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FINAL REPORT:

REACTOR RUPTURE TESTING

OF ZIRCALOY-2-CLAD COEXTRUDED FUEL RODS

IN THE ENGINEERING TEST REACTOR

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FINAL REPORT:
IN-REACTOR RUPTURE TESTING
OF ZIRCALOY-2-CLAD, COEXTRUDED FUEL ELEMENTS
IN THE ENGINEERING TEST REACTOR

By

R. L. Call and D. C. Kaulitz
Metallurgy Development
Reactor and Fuels Laboratory
Hanford Laboratories

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RM Den, 3-10-94.
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FINAL REPORT:
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IN THE ENGINEERING TEST REACTOR

INTRODUCTION

One of the problems involved in the design and operation of the Hanford N-Reactor is determining the manner and rate of fuel element failure once water has penetrated the cladding. Specifically, when the uranium core of a fuel element comes in contact with water at high temperatures and pressure, how fast is the reaction, how much damage will be done, and at what rate will the fuel material be released into the coolant stream?

To provide data useful in the design of the reactor and for the initial stages of operation, considerable amount of testing has been done in out-of-reactor loops, in-reactor loops, and autoclaves. Of these tests, those which have provided the most direct data on the mode and rate of failure of a fuel element are the in-reactor rupture tests performed in the Engineering Test Reactor (ETR) at Idaho Falls, Idaho.

An associated problem is the development and testing of instrumentation for detecting fuel element failures in the N-Reactor. If a failure could be detected and verified early enough, massive failure of the fuel element and the associated contamination of the reactor can be minimized.

The in-reactor rupture test program was conducted to provide answers to these two problems. This report describes the rupture test program from the point of view of the first problem, the failure behavior of fuel elements. The second problem, the development and testing of rupture detection instruments, is discussed elsewhere.⁽¹⁾

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SUMMARY AND CONCLUSIONS

A series of seven in-reactor rupture tests was performed in the GEH-P7 Loop of the ETR. In these tests the fuel elements were ruptured "on command" by a hydraulically driven chisel which sheared off a projection welded over a hole drilled through the cladding of a fuel element.

All fuel elements tested were coextruded, Zircaloy-2-clad uranium. In the first three tests, seven-rod cluster fuel elements were used; in the fourth test, a tube-in-tube fuel element was used; and in the last three tests, heavy-walled single tube fuel elements were used. In the first three tests, the defect was on a peripheral rod of the cluster. In the fourth test, the defect was on the outer surface of the outer tube and in the fifth, sixth, and seventh tests, it was on the outer surface of the single tube. The fuel elements for the first, fourth, and fifth tests had not been irradiated before they were charged into the ETR. The fuel elements for the second and third tests were irradiated to 2400 Mwd/ton in a cold-water facility at Hanford and the fuel elements for the sixth and seventh tests were irradiated to 400 Mwd/ton and 1700 Mwd/ton, respectively, in a hot-water facility at Hanford before being charged into the ETR.

The first test was terminated 7 hours after the defect projection was sheared off without massive failure of the fuel element having occurred. The second test was terminated 14 hours after the defect projection was sheared off, and again no massive failure had occurred. In each case, a plug of UO_2 had formed under the defect, blocking further water entry and preventing massive failure of the fuel element.

In the third test, the rupture monitors signalled a massive failure 30 minutes after the defect projection was sheared off. After an additional 3 minutes, the loop water activity had reached the predetermined level at which the test was to be terminated. For the fourth test, the time was 18 minutes from the time the defect projection was sheared off until the start of the massive failure and an additional 12 minutes until the test was

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terminated. For the fifth test, the times were 46 minutes and 99 minutes. For the sixth test, the times were 38 minutes and 22 minutes (this test was terminated before activity levels required it) and for the seventh test, the times were 9 minutes and 5 minutes.

The weights of uranium converted to UO_2 in the last five tests were:

Third test	53 grams
Fourth test	43 grams
Fifth test	1080 grams
Sixth test	40 grams
Seventh test	25 grams

The tests demonstrated that under comparable conditions, irradiated fuel elements have a shorter incubation period (the time from initiation of the failure until massive release of corrosion products into the coolant) and a faster corrosion rate than do unirradiated fuel elements. Both of these effects are due at least in part to irradiation-induced cracking which occurs in the uranium. There is no evidence that the uranium corrosion rate itself is changed appreciably by irradiation. Cracking merely exposed a greater surface of uranium to the attack of the high-temperature water coolant.

The Zircaloy-2 baskets in which the fuel elements for the third, fifth, sixth, and seventh rupture tests were placed before being charged into the ETR were analyzed for hydrogen content following the rupture tests. Only in the case of the fifth test was there evidence of any appreciable increase in the hydrogen content. In this test, the ruptured fuel element was in contact with the basket for an hour or more during the test.

DISCUSSION

Description of the Rupture Device

One of the desired pieces of information from the rupture test program was the "incubation period" of a ruptured fuel element. The

incubation period is defined as the time from the initial penetration of water through the cladding of a fuel element until there is large-scale release of uranium oxide and fission products into the coolant stream. Uranium corrodes rather slowly in cold water, but with great speed in water above 200 C (392 F).⁽²⁾ If a fuel element having an open hole in the cladding were charged into a recirculating loop in a reactor, considerable corrosion could occur during the time the loop was being brought up to temperature, and the incubation time would be rather uncertain. Therefore, a method was devised whereby a fuel element could be ruptured in-reactor under steady-state operating conditions.

The method chosen required that a projection which had been welded over a hole drilled in the cladding of a fuel element be sheared off. A hydraulically operated chisel controlled from outside the reactor was designed to do the actual shearing. Figure 1 shows the rupture mechanism attached to a seven-rod cluster fuel element. With this method, fuel elements could be irradiated prior to rupture testing in the ETR. Also, the fuel element could be irradiated for several days, if desired, before the rupture was initiated. Figure 2 shows the tools used for remotely attaching the rupture mechanism to irradiated fuel elements. This method of rupturing fuel elements allowed considerable flexibility in the test program because it did not tie up valuable test loop space while the rupture-test elements were being irradiated. It did suffer from one drawback, however. The fuel elements which were to be irradiated before being rupture tested had to be prepared and charged into a reactor several months before the rupture test was performed, and there was always the chance of failure in one of these fuel elements or that the irradiation might be terminated ahead of schedule for some other reason. As it turned out, this proved to be a minor difficulty.

Fabrication of the Fuel Elements

The fuel elements used in the first three tests were seven-rod clusters. The rod stock from which the clusters were made was coextruded

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FIGURE 1

In-Reactor Rupture Mechanism

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FIGURE 2

Tools for Attaching the Rupture Mechanism
to Irradiated Fuel Elements

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by Nuclear Metals, Inc. (NMI) at Cambridge, Massachusetts.⁽³⁾ The rods were a nominal 0.592-inch OD with a cladding thickness of 0.020 inch for the first test and 0.030 inch for the second and third tests.

The fuel elements were fabricated as follows: the coextruded rod stock was cut to length and the uranium counterbored from the ends to a depth of 0.300 inch. The rod ends were then pickled in hot HNO₃ to remove any remaining uranium from the inside surfaces of the cladding of the counterbores. Next, Zircaloy-2 end caps were welded into place using the electron beam welding process. The rods were then beta-heat-treated at 710 C (1310 F) in trichloride salt for 5 minutes, and air cooled. Slots were machined into the end caps to receive the triangular end supports and the rods were tested ultrasonically to check the integrity of the cladding-to-core bond layer.

At this time, one of the rods for each cluster was prepared for intentional rupturing. A defect projection was welded to the surface of each of these rods. A 0.025-inch-diameter hole was drilled through this projection, through the cladding and into the uranium. The open end of the hole was then welded shut. Figure 3 shows a rod with a defect projection welded into place. A sketch of a cross section through a rupture projection can be seen in Figure 1.

FIGURE 3

Defect Projection
Welded into Place
on Coextruded
Fuel Rods
~3.5X

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After the defected rods were prepared, all the rods were pickled in a HNO_3 -HF solution and autoclaved for 72 hours in 400 C (752 F), 1500 psi steam. The rods were then welded to the end supports and the fitting for attaching the rupturing mechanism was welded to one end of each cluster. Completed clusters are shown in Figure 4.

The fuel element used in the fourth test consisted of two concentric tubes. The outer tube had an OD of 1.920 inches and an ID of 1.450 inches. The inner tube had an OD of 1.050 inches and an ID of 0.500 inch. Cladding thickness was a nominal 0.020 inch on all surfaces. The billets for these extrusions were assembled at Hanford and then shipped elsewhere for extrusion. The outer tube stock was extruded by the Bridgeport Brass company of Adrian, Michigan, and the inner tube stock was extruded by Nuclear Metals, Inc. Details of the billet preparation and coextrusion process are given by Nicholas and Guay.⁽⁴⁾

The process for fabricating the fuel element was as follows. The pieces were first cut to length and the copper was pickled off the cladding. Next, the pieces were beta heat-treated at 730 C (1346 F) for 5 minutes and air-cooled. The cladding was then vapor-blasted. Ultrasonic and eddy current tests were performed at this point to check the cladding thickness and the integrity of the uranium and of the cladding-to-core bond layer. After this was done, the uranium was counterbored from the ends of the pieces to a depth of 0.250 inch. The ends of the fuel tubes were pickled in hot HNO_3 to remove any traces of uranium from the inner surfaces of the cladding in the counterbore. Annular end caps were fitted into the counterbored ends and welded in place using the electron beam welding process. The fitting for attaching the rupturing device was now welded to one end of the outer tube. A specially built jig was attached to the outer tube to act as a guide for drilling the hole through the cladding. A 0.037-inch hole was drilled through the outer cladding of the outer tube and a projection welded over it similar to the ones used for the defected rods discussed earlier.

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FIGURE 4

Defected Seven-Rod Clusters for In-Reactor Rupture Tests
~0.5X

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The outer surfaces of both tubes were vapor-blasted again and supporting rails or "self-supports" were spot-welded in place. The tubes were then pickled in a solution of HNO_3 and HF and autoclaved for 72 hours in 400 C (752 F), 1500 psi steam. After the fuel tubes were removed from the autoclave they were visually inspected and shipped to the ETR for rupture testing. Figure 5 shows the assembled fuel element after its removal from the autoclave.

FIGURE 5

Defected Tube-in-Tube Fuel Element
~1.2X

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The fuel elements used in the fifth, sixth, and seventh rupture tests were tubular fuel elements but were thick-walled single tubes rather than the tube-in-tube geometry used in the fourth rupture test. The tube stock from which the fuel elements for the fifth and seventh tests were made was fabricated by NMI⁽⁵⁾ and that for the sixth test was fabricated at Hanford.⁽⁶⁾ The process used for fabricating these fuel elements was essentially identical with that used for the fuel element of the fourth rupture test. Two completed fuel elements of the type used in the last three tests are shown in Figure 6.

FIGURE 6

Defected Single-Tube Fuel Elements
~0.5X

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Irradiation of Defected Fuel Elements Prior to Rupture Testing

One of the variables being investigated was the effect of irradiation on the incubation time and uranium corrosion rate. Accordingly, several fuel elements which had been prepared for rupture testing were irradiated at Hanford prior to shipping them to the ETR. Two seven-rod cluster fuel elements were irradiated in cold water irradiation facilities to 2400 Mwd/ton.^(7,8) Before irradiation, these fuel elements were inserted into aluminum sleeves. The sleeves acted as flow splitters, controlling the velocity of the coolant water past the fuel elements; they also served to protect the fuel elements during postirradiation handling and shipment to the ETR. One of these clusters is shown in Figure 7 with its aluminum sleeve. The volume average temperature of the uranium in the peripheral rods of the clusters during the cold-water irradiation was 330 C (626 F).

The fuel element for the sixth rupture test was irradiated to 400 Mwd/ton in high temperature water in an irradiation facility in a Hanford reactor before it was shipped to the ETR. The fuel element for the seventh rupture test was irradiated to 1700 Mwd/ton in the same facility. Before these fuel elements were charged into the reactor they were inserted in Zircaloy-2 sleeves. These sleeves, as well as the sleeves for the fuel elements for the second and third rupture tests, were designed to provide the proper flow split around and through the fuel elements and to protect the fuel elements from damage during postirradiation handling and shipping. The fuel element for the sixth rupture test and its Zircaloy-2 sleeve can be seen in Figure 8. The pins shown at either end of the sleeve were welded to the sleeve after the fuel element was inserted. These pins held the fuel element in place and prevented damage to the "self-supports" during handling and shipping prior to the actual rupture test. Details of the Hanford irradiation of the fuel elements for the sixth and seventh rupture tests are given by Kratzer.⁽⁹⁻¹²⁾ The volume mean temperature of the uranium during the irradiation was 380 C (716 F).

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FIGURE 7

Defected Seven-Rod Cluster Fuel Element and Flow-Splitter Sleeve
~0.4X

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FIGURE 8

Defected Single-Tube Fuel Element
and Flow-Splitter Sleeve
~0.4X

Out-of-Reactor Testing

A considerable number of out-of-reactor rupture tests were performed before the in-reactor rupture tests were run. The preliminary testing was done to define some of the variables and establish bases for the in-reactor tests. Stephan, et al.⁽¹³⁾ performed several tests in a windowed autoclave on coextruded rod material with holes drilled through the cladding. The windowed autoclave was used so the fuel rods could be observed and photographed as they failed. These tests showed that a blister in the cladding first formed around the hole and the blister continued to grow until the cladding broke and released large amounts of UO_2 into the autoclave. These tests also established some preliminary corrosion rates.

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Autoclave tests were also performed at Hanford using pieces of the same rod material used in the second and third rupture tests. These tests were conducted in an induction heated autoclave which could be heated rapidly. The tests showed that with a 0.025-inch hole drilled through the cladding, the incubation time in 300 C water was approximately 40 minutes. With a defect projection over the hole (the top of the projection was sheared off to admit water) the incubation period was increased to approximately 70 minutes. The corrosion rate of the uranium was essentially the same in either case.⁽¹⁴⁾ Figure 9 shows one of the autoclave test pieces after several different exposure times. Figure 10 is a cross section through the piece shown in Figure 9 and shows the manner in which the corrosion was progressing. This type of corrosion attack is typical of unirradiated rod material when it is tested out-of-reactor.⁽¹⁵⁾

FIGURE 9

Coextruded Rod Material
Defect-Tested in an Autoclave

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FIGURE 10

Cross Section Through Coextruded Rod Material
Shown in Figure 9
(Electrolytically Polished)
~7X

A section of the outer tube extrusion used in the fourth rupture test was prepared for out-of-reactor testing. This piece was prepared in the same way as the test piece itself, except for being autoclaved. This out-of-reactor test piece is shown in Figure 11 with the rupturing device attached. This piece was tested in an out-of-reactor loop with the water

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FIGURE 11

Outer Tube of Tube-in-Tube Fuel Element
for Out-of-Reactor Rupture Testing
~0.5X

temperature at 300 C (572 F). The loop water was brought up to temperature and the defect cap sheared off. One-half hour later, the loop was cooled and the fuel element examined. A blister had formed around the weld at the base of the defect projection and the cladding was cracked. The piece was put back in the loop and water temperature raised to 300 C (572 F) as rapidly as possible. After an additional hour of testing, the loop was cooled and the piece examined again. Extensive blistering was visible around the defect projection and the cladding was badly cracked. By this time, 66 grams of uranium had been lost from the fuel element. The piece was returned to the loop for an additional one-half hour and then removed again. The blistering and cracking was even more

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extensive this time. Total weight loss after 2 hours in the loop was 71 grams. Figure 12 shows the test piece after each of the three stages of testing.

One-Half Hour After Defect Cap Was Sheared Off

1½ Hours After Defect Cap Was Sheared Off

2 Hours After Defect Cap Was Sheared Off

FIGURE 12

Outer Tube of Tube-in-Tube Rupture Test Fuel Element at Various Times
After Start of Rupture Test in Out-of-Reactor Loop
Water Temperature, 300 C
~0.6X

55-60; 54-60; 56-60

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This out-of-reactor test piece was sectioned at the conclusion of the test. Figure 13 shows a cross section through the center of the defect. This figure indicates that corrosion was progressing essentially on a front perpendicular to the cladding surfaces. Again, this is typical of unirradiated tubular material tested out-of-reactor.

FIGURE 13

Cross Section Through Piece Shown in Figure 12
As Cut, ~2X

Figure 14 shows two corners of the corrosion pocket. This figure reveals that the corrosion attack progressed at least as fast in the bulk of the uranium as it did along the cladding-to-core bond layer. This is also typical of unirradiated material. The behavior differences between unirradiated material are discussed later in this report.

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FIGURE 14

Corners of the Corrosion Pocket Shown in Figure 13
(Etched by Ion Bombardment) 50X

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One additional out-of-reactor rupture test will be discussed here. In this test, a piece of the NMI extrusion from which the fuel elements for the fifth and seventh rupture tests were made was used. This piece was prepared in the same manner as the fuel elements for tests five, six and seven, including a defect projection over the 0.037-inch hole through the cladding. The projection was sheared off and the piece inserted into the out-of-reactor loop used previously. The water was brought up to 300 C (572 F) with the test section of the loop bypassed. The test section was valved in and the water temperature dropped to 280 C (536 F). Normally, the temperature is brought back up to 300 C (572 F) in 15 minutes, but because of a leak in the loop piping, it took 1 hour to bring the temperature up. At this time, the evolution of hydrogen in the loop signalled the end of the incubation period--the cladding had cracked and was releasing hydrogen and UO_2 into the loop water. Temperature was maintained for 40 more minutes and then the test was terminated. Weight loss during the test was 135 grams. Figure 15 shows the test piece at the conclusion of the test. Figure 16 is a cross section through the rupture. The sample shown was wrapped with sirc and mounted in plastic to hold the cracked pieces of cladding together during the cutting and polishing operation.

FIGURE 15
Heavy-Walled Tubular Fuel Element
Rupture-Tested in an Out-of-Reactor Loop in 300 C Water
~0.6X

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FIGURE 16

Cross Section Through the Piece Shown in Figure 15
(As Polished) ~2X

In-Reactor Rupture Tests and Postirradiation Examinations

The fuel element for the first test in the series was a seven-rod cluster which had not previously been irradiated. The rupture device was attached to this fuel element and the assembly inserted into a thin-walled Zircaloy-2 tube, called a basket. The basket is designed to fit inside the pressure tube in the reactor with a minimum clearance of 1/16 inch between the pressure tube and the basket. Thus, if a fuel element becomes warped, or swells excessively, it is still possible to remove the basket and fuel element without damaging either the pressure tube or the fuel element.

After the test device was assembled, it was shipped to the ETR, inserted in the GEH-P7 Loop, and the necessary thermocouple and hydraulic line connections made. The reactor was brought up to power and 1 hour after full power was reached, the defect cap was sheared off. A 40-mr

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increase in gamma activity in the loop water was observed at this time and then no further increases were noted.

The out-of-reactor tests of coextruded rod material in all cases had shown massive failure in 2 hours or less. Therefore, the test proposal for the first in-reactor test⁽¹⁶⁾ requested a maximum of 4 hours of reactor operation after the defect cap was sheared off. When, after 4 hours, there was no indication that the expected massive failure of the defected rod had occurred, permission was obtained to continue operating for 3 additional hours. At the end of this time there were no indications of a massive failure of the fuel element so the reactor was shut down and the test assembly removed and returned to Hanford for examination.

Calculated power and temperature conditions at the defect during the test were as follows:

Specific power	20.7 kw/ft of rod
Local bulk water temperature	256 C (493 F)
Cladding surface temperature	281 C (506 F)
Uranium surface temperature	319 C (575 F)
Volume average uranium temperature	388 C (730 F)

The defected fuel element is shown in Figure 17 as it appeared following the test. The chisel which sheared off the defect projection is to the right of the defect, which is near the center of the figure. The defect cap has been sheared off and the hole is open to the water.

The defected rod was sectioned through the center of the defect (Figure 18). A photomicrograph of the defect itself is shown in Figure 19. These last two figures indicate that the hole in the cladding was open down to the uranium core. However, a small dense pocket of UO_2 had formed under the hole and had blocked, or at least greatly restricted, further water entry to the uranium. Thus, corrosion was greatly inhibited. Further details of the radiometallurgy examination are given by Teats.⁽¹⁷⁾

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FIGURE 17

First ETR Rupture Test Fuel Element "As Received"
in a Radiometallurgy Cell

~2X

FIGURE 18

Cross Section Through Defect of Fuel Element
in Figure 17
(Etched by Ion Bombardment)

~5X

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FIGURE 19

Defect and UO_2 Pocket of First Rupture Test
(Etched by Ion Bombardment) 50X

A similar experience was reported by Tuxworth and Krenz.⁽¹⁸⁾ In their test, a coextruded Zircaloy-2-clad fuel rod with a U-2 wt% Zr core (cladding thickness, 0.030 inch) was charged into the X-2 Loop of the NRX reactor. The test piece had a 0.010-inch-diameter hole drilled through the cladding. After 30 hours in 285 C (545 F) water at full reactor power, there was no evidence of massive failure of the test piece. The reactor was given a drastic thermal and power cycle at this time and after about 7 more hours, a rising activity signal indicated that massive failure had occurred. In a subsequent test,⁽¹⁸⁾ in which the drilled hole was 0.019 inch in diameter, the piece failed after 5 hours in the reactor.

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In view of these two tests and the many out-of-reactor tests performed at Hanford and elsewhere, it was believed that a 0.025-inch hole would not plug and prevent failure. However, this very thing did happen with the first rupture test.

As was discussed in a previous section, the defected fuel element for the second rupture test was irradiated at Hanford to 2400 Mwd/ton before it was shipped to the ETR. At the ETR, the aluminum sleeve in which this fuel element had been irradiated was cut open and the fuel element removed. The rupture device was then attached by means of the tools shown in Figure 2, and the assembly inserted into a Zircaloy-2 basket and charged into the P7 Loop of the ETR.

Because several months had elapsed since the test fuel element had been discharged from the Hanford reactor, the ETR was operated for 3 days to build up short half-life fission products before the defect projection was sheared off.⁽¹⁹⁾ Also, because of the experience with the first test, permission was obtained to operate for as long as 14 hours, if necessary, after the defect cap was sheared off.

Two hours after the defect cap was sheared off, a 7-mr burst of activity in the loop water was detected by the rupture monitors. This activity gradually died away and after about 1 additional hour the reactor was cycled several times in an attempt to break loose the UO_2 plug if one had formed in the hole through the cladding. Two more small bursts of activity were observed by the loop rupture monitors, one about 4 hours after the defect projection was sheared off and one about 4 hours after that. No further activity was seen, so the test was terminated after a total of 14 hours had elapsed from the time the defect projection was sheared off. Calculated power and temperature conditions at the defect during the test were as follows:

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Specific power	30.9 kw/ft of rod
Local bulk water temperature	235 C (455 F)
Cladding surface temperature	265 C (510 F)
Uranium surface temperature	345 C (653 F)
Volume average uranium temperature	444 C (831 F)

The defected fuel element was returned to Hanford for examination and looked very much like the first rupture test piece when it was received (see Figure 17). The defected rod was sectioned through the defect and this time a spherical pocket of UO_2 about 60 mils in diameter was found under the defect. Figure 20 shows the cross section of the rod "as polished" and Figure 21 shows the details of the corrosion pocket itself. The cracks which can be seen in these two figures radiating out from the corrosion pocket into the uranium indicate that fuel element failure was imminent. Additional details of the radiometallurgy examination are given by Gruber. ⁽²⁰⁾

The defected fuel element for the third rupture test was the same as the one for the second rupture test (irradiated to 2400 Mwd/ton at Hanford), and the test conditions were almost the same. ⁽²¹⁾ However, because of the behavior of the first two tests, the decision was made to forego the initial 3-day period of operation before shearing the defect projection and permission was obtained to continue operation for as long as 7 days after it was sheared off, if necessary, to obtain a massive failure of the fuel element.

After the reactor had been at power for 4 hours, the defect projection was sheared off. A slight rise in the activity of the loop water was observed by the rupture monitors at that time. Thirty minutes later, the readings of the rupture monitors began to rise rapidly and in another 3 minutes, the readings had reached the predetermined level at which the reactor was to be scrammed. After the scram, the readings of the rupture monitors continued their rapid rise for a few minutes and then began to drop off rapidly. Power and temperature conditions for this test were the same as given for the second rupture test.

FIGURE 20
 Cross Section Through the Defect
 of the Second Rupture Test
 (Rough Polished)
 ~4X

FIGURE 21
 Defect and UO₂ Pocket
 of the Second Rupture Test
 (Etched by Ion Bombardment)
 50X

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The defected fuel element of the third rupture test is shown in Figure 22. The cladding around the defect is swollen and cracked and it is obvious that considerable corrosion of the uranium has occurred. The ruptured rod was removed from the cluster to determine the extent of cracking of the cladding and uranium corrosion (Figure 23). The ruptured end of the defected rod was cut from the rest of the rod, weighed, and measured. The initial weight of this piece was then calculated and the weight loss during the rupture test was estimated to be 53 grams.

FIGURE 22

Defected Fuel Element of Third Rupture Test
"As Received" in a Radiometallurgy Cell
~ 2X

FIGURE 23

Defected Rod of the Third Rupture Test
~ 1.7X

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The severed piece was impregnated with plastic to immobilize the loose pieces of uranium within the swollen section of cladding and was then sectioned as shown in Figure 24. Figure 25 showing the cut faces of three parts of the sectioned piece, indicates the extent of corrosion and fragmentation of the uranium. A metallography sample was also cut from the midlength of the ruptured rod. This sample revealed that extensive cracking had occurred in the uranium, probably during the irradiation at Hanford. It thus appears likely that the third rupture test fuel element failed as rapidly as it did because a crack or crack network existed at the defect and thus a relatively large surface was exposed to the water when the defect projection was sheared off. In the case of the second rupture test, although the uranium in the defected rod was cracked, the crack network did not extend into the defect and this allowed a small pocket of UO_2 to form and block off further water entry. The first two tests are thought to be anomalies and the third test is assumed to be a much better representation of what will occur in an in-reactor rupture. A summary of the first three rupture tests and a discussion of the rupture monitoring instruments used is given by Call, Green, and Kaulitz.⁽¹⁾

FIGURE 24

Cutting Sketch of the Defected Rod
from the Third Rupture Test

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End
Cap

Uranium

Cut Face of Piece 1
~1.2X

Right Face of Piece 2
~2.5X

Cut Face of Piece 3
(Rough Polish Only)
~1.2X

FIGURE 25

Cut Faces of Pieces 1, 2, and 3
of Figure 24
(As Polished)

The fuel element for the fourth rupture test consisted of two concentric tubes. The defect was on the outer surface of the outer tube. The fuel element was not irradiated before it was charged into the ETR. (22) After the reactor had been at full power for 1 hour (because of difficulties in bringing the reactor to power, the total exposure was equivalent to about 4 hours at full power) the defect cap was sheared off. A 3- to 4-mr increase in loop activity was observed at this time and 20 minutes later the

13929; 13930; 13931

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activity level began rising, signalling the end of the incubation period. After an additional 10 minutes, the readings were high enough that the reactor was scrammed. Power and temperature conditions for the outer fuel element at the defect during the test were:

Specific power	57.1 kw/ft
Local bulk water temperature	262 C (503 F)
Cladding surface temperature	301 C (572 F)
Uranium surface temperature	322 C (612 F)
Volume average uranium temperature	336 C (637 F)

The extent of the rupture can be seen in Figure 26. The damage to the chisel of the rupture device was done during postirradiation handling. A 3-inch-long section which included the ruptured area was cut from the defected outer tube. This piece (Figure 27) showed no distortion of the inner cladding under the ruptured area.

The 3-inch section was weighed and measured and its initial weight calculated. The weight loss thus obtained was 43 grams. The 3-inch piece was sectioned through the defect and polished and etched (Figure 28). Examination indicated that corrosion penetrated through the uranium core to the inner cladding but progressed much more rapidly just under the outer cladding, penetrating approximately five times as far just under the outer cladding surface as it did radially through the core.

Photomicrographs of the right and left corners of the corrosion pocket (Figures 29 through 32) show that the corrosion was progressing along the uranium side of the cladding-to-core bond layer. The manner of attack of the corrosion here is quite different from that experienced by the out-of-reactor test piece (Figures 13 and 14). It is possible that the heat flux and/or gamma flux which exists in the fuel element while it is being irradiated have a pronounced effect on both the manner of the corrosion attack and the rate at which the uranium corrodes. Additional details of the postirradiation examination are given by Gruber. ⁽²³⁾

FIGURE 26

Defected Fuel Element
from the Fourth Rupture Test
"As Received"
in a Radiometallurgy Cell
~0.3X

FIGURE 27

Section of the Outer Tube
of the Fourth Rupture Test
Showing Inner Cladding
Under the Rupture
~1.9X

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A-119; A-59

As Polished
~1.8X

Etched by Ion Bombardment
~1.5X

FIGURE 28
Cross Section Through the Defect
of the Fourth Rupture Test Fuel Element

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FIGURE 29

Left Corner of the Corrosion Pocket
of Figure 28
(Etched by Ion Bombardment)
50X

A-93

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FD-302 (Rev. 4-15-64)

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FIGURE 31

Right Corner of the Corrosion Pocket
of Figure 28
(Etched by Ion Bombardment)
50X

A-95

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FIGURE 32

Lower Right Corner of the Corrosion Pocket
Shown in Figure 31
(Etched by Ion Bombardment)
250X

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The fuel element for the fifth rupture test was a heavy-walled single tube fuel element which had not been previously irradiated.⁽²⁴⁾ The defect was on the outer surface of the tube.

After the experiment had been charged and the reactor had been at power for 2 hours, the defect projection was sheared off. Twenty minutes later, the loop activity monitors observed a gradual increase in activity. The activity continued to increase slowly and fairly uniformly until the test was terminated. One hour and 20 minutes after the start of the test, the pressure drop across the test section of the loop was observed to be 15 psi. It had been 9.7 psi at the start of the test. The time at which the pressure drop began increasing is not known. Two hours after the start of the test, the pressure drop was 16 psi and 25 minutes later it had increased to 18 psi. At this time, the loop activity had reached the level at which the test was to be terminated. Power and temperature conditions at the defect during the test were:

Specific power	75.5 kw/ft
Local bulk water temperature	244 C (470 F)
Cladding surface temperature	281 C (537 F)
Uranium surface temperature	336 C (637 F)
Volume average uranium temperature	400 C (752 F)

When the fuel element (still in its basket) was received at Hanford, it was found to have swelled during the rupture test until it had filled the 0.080-inch annulus between the outside diameter of the fuel element and the inside diameter of the basket. The swelling did not stop there, but continued until the basket itself was deformed and was approximately 0.1 inch larger in diameter at the rupture than it was elsewhere. The basket with the fuel element inside it can be seen in Figure 33. To remove the fuel element from the basket, it was necessary to cut the basket and fuel element on either side of the swollen area. This swollen section was then dipped in HNO_3 to dissolve the UO_2 , making it possible to push the section of fuel element from the basket. Figure 34 shows the section of

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FIGURE 33

Zircaloy-2 Basket
Containing the Fifth Rupture Test Fuel Element
~0.5X

15165

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270°

180°

90°

0°

FIGURE 34
Section of the Fifth Rupture Test Fuel Element
~0.7X

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fuel element after it was removed from the basket. The end cap broke off the upper end of this piece when the basket and fuel element were being cut. The weight of uranium converted to UO_2 was calculated to be 1080 grams.

The piece shown in Figure 34 was cut at its midlength and half was polished and etched (Figure 35). Figure 36 shows a section of the inner cladding shown in Figure 35. The fragmentation of the upper surface of the cladding in Figure 36 was caused by the formation of a massive layer of zirconium hydride when the fuel element was corroding. This hydride layer cracked and parts broke off either as the inner cladding was being deformed during the test or during cutting and polishing operations.

FIGURE 35

Cross Section Through the Midlength of the Piece
Shown in Figure 34
(Etched by Ion Bombardment)
~2X

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FIGURE 36

Inner Cladding at Top Center of Figure 35
(As Polished)
75X

The fuel element for the sixth rupture test was a heavy-walled single tube fuel element which had been irradiated to 400 Mwd/ton in high temperature water at Hanford. The test proposal⁽²⁵⁾ specified that the piece which had been irradiated to 1700 Mwd/ton was to be used, but the low exposure piece was used instead.

Equipment similar to that shown in Figure 2 was used to attach the rupturing device to the fuel element and insert the assembly into the basket. After the experiment was charged and the reactor had been at power for 3 hours, the defect projection was sheared off. Thirty-eight minutes later the rupture monitors on the loop began recording a rise in the loop water activity. The rise in activity continued slowly and steadily until the

test was terminated 1 hour after it had started. The pressure drop across the test section increased from 15.5 psi to 16.5 psi during the test, and water activity levels rose to about one-fifth of the levels at which a scram was required. The test was ended at this point so this fuel element would not be corroded to the same extent as occurred in the fifth test. Power and temperature conditions at the defect during the test were:

Specific power	75.5 kw/ft
Local bulk water temperature	264 C (506 F)
Cladding surface temperature	292 C (557 F)
Uranium surface temperature	344 C (652 F)
Volume average uranium temperature	408 C (765 F)

Figures 37 and 38 show the extent of the damage to the cladding and the extent of the corrosion. Figure 39 shows the right and left corners of the corrosion pocket. Although the corrosion was progressing much faster along the cladding than it was radially through the core (Figure 38), Figure 39 shows that at the cladding-to-core bond layer the corrosion was progressing on a front normal to the bond layer. This same type of corrosion attack was observed in both the fifth and (as we shall see presently) seventh rupture tests. In the fourth rupture test, however, the corrosion proceeded along the bond layer by means of cracks which extended beyond the main corrosion pocket (see Figures 29 through 32). The weight of uranium converted to UO_2 in the sixth test was estimated to be 40 grams.

The fuel element for the seventh test was irradiated to 1700 Mwd/ton in high temperature water before it was shipped to the ETR. The conditions for this test were the same as for the sixth test.⁽²⁶⁾ Again, the test apparatus was assembled under water using equipment similar to that shown in Figure 2.

Three hours after the reactor had reached full power, the defect projection was sheared off. Nine minutes later, the rupture monitors showed that loop water activity was increasing. In an additional 5 minutes, the activity had reached the level at which the test was to be terminated. Power and temperature conditions for this test were the same as for the sixth test.

FIGURE 37

Sixth Rupture Test Fuel Element
"As Received" in a Radiometallurgy Cell
~1X

FIGURE 38

Cross Section Through the Rupture
Shown in Figure 37
(As Polished)
~2X

A-5776; A-5775
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FIGURE 39

Left and Right Corners of the Corrosion Pocket
Shown in Figure 28
(As Polished)
250X

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In the 14 minutes the reactor was at power during the seventh rupture test, the corrosion penetrated along the cladding for $1\frac{1}{2}$ inches axially in either direction from the defect and 90 degrees circumferentially in either direction. The cladding was also cracked through the center and along the edges of the blister which had formed. Figure 40 shows the ruptured fuel element after it was removed from its basket and Figure 41 shows the cut faces after the piece was sectioned through the defect. The areas at the left and right limits of the corrosion penetration shown in the lower part of Figure 21 are shown in Figure 42. Again, as in the fifth and sixth rupture tests, there was no cracking at the bond layer (as there was in the fourth rupture test), although the corrosion was progressing much faster along the cladding than it was through the fuel. The weight of the uranium converted to UO_2 was estimated to be 25 grams.

The incubation periods and corrosion rate data from the tests are summarized in Table I and in Figures 43, 44, and 45. The table and figures show that under comparable conditions irradiated material has a shorter incubation period and a faster rate of corrosion following the incubation period than does unirradiated material. Both of these effects are due, at least in part, to the irradiation-induced cracking which occurs both in the uranium and on the uranium side of the bond layer. There is no evidence that the uranium corrosion rate itself is changed appreciably by irradiation. Cracking merely exposes a greater surface to the attack of the water.

Examination of Rupture Test Baskets

One of the points of concern in the design and operation of the NPR was whether the rupture of a fuel element would cause hydriding of the process tube. Accordingly, the baskets used in all but one of the rupture tests (the fourth rupture test) were made from Zircaloy-2. Because there was no massive failure in the first two tests, these baskets were not examined. The basket for the third test was cut longitudinally in the region which was adjacent to the defect. The inner surface of the basket in this area can be seen in Figure 46. The light-colored spot in the upper left was,

A-5355; A-5356; A-5357
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FIGURE 40

Defected Fuel Element from Seventh Rupture Test
"As Received" in a Radiometallurgy Cell
~1X

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(As Cut)

Sample
Mounting
Ring

(As Polished)

FIGURE 41

Cross Section Through Defect of Fuel Element
Shown in Figure 40

~2X

A-5359; A-5601

A-
A-5602
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↑
Cladding

Left Limit

↑
Uranium

Right Limit

↑
Cladding

FIGURE 42

Left and Right Limits
of the Corrosion Penetration in the Face
Shown in the Lower Part of Figure 41
(As Polished)
250X

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TABLE I
SUMMARY OF RUPTURE TEST DATA

Test No.	Fuel Element Type	Previous Irradiation (Mwd/ton)	Incubation Period (Minutes)	Period from End of Incubation to and of Test (Minutes)	Weight of Uranium Connected to Oxide (Grams)	Temperatures (C)			Remarks
						Local Bulk Water	Cladding Surface	Uranium Surface	
1	7-rod cluster	none	--	--	0.0015*	256	281	319	No massive failure 7 hours after defect sheared off so test terminated
2	7-rod cluster	2400	--	--	0.005*	235	265	345	No massive failure 14 hours after defect projection sheared off so test terminated
3	7-rod cluster	2400	30	33	53	235	265	345	Uranium badly cracked
4	Tube-in-tube	none	20	10	43	262	301	322	Corrosion and cracking along bond layer progressing much faster along cladding than through fuel
5	Single tube	none	46	99	1080	244	281	336	Corrosion front progressing normal to cladding
6	Single tube	400	38	22	40	264	292	344	Corrosion progressing on a plane front; faster along cladding than through fuel
7	Single tube	1700	9	4	25	264	292	344	Corrosion progressing much faster along cladding than through fuel

* Estimated

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FIGURE 43

Comparison of In-Reactor and Out-of-Reactor Rupture Tests on Coextruded Rods

FIGURE 44

Comparison of In-Reactor and Out-of-Reactor Rupture Tests on Coextruded Tubes

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FIGURE 45

Comparison of In-Reactor and Out-of-Reactor Rupture Tests on Coextruded Tubes

FIGURE 46

Inside Surface of the Basket of the Third Rupture Test in the Area of the Defect ~1.2X

13895
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[REDACTED] **DECLASSIFIED** [REDACTED]

as nearly as could be determined, the area of the basket closest to the defect. A sample was cut from this region, the cutting plane passing through the light-colored spot. This piece was polished and chemically etched to reveal any precipitated hydrides. No evidence was found which would indicate that the level of hydrogen in the basket had increased during the test. A section of the basket from the fifth rupture test was given a wet chemical analysis for hydrogen content. This section was cut from the area adjacent to the defect of the fuel element. A piece of the tubing from which the basket was fabricated was also chemically analyzed for hydrogen. The piece from the basket showed a hydrogen content of 98 ppm while the other piece showed only 22 ppm.

Samples from the baskets of the sixth and seventh rupture tests were also analyzed chemically. In each case, a sample was taken from the part of the basket which was adjacent to the defect in the fuel element and another sample was taken from a spot which was about 2 feet from the defect. The results are shown below.

Sixth Rupture Test

Sample adjacent to defect	38 ppm H ₂
Sample 2 feet from defect	57 ppm H ₂

Seventh Rupture Test

Sample adjacent to defect	32 ppm H ₂
Sample 2 feet from defect	33 ppm H ₂

Thus, only in the fifth rupture test was there any increase in the hydrogen content of the basket because of the rupture, and that increase was not very large. Therefore, we can conclude that where the rupture is in contact with the basket for an hour or more, some hydriding will occur. However, if water has access to the rupture and can sweep the hydrogen and UO₂ away as it is formed, little or no hydriding will result.

[REDACTED] [REDACTED]

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1	Union Carbide Nuclear Company (Y-12 Plant)
1	United Nuclear Corporation (NDA)
1	USAF Headquarters
2	University of California, Berkeley
2	University of California, Livermore
4	Westinghouse Bettis Atomic Power Laboratory
1	Westinghouse Electric Corporation
1	Westinghouse Electric Corporation (Lima)
1	Westinghouse Electric Corporation (NASA)
1	Westinghouse Electric Corporation, Lima (AF)
1	Yankee Atomic Electric Company (NYOO-222)
40	Division of Technical Information Extension

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