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C. E. Lahm
J. F. Koenig
B. R. Seidel

Argonne National Laboratory
Idaho Falls, Idaho

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C. E. Lahm, J. F. Koenig, B. R. Seidel

Argonne National Laboratory
Idaho Falls, Idaho 83403-2528, U.S.A.

ABSTRACT

Metallic fuel elements irradiated in EBR-II at temperatures significantly higher than design, causing liquid phase attack of the cladding, were subsequently irradiated at normal operating temperatures to first breach. The fuel element lifetime was compared to that for elements not subjected to the over-temperature transient and found to be equivalent.

INTRODUCTION

Experimental Breeder Reactor II (EBR-II) has used metallic driver fuel since initial criticality in 1961. U-5Fs fuel, where Fs or Fissium is nominally 2.5% Mo, 1.9% Ru, 0.3% Rh, 0.2% Pd, 0.1% Zr, and 0.01% Nb (wt. %) was the initial fuel alloy. This mixture of fission products is the composition of fuel which was pyrometallurgically reprocessed in the EBR-II Fuel Cycle Demonstration of the 1960's. This alloy served as driver fuel until recently when it was replaced with U-10Zr(wt. %). Early fuel element design deficiencies which produced breach at very low burnup were identified and corrected allowing the administrative burnup limit for the U-5Fs fuel element to be increased to 8 at.%. At this burnup, irradiation induced swelling of the subassembly hardware limited exposure and required removal of the subassembly, although the elements had demonstrated longer life. End-of-life for peak nominal irradiation temperatures could be expected at a burnup of 10.3 at.% with a standard deviation (σ) of 0.15, while irradiation at lower temperature indicated end-of-life burnup >18 at.% could be achieved.

The standard driver subassembly contains 91 cylindrical fuel elements contained within a 5.817 cm. (2.290-in.) hexagonal subassembly. A spacer wire is wound helically around each fuel element to maintain the triangular lattice spacing and to provide mixing of the sodium coolant within the subassembly. The Mark-II fuel element, Figure 1, consists of a 3.3 mm diameter metallic U-5Fs fuel pin thermally-bonded with sodium to a 4.42 mm O.D. x 0.30 mm wall thickness 316 SS cladding. Fuel restraining dimples are pressed into the cladding to prevent excessive axial fuel growth or motion.

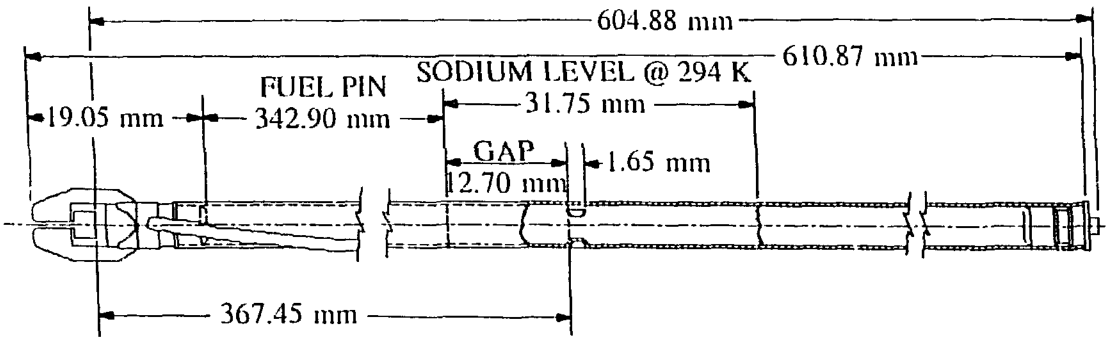


Figure 1

During irradiation, the fuel swells radially and axially, primarily due to the accumulation of noble gas fission products, until the bond sodium is displaced and the fuel is in full contact with the cladding. This fuel swelling is essentially complete by approximately 3 at.% burnup, after which the cladding restricts both radial and axial growth. Mechanical interaction between the fuel and cladding (FCMI) is very small due to the high porosity of the fuel. However, it is assumed that at very high burnup large amounts of solid fission products will fill the porosity and increase the mechanical stress. Chemical interaction between the fuel and cladding consists of interdiffusion of constituents, primarily nickel from the cladding and rare earth fission products from the fuel. At end-of-life burnups (≈8 at.%), there is approximately 0.0127 mm of cladding wastage due to chemical interaction.

Failure modes for these fuel elements were determined for two general classes, normal end-of-life failure and over-temperature (off-normal) conditions. Fuel elements irradiated to end-of-life indicated that breach occurred in the fuel restrainer dimple of the element, due to stress rupture of the cladding. The production of fission gas, which is gradually released to the plenum region, is the largest contributor to the cladding stress. At elevated temperatures, another failure mode identified for metallic fuel elements was caused by a liquid phase forming at the interface between the fuel and cladding which attacked and caused thinning of the cladding. This phenomenon is often referred to as "eutectic" attack although true eutectic compositions are not required when temperatures are above the eutectic temperature. Experience with this high-temperature mode of failure was obtained through both out-of-reactor and in-reactor tests.[1] Reactors subjected to extreme off-normal transient events, including temperature excursions above the eutectic temperature, must be able to tolerate limited damage to the fuel elements to allow further operation. In order to determine the effect of limited high-temperature transient operation on fuel element lifetime, fuel elements which had experienced high-temperature operation without breach were further irradiated until first failure.

EXPERIMENT DESCRIPTION

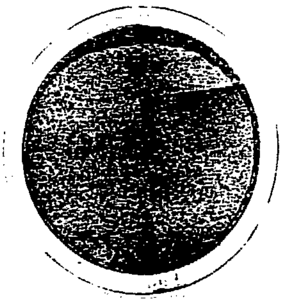
Mark-II metallic fuel elements, which only exhibit liquid phase attack at temperatures above 715°C, were operated at temperatures up to 800°C in EBR-II in a 61-element subassembly, XY-22, in order to characterize high temperature breach.[1] Fuel elements with a large range of burnups were included in the test in order to compare the damage caused by the over-temperature operation at various stages in fuel element life. The subassembly operated at elevated temperature for ≈42 minutes when failure of a high burnup element (7.69 at.%) occurred and the test was terminated. The failure was identified as being due to stress rupture at the fuel restrainer dimple and both mode and time-to-failure agreed very well with pre-test predictions. The unbreached elements, having sustained some limited damage to the cladding due to liquid phase formation, were removed and irradiated in a subassembly (X427) at normal operating temperatures until first breach. Experiment X427, contained all the remaining elements from the in-reactor eutectic penetration tests and enough fresh elements to fill a 91-element bundle.

The XY-22 test indicated that low-burnup elements had more cladding attack than the high-burnup elements, and the high-burnup elements failed due to stress rupture in the dimple, similar to normal end-of-life failure. It was expected that the low-burnup elements could breach early due to thinning of the cladding in the fuel region prior to the normal dimple failure, so all elements were irradiated at the same time to determine which would fail first. Breach was detected after an increment of ≈2 at.% burnup beyond the initial high-temperature test. Two of the high burnup elements, at 10.0 at.% and 10.2 at.% burnup, both higher than the administrative burnup limit of 8 at.%, exhibited a weight loss normally associated with breach. This indicated that the normal end-of-life failure mode was to be expected for the high-burnup elements, even after an extended over-temperature event. It was also necessary to determine if the mode of failure changed as a function of burnup. All the medium to high burnup elements were then removed from the subassembly and the low burnup elements were allowed to continue irradiation until normal end-of-life was exceeded. The final burnup for these elements was >11 at.% when the test was terminated without breach.

RESULTS

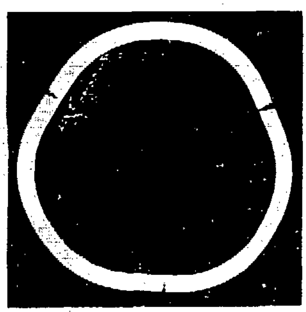
The test demonstrated that damage to the cladding due to short term over-temperature events would not significantly reduce the lifetime of these metallic fueled elements. The first failure of a high-burnup element occurred at 10.0 at.% burnup, which is within the 2-σ band for the database. Post irradiation examination of the elements showed evidence of previous high temperature attack, but no significant cladding degradation. Several examples of fuel restructuring due to the high temperature operation were observed. Figure 2 is an example of an element which was at ≈3 at.% when exposed to the over-temperature event. When examined at 5.2 at.% burnup, the normally uniform fuel/clad interaction layer can be seen to be enhanced and much thicker on one side of the element. This reflects the operating conditions in the fuel bundle at the time of the over-temperature event.

Figure 2



The metallic fuel, which had become very porous due to accumulated fission gas, sometimes appeared to sinter and shrink away from the cladding at elevated temperatures at the top of the fuel column. This also had no observable effect on subsequent operation of the fuel for the additional ≈2 at.% burnup increment required to obtain the first breach. The dimples, which are under reverse bending, normally begin to crack at end-of-life burnups, and the cracks gradually penetrate from the outside of the element to the inside. Figure 3 shows that all three dimples in the 10 at.% burnup element had cracks initiated at the time of breach.

Figure 3



Examination of the low-burnup elements at termination of the test at 11 at.% burnup indicated that small cracks had initiated at the dimples, but penetration was less that 1/3 the wall thickness. These elements had fuel/clad interaction layers of limited thickness and no significant thinning of the cladding was evident.

DISCUSSION

Although no deleterious effects on fuel element lifetime were demonstrated with this test, a contributor to this result would be the fact that the fuel restrainer dimple used in these elements causes early failure by acting as a stress riser for both steady-state and over-temperature events. Fuel elements currently being used in EBR-II do not have fuel restrainer dimples and may have a sufficiently high end-of-life burnup to be affected by the cladding wastage incurred during over-temperature operation. Design of advanced reactor fuel elements has indicated that predicted stress rupture failure during anticipated over-temperature events at end-of-life may be used to set burnup limits and that limited liquid phase attack may be important only at beginning-of-life when significant thinning of the cladding could occur before failure.

ACKNOWLEDGEMENTS

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