Post Irradiation Examination of Failed Fuel Bundle from TAPS# 3 PHWR


Abstract

The 37-pin fuel bundle was removed as failed bundle from the 540 MWe Pressurized Heavy Water Reactor (PHWR) of Tarapur Atomic Power Station-3 (TAPS-3) after a residence of 147 days in the reactor after accumulating a burn-up of 3576 MWd/tU. Leak testing by liquid nitrogen-alcohol test also confirmed the presence of through the wall cracks. Ultrasonic testing (UT) indicated crack in the clad near the failure locations of all the failed fuel pins. The Ultrasonic testing showed presence of lack of fusion and root cracks in the end plug welds which were confirmed by metallography. Gamma scanning of failed pin showed variation of Cs$^{137}$ counts near the failure location as compared to uniform counts in an un-failed fuel pin. Variation in Cs$^{137}$ near the defect location indicates the possibility of a higher fuel temperature, causing migration of volatile cesium (Cs) from hotter to cooler locations.

Detailed metallographic observations were carried out in the fuel pins which gave an estimate about the center line temperature, clad oxide layer, restructuring details, multiple cracking of the clad layer. Hydride blister was observed towards the outer surface of the cladding. The sun-burst type of hydride blister on the inner surface was also found. Internal hydriding and weld defects were the root cause of failure of the fuel pins based on the observations of clad diameter increase, presence of blister, higher fuel temperature, thicker oxide layer on clad inner surface and higher level of hydrogen in the clad near the failure location. It was recommended that strict control of moisture/hydrogen in the fuel pin is required to avoid such fuel failures by controlling fuel pellet drying parameters like temperature, duration and vacuum level. It was also suggested to improve the quality of welds by ultrasonic testing.

1. Introduction

Fuel bundle No. 37491 was loaded in the 540 MWe Pressurized Heavy Water Reactor (PHWR) in Tarapur Atomic Power Station-3 (TAPS-3) in channel P-18 at the 4th string position. The bundle was pushed from 4th position to the 12th position as it was suspected to have failed and stayed at that position for one day. It was finally discharged from the reactor due to fuel failure after a residence of 147 days in the reactor and accumulating a burn-up of 3576 MWd/tU. The fuel bundle was received at hot cells of Post Irradiation Examination Division for post irradiation examination (PIE), after a cooling period of 1.5 years. PIE of the failed and un-failed fuel pins of the bundle included visual examination, leak testing, laser profilometry, ultrasonic testing, gamma scanning, metallography of fuel pin and end plug sections, hydrogen content determination in the cladding and ring tension tests on cladding samples. Four fuel pins were found to have failed in this fuel bundle. This report describes important findings of the examinations carried out and the primary cause of fuel failures. Fuel failures have been reported for different reactors [1, 2]. Internal hydriding failure has reported by different authors [3-6]. Degradation in fuel pin due to operation with weld defects has also been reported [7].
2. Fuel design and power history

The bundle was of 37-element design with natural UO$_2$ fuel, cladded in Zircaloy-4. The schematic of the fuel bundle is shown in Fig. 1. The fuel bundle consists of an assembly of 37 cylindrical fuel elements of 13.08 mm diameter and 493 mm length, joined together by spot welding the elements to the end plates at both the ends. The fuel bundle has one element at the centre and 6, 12 and 18 elements arranged in concentric rings separated by thick and thin spacers spot welded at the mid-length of the fuel pins. The outer ring fuel pins have three bearing pads spot welded to the sheath. The fuel bundle had operated at estimated power level of 450 kW and fuel pins in different rings were operating in the range of 20 to 30 kW/m linear heat ratings.

![Diagram of 37-element fuel bundle](image)

Fig. 1. Schematic of 37-element fuel bundle showing the arrangement of fuel pins and failed pins arrow marked.

3.1 Bundle dismantling and visual examination of fuel pins

The fuel bundle was dismantled using a pneumatic hack saw machine. The end plates were removed from the end plugs by cutting at the spot weld location. The fuel pins were cleaned thoroughly with alcohol and observed under camera in the hot cell to examine the condition of the appendages, end plug welds and the integrity of the cladding. Examination of the fuel pins of the bundle revealed presence of cracks in three outer ring fuel pins (P-18, P-09, P-04) and one in intermediate ring (I-1-7). Fig. 2. shows the defects observed on the cladding surface of the four fuel pins.

![Defects on fuel pins](image)
Fig. 2. Defects observed on the fuel pins (a) P-18, (b) P-09, (c) P-04 (d) I-1-7 pin

The outer fuel pin, P-18 revealed a perforation with an axial crack at 130 mm and one more crack at 145 mm from the end plug weld. The perforations in the fuel pins P-09, P-04 and I-1-7 were observed at a distance of 40 mm, 150 mm and 30 mm from the end plug weld, respectively. The appendages of all the fuel pins were intact. Dark ring was observed on the clad surface near the end plug weld in a few pins as shown in Fig. 2d.

3.2 Leak testing of fuel pins

Leak testing of all the fuel pins of bundle was carried out by liquid nitrogen-alcohol leak test. Four pins P-18, P-09, P-04 and I-1-7 were found to be leaky during leak testing. Bubbles coming out from the pins immersed in alcohol bath are shown in Fig. 3. Leak testing confirmed the presence of through-wall defect in the fuel pins. Liquid nitrogen-alcohol test is suitable for hot cells to be carried out with the master slave manipulators. The fuel pins are kept immersed in liquid nitrogen for 5 minutes, the pin is taken out of liquid nitrogen and placed in a tray containing alcohol. In case of a leak, liquid nitrogen seeps into the fuel pin and fills up the internal spaces. On its transfer to the alcohol bath, the pin warms up, converting liquid nitrogen into gas. This builds up the nitrogen gas pressure inside the fuel pin leading to its escape through the leak. The escaping nitrogen gas will be visible as bubbles in the transparent alcohol immersion. Both, liquid nitrogen and alcohol evaporate and leave no radioactive waste after the test which is desirable. Leak locations were identified in four failed fuel pins.

Fig. 3. Bubbles emanating from failed fuel pin P-09 during leak testing.

3.3 Laser Profilometry for diameter measurement

A laser based profilometer was used to measure the diameter of the fuel pins at different axial locations. Increase in diameter of the fuel pins was observed at an axial location which coincides with the failure location in the fuel pin. The diameter profiles of the failed fuel pins showing the location of higher diameter are shown in Fig. 4. It was observed that the diameter in the fuel pins P-09 and P-04 was relatively uniform along the length of the fuel pin except the failure location. Pin I-1-7 showed variations in the fuel pin diameter at three locations.
However, fuel pin P-18 showed variations in diameter all along the length with the maximum diameter at the failure location. Laser diameter measurement can also find out the ridging/bamboo-effect in the fuel pins. Fuel swelling or collapse was not observed in any of the fuel pins of this low burn-up fuel bundle.

![Diameter profile of the failed fuel pin P-18. Diameter increased at failure location.](image)

**B u n d l e n o : 0 3 7 4 9 1 P**

3.4 Ultrasonic testing

Ultrasonic testing was carried out to check the soundness of the clad and end plug weld. UT signals indicating crack in the clad were observed near the failure locations of all the failed fuel pins. Length of the crack was found to be ranging from 9 to 100mm more than visually observed. The UT defect signals showed presence of lack of fusion and root cracks in the weld, which were marked for metallography. Ultrasonic testing detected lack of fusion and root crack defects which were found by metallography as shown in Fig. 5 & 6.

![Lack of fusion observed in P-09 weld](image)

![Root crack was also found in the weld](image)

**Fig. 5. Lack of fusion observed in P-09 weld**  **Fig. 6. Root crack was also found in the weld**

Similar root crack defect in the sheath near the weld was also found in the end plug weld of I-1-7 failed fuel pin. The outer surface near the weld had a dark circle. The end plug body and inner ring of the fuel pin P-04 had seen massive hydriding.
3.5 Gamma spectrometry and axial gamma scanning

Gamma-scanning is a non-destructive method for measuring the relative distributions of fission products in irradiated fuel pins that helps to generate information on axial burn-up distribution and distribution of specific fission products. Gamma scanning was carried out using a high purity germanium (HPGe) detector. Fig. 7. shows the axial gamma scan of the failed outer fuel pin, P-18 with variation of Cs$^{137}$ counts near the failure location as compared to uniform counts in an un-failed fuel pin. Variation in Cs$^{137}$ near the defect location indicates the possibility of a higher fuel temperature, causing migration of volatile Cesium (Cs) from hotter to cooler locations. The gamma activity in an un-failed fuel pin is nearly uniform along the axial length. Maximum variation in activity near failure location was noticed in fuel pin P-09, lesser in P-04 and negligible variation in I-1-7.

![Gamma Scan of Fuel Pin P-18](image)

Fig. 7. Variation in Cs$^{137}$ activity near the failure site in fuel pin P-18

3.6 Metallographic examination

**Failed fuel pin P-18**

Severe cracking and restructuring is observed in the fuel sections as compared to the fuel section from the un-failed fuel pin. Fig. 8a, b, c and 12 (c) show the fuel sections from the failure location with crack/opening in the cladding. Fuel wash-out is observed in the fuel section in Fig. 8b. The radial extent of intergranular (IG) porosity region observed in the fuel sections is different at different axial locations of the fuel pin indicating variation in the fuel centre temperature along the length of the fuel pin as shown in Fig. 8.

![Fuel Pin Cross Sections](image)

Fig. 8. Fuel pin cross section(a) 58mm from one end (b) leaky site 144mm (c) away at 440mm
Failed fuel pin P-09

A massive perforation in the cladding at about 40 mm from the end plug weld was observed in the fuel pin P-09. Metallographic samples at about 45 mm, 48 mm and 55 mm from the end plug weld were examined and the respective photo-macrographs are shown in Fig. 9. Fuel had fallen off from the sample at the failure location with a large opening in the clad.

Fig. 9. Photo-macrographs of fuel sections taken at different axial locations of the fuel pin P-09. The failure location near the bearing pad is marked by arrow. A dark ring was also observed on the outer surface near the end plug weld. Lack of fusion and root crack defects had formed during welding were found in this weld as shown in earlier picture.

Failed fuel pin P-04

Perforation was observed in the fuel pin P-04 at a distance of ~150 mm from the end plug weld and the fuel sections at different axial locations of the fuel pin are shown in the Fig. 10.

Fig. 10. Photo-macrographs of fuel sections at different axial locations of pin P-04 and end plug

Hydriding of other end plug
Failed fuel pin I-1-7

Perforation in the fuel pin I-1-7 was at about 30 mm from the end plug weld and metallographic samples were taken near the defect (~35 mm) and away from the defect (~96 mm). Restructuring of fuel was absent in the transverse sections of the fuel pin as shown in Fig. 11a. However, extensive damage in the cladding was observed in the section taken near the failure region. The fuel pin was observed to have a dark ring near the weld line on the clad outer surface as indicated by the arrow. The dark colouration near the weld line and root cracks (tearing at the inner surface of the clad tube) may be due to high heat input Fig. 11b.

![Fig. 11a. Photo-macrographs of fuel cross sections taken at different axial locations of the fuel pin I-1-7. Arrow shows the defect location.](image)

![Fig. 11b. Shows the root crack (tearing at the inner surface of the clad tube)](image)

3.7 Hydrogen (H) / Deuterium (D) content estimation

Hydrogen content in the cladding was analysed by Differential Scanning Calorimetry (DSC) and the H/D analysis was carried by Hot Vacuum Extraction-Quadrupole Mass Spectrometry (HVE-QMS). As per the technical specifications, the hydrogen content in the clad should be less than 25 ppm. Hydrogen content in the cladding of un-failed fuel pin was 24 ppm nearly as fabricated, indicating negligible pick-up. However, the H content in the cladding of pin I-1-7
near failure location was found to be up to about 250 ppm. Failed pin P-18 showed up to 95 ppm H and 217 ppm D in the cladding. High levels of hydrogen in the cladding are possibly due to a source of hydrogen inside the fuel pin. After failure, D$_2$O coolant entering into the fuel pin led to oxidation of the clad and fuel, releasing deuterium, fraction of which was picked up by the cladding.

4.0 Conclusion

Post irradiation examination of fuel bundle no. 37491 irradiated up to a burn-up of 3576 MWd/tU has been carried out to investigate the cause of fuel failure. PIE has shown that out of the 37 fuel pins of the bundle, three fuel pins from the outer ring and one from the intermediate ring had failed.

Root cause of failure

1) Primary/ Internal hydriding is the root cause of failure of the fuel pin P-18 based on the observations of clad diameter increase, presence of blister, higher fuel temperature, thicker oxide layer on clad inner surface and higher level of hydrogen in the clad near the failure location. Observations in the fuel pins P-04 and I-1-7 were similar to that of fuel pin P-18. Moisture in the pellet or insufficient baking of the graphite layer could be the possible source of hydrogen inside the fuel pin.

2) Dark ring observed on the clad surface near the end plug weld in a few pins of the fuel bundle which may be due to higher heat input. Root crack defects were observed in two fuel pins which are generated either due to higher heat input or higher tensile stress. The lack of fusion defect and root crack observed in the fuel pin suggests that fuel might have failed due to weld related defects allowing coolant ingress. The incomplete weld fusion may have opened up during high temperature reactor operation.

RECOMMENDATION

1) Strict control of moisture/ hydrogen in the fuel pin is required to avoid such fuel failures by controlling fuel pellet drying parameters like temperature and duration. Temperature during pellet drying should be increased to 150°C and preferably carried out under vacuum. After drying, pellets should be loaded into the clad tube within a short interval to avoid moisture pick-up from the atmosphere. However, complete baking of graphite layer should also be checked.

2) Better control on the welding parameters during fuel pin fabrication will eliminate weld related defects. The grossly defective welds may be eliminated by proper ultrasonic testing of end cap welds on 100% basis.

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References


