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IN-REACTOR CLADDING BREACH OF EBR-II DRIVER-FUEL ELEMENTS

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*This work was performed under the auspices of the United States Energy Research and Development Administration.

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Knowledge of performance and minimum useful element lifetime of Mark-II driver-fuel elements is required to maintain a high plant operating capacity factor with maximum fuel utilization. To obtain such knowledge, intentional cladding breach has been obtained in four run-to-cladding-breach Mark-II experimental driver-fuel subassemblies operating under normal conditions in EBR-II. Breach and subsequent fission-product release proved benign to reactor operations. The breaches originated on the outer surface of the cladding in the root of the restrainer dimples and were intergranular. The Weibull distribution of lifetime, given by

$$F(BU) = 1 - \exp\left[-\left(\frac{BU - 10.0}{1.53}\right)^{1.94}\right],$$

accurately predicts the observed minimum useful element lifetime of 10 at.% burnup, with breach ensuing shortly thereafter. Possible causes of breach have been postulated, but final assignment of cause must await future examinations. The ultimate lifetime of the fuel elements may well be increased somewhat by removing the restrainer dimples or replacing them with an alternate design.

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Introduction

Experimental Breeder Reactor II (EBR-II) is the only operating sodium-cooled fast breeder reactor in the United States. The reactor functions primarily as a materials-irradiation test facility, but several benefits are derived from the total mission of EBR-II. Operating at 62.5 MWt, EBR-II generates 20 MW electrical for distribution; provides plant operating experience, including experience with component reliability and servicing; and provides evidence that LMFBR's can operate safely and at high capacity factor -- 76% in calendar year 1976.

To prevent costly losses in plant operating capacity factor due to untimely breaches of the cladding in driver-fuel elements, a burnup limit for driver fuel must be established. However, the limit cannot be set unless the ultimate minimum useful lifetime of an element is known. Postirradiation examinations generate performance data resulting from irradiation of driver fuel to high burnup as part of a fuels qualification and surveillance program. In-reactor breaches obtained by the run-to-cladding breach (RTCB) program establish element lifetimes for normal and off-normal operating conditions.

The element burnup at breach is used as an input parameter for the statistical analyses required to predict element lifetime and reliability. The Weibull statistical model for determining element lifetime, which has been sucessfully applied to other EBR-II fuel designs (1,2), is being used to quantify the lifetime of the Mark-II element. (See next section for description of the Mark-II design.) Earlier results for nonreference design Mark-II fuel elements clad with Type 304L stainless steel are described in Ref. 2.

This paper characterizes the end-of-life breach in Mark-II driver-fuel elements and demonstrates the applicability of the Weibull statistical model in determining the lifetime of the Mark-II element. Element lifetime and possible mechanisms of breach are also discussed.

Irradiation Experiment

Design of Mark-II Driver-fuel Element

The Mark-II driver-fuel element (see Fig. 1) consists of a fuel pin of 67%-enriched uranium-5 wt% fissium* 343 mm long which is sodium-bonded within Type 316 stainless steel cladding. The cladding is fabricated from fully annealed welded tubing. A lower end fitting is affixed to the tubing to position the element within the subassembly. A spacer wire of Type 316 stainless steel is attached to the element with a 152-mm helical pitch to aid in positioning the element and in distribution of the flow of the primary sodium. A top end fitting is welded to the top of the cladding after the fuel pin and bond sodium have been loaded. The last step in fabrication of the elements is indenting the restrainer dimples 13 mm above the fuel pin to restrict axial fuel motion.

The Mark-II element is designed to provide for 33% radial fuel growth before the fuel contacts the cladding. This allows interconnected fuel porosity to develop and fission gas to be released to the element plenum before the cladding is stressed by the fuel. The plenum initially contains

*Fissium is an equilibrium concentration of fission-product elements left by the pyrometallurgical reprocessing cycle designed and demonstrated by EBR-II and consists of 2.4 wt % molybdenum, 1.9 wt % ruthenium, 0.3 wt % rhodium, 0.2 wt % palladium, 0.1 wt % zirconium, and 0.01 wt % niobium.

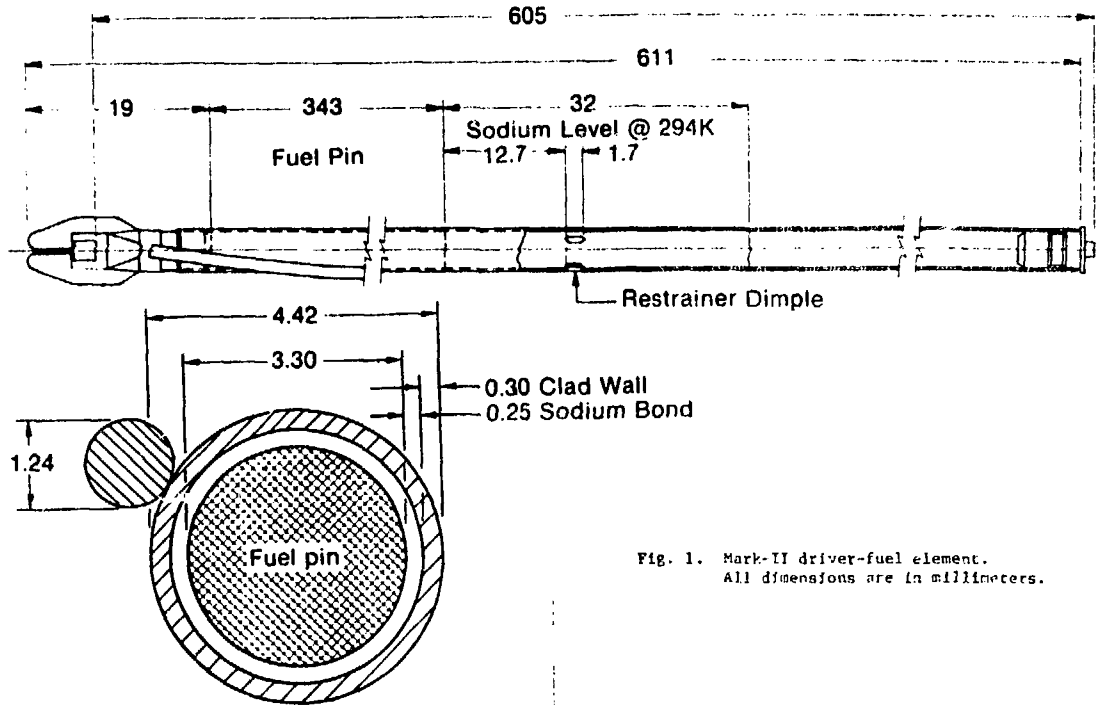


Fig. 1. Mark-II driver-fuel element.
All dimensions are in millimeters.

2.4 x 10^{-6} m^3 of argon at one atmosphere. For experimental Mark-II subassemblies that will be run to cladding breach, an identification tag composed of a unique mixture of xenon isotopes is included in the plenum.

Ninety-one elements are contained in a subassembly. The subassembly duct has an hexagonal cross section and is made of annealed Type 304 stainless steel. The subassemblies are cooled with primary sodium flowing from the bottom to the top, so the peak cladding temperature is at the top of the fuel column.

Description of Driver-fuel Irradiations

The total experimental irradiation program provides for irradiation of driver-fuel elements under normal operating conditions as well as conditions of high temperature, high heat rating, element-element, and element-subassembly interaction. The data on which this paper is based were obtained from incrementally irradiating experimental subassemblies of Mark-II fuel elements to the point of cladding breach or near cladding breach. The high burnup results are derived from the irradiation of the "first-production" of elements to be qualified for reactor use. These elements (about one core loading) were fabricated at EBR-II using welded tubing for the cladding. Reference design elements clad with seamless tubing, "second-production", are being irradiated to high burnup and their performance will be reported later.

The RTCB program with "first-production" fuel consisted of six experimental subassemblies identified as X207 through X212. Four of these RTCB subassemblies, X208 through X211, have been irradiated to cladding breach in the normal temperature environment to establish the normal element lifetime. These subassemblies reached 10.6 to 10.8 at.% burnup (7.5 x 10^{22} n/cm^2, E > 0.1 MeV) in row-6 reactor core positions where the peak cladding temperatures ranged from 590°C at beginning of life to 560°C at end of life. Subassembly X207 was operated in a high heat rating position to determine the effect of this parameter on lifetime. This subassembly is not included in the following discussions, because its cladding breach and subsequent fission-gas release were not characteristic of the other observed breaches, and the breached element could not be nondestructively identified. A leak in the top end weld was most consistent with the gas-release characteristics of X207. Subassembly X212 was operated in an environment of higher-than-normal temperature to characterize its performance but was not run to cladding breach.

Each of the subassemblies was examined for performance when burnup was near 6 at.% and was then reconstituted with the central seven elements replaced to minimize both element-element and element-subassembly interaction. (These interactions are being investigated in the RTCB program with "second-production" fuel.) The four subassemblies which operated in the normal environment were then irradiated until a cladding breach and subsequent fission-gas release were obtained and sufficient xenon-tagged gas (3,4) could be collected to identify the subassembly containing the breached element.

Experimental Results

Element Performance

The physical attributes of the element which might affect reactor operations or safety were characterized as a function of burnup to establish a baseline of normal element performance. Element diametral change, plenum pressure, fuel growth, fuel-cladding interaction, and cladding microstructure delineate the features which would restrict element performance and possibly result in cladding breach. The performance characteristics of Mark-II driver-fuel elements to 6 at.% burnup have been found to be adequate and have been reviewed extensively elsewhere (5,6). A brief summary of the characteristics of high-burnup first-production Mark-II elements follows.

The magnitude and position of maximum total strain is measured by element profilometry. Since elements adjacent to the subassembly wall are overcooled and exhibit less diameter increase than the inner-position elements, the results reported here are based on the characteristics of only the inner-position elements. The maximum diametral increase of unbreached elements irradiated in X208 to a peak element burnup of 10.6 at.% was 4.2 ± 0.5%. The maximum diametral increase for breached elements was 4.3 ± 0.4% measured at an average elevation of 54 ± 25 mm above the core midplane. All the elements exhibited a broad peak of maximum dilation above the core midplane which dropped off sharply at the top of the fuel column, as shown in Fig. 2. As a

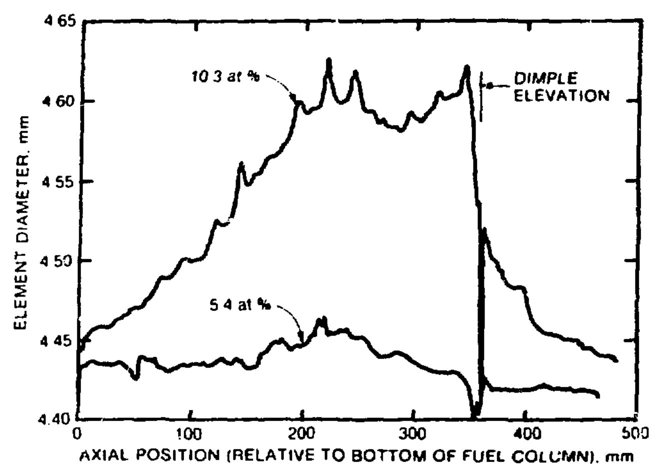


Fig. 2. Diameter increase exhibited by Mark-II element 54 of subassembly X208 at intermediate and high burnup. Nominal preirradiation diameter is 4.42 mm.

function of burnup the diameter increase of Mark II elements clad with Type 316 stainless steel is approximately one-third that of nonreference Mark-II elements clad with Type 304L stainless steel (see Fig. 3). The fraction of total strain due to swelling for both types of cladding is approximately two-thirds for irradiations up to 6 at.% burnup. Immersion density measurements to determine the swelling contributions near 10 at.% burnup will be performed soon.

At increased operating temperatures, the diameter increase has been found to be significantly larger. At 8.6 at.% burnup elements operated at 130% of normal ΔT in X212 exhibited total strains of 6.1 ± 0.3%, which would be characteristic of elements operated to a burnup of 12 at.% at normal temperatures.

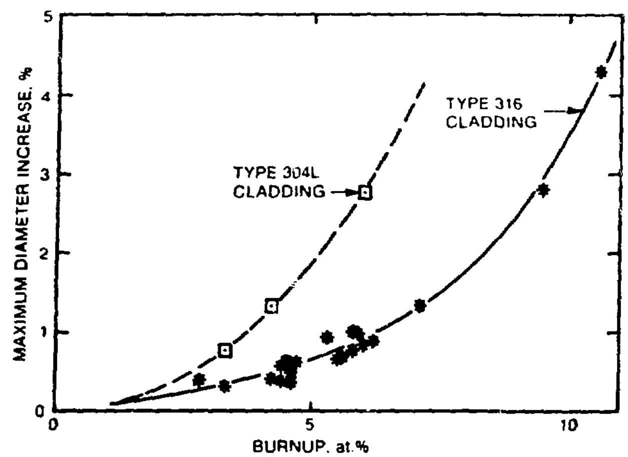


Fig. 3. Maximum diameter increase for reference-design Mark-II elements clad with Type 316 annealed stainless steel and nonreference elements clad with Type 304L annealed stainless steel.

The element plenum pressure at operating temperature is obtained by puncturing the elements by laser at room temperature, measuring the pressure and volume, and correcting the volume for thermal expansion of the bond sodium. The characteristic plenum pressure as a function of burnup is plotted in Fig. 4. At 10.6 at.% burnup, the plenum pressure at the operating temperature of 560°C is 18 MPa.

As the fuel swells and comes into contact with the cladding, an interaction zone, shown in Fig. 5, is established due to interdiffusion. The width of the interaction zone is greatest at the top of the fuel column; at 10.3 at.% burnup, 13 μm of the total zone thickness of 76 μm are within the cladding. The total width of the interaction zone at the core midplane is 64 μm with 8 μm within the cladding.

Since no previous breaches in elements with Type 304L cladding had occurred at a fuel restrainer (2), breach of Mark-II elements in the dimple was unexpected. The restrainer dimples, therefore, also had to be evaluated as to function and performance. The purpose of the restrainer is to restrict axial fuel displacement (liftoff) and inhibit axial fuel swelling. The maximum observed liftoff of the fuel pin with respect to the bottom of the element was found to be 3 mm, and this did not increase after a burnup of 3.2 at.% was achieved. At that burnup, fuel-cladding contact was complete. The fuel had not yet contacted the restrainer, and fuel-cladding interaction prevented further axial motion. The restrainer dimples are therefore not necessary to prohibit fuel-pin liftoff. Swelling, however, caused the fuel to contact the dimples at about 5 at.% burnup. The fuel continued to swell past the restrainer at a reduced rate until at 10.6 at.% burnup, the fuel had grown 13 mm past the dimples. The restrainer dimples therefore restrict fuel swelling in only a limited manner.

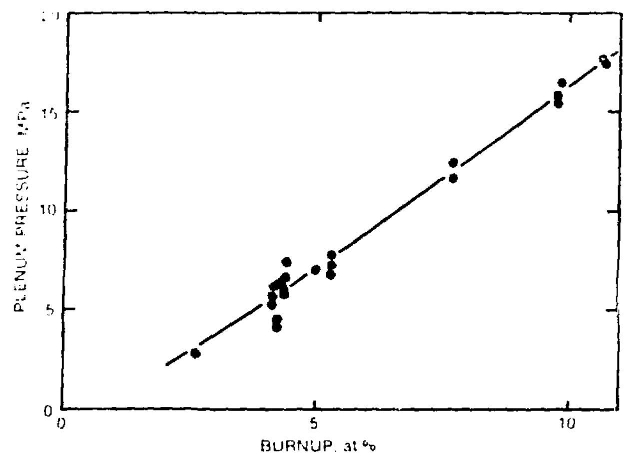


Fig. 4. Plenum pressure of Mark-II elements as a function of burnup at 537°C.

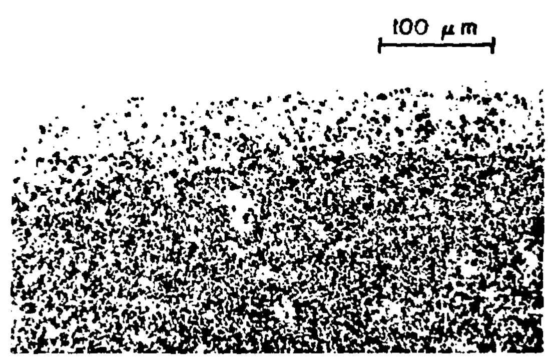


Fig. 5. Fuel-cladding interaction resulting at 10.3 at.% at the core-midplane elevation of element 54 of subassembly X208.

Breach Event

An increase in the ^{135m}Xe activity in the reactor primary cover gas is the first indication of breach of a Mark-II driver-fuel element. Most of the ^{135m}Xe gas results from the decay of ^{135}I, a short-lived fission product soluble in the bond sodium. Since the iodine is carried through the breach and into the primary system by the bond sodium, a prompt increase in ^{135m}Xe activity signals the breach before plenum gas is released. The plenum pressure continues to force the bond sodium and contained fission products through the breach until the plenum gas is released, causing increases in ^{133}Xe, ^{135}Xe, and krypton isotope activity in the cover gas. The ^{137}Cs activity in the primary sodium also increases as the bond sodium containing the cesium is released. Ultimate in-reactor identification (3,4) of the breached subassembly is obtained by analysis of the released xenon tag gas, which is incorporated in every fueled EBR-II experiment. The subassembly is removed from the reactor as soon as identification is made. Sometimes, as in the case of X208 and X211 in the work reported here, more than one breach may be incurred within the time necessary to release sufficient tag gas for acceptable analysis. Breach has been benign to reactor operation and no propagation of breach has been observed.

Breach Identification and Characteristics

During dismantling of the RTCB subassemblies, each element was visually inspected for cladding defects. A light-colored bond-sodium deposit was always seen in the dimples of the elements sharing a coolant channel where one of the elements was breached (see Figs. 6 and 7). All elements were

Fig. 6. Disassembly of subassembly X210 exhibiting bond sodium in one dimple of breached element 29 (second from right) and on the cladding of neighbor elements sharing the same coolant channel.

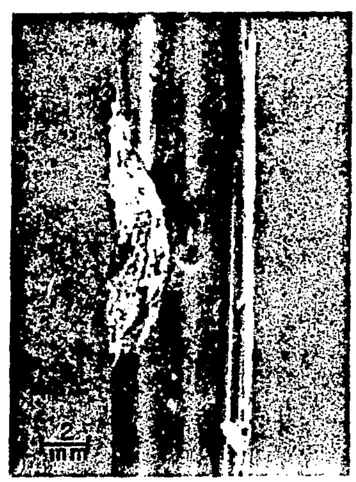


Fig. 7. Breached and unbreached dimples of element 29 at 10.5 at.% burnup of subassembly X210. Note bond sodium including fission products in breached dimple on left.

[illegible] about 1.4 g, which is equivalent to the bond sodium [illegible] elements. [illegible] breached first-production element [illegible] deposit in at least one dimple, (Fig. 7). [illegible] the deposit indicated [illegible], ^{137}Cs, ^{140}Ba-La, [illegible] with [illegible] by a factor of [illegible] more (7).

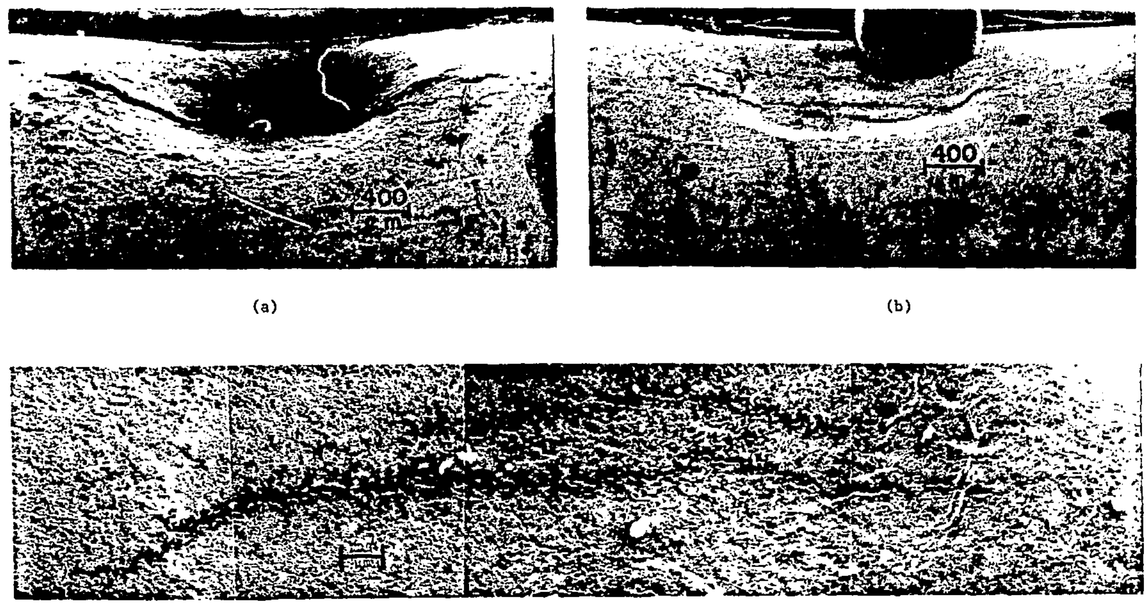
[illegible] and unbreached elements were sectioned for destructive examination. [illegible] outer surface of the three dimple regions of a breached element was examined by scanning electron microscopy (SEM). One or two major axial intergranular cracks were observed centered within each of the three dimples extending to the boundary of the dimple, as shown in Fig. 8. The typical [illegible] was [illegible] mm long and had a maximum opening of 100 μm. Some of the cladding surface at the dimple was corroded, as can be seen in Fig. 9. The [illegible] of the surface, to a depth of 2 μm, is believed to have been caused by [illegible] formed when the subassembly was washed with moist argon and water [illegible] from the reactor. To prevent corrosion of the breached cladding, [illegible] subassemblies were not washed. Plastic strain in the dimple area, resulting from the dimpling operation, was evident in the region of the crack by the observed slip bands and twins characteristic of a deformed structure (see Fig. 10), but the grain size in the dimple region near the defect was not different from that adjacent to the dimple.

Transverse metallography revealed intergranular cracks originating on the outer cladding surface in both breached and unbreached elements. (See Figs. 11 and 12.) The defects in the cladding of the unbreached element (Fig. 12) extend most of the way through the cladding, indicating that limited further irradiation of the element would have caused breach. Metallography also indicated that cracks existed neither in areas outside the dimple at the same elevation nor at core midplane. A definite change in geometry occurred in the dimple region, but there is no indication of wall thinning. As shown in Fig. 11, in the dimple where the breach occurred, the cladding was forced back toward its original circular cross section. Even in the unbreached element, the deeper the crack, the shallower the dimple appears to be. The defect structure suggests that the fuel exerts a reverse bending moment on the dimple, thereby generating a crack in the root of the dimple. No correlation was found between the position of the tube seam weld and the position of the cracks in the dimple.

Element Lifetime Statistics

The reliability of reactor components, particularly fuel elements, must be quantified and maintained sufficiently high to ensure system reliability. Material properties are useful in predicting lifetime if performance criteria based on properties can be established and evaluated, but in general they are limited in quantifying reliability. Statistical models based upon measured lifetimes, however, provide true measures of reliability and expected lifetimes and have proved to be accurate descriptions of component lifetimes (1,2).

The Weibull statistical model was chosen for our analysis because of two principal reasons. First, the model is the most appropriate to describe fuel-element breach because the distribution is derived for the situation where a large number of flaws exist in an item and failure of the item results from the severest flaw (8,9). In addition, the Weibull distribution was chosen because the smallest extreme from a Weibull distribution follows a Weibull distribution and because the family of Weibull distributions can be written to include increasing and decreasing failure rates as well as constant failure rates. These properties of the Weibull distribution allow one to determine lifetime distributions from a limited number of early failures in a set and, thus, characterize the failure rate and reliability as a function of life.



(a) (b) (c)

Fig. 8. SEM photographs of outer cladding surface of the three dimple indentations of element 54 at 10.3 at.% burnup of subassembly X208.

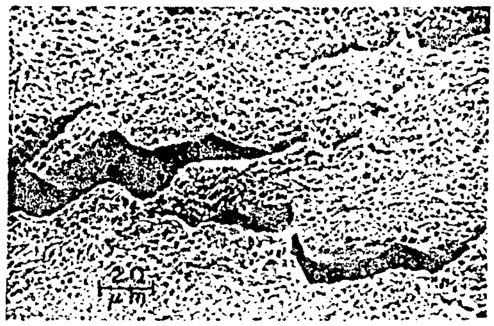


Fig. 9
Surface corrosion within one dimple of element 54 at 10.3 at.% burnup of subassembly X208.

Fig. 10

Crack at outer surface of dimple of element 54 at 10.3 at.% burnup of subassembly X208. Note the intergranular nature of the defect and the surface slip lines resulting from the dimpling operation.

The cumulative Weibull distribution function is given by

$$F(x) = 1 - \exp\left[-\left(\frac{x - x_o}{\eta}\right)^{\beta}\right] , \qquad (1)$$

where x = response parameter;

$F(x)$ = cumulative probability at x, or the fraction of the population accounted for at x;

x_o = origin of the distribution, or threshold parameter $\left[F(x - x_o) = 0\right]$;

η = scaling parameter ($\eta > 0$);

$\eta + x_o$ = characteristic life $\left[F(\eta + x_o) = 63\%\right]$; and

β = shape parameter, or Weibull slope ($\beta > 0$).

To apply the Weibull model, one must first determine the failure mode. If failures result from competing modes, the component lifetimes for each mode must be classified and the analysis performed for each mode separately. Since all the breaches obtained in the "first-production" Mark-II elements were located in the dimple region, possessed the same physical characteristics, and exhibited the same fission product release characteristics, the analyses assumed a single mode of breach.

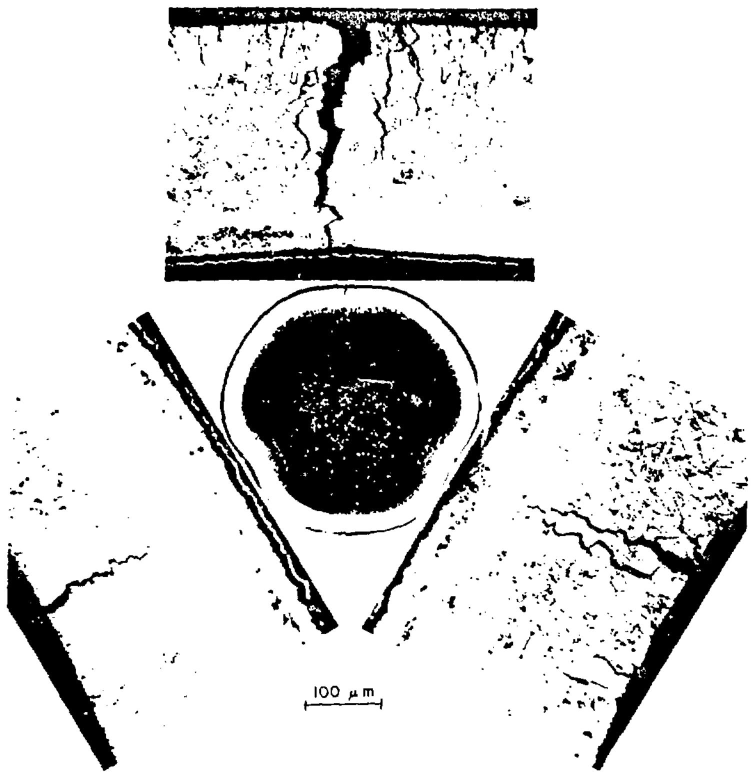


Fig. 11. Cross section of cladding at the dimple elevation of breached element 65 at 10.1 at.% burnup of subassembly X208. The cracks originate on the outer surface and are intergranular. The greater the outward deflection of the dimple, the deeper the crack.

The experimental median rank of the cumulative failure probability, $F(x)$, is obtained for the set of breaches employing the binomial correction given by Johnson (10):

$$F(x) = \frac{j - 0.3}{N + 0.4} \qquad (2)$$

where j is the mean order number or the number of breaches out of N observations.

Elements are suspended if they are removed from the test before they incur breach. Therefore, all unbreached elements at the end of the test and other elements removed for examination during the c[illegible]rse of the test are distinguished from the elements run to cladding breach. The mean order number

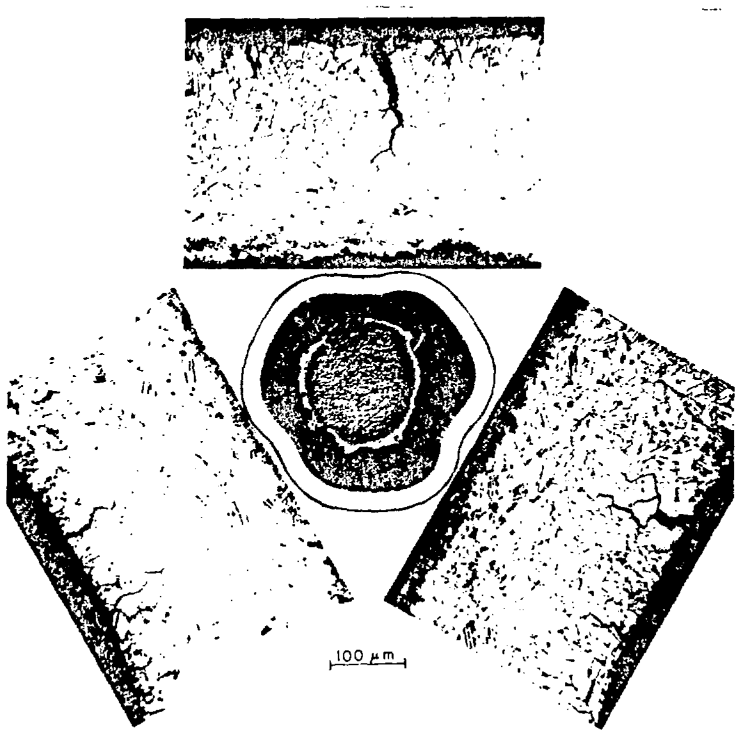


Fig. 12. Cross section of cladding at the dimple elevation of unbreached element 55 at 10.3 at.% burnup of subassembly X208. The cracks originate on the outer surface and are intergranular. The greater the outward deflection of the dimple, the deeper the crack.

must therefore be adjusted accordingly. The new increment in rank, Δn, is

$$\Delta n = \frac{(N + 1) - (\text{previous order number})}{1 + (\text{number of items remaining})} . \quad (3)$$

The adjusted mean order number is determined from the new increment by

$$j = \sum_{i=1}^{j} \Delta n_i . \quad (4)$$

The parameters of the distribution are determined by linear least-squares fit of the transformed equation

$$\ln\left\{\ln\left[\frac{1}{1 - F(x)}\right]\right\} = \beta \ln(x - x_o) - \beta \ln \eta . \quad (5)$$

Method of Analysis

Three basic methods of lifetime testing and analysis have been applied to the breach of EBR-II Mark-II driver-fuel elements.

The first method of lifetime testing is performed by operating a set of components to failure and determining the distribution of failure times. Owing to reactor operating limitations, this method is generally unacceptable for unencapsulated nuclear fuel elements, but it has been employed very successfully for encapsulated fuel elements (1,2). However, the first high-burnup driver-fuel subassembly to exhibit breach in the normal environment, X208, unintentionally generated multiple breaches. Once the initial breach occurred, breach in high-burnup elements soon followed but no propagation of breach was observed. Increases in reactor cover gas activity due to fission-product release pinpointed the time at which each breach event occurred, but the element responsible for each release could not be determined directly. A conservative and reasonable assumption is that the elements with the highest burnup will breach first. Since the primary response parameter is burnup (i.e., x = BU), the breached elements were ordered according to maximum burnup at time of breach. The cumulative failure probability was calculated for each ordered event after first suspending 32 of the 91 elements in the subassembly which had not achieved burnup equivalent to 10.12 at.% (the lowest burnup of the seven breached elements at the time of the first breach). Table I lists the breached elements, the corresponding burnups at breach, and the cumulative probabilities. The fitted Weibull slope, or shape parameter, is very high, which indicates the strongly increasing probability of breach exhibited by the fast failure rate once the threshold for breach was surpassed.

Table I. Weibull Analysis of Breached Mark-II Driver-fuel Elements Operating in Normal-environment Subassembly X208

Rank	Element	Burnup, at.%	Mean Order Number	Cumulative Probability, F(BU)
1	E65	10.12	1.53	0.0135
2	E55	10.18	3.07	0.0303
3	E54	10.26	4.60	0.0470
4	E43	10.27	6.13	0.0638
5	E24	10.28	7.67	0.0806
6	E8	10.30	9.20	0.0974
7	E25	10.31	10.73	0.1142

Distribution of Breach:

Threshold Parameter, $BU_0 = 0.0$

Shape Parameter, $\beta = 110.52$

Scaling Parameter, $\eta = 10.5$

Explanation of Variance = 0.97

A second method of lifetime testing, termed "sudden death testing" by Johnson (10), is advantageous when one is most interested in the first failures and the time required to obtain additional failures is prohibitive. Rather than obtaining several breaches over a wide range of burnup for elements within a single subassembly, a number of subassemblies are irradiated to the first breach in each and then terminated. Since the distribution of first breaches follows the Weibull distribution, the Weibull distribution for the total population may be determined. Johnson (10) has shown that the two-parameter Weibull distribution (i.e., $x_0 = 0$) for the total population possesses the same slope as the distribution of the first failures but that the characteristic life is a factor N to the power ($1/\beta$) times the "characteristic life of the first failure." The first breaches obtained in the four normal-environment driver subassemblies were analyzed by the "sudden death" technique. The data and results are given in Table II.

Table II. "Sudden Death" Analysis of First Breaches of Mark-II Driver-fuel Elements Operating in Normal-environment Subassemblies X208, X209, X210, and X211

Rank	Subassembly	Burnup, at.%	Mean Order Number	Cumulative Probability, F(BU)
1	X208	10.12	1	0.1599
2	X209	10.43	2	0.3857
3	X210	10.52	3	0.6143
4	X211	10.57	4	0.8409

Distribution of First Breaches:	Distribution of Total Population:
Threshold Parameter, $BU_0 = 0.0$	Threshold Parameter, $BU_0 = 0.0$
Shape Parameter, $\beta = 49.34$	Shape Parameter, $\beta = 49.34$
Scaling Parameter, $\eta = 10.51$	Scaling Parameter, $\eta \cdot N^{1/\beta} = 11.50$
Explanation of Variance = 0.92	Explanation of Variance = 0.92

The third method useful for lifetime analysis is termed the "suspended-set and failed-set" (10) technique. The method is appropriate when the number of suspended items and failed items is known over several intervals of the response parameter. The analysis is performed by determining the median rank for the last failure in each failed set. Along with the corresponding value of the response parameter at the end of each set, the best fit according to Eq. (5) is obtained. The data resulting from the four normal environment RTCB subassemblies are given in Table III. The new increment, mean order number, and median rank are calculated from Eq. (3), (4), and (2), respectively.

A threshold parameter of 10.0 at.% burnup was obtained for the three-parameter distribution (i.e., $BU_0 = 10.0$) by maximizing the explanation of variance due to regression. The three parameters obtained by the grouped-data-set analysis is the best estimate of the lifetime distribution. The data points, regression line, and 95% confidence limits for the line as a whole are plotted in Fig. 13. The characteristics of the breach distribution are more apparent in the linear plot of Fig. 14, where the curves resulting from each of the foregoing analyses are plotted. This figure shows that each distribution predicts a very low probability of breach below 10 at.% burnup followed by a rapidly increasing probability of breach. The three-parameter grouped-data-set distribution (curve D, Fig. 14) exhibiting a burnup threshold of 10.0 at.% most accurately represents the data. Consequently, no breach can be expected below 10.0 at.%.

The reliability, R, of a system of N elements is determined by the function

$$R = [1 - F(BU)]^N . \qquad (6)$$

Table III. Suspended-set and Failed-set Weibull Analysis of Breaches Incurred by Mark-II Driver-fuel Elements Operating in Normal-environment Subassemblies X208, X209, X210, and X211

Burnup Interval, at.%	Total Number of Elements	Number of Suspended Elements	Number of Remaining Elements	New Increment, Δn	Number of Breached Elements	Mean Order Number	Median Rank, F(BU)
5.0 - <10.9	364						
5.0 - <10.2	210	208	156	2.32	2	4.65	0.0119
10.2 - <10.3	32	29	125	2.86	3	13.23	0.0355
10.3 - <10.4	35	33	89	3.91	2	21.05	0.0569
10.4 - <10.5	29	28	59	6.43	1	27.48	0.0746
10.5 - <10.6	26	23	35	9.38	3	55.61	0.1518

Parameters	Type of Distribution: Two-parameter	Type of Distribution: Three-parameter
Threshold Parameter, BU_o	0.0	10.0
Shape Parameter, β	62.50	1.94
Scaling Parameter, η	10.91	1.53
Characteristic Life, $\eta + x_o$	10.91	11.53
Explanation of Variance	0.95	0.98

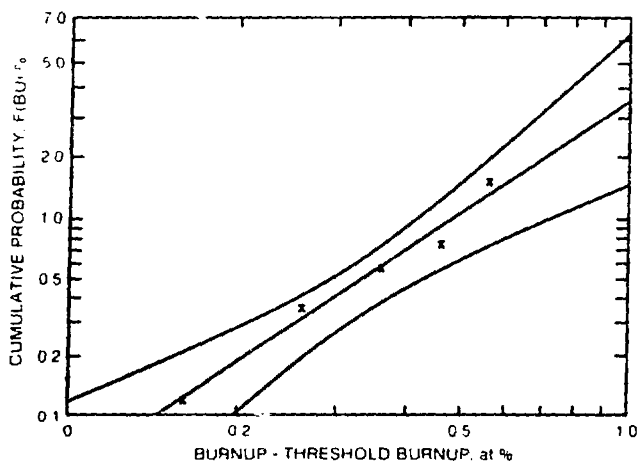


Fig. 13. Cumulative probability of breach (including 95% confidence) as a function of burnup minus threshold burnup resulting from "suspended-set and failed-set" analysis of all Mark-II breach events for "first-production" fuel. The data and results of this three-parameter distribution are given in Table III.

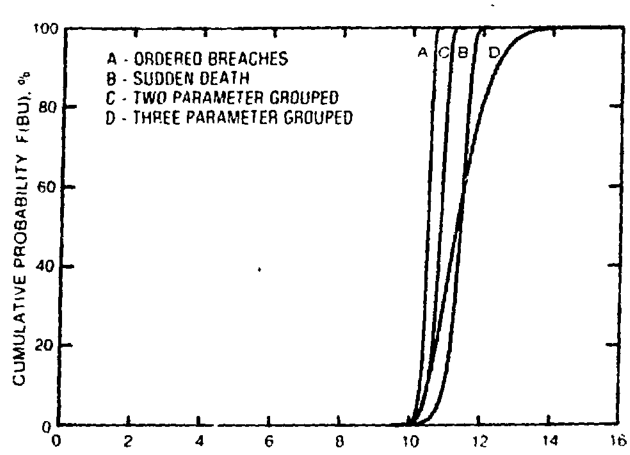


Fig. 14. Comparison of cumulative probability of breach obtained by four different analyses. Each indicates rapid rate of breach once 10 at.% burnup is attained.

Table IV shows the calculated burnup at which the first breach in systems of 91 and 1000 elements would be expected to occur (50% system reliability). The burnup which must be surpassed before the first breach can be expected to occur (95% system reliability) and the burnup at which the breach would certainly have occurred (5% system reliability) are included to indicate the expected range of burnups for first failure in the elements.

Table IV. Burnup Expected for First Breach in a Subassembly and a Core Loading

Number of Elements	Lower Bound (95% Reliability), at.% Burnup	Median (50% Reliability), at.% Burnup	Upper Bound (5% Reliability), at.% Burnup
91	10.07	10.16	10.30
5000	10.04	10.06	10.07

Discussion

Characteristics of Breach

All breaches of Type 316 stainless steel reference-design Mark-II driver-fuel elements have been located within the dimple. The fully annealed cladding is deformed by a maximum radial displacement of 36% during the dimpling operation. Optical and scanning electron microscopy have revealed slip and twinning in the dimple region. An increase in hardness corresponding to 15% cold work is observed in the root of the dimple. As a result of the dimpling operation, the inner surface of the cladding at the dimple exhibits a residual tensile stress as fabricated. During irradiation, the internal load due to fuel swelling and plenum gas pressure increases and causes reverse bending, resulting in significant tensile stresses on the outer surface at the root of the dimple.

A stress analysis (11) of the dimple region indicates a stress-intensity factor of 4.35 over the normal loading on the cladding. Any stress-assisted mechanism of breach will, therefore, be accelerated in the dimple region. Stress alone, however, is not believed to be the mechanism of breach, because the defects are not catastrophic.

Although the strain in the dimple is difficult to measure, the localized strain is estimated to be 15%. Total diameter increases of $4.3 \pm 0.5\%$ are obtained at axial positions between the core midplane and the top of the fuel column at normal operating temperatures and about 6% at higher temperatures. Since 40% of the increase typically results from swelling, about 4% mechanical strain can be achieved in the fueled region without incurring breach.

The Mark-II breaches originate on the outer surface and are intergranular. Breach of nonreference Mark-II elements (2) and Mark-IA elements (1) clad with Type 304L stainless steel have also originated on the outer surface. The defects also were intergranular, and intergranular stress corrosion and grain-boundary carbide precipitation were attributed as mechanisms of breach. Since the characteristics of breach are very similar for the two materials, the same mechanisms are believed to be operating. Grain-boundary embrittlement and/or stress corrosion appear to be the dominant mechanisms. The corrosion or embrittling species have not been determined. There is more than adequate time for fission products to diffuse along the cladding grain boundaries to the outer cladding surface where crack initiation began. Final assignment of the cause of breach must await Auger spectroscopy, transmission electron microscopy, and swelling and mechanical-strain analysis.

Breach of nonreference design elements clad with Type 304L stainless steel having restrainer dimples occurred within the fueled region rather than in the dimple. One encapsulated element of the same design and material reached 16.4 at.% burnup without breach. The fact that no Type 316-clad elements have breached outside the dimple indicates that the combination of material and dimple geometry may cause premature breach. One conclusion drawn from these results is that element lifetime could be extended if the design did not include the restrainer dimples.

<u>Characteristics of Lifetime</u>

Characterization of fuel-element lifetime is necessary, particularly from the viewpoint of reactor operations, to maximize fuel utilization. High system reliability can be maintained by establishing a burnup limit at a burnup lower than the burnup at which the first breach is expected. The Weibull statistical model provides a means of reliably quantifying these parameters.

The breaches of Mark-II driver fuel are characteristically end-of-life breaches in that none are observed at low or intermediate burnup, but promptly occur once 10 at.% burnup is attained. The growth of the defects in each of the three dimples of an element is closely related to burnup. Since the Weibull model is theoretically derived on the basis of the worst flaw in the system and accounts for breach threshold and a whole family of breach rates, the Weibull distribution is the best choice to characterize lifetime. The analysis indicates that although no breach can be expected prior to 10 at.% burnup, 63% of the elements will have incurred breach by 11.5 at.%.

Other criteria predicting lifetime could be established. Material property correlations may become more useful as the mechanisms of breach are further characterized. Obviously, the model and criteria must have some physical relationship to the breach character. In addition, the correlations must relate the following parameters to the breach defect: the operating conditions of fluence, power, and temperature; the material properties of composition and microstructure; and the chemical and mechanical behavior of the irradiated material.

Conclusions

Mark-II driver-fuel elements perform satisfactorily with high reliability to above 10 at.% burnup at which time breach has an ever increasing probability of occurring. The breach originates on the outer surface of the cladding in the root of the dimples and is intergranular. The ultimate element lifetime could probably be increased if the element were not dimpled.

The Weibull statistical model accurately predicts the minimum useful element lifetime that was experimentally observed. This model should come into wide use, because it can predict the reliability of a component within its lifetime based upon limited real-life operating experience. Based on the minimum useful element lifetime determined by Weibull analysis, a reactor core can be operated within the range of required reliability.

Acknowledgments

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