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Testing of Zircaloy-2 Clad Seven-Rod
Cluster Fuel Elements.

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INTERIM REPORT

IN-REACTOR RUPTURE TESTING OF ZIRCALOY-2 CLAD SEVEN-ROD
CLUSTER FUEL ELEMENTS

Classification Cancelled and Changed To R. L. Call, J. W. Green and D. C. Kaulitz

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INTERIM REPORT

IN-REACTOR RUPTURE TESTING OF ZIRCALOY-2 CLAD SEVEN-ROD
CLUSTER FUEL ELEMENTS

R. L. Call, J. W. Green and D. C. Kaulitz

May 3, 1960

INTRODUCTION

In order to evaluate the rupture characteristics of the fuel proposed for the NPR, a system was developed to permit "push button" ruptures in the 3X3 loop at the ETR. A system was also installed that would permit evaluation of the various proposed instruments being considered for the rupture detection system to be used on the NPR. A series of three rupture tests have been performed to date; these, and future tests, will determine the failure delay time or "incubation period" of unirradiated and irradiated fuel elements.

SUMMARY

The high pressure loop installed in the 3X3 reflector position of the ETR and the associated instrumentation to detect and study failure mechanisms handled the rupture tests without difficulty. Failure of the elements was initiated by shearing off a projection on the fuel elements.

The first test of the series used previously unirradiated seven-rod clusters. After the projection was sheared off the fuel elements were operated for seven hours with no failure. Failure is defined as having occurred when sufficient uranium oxide has formed to split open the cladding and release large amounts of fission products into the loop water. The second and third tests used fuel which had been irradiated to 2400 MWD/T at Hanford prior to insertion into the ETR. The second test was operated for 14 hours after the projection was sheared off--again with no failure. The third test was operated for only 33 minutes after the projection was sheared off before fission product activity in the loop water caused the test to be terminated.

DISCUSSION

Description of Equipment - The loop that the rupture tests were operated in is located in the reflector of the ETR in the position designated as R-3X3-P7. The facility is a high pressure, high temperature closed loop for the circulation of demineralized water over prototype fuel elements. The loop is designed to handle a total heat load of 500 KW at a water pressure of 2000 psi and an outlet temperature of 600 F. The maximum flow is 70 gpm. All necessary control, fill and vent valves are remotized for rupture operation. The main cubicle or loop area is shielded so high exposure elements can be failed without endangering personnel. The loop is also designed so it can be decontaminated with a minimum amount of time.

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The loop is instrumented with gross gamma monitors, delayed neutron monitors and a multi-channel gamma spectrometer. These and other instruments permit the rupture to be detected as soon as any fissionable material is released to the primary coolant.

Description of Fuel Elements - The fuel elements used in this series of in-reactor rupture tests were fabricated from rod stock coextruded in Zircaloy-2 cladding by Nuclear Metals, Inc. of Cambridge, Massachusetts. The rods were a nominal 0.593 inches O.D. with a cladding thickness of 0.020 inches for the first test and 0.030 inches for the second and third tests. The rods were formed into seven-rod cluster with the inter-rod spacing at 0.055 inches. The seven rods were welded to triangular Zircaloy-2 end supports.

One of the rods of each cluster was designed for intentional rupture by welding a saddle with a projection on the cladding of the fuel rod. A .025 inch hole was drilled through the projection and into the uranium. The open end of the hole in the projection was then welded shut. Figure 1 is a closeup view of a defected rod. All rods were autoclaved in 400 C, 1500 psi steam for 72 hours before final assembly.

Each seven-rod cluster element had a special ring welded to one end fitting. This ring was so designed that a hydraulic cylinder that actuated a chisel could be attached remotely to the element. The ring and cylinder would only permit the two to be attached in such a manner that the chisel would line up with the projection or saddle. This remote assembly permitted the fuels to be irradiated in production reactors, discharged and transported to the ETR. At that time, the hydraulic cylinder with the attached chisel was assembled to the irradiated fuel.

A hydraulic line to operate the cylinder, and thermocouples to measure the ΔT across the test samples were attached at this time. The entire unit was loaded into a thin-walled tube (a "basket" in ETR terminology) and this basket assembly was then loaded into the pressure tube of the loop in the ETR. Figure 2 shows an assembled cluster with the end fitting welded in place. A hydraulic jack was used to advance the chisel that sheared defect, immediately after shearing the chisel was retracted by the loop pressure.

Figure 3 is a cross-sectional view of a complete assembly before insertion into the test reactor.

Irradiation Prior to Rupture Testing - The defected clusters for the second and third rupture tests were irradiated to 2400 MWD/T at Hanford prior to charging them into the ETR. These clusters were placed inside aluminum baskets and charged into a single-pass, reactor test hole cooled by reactor process water. Figure 4 shows one of these fuel elements and its basket. The uranium used for the irradiated cluster rupture tests was 1.6 per cent enriched so that the desired exposure could be accumulated in a short time. Irradiation and temperature conditions for the Hanford irradiation were:

Outlet temperature	37 C
Pressure	200 psia
Specific power	25.7 kw/ft of rod
	or
	31.0 watt/gm

FIGURE 1

Close-Up of a Defected Rod Showing the Rupture Saddle Welded in Place.

FIGURE 2

One of the Seven-Rod Cluster Fuel Elements Used in the In-Reactor Rupture Tests.

FIGURE 3

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FIGURE 4

A Defected Seven-Rod Cluster Element and the Basket in Which it Was Irradiated at Hanford Prior to the Rupture Test at the ETR.

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Surface heat flux	594,000 BTU/hr-ft ²
Cladding surface temperature	48 C
Uranium core temperature	375 C

First Rupture Test

As was noted above, the first test of the series used previously unirradiated clusters. Three clusters (one defected) were used in making up the fuel charge. Each cluster was 9.5 inches long with a uranium length of eight inches. All three clusters contained natural uranium. After the clusters were charged, the reactor was operated at full power for one hour and then the defect projection was sheared off. An increase of 40 mr of gamma activity in the loop water was noted at that time. No further activity increase was noted although the reactor was operated for seven hours after the defect had been opened. After the seven hour period, the reactor was shut down and the rupture test removed. The defected rod was sectioned through the defect and polished. A small lens-shaped pocket of uranium oxide, approximately 40 mils in diameter by 12 mils deep was observed under the defect. An estimated 1.5 milligrams of uranium had been converted to oxide. The oxide pocket can be seen in both Figure 5, a macro of the cross section through the defect, and in Figure 6, a photomicrograph of the defect. Tests performed at Hanford in high temperature, high pressure, out-of-reactor, recirculating loops in the same manner as the in-reactor tests and using similar material showed that failure should occur in two hours or less after the defect was opened to the loop water. As can be seen from Figure 6, failure in the sense of sufficient oxide formation to split open the cladding, did not occur.

Irradiation and temperature conditions for the first test were:

Loop inlet temperature	234 C
Loop outlet temperature	258 C
Flow	70 gpm
Loop pressure	2000 psia
Specific power	22.2 kw/ft of rod
	or
	24.8 watt/gm
Surface heat flux	488,000 BTU/hr-ft ²
Cladding surface temperature	286 C
Uranium core temperature	501 C

Second Rupture Test

The charge for the second rupture test consisted of a 1.6 per cent enriched irradiated cluster and two unirradiated natural uranium clusters as heaters. The irradiated cluster was 11.6 inches long with a 10.0 inch uranium length and the heater clusters were 10.0 inches long with an 8.4 inch uranium length. It was necessary to attach the rupture mechanism to the defected cluster under several feet of water. Figure 7 shows the jig and assembly tool used to perform this operation. The defected cluster and the rupture mechanism were then inserted into the basket.

Several months elapsed between the discharge of the defected clusters for the second and third rupture tests from a Hanford reactor and their testing in the ETR. Therefore, after the second rupture test was charged, the ETR was operated for three

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FIGURE 5

Cross Section Through the Defected Rod
of the First ETR Rupture Test. 1-1/2X.

FIGURE 6

Photomicrograph of a Cross Section Through
the Defect of the First Rupture Test. 50X.

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ASSEMBLY TOOL

RUPTURE EXPERIMENT

FIGURE 7

days to build up short half-life fission products in the defected cluster before the defect was opened. Two hours after the defect was opened up, a seven mr burst of activity was observed in the loop water. No further activity was observed so permission was obtained to cycle the reactor from zero power to full power several times. Full power operation produced a core temperature of approximately 800 C in the defected cluster and it was hoped that this thermal cycling would promote failure of the defected rod. Fourteen hours after the defect was opened, the reactor was shut down and the test assembly removed.

The defected rod was sectioned through the defect and a spherical pocket of uranium oxide approximately 60 mils in diameter was found under the defect. An estimated five milligrams of uranium were converted to oxide. Cracks were found in the uranium both in the above section and in a section cut approximately midway between the ends of the rod. Figure 8 shows the cross section through the defect in a rough-polished condition. Large cracks can be seen in the uranium. Figure 9 is a photomicrograph of the defect itself. As can be seen in this photograph, the uranium around the defect is badly cracked. Figure 10 is a photomicrograph of the uranium-cladding-oxide junction in the upper left part of Figure 9. A crack can be seen in the cladding starting from this junction. The appearance of the crack in the cladding indicates that the rod was very close to failure.

Irradiation and temperature conditions during ETR testing were:

Loop inlet temperature	278 C
Loop outlet temperature	287 C
Flow	70 gpm
Pressure	2000 psia
Specific power	27.0 kw/ft of rod
	or
	32.5 watt/gm
Surface heat flux	594,000 BTU/hr-ft ²
Cladding surface temperature	323 C
Core temperature	633 C

Third Rupture Test

The third rupture test was similar to the second, except that the defect projection was sheared off four hours after the reactor reached the power level requested for the test. Thirty-three minutes after the defect was opened, the loop water activity was so great that reactor shutdown was required. The loop was cooled as rapidly as possible and the test assembly removed. Figure 11 shows the cluster as it appeared when it was received in the examination cell. The defected rod was swollen so that it touched the three rods adjacent to it. Figure 12 is a view of the defected rod after it was cut from the cluster. As can be seen, the uranium was gone from this region of the rod except for two loose pieces, one of which can be seen through the split in the cladding. An estimated 53 grams of uranium were converted to oxide in this test.

The defected rod was put in a tube which was poured full of a thermo-setting clear plastic to immobilize the loose pieces. A longitudinal section was made through the end cap. This section can be seen in Figure 13. A loose piece of uranium can

FIGURE 8

Rough-Polished Cross Section Through the Defect of the Second Rupture Test. 4X.

FIGURE 9

Photomicrograph of the Defect in the Second Rupture Test. Note the Cracks in the Uranium. 50X.

FIGURE 10

Photomicrograph of the Uranium-Cladding-Oxide Junction in the Upper Left of Figure 9. Note the Crack in the Cladding at the Junction. Surface Prepared by Ion Bombardment. Polarized Light. 250X.

FIGURE 11

Defected Cluster of the Third Rupture Test "As Received". 2X.

FIGURE 12

Defected Rod of the Third Rupture Test.

FIGURE 13

Longitudinal Section Through the End Cap of the Defected Rod of the Third Rupture Test. 1-1/2X.

FIGURE 14

Transverse Section Through the Defected Rod of the Third Rupture Test. The Section was Made Near the Defect. 3X.

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be seen in this section. A transverse section through the rod near the defect is shown in Figure 14. The uranium in this section is badly cracked. A longitudinal section through the swollen part of the rod away from the end cap is shown in Figure 15. The uranium in this area is also severely cracked.

CONCLUSIONS

The loop, rupture mechanism and rupture detection system form a workable and successful means for defecting and operating fuels while the reactor is at power. The rupture mechanism is easily operated and is being adapted to geometries other than clusters. It permits fuel elements to be irradiated in a production reactor until they have obtained the desired exposure and then they can be sent to a test reactor for rupture testing. It is apparent from the three in-reactor tests that have been run, that even with very similar material there can be a great difference between the time to failure of two separate tests. Also, out-of-reactor tests performed on unirradiated material from the same extrusions as were used for making the defected rods for the in-reactor tests have shown that the rupture saddle increases the incubation period by about one-half hour. What effect the rupture saddle has on irradiated material is not known. Further in-reactor tests will be conducted to establish whether the tests performed to date were representative tests. It is possible that the cracking observed in the third test was responsible for the rapid failure.

ACKNOWLEDGEMENT

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FIGURE 15

Longitudinal Section Through the Swollen Part of the Rod
Away from the End Cap. Third Rupture Test. 1-1/2X.

RESULTS OFETR LOOP RUPTURE INSTRUMENTATION TESTSDESCRIPTION

Instrumentation used to monitor fuel rupture conditions in the ETR loop consists of (a) a 200 channel gamma energy analyzer, shown in the two relay racks to the left in Figure 16; (b) six scintillation detector gross gamma monitors, shown in the upper part of the third rack from the left in Figure 16; (3) a GM tube gross gamma monitor, shown in the lower part of the third rack from the left in Figure 16; (d) a delayed neutron monitor, shown in the right hand rack. The lower part of the righthand rack shows the meter to indicate sample flow rate to the above detectors.

The GM tube gross gamma monitor and the delayed neutron monitor "look at" sample flows from the loop to detect increases in gamma or neutron activity indicative of a ruptured fuel element. The six scintillation gross gamma monitors are located at various points around the loop to monitor total gamma activity so the reactor can be shut down before predetermined safe radiation levels are exceeded. The most sensitive (due to location) of these is also used as a confirmation for the rupture monitor. The above instrumentation is shown on SK-1-26563, H-3-9200, H-9193, H-3-9194, and H-3-9195

CONCLUSIONS

The three rupture tests run to date have demonstrated that the GM tube gross gamma monitor proposed for NPR rupture detection is capable of indicating the presence of ruptures with emission rates ranging from 1.0 milligram over several hours up to rates of several grams per minute. In the case of the lower emission rates, a gamma energy spectrometer is used to verify the presence of a ruptured fuel element by the observation of fission products in the sample stream.

Operationally, the early detection provided by this system will permit early diversion valve operation and thus minimize loop contamination. Also, the rupture rate of the fuel element might be controlled to a degree by early cooling of the process channel.

DISCUSSION

In the first test, described in detail earlier in the report, an unirradiated fuel element was ruptured and left in the loop for approximately seven hours reactor operation. Figure 17 shows the readings obtained on the GM tube gross gamma monitor, the scintillation crystal gamma monitor, and the delayed neutron monitor. Figure 18 shows the change in symmetry of the gamma energy spectrum, denoting the presence of fission products in the sample stream. Two distinct increases in gamma activity can be seen in Figure 17. The first increase appeared 90 seconds after the rupture. Time delay of the sample was calculated as 80 seconds. Later examination of this fuel element in the Radiometallurgy laboratory showed total emission of uranium to be in the order of 1.0 milligram.

FIGURE 16

Rupture Detection Instruments

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FIGURE 17

Test No. 1

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FIGURE 18
.0198 Mev/Channel

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The second test, an irradiated fuel element described earlier, remained in the loop for approximately 15 hours of reactor operation after the rupture. Figure 19 shows the GM tube gross gamma, scintillation crystal, and delayed neutron monitor readings. Figure 20 shows the gamma energy spectrum. It is interesting to note that very minor emission was indicated until a thermal shock was provided by rapidly lowering and raising the reactor power. Later examination of this element showed total uranium emission to be in the order of 5 milligrams.

The third element tested, an irradiated element similar to the second one, behaved quite differently than either of the others. As can be seen in Figure 21, in about 30 minutes after rupture all instruments had gone full scale. Later examination of this element showed a total uranium emission of 53 grams. In this instance, any type of instrument would have shown the rupture when emission was at its peak. Of interest here is the early indication offered which, in a similar case, would permit diversion valve operation in the NPR prior to extensive loop contamination.

RECOMMENDATION

On the basis of these three tests, which appear to cover the extremes of slow and fast acting ruptures, a continuous monitoring gross gamma monitor is feasible for the NPR rupture monitor system. A gamma energy analyzer is recommended as a back-up to provide confirmation on the smaller emission rates.

Additional rupture tests will be required to bridge the gap between the very slow and very fast ruptures. This additional data is valuable to the improved knowledge of NPR type fuel element rupture behaviors and the associated operating problems.

FIGURE 19

Test No. 2

FIGURE 20

.0161 Mev/Chanlel

FIGURE 21

Test No. 3

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