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STATUS REPORT OF IRRADIATED NPR FUEL ELEMENT RUPTURE STUDIES IN THE IRP.

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STATUS REPORT OF IRRADIATED NPR FUEL
ELEMENT RUPTURE STUDIES IN THE IRP

INTRODUCTION

The Irradiated Rupture Prototype (IRP) has been used for rupture testing irradiated NPR prototype fuel elements. Most of the tests have been made to determine the rupture effect of different reactor exposures, fuel element geometries and water cooldown rates following the start of the rupture. This report summarizes the results obtained to date, mentions where information is lacking and gives further tests scheduled for the IRP.

SUMMARY

Nineteen rupture tests have been run in the IRP (Irradiated Rupture Prototype) with uranium-core fuel rods and tubes which had been previously irradiated from 1200 to 3550 MWD/T in the KER Loops or in a KW test hole. Several rods which were used demonstrated the drastic ruptures which result from irradiation exposures to 2250 MWD/T. Several inches of the length of the rods were swollen and torn even when the water temperature was cooled immediately from 300 C after the start of the rupture. Six of the rupture tests used KSE-3 fuel elements which were exposed to 1200, 2000, and 3555 MWD/T. One of each of the two tubes at the same exposure was cooled rapidly (scram cooldown) after the start of the rupture and one of each was cooled slowly (programmed cooldown). Ruptures in the 1200 MWD/T tubes were not too severe. Ruptures of the 2000 and 3555 MWD/T tubes produced very severe ruptures in the tubes which were cooled slowly. It is extremely desirable from a rupture standpoint to cool the fuel elements as fast as possible following rupture indications.

Several problem areas which should be further investigated are (1) the rate of cooldown to minimize both the rupture and the thermal stresses on the reactor piping, (2) the consequence of different end cap closure failures, (3) trying to identify the rupture as to type and location, (4) the effect of different geometries and core additions, (5) the effect of different irradiation conditions, (6) different types of ruptures (other than pinholes), and (7) different core material, cladding or design.

Four fuel elements are currently scheduled for testing in the IRP. These are the first rupture tests to be made with actual NPR geometries. They will be tested at conditions presently scheduled for the NPR. This includes a 5 minute hold period at 300 C and then cooling the water at the scram or programmed cooldown rates.

EXPERIMENTAL RESULTS

All of the fuel elements used in the IRP tests were predefected with a 0.025 inch hole. They were tested in the loop by preheating the water to 315 C and then valving in a cask containing the fuel element. The rupture corrosion product was collected in a 5-micron filter and the activity determined by a Beckman gross gamma probe, a Beckman pico ammeter and a Brown recorder. Following the ruptures the elements were returned to Radiometallurgy for weighing and examination. The list below shows in brief the results of all the tests run to date.

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Test No. 1

The 0.84" O.D. rod with a 0.030" Zr-2 clad was irradiated to 1200 MWD/T in KER at 250-265 C. The rod had an incubation time of 63 minutes at 300 C. It was then exposed for 80 minutes at 300 C and rapid cooled. Weight loss of the rod was 43 grams and the rod was ruptured over the entire circumference for 1 1/4" in length.

Test No. 2

The 0.84" O.D. rod had a 0.020" Zr-2 clad and was irradiated in KER at 250-265 C for 2250 MWD/T. Following a 34 minute incubation period the rod was exposed for an additional 40 minutes at 300 C. Weight loss of the rod was 23 grams and the fuel element was ruptured for 1 1/4" in length around the entire circumference.

Test No. 3

This rod was identical to that in Test No. 2. It was accidentally defected at the end cap by the cut-off saw during separation from the other rods. It started rupturing as soon as it was exposed to the water. The water was cooled slowly from 280 C. There was a 1/4" circumferential dumbbell swell at the end cap area.

Test No. 4

This rod was 0.084" O.D. and it was irradiated at 35 C in KW Reactor to 2400 MWD/T. After a 26 minute incubation period at 300 C the water temperature was cooled slowly (1.85 C/minute). The whole core was swollen and torn for 4" in length. Weight loss was 183 grams.

Test No. 5

This rod was identical to the rod in Test No. 4. There was an 11 minute incubation period and a fast cooldown from 300 C (temperature lowered to 220 C in one minute and then lowered 1.85 C/minute). The rod was broken in two at the original defect and the rod was swollen slightly at the break. Weight loss was 15 grams.

Test No. 6

This rod was identical to those used in Tests No. 2 and 3. It had a one minute incubation and a slow cooldown from 300 C. Weight loss was 23 grams and the rod was ruptured for 1 1/4" in length and around the entire circumference.

Test No. 7

This rod was identical to those used in Tests No. 2, 3, and 6. Incubation time was 3 minutes. A fast cooldown was used after the start of the rupture. The rod was slightly swollen for 1 1/4" in length over 1/2 of the circumference. Weight loss was 6 grams.

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This rod was identical to those used in Tests No. 2, 3, 6 and 7. Incubation time was 40 minutes. It was run isothermal at 300 C for 30 minutes. At this time the loop activity was so high that the test was stopped and the loop decontaminated.

Test No. 9

This test was a continuation of the previous Test No. 8. The rod was run an additional 20 minutes at 300 C, making a total of 50 minutes at 300 C. The rod had lost 150 grams of uranium and the Zr-2 cladding was torn and spiraled for 6" in length.

Test No. 10

This fuel element was a KER inner tube, unalloyed, which was irradiated to 3200 MWD/T at 270 C. It had a 7 1/2 minute incubation time. The test was run isothermal at 300 C for 4 minutes then cooled as rapidly as possible (4 minutes to less than 200 C) due to high loop activity. The element was broken into 7 large pieces and dozens of smaller pieces and the tube was ruptured over the entire surface. No weight losses were recorded due to loss of several of the smaller pieces.

Test No. 11

This fuel element was the same as that used in Test No. 10 except the core was an alloy of uranium and zirconium (U, 2.0 Zr). Incubation time was 10 1/4 hours. The element was then run isothermally at 300 C for 68 minutes. It was broken in two with a dumbbell shape at each end of the break. Weight loss was 68 grams.

Test No. 12

This was a KER rupture suspect which was run for 18 hours at 300 C with no rupture.

Test No. 13

The fuel element used was a KER single tube (KSE-3) irradiated to 1200 MWD/T at 240 C. Following a 60 minute incubation period a NPR modified fast cooldown, scram cooldown, was used (the water temperature was held at 300 C for 5 minutes, then cooled to 160 C in six minutes and then cooled at 1.85 C/minute). Weight loss of the element was 22 grams and the ruptured consisted of a single raised and torn blister about 7/16" in diameter. Due to the lack of undercutting the bond appeared strong.

Test No. 14

This fuel element was identical to that used in Test No. 13. A NPR programmed slow cooldown was used (water held at 300 C for 5 minutes and then reduced to 272 C at 2.8 C/minute and then 1.85 C/minute from 272 C to 106 C). A single

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3/4" diameter raised and torn blister was present. Weight loss was 35 grams. The bond appeared strong on this element.

Test No. 15

This rod was identical to the rods used in Tests No. 2, 3, 6, 7, 8 and 9. It had a incubation period of 22 minutes at 300 C. After 15 minutes at 300 C the temperature was lowered to 200 C for 315 minutes. The corrosion as evidenced by activity readings was quite small. The rod was again run at 300 C for 90 minutes and 200 C for 1500 minutes. The activity release was 100 times as fast at 300 C as it was at 200 C. The rupture consisted of a multitude of small diameter raised and torn blisters extending for about 3" in length over the entire circumference. Weight loss was 101 grams.

Test No. 16

The element used was a KER single tube irradiated at 242 C to 2000 MWD/T. After a 86 minute incubation period a NPR fast or scram cooldown was used. Weight loss was 30 grams with the rupture covering an area about 2" long and 2 1/2" wide.

Test No. 17

The fuel element used was identical to the one used in Test No. 16. A NPR programmed slow cooldown was used after the 62 minute incubation period. The element was swollen and torn for about 9" in length over the entire circumference. Weight loss was 485 grams.

Test No. 18

A KER single tube was used which had been irradiated at 190 C to 3555 MWD/T. Incubation time was 160 minutes. A NPR fast or scram cooldown was used after the start of the rupture. The weight loss was 38 grams and the rupture consisted of a .1" diameter raised area.

Test No. 19

The fuel element used was identical to the one used in Test No. 18. A NPR programmed cooldown was used after a 137 minute incubation. The fuel element was broken into two pieces with long cracks existing in both pieces adjacent to the fractured. The weight loss was 278 grams.

Several important facts were learned from these tests. From the tests using the KER single-tube elements (Tests No. 13, 15, 16, 17, 18 and 19), the importance of the amount of in-reactor exposure can be determined. At exposures of about 1200 MWD/T the ruptures consist of local area of corrosion, indicating good bonds between the uranium and Zr-2, and low stress in the uranium core. Increasing the exposure to 2000 MWD/T caused undercutting of the U-Zr-2 bond which resulted in large areas of the fuel element being affected. Exposures above 2250 MWD/T caused fragmentation of the elements besides having undercutting. This resulted in extremely large amounts of the core being exposed to the water with resulting large amounts of fission products being released.

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The advantage of cooling the water as fast as possible following a rupture indication was very pronounced with the fuel elements which were irradiated over 1200 MWD/T. In Tests No. 16 and 17 with similar fuel elements irradiated to 2000 MWD/T there was a factor of 16 higher for the weight loss of the slow programmed cooldown fuel elements as compared to the fast scram cooldown fuel elements. The difference in Tests No. 18 and 19 with similar fuel elements irradiated to 3555 MWD/T was 8. The 1200 MWD/T fuel elements had a factor of 1 1/2 in the weight loss of the programmed cooldown when compared to the scram cooldown.

In the NPR cooldown tests, the fuel corrosion almost stopped when the water temperature was 200 C and below.

The effects of fuel element irradiation in cold water were very pronounced. Subsequent rupturing at 300 C was faster and considerably worse than with fuel elements irradiated at higher water temperatures.

Geometry of the fuel material produces different rupture characteristics with different release rates.

The use of the U, 2.0 Zr core material produces an extremely slower rupture than did the U core elements.

Continued exposure of the fuel element to 200 C water did not cause much corrosion in contrast to autoclave studies of unirradiated fuel elements in which the swelling was worse than at 300 C.

The results of the IRP rupture tests using irradiated fuel materials in an out-of-reactor loop were quite comparable to tests performed in-reactor with similar fuel materials.⁽¹⁾

PROGRAM FOR FURTHER STUDIES

1. In considering the problems involved in NPR during a fuel element rupture, thought must be given to the other reactor operating conditions which tend to compound the rupture severity. NPR has two opposing factors regulating the reduction of water temperature following detection of a rupture. To reduce the severity of the rupture and to keep the amount of fission products to a minimum it is desirable to cool the water as fast as possible. To keep the thermal stresses in the reactor piping and steam generators at a low level, the water should be cooled slowly. At present there are three shutdown schedules being considered for NPR: (1) a scram cooldown (similar to the NPR fast cooldowns used in the rupture tests), which will be used in emergencies similar to existing reactor scrams; (2) a programmed slow cooldown which will be used for conditions less than the scram emergencies; and (3) a regular shutdown where the water temperature will be lowered gradually.

Several of the problems which need further testing center upon this rate of reactor cooldown. One of the first things to be considered is how long will the water temperature be kept at operating levels before the reactor will be shut down. This time may be as long as 15 minutes with a slow rupturing element or as short as 1 minute, depending upon the operation method used.

1. Call, R.L. and D.C. Kaulitz, "Final Report: In-Reactor Rupture Testing of Zircaloy-2 Clad, Coextruded Fuel Elements in the Engineering Test Reactor," HW-74384. July, 1962. Confidential.

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The time for a primary monitor signal is 1 minute, which is the holdup time for the N-16 decay. At the end of this time the reactor can be scrammed, a programmed shutdown can be started, or the reactor can continue operation until more rupture verification can be obtained. The next rupture verification will come from the monitors located on the diversification pipes. This signal is expected to require an additional 2-4 minutes. Any gross rupture requiring reactor shutdown should be detected by this system. Failing to confirm on the diversification pipes will most likely be evidence of a false indication or an extremely slow rupturing fuel element. The third method of rupture monitoring will be from the sample room where sample turrets will be used which require about 15 minutes to complete a revolution to sample all tubes.

Five minutes as a hold time at 300 C before starting the cooling appears to be a good value to use in the further rupture tests. If the rupture is of some consequence the reactor will be scrammed and the water cooled by this time. A strong bond rupture, one which corrodes only the uranium in a centralized area, may corrode slowly and be at operating temperatures longer than 5 minutes; but, because it is corroding slowly, it will not represent as great a hazard as an undercutting or fragmentation rupture of the shorter hold times.

Another consideration is the type of rupture which is occurring. If the rupture is simply a small bulge and not large splitting, the reactor could be shut down at a slower rate. This is an extremely difficult problem to analyze and must be characterized by the rate of fission product release. Another very serious problem is the determination of the location of the rupture or which part of the fuel element has failed. If the inner tube is rupturing there is not nearly as much incentive to cool the reactor fast as there would be with an outer tube rupture. Because a rupture occurring on the outside of an outer tube may cause sticking in the process tube, or other process tube damage, the reactor should be shut down rapidly.

2. Several other problems result from the uranium core and the shape of the fuel elements. To date, no fuel element rupture studies have been made in the IRP with full-size NPR outer tubes. Geometry has an effect on the size and extent of the rupture and could produce more severe rupturing than anticipated. The core of the fuel elements for use in the NPR are somewhat different from those previously tested. Small amounts of Fe (100 ppm) and Si (50 ppm) have been added to the uranium core to improve the coextrusion properties of the fuel elements. The effect of these additions have not been evaluated.
3. Irradiation parameters have to be evaluated. Fuel elements which have been irradiated to exposures of 2000 MWD/T rupture at a much faster rate than do those irradiated to 1200 MWD/T or less. However, it is not known whether this is a gradual change or if the rupture behavior changes abruptly at some exposure level. The varying water temperatures, fuel element surface, temperatures, and core temperatures in some combination which could extend along the length of the tube could produce remarkably different results. In some out-of-reactor studies at 200 C, the fuel elements began rupturing and swelled nearly the entire surface before the Zr-2 cladding was broken. If this should happen, a large release rate would occur when the break did

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occur, or the fuel element could swell enough to stick in the process tube before the rupture was detected. Extremely low irradiation temperatures produce ruptures more serious than at higher temperatures as evidenced by IRP Tests No. 4, 5, 6 and 7. While the NPR irradiation temperatures will not be as low as those in Tests 4 and 5 it does indicate that rupture severity depends on irradiation temperature.

4. Different types of ruptures potentially could proceed faster and cause more damage than the pinhole type rupture used in the IRP tests. Cleavage-type failures could be worse if the reactor operated for the longer operating periods after rupture detection. A pin-hole type failure has high potential for large swelling because the initial swelling during the incubation period occurs without a rupture indication being received. An end cap failure, which can easily be simulated in IRP tests, would seem to be a potential source of rupture in the reactor because of the large amount of welding and brazing. End cap failures would expose a large amount of uranium in a relatively short period of time and large amounts of fission products would be released. Several end cap closures have been proposed for NPR fuel elements and modifications to the selected closure are being considered to reduce the manufacturing costs. These modifications could result in an unbonded end cap and no secondary closure if a failure in the primary weld is experienced.
5. Fuel element cores other than uranium, claddings other than Zr-2, and fuel element designs other than tube-in-tube design would mean vastly different fuel element rupture performance. An alloy core such as U, 2.0 Zr can improve the rupture performance markedly. This feature could provide the means for irradiating the fuel to higher levels than now designated before the ruptures become the limiting feature in the irradiations. Use of cladding other than Zr-2, such as stainless steel, could improve the corrosion which may be serious with Zr-2; but rupturing could be considerably worse than with U, Zr-2 because of the lack of the strong bond now obtained between the uranium and Zr-2. Fuel elements which are markedly different in design (e.g., single tube or fluted element) from the tube-in-tube elements will exhibit different rupture behavior.

SPECIFIC TESTS PLANNED FOR THE IRP

At present, four tests are planned for the IRP. These are as follows:

Test No. 1

This test will use a NPR outer tube which has been irradiated to 1730 MWD/T at 260 C. The rupture will be started at 300 C and a hold time of 5 minutes at 300 C will be used. If the loop activity is not too high at this time, the water will be cooled at the current NPR programmed cooldown rate. This test will provide a test with a high-exposure NPR outer tube and a realistic cooldown schedule.

Test No. 2

This test will also use a NPR outer tube but one which was second from the upstream end in the tube charge and as such had a low irradiation temperature (~ 228 C) and a low exposure (~ 1000 MWD/T). The same test conditions will

be used as in Test No. 1. This test will provide information on a low exposure at the lowest NPR temperatures with a outer fuel element.

Test No. 3

A NPR inner fuel element exposed to 2100 MWD/T at 260 C will be used. The test will be run at 300 C, followed by a 5-minute hold period at 300 C and then a cooldown used in previous tests will be used. From this test a comparison can be made with previous tests to determine the effects of the Fe and Si additions to the uranium core of this element.

Test No. 4

A NPR inner tube identical to the one in Test No. 3 will be used. After the incubation period, the temperature will be held at 300 C for 15 minutes (the longest time presently considered before reactor shutdown); then a modified cooldown will be used if the loop activity is not too high. This test should demonstrate the worst rupture of an inner tube.

Other tests need to be scheduled as fuel elements are available and as the results of previous tests are evaluated.

The frequency of testing is about one every three weeks. Decontamination studies may be run in conjunction with each test and require considerable time. Testing of the first NPR loading is scheduled for the next two years. After that period of time, second and third loading material will be tested after irradiation in test loops.

K D Hayden

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