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PERFORMANCE IN THE EBR-II
OF A MIXED-OXIDE FUEL ELEMENT
WITH AN INTENTIONAL CLADDING DEFECT

Report Coordinated by

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EBR-II Project

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ABSTRACT

A technique involving dissolution of a soluble material in the cladding of an element was used to obtain a fission-gas release from a low-burnup (~1 at. %) mixed-oxide fuel element to the primary-system cover gas in EBR-II. The release of short-half-life fission gas was a small fraction (<0.6%) of the total inventory in the element, the ^{133}Xe release being double the release of the shorter-half-life ^{135}Xe . No plutonium was detected in the primary coolant after the event, nor was difficulty encountered in the hot cell during disassembly or handling of the element.

The gas from this element was identified by the xenon tag initially charged in the element plenum. The satisfactory identification of the source of the gas demonstrates the suitability of this technique for low-burnup elements.

I. INTRODUCTION

The operation of many mixed-oxide fuel elements in a liquid-metal-cooled fast breeder reactor will eventually lead to a condition in which the cladding allows release of the stored gas energy and fission products from the fuel element to the primary-system coolant and cover gas. At present, the events that occur during the gas release are poorly understood. To gain information in this area, experimental subassemblies containing mixed-oxide fuels have been loaded into EBR-II and will be irradiated until a fission-product release occurs from the element to the primary reactor system. Most of the tests consist of irradiating a "typical" (or available nearly typical) mixed-oxide fuel element until the cladding releases the gas inventory by a natural end-of-life process. A gas release could also occur early in the element lifetime from a cladding defect. Because the total fission-product inventory and plenum pressure would be less, the magnitude of the early release of gaseous fission products to the primary-system cover gas may be lower. To obtain more information in this area, an experimental subassembly with a defect in one element was inserted in the core. The

defect was programmed to "open" after a short irradiation period to determine the "fingerprint" release of fission products from a low-burnup oxide element to the primary-coolant system.

This program was a joint undertaking with Westinghouse FFTF personnel at the HEDL site. The predefecting technique that allowed the release of fission gas to the primary system from a low-burnup oxide element was conceived and proof-tested at HEDL. The fuel elements for the test were also provided by the HEDL organization.

This report describes the irradiation environment, the fission-product signals determined by the reactor-monitoring system, and the results of nondestructive tests.

II. OBJECTIVES

The primary objective of the test was to determine the magnitude of the fission-product inventory in the primary coolant system, as measured on the normal EBR-II reactor-monitoring system, when the cladding of a low-burnup mixed-oxide element "opened." Secondary objectives include the test of the programmed defect mechanism, an in situ test of the xenon-tag detection technique, and handling of subassemblies with exposed mixed-oxide fuel after cladding breaching. Also, this experiment represents the first in which a mixed-oxide fuel element was intentionally irradiated in EBR-II until fission products were released to the primary coolant system.

The response of the primary monitoring system is important because the magnitude of the fission-product release to the primary-system coolant and cover gas is important in formulating procedures to handle future releases. This low-burnup test, coupled with the forthcoming results of tests of a high-burnup element, will be used to modify the emergency operating procedures for releases to the primary system from oxide fuel elements. The release-to-birth ratios of various fission-product isotopes might be used to determine effective holdup of fission products for an element of this heat rating.

III. ELEMENT DESCRIPTION

Information on the mixed-oxide elements used in this test is summarized in Table I.

The defect technique allowed a 0.005-in.-dia hole through the cladding to "open" after an exposure in high-temperature sodium. The defect was 1/2 in. from the bottom of the fuel column. The defect consisted of the hole in the cladding, filled with a silver solder, which was

covered with a copper patch on the outside of the cladding. The copper was covered with a nickel flashing. Dissolution of the copper by the sodium (by entrance of sodium at the ends of the patch) eventually allowed the release of the element gas pressure. The time for the release was dependent on the length of the copper dissolved and was adjusted to allow at least 100 hr of sodium exposure.

TABLE 1. Fuel-element Description

<u>Fuel ($\text{UO}_2\text{-PuO}_2$)</u>	
Composition $[\text{Pu}/(\text{Pu} + \text{U})]$, %	25
Uranium composition, % ^{235}U	65
Plutonium composition, % $^{239}\text{Pu} + ^{241}\text{Pu}$	88
Diameter, in.	0.194
Pellet density, % TD	90
Smear density, % TD	85
Length, in.	13.5
Weight, g	65.2
<u>Insulator Pellets (Natural UO_2)</u>	
Diameter, in.	0.194
Top length, in.	3.72
Bottom length, in.	0.50
<u>Reflector (Type 316 stainless steel)</u>	
Diameter, in.	0.194
Length, in.	4.36
<u>Cladding (Type 316 stainless steel, 20% cold work)</u>	
Outside diameter, in.	0.230
Wall, in.	0.015
<u>Wire Wrap (Type 316 stainless steel, 20% cold work)</u>	
Diameter, in.	0.042
<u>Plenum</u>	
Volume, cm^3	6.1
Gas	Helium + xenon tag

The fuel elements used in this experiment were tagged with a xenon mixture having isotopes that are not produced in the fission-product birth-decay scheme.¹ Adjusting the ratio of isotopes used in the gas mixture resulted in a unique gas tag. Analysis of the primary-coolant cover gas for the xenon isotopes used in the tag allowed identification of the source. The element with the defect was tagged with a xenon mixture different from that in the remaining elements in the subassembly so that the source was readily identified.

IV. ENVIRONMENTAL CONDITIONS

The element was loaded, as Test A of the run-to-cladding-breaching series, in a high-risk Mark-E subassembly, X085, as shown in Fig. 1, which also shows coolant temperatures in different sectors of the subassembly. The special triple-wall subassembly contains a catch basket at the bottom and a screen at the top of the subassembly to contain any material released

Fig. 1. Loading Diagram and Coolant Temperatures at Top of Fuel in Experimental Subassembly X085

during the cladding breaching. The defected element identified as EW23 was in the center of the subassembly and was surrounded by two rows of fuel elements. The outer row contained 18 stainless steel elements to minimize the total number of fuel elements required for the test.

The subassembly was loaded in a 4N2 position in EBR-II, which resulted in element heat ratings of ~ 12 kW/ft. The coolant flow rate in the subassembly of 44 gpm resulted in a peak coolant temperature of $\sim 1100^\circ\text{F}$. The pertinent environmental and irradiation conditions are summarized in Table II.

The element heat ratings, listed in Table III, were obtained from the fission rates in the Guide for Irradiation Experiments in EBR-II² and the as-built weights and lengths. These values were used as input to the HECTIC³ program, with the subassembly geometry shown in Fig. 1 for the hot and cold sectors of the subassembly. This program calculates the coolant flow and temperature distribution in the subassembly sectors. The hexagonal-can geometry was divided into 12 symmetrical sections for the analysis. The subassembly coolant flow rate for a core pressure drop of 40.8 psi, the reference pressure drop in EBR-II, was 43 gpm (at 800°F). Because of the many experiments with low coolant flow and the constant total reactor flow, the core pressure drop was higher and resulted in an increased subassembly coolant flow. The subassembly flow rates for runs 47-49 are listed in Table IV. The subassembly heat production will also change during irradiation as loading changes occur in the core. The calculated heat productions for runs 47-49 are also shown in Table IV, as are the values used in the HECTIC calculation for the heat-transfer and flow analysis.

Because most of the irradiation exposure was accumulated under run-47 conditions, average values corresponding to those conditions were used for the heat-transfer calculation. Because of the row of dummy, non-heat-producing elements in the outer row, the subassembly temperature distribution was altered considerably from that of a fully loaded subassembly. Figure 1 shows the exit (or maximum) temperature distribution for coolant at the top of the fuel for two sectors. The coolant channels on the outside of the elements run essentially at the inlet temperature. For

TABLE II. Irradiation Summary for Experimental Subassembly XD85

	Core Position	MWd
Runs 47A-49A	4E2	1544
Run 49B	4F2	590
		2134
	Burnup, at. % (calculated)	
	Peak	Average
Defected element	0.88	0.78
Peak element	0.90	0.80
Fluence	0.8×10^{22}	
	Peak Heat Ratings, kW/ft	
Conditions at 62.5 MWt		
Hot	11.8	
Center	11.8	
Cold	11.1	
	Temperatures, °F (Element EW23)	
Maximum coolant	1084	
Maximum cladding	1155	
Maximum fuel surface, ^a	1780	
Maximum fuel centerline, ^a	4090	
Mixed-outlet coolant	835	
	Subassembly Flow Rate, gpm at 800°F	
Reference	43	
Run 47	44 ^b	

^aBased on a fuel-cladding gap conductance of 1000 Btu/hr-ft²-°F^bUsed in this analysis.

TABLE III. Element Heat Ratings

Position	Element	Heat Rating		Position	Element	Heat Rating	
		Peak, kW/ft	Total, kW			Peak, kW/ft	Total, kW
1	D ^a	0.39	0.39	20	EW13	11.4	11.5
2	D	0.39	0.39	21	EW14	11.2	11.3
3	D	0.39	0.39	22	D	0.39	0.39
4	D	0.39	0.39	23	D	0.39	0.39
5	D	0.39	0.39	24	EW15	11.5	11.5
6	EW1	11.7	11.7	25	EW16	11.4	11.4
7	EW2	11.8	11.8	26	EW17	11.3	11.3
8	EW3	11.5	11.6	27	EW18	11.4	11.4
9	D	0.39	0.39	28	D	0.39	0.39
10	D	0.39	0.39	29	D	0.39	0.39
11	EW4R	11.6	11.7	30	EW19	11.5	11.6
12	EW5	11.5	11.6	31	EW20	11.2	11.2
13	EW7	11.5	11.5	32	EW21	11.1	11.2
14	EW9	11.4	11.5	33	D	0.39	0.39
15	D	0.39	0.39	34	D	0.39	0.39
16	D	0.39	0.39	35	D	0.39	0.39
17	EW10	11.6	11.7	36	D	0.39	0.39
18	EW12	11.5	11.6	37	D	0.39	0.39
19	EW23	11.8	11.9				
				Total 226			

^aSolid stainless steel rod.

TABLE IV Subassembly Powers and Flow Rates

Run	Flow, gpm at 800°F	Power, kW/subassembly
47A	44	223
47B	44	234
49A	46	229
49B	46	230
HECTIC calculations	44	226

element EW1, the maximum calculated coolant temperature difference across the cladding was 230°F. For the next inner row of channels, the maximum difference was of the order of 20°F; the difference for the center element was only 7°F. Because the maximum coolant temperatures occur at the top of the element, the difference would be smaller at lower elevations in the nominal 13.5-in. fuel length.

The coolant flow around an element was averaged with respect to the component-channel flow rate to obtain an average coolant temperature. This temperature was used to calculate the average cladding and fuel temperature. For these calculations, a fuel-cladding gap conductance of 1000 Btu/hr-ft²-°F was used for the initial 0.006-in. fuel-cladding diametral gap. For the heat-transfer analysis, the fuel was assumed to have swelled, be in contact with the cladding, and have restructured into three density regions in accordance with the General Electric model.⁴ For the calculation, the element smear density was used. The results of the calculations are shown in Table V for the predefected element (EW23). The results are given as a fraction of the total 13.5-in. length with the coolant (average), outside cladding, inside cladding, fuel surface, and fuel centerline temperatures (in °F). Also given are the equiaxed, columnar, and void diameters in inches. For element EW23, the coolant temperature at the elevation of the defect was 713°F, and the cladding was at 735°F on the outside and 795°F on the inside.

TABLE V Temperature Distributions in Oxide Fuel Element EW23

X/L3	Heat Rating kW/ft	Temperatures °F					Diameter in		
		Coolant	Cladding Out	Cladding In	Fuel Surface	Fuel Center	Equiaxed	Columnar	Void
0.0	9.23	700	722	781	1383	3372	0.102		0.034
0.05	9.68	717	740	801	1432	3485	0.113		0.037
0.10	10.13	735	758	823	1483	3604	0.122		0.040
0.15	10.52	753	778	844	1530	3707	0.130		0.043
0.20	10.92	773	798	866	1578	3816	0.136		0.045
0.25	11.24	792	819	888	1621	3898	0.141	0.051	0.047
0.30	11.46	813	840	910	1657	3965	0.145	0.073	0.048
0.35	11.68	834	861	932	1694	4026	0.148	0.081	0.050
0.40	11.79	855	882	954	1722	4063	0.150	0.086	0.050
0.45	11.82	876	903	975	1745	4084	0.151	0.089	0.051
0.50	11.76	897	924	995	1761	4086	0.152	0.090	0.051
0.55	11.66	918	945	1014	1775	4081	0.152	0.089	0.051
0.60	11.46	939	965	1033	1780	4053	0.151	0.086	0.051
0.65	11.21	959	985	1051	1782	4010	0.150	0.081	0.050
0.70	10.91	979	1004	1068	1779	3967	0.148	0.073	0.049
0.75	10.56	998	1023	1084	1773	3910	0.146	0.056	0.048
0.80	10.16	1017	1040	1099	1761	3833	0.143		0.047
0.85	9.77	1035	1057	1113	1750	3758	0.139		0.046
0.90	9.32	1052	1073	1126	1734	3668	0.134		0.044
0.95	9.00	1068	1089	1140	1727	3611	0.131		0.043
1.00	8.88	1084	1105	1155	1733	3564	0.130		0.043

For a flow rate of 44 gpm, the mixed subassembly-outlet coolant temperature was 835°F.

The heat rating of the elements was chosen so that a portion of the fuel pellet would be converted to columnar grains. Because the gas-release

fractions of the short-lived noble-gas isotopes depend on fuel structure, as well as on volume of fuel restructured, it was desirable to operate with a portion of the fuel in the columnar region, as with most experiments in EBR-II.

V. IRRADIATION HISTORY

The subassembly was installed in the reactor vessel in core position 4E2 on October 28, 1970, for the start of run 47A. The design flow rate (for a core pressure drop of 40.8 psi) through the subassembly was 43 gpm. For this run, the higher core pressure drop resulted in a calculated flow of 44.1 gpm (at 800°F), which was used in the calculations. The reactor accumulated 975 MWd in run 47A before it was manually shut down on November 14, 1970, for repair of the intermediate heat exchanger. The reactor was cooled to as low as 300°F during the period of heat-exchanger repair. The reactor power was increased to 62.5 MWt on March 3, 1971, for run 47B, during which the reactor accumulated an additional 505 MWd. The reactor was shut down on March 13, 1971, because of an increase in cover-gas activity. During run 48 (A through E), the subassembly remained out of the core during the search for the activity source. The subassembly was reloaded in position 4E2 for run 49A (May 18, 1971). In this run, an additional 63 MWd was accumulated at a coolant flow rate of 46 gpm before the reactor was shut down on May 19, 1971. The subassembly was moved to position 4F2 for run 49B (May 20, 1971), in which 590 MWd was accumulated. Due to an increase in activity in the primary-system cover gas, run 49B was ended on May 31, 1971. The xenon-tag analysis of the cover gas indicated that the tag used in the predefected element had been released; therefore the activity source was the predefected element from experiment X085.

VI. RELEASE OF FISSION PRODUCTS TO PRIMARY-SYSTEM COVER GAS

The events that occurred during the release of fission products to the primary-system cover gas are summarized below.

At 0140 on May 31, 1971, the reactor-cover-gas monitor (RCGM) and the germanium-lithium argon-scanning system (GLASS) recorded a substantial increase in the cover-gas activity. (See Refs. 5 and 6 for a discussion of the EBR-II systems for monitoring fission products.) The GLASS system, in its initial operation, soon saturated, so that the on-line gamma-spectrum measurements could not be made. Limits specified by emergency procedures were soon exceeded; an anticipatory shutdown was started at 0141, and the reactor-building-evacuation alarm was sounded. About 6-7 min later, strong increases in the signals from channels A and B

were noted on the fission-gas monitor (FGM). Because recorders in the control room indicated no significant increase in building radiation levels, Health Physics personnel entered the reactor building at 0152 to obtain a cover-gas sample and start the continuous gas sampler. A rough survey of the reactor cover-gas sample indicated an increase from a normal level of 0.5 to about 45 mR/hr.

By 0205, all readings from the RCGM and FGM were off scale. The reactor building was again entered, and changes were made in range settings to bring the readings back on scale. Shortly thereafter, radiation levels in the reactor building, as indicated by control-room recorders, began to increase. A Health Physics technician equipped with supplied air reentered the building at 0303 to obtain another cover-gas sample and retrieve an air sample.

By 0330, a continuous air monitor on the operating floor indicated an increase in activity to about 10,000 cpm from a normal level of 1500. At this time, actions for partial building isolation were begun. No increase was noted in the activity level of the exhaust air. During the next hour, building radiation alarms were activated. One, on the operating floor, alarmed at 0331, and another, in the subbasement, alarmed at 0420.

At 0540, the two primary-coolant pumps were secured. Thirty minutes later, at 0610, another cover-gas sample was taken. At 0630, personnel began xenon-tag trapping.

The xenon activities in the cover gas are summarized in Table VI and shown in Fig. 2. The ^{133}Xe concentration in the cover gas increased from an ambient level of about 1.3×10^{-3} $\mu\text{Ci/ml}$ to a peak of 0.36 $\mu\text{Ci/ml}$, an increase by a factor of 270. The concentration of the shorter half-life ^{135}Xe increased from 2.5×10^{-3} to 0.25 $\mu\text{Ci/ml}$, an increase by a factor

TABLE VI. Release of Fission Products to Primary-system Cover Gas

Time: May 31, 1971	Reactor Power	Fission Products, $\mu\text{Ci/ml}$		
		^{133}Xe	^{135}Xe	^{41}Ar
0140	62.5 MWt	1.33×10^{-3}	2.52×10^{-3}	2.7×10^{-3}
0205	50 kWt	2.82×10^{-1}	2.33×10^{-1}	
0306	0	3.16×10^{-1}	2.48×10^{-1}	5.03×10^{-4}
0510	0	3.53×10^{-1}	2.35×10^{-1}	1.64×10^{-4}
0630	0	3.60×10^{-1}	2.19×10^{-1}	
1120	0	3.34×10^{-1}	1.42×10^{-1}	
1450	0	3.13×10^{-1}	1.05×10^{-1}	
1000	0	3.05×10^{-1}	8.18×10^{-2}	
1650	0	3.08×10^{-1}	8.99×10^{-2}	
2030	0	2.95×10^{-1}	6.67×10^{-2}	
2250	0	2.98×10^{-1}	5.47×10^{-2}

Fig. 2. Xenon Activity in Cover Gas and Power Operating History during Release to Primary System from Subassembly X085

of 100. The FGM signal increased by a factor of about 50 above the background, as shown in Fig. 3. A careful inspection of strip-chart records showed no perceptible change in any of the signals for detection of fuel-element rupture (delayed-neutron--FERD). The increases shown in the monitoring systems are summarized in Table VII. At no time before, during, or after the release did recorders indicate any anomalous change in reactivity, power, or subassembly outlet temperature.

As cited above, the xenon-tag technique was used to identify the defected element. About 5 ft³ of cover gas was cold-trapped on activated charcoal. The xenon fraction was then collected and analyzed with a mass spectrometer. The results confirmed that xenon-tag mixture had been released to the cover gas and that the mixture corresponded to that in the

predefected element in Test A (subassembly X085), the first run-to-cladding-breaching experiment. The pertinent xenon-tag results are summarized in Table VIII. A comparison of the measured isotopic ratios with those associated with other xenon-tagged experiments revealed, beyond any reasonable doubt, that the released tag could have come only from X085. The fact that the $^{129}\text{Xe}/^{124}\text{Xe}$ and $^{129}\text{Xe}/^{128}\text{Xe}$ ratios were larger than those of the library sample (BD-284) may be attributed to the natural xenon contamination of the cover gas. Only a small amount of ^{129}Xe , the most abundant of the lighter isotopes, is needed to increase these ratios by the amount noted.

Fig. 3. Increase in Counts of Fission-gas Monitor from Subassembly X085

TABLE VII. Response of EBR-II Fission-product-monitoring System

System	Signal/Background
FERD	1
FGM	50
^{135}Xe	100
^{133}Xe	270

TABLE VIII. Analysis of Xenon Tags in Cover Gas

Isotopic Ratio	Test A (Subassembly X085) Prefected Element	Measured Value from Argon Cover Gas	
		Uncorrected	Corrected ^a
129/124	11.5	14.8	11.7
128/124	28.4	28.8	28.8
126/124	0.342	0.34	0.339
129/128	0.405	0.51	0.405

^aIsotopic ratios corrected for ¹²⁹Xe contribution from natural xenon in cover gas

Analyses of sodium samples taken on May 28 and June 1 indicated an increase in the ¹³¹I level. On May 28, the ¹³¹I level was 7.2×10^{-5} $\mu\text{Ci/g}$, in good agreement with the predicted value of 8.0×10^{-5} $\mu\text{Ci/g}$ for the tramp (background) uranium in the sodium. On June 1, the level of ¹³¹I increased to 14.7×10^{-5} $\mu\text{Ci/g}$, as compared to the predicted value of 0.8×10^{-5} $\mu\text{Ci/g}$. No change was noted in the ¹³⁷Cs level from May 28 to June 1. These results are shown in Fig. 4. Sodium analysis also indicated that the plutonium levels were below the detectable limit, <1 (dis/g)/sec.

Fig. 4. Activities of ¹³¹I and ¹³⁷Cs in Sodium during Release to Primary System from Subassembly X085

At the end of run 49B, subassembly X085 was moved from the core to the storage basket.

VII. COMPARISON OF INCREASE IN FISSION-PRODUCT ACTIVITY IN COVER GAS WITH INVENTORY IN ELEMENT

The calculated equilibrium concentrations of ^{133}Xe and ^{135}Xe in the element were 701 and 705 Ci, respectively. For ^{135}Xe , with a shorter half-life (9.16 hr), the equilibrium concentration was achieved because sufficient operating time elapsed between the last scram and the release. For the longer-half-life ^{133}Xe (5.27 days), however, the short-term power outages (see Fig. 2) would not permit the saturation concentrations to be reached. Instead, about 70% of the saturation level was achieved. If all the saturation activity is released to the 625 ft³ of primary-system cover gas (at operating conditions), each isotope concentration would be 83 $\mu\text{Ci}/\text{std cm}^3$, or about 40,000 times the normal background levels. The actual gas release was less than 1% of the inventory, perhaps because of lack of pressure equalization between the element and the coolant or fission-product holdup in the fuel pellets. The plenum pressure in the element would be 43 psia, if no fission gas is released from the fuel, or 120 psi, if 100% of the fission gas is released (0.246 gas atom/fission). The static coolant pressure outside the element at the elevation of the defect would be 32 psia at conditions of full coolant flow, or 19 psia with the pumps shut down. For full-flow conditions, the maximum gas-release fraction from the element to the primary-system coolant, based on static pressure equilibrium, could vary from 73% for complete gas release to the primary system to 26% for essentially zero gas release. During the shutdown condition, the release fraction would increase to 80% for 100% gas release and 52% for zero gas release. The actual gas release to the primary system was 0.62% of the element inventory of ^{133}Xe and 0.30% for ^{135}Xe . The equilibrium concentration of ^{131}I (which would not be achieved for the isotope with an 8.06-day half-life) would be 34 Ci. For the primary-coolant volume, the equilibrium concentration would be $\sim 1.1 \mu\text{Ci}/\text{g}$. The measured concentration increase was less than 0.01% of the element inventory.

The low release fraction may have partially been due to the patch restricting the pressure equilibrium. In addition, the small gas release of the xenon isotopes may have been caused by holdup (diffusion) in the fuel. The higher release of ^{133}Xe (5.27-day half-life) in comparison with ^{135}Xe (9.2-hr half-life) indicates that diffusion (or a rate-controlled process) in the fuel may control the fraction of the xenon isotope released. Recoil fission fragments, calculated from data on UO_2 pellets,⁷ could account for about 0.065 $\mu\text{Ci}/\text{cm}^3$ in the cover gas for ^{133}Xe and 0.095 $\mu\text{Ci}/\text{cm}^3$ for ^{135}Xe ; these values are 18% of the measured ^{133}Xe activity and 38% of that for ^{135}Xe . Diffusion or knock-on from the surface can account for about the same magnitude of release; however, the ^{133}Xe release fraction would be larger than that for ^{135}Xe . The uncertainty in the low-temperature diffusion coefficient, however, is large, so that error in the calculation is high. Also, the actual surface area, a function of pellet density, may affect the coefficient.

The model used in the heat-transfer calculations predicted a void all the way through the fuel that varied from a 0.034-in. diameter at the bottom, to a maximum of 0.051 in. at the center, to 0.043 in. at the top. The neutron radiographs, however, indicate that the central void does not extend through the end pellets for element EW23. This result indicates that either the rate processes in void formation had not allowed the "equilibrium" radii used in the heat-transfer analysis to be achieved, or the fuel-cladding-gap coefficient was higher than the 1000 Btu/hr-ft²-°F used in the analysis. Until the metallurgical cross sections of the fuel pellets are made to check the lack of an axial void through the fuel, the relation of gas release to fuel structure can only be estimated. If a complete axial void does not exist, the gas that accumulates in the center void would probably not be released until the fuel cracked from a thermal transient. The power decrease after the release of fission products to the primary system should have cracked the fuel to allow the gas release.

The iodine isotopes would be a vapor at the temperatures of the element if they remain unreacted. As such, the release fraction should be about the same as the nearly inert xenon. Since the release was a decade less than that for the xenon isotopes, however, the highly reactive iodine must be combined in a manner that lowers its release fraction.

VIII. POSTIRRADIATION EXAMINATION

After 23 days of cooling, the subassembly was transferred to the fuel-unloading machine (FUM), where the sodium was allowed to drain. During this process, argon was forced down through the subassembly to remove both excess sodium and decay heat from the subassembly. The subassembly was then transferred to the interbuilding transfer coffin (IBC) for transfer to the Fuels and Examination Facility (FEF). During this time, the decay heat was removed from the subassembly by forced argon cooling. The ¹³³Xe activity in the argon of the IBC increased to 0.54 $\mu\text{Ci}/\text{cm}^3$ during the transfer operation. This value, which is greater by a factor of about 80 than the ¹³³Xe activity in the argon, clearly indicated that the element was still evolving fission-product gas during the transfer. The subassembly was given a moisturized-argon purge for 1.5 hr to oxidize the remaining sodium. The procedure is given below.

1. The subassembly in the IBC was moved to the sodium-removal station in the FEF. Cooling was provided by recirculating argon at 30 cfm in the shielded coffin.

2. Moisturized argon (argon bubbled through water) was added to the recirculating argon at 0.4 cfm for 60 min, and the resulting gas mixture was removed from the coffin at the same rate.

3. The moisturized-argon flow was increased to 7 cfm for 30 min, and the resulting gas mixture was removed at the same rate.

4. The coffin was purged with dry argon at 30 cfm to remove any accumulated hydrogen formed during the previous steps.

5. The subassembly was rinsed by flowing deionized water up through the subassembly at 5 gpm; a total of 25 gal of water was used.

6. The subassembly was dried by blowing dry argon through the coffin at 30 cfm for 60 min.

A. Subassembly Examination

A straightness check on the subassembly indicated that no measurable bowing had occurred. Flat-to-flat measurements of the subassembly hexagonal tube near its ends and at two points in the core region indicated no significant changes in these dimensions.

No difficulties were encountered during dismantling of the subassembly. Visual examination of subassembly hardware revealed no unusual discolorations or deformations. Visual examinations of the elements with a Kollmorgen hot-cell periscope during the dismantling also revealed no unusual features on any of the elements except the defected element. The nickel patch on the defected element was visible, but no other unusual features were observed.

B. Nondestructive Examination of Element

Detailed postirradiation, nondestructive examinations were performed on the defected element and the six elements adjacent to it in the subassembly. These examinations consisted of (1) visual examinations at magnifications up to about 4 diameters, (2) neutron radiography (by use of the TREAT reactor) at 0 and 90° azimuthal orientations with both dysprosium and indium transfer foils, (3) profilometry, (4) bowing and length measurements, (5) balance-point determinations, and (6) weighing.

A brief description of the results of the postirradiation examinations follows:

1. Visual Examinations.

Visual examinations showed all the elements examined to be in excellent condition, except for the patch on the defected element. No discolorations or defects were observed in any of the elements surrounding the defected element. A few small areas had a light coating of sodium residue. These areas appeared to be the regions in which the spacer wire from adjacent elements had come in contact with the element when in the subassembly array.

Examinations of the area of the defect in element EW23 showed that the nickel plating had not been removed while the element was in the reactor. The plating had bulged and become ridged, but no large holes or cracks were observed. It was not possible to identify the point where the fission-product gas had escaped from the element. Photographs of the patch on the defected element are shown in Figs. 5 and 6.

2. Neutron Radiography

The seven elements were neutron-radiographed at TREAT in two azimuthal orientations (0 and 90° with respect to the T-bar slot). Both dysprosium and indium transfer foils were used to obtain fuel-outline and fuel-penetration exposures, respectively.

The neutron radiographs show that a narrow (~0.02-in.-dia) centerline void formed in the elements. Each pellet is distinct because of the dished-end design of the pellets. There is no evidence of the defect in

Fig. 5. Element EW23: Patch Area at 240° Clockwise.
Mag. 5X. ANL Neg. No. 103-P5392.

Fig. 6. Element EW23: Patch Area at 120° Clockwise.
Mag. 5X. ANL Neg. No. 103-P5391.

element EW23 in any of the radiographs. The radiographs revealed no unusual or abnormal conditions in any of the elements. The radiographs of the element indicate that the central void does not extend axially through all of the pellets.

Cladding Diameter. During irradiation, diameter profiles were obtained with a contact profilometer for the defected element and the six elements adjacent to it in the subassembly. The measurements were made in an azimuthal orientation about 90° from the element spacer wire. The elements were rotated with a variable-speed motor in an effort to maintain the contact probes at the proper orientation with the wire. The effort was not completely successful, and the probes contacted the spacer wires on several occasions while the seven elements were being measured. The accuracy of the profilometer is ± 0.0002 in.

The maximum changes in diameter for the seven elements are summarized in Table IX. These maximum increases were obtained by

subtracting the average diameters indicated on the profilometer trace near the top regions of the elements from the peak diameters of the elements as indicated on the profilometer traces. The average maximum diameter change for the elements was about 0.2%.

TABLE IX. Maximum Diameter Changes for Elements from Subassembly X085

Element Number	Diameters, in		Maximum Diameter Change	
	Maximum	Average Minimum	in	%
EW5	0.2304	0.2299	0.0005	0.22
EW7	0.2306	0.2302	0.0004	0.17
EW12	0.2305	0.2299	0.0006	0.27
EW23 ^a	0.2303	0.2299	0.0004	0.17
EW13	0.2303	0.2298	0.0005	0.22
EW16	0.2301	0.2298	0.0003	0.13
EW17	0.2302	0.2298	0.0004	0.17

^a The region of the nickel plating covering the patch, a maximum diameter of 0.2369 in. was recorded.

The profilometer trace of the defected element showed no indication of unusual diameter increases at either side of the patch. The element diameter increased in a step to 0.231 in. at the patch and then rapidly fluctuated in the area of the bulges or ripples in the patch itself. A peak diameter of 0.2369 in. was recorded in the region of the patch.

The diameter profile is presented in Fig. 7 for element EW23.

Fig. 7. Diameter Profile of Element EW23, Subassembly X085

3. Element Length

The overall lengths of seven elements were measured with a remotely controlled device that incorporates a precision indexing platen and a dial-indicator measuring system. The reproducibility of the length measurement was ± 0.01 in. No corrections for element bowing or temperatures were made for the data obtained.

Overall length measurements for the elements are listed in Table X. The data indicate a slight decrease in the length of all the elements measured. Although the decrease is of about the same magnitude as the accuracy of the measurements, the fact that all the elements show a length decrease indicates that the decrease is real. The decrease may be due to bowing of the elements, but may also be due to a reduction in the volume of the cladding caused by annealing of the cold-worked material as a result of reactor service.

TABLE X. Overall Length for Elements from Subassembly X085

Element Number	Length, in.		
	Preirradiation	Postirradiation	Change
EW5	39.98	39.97	-0.01
EW7	39.99	39.97	-0.02
EW12	39.99	39.98	-0.01
EW23	39.88	39.87	-0.01
EW13	39.99	39.97	-0.02
EW16	39.99	39.97	-0.02
EW17	40.01	40.00	-0.01

The bowing of the elements was measured in the device used for the length measurements. The elements were measured in a vertical position with support near their top and bottom ends so that the element was free to assume its unrestrained configuration. Coordinates (X and Y) of the element in the horizontal plane were determined at several axial locations with respect to a reference established on the machine. These bowing coordinates for the element were determined by probes on the machine that stop when electrical contact is made with the element. The coordinates were used to calculate the relative bowing (deviation from a straight-line chord) of the element at the various axial locations measured. The accuracy of the bowing measurements is ± 0.02 in.

The relative bowing for element EW23 is shown in Fig. 8. The maximum bowing and deviation are given in Fig. 9 for seven elements in the subassembly.

4. Balance Points

Balance points were determined by use of a device that allows the element to be moved along a capsule holder, which rests on a V-shaped

steel fulcrum, until the balance point of the element is reached. The accuracy of the device is ± 0.005 in.

Fig. 8

Bowing of Element EW23, Subassembly X085.
(Angles measured counterclockwise from sub-assembly index notch.)

SYMBOL "°" INDICATES DIRECTION OF BOW

POSITION	CAPSULE	BOW, in.	DIRECTION, °	AXIAL POS, in.
12	EW5	0.082	234	24.0
13	EW7	0.199	92	24.0
18	EW12	0.150	252	24.0
19	EW23	0.035	332	21.0
20	EW13	0.101	35	23.0
25	EW16	0.266	248	21.0
26	EW17	0.146	25	21.0

(ANGLES MEASURED COUNTERCLOCKWISE FROM SUBASSEMBLY INDEX NOTCH)

Fig. 9. Maximum Bowing of Elements in Subassembly X085

The balance points for the seven elements are given in Table XI. All the changes were within the accuracy of the device, except that of the defected element, EW23. The balance point for EW23 moved 0.009 in. toward the top end of the element, indicating a weight shift for the element from its bottom end (core region) and nearer to its top region (plenum region).

TABLE XI. Balance Points of Elements from Subassembly X085

Element Number	Balance Points		
	Preirradiation, in. from Top	Postirradiation, in. from Top	Change, in.
EW5	22.595	22.597	+0.002
EW7	22.560	22.563	+0.003
EW12	22.590	22.593	+0.003
EW23	22.582	22.573	-0.009
EW13	22.583	22.583	0.000
EW16	22.585	22.583	-0.002
EW17	22.597	22.599	+0.002

5. Element Weight

The seven elements were weighed with a remotely controlled balance having an accuracy of ± 0.1 g. Weights of all elements were within 0.1 g of preirradiation weights. The weights are listed in Table XII.

TABLE XII. Weights of Elements from Subassembly X085

Element Number	Weight, g		
	Preirradiation	Postirradiation	Change
EW5	190.6	190.6	0.0
EW7	190.6	190.6	0.0
EW12	190.3	190.4	+0.1
EW23	192.6	192.6	0.0
EW13	190.2	190.3	+0.1
EW16	190.6	190.7	+0.1
EW17	190.8	190.8	0.0

6. Element Gamma Scan

Two elements from subassembly X085 were gamma-scanned with the FEF Precision Gamma Scanner (PGS). The data were obtained on these elements by counting for 5 min at discrete positions on the elements. All gamma-ray energy levels to 3.2 MeV were analyzed; and counting rates for ^{141}Ce , ^{103}Ru , ruthenium daughter 106, ^{137}Cs , ^{95}Zr , ^{95}Nb , ^{58}Co , ^{54}Mn , barium daughter 140, and ^{59}Fe were reported. The counting rates were all normalized to give the counting rate at the end of the elements' irradiation date, rather than at the time the elements were scanned.

Element EW23 (the predefected element) was counted at 0.1-in. intervals along its longitudinal axis and at 0.02-in. intervals diametrically across it at five axial locations. Element EW5 was counted at 0.25-in. intervals along its longitudinal axis.

The slit opening of the PGS collimator was set at 0.020 in.; width of the opening is 0.5 in. The slit was positioned horizontally for axial scans and vertically for diametral scans. The slit was centered at the axial position on the elements corresponding to the bottom of the reactor core, and 0.4, 0.8, 1.2, and 1.6 in. above this initial position for the diametral scans on element EW23.

The axial scans showed no unusual distribution of fission products in the elements.

The radial profiles are shown in Figs. 10-13. Figures 10 and 11 show the radial ^{58}Co activity at different elevations. As expected, the activity peaks at the edges of the element, where cladding is thickest. Figure 12 shows the radial ^{95}Nb activity, which, as expected, peaks at the center of the pellet, where fuel is thickest. The ^{137}Cs activity (Fig. 13) shows that the cesium has migrated toward the edges of the fuel.

The close similarity in the axial-distribution profiles for the fission products in elements EW23 and EW5 shows that no significant relocation of fuel occurred during the breaching (because of predefecting) of the cladding of element EW23. The relatively uniform ^{137}Cs distribution in element EW23 also indicates that no significant amounts of this fission product were lost during the subsequent handling of the fuel element.

Fig. 10. Diametral Distribution of ^{58}Co for Element EW23 at Three Axial Locations, from 0 to 0.8 in. above Bottom of Core

Fig. 11. Diametral Distribution of ^{58}Co for Element EW23 at Two Axial Locations, 1.2 and 1.6 in. above Bottom of Core

Fig. 12. Diametral Distribution of ^{95}Nb for Element EW23 at Five Axial Locations, from 0 to 1.6 in. above Bottom of Core

Fig. 13. Diametral Distribution of ^{137}Cs for Element EW23 at Five Axial Locations, from 0 to 1.6 in. above Bottom of Core

C. Discussion

Postirradiation examination showed no detectable evidence of any changes in the elements adjacent to the defected element as a result of the gas release to the primary system from that element. The only observable changes in the condition of the defected element were rippling or ridging in the plating covering the defect and an extremely small shift in the balance-point location of the element.

There were no problems in handling the defected element in the FEF air cell because of the defect.

The examination results showed that this element breaching was benign in that no observable damage occurred to any of the elements or the subassembly.

IX. SUMMARY

The predefected cladding of a mixed-oxide fuel element allowed a fission-product release to the primary-system cover-gas after 0.8 at. % burnup. The most significant result of the release was the relatively low

fractions of the short-half-life fission gas released in comparison with the total inventory. The 100%-higher release of the longer-half-life isotope ^{133}Xe in comparison with ^{135}Xe also indicates that diffusion from the fuel may limit the gas-release fractions of the shorter-half-life fission products. The xenon fission gas released to the plenum was only 0.6% of the total element inventory for ^{133}Xe and 0.3% for ^{135}Xe . About one-third of the measured release may be attributed to recoil release. Knock-ons or diffusion from the surface may account for the remainder. The uncertainty in the diffusion coefficient, as well as in the surface area, prevents accurate prediction of the magnitude of this source.

The ^{131}I inventory in the sodium coolant increased after the gas release, but represented only a small fraction of the total inventory. No increase was seen in the ^{137}Cs activity. Plutonium in the sodium coolant was less than the detectable limit, <1 (dis/g)/sec.

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R. M. Fryer	Fission-product detection
R. R. Smith	Fission-product detection
R. V. Strain	Postirradiation examination

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