TITLE: THE LOSS-OF-BOND TEST OF SODIUM-BONDED LMFBR (U,Pu)-CARBIDE FUEL ELEMENTS

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THE LOSS-OF-BOND TEST OF SODIUM-BONDED LMFBR (U, Pu)-CARBIDE FUEL ELEMENTS

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ABSTRACT

Nine sodium-bonded (U, Pu)-carbide fuel elements were irradiated in EBR-II to simulate, and to assess the consequences of, a loss-of-sodium-bond event during irradiation. Each element contained a bond-voiding device that was designed to eject the bond sodium into an evacuated reservoir when operating power was reached. The test matrix included elements that contained both shrouded and unshrouded fuel columns; two different power levels were also included in the experiment. Two elements were removed after ~40 hours of irradiation; the remainder continued to operate to ~3 at.% burnup. Results of both the short-term and the goal-burnup examinations are presented which indicate that sodium-bond loss will not jeopardize the safe operation of sodium-bonded carbide fuel elements.

INTRODUCTION

The steady-state irradiation behavior of sodium-bonded uranium-plutonium carbide fuels in EBR-II has been extensively investigated. The high-conductance thermal bond of this element design permits operation at high linear power levels while maintaining relatively low fuel temperatures. The loss of this bond, especially near the beginning of life when the fuel-cladding annulus is large, would result in abnormally high fuel temperatures, which could possibly lead to cladding attack and loss of element integrity. This possibility has been of major concern in the consideration of the sodium-bonded carbide fuel element design. It has been postulated that the rapid expulsion of the sodium from the fuel-cladding annulus could result from a variety of conditions, e.g., cladding failure, rapid growth of fission-gas bubbles trapped in the bond, or transient overpower conditions.

TEST CONDITIONS

An experiment was designed to simulate a loss-of-bond event in EBR-II and to assess its consequences on the irradiation behavior of carbide fuel elements. The test matrix included nine specially designed carbide fuel
elements, each containing a bond-voiding device. This device involved the use of a Cu-Mn braze joint in a section of sealed tubing connecting the sodium-filled annulus to an evacuated reservoir located in each element below the fuel column; the braze joint was designed to melt when operating power was reached. The design and operating conditions of the nine elements are shown in Table I. As indicated, the experiment contained both shrouded and unshrouded fuel pellets operating at two different power levels. Fuel shrouds are thin-walled, slotted tubes that fit closely around the fuel-pellet column and act as fuel-fragment restraint devices.\(^1\)

TABLE I

LOB-1 Test Conditions

<table>
<thead>
<tr>
<th>Element</th>
<th>Diam. Gap (mm)</th>
<th>Peak Linear Power (kW/m)</th>
<th>Bond Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL1(^a)</td>
<td>0.76</td>
<td>77</td>
<td>Comp.</td>
</tr>
<tr>
<td>KL2</td>
<td>0.51</td>
<td>77</td>
<td>Comp.</td>
</tr>
<tr>
<td>KL5(^a)</td>
<td>0.81</td>
<td>90</td>
<td>Comp.</td>
</tr>
<tr>
<td>KL6</td>
<td>0.56</td>
<td>89</td>
<td>None</td>
</tr>
<tr>
<td>KL7(^a)</td>
<td>0.76</td>
<td>77</td>
<td>Comp.</td>
</tr>
<tr>
<td>KL8(^a)</td>
<td>0.76</td>
<td>78</td>
<td>None</td>
</tr>
<tr>
<td>KL9</td>
<td>0.51</td>
<td>77</td>
<td>Comp.</td>
</tr>
<tr>
<td>KL10(^a)</td>
<td>0.76</td>
<td>78</td>
<td>Part.</td>
</tr>
<tr>
<td>KL11</td>
<td>0.81</td>
<td>90</td>
<td>Comp.</td>
</tr>
</tbody>
</table>

\(^a\)Elements with shrouded fuel columns.

The initial phase of the test was conducted for \(\sim40\) hours after reaching full EBR-II operating power. The subassembly was then removed from the reactor, and the elements were nondestructively examined for bond-loss verification. Neutron radiography indicated that total or partial bond loss had been achieved in seven of the nine carbide elements. Elements KL5 (shrouded) and KL9 (unshrouded), both of which experienced total bond loss, were removed for destructive examination, while the remaining elements were reconstituted for continued irradiation to a goal burnup of 3 at.%. Some results of the short-term irradiation have been previously presented.\(^2,3,4\)

The five elements that had experienced some degree of bond loss and also reached goal burnup were destructively examined at the conclusion of the test. These elements included KL1 (stainless steel shroud, 77 kW/m), KL2 (unshrouded, 77 kW/m), KL7 (molybdenum shroud, 77 kW/m), KL10 (stainless steel shroud, 78 kW/m, partial bond loss), and KL11 (stainless steel shroud, 90 kW/m).
EXAMINATION RESULTS AND DISCUSSION

During the initial irradiation period, none of the access tubes below the transition joint in the voiding devices separated. However, bond loss was achieved in most of the elements, as indicated by the amounts of sodium in the voiding-device reservoirs and the overall condition of the fuel stacks shown in neutron radiographs. Two elements, KL6 and KL8, did not void sufficiently to uncover the fuel stacks in either irradiation period. The neutron radiographs of the four elements incorporating Type 316 stainless steel shrouds that had partially (KL10, upper half of fuel column) or completely (KL1, KL5, and KL11) voided their bonds showed intermittent and relatively large voids along the axis of their fuel columns plus scattered smaller voids in the remainder of the fuel and accompanied by numerous areas of apparent fuel-cladding contact during the initial 40-h irradiation. After the final irradiation to ~3 at.% burnup, most of the apparent voids had coalesced into a continuous central void extending the length of the obviously unbonded regions. These effects are illustrated in Fig. 1, which shows neutron radiographs of the upper portions of the fuel stacks of elements KL2, KL5, KL9, and KL11 after the initial 40-h irradiation as compared to the same region of KL11 after the final irradiation period. Elements KL2 and KL9 did not contain shroud tubes and did not exhibit the obvious void formations during either irradiation period.

Profilometry measurements and fuel-column lengths determined from radiograph measurements were made after both the short-term and goal-burnup irradiation periods. Although some ovalities did develop, the average diameter of all elements did not change during the 40-h irradiation. However, at ~3 at.%, three elements (KL5, KL10, and KL11) showed significant increases in average diameter in the unbonded areas with evidence of fuel-cladding mechanical interaction. The other elements showed diametral increases more consistent with typical sodium-bonded elements at this burnup level, with little or no evidence of FCHI. The maximum-average ΔD/D values are shown in Table II along with total ΔL/L values, measured burnups, and fission-gas-release values. The fuel columns did show a slight decrease in length after the initial irradiation period, as indicated in Table II by the values for elements KL5 and KL1. There was no evidence of severe fuel slumping in any of the elements. Although all elements showed definite length increases during the long-term irradiation period, the results are difficult to compare with normal behavior because of the unusual conditions of high fuel density and abnormally high temperatures. For the same reason, the fission-gas-release values are considerably greater than expected for normal elements at the 3 at.% burnup level.

Metallographic sections were taken from all elements that were destructively examined at locations of voids, points of apparent fuel-shroud reactions, or specific reference points (e.g., core midplane). Section KL5-M1 (taken after the initial 40-h irradiation period) was located ~119 mm above the core midplane at one of the points of possible fuel-cladding chemical interaction as indicated by the neutron radiograph and later suggested by an image-enhancement technique and by tomography measurements. The photomosaic in the chemically etched condition of this transverse section is shown in Fig. 2. Metallographic sections at other locations in the same
Fig. 1. Neutron radiographs of LOB-1 elements at interim and terminal examinations.
Fig. 2. Photomosaic from element KL5, chemically etched; location at 119 mm above core midplane; 0.05 at.% burnup.
element showed varying degrees of the same overall effects. Most of these effects were caused primarily by the reaction of the stainless steel shroud tube with the (U, Pu)C fuel. A central hole in the fuel, usually offset from the element axis, was observed in all transverse sections. Other smaller voids of varying sizes were located near the central hole; columnar grains radiated from the central hole with some extending nearly to the fuel-pellet periphery where the grains become nearly equiaxed in some locations. Two extensive areas that contained new phases formed by the reaction of fuel and shroud were located at the periphery of the fuel, and another similar area surrounded the central hole. In one other transverse section, the central hole was completely filled with the new phases; smaller amounts of similar material were detected at many locations in grain boundaries when observed at higher magnifications. Many of the grains also contained needle-like precipitates; such microstructures have usually been interpreted as MC$_2$ or other complex carbide precipitates in MC. There were no indications of the presence of M$_2$C$_3$. Electron microprobe examinations indicated that those areas with significant portions of reaction products contained up to three phases in addition to (U, Pu)C. These phases were primarily complex carbide phases with varying proportions of U, Pu, Fe, Cr, and Ni. Radial concentration profiles showed some variation of U and Pu distributions within the fuel, but there were no indications that either U or Pu had penetrated into the stainless steel cladding.

### TABLE II

LOB-1 Test Results

<table>
<thead>
<tr>
<th>Element</th>
<th>$\Delta D/D$ (%)</th>
<th>$\Delta L/L$ (%)</th>
<th>Burnup (at.%)</th>
<th>Fission-Gas Release (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL1$^a$</td>
<td>0.29</td>
<td>0.50</td>
<td>2.78</td>
<td>9.3</td>
</tr>
<tr>
<td>KL2</td>
<td>0.18</td>
<td>0.82</td>
<td>2.74</td>
<td>8.5</td>
</tr>
<tr>
<td>KL5$^a$</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.05</td>
<td>14.4</td>
</tr>
<tr>
<td>KL6</td>
<td>0.14</td>
<td>3.05</td>
<td>3.2</td>
<td>-</td>
</tr>
<tr>
<td>KL7$^a$</td>
<td>0.19</td>
<td>1.02</td>
<td>2.80</td>
<td>16.9</td>
</tr>
<tr>
<td>KL8$^a$</td>
<td>0.10</td>
<td>1.04</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>KL9</td>
<td>0.00</td>
<td>-0.33</td>
<td>0.04</td>
<td>2.9</td>
</tr>
<tr>
<td>KL10$^a$</td>
<td>0.38</td>
<td>0.52</td>
<td>2.72</td>
<td>8.5</td>
</tr>
<tr>
<td>KL11$^a$</td>
<td>0.74</td>
<td>0.91</td>
<td>3.14</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Note: Elements with shrouded fuel columns.
The neutron radiograph of element KL9 (unshrouded fuel, following 40-h irradiation period) showed no obvious points of unusual behavior throughout the fuel column (upper portion shown in Fig. 1). Only one metallographic section, at the core midplane, was taken from this element. The photomosaic in the as-polished condition is shown in Fig. 3 for section KL9-M2. There was slight grain growth and some grain-boundary separation in portions of the fuel, particularly in the hotter central region of the cross-section. There was also some unevenness associated with rounded pores at isolated points on the fuel periphery. A metallic-appearing phase was detected in grain boundaries to varying depths along most of the fuel periphery, but this phase could not be identified by electron microprobe techniques.

A metallographic section taken at the core-midplane location of element KL11 after the 3 at.% burnup period is shown in Fig. 4. This element is assumed to have had a structure similar to that of element KL5 after the short-term irradiation (see Fig. 1). Although this element operated at the higher (90 kW/m) of the two power levels in the experiment, the metallographic characteristics of all elements containing shroud tubes were very similar. The most notable differences in the sections at goal burnup are the absence of the columnar grains radiating from the central hole and the preponderance of voids or fission-gas bubbles scattered throughout the fuel cross-section. However, many of these voids exhibit radial alignments which appear to be vestiges of the earlier columnar grains due to the collection of voids or fission gases at the grain boundaries. This enhanced porosity is believed to be a real phenomenon and not a manifestation of sample preparation; this conclusion is based on the observation that fuel areas in other samples that are adjacent to unmelted shroud do not exhibit the porosity effects. (See Fig. 5; section KL11-M3.) The additional phases surrounding the central hole and at isolated locations on the fuel periphery appear to be similar in both irradiation periods. However, the phases (unidentified) in the long-term irradiation appear to be more structured at high magnifications than those in the short-term period. They probably represent the phases more nearly in equilibrium in this complex system at the prevailing temperatures established during the longer irradiation period.

Likewise, the metallographic characteristics of sections from unshrouded elements at goal burnup are generally similar to those from the short-term irradiation period and maintain the principal differences from the shrouded elements. A representative sample taken at the core midplane location of element KL2 (unshrouded) after the 3 at.% burnup period is presented in Fig. 6. The principal differences between this sample and that shown in Fig. 3 are the diminished fuel-cladding gap, increased degree of porosity, and the asymmetrical extension of the porous zone caused by a nonuniform temperature distribution. No other detrimental effects were noted in elements without shrouds.

CONCLUSIONS

An experiment to expel the sodium bond from LMFBR sodium-bonded carbide fuel elements during irradiation was successfully performed in EBR-II. The results of the test dramatically demonstrated the capability of such ele-
Fig. 3. Photomosaic from element KL9, as-polished; location at core midplane; 0.04 at.% burnup.
Fig. 4. Photomosaic from element KL11, as-polished; location at core midplane; 3.14 at.% burnup.
Fig. 5. Photomosaic from element KL11, as-polished; location ~25 mm from bottom of fuel column.
Fig. 6. Photomosaic from element KL2, as-polished; location at core midplane; 2.74 at.\% burnup.
ments to maintain their integrity and to continue operation for significa-
tly extended periods of time following bond loss. Although complex chemical
reactions did occur in elements that incorporated a stainless-steel shroud,
neither the shrouded nor unshrouded carbide fuel showed significant inter-
action with the cladding. Even at the elevated fuel temperatures encoun-
tered in such a system, the overall effects were quite benign. Thus, it has
been clearly shown that sodium-bond loss will not compromise the safe opera-
tion of sodium-bonded carbide fuel elements.

ACKNOWLEDGMENTS

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