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Investigation of Water-Logged Spent Fuel Rods under Dry Storage Conditions

September 1986

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INVESTIGATION OF WATER-LOGGED
SPENT FUEL RODS UNDER
DRY STORAGE CONDITIONS

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SUMMARY

Tests were conducted to determine the amount of moisture contained in breached, water-logged spent fuel rods and the rate of release. Two well-characterized BWR fuel rods with reactor-induced breaches were tested in a hot cell. These rods contained approximately 6 to 10 g of moisture, most of which was released during heating tests simulating normal cask drying operations. Additional testing with two intentionally defected fuel rods (BWR and PWR) was performed to evaluate the effect of the cladding breach on migration of moisture along the length of the fuel rod. The results showed that the moisture released from reactor-breached spent fuel rods was insufficient to cause degradation of fuel or dry storage system components.

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INTRODUCTION

Of the early light water reactor (LWR) fuel rods, being stored in spent fuel pools, up to 1% are believed to contain reactor-induced breaches. Some of the breached fuel has become water-logged due to exposure to the high-pressure reactor coolant and as a result of storage in the pools. While improvements in the fuel design, fuel manufacture, and reactor operating procedures have substantially reduced fuel failure in newer rods, older fuel rods, with low rates of decay heat, are prime candidates for dry storage. To determine fuel rod behavior in dry storage, a previous study conducted at the Battelle Columbus Division for the Commercial Spent Fuel Management (CSFM) Program Office^(a) examined water-logged boiling water reactor (BWR) fuel rods containing reactor-induced cladding breaches (Kohli et al. 1985). The primary objective of that work was to investigate fuel oxidation in breached fuel rods on exposure to air and argon at high temperatures. During the course of that investigation, however, preliminary evidence showed that vacuum pumping at temperatures as low as 373K resulted in significant moisture release from the breached fuel rods. These results suggested that the effects on the fuel and on the storage system components from the release of moisture to the dry storage atmosphere needed further definition.

Recently, Peehs and Fleisch (1986) described the behavior of water-logged pressurized water reactor (PWR) fuel rods on heating at 673K in a hot cell. The bulk of the water (3 to 6 g per rod) was released during a simulated cask drying operation, with the temperature of release (~673K) indicating that at least part of the water was bound chemically with the fuel. The presence of ⁸⁵Kr and tritium was also detected in the moisture released.

The primary objective of the work discussed in the following text was to determine how much releasable water is contained in breached spent fuel rods, the amount of water released during an exposure to vacuum and temperature, and

(a) Work supported by U.S. Department of Energy, Office of Civilian Radioactive Waste Management through the Commercial Spent Fuel Management Division of the Richland Operations Office. The project was managed by the PNL Commercial Spent Fuel Management Program Office.

the effects of the water on spent fuel rod integrity under dry storage conditions. The secondary objective was to determine the degree of water migration in a fuel rod and whether there are differences in this migration behavior between reactor-breached and intentionally defected rods and between BWR and PWR fuel rods. The absorption and release of water in an intentionally defected rod could be significant in the event of a rod breach prior to cask loading or during wet consolidation because the presence of the water could result in fission gas release to the cask atmosphere during cask drying, as was observed by Peehs and Fleisch (1986). Furthermore, moisture could potentially react with Cs fission products to form a corrosive atmosphere for storage system seals, such as metal seals in a cask lid assembly.

To achieve the objectives, two well-characterized BWR fuel rods containing reactor-induced breaches and two intentionally defected fuel rods (one BWR and one PWR) were tested in the hot cell at a heating rate simulating the temperature rise in a storage cask during pump-down and dryout operations. Because the initial moisture content of the reactor-breached rods was unknown, a pre-determined amount of moisture added to the intentionally defected rods enabled the extent of moisture release to be determined. The moisture release from the fuel rods was determined by weight changes monitored on a moisture absorbent. This report describes the results of the tests, along with pre-test characterizations and the test apparatus, specifications, and procedures.

CONCLUSIONS

Based on the results of this limited series of tests, the following conclusions can be drawn:

1. The bulk of the uncombined moisture contained in water-logged, reactor-breached fuel rods was released within 3600 to 4800 s during heating in an axial temperature gradient 473/673/473K. The moisture was completely removed within 13,200 s, regardless of the size of the breach, in agreement with recent results of another study (Peehs and Fleisch 1986).
2. Water injected into the plenum of breached rods at 13.8 MPa pressure to simulate reactor coolant system pressure is rapidly transported down the rod when heated and released through cladding breaches.
3. Axial migration of water in fuel rods occurs only if the fuel has previously been exposed to reactor coolant, i.e., breached fuel rods. In intentionally defected fuel rods, water added to the rod tends to be absorbed by the fuel and moisture does not migrate axially.
4. In intentionally defected fuel rods, some fission gas is released from the fuel on heating in the presence of water.

PRE-TEST CHARACTERIZATION OF FUEL RODS

Two fuel rods with reactor-breached cladding (BWR) and two intentionally defected fuel rods (one each BWR and PWR) were characterized before the experiments began.

REACTOR-BREACHED FUEL RODS

The two reactor-breached BWR fuel rods were extensively characterized prior to testing. Rod 147 taken from a 7 x 7 assembly with an average burnup of 22.4 MWd/kgU was nominally 1.44 cm in diameter. Rod 113 taken from an 8 x 8 assembly with an average burnup of 15.6 MWd/kgU was nominally 1.28 cm in diameter. The rods were in pool storage for about 4 yr before they were shipped dry to the Battelle Hot Cell Laboratory in West Jefferson, Ohio. There, they were stored dry and open to flowing air atmosphere in the hot cell at an average cell temperature of 296K for approximately 4-3/4 yr prior to examination and testing.

Visual examination with a stereo-optical viewing system revealed that both fuel rods contained large reactor-induced cladding breaches. Rod 147 had a large hole approximately 4 cm from the bottom end (Figure 1a) and two long cracks at 229 and 244 cm from the bottom (Figure 1b and 1c). By metallographic examination of sibling rods, these cracks were identified as secondary hydride breaches (Figure 2). Rod 113, on the other hand, showed two large open holes at approximately 89 and 92 cm from the bottom through which the fuel was visible (Figure 3a and 3b). In addition, a significant bulge (not a through-wall crack according to eddy current tests) was observed at approximately 246 cm from the bottom (Figure 3d), which is assumed to be the start of a secondary breach. A continuous videotape recording was made of the surface features of each rod along the entire length. The fuel rod identification numbers were used as the 0 degrees azimuthal reference orientation marks. To cover the entire surface, each rod was videotaped from bottom to top at 120-degree azimuthal intervals by rotating in a clockwise direction looking at the bottom of each rod.

FIGURE 1. Breaches in Fuel Rod 147 at Different Axial Locations Above Rod Bottom; a. 4 cm, b. 229 cm, c. 244 cm.

7X

HC 51277

400X

HC 51267

FIGURE 2. Reactor-Induced Hydride Breach in Sibling BWR Fuel Rod 123

90°

a.

270°

b.

FIGURE 3. Defects in Fuel Rod 113 at Different Axial Locations Above Rod Bottom; a. 89 cm, b. 92 cm, c. 89 and 92 cm, d. 246 cm.

c.

d.

FIGURE 3. (contd)

Pretest profilometry measurements revealed large bulges in Rod 147 at 229, 244, and 249 cm and a smaller bulge at 190 cm above the bottom, as shown in Figure 4. For Rod 113, the profilometry measurements revealed several large bulges from 58 to 104 cm above the bottom. Other large bulges were evident at 116, 150, 193, 204, 246, and 249 cm above the bottom (Figure 5).

Gamma activity was scanned on both fuel rods. Some fuel loss was observed from the breached locations at 241 to 246 cm and 89 cm above the bottom of Rods 147 and 113, respectively (Figures 6 and 7).

INTENTIONALLY DEFECTED FUEL RODS

The two intentionally defected fuel rods were also extensively characterized prior to testing. PWR Rod 512 was taken from a fuel assembly with an average burnup of approximately 40 MWd/kgU. BWR Rod 1937 was taken from the same assembly as Rod 147.

Visual examination of these rods showed them to be intact with no evidence of any breaches. The gamma activity scans and profilometry measurements revealed no unusual features or abnormalities. Both fuel rods were punctured (1-mm holes) for fission gas collection and void volume measurements. As shown in Table 1, substantial volumes of fission gas were collected from each rod, providing further evidence that these fuel rods were not reactor-breached.

FIGURE 4. Profilometry Scan of Fuel Rod 147

FIGURE 5. Profilometry Scan of Fuel Rod 113

FIGURE 6. Gamma Scan of Fuel Rod 147

FIGURE 7. Gamma Scan of Fuel Rod 113

TABLE 1. Results of Fission Gas Collection from Intentionally Defected Fuel Rods

<u>Rod No.</u>	<u>Fuel Rod Type</u>	<u>Total Gas Collected, cm³ STP</u>	<u>Plenum Volume, cm³</u>	<u>Internal Void Volume, cm³</u>	<u>Percent Fission Gas Released</u>
512	PWR	550	8	14	0.5
1937	BWR	517	18	57	21

TABLE I. Results of Pission Gas Collection from Intentionally
Defected Fuel Rods

Rod No.	Fuel Rod Type	Total Gas Collected, cm ³ STP	Pission Volume, cm ³	Internal Void Volume, cm ³	Percent Pission Gas Released
315	PWR	250	8	14	0.5
1931	BWR	217	18	21	21

TEST DESIGN

This section describes the apparatus developed for the tests both inside and outside the hot cell, the test specifications, and the general procedure for the experiments.

APPARATUS

The equipment illustrated in Figure 8 was designed and fabricated for this study to simulate dry storage conditions and to measure subsequent moisture release from the fuel rods. It consists of a two-zone, stainless steel furnace tube (Zone M, ~120 cm long; Zone N, ~180 cm long) containing three collars to support the fuel rod during the test. The furnace tube is connected to the gas

FIGURE 8. Experimental Setup for Fuel Rod Moisture Release Tests

inlet, drying, and gas collection system with pressure-tight Swagelok®(a) fittings. An argon cover gas flow was used to ensure that all moisture released from the fuel rod was carried out of the hot cell into the drying tower, which initially contained calcium chloride. Later, calcium sulfate was used in place of calcium chloride to reduce the degradation of the drying tower caused by the exothermic reaction.

The apparatus was designed to simulate axial temperature gradients in a storage cask. The temperature of the center 180 cm of the fuel rod (Zone N) was raised from 298K to approximately 673K at a heating rate of approximately 100K/h under vacuum pumping to simulate the temperature rise in a storage cask during pump-down and dryout operations. The temperature at either end of the rod (Zone M, approximately 120 cm long) was maintained at 473K during the test. The test temperature was maintained until no further moisture release was observed, as indicated by a weight change of ± 0.01 g of the desiccant. The temperatures were controlled to within 10K. The test atmosphere was argon, which was analyzed to determine whether detectable fission gas was released.

To determine the experimental parameters for in-cell testing of the fuel rods, a simulated out-of-cell test was conducted with a stainless steel solid rod. The purpose of the out-of-cell experiment was to check out all systems and to determine parameters such as argon cover gas flow rates, time to achieve test temperature, temperature ramp rates, and pump-down rate. In addition, the furnace temperature gradient was established with a series of thermocouples located along the tube. The temperature variation at any location within Zone N did not exceed ± 10 K with the axial temperature profile shown in Figure 9. Following successful out-of-cell testing, the apparatus was installed in the hot cell to perform tests with the fuel rods.

SPECIFICATIONS

Several tests were performed with each of the fuel rods. The specifications for each test are given below.

® Crawford Fitting Company, Solon, Ohio.
(a) Use of trade name does not imply PNL endorsement.

FIGURE 9. Axial Temperature Profile of the Furnace Tube

Rod 113

Three tests were designed for Rod 113.

Test I. The rod was tested in the as-stored condition. The moisture contained in the rod was measured by heating the rod in the specified temperature gradient.

Test II. In this test, approximately 10 g of water were added to the fuel rod through a 2.4-mm hole drilled in the plenum. The plenum was then sealed, and the moisture release was measured in the 473/673/473K gradient.

Test III. Depending on Test II, if water was not recovered from the plenum, a 2.4-mm hole would be drilled in the cladding approximately 300 to 330 cm from rod bottom. The rod would then be heated in a 473/673/473K gradient, and the moisture release measured.

Rod 147

Four tests were carried out for Rod 147.

Test I. This test was similar to Test I with Rod 113. The moisture release was measured from the rod tested in the as-stored condition.

Test II. In this test, a 2.4-mm hole was drilled in the plenum region of the rod. The rod was then heated in the temperature gradient specified earlier, and the moisture release was measured.

Test III. The third test with this fuel rod required the addition of approximately 10 g of water to the rod through the 2.4-mm hole drilled in the plenum for Test II. After sealing the plenum, the rod was heated in the furnace tube, and moisture release was measured.

Test IV. For the last test in this series, water was injected at 13.8 MPa (2000 psi) into the rod at ambient temperature. The rod was weighed to determine the amount of moisture absorbed following vacuum injection. The rod was then heated in the furnace tube, and the moisture release was measured.

Rod 1937

Only one test was performed with BWR Rod 1937. Approximately 10 g of water were added to the rod through a 2.4-mm hole drilled in the plenum region, and the plenum was sealed. A second hole, approximately 2.4-mm in diameter, was drilled in the cladding between the ends of the seventh and eighth fuel pellets from the bottom of the rod (~9 cm). The rod was then heated in the specified temperature gradient, and the moisture release was measured.

Rod 512

One test was also conducted with PWR Rod 512. The specifications for this test were identical to those for BWR Rod 1937. The plenum was injected with water (10 g) and sealed. The second 2.4-mm hole was drilled at approximately 11 cm from the bottom of the rod (between the seventh and eighth fuel pellets). The rod was heated in the furnace tube, and the moisture release was measured.

PROCEDURE

The general procedure for all tests was to prepare each fuel rod for the specific experiment prior to loading into the furnace tube. This preparation involved (as required) drilling the cladding holes with a center drill; water addition to the rod using a syringe; high-pressure water injection of the fuel rod placed in an evacuated tube; and rod weighing using a digital balance or a load cell.

Following preparation, the rod was loaded into the furnace capsule, and the power and vacuum and argon gas flow lines were connected. The fuel rod was heated at the predetermined rate (100K/h) while evacuating the furnace tube to simulate cask dryout conditions. The amount of moisture released during this heating period was noted by recording the weight change of the desiccant at 240-s intervals. When the temperature of Zone N reached the maximum of 673K, the vacuum line was closed and the argon gas flow was started. Samples of the argon cover gas were obtained to determine the presence of detectable fission gas. Further moisture release was noted from the weight change of the desiccant.

The experiment was discontinued when no further weight change (± 0.01 g) was observed in the desiccant. Once the experiment was completed, the fuel rod was removed and reweighed, if necessary, or it was prepared for the next test.

The general procedure for all tests was as follows: each fuel rod for the specific experiment prior to loading into the furnace tube. This preparation involved (as required) drilling the standard holes with a center drill; water injection to the rod using a syringe; high-pressure water injection to the fuel rod placed in an evacuated tube; and rod weighing using a digital balance on a lead cell.

Following preparation, the rod was loaded into the furnace capsule, and the power and vacuum and argon gas flow lines were connected. The fuel rod was heated as the predetermined rate (about 10°C/min) while evacuating the furnace tube to achieve a low oxygen content. The amount of moisture released during this heating period was noted by recording the weight change of the desiccant at 15-20 intervals. When the temperature of Zone II reached the maximum of 575°C, the vacuum line was closed and the argon gas flow was started. Samples of the argon cover gas were obtained to determine the presence of gaseous fission gas. Further moisture release was noted from the weight change of the desiccant.

The experiment was discontinued when no further weight change (20.00 g) was observed to the desiccant. Once the experiment was completed, the fuel rod was removed and reweighed, if necessary, or it was prepared for the next test.

RESULTS AND DISCUSSION

The out-of-cell tests showed that the in-cell portion of the apparatus would successfully simulate dry storage conditions during cask dryout. This section gives the results obtained from experiments conducted within the hot cell.

ROD 113

Only two of the tests were required for Rod 113.

Test I

The first experiment was performed with Rod 113 taken directly from storage. The rod was loaded into the furnace capsule, and the electrical power and vacuum and argon gas flow lines were connected. The results of this experiment are graphically illustrated in Figure 10, where time, temperature, pressure, and weight gain data for the test are recorded. As can be seen, the bulk of the moisture was released from the fuel rod in the first 1800 s after startup, at a temperature of approximately 373K. No further moisture release was measurable, as the temperature was raised to a maximum of 723K and then maintained at 653K for 120 s.^(a) Argon cover gas samples were obtained at the times indicated in Figure 10 and analyzed. The results of analysis (Table 2) showed the complete absence of detectable fission gas xenon or krypton. This result is in contrast to the results reported by Peehs and Fleisch (1986) in which both ^{85}Kr and tritium were released during testing of two water-logged PWR fuel rods. Also, very little moisture was found in the present test, suggesting that the rod contained almost no moisture to begin with. This assumption was confirmed by inspecting the weight gain data; the total quantity of moisture released from Rod 113 was only 0.8 g.

(a) This test was performed in a two-step Zone N heating mode to simulate cask drying operations (Zone M was maintained at 373K). However, since the bulk of the moisture was removed at a temperature of 373K, all subsequent tests were conducted in a single heating mode (Zone N = 673K; Zone M = 473K).

FIGURE 10. Results of Moisture Release Test I with Fuel Rod 113

TABLE 2. Argon Cover Gas Analysis from Test I with Rod 113

Gas Sample	Constituent, mol%								
	He	N ₂	O ₂	A	H ₂	CO ₂	H ₂ O	Xe	Kr
1	ND (a)	56.56 (a)	15.77 (b)	26.53	0.20	0.20	0.72	ND	ND
2	ND	0.43	0.19	99.16	0.22	ND	0.09	ND	ND

(a) ND = Not detected; detection limit = 0.0001%.

(b) These high values for oxygen and nitrogen are probably due to inleakage of air in the gas collection system; otherwise, significant fuel oxidation would have occurred in the rod.

Because the internal void volume of the rod was 57 cm^3 (based on sibling Rod 1937 measurement), three possible reasons for the low moisture release from the rod were considered: 1) The test conditions did not provide sufficient driving force to release the moisture trapped in the void spaces in the fuel column. This would be particularly true if the water were combined chemically (U-O-H, Cs-O-H compounds) rather than physically (pores, surface adhesion) in the fuel. These tests do not lend themselves to detection of water tightly bound to the fuel. 2) The rod had been stored in an open tube and exposed to the flowing air atmosphere in the hot cell for approximately 4-3/4 yr (since 1979) prior to testing; consequently, additional drying could have occurred, aided by air flow through the cell. 3) More importantly, as shown previously (Kohli et al. 1985), vacuum pumping alone does not provide sufficient driving force to remove the moisture contained in the plenum of reactor-breached BWR rods. Less than 30% of the moisture in these rods was released through large, open breaches located sufficiently distant ($\sim 175 \text{ cm}$) from the plenum. Significant quantities of additional moisture were then removed from the rods after drilling a hole in the plenum and vacuum pumping at 375 to 403K. The results of these tests with sibling rods indicated that the bulk of the moisture in Rod 113 could also be present in the plenum. Because the plenum was maintained at approximately 373K in the present test, there was sufficient thermal driving force to release moisture had a reactor breach been present in the plenum.

To test the third hypothesis, a 2.4-mm hole was drilled in the plenum and the test was repeated. No further moisture was released, however, lending credence to the second hypothesis of rod dryout due to long storage in the hot cell.

Test II

Using a syringe, approximately 10 cm^3 of water were added to the plenum through the fission gas punch hole. The hole was then sealed with a Swagelok connector. The rod was loaded into the test chamber, and the experiment was started. The results are shown in Figure 11, which gives time, temperature, pressure, and weight change data. About 75% of the added water was released within a test period of 3600 s while the temperature was increased to approximately 400K. The remaining moisture was released at a much slower rate,

FIGURE 11. Results of Moisture Release Test II with Fuel Rod 113

although the temperature was raised to 673K. Apparently, all of the moisture was released even before the argon gas flow was started; 10 g of water had been collected until then, and no further weight gain was registered on the balance.

Test III

Because all the water added to the plenum was recovered from this rod in Test II, Test III was not necessary.

ROD 147

All four tests designed for Rod 147 were conducted.

Test I

The rod was taken directly from cell storage and heated in the test capsule. Pressure, temperature, and weight change as a function of time were

recorded. As in the initial experiment with Rod 113, no moisture release was measured, although the test temperature was raised to 673K and maintained for 1200 s.

Test II

Because no water was released in the first test and again with the premise that the bulk of the water in the fuel rod was present in the plenum region, a 2.4-mm hole was drilled in the plenum and the test was repeated. As shown in Figure 12, approximately 0.5 g of water eventually was collected from the rod, although moisture release did not commence until a test temperature of 450K was reached. Also, all of the moisture was released within 3000 s, which agrees with results of Test II of Rod 113.

Test III

Next, approximately 10 cm^3 (10 ± 0.2) of water were added to the plenum, which was then sealed with a Swagelok fitting. The rod was loaded into the test chamber, and the experiment was performed as specified. The results are

FIGURE 12. Results of Moisture Release Test II with Fuel Rod 147

shown in Figure 13. Again, most of the added water was released in the first 3600 s; afterwards the rate of release was much slower. The total moisture collected was 10.1 g.

Test IV

In the final test with Rod 147, the plenum hole was sealed with a Swagelok fitting, and the rod was weighed (5661 g) prior to vacuum injection. It was placed in a stainless steel pressurization tube with a 2.5-cm diameter and a 2.1-mm wall thickness. At one end of the tube, a threaded pipe with a suitable fitting was welded to it through which water was filled in the pressurization tube. At the other end of the tube, a 2.5-cm Swagelok fitting was adapted to fit a 0.8-cm T-joint. One branch of the T-joint was connected to the vacuum pump for evacuation; the other branch was connected to a 0.16-cm-diameter helium pressurization line. The tube was evacuated to 5 Pa pressure and then

FIGURE 13. Results of Moisture Release Test III with Fuel Rod 147

filled with water. Next, the water was forced into the rod at a helium pressure of 13.8 MPa, and the rod was reweighed (5715 g). The total water introduced into the rod was 54 g.

Following water-logging, the fuel rod was loaded into the test chamber, and the experiment was started. The results are shown in Figure 14. Inspection of the data shows that over 30% of the added water was released within the first 3600 s, followed by slower water release. Peaking of the weight curve in Figure 14 was due to saturation of the desiccant. Again, these results agree with results of earlier tests with respect to the rate of moisture release. This agreement is surprising in some respects because water ingress in the present test also could have occurred through the breaches in the fuel rod located away from the plenum. Subsequent water release would require essentially no axial migration, because the plenum was sealed. The insensitivity of the water release rate is further demonstrated by the water-logging tests with Rod 113. During those tests, the water was released from breaches located at least 280 cm from the sealed plenum where the water was initially injected. Apparently, axial migration of the water readily occurs.

FIGURE 14. Results of Moisture Release Test IV with Fuel Rod 147

ROD 1937

As required for the test with this fuel rod, 10 g of water were added through a 1-mm hole in the plenum region, and the plenum was sealed with a Swagelok fitting. A second hole was drilled in the cladding between the seventh and eighth fuel pellets (~9 cm from the bottom of the rod), and the rod was loaded into the furnace tube to start the test. To 424K no water release was measured in the drying tower. The hot cell stack alarm was set off, indicating the release of fission gases from the rod (all particulate matter would be captured on the micropore filters located in the hot cell). In addition, the vacuum pump located outside the cell gave a radiation reading of 4 mR/h. As a result, an argon cover gas sample was collected, and the test was discontinued. Analysis of the gas sample (Table 3) showed it to contain mainly argon (96.5%) and helium (3%) with traces of hydrogen and nitrogen. No xenon or krypton was detected (detection limit = 0.0001%). The small amount of hydrogen in the cover gas sample suggests that the bulk of the added water was combined with the fuel. If all of the water had oxidized the Zircaloy cladding, the hydrogen content of the cover gas sample should have been approximately 50 times higher (~10%) due to the following reaction:

The oxygen and nitrogen in Table 3 could have resulted from air ingress into the capsule or gas sample.

TABLE 3. Analysis of Argon Cover Gas Samples from Fuel Rods 1937 and 512

Rod No.	Constituent (mol%)					
	Ar	H	He	N	O	CO ₂
1937	96.5	0.19	3.16	0.13	0.006	0.006
512	86.3	0.24	1.05	9.53	2.90	0.02

ROD 512

For the test with PWR Rod 512, 6 g of water were injected through a hole in the plenum region. The plenum was sealed. As before, a second 1-mm hole was drilled in the cladding at approximately 11 cm from rod bottom (between the seventh and eighth fuel pellets), and the test was started. When the temperature reached 605K, the hot cell alarm was set off. No water release was measured in the drying tower. The radiation reading at the vacuum pump was 8 mR/h. This test was also discontinued.

Assuming the residual fission gas could be vented out, the plenum seal was removed, and the rod was reheated under vacuum pumping to 673K for 600 s. No further gas release was measured, suggesting that the residual fission gas had been released during the test. Hence, the rod was reprepared for a second water-logging experiment. Again, only 6 g of water could be added to the plenum, which was resealed, and the test was started. This time the furnace temperature was 673K when the stack alarm was set off. However, no water release was measured in the drying tower. A cover gas sample was collected, and testing was discontinued. Analysis of the argon cover gas (see Table 3) gave results very similar to those for Rod 1937, except for relatively high values for nitrogen (9.53%) and oxygen (2.9%). These high values may be due to inleakage of air in the gas collection system; otherwise, significant fuel oxidation would have occurred in the rod.

The lack of water release during both tests with this fuel rod supports the view that the water is combined with the fuel. Furthermore, it helps to explain the release of residual fission gas following water addition, because the reaction with the water would tend to release gas contained in the pores and bubbles in the fuel. Since such a reaction tends to be diffusion controlled and directly dependent on the amount of water available, fission gas will be released only in the presence of water, as was observed. In the tests of Peehs and Fleisch (1986), the two reactor-breached fuel rods apparently were only partially saturated with water prior to testing. During subsequent heating to 673K, further oxidation of the fuel took place, and additional fission

gas was released. The evidence from the present tests also suggests that axial migration of water in LWR fuel rods takes place only if the fuel has been saturated with water and no further oxidation occurs.

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