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FISSION-PRODUCT RELEASES TO THE
PRIMARY SYSTEM OF EBR-II FROM
APRIL 1975 TO MARCH 1977

by

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EBR-II Project

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ABSTRACT

This report describes the 14 releases of fission products that occurred in EBR-II from April 1975 to March 1977. Each release was readily detected, and all but one (in a driver-fuel subassembly) was identified with a particular subassembly. Xenon tagging was the primary method of identification, although other methods were used where appropriate. Methods of monitoring and identifying fission-product sources are discussed, and each release and identification is described. Effects of breached elements on plant availability were minimal in this period. From all evidence, cladding breaching on elements in EBR-II continues to be a benign process.

I. INTRODUCTION

Experimental fuel elements have been irradiated in EBR-II since 1965. Cladding breaches have developed in a small portion of these elements to cause release of fission products to the primary system of the reactor. Although several early releases of fission products were caused by such things as defective closure welds, most of the releases to date have been from elements intentionally left in the reactor until the cladding breached. To limit activity in the argon cover gas, an often-protracted search has been made to identify each source and to remove it as soon as possible from the core.

References 1-9 describe the searches made for elements with breached cladding from 1967 to March 1975. The present report summarizes such operations from April 1975 to March 1977. During this period, cladding breaches developed in the unencapsulated elements of 13 experimental subassemblies and of one driver-fuel subassembly. This report includes summaries of methods to monitor and identify sources of fission-product releases; descriptions of the releases, in chronological order; and a discussion of experience gained from identifying the sources and their impact on EBR-II operations.

II. METHODS OF MONITORING AND IDENTIFYING FISSION-PRODUCT SOURCES

A. Monitoring Sources

The fission products released from an element with breached cladding in EBR-II are monitored in several ways. The activities of selected fission-gas isotopes are measured qualitatively by the fission-gas monitor (FGM),⁵ the reactor cover-gas monitor (RCGM),¹⁰ and the germanium-lithium argon-scanning system (GLASS).¹¹ These monitors use a common supply of argon cover gas, which is extracted from the T nozzle of the reactor; the gas is aged about 2 min to suppress the 38-s activity of ²³Ne. Periodically, 10-mL "grab" samples of cover gas are obtained from the same nozzle and counted in the laboratory to directly measure the activities of ¹³³Xe and ¹³⁵Xe. At the time of a release, a "tag sample" of about 15 ft³ (0.41 m³) of cover gas is also treated cryogenically to concentrate the isotopes of xenon for mass spectrometry. The presence of ¹²⁴Xe and ¹²⁶Xe in this sample indicates that the release is from an element containing a xenon tag. Any delayed neutrons released from the source are detected in a bypass flow of the primary sodium by the fuel-element-rupture-detector (FERD) system.⁵ Finally, samples of sodium taken from the primary tank are analyzed for the presence of ¹³¹I, ¹³⁷Cs, ²³⁵U, and ²³⁹Pu. Plutonium has never been detected in the primary sodium.

During normal operation, fairly reproducible background fission-product activities caused by fissioning of a small quantity of "tramp" uranium in the core are observed in the sodium and in the cover gas. The uranium is thought to be present as a contaminant on or near the surfaces of stainless steel components.

Table I summarizes the fission-product activities routinely monitored in EBR-II and their normal background activity levels when no sources other than tramp uranium are in the reactor.

TABLE I. Fission Products Monitored in EBR-II

Isotope	Half-life	Decay Constant, s ⁻¹	Monitoring System	Normal Background Activity at 62.5 MWt, $\mu\text{Ci/ml}^a$
^{85m} Kr	4.4 h	4.38×10^{-5}	GLASS, RCGM	3.4×10^{-4b}
⁸⁷ Kr	76.0 min	1.52×10^{-4}	GLASS	1.5×10^{-4b}
⁸⁸ Kr	2.79 h	6.90×10^{-5}	GLASS, FGM	5.6×10^{-4b}
⁸⁹ Kr	3.18 min	3.63×10^{-3}	FGM	
¹³³ Xe	5.27 d	1.52×10^{-6}	GLASS, RCGM, argon grab sample	1.5×10^{-3c}
^{135m} Xe	15.7 min	7.36×10^{-4}	GLASS	2.3×10^{-5b}
¹³⁵ Xe	9.16 h	2.10×10^{-5}	GLASS, RCGM	2.5×10^{-3c}
¹³⁸ Xe	14.2 min	8.13×10^{-4}	GLASS, FGM	7.5×10^{-5b}
¹³¹ I	8.07 d	9.95×10^{-7}	Sodium sample	$4.0 \times 10^{-5} \mu\text{Ci/g}^c$
¹³⁷ Cs	30.1 yr	7.30×10^{-10}	Sodium sample	$6.5 \times 10^{-2c,d}$

^aConversion factor: 1 $\mu\text{Ci} = 37 \text{ kBq}$.

^bBased on GLASS data.

^cBased on laboratory analyses of argon or sodium samples.

^dReleased from subassembly X011 in May 1967 (Ref. 1) and from subassemblies X180, X213, and X194 in October 1974-January 1975.¹⁰

B. Identifying Sources

Eight methods have been developed over the years to help identify fission-product sources in EBR-II. Table II summarizes how each method is used during a release to identify its source. No method is used exclusively. If one method strongly indicates a particular subassembly as a source, the other methods are applied to that subassembly. If the diagnosis is then inconclusive, the search continues. Fortunately, the use of xenon tagging has reduced such iteration to a minimum.^{8,9}

TABLE II. Methods Used to Identify Sources of Fission-product Releases in EBR-II

Method	Data Source	Purpose	Advantages	Disadvantages
1. Weibull failure	a. Previous failures b. Surveillance	Ranks suspects by failure probability	Predicts breach in advance; helps rank otherwise equal suspects	Assumes common mode of failure; limited by previous experience
2. ^{135m}Xe behavior	GLASS activity	Indicates release of bond sodium	Rapid	None; occasionally overlooked
3. Normalized excursion parameter	GLASS activity	Discriminates between metal and oxide	Rapid	Empirical; uses complex release characteristics that may give ambiguous results
4. Ratio $^{131}\text{Xe}/^{134}\text{Xe}$	Tag sample	Discriminates between metal and oxide	Uses abundant stable isotopes of xenon	Can be affected by tag in low-burnup elements
5. Ratio $^{134}\text{Xe}/^{133}\text{Xe}$	a. Tag sample b. Power history	Discriminates between metal and oxide	Identifies type and burn-up of suspect	Ratio changes for same element; affected by fuel and breach geometry
6. Fission-gas volume	a. Grab sample b. Tag sample	Identifies suspects by gas release	Eliminates low-burnup suspects	Usually limited applicabilities
7. Xenon tag	a. Grab sample b. Tag sample c. Surveillance	Identifies suspects by tag composition	Limits choice to one to three suspects	Exposure changes in tag; tag releases sometimes small; contamination
8. Fission-gas and tag volumes	a. Grab sample b. Tag sample c. Surveillance	Discriminates between suspects with similar tag compositions	Ranks xenon-tag suspects	As for preceding item; also early tag volumes were variable

Method 1, based on cladding-failure statistics, relies solely on previous experience and is used when several cladding breaches have already occurred in a large group of similar elements, such as the driver-fuel elements in EBR-II.^{12,13} The method is applied with somewhat less certainty to predict the likelihood of cladding failure in smaller groups of experimental elements.¹⁴

Methods 2 and 3 use the raw activity data obtained during a release. If the ^{135m}Xe activity increases while the ^{138}Xe activity stays at background level, or if the decay of ^{135m}Xe is much slower than the decay of ^{138}Xe after the initial release, the source is likely to be a sodium-bonded element that is losing some of its bond, and iodine, to the primary coolant. In a similar fashion, if the initial release contains significant amounts of short-lived gas isotopes and the ^{135}Xe decays along with ^{138}Xe , the source is more likely to be a gas-bonded element than a sodium-bonded element.¹¹ Although rapid, both methods are used with caution, because extraneous factors can easily affect the measured activity of short-lived radioisotopes.

The five methods (4-8) that involve mass spectrometry of samples of cover gas are lengthy, but generally lead to an accurate diagnosis. Two of these methods (4 and 5) help identify the type of source by measured ratios of

the xenon isotopes. The ratio of stable ^{131}Xe to stable ^{134}Xe has been consistently lower for uranium fuels than for fuels containing uranium and plutonium.¹⁵ Similarly, the ratio of stable ^{134}Xe to radioactive ^{133}Xe increases with burnup in a different manner for the two types of fuel.¹⁶ Method 6 compares the measured volume of fission gas released from a source with the calculated volumes of fission gas in the plenums of all elements in the core. In this way, elements with not enough fission gas in their plenums can be eliminated as suspects. The calculated plenum contents are based on empirical correlations of fission-gas release^{17,18} and are updated for each EBR-II run.

The last two quantitative methods (7 and 8), involving recognition of a xenon tag, are the most accurate, and, because all experimental EBR-II elements are now tagged, are also the most frequently used. A xenon tag is about a 1-mL volume of a mixture of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe that is added to an element during fabrication. The elements in each tagged EBR-II subassembly contain the same unique tag. Method 7 simply matches the measured tag composition in the cover gas to the closest tag composition known to be in the reactor. This comparison must allow for the composition changes that occur because of ^{124}Xe burnout and ^{128}Xe production during irradiation.¹⁹ Method 8 allows discrimination between tags of similar composition by comparing the measured volume ratio of fission gas to tag gas in the cover gas with the calculated ratios for the elements in the suspect subassemblies.²⁰ The calculated ratios are obtained from the known amounts of tag in the elements and the estimated accumulation of fission gas in the element plenums.

III. CHRONOLOGY OF FISSION-PRODUCT RELEASES

A. Subassembly X207 (Run 77B)

After the annual shutdown for maintenance, the reactor reached 62.5 MWt on April 29, 1975, for the start of run 77A. The absence of unusual short-lived fission-gas activity confirmed that the source of the release, before the shutdown, had been successfully identified as subassembly X202.⁹ No abnormal activity was observed in the cover gas until June 14, 1975, during run 77B, when the activity of ^{133}Xe slowly increased. The absence of any enhanced short-lived isotope activity indicated a very slow release of fission gas from the breach site. By June 17, the ^{133}Xe activity detected by GLASS was about 10 times above background, whereas activities of all other monitored isotopes remained at their background levels. A cover-gas sample taken between 0835 and 1005 on June 16 showed that no xenon tag had been released. A measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.428 indicated that the source was either a metal-fueled element or a high-burnup plutonium-bearing fuel element. Figure 1 shows the activity data measured by GLASS on June 13-26.

Fig. 1. GLASS Activity Data for June 13-26, 1975, during Release from Subassembly X207

The reactor was tripped for an unrelated reason at 1942 on June 16. Immediately after the trip, the ^{133}Xe , ^{135}Xe , $^{85\text{m}}\text{Kr}$, and $^{135\text{m}}\text{Xe}$ activities increased to 56, 2.7, 1.5, and 25 times their normal background levels, respectively. The presence of $^{135\text{m}}\text{Xe}$ and the absence of ^{88}Kr , ^{87}Kr , and ^{138}Xe strongly indicated that bond sodium had been released, ^{135}I being the source of the $^{135\text{m}}\text{Xe}$. There were many untagged Mark-II driver subassemblies in the core for run 77B, each of which could contain the breached element. Since no delayed neutrons had been detected and the cover-gas activities were still low, the reactor was returned to full power at 1307 on June 17 to provide further information to help identify the source of the release.

No new release of fission products was immediately observed. The cover gas was purged at $0.084 \text{ m}^3/\text{min}$ ($3 \text{ ft}^3/\text{min}$) for 7 h starting at 2032 on June 20 to reduce ^{133}Xe activity to below background level. After the purge, the ^{133}Xe activity increased very slowly and reached 1.7 times its background level at 1924 on June 24, when the reactor was again tripped for an extraneous reason. Immediately after the trip, the ^{133}Xe activity increased suddenly to 2.4 times its background level. When full power was reestablished, the ^{133}Xe activity stabilized at 3.2 times its normal background level.

At 0900 on June 24, the reactor tripped because of low flow from primary pump No. 2. Once again the ^{133}Xe activity took a step increase, to 10 times normal background, and the ^{135}Xe activity also increased significantly. The reactor reached full power again at 1912 on June 24. About 1 h later, the activities of ^{135}Xe , ^{85}Kr , and $^{135\text{m}}\text{Xe}$ had stabilized at 1.8, 1.5, and 1.3 times background, respectively. The ^{133}Xe activity continued to increase to a maximum of about 165 times background shortly after the reactor was shut down at 1712. A cover-gas sample previously taken between 0850 and 1020 showed that a xenon tag had been released with a composition similar to those in subassemblies X155A, X199, X207, and X215A. Table III gives details of the four suspect tagged subassemblies and the cover-gas analysis.

TABLE III. Summary of Primary Suspect Subassemblies and Cover-gas Analysis for Fission-product Release during Run 77B (June 1975)

Subassembly Number	Fuel Type	Peak Burnup, at. %	Xenon-tag Ratios								Total Volume of Stable Fission Gas in Plenum, mL	Age Factor ^b
			As-loaded				Corrected ^a					
			129/124	128/124	126/124	129/126	129/124	128/124	126/124	129/126		
X155A	Oxide	9	41.72	5.87	0.413	101.0	50.67	8.62	0.501	101.1	110	3.5
X199	Oxide	6	44.2	8.11	0.422	104.7	98.47	9.91	0.462	104.9	70	3.5
X207	Mk-II	7	38.33	7.60	0.493	77.75	47.31	9.50	0.565	83.10 ^c	58	1.2
X215A	Oxide	1	42.48	9.99	0.471	90.19	42.62	10.52	0.467	89.45	1.1	0.058
Measured in Cover Gas (6/25/75)												
							47.31	9.23	0.581	81.49	4	

^aCorrected for production of ^{128}Xe and burnout of ^{124}Xe .

^bCalculated fission-gas/tag-gas ratio divided by measured ratio.

^cCorrected for 0.47-ppb background xenon contamination.

On the basis of the predicted fission-gas inventories, subassembly X215A was eliminated as a suspect, because its elements had too low a burnup to be responsible for a release about 13 mL of fission gas. Among the other suspects, the corrected tag ratios, the fractional tag and fission-gas releases, and the earlier evidence of bond-sodium release indicated that the most likely source of the release was subassembly X207, containing experimental Mark-II elements at an average burnup of 6.5 at. %. However, to ensure that the source was removed from the core by one fuel handling, all three subassemblies--X155A, X199, and X207--were moved to the storage basket.

The absence of short-lived fission-gas isotopes during the startup for run 77C on June 26 confirmed that one of the three suspect subassemblies removed from the core contained the source of fission gas. Isolation tests of the three subassemblies in the fuel-unloading machine (FUM) later showed that subassembly X207 contained the breached element. Up to this time, all efforts to identify the breached element had failed, because a small fraction of its fission gas was released only in the reactor, and the breach site apparently resealed after the subassembly was removed from the reactor.

No significant release of ^{137}Cs or ^{131}I from the breached element was detected by analysis of primary-sodium samples. Figure 2 shows the ^{133}Xe and ^{135}Xe activities in the cover gas on June 24-26, as determined by radiometric analysis of cover-gas samples. The peak activities were $0.23\ \mu\text{Ci/mL}$ ($8.5\ \text{kBq/mL}$) for ^{133}Xe and $0.0052\ \mu\text{Ci/mL}$ ($0.19\ \text{kBq/mL}$) for ^{135}Xe .

B. Subassembly X232 (Run 78)

Reactor startup for run 78 began on July 15, 1975, and full power was reached on the same day. At 0026 on July 22, the reactor was tripped automatically because the delayed-neutron count rate on all three channels of FERD increased to about 2.5 times normal. Figure 3 shows the activity for channel 1B. The fission-gas monitors also recorded a sharp increase in isotope activities. Figure 4 shows the GLASS activity data. Figure 5 shows the activities for ^{133}Xe and ^{135}Xe during the same period, as measured by radiometric analysis. The peak values were $0.345\ \mu\text{Ci/mL}$ ($12.8\ \text{kBq/mL}$) for ^{133}Xe and $0.48\ \mu\text{Ci/mL}$ ($17.8\ \text{kBq/mL}$) for ^{135}Xe .

A cover-gas sample taken between 0315 and 0445 on July 22 indicated that a xenon tag had been released. The measured ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{124}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$, were 47.02, 7.15, 0.57, and 82.54, respectively; these values very closely matched the corresponding as-loaded tag ratios of 47.86, 7.19, 0.587, and 81.52 for the elements in subassembly X232. This subassembly contained mixed-oxide elements that had been in the reactor only five days (i.e., they had been loaded new for run 78). Subassembly X232 was removed to the storage basket, and the reactor was returned to full power by 0700 on July 23. The absence of short-lived fission-gas activity confirmed that subassembly X232 contained the source of the release.

Fig. 2. Activities of ¹³³Xe and ¹³⁵Xe in Cover Gas during June 24-26, 1975.
 Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719 × 10⁻⁴ m³/s.

Fig. 3. Signals for Delayed-neutron Activity Measured by FERD Channel 1B: July 22, 1975

Fig. 4. GLASS Activity Data for July 21-23, 1975, during Release from Subassembly X232

Fig. 5. Activities of ^{133}Xe and ^{135}Xe in Cover Gas during July 21-23, 1975.
 Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719×10^{-4} m³/s.

The total amount of stable fission gas released from the breached element was calculated to be about 0.37 mL, which corresponded to a calculated fractional release of 0.92. The high fractional release and release rate of fission gas were undoubtedly responsible for the FERD signals. This behavior emphasizes that FERD can be activated not only by exposed fuel, but also by delayed-neutron-emitting iodine and bromine vapors that escape at the same time as stored fission gas.

No appreciable amount of ^{137}Cs was released to the sodium. The initial equilibrium release of ^{131}I was calculated to be 5.5 Ci (204 GBq); an additional release of about 10 Ci (370 GBq) was measured while the subassembly was in the storage basket.

Identification of the breached element was hampered by the low fission-gas inventory of the elements in this subassembly. Immersion in liquid nitrogen, followed by immersion in alcohol, finally identified the breached element as AH-12. A cladding breach was then apparent on AH-12 by emanation of a fine stream of bubbles. The breach site was near the top of the fuel column, beneath a wire wrap. Figure 6 shows the breach site after the wire wrap had been removed.

Fig. 6. Breach Site of Fuel Element AH-12 from Subassembly X232 after Removal of Wire Wrap

This subassembly had been removed from the core on July 22, but was still in the storage basket. No new xenon tag was detected in the cover gas, and

C. Unidentified Mark-II Driver-fuel Subassembly (Runs 79 and 80)

Full-power operation for run 79 began on September 11, 1975. Normal background activity was observed in the cover gas until October 12, after 1890 MWd of operation. At 0150 on that day, the RCGM and GLASS monitors indicated a sudden increase in ^{133}Xe activity, and the activity continued to increase through the day. One day later the ^{133}Xe activity had reached 100 times normal background, and ^{135}Xe activity, about 1.35 times background; no increase in activity was noted for any shorter-lived fission-gas isotopes. Analysis results from a cover-gas sample taken from 0845 to 1015 on October 13 indicated the presence of a minute quantity of the xenon tag from subassembly X232.

about 0.4 mL of fission gas had been released from the source. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.420 indicated that the source might be a driver-fuel element.

The ^{133}Xe activity in the cover gas reached a nearly constant level late on October 13, and the cover gas was purged to reduce activity and remove the residual tag that had entered the cover gas from subassembly X232. The ^{133}Xe activity increased quickly after the purge to about 30 times background, then more slowly to 90 times background late on October 17, when the cover gas was purged again. From then until the scheduled shutdown of run 79 on October 26, the ^{133}Xe activity increased quite steadily at a rate of 4-6 $\mu\text{Ci/mL}\cdot\text{h}$ (148-222 $\text{kBq/mL}\cdot\text{h}$). The cover gas was purged four times to keep the ^{133}Xe activity below 250 times background. The peak activity of ^{135}Xe during this period was just above two times background. The activities of all shorter-lived isotopes remained at their normal background levels. Subassembly X232 was removed from the reactor storage basket and sent to the Hot Fuel Examination Facility (HFEF) on October 22.

Figure 7 shows the GLASS activity data for October 12-25. These data clearly show that only ^{133}Xe and some ^{135}Xe were released. Figure 8 shows

Fig. 7. GLASS Activity Data for October 12-25, 1975, during Release from an Unidentified Mark-II Driver-fuel Subassembly. ANL Neg. No. 104-77-371.

Fig. 8. Activities of ^{133}Xe and ^{135}Xe in Cover Gas during October 12-26, 1975. Conversion factors: $1 \text{ Ci} = 37 \text{ GBq}$; $1 \text{ ft}^3/\text{min} = 4.719 \times 10^{-4} \text{ m}^3/\text{s}$.

had been found to decrease with fuel burnup in the plenums of previously irradiated Mark-II driver-fuel elements. The results of this analysis were inconclusive, because the measured amount of ^{128}Xe had to be corrected for the presence of natural xenon in the cover gas. The results did indicate, however, that the burnup of the defective element was above 2 at. %, and probably above 3 at. %.

The extended shutdown between runs 79 and 80, which was required for other reasons, was used to try to identify the subassembly containing the defective element. Each of 14 subassemblies was isolated in the FUM. After each test, the FUM atmosphere was analyzed for the presence of fission gas; none was found for any of the subassemblies. Ten of the subassemblies

the results of radiometric analysis of the cover gas for these two isotopes. Xenon-tag analyses of the cover gas were also done on six dates (October 17, 20, 23, 24, 25, and 26). Each analysis detected no new xenon tag, although remnants of the tag from subassembly X232 were initially present despite purging. These results showed that the source did not contain a tag and that, surprisingly, the breached element in subassembly X232 was still releasing trace quantities of xenon tag two months after it had been discharged to the storage basket from the core.

The low $^{131}\text{Xe}/^{134}\text{Xe}$ ratios measured in the cover gas October 13-26 and the small total release of fission gas (about 0.4 mL) indicated quite strongly that the source was an untagged Mark-II driver-fuel element with a breach, quite possibly in a defective upper weld, that released only aged fission gas. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratios ranged from 0.406 to 0.426. Attempts were made at this time, and later, to determine the likely burnup of the defective element from the measured $^{134}\text{Xe}/^{128}\text{Xe}$ ratio in the cover gas. Figure 9 shows how this ratio

contained driver-fuel elements at burnups above 3 at. %, and four contained untagged mixed-oxide elements at high burnup that could conceivably also release aged fission gas. Table IV lists the subassemblies and their burnups.

Fig. 9. Decrease in $^{134}\text{Xe}/^{128}\text{Xe}$ Ratio with Burnup of Mark-II Driver-fuel Elements

TABLE IV. Subassemblies Tested in Fuel-unloading Machine for Fission-gas Release at End of Run 79

Subassembly Number	Fuel Type	Peak Burnup, ^a at. %
B-3261	Mark-II	4.69
B-3264	Mark-II	4.31
B-3267S	Mark-II	4.70
B-3268	Mark-II	4.37
B-3276	Mark-II	3.81
B-3277	Mark-II	4.24
C-2600S	Mark-II	3.84
C-2626	Mark-II	4.70
C-2628A	Mark-II	4.49
C-2632H	Mark-II	3.97
X076A ^b	Mixed oxide	16.00
X088A ^b	Mixed oxide	11.00
X094B ^b	Mixed oxide	13.00
X143A	Mixed oxide	19.50

^aOn lead element.

^bEncapsulated elements.

Continued operation with the unidentified source in the reactor appeared to be quite safe, based on the experience gained in run 79. Furthermore, no difficulty would be encountered in identifying a new source, since all experimental elements now contained a xenon tag. Accordingly, startup for run 80 began on November 23. GLASS activity data and grab-sample analyses quickly showed that the source was still in the core and releasing ^{133}Xe . Operation continued as planned.

On November 28, run 80A was terminated to remove the next source of fission-product activity (subassembly X141A), which was easily identified by its xenon tag as described in Sec. D below. During run 90B, from December 3, 1975, to January 15, 1976, the ^{133}Xe activity in the cover gas continued at abnormally high values, generally 150-200 times background. These activities were near-equilibrium levels, required no continuous purging, and caused no difficulties in routine operations. However, after two trips of the reactor (on December 27, 1975, and January 7, 1976), activity surges occurred 4-5 days after startup, and these required limited purging of the cover gas. Figure 10 shows the results of radiometric analysis of the cover gas for ^{133}Xe and ^{135}Xe activities from November 23, 1975, to February 11, 1976.

Run 80B ended on January 15, 1976. Startup for run 81A was on January 23, when the ^{133}Xe activity in the cover gas was about seven to eight times background. By February 11, the ^{133}Xe activity had declined to normal background, although a small bubble of gas temporarily doubled the ^{133}Xe activity on February 1. This behavior indicated that the source had been removed during the last shutdown. Only six Mark-II driver-fuel subassemblies had been removed after run 80B; two of these contained elements at too low a burnup to account for the amount of fission gas released in the reactor. One of the other four subassemblies (B-3276) had been temporarily removed for run 80A, when the source was still in the core, and was therefore not suspect. Thus, a defective element in one of the remaining three subassemblies (B-3274S, -3293T, or -3278) had been the source of ^{133}Xe activity over October 13-January 15. Only subassembly B-3276, which had been exonerated by removal for run 80A, had been among the 10 subassemblies previously tested in the FUM. Table V shows the burnups of the three suspect subassemblies at stages during the search; all were above 3 at. % burnup on October 12, 1975, in agreement with the burnup estimates made at that time on the basis of the measured $^{134}\text{Xe}/^{128}\text{Xe}$ ratio in the cover gas.

After discharge from EBR-II, all three subassemblies were thoroughly washed in the interbuilding coffin (IBC) in an attempt to identify the one containing the breached element; no activity was released during this process or any subsequent ones. Because the breached Mark-II element in subassembly X207 was never identified after having released more fission gas than the present breached element (see Sec. III.A above), further attempts to identify the element were stopped. A defective upper weld seems to be the most likely cause for the very low release of fission gas from this unidentified element.

Fig. 10. Activities of ^{133}Xe and ^{135}Xe in Cover Gas from November 23, 1975, to February 11, 1976. Conversion factors = $1 \text{ Ci} = 37 \text{ GBq}$; $1 \text{ ft}^3/\text{min} = 4.719 \times 10^{-4} \text{ m}^3/\text{s}$.

TABLE V. Three Suspect Mark-II Driver-fuel Subassemblies Removed at End of Run 80B

Subassembly	Reactor Position	Maximum Burnup, at. %			
		Run 79A			Run 80B, End
		Begin	Oct 12	End	
B-3274S	6A1	3.08	3.60	3.81	4.52
B-3293T	7B1	3.33	3.78	3.96	3.68
B-3278	6A4	2.76	3.34	3.58	4.39

D. Subassembly X141A (Run 80A)

The reactor reached full power for run 80A at 0212 on November 24, 1975. By November 28, the ^{133}Xe , ^{135}Xe , and $^{85\text{m}}\text{Kr}$ activities had increased steadily from below normal background levels to 15, 2.3, and 1.15 times those levels, respectively. The higher-than-normal background activities were attributed to slow leakage of fission gas from the unidentified Mark-II driver subassembly.

At 2136 on November 28, the reactor was shut down because of high fission-gas activities in the primary cover gas. Figure 11 shows the GLASS activity data at the time. The recorded peak activities were $3.3 \mu\text{Ci/mL}$ (122 kBq/mL) for ^{133}Xe and $4.8 \mu\text{Ci/mL}$ (178 kBq/mL) for ^{135}Xe . (See Fig. 12.) A cover-gas sample taken between 0035 and 0225 on November 29 indicated that a xenon tag had been released. The measured tag ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{124}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$ were 17.84, 2.65, 0.406, and 43.89, respectively, these values closely matched the corresponding corrected tag ratios (17.54, 2.73, 0.370, and 47.4) for subassembly X141A. This subassembly contained mixed-oxide fuel elements at a peak burnup of 6.5 at. %.

Fig. 11. GLASS Activity Data for November 28-29, 1975, during Release from Subassembly X141A

Fig. 12. Activities of ^{133}Xe and ^{135}Xe in Cover Gas during November 28-30, 1975.
 Conversion factors: $1\text{ Ci} = 37\text{ GBq}$; $1\text{ ft}^3/\text{min} = 4.719 \times 10^{-4}\text{ m}^3/\text{s}$.

Subassembly X141A was removed from the core along with several other subassemblies due for discharge. The reactor was returned to full power on December 3 for run 80B. The ^{133}Xe and ^{135}Xe activities increased to above their background levels, but the activities of short-lived isotopes remained at their background levels. This behavior suggested that the unidentified leaking Mark-II driver subassembly was still in the core, but that subassembly X141A was the source of the large release of short-lived fission-gas isotopes on November 28. Gamma scanning of the plenum region of the elements in this subassembly confirmed element P-41 as the one that had breached to give the large release of fission gas.

No appreciable release of ^{137}Cs was detected from analysis of primary-sodium samples. The initial equilibrium release of ^{131}I was about 0.16 Ci (5.9 GBq); the total equilibrium release of ^{131}I was about 0.25 Ci (9.2 GBq). A total of 34 mL of stable fission gas was estimated to have been released from the breached element.

E. Subassembly X241 (Run 82A)

Full-power operation for run 82A started on April 15, 1976, and continued without interruption until May 6. At 0455 on May 6, all cover-gas monitors indicated a release of fission products, although FERD detected no increased count rate. Figure 13 shows the GLASS activity data for May 6-8. The reactor was shut down at 0606 on May 6 because of high cover-gas activity. Analysis of a sample of cover gas taken at 0830-1005 indicated that a xenon tag had been released. The most likely source of the fission products was a mixed-oxide element in subassembly X241. The only other suspect was a replacement mixed-oxide element in subassembly X154A; however, the amount of the gas release calculated for that element was too low to match the volume ratio of fission gas to tag gas measured in the cover gas. Table VI compares the results of the cover-gas analysis with the corrected tag compositions of the two suspect subassemblies.

In view of the strong evidence that X241 was the source of the fission products, only this subassembly was removed from the core. Full-power operation was resumed at 2240 on May 7. The absence of short-lived fission-gas activity in the cover gas confirmed that X241 had been the source of the fission products. The subassembly continued to release long-lived fission gas while in the storage basket. Figure 14 shows the results of radiometric analysis of the cover gas for ^{133}Xe and ^{135}Xe over May 6-12. The peak measured activities were 0.81 $\mu\text{Ci/mL}$ (30 kBq/mL) for ^{133}Xe and 0.71 $\mu\text{Ci/mL}$ (26 kBq/mL) for ^{135}Xe . A total of 3.1 mL of stable fission was released in the reactor, of which 1.1 mL was released at power. Analysis of a primary-sodium sample indicated an equilibrium release of ^{131}I of about 0.06 Ci (2.2 GBq).

Fig. 13. GLASS Activity Data for May 6-8, 1976, during Release from Subassembly X241

TABLE VI. Summary of Primary Suspect Subassemblies and Cover-gas Analysis for Fission-product Release during Run 82A (May 1976)

Subassembly Number	Fuel Type	Peak Burnup, at. %	Xenon-tag Ratios								Match Factor ^b	Age Factor ^c
			As-loaded				Corrected ^d					
			129/124	128/124	126/124	129/126	129/124	128/124	126/124	129/126		
X154A	Oxide	0.5	45.81	4.40	0.493	92.90	46.47	4.47	0.500	92.90	8.3	0.09
X241	Oxide	2.5	37.58	3.29	0.446	84.36	39.32	3.58	0.466	84.32	5.3	0.74-1
							Measured in Cover Gas (5/6/76)					
							38.90	3.75	0.434	89.6		

^aCorrected for production of ^{128}Xe and burnout of ^{124}Xe .

^bDeviation between corrected and measured xenon-tag ratios, with 129/124, 128/124, 126/124, and 129/126 ratios as coordinates in four-dimensional space. Match factor equals zero when match is perfect.

^cCalculated fission-gas/tag-gas ratio divided by measured ratio.

Fig. 14. Activities of ^{133}Xe and ^{135}Xe in Cover Gas during May 6-12, 1976.
Conversion factors: $1 \text{ Ci} = 37 \text{ GBq}$; $1 \text{ ft}^3/\text{min} = 4.719 \times 10^{-4} \text{ m}^3/\text{s}$.

F. Subassembly X242 (Run 82B)

Full-power operation for run 82B started on May 7, 1976. Operation continued uneventfully until the shutdown on May 31. The ^{133}Xe activity in the cover gas was above background during this time because of the release of aged fission gas from the breached element in subassembly X241 in the storage basket. By May 31, the ^{133}Xe activity had declined to about three times background. Analysis of a cover-gas sample on May 19 showed that 0.007 mL of the xenon tag from X241 remained in the cover gas.

Shutdown for the end of run 82B was started at 2225 on May 31. Just after reactor power was reduced to 50 MWt at 2323, an increase was noted in the activity of all isotopes monitored by GLASS and RCGM. After about 1.5 h at 50 MWt, the activities of all isotopes started to decay in accordance with their own half-lives; this decay indicated that the release had stopped. The recorded peak activities of ^{133}Xe , ^{135}Xe , and ^{138}Xe were 86, 65, and 26 times

what their respective background values had been early on May 31; apparently, therefore, a low total release of fission gas was occurring. The reactor power was raised to 62.5 MWt to promote release of more fission gas (and xenon tag if any) and to allow easier identification of the source. Residual tag from subassembly X241 was known to be still in the cover gas. Figure 15 shows the GLASS activity data for May 30-June 5.

The reactor was shut down at 0215 on June 1, when the cover-gas activity reached 250 times background. Analysis of a cover-gas sample taken at 0410-0540 indicated that about 0.017 mL of xenon tag was present in the cover gas and that the tag composition was close to the corrected composition of the tags in subassemblies X154A and X242. (See Table VII.)

If no residual tag was assumed present in the cover gas, the tag composition of freshly loaded elements in subassembly X154A was closer than the tag of subassembly X242 to the measured cover-gas composition. However, the calculated fission-gas/tag-gas ratio for the new elements in X154A did not match the measured ratio in the cover gas. Furthermore, if the tag from subassembly X241 were assumed to be still present in the cover gas with a composition similar to that measured on May 19, the tag from X242 matched the cover-gas composition as well as the tag from X154A.

Calculations with a new code, MIXTAG,²¹ indicated that the likely mixture in the cover-gas sample of June 1 contained about 56% of the residual tag from X241, 22% of background xenon, and 22% of the tag from the suspect subassembly X242. On the basis of this analysis and the measured fission-gas/tag-gas ratio, subassembly X242 was considered the prime suspect and removed from the core. Startup on June 5 for run 83 confirmed that subassembly X242 was the source of activity on May 31.

Figure 16 shows the results of radiometric analysis of the cover gas for ^{133}Xe and ^{135}Xe activity over May 31-June 2. The peak measured activities were 0.54 $\mu\text{Ci/mL}$ (20 kBq/mL) for ^{133}Xe and 0.37 $\mu\text{Ci/mL}$ (14 kBq/mL) for ^{135}Xe . About 0.42 mL of stable fission gas was calculated to have been released. Analysis of a sample of primary sodium indicated an equilibrium release of ^{131}I of about 0.02 Ci (0.74 GBq). There was no detectable release of ^{137}Cs .

Fig. 15. GLASS Activity Data for May 30–June 5, 1976, during Release from Subassembly X242

TABLE VII. Summary of Primary Suspect Subassemblies and Cover-gas Analysis for Fission-product Release during Run 82B (May 1976)

Subassembly Number	Fuel Type	Peak Burnup, at. %	Xenon-tag Compositions ^a								Fission-gas/Tag-gas Ratio	
			As-loaded				Corrected ^b				Predicted ^c	Measured
			124	126	128	129	124	126	128	129		
X242	Oxide	2	1.55	0.76	7.36	90.34	1.50	0.75	7.56	90.19	14.7–27.5	17.7
X154A	Oxide	1	1.93	0.95	8.51	88.6	1.90	0.95	8.55	88.59	2.2	17.7
Measured in Cover Gas (5/31/76)												
			1.64	0.76	8.22	89.37						

^a Mole percent based on ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe only.

^b Corrected for production of ^{128}Xe and burnout of ^{124}Xe .

^c Based on semiempirical correlation of expected amount of plenum gas with measured tag volume for sample pin.

Fig. 16. Activities of ^{133}Xe and ^{135}Xe in Cover Gas during May 31-June 2, 1976.
 Conversion factors: $1\text{ Ci} = 37\text{ GBq}$; $1\text{ ft}^3/\text{min} = 4.719 \times 10^{-4}\text{ m}^3/\text{s}$.

G. Subassembly X138D (Run 83)

Run 83 began on June 5, 1976. At about 0500 on June 8, GLASS data indicated an increase in the ^{135m}Xe activity in the cover gas. The release continued intermittently for the next 22 days of operation, and increased activities were also eventually recorded for ^{133}Xe , ^{135}Xe , and ^{85m}Kr . The source of this release was later identified as subassembly X208, containing Mark-II driver-fuel elements at high burnup, after a xenon tag had been released to the cover gas. (See Sec. H below.)

On June 21, the activities of ^{133}Xe , ^{135}Xe , ^{85m}Kr , and ^{135m}Xe in the cover gas were above their normal background level because of continued release from subassembly X208, which was not yet identified as a source. At about 1635, there was an abrupt, large increase in the activity of all isotopes monitored by GLASS and RCGM. The cover-gas activity rapidly exceeded 250 times background, and the reactor was shut down at 1641. No associated increases in delayed-neutron activity were recorded. Figure 17 shows the GLASS activity data for this period.

Fig. 17. GLASS Activity Data for June 21-22, 1976, during Release from Subassembly X138D

Analysis of a cover-gas sample taken at 1725-1810 on June 21 indicated that a xenon tag had been released. Furthermore, the sample composition showed that subassembly X138D could be the only source of the release. This subassembly, containing mixed-oxide elements with burnups ranging from 1 to 12 at. %, had a xenon tag with the highest $^{129}\text{Xe}/^{124}\text{Xe}$ and $^{128}\text{Xe}/^{124}\text{Xe}$ ratios of all xenon tags in the core. Table VIII compares the measured cover-gas composition with those of the several tags in subassembly X138D. In view of this conclusive evidence, only subassembly X138D was removed from the core. The absence of high cover-gas activity during and after startup on June 23 confirmed this subassembly to be the source of release.

Figure 18 shows the results of radio-metric analysis of the cover gas for ^{133}Xe and ^{135}Xe activity on June 20-22, 1976. The peak measured activities were $6.3 \mu\text{Ci/mL}$ (233 kBq/mL) for ^{133}Xe and $2.8 \mu\text{Ci/mL}$ (104 kBq/mL) for ^{135}Xe . The initial release of stable fission gas was calculated to be about 9.5 mL, or about 7% of the plenum inventory, and the total release volume was about 19 mL. The release of any ^{131}I or ^{137}Cs

TABLE VIII. Summary of Subassembly X138D and Cover-gas Analysis for Fission-product Release during Run 83 (June 1976)

Tag Number	Peak Burnup, at. %	Xenon-tag Ratios							
		As-loaded				Corrected ^a			
		129/124	128/124	126/124	129/126	129/124	128/124	126/124	129/126
8X6607	9.2	66.36	7.23	0.679	97.69	77.46	10.90	0.793	97.69
8X6607	10.3	66.36	7.23	0.679	97.69	78.78	11.71	0.806	97.69
8X6607	11.6	66.36	7.23	0.679	97.69	80.33	12.79	0.822	97.69
1X6608	1.3	66.77	7.75	0.782	85.42	68.45	8.01	0.801	85.42
1X6608	6.7	66.77	7.75	0.782	85.42	74.94	10.33	0.877	85.42
1X6608	9.1	66.77	7.75	0.782	85.42	77.82	12.13	0.911	85.42
1X6608	10.2	66.77	7.75	0.782	85.42	79.15	13.13	0.927	85.42
						Measured in Cover Gas (6/21/76)			
						77.05	11.70	0.867	88.90

^aCorrected for production of ¹²⁸Xe and burnout of ¹²⁴Xe.

Fig. 18. Activities of ¹³³Xe and ¹³⁵Xe in Cover Gas during June 20-22, 1976. Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719 × 10⁻⁴ m³/s.

from the breached element could not be measured, because release from the breached Mark-II driver-fuel elements in subassembly X208 predominated.

H. Subassembly X208 (Run 83)

As described in Sec. G above, run 83 began on June 5, 1976, and continued uneventfully for the next two days. At 0200 on June 8, GLASS indicated an increase in the activity of ^{135m}Xe in the cover gas. This increase was followed about 6 h later by an increase in the ^{135}Xe activity. Both activities stabilized at values five to six times normal background over the next 24-30 h. Activities of all other monitored isotopes remained at background levels. This behavior strongly suggested that bond sodium was being released, bringing with it ^{135}I , the precursor of both gas isotopes. Analysis of a cover-gas sample taken at 0900 on June 9 showed that no detectable amounts of a xenon tag had been released.

The ^{135m}Xe and ^{135}Xe activities persisted at values considerably above normal background for the next 12 days of operation, although at no time was purging required to reduce the activity of the cover gas. The ^{133}Xe and ^{85m}Kr activities also showed variable increases during this period. The ^{135m}Xe activity definitely decreased starting at about 0400 on June 13 and markedly increased on June 16 (at 0500) and June 19 (at 0400). The increase on June 19 was clearly accompanied by increases in ^{133}Xe , ^{135}Xe , and ^{85m}Kr activities. Because no xenon tag had been detected on June 9 and there had subsequently been only a small release of fission gas, no tag samples were taken over this period. Samples of primary sodium were taken on June 12 and 17, but the results of analysis were not available until a week later, because ^{24}Na activity had to decay sufficiently before the analysis could be run.

At 1200 on June 21, the ^{133}Xe , ^{135}Xe , ^{85m}Kr , and ^{135m}Xe activities in the cover gas were, respectively, at 18, 22, 2.7 and 214 times the normal background due to the source, which was probably a sodium-bonded element. Because no results of sodium analysis were available, it was not known whether more than one sodium-bonded element might have breached its cladding. At about 1635 on June 21, the very rapid release of fission gas occurred from the breached element in subassembly X138D (see Sec. G above), and the reactor was shut down at 1641.

Before, during, and for about 12 h after the startup for run 83B on June 22, the cover gas was purged thoroughly to reduce activity and the amount of the xenon tag from subassembly X138D. The absence of marked short-lived isotope activity on startup confirmed that subassembly X138D had been the source of release on June 21. However, the source of previous smaller isotope activity, particularly of ^{135m}Xe , was clearly still in the core. A tag sample of cover gas was taken on June 23, but was not immediately analyzed.

A general increase in cover-gas activity on the following day (June 24), which included some short-lived activity, prompted the taking of another tag sample. Analytical results for this second sample showed that the tag from

subassembly X138D was still in the cover gas, but now differed somewhat in composition from that measured on June 21. Analysis of the sample taken the previous day showed a similar but smaller shift in composition. These results indicated that a new tag was being released in the core and was mixing in increasing proportion with the tag from subassembly X138D. Analysis of a third sample taken on June 25 confirmed this trend.

The three-dimensional "map" of xenon-tag ratios (Fig. 19) clearly shows the results of tag-sample analyses carried out June 23-29. The sequential measurements of cover-gas compositions all lie on a projected straight line in the $^{129}\text{Xe}/^{124}\text{Xe}$ - $^{128}\text{Xe}/^{124}\text{Xe}$ -ratio plane that connects the tag compositions of subassemblies X138D, X196, and X208.

To confirm the correlation shown in Fig. 19, calculations were performed with the MIXTAG code. The code takes as input the best estimated compositions of previous tag releases and examines each tag in the core as suspect. Three parameters are determined: mix factor (unity for a perfect fit), match factor (zero for a perfect fit), and mole fraction of each tag in the tag mixture. Tags with a mix factor greater than unity can be mathematically discounted as suspects. The primary suspect is the tag with a mix factor equal to 1.0 and a match factor nearest to zero.

The calculations were repeated at each successive analysis of the cover gas. The results (see Table IX) clearly showed that subassemblies X196 and X208 were the likely sources of release for two reasons: (a) Their xenon tags consistently gave a good fit to the cover-gas composition when mixed with the X138D tag, and (b) their xenon tags not only gave a good fit, but increased in concentration with time in the mixture of tags.

Subassembly X196 contained oxide elements at a peak burnup of about 1.5 at. % and with a calculated fission-gas/tag-gas ratio of about 11. The latter value is small compared with the measured value of about 90 in the cover gas. Subassembly X208 contained sodium-bonded Mark-II driver-fuel elements near a peak burnup of 9.2 at. % and with a calculated fission-gas/tag-gas ratio of 80-100.

In view of the strong evidence from (a) xenon tagging, (b) the volume ratios of fission gas to tag gas in the cover gas, (c) GLASS data that indicated release of bond sodium, and (d) cladding-failure statistics (which indicated a cladding breach was imminent during the run), only subassembly X208 was removed from the core. The primary reason for this decision was that, although cover-gas activity was not limiting reactor operations, if a cladding breach developed in yet another subassembly and released a third tag to the cover gas, identifying the third subassembly would be extremely difficult. Accordingly, the reactor was shut down on June 30, and subassembly X208 was removed from the core. The absence of unusual cover-gas activity during and after startup for run 83C later that day confirmed this subassembly as the source of activity June 8-30.

Fig. 19. Xenon-tag Ratios for Run 83B, Showing Shift in Cover-gas Xenon Ratios toward Those Expected in Subassembly X208 during June 23-29, 1976

TABLE IX. Summary of MIXTAG Analyses for Fission-product Releases from Subassemblies X138D and X208 during Run 83B

Suspect Subassembly	Tag Number	Date of Analysis ^a														
		June 23, 1976			June 24, 1976			June 25, 1976			June 28, 1976			June 29, 1976		
		Mix Factor	Percent Suspect ^b	Match Factor	Mix Factor	Percent Suspect ^b	Match Factor	Mix Factor	Percent Suspect ^b	Match Factor	Mix Factor	Percent Suspect ^b	Match Factor	Mix Factor	Percent Suspect ^b	Match Factor
X076	8X0902	1.00	6.03	0.20	1.00	21.76	1.12	1.00	24.07	1.33	1.00	24.34	1.18	1.00	23.47	1.08
X163	4X0706	1.00	1.85	0.26	1.00	7.07	0.56	1.00	7.91	0.54	1.00	7.83	0.70	1.00	7.49	0.72
X196	3X1704	1.00	7.79	0.12	1.00	29.27	0.09	1.00	32.64	0.08	1.00	32.52	0.13	1.00	31.18	0.19
X203	3X5209	1.00	58.99	0.17	3.39	-	-	3.89	-	-	3.89	-	-	3.68	-	-
X208	3X2805	1.00	14.50	0.14	1.00	54.65	0.13	1.00	60.97	0.06	1.00	60.68	0.21	1.00	58.16	0.26
X224	4X1204	1.00	4.07	0.18	1.00	15.41	0.28	1.00	17.21	0.22	1.00	17.09	0.38	1.00	16.37	0.42
X225	4X0704	1.00	2.66	0.18	1.00	10.06	0.25	1.00	11.23	0.19	1.00	11.16	0.35	1.00	10.69	0.39
X226	4X2007	1.00	4.37	0.28	1.00	16.77	0.64	1.00	18.78	0.63	1.00	18.57	0.78	1.00	17.75	0.80
X235	4X1206	1.00	2.72	0.27	1.00	10.41	0.59	1.00	11.66	0.58	1.00	11.53	0.73	1.00	11.03	0.76
X246	4X0706	1.00	1.85	0.26	1.00	7.07	0.56	1.00	7.91	0.54	1.00	7.83	0.70	1.00	7.49	0.72
X251	4X2608	1.00	6.18	0.26	1.00	23.68	0.60	1.00	26.51	0.58	1.00	26.23	0.73	1.00	25.08	0.76
X3282	4X0906	1.00	2.19	0.27	1.00	8.41	0.59	1.00	9.41	0.58	1.00	9.31	0.73	1.00	8.91	0.76

^aThe composition of the cover gas on June 21 was assumed as the contaminant to mix with the fresh tag.^bThe percentage of xenon tag contributed from the suspected leaking subassembly in the total xenon tag in the cover gas.

Examination in the HFEF showed that elements 8, 24, 28, 43, 54, 55, and 65 had weight losses of 1.35-1.55 g, which suggested a total loss of bond sodium from these seven fuel elements. However, all the breach sites were still too small to be seen.

The percentage of ^{131}I released from a breached element in a previously irradiated subassembly (X180) that had lost bond sodium was $\sim 0.1\%$. On this basis, Table X lists the probable number of breached elements in X208 according to the primary-sodium analysis. Figure 20 shows ^{138}Xe and $^{135\text{m}}\text{Xe}$ activities for June 7-July 1, 1976. When the ^{138}Xe activity is at normal background level (~ 1.2 counts/s), the source of $^{135\text{m}}\text{Xe}$ activity is the decay of ^{131}I released into the primary sodium. When the ^{138}Xe activity is above its normal background level, the sources of $^{135\text{m}}\text{Xe}$ are decay products of ^{131}I in sodium and direct release of $^{135\text{m}}\text{Xe}$ activity from the breached element. Both the $^{135\text{m}}\text{Xe}$ activity in the cover gas and the ^{131}I activity in the sodium indicate the most probable time for the breaching of seven elements. (These times are shown by the numbered arrows in Fig. 20.)

Fig. 20. Data for $^{135\text{m}}\text{Xe}$ and ^{138}Xe Activities from GLASS for June 7-July 1, 1976. Conversion factor: $1 \text{ ft}^3/\text{min} = 4.719 \times 10^{-4} \text{ m}^3/\text{s}$.

TABLE X. Summary of Release of ^{131}I from
Primary Sodium on June 12-30, 1976

Primary-sodium Sampling Date (1976)	Number of Probable Breached Elements	Percentage Release of ^{131}I per Element
June 12	2 ^a	0.11 ^a
June 17	3 ^a	0.11 ^a
June 22	5 ^b	0.12 ^b
June 30	7 ^b	0.12 ^b

^aPercentage release of ^{131}I per element assumed to be about 0.1% with total loss of bond sodium.

^bEquilibrium release of ^{131}I from X138D assumed to equal 0.51 Ci (19 GBq).

Based on the cover-gas analysis, an estimated total of ~11 mL of stable fission gas was released. The measured equilibrium release of ^{131}I was about 2.7 Ci (100 GBq). A total of 37 Ci (1.4 TBq) of ^{137}Cs was released to the sodium--40% of the ^{137}Cs inventory in seven elements.

I. Subassembly X209 (Run 84)

Full-power operation for run 84 began on July 31, 1976. Except for a reactor trip on August 16, caused by a spurious trip of primary pump No. 2, operation was uneventful until August 27. At about 1500 that day, data from GLASS showed a gradual increase in the $^{135\text{m}}\text{Xe}$ and ^{135}Xe activities in the cover gas. The absence of enhanced activity of all other monitored isotopes indicated that the likely source of the xenon activities was ^{135}I in sodium being released from a breached sodium-bonded element. About 12 h later, the ^{133}Xe and $^{85\text{m}}\text{Kr}$ activities also started to increase. These increases indicated the gradual release of aged fission gas, as well as bond sodium, from the plenum of the element.

Shortly after the $^{135\text{m}}\text{Xe}$ activity had reached its maximum in the cover gas--0.29 nCi/mL (~10.7 Bq/mL), about 14 times normal background--and had started to decline because of the complete release of bond sodium, the activities of all other monitored isotopes in the cover gas increased sharply. Clearly, a more direct path for fission gas from the plenum to the breach site on the element had now been established. The reactor was shut down at 1426 on August 30 because of high cover-gas activity. Figure 21 shows the GLASS activity data for August 27-31.

Fig. 21. GLASS Activity Data for August 27-31, 1976. Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719 x 10⁻⁴ m³/s.

Analysis of a sample of cover gas taken 0915-1045 on August 30 showed the presence of xenon-tag isotopes. When the measured tag composition was expressed as mole percent of its constituents, the most likely sources of the release were subassemblies X209 and X271. However, in terms of measured tag ratios, subassemblies X209 and X211 were the more likely suspects. All three subassemblies contained sodium-bonded Mark-II driver-fuel elements. The measured volume ratio of fission gas to tag gas (70) indicated that the burnup of elements in subassembly X271 was too low for one of them to be the source. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio in the cover gas also confirmed that the source was a uranium-fissioning driver-fuel element. Table XI gives the analysis of the cover-gas data. Because of this analysis and the fact that, of the three subassemblies, X209 had the highest probability of cladding breach based on failure statistics, only subassembly X209 was removed from the reactor. The absence of enhanced activity of short-lived isotopes during startup on September 1 confirmed that this subassembly had been the source of activity for August 27-30.

TABLE XI. Summary of Data for Primary Suspect Subassemblies for Release of August 27-31, 1976

Subassembly Number ^a	Peak Burnup, at. %	MATMOL ^b	MATRAT ^c	Calculated Fission-gas/Tag-gas Ratio
X209	10.4	1.2	4.2	67-105
X211	9.4	8.5	6.2	67-132
X271	2.4	0.25	11.1	7-10
				Measured Ratio (8/30/76)
				70

^aAll Subassemblies contain Mark-II driver fuel.

^bMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe and ^{129}Xe .

^cMatch factor based on the ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

About 5 mL of stable fission gas was released while subassembly X209 was in the reactor, and an additional 17 mL after it had been removed to the storage basket. Figure 22 shows the ^{133}Xe activity and its equilibrium release rate over August 27-September 4. Analysis of primary-sodium samples indicated a release of ^{131}I of 0.9 Ci (~33 GBq) (a fractional release of about 0.004) and a release of 5.8 Ci (~215 GBq) of ^{137}Cs (a fractional release of about 0.4) from the breached element. The fractional release of ^{137}Cs was equivalent to a complete release of bond sodium from one fuel element. Examination in HFEEF showed element 20 to have lost 1.5 g, equivalent to the loss of most of its sodium bond.

Fig. 22

Activity and Release Rate of ^{133}Xe in EBR-II Cover Gas, August 27-September 4, 1976. Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719 x 10⁻⁴ m³/s.

J. Subassembly X210 (Run 85A)

Run 85A started on September 25, 1976. Although four unrelated trips of the reactor occurred during the next month of operation, no unusual fission-gas activities were recorded in the cover gas until October 28. At 0600 that day, about 12 h after the last of the trips, data from GLASS showed an increase in the activities of ^{135m}Xe and ^{135}Xe , which continued slowly through the next two days. As the ^{135m}Xe activity reached a maximum value of 0.12 nCi/mL (4.4 Bq/mL)--about five times normal background--the ^{133}Xe and ^{88}Kr activities also started to increase. This activity behavior was typical of the release of sodium and a small amount of aged fission gas from a sodium-bonded element.

At 0200 on October 30, the count rate increased significantly on all three channels of the FERD. By 0330, the count rate on one of the channels had reached the trip value, and reactor power was reduced to 30 MWt to avoid an unnecessary trip. At this stage, the amount of fission gas released was too small for accurate identification of the source of the release. The reactor power was therefore raised to 60 MWt to promote the release of more fission gas and xenon tag, if present; count rates on the FERD channels returned to values slightly above normal background. After 10 min at 60 MWt, release of fission gas from the source increased rapidly, and shutdown of the reactor was required at 0611 because of high cover-gas activity. Figure 23 shows the GLASS activity data for October 28-30.

Analysis of a sample of cover gas taken 0825-1005 on October 30 showed the presence of xenon-tag isotopes and strongly indicated that subassembly X210, containing sodium-bonded Mark-II elements, was the source of the release. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.416 also indicated the source to be a uranium-fissioning element. Table XII summarizes the analysis of the cover-gas data. On the basis of this analysis, subassembly X210 was removed from the reactor. The absence of unusual short-lived activity during and after startup for run 85B on November 2 confirmed that subassembly X210 had been the source of the release of October 28-30.

TABLE XII. Summary of Data for Suspect Subassembly X210
for Release of October 28-November 7, 1976^a

Tag Volume, cm ³	MATMOL ^b	MATRAT ^c	Calculated Fission-gas/ Tag-gas Ratio
1.52	1.33	2.19	53
0.85	0.19	2.09	95
			Measured Ratio (10/30/76)
			85

^aSubassembly contains Mark-II driver fuel at 10.8 at. % peak burnup.

^bMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe .

^cMatch factor based on ratios $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

Fig. 23. GLASS Activity Data for October 28-30, 1976

About 20 mL of stable fission gas was calculated to have been released while subassembly X210 was in the reactor, and a further 24 mL after it was removed to the storage basket. Figure 24 shows the activity and release rate of ^{133}Xe in the cover gas for October 28-November 7.

Examination of the analysis of the primary-sodium samples indicated that a small amount of ^{131}I had been released as early as September 30, 29 days before the observed increase of fission-gas activities on GLASS. Figure 25 plots the quantity of ^{131}I detected in the primary sodium during September 30-November 3. If the iodine release was from subassembly X210, these results indicate very slow development of a cladding breach, probably by grain-boundary separation of the steel. Thus, for a sodium-bonded fuel element, sodium analysis may be a more sensitive and earlier indicator of a cladding breach than GLASS.

Analysis of primary-sodium samples indicated a total release of 9.9 Ci (366 GBq) of ^{131}I at equilibrium and about 4-11 Ci (148-407 GBq) of ^{137}Cs . The large uncertainty in the measured ^{137}Cs release is due to the high background ^{137}Cs activity in the primary sodium from previous elements with breached cladding.

Fig. 24

Activity and Release Rate of ^{133}Xe in FBR-II Cover Gas, October 28–November 7, 1976. Conversion factors: $1 \text{ Ci} = 37 \text{ GBq}$; $1 \text{ ft}^3/\text{min} = 4.719 \times 10^{-4} \text{ m}^3/\text{s}$.

Fig. 25
Iodine-131 Released to Primary Sodium, September 30–November 3, 1976. Conversion factor: $1 \text{ Ci} = 37 \text{ GBq}$.

Further study of the values shown in Table XII suggested that fission gas was probably released from an element with a tag volume close to 0.85 mL. Weighing indicated that element 29 (which had an initial tag volume of 0.87 mL) had lost 1.8 g, corresponding to complete release of sodium bond and substantial release of plenum gas. (The calculated release of plenum gas was 55%.) A visible crack was also observed in the cladding of element 24, although that element showed no weight loss.

K. Subassembly X211 (Run 85B)

Run 85B began on November 2, 1976. No unusual fission-gas activities were observed in the cover gas until 0700 on November 11. At that time, the activities of ^{135m}Xe and ^{135}Xe , as monitored by GLASS, began to increase slowly; perceptible increases were also noted in the activities of all other monitored isotopes. The gradual increase in the ^{135m}Xe and ^{135}Xe activities continued for the next two days. Experience strongly suggested the source to be a sodium-bonded driver-fuel element. At about 1400 on November 13, the activities of all isotopes except ^{135m}Xe increased rapidly. A small temporary increase in ^{135m}Xe activity was observed at about 2230. The reactor was shut down at its normal background value. Figure 26 shows the GLASS activity data for November 11-14.

Fig. 26. GLASS Activity Data for November 11-14, 1976

Analysis of a sample of cover gas taken 1030-1200 on November 12 (early in the release) showed only a trace amount ($<0.006 \text{ cm}^3$) of xenon tag--too small for the mass spectrometer to provide accurate identification. However, after the substantial increase of fission gas on November 13, a second cover-gas sample was taken 2230-2400; results showed a tenfold increase in xenon tag (to 0.066 cm^3) in the cover gas.

Further analysis of the data with the MIXTAG code indicated that a new xenon tag was mixed with the residual tag from subassembly X210, which had given a release on October 28 (see Sec. J above). The likely source of the present activity was subassembly X211, containing Mark-II driver-fuel elements at 10 at. % burnup. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.415 confirmed the source to be a uranium-fissioning element. Table XIII gives the details of the cover-gas analysis.

TABLE XIII. Summary of Data for Suspect Subassembly X211 for Release of November 11-15, 1976^a

MATMOL ^b	MATRAT ^c	Calculated Fission-gas/ Tag-gas Ratio
0.24 ^d	5.3 ^d	-
0.15 ^e	-	53-172
		Measured Ratio (11/13/76)
		77

^aSubassembly contains Mark-II driver fuel at 11 at. % peak burnup.

^bMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe .

^cMatch factor based on ratios $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

^dAssumes no contamination from xenon tag of subassembly X210.

^eAssumes 6.6% of the xenon tag was from subassembly X210.

On the basis of the strong evidence provided by the tag analysis, release characteristics, and cladding-failure statistics, subassembly X211 was removed from the reactor. Absence of unusual short-lived activity in the cover gas during and after startup for run 86 on November 21 confirmed that subassembly X211 had been the source of activity during November 11-14.

About 7 mL of stable gas was calculated to have been released while the reactor was at power, and a further 5 mL after the reactor was shut down. Figure 27 shows the activity and release rate of ^{133}Xe in the cover gas for November 11-15. Analysis of primary-sodium samples indicated a ^{131}I release of 0.84 Ci (~ 31 GBq). Examination in HFEF showed that elements 20 and 29 lost 1.5 and 1.9 g, respectively.

Fig. 27. Activity and Release Rate of ^{133}Xe in EBR-II Cover Gas, November 11-15, 1976. Conversion factors: 1 Ci = 37 GBq; 1 ft³/min = 4.719×10^{-4} m³/s.

L. Subassembly X163 (Run 96)

Run 86 began on November 21, 1976. At about 1600 on November 23, data from GLASS showed an increase in the activities of $^{135\text{m}}\text{Xe}$ and ^{135}Xe . These activities reached a maximum of five times normal background 24 h later. Xenon-135m activity declined to its normal background value by 1200 on November 26, and the longer-lived ^{135}Xe , by late on November 27. The activities of all other monitored isotopes were at normal levels through this period, except for the ^{133}Xe that was decaying from the earlier release from subassembly X211. This behavior indicated the release of sodium from a sodium-bonded element with a low internal pressure for bond expulsion. The likely source was either one of many driver-fuel elements at low burnup or a

sodium-bonded advanced-fuel element (of which there were four subassemblies in the reactor for run 86). Because no driver-fuel elements have breached below 6.5 at. % burnup, a sodium-bonded advanced-fuel element appeared the more likely source.

Activities in the cover gas were normal for the next 15 days. On December 10, shortly after a temporary reactor-power reduction to 47 MWt for other reasons, the ^{133}Xe activity started to increase slowly, reaching about three times the normal background by December 15. Analysis of a cover-gas sample taken 0900-1030 that day indicated about 0.016 cm^3 of the xenon tag from subassembly X211, which had caused the major release of activity on November 13. Experience indicated that such a long steady increase in activity was probably from a new source in the reactor rather than from subassembly X211 in the storage basket. The cover gas was purged to remove the residual tag.

An increase in ^{133}Xe activity was next observed at 1000 on December 20. At 1200 on December 22, ^{135}Xe activity also started to increase slowly. When the ^{133}Xe and ^{135}Xe activities had reached 110 and 1.7 times background, respectively, the cover gas was thoroughly purged. Analysis of samples of cover gas taken on December 22 and 28 showed a small total release of fission gas. Although the measured $^{134}\text{Xe}/^{128}\text{Xe}$ ratios (<2000) indicated the presence of a xenon tag, the absence of ^{124}Xe and ^{126}Xe and the very low volume of tag calculated to be in the cover gas ($<0.008 \text{ cm}^3$) cast doubt on whether a tag was present. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratios of 0.413 and 0.423 were typical of a uranium-fissioning source. The release was quite different from that of November 23-27 and was similar to a release observed a year before from a driver-fuel element that was believed to have a defective upper weld. (See Sec. III.C above.) There now appeared to be the possibility of two sources in the reactor: one that had released some bond sodium, but was dormant, and a second that was releasing only aged fission gas.

At about 0700 on January 1, 1977, the activity of $^{135\text{m}}\text{Xe}$ in the cover gas began to show a significant increase, followed shortly by an increase in ^{135}Xe activity. On January 2, at 0636, a sudden 40% increase in count rate was observed on all three channels of the FERD. Count rates remained high until 0712, when the reactor power was reduced to 50 MWt. When power was reduced, the ^{138}Xe , $^{135\text{m}}\text{Xe}$, ^{135}Xe , ^{88}Kr , and $^{85\text{m}}\text{Kr}$ activities increased by factors of 5-10. The reactor was brought back to 62.5 MWt in steps, full power being achieved at 1320. The FERD count rates remained near normal levels during this time. A second increase in FERD count rates, similar to that at 0636, was observed at 1743 the same day, with a corresponding increase in cover-gas activities. At 2208, a third increase in FERD count rates to near trip levels was observed, and an anticipatory shutdown was made.

Analysis of a cover-gas sample taken 0840-1010 on January 3 showed the presence of xenon-tag isotopes, but in concentrations far too low to allow

identification of their source. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.415 still indicated a uranium-fissioning source. Since the cover-gas signals were consistent with release of bond from a sodium-bonded element, the decision was made to remove subassembly X250. This subassembly contained Mark-II driver-fuel elements near 10 at. % burnup and had the highest known probability for cladding breach of any sodium-bonded element in the reactor. In addition, three recently loaded subassemblies of Mark-II elements with low burnup (B-3435A, B-3436A, and C-2684A) were removed in the expectation that one of them contained the element that had released only ^{133}Xe to the cover gas. The cover gas was thoroughly purged to reduce activity.

Startup for run 86C began on January 4. At full power, cover-gas activities were near normal levels, except for ^{135}Xe and ^{135m}Xe , which were both at about three times the normal background. The ^{135m}Xe activity declined slowly through the next two days. At 1100 on January 6, reactor power was lowered to 30 MWt and raised again to promote the release of xenon tag from the source; none was found by analysis of a cover-gas sample. The ^{135m}Xe activity was observed to slowly increase again at about 2400 on January 6. At 1100 on January 7, the increase accelerated, and soon the activities of ^{138}Xe and other short-lived isotopes increased. Several hours later, the activities of ^{133}Xe and ^{135}Xe also began to increase, and the reactor was shut down at 2300 because of high cover-gas activity. Figure 28 shows the GLASS activity data for January 1-8, 1977.

Fig. 28. GLASS Activity Data for January 1-8, 1977. ANL Neg. No. 104-77-366.

Analysis of a sample of cover gas taken 0030-0215 on January 8 showed the presence of xenon-tag isotopes and strongly indicated that subassembly X163, containing sodium-bonded nitride elements near 8 at. % burnup, was the source of the release. The low measured volume ratio of fission gas to tag gas (~10) also suggested that an element in this subassembly was the likely source, because the release of fission gas from sodium-bonded advanced fuels was known to be low. The release of a small amount of sodium over November 23-27 also indicated that more than one element may have breached, although this possibility could not be confirmed from the data. Run 86 ended with the shutdown on January 7, and subassembly X163 was removed as the likely source. The absence of unusual short-lived activity during and after startup for run 87 on January 16 confirmed that X163 had been the source of release. Table XIV gives the results of the cover-gas analysis on January 8.

TABLE XIV. Summary of Data for Suspect Subassembly X163
for Release on January 8, 1977^a

Tag Number ^b	MATMOL ^c	MATRAT ^d	Calculated Fission-gas/ Tag-gas Ratio
8X2803	0.51	4.13	4-45
			Measured Ratio (1/8/77)
			12

^aSubassembly contains sodium-bonded carbide and nitride at 8 at. % peak burnup.

^bNitride fuel elements contain this tag.

^cMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe .

^dMatch factor based on ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

About 9 mL of stable gas was calculated to have been released while the reactor was at power, and a further 2 mL after the reactor was shut down. Figure 29 shows the activity and equilibrium release rate of ^{133}Xe in the cover gas for November 23, 1976, through January 7, 1977. Analysis of primary-sodium samples indicated an equilibrium release of 0.69 Ci (~25 GBq) of ^{131}I . Examination in HFEF showed that two elements (15-20 and ONI-1) lost weight by 1.1 and 3.2 g, respectively.

Fig. 29. Activity and Release Rate of ^{133}Xe to EBR-II Cover Gas, November 23, 1976-January 7, 1977. Conversion factors:
 1 Ci = 37 GBq; 1 ft³/min = 4.719×10^{-4} m³/s.

M. Subassembly X181D (Run 87A)

Run 87A began on January 15, 1977. For this run, a fission-product source consisting of tubes of a very dilute uranium-nickel alloy was in the reactor as subassembly X288. This source produced a near-constant recoil release of fission products to the primary system. It produced cover-gas activities and delayed-neutron signals of about 20 times normal background.

Fig. 30

Activity and Release Rate of ^{133}Xe to
EBR-II Cover Gas, January 19-20, 1977.
Conversion factors: 1 Ci = 37 GBq;
1 ft³/min = 4.719×10^{-4} m³/s.

By the afternoon of January 19, the activities of all short-lived gas isotopes in the cover gas had long since reached equilibrium, and the ^{135}Xe activity was essentially at equilibrium from the recoil source. At about 1730 on the same day, the activities of all other isotopes were increasing slowly. At 2000, the activities of all isotopes increased dramatically, and the reactor was shut down at 2100 when the ^{133}Xe activity exceeded 250 times normal background. Figure 30 shows the activity and equilibrium release rate of ^{133}Xe in the cover gas for January 19-20.

Analysis of a cover-gas sample taken between 2315 on January 19 and 0045 on January 20 clearly showed the presence of xenon-tag isotopes. The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio of 0.446 indicated mixed (plutonium and uranium) fissioning. The xenon-tag analysis indicated that subassemblies X181D, X215C, and X227A were the most likely sources of the release.

The measured volume ratio of fission gas to tag gas eliminated subassemblies X215C and X227A from the suspect list because of their low burnups. Table XV gives the results of the analysis. Calculations of probability of cladding failure also indicated an element in X181D to be the likely source of the release. On the basis of this analysis, only subassembly X181D was

removed from the core. During the startup for run 87B on January 23, the activities of short-lived gas isotopes from the fission-product source increased in the same way with reactor power as they had during the initial startup on January 14; the absence of unusual short-lived activity therefore confirmed that subassembly X181D had been the source of the release over January 19-20. About 43 mL of stable fission gas was released from subassembly X209. After the contribution of ^{131}I activity from the source test was deducted, the equilibrium release of ^{131}I from subassembly X181D was about 0.3 Ci (11.1 GBq).

TABLE XV. Summary of Data for Primary Suspects
for Release of January 19-20, 1977

Subassembly Number ^a	Peak Burnup, at. %	Tag Number	MATMOL ^b	MATRAT ^c	Calculated Fission-gas/ Tag-gas Ratio
X181D	10.5	4X4206	0.8	3.9	113
X215C	2.4	4X4210	3.6	2.4	0.4
X227A	3.4	4X4206	3.3	4.0	36-38
					Measured Ratio (1/19/76)
					59

^aAll subassemblies contain mixed-oxide fuel elements.

^bMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe .

^cMatch factor based on ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

N. Subassembly X240 (Run 87B)

Run 87B began on January 23, 1977, and continued uneventfully until February 13. During this period, the fission-product source in subassembly X288 produced high delayed-neutron signals and steady cover-gas activities that were about 20 times normal. At midday on February 13--about 12 h before the scheduled shutdown for run 87B--a very rapid increase was observed in the activities of all fission-gas isotopes monitored by GLASS, the RCGM (reactor cover-gas monitor), and the FGM (fission-gas monitor). The reactor was shut down at 1230 because of high cover-gas activity.

Analysis of a sample of cover gas taken between 1630 and 1800 on February 13 showed that about 2.5 mL of fission gas had been released, although there were no detectable quantities of ^{124}Xe and ^{126}Xe . The measured $^{131}\text{Xe}/^{134}\text{Xe}$ ratio (0.429) and the rapid release of all radioactive gas isotopes indicated that the likely source of the release was a plutonium-bearing oxide element. The unusually low measured $^{134}\text{Xe}/^{133}\text{Xe}$ ratio of 8.1 also indicated the release of fresh fission gas from a breach site that was probably in the fuel-column region. Figure 31 shows the activity and equilibrium release rate of ^{133}Xe in the cover gas for February 13-18. Figure 32 shows the GLASS activity data for the same time period.

Fig. 31. Activity and Release Rate of ^{133}Xe to EBR-II Cover Gas, February 13-18, 1977. Conversion factors:
 $1\text{ Ci} = 37\text{ GBq}$; $1\text{ ft}^3/\text{min} = 4.719 \times 10^{-4}\text{ m}^3/\text{s}$.

Fig. 32. GLASS Activity Data for February 13-18, 1977. Conversion factor: 1 Ci = 37 GBq.

Although the low measured $^{134}\text{Xe}/^{133}\text{Xe}$ ratio indicated that the cladding breach was not connected to the plenum, and therefore that a xenon tag--if present--might not have been released, the available data could only indicate that the source was an untagged mixed-oxide element. There were two sub-assemblies of such elements in the reactor for run 87B: X212 (in which the elements were encapsulated) and X214. Because of the rapid release of all gas isotopes, the possibility that the source was an encapsulated element could be dismissed. Accordingly, only subassembly X214 was removed from the core as suspect.

Startup for run 87C was delayed several days because of difficulties in fuel handling. During startup, on February 17, a voltage dip in the 138-kV INEL loop caused the reactor to trip at 17 MWt. On resumption of startup shortly after that, the GLASS activity data indicated that the source was still in the reactor. An anticipatory shutdown was made at 40 MWt when the cover-gas-activity limit of 250 times normal background was exceeded.

A second sample of cover gas was taken 2040-2110 on February 17. This time, about 6.3 mL of fission gas had been released from the source,

including 0.044 mL of a xenon tag. (See Table XVI.) The measured cover-gas composition agreed closely with the corrected composition of a xenon tag in subassembly X240, which contained mixed-oxide elements at 13 at. % burnup. The measured volume ratio of fission gas to tag gas (143) and the $^{131}\text{Xe}/^{134}\text{Xe}$ ratio (0.432) also indicated the likely source to be a mixed oxide at high burnup. Subassembly X240 was removed from the core to the basket, and subassembly X214 was returned to its grid location, being newly exonerated as a suspect. The absence of unusual short-lived fission-gas activity during and after startup for run 87D late on February 18 confirmed that subassembly X240 had been the source of the activity release on February 13.

TABLE XVI. Summary of Primary Suspect Subassembly X240 and Cover-gas Analysis for Release of February 13-18, 1977

Tag Number	MATMOL ^a	MATRAT ^b	Calculated Fission-gas/Tag-gas Ratio
4X5816	0.07	9.66	177
			Measured Ratio (2/17/77)
			143

^aMatch factor based on mole percent of ^{124}Xe , ^{126}Xe , ^{128}Xe , and ^{129}Xe .

^bMatch factor based on ratios of $^{129}\text{Xe}/^{124}\text{Xe}$, $^{128}\text{Xe}/^{129}\text{Xe}$, $^{126}\text{Xe}/^{124}\text{Xe}$, and $^{129}\text{Xe}/^{126}\text{Xe}$.

About 38 mL of stable fission gas was released from subassembly X240. Because of the high and uncertain ^{131}I activity from the source test, no significant ^{131}I release from subassembly X240 could be detected.

IV. SUMMARY AND CONCLUSIONS

During this reporting period, 14 major releases of fission products occurred in the EBR-II system. Seven releases were from mixed-oxide fuel elements, five were from experimental Mark-II driver-fuel elements, one was from an unidentified driver-fuel element, and one was the first release to be obtained in EBR-II from sodium-bonded nitride fuel. Except for the unidentified driver-fuel element (which released ^{133}Xe only), all sources were identified by the release of an identifiable xenon tag.

Identification of the sources of releases by xenon tag was particularly effective during this reporting period. This experience confirmed the validity of empirical correlations that were developed during the last reporting period to account for in-reactor changes in the composition of xenon tags. A computer program, MIXTAG, was used on several occasions when more than one tag was present in the cover gas at one time. Proving out of this code has added considerable confidence in our ability to identify breached elements in EBR-II, provided cover-gas analyses are available.

Finally, review of data from postirradiation examinations--where available--has indicated the generally excellent condition of breached elements after irradiation. All attempts to locate the breach site in one of these elements (in subassembly X207) failed. Activity of ^{137}Cs in the primary sodium rose sharply through breaching of Mark-II elements during this period. So far, however, primary-sodium activity has not directly affected plant availability. Downtime caused by identification of breached elements was near its minimum possible value.

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