PIE of MOX fuel : An Advanced PHWR Fuel

Prerna Mishra, B.N. Rath, Ashwini Kumar, U. Kumar, P.M. Satheesh, V.P. Jathar, G.K. Mallik and J.L. Singh

Post Irradiation Examination Division, Bhabha Atomic Research Centre,
Mumbai-400085, prenam@barc.gov.in

Corresponding author: Prerna Mishra <prernam@barc.gov.in>

1. Abstract / Introduction

The requirement to increase the discharge burnup of Pressurised Heavy Water Reactor (PHWR) fuels using higher fissile content led to the concept of advanced fuels like mixed oxide (MOX) fuels. Test irradiation of fifty number of MOX bundles was carried out in the KAPS-1 reactor in different locations. The bundles were irradiated to peak burnups of 20,000 MWD/tHE. Few of the fuel bundles were brought to the hot cells of Post Irradiation Examination Division for performance assessment. The details of examinations carried out on a high burnup fuel bundle irradiated to burnup of 20,331 MWd/tHE and the results obtained are presented in this paper.

2. Fuel Bundle Design

MOX fuels with mixture of oxides of Plutonium (from reprocessed fuel) with natural uranium were studied for loading into the operating reactors.

The Mixed OXide MOX-7 bundle design is a 19-element cluster, with inner seven elements (intermediate and central fuel pins) having MOX pellets consisting of plutonium dioxide mixed in natural uranium dioxide and outer 12 elements having only natural uranium dioxide pellets. The Plutonium content used was 0.4%. This makes the fissile content of inner elements 1.1% and that of outer elements 0.7%. This leads to flux flattening across the different rings of the bundle leading to generation of higher bundle power compared to natural uranium bundles. The fuel bundles were fabricated at AFFF, Tarapur.

3. Irradiation history

Fuel bundle No. MX00043 was irradiated at KAPS-1 and accumulated a burnup of 20331 MWd/tHE in 606 full power days (FPD). Peak power and peak LHR of the fuel bundle was 448 kW/m and 53.6 kW/m, respectively. Figure 1 shows the irradiation history of the fuel bundle.

4. Post Irradiation Examination

Various non-destructive (NDT) and destructive (DT) techniques were used for performance assessment of the fuel pins of the bundle. PIE of the fuel pins included visual examination, liquid Nitrogen-Alcohol leak testing, laser profilometry, ultrasonic testing, gamma scanning, metallography and optical microscopy (OM), β-γ autoradiography and α-autoradiography.

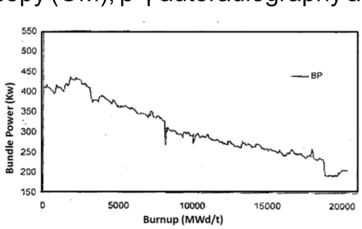


Figure 1. Irradiation history of the fuel bundle.

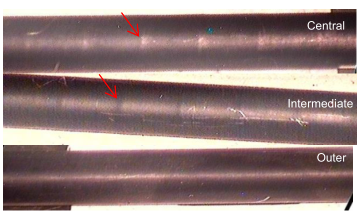


Figure 2. Ridges on central and intermediate fuel pins.

5. Results and Discussion

Visual Examination of the fuel bundle showed that all the endplate to fuel pin spot welds were intact. Length of the fuel bundle was 497.72 mm and the diameter at and away from the bearing pad was 81.08 mm and 78.66 mm, respectively.

Visual examination of individual fuel pins after bundle dismantling showed circumferential parallel lines on the fuel pins from the intermediate ring and the central fuel pin as shown in Figure 2. The distance between the lines correspond to the pellet length indicating formation of ridges in the fuel pins. Absence of significant flaw indication during ultrasonic testing and no leak during leak testing confirmed all the fuel pins to be intact.

Higher diameter at regular axial locations was noticed in the fuel pins of the bundle, which were the locations of the pellet interfaces, indicating pellet ridging. Absence of chamfered and dished pellets in MOX fuel pins led to higher ridging in these fuel pins. Figure 3 shows a typical diametre profile of an intermediate and outer fuel pin. Bow in the MOX fuel pins was found to be ~0.7 mm.

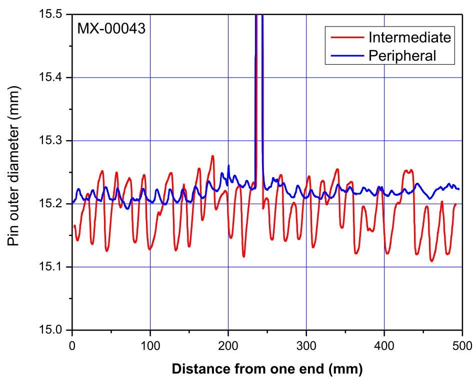


Figure 3. Diametre profile of intermediate and outer fuel pin.

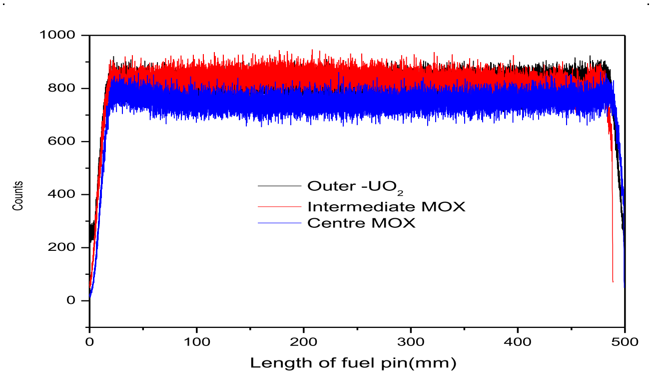


Figure 4. Axial gamma scans of fuel pins from different rings of the fuel bundle.

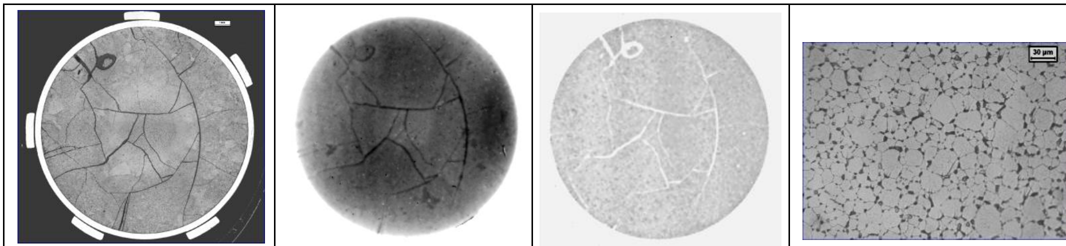
Gamma-scanning was carried out to study the relative distributions of fission products in the fuel pins. Figure 4 shows the comparison of axial gamma scans of fuel pins from different rings of the fuel bundle with uniform ^{137}Cs activity along the length of the fuel pins. ^{137}Cs counts observed in the outer and intermediate fuel pins were in the similar range indicating similar burnup contribution from these fuel pins. Lesser counts were observed in the central fuel pin.

Estimation of the quantity of the released fission gases in the fuel pins showed that the released fission gas pressure at RT in the outer and intermediate fuel pins was in the range 2.5 to 2.9 atm and 2.6 to 10.4 atm, respectively.

Photomacrograph of the fuel section from the intermediate pin shows intergranular porosity region with a fuel fractional radius of 0.26, whereas, it is not resolved in the outer pin and absent in the central pin. The β-γ autoradiograph shows a central bright region (with less ^{137}Cs activity) in the fuel section with fuel fractional radius of 0.21 in the intermediate pin and 0.30 in the outer fuel pin but is absent in the section from the central pin. Uniform Pu distribution was observed in the α-autoradiographs of intermediate and central fuel pin, indicating absence of Pu segregation.

Grain size at fuel centre was 16 µm, 17 µm and 9 µm in the outer, intermediate and central fuel pins, respectively, showing grain growth in outer and intermediate fuel pins. Photomacrograph, β-γ autoradiograph, α-autoradiograph and grains at fuel centre of intermediate fuel pin with fission gas bubbles at grain boundaries are shown in Figure 5.

Average oxide layer thickness of 4.9 µm was observed on the inner surface of the clad of the intermediate fuel pins. Average oxide layer thickness of 3-4 µm was observed on the outer surface of the clad of the fuel pins.



(a) (b) (c) (d)

Figure 5. (a) Photomacrograph, (b) β-γ autoradiograph, (c) α-autoradiograph and (d) the grains at fuel centre of intermediate fuel pin of intermediate fuel pin.

6. Conclusions

Post Irradiation Examination of a high burnup MOX fuel bundle irradiated to a burn up 20331 MWD/tHE has shown good performance of the fuel. The main findings of the examination are:

- The fuel bundle has successfully achieved the burnup without failure. All the fuel pins of the fuel bundle were intact with all its appendages in place.
- Circumferential parallel lines on fuel pin surface and higher diameter at pellet interface showed presence of ridges on the intermediate and central fuel pins with ridge height of 45 and 65 µm, respectively.
- Gamma scanning showed similar burnup contribution from outer and intermediate fuel pins with relatively lesser contribution from the central fuel pin.
- Maximum fission gas pressure of 10.4 atm was obtained in the intermediate (MOX) fuel pin.
- Presence of intergranular porosity region and fission gas bubbles at the grain boundaries at the fuel centre in intermediate fuel pins indicate generation of more fission gas.
- Similar grain size at fuel centre shows similar fuel centre temperatures (FCT), however, more Cs migration in outer fuel pins shows relatively higher FCT than in intermediate fuel pin.
- Pu segregation in the fuel is absent.

Good performance of the fuel provides an option of use of the MOX fuel in PHWRs to enhance fuel discharge burnup.

References

1. S. A. Bhardwaj, M. Das, September 15-19, 1986, Fuel design evolution in Indian PHWRs, International Symp. on improvements in water reactor fuel techn. and utilization, IAEA, Stockholm.

2. S.S. Bajaj, P.N. Prasad, M. Ravi, A.N. Kumar, 2003, “Fuel Design and Performance in Indian Reactors”, International Conf. on "Characteristics of Quality Control of Nuclear Fuels", Hyderabad.