. Increased forces may be beneficial to reduce porosity, but should be limited to prevent deformation of the spade portion of the bottom end plug. Processing equipment requires some flexibility in its design to optimize this parameter.

B. Distribution of Porosity

The distribution of porosity along the annulus is an important factor in determining the performance of a fuel element in the reactor. Assuming that the 15% total porosity of an element was concentrated in a 360° void along the top 2 in. of the slug, the heat produced in the slug during a reactor start-up would surely melt the top portion of the slug and result in axial fuel redistribution. Therefore, an examination of the porosity distribution in these test elements was considered to be a key part of this study.

In some cases, the settled Series A elements contained long linear void regions that occurred along the full length of the slug. If this area was directly proportional to the void volume, the calculated porosity would range from 20 to 40% of the annulus. In fact, the porosity of all settled Series B elements that were impacted averaged 17.7% with the maximum value of 23%. This apparent anomaly can be explained by considering the eccentric configuration of an element cross-section in Fig. 9. The actual porosity was much lower because the fuel slug was not centered in the cladding tube and the large linear defect areas occurred in low volume locations where the slug surface was tangent to the clad surface. As the slug settles and displaces the liquid sodium, the surface energy of the sodium holds the liquid column in the thickest area of the annulus. Prior to wetting, surface tension makes it more difficult to force the liquid sodium into the thin side of the annulus. The sodium fills the annulus from the thickest side and forms a linear void along the full length of the slug on the opposite side. From Fig. 9, a full-length 180° void can have as little as 15% porosity. During cooling, the contraction of the sodium column mainly occurs in the radial direction and produces no large shrinkage void at the top of the slug.

Series B

Fig. 9. Area Distribution of Annulus for Maximum Slug Eccentricity

After wetting, the sodium completely surrounded the fuel slug and had no free surfaces from which to contract. The shrinkage was then directed axially and produced the large top end voids shown in Figs. 5, 6, 7 and 8. The general porosity reduction during wetting was achieved by drawing some of the sodium out of the plenum, leaving a gap between the slug and the sodium plug. This gap was not observed in the unwetted elements. As wetting proceeded, the voids became more spherical and tended to exist in the thicker region of the annulus. The circumferential redistribution of the voids reduced the void area significantly without any change in the annular porosity. It is only after wetting that production element porosities can be improved by multiple impacting, because the voids are surrounded by sodium and can migrate toward the plenum. Impacting also maintains the sodium above the fuel in contact with the annular sodium so that it can be drawn down into the annulus during cooling.

Bond voids less than 240° around the fuel slug should not result in fuel temperatures high enough to produce fuel slumping or redistribution, based on the thermal analysis performed in Ref. 1. Most of the voids observed in both wetted and unwetted elements were less than 200° . The largest top end shrinkage void was 200° by 2.25 in. long. Bond sodium was confined to the region of tangency between the top end of the slug and the cladding, which means that only about 15% of the cross-section was filled with sodium. The thermal expansion of sodium in five "perfect" production elements was determined by heating them to 370°C and quenching the plenum sodium. Plenum sodium heights were an average of 0.20 in. higher for the quenched elements which was equivalent to an 0.80 in. expansion in the full annulus. Thermal expansion of the bond sodium may be expected to reduce the 2.25 in. defect to 1.25 in. long. The partial sodium bond that existed along these shrinkage voids would be sufficient to prevent fuel melting according to the referenced analysis.

The ex-reactor studies have shown the upper range of annular porosity to be about 15% after the sodium wets the fuel element components. Twenty-five experimental elements that were settled and not bonded have been irradiated to 11.5 at.% burnup in X429 without exhibiting any evidence of fuel melting. It remains to be demonstrated on a larger scale that this level of porosity in

the annulus will not result in premature fuel failure in the reactor environment. It is also necessary to establish the range of porosities on a much larger population of elements to define the process capability and the characteristics of liquid sodium.

V. CONCLUSIONS

1. Settling fuel elements at temperatures below 250°C results in annular porosities ranging from 14 to 21% at room temperature. After wetting at temperatures above 370°C, the porosity decreased to a range of 0 to 15%.
2. Axial impacting was required to settle fuel slugs and decreases the annular porosity after wetting.
3. Differential eddy current inspection did not provide a quantitative measure of annular porosity in the test elements. The inspection may be of limited value to evaluate slug position and plenum sodium heights.
4. Porosity calculated from the excess sodium in the plenum agreed with the average porosity determined from the direct void area measurements.
5. The high surface tension of liquid sodium causes the thick side of the annulus to fill preferentially. Annular porosity increased as the annulus cross-section decreased.
6. Liquid bond sodium wet the fuel and cladding surfaces inside the element after 8 hours at the reactor inlet sodium temperature (370°C).
7. The size of the top end voids were exaggerated by shrinkage of the sodium during cooling. When the 5.5% shrinkage is subtracted from the room temperature porosity, all test elements would have contained less than 10% porosity at the normal reactor operating temperature.

8. Based on the heat transfer calculations in Ref. 1, defects observed during this study would not have resulted in fuel melting during irradiation in EBR-II.
9. Since the process sequence for sodium and slug settling had no effect on the annular porosity, the simplest "one-step" loading sequence is recommended for test fuel fabrication.

VI. REFERENCE

1. E. E. Feldman, Argonne National Laboratory, unpublished data (1989).

APPENDIX A

Series A Element Loading Data

	A	B	C	D	E	F
1	Bond Test Elements		Slug	Slug	Sodium	Calculated
2	Series A		Diameter	Length,	Weight,	Sodium
3	Description	Jacket ID	in.	in.	g	Height,in
4	Settled Open - Std	A1-1	0.172	13.491	1.876	0.25
5	Settled Open - Std	A1-2	0.1727	13.498	1.837	0.25
6	Settled Open - Std	A1-3	0.1728	13.488	1.828	0.25
7	Settled Open - Std	A1-4	0.173	13.498	1.819	0.25
8	Settled Open - Std	A1-5	0.1734	13.492	1.797	0.25
9	Settled Open - Pol	A2-1	0.1725	13.492	1.846	0.25
10	Settled Open - Pol	A2-2	0.172	13.496	1.874	0.25
11	Settled Open - Pol	A2-3	0.1722	13.494	1.867	0.25
12	Settled Open - Pol	A2-4	0.1717	13.521	1.896	0.25
13	Settled Open - Pol	A2-5	0.1725	13.493	1.848	0.25
14	Settled Closed - Std	A3-1	0.1733	13.493	1.798	0.24
15	Settled Closed - Std	A3-2	0.173	13.493	1.818	0.25
16	Settled Closed - Std	A3-3	0.1736	13.491	1.782	0.25
17	Settled Closed - Std	A3-4	0.1733	13.490	1.800	0.25
18	Settled Closed - Std	A3-5	0.1731	13.493	1.814	0.25
19	Settled Closed - Pol	A4-1	0.1721	13.508	1.873	0.25
20	Settled Closed - Pol	A4-2	0.172	13.492	1.876	0.25
21	Settled Closed - Pol	A4-3	0.1723	13.491	1.861	0.26
22	Settled Closed - Pol	A4-4	0.1733	13.488	1.802	0.25
23	Settled Closed - Pol	A4-5	0.1726	13.497	1.844	0.25
24	Settled Open - Pol	A5-1	0.1725	13.496	1.847	0.25
25	Settled Open - Pol	A5-2	0.1727	13.490	1.832	0.24
26	Settled Open - Pol	A5-3	0.1727	13.493	1.837	0.25
27	Settled Open - Pol	A5-4	0.1722	13.501	1.864	0.25
28	Settled Open - Pol	A5-5	0.172	13.494	1.874	0.25

Series A Element Sodium Height Measurements

	A	B	C	D	E	F	G	H
1	Bond Test Elements		Calculated	Initial	Dir. Settle	200C-1hr	435C-1hr	370C-24hr
2	Series A		Sodium	Sodium	Sodium	Vib. Sodium	Stat Sodium	Stat Sodium
3	Description	Jacket ID	Height,in	Height,in.	Height,in.	Height,in.	Height,in.	Height,in.
4	Settled Open - Std	A1-1	0.25	0.700	0.650			0.35
5	Settled Open - Std	A1-2	0.25	0.630	stripped			
6	Settled Open - Std	A1-3	0.25	0.520	0.610	stripped		
7	Settled Open - Std	A1-4	0.25	0.630	0.790	0.710	0.450	
8	Settled Open - Std	A1-5	0.25	0.600	0.720		0.500	
9	Settled Open - Pol	A2-1	0.25	0.750	0.700	0.680	0.600	
10	Settled Open - Pol	A2-2	0.25	0.700	0.890		0.780	
11	Settled Open - Pol	A2-3	0.25	0.740	stripped			
12	Settled Open - Pol	A2-4	0.25	0.600	0.720	stripped		
13	Settled Open - Pol	A2-5	0.25	0.670	0.800			0.68
14	Settled Closed - Std	A3-1	0.24	0.550	0.600		0.480	
15	Settled Closed - Std	A3-2	0.25	0.580	0.760			0.33
16	Settled Closed - Std	A3-3	0.25	0.550	0.650	0.710	0.600	
17	Settled Closed - Std	A3-4	0.25	0.550	0.700	stripped		
18	Settled Closed - Std	A3-5	0.25	0.610	stripped			
19	Settled Closed - Pol	A4-1	0.25	0.750	0.880	0.830	Stripped	
20	Settled Closed - Pol	A4-2	0.25	0.650	0.740		0.650	
21	Settled Closed - Pol	A4-3	0.26	0.850	1.000	stripped		
22	Settled Closed - Pol	A4-4	0.25	0.620	stripped			
23	Settled Closed - Pol	A4-5	0.25	0.700	0.840			0.68
24	Settled Open - Pol	A5-1	0.25	0.700	0.800	stripped		
25	Settled Open - Pol	A5-2	0.24	0.800	0.600			0.5
26	Settled Open - Pol	A5-3	0.25	0.580	stripped			
27	Settled Open - Pol	A5-4	0.25	0.600	0.500	0.480	0.320	
28	Settled Open - Pol	A5-5	0.25	0.800	0.900		0.650	

Appendix A (cont'd)

Series A Element Porosity Calculations

	A	B	M	N	O	P	Q
1	Bond Test Elements		Initial	Dir. Settle	200C-1hr-V	435C-1hr-S	370C-24hr-S
2	Series A		Porosity,	Porosity,	Porosity,	Porosity,	Porosity,
3	Description	Jacket ID	% of Annulus	% of Annulus	% of Annulus	% of Annulus	% of Annulus
4	Settled Open - Std	A1-1	12.794	11.371			2.831
5	Settled Open - Std	A1-2	11.012	Stripped			
6	Settled Open - Std	A1-3	7.954	10.586	Stripped		
7	Settled Open - Std	A1-4	11.158	15.866	13.512	5.86	
8	Settled Open - Std	A1-5	10.301	13.883		7.32	
9	Settled Open - Pol	A2-1	14.523	13.076	12.497	10.18	
10	Settled Open - Pol	A2-2	12.940	18.347		15.22	
11	Settled Open - Pol	A2-3	13.896	Stripped			
12	Settled Open - Pol	A2-4	9.899	13.274	Stripped		
13	Settled Open - Pol	A2-5	12.098	15.860			12.387
14	Settled Closed - Std	A3-1	9.073	10.560		6.99	
15	Settled Closed - Std	A3-2	9.713	15.011			2.354
16	Settled Closed - Std	A3-3	9.064	12.071	13.874	10.57	
17	Settled Closed - Std	A3-4	8.933	13.395	Stripped		
18	Settled Closed - Std	A3-5	10.524	Stripped			
19	Settled Closed - Pol	A4-1	14.213	17.921	16.495	Stripped	
20	Settled Closed - Pol	A4-2	11.377	13.939		11.38	
21	Settled Closed - Pol	A4-3	17.098	21.411	Stripped		
22	Settled Closed - Pol	A4-4	10.883	Stripped			
23	Settled Closed - Pol	A4-5	12.931	16.995			12.350
24	Settled Open - Pol	A5-1	13.044	15.937	Stripped		
25	Settled Open - Pol	A5-2	16.206	10.377			7.463
26	Settled Open - Pol	A5-3	9.522	Stripped			
27	Settled Open - Pol	A5-4	10.105	7.241	6.669	2.09	
28	Settled Open - Pol	A5-5	15.773	18.019		11.50	
29	Averages		11.80	14.29	12.61	9.01	7.48

Appendix A (cont'd)

Series B Element Loading Data

	A	B	C	D	E	F	G
1	Bond Test Elements	Jacket	Clad	Slug	Slug	Excess	Sodium
2	Description	No.	Diameter	Diameter	Length	Sodium	Weight
3	Dropped 6 in., 5 times	B1-1	0.194	0.1738	13.497	0.25	1.367
4	Dropped 6 in., 5 times	B1-2	0.194	0.1726	13.487	0.25	1.436
5	Dropped 6 in., 5 times	B1-3	0.194	0.1731	13.490	0.25	1.407
6	Dropped 5 in., 5 times	B2-1	0.194	0.173	13.492	0.25	1.413
7	Dropped 5 in., 5 times	B2-2	0.194	0.1731	13.500	0.25	1.408
8	Dropped 5 in., 5 times	B2-3	0.194	0.1713	13.498	0.25	1.512
9	Dropped 4 in., 5 times	B3-1	0.194	0.1727	13.497	0.25	1.431
10	Dropped 4 in., 5 times	B3-2	0.194	0.1729	13.497	0.25	1.419
11	Dropped 4 in., 5 times	B3-3	0.194	0.1729	13.498	0.25	1.419
12	Dropped 3 in., 5 times	B4-1	0.194	0.173	13.498	0.25	1.414
13	Dropped 3 in., 5 times	B4-2	0.194	0.1727	13.496	0.25	1.431
14	Dropped 3 in., 5 times	B4-3	0.194	0.1724	13.476	0.25	1.446
15							
16	Dropped 6 in., 5 times	B5-1	0.194	0.1721	13.494	1.25	1.934
17	Dropped 6 in., 5 times	B5-2	0.194	0.1733	13.498	1.25	1.865
18	Dropped 5 in., 5 times	B6-1	0.194	0.173	13.495	1.25	1.882
19	Dropped 5 in., 5 times	B6-2	0.194	0.173	13.486	1.25	1.881
20	Dropped 4 in., 5 times	B7-1	0.194	0.1734	13.484	1.25	1.858
21	Dropped 4 in., 5 times	B7-2	0.194	0.1727	13.498	1.25	1.900
22	Dropped 3 in., 5 times	B8-1	0.194	0.1728	13.496	1.25	1.894
23	Dropped 3 in., 5 times	B8-2	0.194	0.1727	13.495	1.25	1.900
24							

Series B Element Porosity Calculations

	A	B	F	J	K	L	M	N	O	P	Q
1	Bond Test Elements	Jacket	Excess	Na Height	Porosity	Na Height	% Porosity	Na Height	Actual	Tot. Linear	Defect
2	Description	No.	Sodium	Settled	Settled-%	370°C-13hr	370°C-13hr	500°C	Porosity	Defects, in.	Vol.-%
3	Dropped 6 in., 5 times	B1-1	0.25	0.65	15.013	0.00	-9.383	0.16A	#VALUE!	2.70	4.67
4	Dropped 6 in., 5 times	B1-2	0.25	0.65	14.228	0.22	-1.067	0.16A	#VALUE!	1.60	2.47
5	Dropped 6 in., 5 times	B1-3	0.25	0.57	11.636	0.25	0.000	0.18	2.545		
6	Dropped 5 in., 5 times	B2-1	0.25	0.7	16.287	0.20	-1.810	0.16A	#VALUE!	2.74	3.73
7	Dropped 5 in., 5 times	B2-2	0.25	0.6	12.718	0.32	2.544	0.16A	#VALUE!	3.37	5.93
8	Dropped 5 in., 5 times	B2-3	0.25	0.75	16.812	0.30	1.681	0.28	0.672		
9	Dropped 4 in., 5 times	B3-1	0.25	0.55	10.710	0.40	5.355	0.16A	#VALUE!	3.71	7.67
10	Dropped 4 in., 5 times	B3-2	0.25	0.62	13.327	0.44	6.844	0.09	12.607		
11	Dropped 4 in., 5 times	B3-3	0.25	0.62	13.326	0.50	9.004	0.16A	#VALUE!	5.00	13.13
12	Dropped 3 in., 5 times	B4-1	0.25	0.72	17.004	0.57	11.577	0.16A	#VALUE!	6.33	16.00
13	Dropped 3 in., 5 times	B4-2	0.25	0.6	12.496	0.29	1.428	0.10	6.784		
14	Dropped 3 in., 5 times	B4-3	0.25	0.75	17.644	0.20	-1.764	0.16A	#VALUE!	2.78	3.67
15				Average	14.20	Average	3.072	Ave. = 0.16	#VALUE!	Average	7.16
16	Dropped 6 in., 5 times	B5-1	1.25	1.55	10.436	1.32	2.435	1.11A	#VALUE!	3.63	7.00
17	Dropped 6 in., 5 times	B5-2	1.25	1.55	11.002	1.38	4.767	1.10	10.268		
18	Dropped 5 in., 5 times	B6-1	1.25	1.64	14.113	1.40	5.428	1.11A	#VALUE!	3.75	9.53
19	Dropped 5 in., 5 times	B6-2	1.25	1.57	11.587	1.40	5.432	1.11A	#VALUE!	3.45	7.73
20	Dropped 4 in., 5 times	B7-1	1.25	1.58	12.170	1.45	7.376	1.12	12.170		
21	Dropped 4 in., 5 times	B7-2	1.25	1.75	17.849	1.55	10.709	1.11A	#VALUE!	3.82	10.67
22	Dropped 3 in., 5 times	B8-1	1.25	1.62	13.269	1.40	5.379	1.11A	#VALUE!	3.95	13.33
23	Dropped 3 in., 5 times	B8-2	1.25	1.62	13.211	1.40	5.356	1.12	9.998		
24				Average	12.955	Average	5.860	Ave. = 1.11	#VALUE!	Average	9.65

Appendix B (cont'd)

SODIUM HEIGHT MEASUREMENT CORRELATION -- RADIOGRAPHY VS DIFFERENTIAL EDDY CURRENT (DEC)

Element Number DEC Height X-Ray Height Difference

A1-1	0.70	0.70	0.00
A1-2	0.66	0.63	0.03
A1-3	0.50	0.52	-0.02
A1-4	0.62	0.63	-0.01
A1-5	0.70	0.60	0.10
A2-1	.38+.35	0.75	-0.02
A2-2	0.75	0.70	0.05
A2-3	0.73	0.74	-0.01
A2-4	0.66	0.60	0.06
A2-5	0.70	0.67	0.03
A3-1	0.57	0.55	0.02
A3-2	0.65	0.58	0.07
A3-3	0.62	0.55	0.07
A3-4	0.60	0.55	0.05
A3-5	0.63	0.61	0.02
A4-1	0.83	0.75	0.08
A4-2	0.70	0.65	0.05
A4-3	0.86	0.85	0.01
A4-4	0.68	0.62	0.06
A4-5	0.80	0.70	0.10
A5-1	0.67	0.70	-0.03
A5-2	.35+.40	0.80	-0.05
A5-3	0.55	0.58	-0.03
A5-4	0.61	0.60	0.01
A5-5	0.78	0.80	-0.02

Element Number DEC Height X-Ray Height Difference

B1-1	0.62	0.65	-0.03
B1-2	0.65	0.65	0.00
B1-3	0.60	0.57	0.03
B2-1	.25+.38	0.70	-0.07
B2-2	0.60	0.60	0.00
B2-3	0.80	0.75	0.05
B3-1	0.60	0.55	0.05
B3-2	0.62	0.62	0.00
B3-3	0.62	0.62	0.00
B4-1	0.75	0.72	0.03
B4-2	0.60	0.60	0.00
B4-3	0.78	0.75	0.03
B5-1	1.60	1.55	0.05
B5-2	1.60	1.55	0.05
B6-1	1.70	1.64	0.06
B6-2	1.63	1.57	0.06
B7-1	1.64	1.58	0.06
B7-2	1.78	1.75	0.03
B8-1	1.70	1.62	0.08
B8-2	1.70	1.62	0.08

APPENDIX C

APPENDIX C (cont'd)

Typical Eddy Current Traces of Wetted Fuel Slugs