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# Confirmation of Failure Causes of PWR Defective Fuels

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#### Abstract

PWR fuels relevant to the failure mechanism have been subjected to post-irradiation examination. Two fuel rods were identified as defective fuel rods during on-site inspection and transported to the PIE facility of KAERI to investigate the root causes of the fuel failure. A series of nondestructive and destructive hot cell examination have been performed for the fuel rods. The results show that the failure of R-rod was oriented from the debris induced fretting mechanism, and K-rod failure could be made by the random hydride.

## **1. Introduction**

Two fuel assemblies irradiated at nuclear power plant were identified as failed through inspection. Each fuel assembly had one failed rod. Both fuel assemblies were determined to be repaired for continued operation in the reactor. Visual inspections were performed on the failed rods and the fuel assemblies in order to determine the causes of failure.

Based on the preliminary analysis of the inspection data, it is postulated that the failure mode for one rod (K-rod) is due to an internal mechanism. However, the actual root cause is indeterminate from the inspection performed. The failure mode for the other fuel rod (R-rod) is a small through-wall hole, most likely caused by a sharp piece of debris that became entrapped within the grid cell occupied by this rod.

The failed fuel rods were extracted and transferred to PIE facility at KAERI for more precise hot cell examination. A series of non-destructive and destructive hot cell examination have been performed for the failed fuel rods.

### 2. Coolant Radioactivity Data Analysis

The plant fuel shows an abrupt increase in  $I^{131}$  release of about 1  $2x10^{-3} \mu$  Ci/cc, at the end of July 1995 just after 50% of plant power increment (Fig. 1). Since the failed fuel rods were both in the core periphery, it is unlikely that one non-fuel-releasing failure could release this much. Thus it is likely that the debris failure occurred at that time. This is supported by an observed continuing increase in the I<sup>131</sup> activity. On August 16, a very large further increase is observed. The plant power decreased from 80% to 30%, and about 40 times of Iodine activity increase was detected. This indicates severe degradation, i.e., the observed axial crack occurred, or expanded, at that time. It is not possible to tell when the second failure occurred, since it is overwhelmed by the fuel-releasing one. After the severe degradation, the fuel release did not worsen too much. However, the level of activity did not decrease, which indicates that either the fuel release had stopped and all released fuel was firmly settled on fuel surfaces elsewhere in the core, or the fuel kept releasing enough to keep up with the coolant cleanup system, which is only capable of removing contamination dissolved and suspended in the coolant. It should be conservatively assumed that the Iodine, after the restart, and off gas activities will remain high, despite the removal of the failed fuel. The I<sup>131</sup> level is 0.2 µ Ci/cc which shows an abrupt increase at the end of July, i.e., at the suggested time of the first fuel release. The ratio of  $I^{131}$  to  $Xe^{133}$  shows an EOC value about 0.3, which is equal to its "tramp" value. This indicates that the activity release is dominated by released fuel (tramp). The ratio  $I^{134}$  to  $I^{131}$  shows a gradual decrease between the suggested first incident of fuel release and the severe degradation on August 15. This indicates a widening of the breach in the fuel-releasing rod.

Concludingly, the root cause of the two failures is probably different for the two. One is a classic case of debris failure, the other either is internal hydriding of an unidentified external cause, possibly end cap "piping" or weld flaw. The coolant activity is much higher than the

direct contribution from the failed rods. Significant fuel release from the rod failed by debris fretting is suggested. The fuel release most likely began early, but was aggravated later (August 16).

## **3. Visual Inspection**

Visual inspection of R-rod indicated the presence of a small through-wall hole at approximately 93mm from rod bottom (Fig.2), which is located within the upper half of the bottom Inconel spacer grid. There is no evidence of any grid-to-rod fretting wear in this region. The through-wall hole, therefore, was most likely caused by a sharp piece of debris that became entrapped within the grid cell occupied by R-rod. This small through-wall site is believed to be the primary defect site. Additional areas of damage on the rod caused by secondary hydride failure were observed at 2,660 mm with a long axial crack below Zircaloy-4 Grid #7 and ghost hydride through Grid #7 region (Fig. 3) (1,2).

Since the probable piece of debris was located within the grid cell, and not below the grid cell, a reasonable expectation existed that the surrounding rods were not damaged. However, if a piece of debris extended below the grid, neighbor rods to the R-rod may have been damaged during operation, although not failed. So, the eight neighbor rods surrounding R-rod were inspected for damage indications and no indications of external wear were found. Inspection of the spent fuel pool rack locations in the vicinity of the fuel assembly inspection stand were also performed to find a piece of debris that may have dislodged from the bottom grid cell during the inspection and no debris was observed.

Visual inspection of K-rod indicated the presence of several regions of secondary hydride damage, but no indication of the location of the primary defect site. Ghost (white-colored) hydride regions were observed at 1,592 mm and 1,420 mm below Zircaloy-4 Grid #4. An open blister region was observed at 1,177 mm below Grid #3, with some material missing from a single fuel pellet visible at this location (Fig. 4, 5 and 6). A brittle region extended about 7.2 mm above the blister. Axial cracks were observed in this region, and some surface oxide and crud appears to be removed. An axial crack was also observed within the ghost hydride region at 1,592 mm. The visual inspection did not reveal any indications of fretting wear along the rod that could have been caused by either debris or grid-to-rod contact. Nor

was there any visual evidence of, or reason to believe that any other external failure mechanism or operational condition may have been involved. Since the visual inspection of K-rod did not indicate any potential external causes, it is postulated that the failure cause is due to an internal mechanism. However, the actual root cause is indeterminate from the inspection performed. Internal failure causes found in Zircaloy-clad fuel over the past several decades are generally associated with fabrication processes(3) and have included such as;

- (1) primary hydriding that may be caused by a high moisture content of fuel pellets, water remaining in tubes before welding, of the presence of other material contaminations within the fuel rod following fabrication that might be a source of hydrogen.
- (2) inter-connected porosity in end-cap material
- (3) end-cap weld defects that cannot be identified during a single rod visual examination.

# 4. Examination Results and Discussion

Several fuel failure mechanisms were considered to find the root cause of failure. Concentrations on debris fretting, spacer grid fretting, primary hydriding, end-plug defect, and end-plug weld defect were put during the non-destructive and destructive examination. For R-rod, the cause of through-wall hole defect and the secondary hydride formation scheme were major concern. For K-rod, finding of other defect or failure except hydride failure and the hydride formation mechanism were major concerns of PIE.

## 4.1 R-rod Examination

At first, for R-rod the orientation of fuel rod that was located in the assembly was determined and through-wall hole shape and dimension were inspected. Defect sizes measured were 0.9 mm and 0.3 mm in length and width, respectively. The defect locates at 93.2 mm from the bottom end of rod and was rotated about 70.3 ° from the front view. Eddy current test was conducted and no other noticeable defect signal was found except the defective zone(Fig.7). In X-ray radiography, no noticeable changes were detected and gamma spectroscopy result shows normal irradiation conditions (Fig. 8). And the vacuum leakage test for the end cap zone of the rod showed no leakage in both ends. In destructive test for R-rod,

macro- and micro-structure of the pellet and cladding tube around defective area were examined precisely (Fig. 9 & 10). Inside and outside oxide layer thicknesses of the cladding tube around through-wall hole area were measured. About 10  $\mu$ m of oxide was measured around the grid spring contact area and about 4  $\mu$ m of oxide thickness was measured around the through-wall hole defect. The internal oxide thickness is about 4 5 times thicker than the external ones. While the external oxides layer distributions show almost uniform states with around 2  $\mu$ m of thickness, the internal oxides shows maximum 10.5  $\mu$ m of measured value at 2,100 mm location (Fig. 11). The oxide thickness of internal clad shows a little bit higher values which means that the failure of this rod was made comparably earlier time of BOC. It is reported that the normal irradiated intact fuel used to show little oxide layers in internal clad surface(4).

Fig. 12 shows a typical secondary hydride failure of R-rod located at 2,660 mm from the bottom end of rod. And the density of fuel pellet is 10.535 10.567 g/ $cm^3$  which shows very small discrepancies with the fabrication data of 10.55 g/ $cm^3$ . It was expected from the burn-up measurement result of this rod and the measured burn-up was about 2,013 MWD/MTU.

The macro- and micro-structure of R-rod showed similar structures to the un-irradiated  $UO_2$  structure except for the region between 1,300 2,120 mm where remarkable grain growth phenomena were shown(Fig.13). It is believed that the intrusion of coolant through the defect led to the oxidation of fuel pellet. Consequently, the O/U ratio increased which lowered the thermal conductivity of fuel and it finally contributed to the raising of fuel temperature up to the temperature point enhancing the grain growth of  $UO_2(5)$ .

## 4.2 K-rod Examination

In K-rod, there are 4 suspicious regions showing extraordinary signals or results through NDT examinations. Cladding failures were observed around 1,177 mm and 1,592 mm region. Between two locations, ECT (Eddy Current Test) signal of a large defect was detected at 1,420 mm location, and finally internal flaw signal was detected at 276 mm, but the magnitude was comparatively small (Fig. 14). X-ray radiography shows a normal stack states of fuel

pellet. The gap interfaces between pellets were maintained in normal states. The average diameter of the fuel rod was  $9.70 \pm 0.02$  mm, and ovality conditions of the clad show normal states except the region around the hydride failure occurred. Gamma scanning examination was carried out to gather the irradiation information of fuel pellets by collecting the gross and specific gamma counts for several isotopes such as Cs, Nb and Zr (Fig. 15).

Microscopic examination of fuel pellet of K-rod was performed by selecting several specimens from the rod (Fig.16). The micro-structures of the pellet irradiated at the lower part of fuel showed about 8 µm of grain size, and the structure of the whole area showed very similar results to the un-irradiated ones. But the structure between 810 1,580 region shows a little bit bigger grain growth rather than that of the normal irradiated fuel pellets. And a large concentric ring type of grains seen in the middle of fuel pellet was identified as a agglomeration of columnar grains which were believed to be formed by the subsequent mechanisms of stoichiometry changes of UO<sub>2</sub> affected by the coolant intrusion. It is reported that the increasing of O/U ratio up to 2.1 used to directly contribute to about 40% of thermal conductivity reduction. These postulations can be supported by the hardness test results of pellet. Fig. 16-a and 16-b show the micro-hardness distributions. Fig. 16-b shows a little bit higher hardness numbers than the ones of 16-a, which means the increasing of O/U ratio due to coolant intrusion and subsequent oxidizing of  $UO_2$  were made in comparatively high temperature environment. The dark area showing about 30 of hardness number are the resin mount which are penetrated through the pores in the center part of pellet during specimen preparation. A large amount of pores possessed by the resin mount can explain that the temperature of this region was very high compared to the other clean area of fuel rod.

Oxides formed inside and outside of fuel cladding tube were measured for specimens selected different 8 locations. Overall oxides thickness distributions are showing 3 10 times thicker values in inside than outside. No oxide formation was seen in both end parts of fuel rod and about 3  $\mu$ m of uniform oxides layers were seen between 1,300 3,000 mm region. In case of the oxides formed inner side of clad, maximum thickness of 11.25  $\mu$ m oxides region was found around the defect area at 1,300 mm and in the remaining part of the rod up to 3,300 mm region, about 10  $\mu$ m of oxides were uniformly distributed.

## **5.** Conclusions

Rapid increases of Iodine-131 activity were detected two times during test operation of plant in the end of July and in the middle of August. Considering that the first Iodine activity peak was happened irrespective of plant power changes and a part of fission plume was found just upper part of the lower defect, it was believed that the first peak was contributed by the defect made in the lower part of R-rod. And considering the power decrease from 80% to 30% when the second Iodine peak was occurred, it was believed that the hydrided cladding tube of K-rod was failed by the thermal stresses acted on the clad accompanied with the power transients.

A precise PIE for the R-rod shows that the failure of this rod was oriented from the debris induced fretting mechanism made by a foreign materials with very sharp and hard end tip. A very hard and sharp tip of debris trapped in the first spacer grid spring shell made a continuous pressure onto the fuel cladding tube until the through hole debris induced fretting failure was made. This is the primary root cause of failure of R-rod.

The final conclusion of failure cause of K-rod could be made as a random hydride failure which might probabilistically be occurred under the normal Q/C and Q/A activities implied in the fuel fabrication process. Even though the exact route for the hydrogen intrusion from outside was not identified, there were not any evidences to exclude the existence of hydrogen sources in the fuel pellets or inside the cladding tube.

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Fig.1. Coolant Radioactivity in NPP



Fig.2. R-rod Image around 93 mm



Fig.3. R-rod Image around 2,660 mm



Fig.4.K-rod at 1,420 mm



Fig.5.K-rod at 1,592 mm



Fig.6.K-rod at 1,177 mm



Fig.7. ECT Result for R-rod



Fig.8. Gross Gamma Scanning Results of R-rod



Fig.9. Thru-Hole Defect of R-rod



Fig.10. Thru-Hole Defect



Fig.11. Oxide-Layer Thickness of R-rod



Fig.12. Secondary Hydride Failure of R-rod



Fig.13. Macro- and micro-structure of Fuel Pellet of R-rod at 2,100 mm



Fig.14. ECT Result for K-rod



Fig.15. Gross Gamma Scanning for K-rod



Fig.16.Micro-hardness results of K-rod at 1,580 mm

(cf. Unirradiated  $UO_2$  Pellet Hardness : 407)