FAST-REACTOR

Argonne National Laboratory

CLADDING FAILURE SIMULATION TESTS IN EBR-II

by

R. R. Smith and C. B. Doe

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CLADDING FAILURE SIMULATION TESTS IN EBR-II

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I. INTRODUCTION

One of the areas of concern in the operation of a nuclear reactor relates to the possible failure of the cladding of one or more fuel elements and the resultant exposure of fuel or release of fission products to the reactor coolant. Furthermore, the mode of failure might very well determine its further consequence. In order to investigate the ability of failure detectors in a reactor to determine that a failure has occurred and to associate it with a response time and type of failure, tests have been performed in EBR-II with simulated failures and the normal detection system. Hopefully, information from these tests will be beneficial in formulating a realistic model of fuel-element failure and in providing a more practical base for evaluating the consequences. Fundamental to the problem, in any event, is the ability to annunciate clearly and unambiguously the onset of failure.

The routine operation of EBR-II, for which the typical loading consists of some 7000 sodium-bonded fuel elements, may inadvertently provide considerable insight into the consequences of cladding failure since it is conceivable that at some time in the future one or more fuel elements will fail. In anticipation of this possibility a considerable effort has been devoted to the development of two failure-monitoring devices, both of which have been designed to measure changes in the rate of release of fission products. One of these, the Charged Wire Detector (CWD), has been operated successfully as a monitoring device for the Mark-IV plutonium loading in EBR-I.¹ A description of this apparatus, its operational characteristics, and its performance under simulated failure conditions have been previously given.²

The operation of the other monitoring system, the Fuel Element Rupture Detector (FERD), is based on the detection of delayed-neutron-emitting species which enter the primary coolant as a consequence of cladding failure. A description of the apparatus, its development, and its application to the failure detection problem have been outlined by Porges.^{3,4} The results of preliminary testing of both systems with exposed fuel under reduced power conditions in EBR-II have been summarized by Smith *et al.*⁵ The results of more recent and more definitive tests under simulated failure conditions constitute the subject of this report.

II. FAILURE MECHANISMS AND IMPLICATIONS

In discussing the consequences and implications of fuel-element failure it is essential to define the conditions under which failure may occur. Three particular situations may be postulated: failure under transient conditions; failure under loss of flow; and failure under normal operating conditions. Of these, only the third is of immediate interest, since if a fuel element does fail it will almost certainly fail during the course of normal operation. Unfortunately, experimentally based information relevant to the failure of an EBR-II type of fuel pin under normal operating conditions is apparently nonexistent. Accordingly, anticipation of the consequences of actual failure must be based partly on what information is available from related experiments and partly on what could happen theoretically.

Two significantly different types of failure have long been considered: one in which a defect develops above the fuel section, and the other in which the cladding fails in the vicinity of the fuel. For the case in which failure originates in the region of a gas void, argon and accumulated fission product gases will be released directly to the primary coolant. Although the venting of gaseous fission products to the coolant will cause an increase in the general contamination level of the coolant, no particular hazard to the core is envisioned. Quite likely the sodium bond between fuel and cladding will remain intact, and heat transfer between fuel material and the primary coolant will continue unchanged.

A more serious situation can result from a leak or a defect in the vicinity of the fuel. In this case the sodium bond will very likely be forced through the defect and will leave the fuel material above the defect essentially unbonded. For the worst situation of this type, i.e., a failure at the bottom of the fuel, the bond will be forced through the defect and in a matter of 0.9 sec fuel material will begin to melt. Whether the molten fuel recasts itself upon contact with the cladding or whether molten fuel extrudes through the defect are questions which remain to be answered and are, in any event, beyond the scope of this report. Of immediate concern, however, is how such failures can be annunciated and how one type of failure can be differentiated from another.

Fortunately, the use of two independent systems, one based on the detection of rare gas fission products in the cover gas (the CWD), and the other based on the detection of delayed-neutron-emitting fission products in the primary coolant (FERD), provides a basis for evaluating the nature of a failure. In the event of a gas-type failure accumulated rare gas fission products in the gas space will be released to the coolant and will ultimately diffuse upward to the cover-gas plenum. Eventually the CWD will annunciate an increase in the concentration of the rare gas fission products. Delayed-neutron-emitting species, presumably bromine and iodine, will remain with the bond which, in turn, should remain intact. The FERD system, then, will "miss" this type of failure.

For a bond-type failure, on the other hand, both rare gas fission products and delayed-neutron-emitting species will be released. Accordingly, both systems will respond. Thus, if only the CWD system registers an increase in fission product concentration, it may safely be concluded that the failure has occurred in the gas-void region. If both systems respond the failure may be identified with a defect in the fuel region.

Except for malfunctions of a conventional nature both monitoring systems have been in active operation for approximately two years. Both have registered relatively steady and apparently genuine signals which, aside from usual background components, reflect the continuous presence of fission products in the primary coolant. At least three sources of resident fission product activity can be cited: the fission of natural uranium impurities in the bulk coolant, the fission of enriched uranium which is present as a contamination on fuel-element surfaces, and from already failed fuel pins. It is conceivable, of course, that background effects from any one or all three of these sources could be sufficiently large to mask the signal originating from an actual failure. Accordingly, it was necessary to simulate an actual failure and to measure the relative strengths of background and signal components.

Initial experiments were conducted in May 1965. Although the results of these tests demonstrated that both systems could easily detect the introduction of a single unclad fuel pin, it became evident after completion of the tests that certain improvements could be made. This indeed proved to be true. The results of the second series of tests, conducted under improved conditions, are given in this report.

III. EXPERIMENTAL

A. The FERD System

Since details relevant to the construction and operation of the FERD system have been treated elsewhere,^{4,5} only those features which have an immediate bearing on the actual test results will be described here. In this system a stream of molten sodium (at approximately 750°F), flowing at 100 gal/min, is pumped through a 2-in. pipe from a position near the discharge side of the primary-secondary heat exchanger to the detection point. Approximately 17 sec after leaving the core, the coolant flows through a 3-ft section which is completely surrounded by graphite moderator bricks. Located in the graphite stack are various neutron-sensitive detectors which monitor the neutron level in the coolant loop.

Three independent counting channels have been set up: two are identical, each of which consists of information from a single 2-in.-diameter, 11-in.-long Reuter-Stokes BF₃ detector; the other consists of a gang of

three 1-in.-diameter BF_3 detectors and three 1-in.-diameter, boron-loaded chambers. The two identical BF_3 channels are identified as Channels 1A and 2A; the third is identified as Channel B. For all channels the signals are converted to count-rate form and are displayed as such on strip-chart recorders located in the control room.

B. The Charged Wire Detector

The release of fission products to the coolant in EBR-II from a failed fuel pin will be accompanied by the diffusion of rare gas species upward into the argon cover-gas region. In principle, any simple beta-gamma detector which monitors the activity of the cover gas should be capable of annunciating an increase in the concentration of rare gas fission products. In practice, the signal associated with credible concentrations of these isotopes would be partially masked by the response of the detector to Ar^{41} which is present in the cover gas in concentrations roughly of the same order as the released rare gas fission products. Cover-gas monitoring as a failure-annunciation technique, then, requires strong discrimination against the radiations of the 1.8-hr Ar^{41} .

A simple and extremely effective method, based on the selective fixation of rare gas daughter species, has been developed to discriminate against Ar^{41} activity.³ The principle of the fixation process is based on the fact that at the instant of beta decay, each of the rare gas daughter species becomes a positively charged, radioactive alkali metal ion. Cover gas, containing the rare gas species, is pumped continuously through an external loop from the cover-gas plenum to an electrostatic-precipitation unit, which consists primarily of a cylinder maintained at a potential of 1500 V positive. A wire driven axially through the cylinder is maintained at ground. Upon beta decay the ionized daughter species (radioactive rubidium and cesium) migrate to the wire and become electronically neutralized. The wire carrying the neutralized daughter species passes through a mercury trap-type gas seal which has a shallow layer of water floating on the surface of the mercury. The strongly electropositive rubidium and cesium daughters react instantly with the water and become permanently fixed in the water layer in the hydroxide form.

The isotope K^{41} , the daughter of Ar^{41} , also reacts with the water, but since K^{41} is radioactively inert, the activity associated with the water fraction is almost exclusively that originating from the decay of rubidium and cesium fission products. It follows that the output of a detector which monitors the activity level of the water fraction may be used as a criterion of the fission product concentration in the cover gas.

The apparatus used for monitoring the EBR-II cover gas consists of the following major components: the electrostatic-precipitation unit, mercury-filled U-tube gas seals, wire drive unit, gas-delivery and -exhaust systems, and the detector system.

1. Electrostatic-precipitation Unit. The electrostatic precipitator, shown in Fig. 1, consists essentially of two concentric cylinders: an inner aluminum cylinder, 2 in. in diameter, and an outer stainless steel cylinder, 4 in. in diameter. Running axially through the inner cylinder, the anode, is a 6-mil stainless steel wire driven at a speed of approximately 12 in./min by a 3-rpm Bodine induction motor. The relationship of the precipitator with respect to other components is also given in Fig. 1. High voltage, 1500 V positive, is supplied to the anode through a conventional Teflon-insulated, high-voltage fitting. Plexiglas end-caps insulate the anode from the outer cylinder. The remainder of the precipitation unit, including the traveling wire, is maintained at ground potential.

1. Gas Pump	8. Wire Takeup Spool	15. Flush-gas Line
2. Pumped-gas Flowmeter	9. Level Wind	16. Precipitator Gas Flowmeter
3. Gas-outlet Solenoid Valve	10. Flush-gas Flowmeter	17. Precipitation Unit
4. Wire-feed Spool	11. Outlet-gas Pressure	18. Upstream Hg Trap
5. Gas-return Throttle Valve	12. Cover and Flush Gas Outlet	19. Downstream Hg Trap behind Lead Bricks
6. Gas Pressure from N ₂ Nozzle	13. Over-pressure Switch	20. Detector in Lead Shield
7. Vacuum Shutoff Switch	14. Cover-gas Inlet	

Fig. 1. Photograph of Principal CWD Components

2. Mercury-filled U-tube Gas Seals. To avoid the leakage of radioactive cover gas to the surroundings from the wire inlet and outlet ports, two mercury seals in the form of U-tubes are used. One, along with other components, is shown in Fig. 1; the other, the downstream trap, is hidden from view in the photograph by the barrel-shaped, lead detector shield. Floating on the surface of the mercury in the upstream leg of the downstream trap is a layer of water approximately 1 in. in depth. The water, through chemical reaction with the rubidium and cesium, daughters serves to integrate the combined activities with respect to time. A system of pulleys in each U-tube enables the moving wire to negotiate the various bends.

3. Wire Drive Unit. The traveling wire is pulled by a motor-driven takeup spool from a feed spool through the upstream mercury trap, the precipitation chamber, and the downstream trap. A level-wind feature incorporated in the takeup spool prevents the pileup of spent wire.

4. Gas Delivery and Exhaust Systems. Argon gas is pumped from the cover-gas plenum through a 10-ft-long, $1/2$ -in. pipe which extends downward into the plenum. The pipe, closed at the lower end, is perforated along the lower 6 in. with a series of $1/4$ -in. holes, which permit gas to enter the pipe and provide for the drainage of condensed sodium vapor. To prevent plugging of the inlet pipe with frozen sodium vapor, a 9-ft-long, 0.188-in.-diameter Calrod heater is installed along the vertical axis of the pipe. A block diagram illustrating the various components and their relationships is given in Fig. 2. The radioactive cover gas flows under pumping action from the pipe to one of two sodium vapor traps illustrated in Fig. 3.

From the vapor traps the gas passes through a sintered bronze filter which removes any sodium mist which fails to coalesce in its passage through the traps. From the demisting filter, the gas is pumped by a diaphragm-type air-control pump back to the cover-gas plenum at a rate of 10 cfm. On the discharge side of the pump a tee in the exhaust line permits a small flow of gas, about 80 ml/min, to enter the precipitation unit.

Gas taken from the pumped loop to the precipitator, passes through a flowmeter, through the inner cylinder, and is exhausted to the reactor stack. To prevent radioactive gas from entering the upstream leg of the downstream trap, approximately 400 ml/min of nonradioactive argon is introduced at a point between the mercury in the downstream trap and the precipitation unit. Along with the radioactive gas which enters the precipitation chamber, the purge flow is exhausted to the reactor stack. A system of gauges, valves, and flowrate meters permits flexibility in maintaining proper gas flowrates.

5. Detector. The detector used to monitor the activities collected in the water fraction is a 2 x 2-in. NaI (thallium-activated) crystal, optically

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Fig. 2. Argon Gas System for Charged Wire Cladding Failure Monitor

Fig. 3. Sodium Vapor Trap

coupled to a photomultiplier tube. To reduce the effects of radiation emitted from the reactor and from the precipitation chamber, the crystal and photomultiplier assembly are enclosed by a cylindrical lead shield approximately 4 in. in thickness. After linear amplification, the pulses from the photomultiplier unit are fed to conventional count-rate meters which may be read either at the apparatus or in the control room. An adjustable set-point alarm system incorporated into the control room unit permits audio-annunciation of signals exceeding a prescribed limit.

Three malfunction devices are used to alert operations personnel to the possibility of equipment failure. Partial plugging of the gas-inlet pipe is sensed by a low-pressure switch system which turns off the gas pump and actuates an audio alarm in the control room.

Plugging of the exit line from the precipitation unit is sensed by a high-pressure cutoff switch system which also turns off the gas pump and initiates an audio alarm signal. Finally, if the wire supply is running low, the wire drive motor stops and an alarm signal is sounded in the control room. Two switches, one located in the control room, and the other mounted on the operating panel, can be closed to interrupt the flow of gas from the cover-gas system.

C. Failure-simulation Tests

The tests simulating failures consisted essentially of measuring the counting rates of the CWD and FERD systems under the following conditions: (1) normal operating conditions, i.e., with no intentionally exposed fuel; and (2) with a single unclad fuel pin deliberately installed in the core.

1. The Unclad Fuel Specimen. The test specimen consisted of a single unclad pin of Mark-IA fuel material weighing approximately 68 g, 0.188 in. in diameter, 14.22 in. long, and enriched in the U^{235} isotope to 52.4%. To simplify handling operations the specimen was installed at the center of a conventional 61-pin control-rod assembly. Since the elimination of the jacket would have increased radial clearances between fuel pins, it was considered necessary to compensate for such increases by replacing the second ring of six fuel pins with a corresponding number of stainless steel rods, each equipped with a longitudinally fixed spacer wire. The dimensions of rods and ribs were chosen such that with the single unclad fuel pin installed at midcenter, all radial clearances remained essentially unchanged. A diagrammatic view through the modified control-rod assembly is given in Fig. 4. Horizontal and vertical cross sections through the assembly are given in Figs. 5 and 6, respectively; details relevant to the six special stainless steel pins are given in Fig. 7. Corresponding information for the unclad fuel is given in Fig. 8. The unclad fuel pin was joined through a stainless steel transition piece to a standard end fitting, commonly referred to as a "spade."

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Fig. 4. Isometric of Bare-pin Location

CENTER PIN .144 DIAMETER; BARE ENRICHED URANIUM SIX (6) SURROUNDING PINS
 .174 304 STAINLESS STEEL RIBS OR STAINLESS PINS .0625 STAINLESS 304.
 THE SEVEN SPECIAL PINS TO BE INSTALLED IN A STANDARD CONTROL ROD ASSEMBLY.
 ID-103-G5337

Fig. 5. Horizontal Section through the Modified Control Rod

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Fig. 6. Vertical Section through the Modified Control Rod

Fig. 7. Stainless Steel Pin

Fig. 8. Unclad Uranium Pin

To prevent the entry of fuel material into the bulk sodium in the event of pin breakage, a section of 1/8-in.-thick stainless steel plate perforated with 0.133-in. holes was welded to the lower surface of the top fitting of the control rod. Effective flow through the plate amounted to approximately 90% of nominal full flow. For additional assurance a short section of stainless steel rod was welded to the lower surface of the flow twister (a fitting located immediately above the fuel). The welded piece was $3\frac{5}{8}$ in. long, 9/64 in. in diameter, and extended downward from the flow twister into the fuel bundle to a depth which separated the piece from the test specimen by approximately 5/16 in. .

The possibility of fuel fragments falling downward through the T-bar grid (in the event of breakage) was considered incredible in view of the much smaller clearances between lower fuel-pin end fittings. As an additional precautionary measure all tests were run at reduced levels of power and flow, i.e., 9.1 MW and 75% nominal full flow, respectively.

2. Time-power History of Reactor Operations. A tabular summary of operating conditions during and preceding the tests is given in Table I.

TABLE I. Summary of Operating Conditions

Date	Time	Conditions
5/3/66	11:37	Power at 0.0 MW
	20:00	Startup
	23:30	At 45 MW
5/6/66	09:00	At 0.5 MW
	09:25	At 1.0 MW
	10:20	Back to 0.5 MW
	13:20	At 25 MW
	17:15	At 45 MW
5/8/66	16:50	Began power reduction
	19:23	Subcritical
5/9/66		Reactor shutdown
5/10/66		Reactor shutdown, test assembly loaded
5/11/66	22:15	At 0.5 MW
	23:10	At 9.1 MW
5/12/66	17:15	Began reducing power
	18:10	Subcritical

If considered necessary the information given above could be used to extrapolate the Na^{24} background effect to full-power (saturated) operating conditions.

3. Results Obtained with the CWD. The best illustration of the sensitivity of the CWD system is given by the information taken during the first 23 hr of the tests. A graphical summary of information read from a strip-chart recorder during this time is given in Fig. 9. Shortly after the system was brought critical and approximately 10 min after the beginning of the power rise, the counting rate from the CWD began to increase. The counting rate continued to increase until 10 hr later, when the modified control rod was fully inserted. At this point a second sharp increase in counting rate may be seen. Eventually the counting rate approached an asymptotic limit as the various alkali metal fission product activities saturated.

Fig. 9: CWD Response

From the results of earlier experiments⁵ it was shown that the activities responsible for the CWD response are Rb^{88} , Rb^{89} , and Cs^{138} . By analyzing a growth curve similar to that of Fig. 9 but taken over a longer period of time, it was found that the relative importances of these species, activity-wise, amounted to 63.7, 12.1, and 24.2%, respectively. Since Rb^{88} and Rb^{89} are characterized by relatively short half-lives, 17.8 and 15.4 min, respectively, it is reasonable to assume that the continued growth after a period of 6 hr is essentially the result of the 32.2-min Cs^{138} . A simple extrapolation of the total activity 10 hr after the fuel insertion of the bare

pin results in an asymptotic value of 40 cps. The total counting rate obtained in this manner, includes, of course, contributions from room background and from the presence of tramp uranium in the system. An estimate of all combined background effects from measurements conducted at 45 MW with the modified control rod removed from the system, i.e., with no intentionally exposed fuel, was found to be approximately 3 cps. Subtraction of this value from the total (asymptotic) counting rate of 40 cps gives 37 cps for the signal associated with the deliberately exposed fuel. The signal-to-noise ratio is, accordingly, $37/3$ or approximately 12.

4. Results Obtained with the FERD System. The performance of the FERD system under test conditions is well illustrated by photographic copies of actual strip-chart recordings. The results for Channel 2A, which consists of a single BF_3 counter, are given chronologically in Figs. 10-13. Beginning at the right-hand side of Fig. 10, the counting rate increased as the system was brought to 9.1 MW. The effects of a power cutback to approximately 5 MW are clearly in evidence. Upon restoration of the power level to 9.1 MW the flow through the FERD loop was cut off. As expected, the counting rate decreased rapidly as delayed-neutron-emitting species trapped in the stagnant sodium decayed. The extremely low counting rate noted after decay, i.e., approximately 1 cps, may be used as an estimate for the upper limit of the Na^{24} background. Upon reinitiation of loop flow the counting rate increased rapidly to 32 cps. At this time the modified control rod was cycled twice between its up and down positions. In both

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Fig. 10. FERD Response, Shortly after Startup, Channel 2A

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Fig. 11. FERD Response, Ten hours after Startup, Channel 2A

ID-103-H5408

Fig. 12. FERD Response, Twenty-one hours after Startup, Channel 2A

ID-103-H5401

Fig. 13. FERD Response, No Exposed Fuel, Channel 2A

cases the insertion was reflected by a marked increase in the counting rate to approximately 60 cps. The information given in Fig. 11 was obtained approximately 10 hr after the information of Fig. 10. Again the loop flow was turned off and the bare pin cycled between its up and down positions. Except for a slightly lower counting rate with the bare pin inserted, the data are remarkably consistent with that taken 10 hr earlier.

The record shown in Fig. 12 was obtained approximately 21 hr after the system was brought to 9.1 MW. Accordingly, the effects of Na^{24} background should be more evident at this time, since the Na^{24} activity after 21 hr of running time should be 62% of its maximum (saturated) value. That Na^{24} background effects are indeed small is clear from the results obtained when the flow through the loop was again turned off. From the data of Fig. 12 it is clear that the Na^{24} background can be no larger than 1.5 cps.

Finally, as illustrated in Fig. 13, the power was reduced to 4.5 MW in an effort to demonstrate linearity between power and counting rate. As expected the twofold reduction in power resulted in an immediate twofold reduction in counting rate. With the shutdown which followed, the counting rate dropped to 1.5-2.0 cps, which again reflected the effects of Na^{24} activity.

A separation of the tramp uranium effect was made possible by removing the bare-pin assembly and by running the system (24 hr later) at a power level of 10 MW. These results are illustrated in Fig. 13. Again the loop flow was turned off in order to establish the Na^{24} background effects. It follows that the difference between the gross counting rate, 6.5 cps, and the Na^{24} background, 1.0 cps, gives the tramp uranium effect: 5.5 cps at 10 MW or 5 cps at 9.1 MW.

Assuming an average of 50 cps for the gross counting rate with the bare pin fully inserted (from Figs. 10-12), a Na^{24} background of 1.5 cps, and a tramp uranium background of 5.0 cps, the true signal associated with the exposed fuel may be shown to be 43.5 cps. The signal-to-noise ratio is then $43.5/6.5$ or 6.7.

Similar data recorded for Channels 1A and B are illustrated in Figs. 14 through 17. Without exception the behaviors noted for both channels are completely consistent with the results with Channel A.

Cursorily, it would seem that the records of all three channels are characterized by strong fluctuations in the signal strength. A certain statistical variation is, of course, to be expected, and it is tempting to assign the origin of the fluctuations noted to statistical considerations. A close inspection of data for all three channels, however, reveals a strong correlation between peaks and troughs in the various signals. (In comparing data for Channels 1A and B attention must be called to a 30-sec time displacement of the two recording pens.) In view of this evidence it must be concluded that some, if not most, of the variations in signal strength are real. Apparently all three channels are reflecting strong changes in the concentration of the delayed-neutron-emitting species at the sampling point. Quite likely time-dependent variations in flow path along the route to the sampling point (at the exit side of the heat exchanger) are primarily responsible.

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Fig. 14. FERD Response, Shortly after Startup, Channels 1A and B

ID-103-H5402

Fig. 15. FERD Response, Ten hours after Startup, Channels 1A and B

ID-103-H5403

Fig. 16. FERD Response, Twenty-one hours after Startup, Channels 1A and B

ID-103-115405

Fig. 17. FERD Response, No Exposed Fuel, Channels 1A and B

DISCUSSION

From the results outlined and discussed above it is clear that both systems are capable of annunciating changes in the rate of release of fission products when a single unclad fuel pin is deliberately installed in the core. Both systems respond unambiguously: the CWD with a S/N ratio of 12, and the FERD with a S/N ratio of 6.7.

Of the two systems, the FERD enjoys the clearcut advantage of a much shorter time response (approximately 20 sec). On the other hand, for reasons outlined in Section II, this system will very likely not respond to a failure which occurs in the gas region. Since the CWD system is sensitive to failures of both types, i.e., bond-type and gas-type, the two systems logically complement each other.

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