Design, Development And Operating Experience Of Thorium And MOX Bundles In PHWRs

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ABSTRACT

In addition to natural uranium bundles, other types of bundles are also irradiated time to time based on the specific requirement/ situation in Indian PHWRs.

In the PHWR 220 MWe units, 35 zircaloy clad thorium bundles, which are of 19-element type, were used for flux flattening in the initial core, such that the reactor can be operated at rated full power. About 230 number of thorium bundles were irradiated and successfully discharged.

MOX-7 bundle design has been evolved, which is a 19-element cluster, with inner seven elements having MOX pellets and outer 12 elements having only natural uranium dioxide pellets. Initially for trial irradiation 50 number of lead MOX bundles have been fabricated and loaded in the KAPS-1 reactor in different locations in different channels. Some of the bundles have been reshuffled to see their power ramp performance. The performance is so far good.

The paper gives the design, development, and operating experience of the Thorium and MOX fuel bundles in PHWRs.

1. INTRODUCTION:

In India, the performance of Nuclear Power Plants has continuously improved over the years. So far, 70 Full Power (FP) years of PHWR(1) operation and 40 FP years of BWR operational experience has been accumulated.

The PHWRs use natural uranium in oxide form as fuel. So far, more than 3, 20,000 number of 19-element fuel bundles have been irradiated in the 12 PHWRs and 5100 number of 37-element fuel bundles in the TAPS-4(2) 540 MWe PHWR. The fuel

1. Pressurised Heavy Water Reactors

2. Tarapur Atomic Power Station Unit 4

performance in Indian reactors has progressively improved over the years (Ref. 1). Efforts have been put to improve the fuel bundle utilization by increasing the fuel discharge burnup of the natural uranium bundles. The discharge burnup of all the reactors have increased in the last 3 years.

In addition to natural uranium bundles, other types of bundles are also irradiated time to time based on the specific requirement/ situation. Short length fuel bundles and on-power refueling provision in PHWRs provides flexibility to use variety of fuel loading patterns and different fuel types and consequently permits optimum use of fuel in the reactor and allows generation of full power all the time. Using this flexibility, alternative fuel concepts are tried in Indian PHWRs.

The different fuel types tried are depleted uranium bundles, dummy aluminum bundles, Thorium bundles and MOX bundles. This paper gives the design, development, fabrication and operating experience of the Thorium and MOX fuel bundles in PHWRs. Following paragraphs cover the alternative fuel designs used in Indian PHWRs.

2. THORIUM BUNDLES

India has a long-term strategy of use of thorium (Ref. 2) in its nuclear power programme. An advanced heavy water reactor is being designed, in addition to deploying Thorium in FBRs in future. It is thus planned to have experience of irradiation of thorium in present power reactors.

It was planned to use Thorium bundles for flux flattening in the initial core such that the reactor can be operated at rated full power in the initial phase. The Thorium bundle is a 19-element fuel bundle with Thorium dioxide as fuel in pellet form (Ref. 3). The pellet shapes used are both flat and single dish type. As shown in Figure-1 the bundle power of these bundles gradually increase with irradiation exposure time due to production of fissile isotope U^{233}(Ref 2). The fuel element Thermo-mechanical analysis was carried out for elements operating on such an envelope. The elements are designed for a peak Linear Heat Rating of 57.5 KW/M and burnup of 15000 MWD/TeTh. The Thorium dioxide pellet specification was evolved which consists of chemical content, density, shape specifications. High density ThO_2 pellets suitable for PHWR were developed at BARC[(3)] (Ref. 4).The fuel element axial and radial gaps have been suitably specified. By carrying out minor modification in their bearing pad positions, proper identification of these bundles was provided. The fuel bundles were fabricated by NFC[(4)].

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3. Bhabha Atomic Research Centre, Mumbai, India
4. Nuclear Fuel Complex , Hyderabad, India

Initially four lead thorium bundles were irradiated in MAPS -1[5] reactor during the eighties. Subsequently, 35 Thorium bundles have been used as a part of initial charge fuel in the 220 MWe PHWRs for flux flattening in the initial core such that the reactor can be operated at rated full power in the initial phase. These bundles are distributed throughout the core in different bundle locations, both in the high power and low power channels. The criterion used for selection of these locations is such that the worths of the shutdown systems are unaffected (Ref 5). This loading was successfully demonstrated in KAPS-1[6] and subsequently adopted in the initial reactor loading of KAPS-2[6], KGS-1 & 2[7] and RAPS 3&4[8]. A special 18 thorium bundle loading configuration was used for flux flattening in the fresh core of RAPS-2[8] after enmass coolant channel replacement (EMCCR) job.

So far, 232 thorium dioxide bundles have been successfully irradiated in different reactors. The maximum fuel bundle power and burnups seen are 408 kW and 13000 MWd/TeTh respectively. These bundles withstood the power ramps normally experienced in reactor while the typical power envelope of thorium fuel is such that power increases with irradiation. Out of the 232 bundles, one bundle is suspected to have failed during operation at relatively low burnup. The thorium dioxide fuel bundle fabrication and irradiation has provided valuable experience. Two of these irradiated thorium bundles are under Post Irradiation Examination(PIE) at BARC[3] hot cells.

It is now planned to irradiate thoria bundles to higher burnups with suitable modification in design. It is also planned to take up loading few thorium bundles regularly during equilibrium reactor operation.

3. MOX-7 BUNDLES

It was planned to load Mixed OXide (MOX) fuel in one of the existing PHWRs. For this purpose, MOX-7 bundle design has been evolved, which is a 19-element cluster, with inner seven elements having MOX pellets consisting of Plutonium dioxide mixed in natural uranium dioxide and outer 12 elements having only natural uranium dioxide pellets(Ref. 6). Figure -2 shows typical MOX fuel bundle.

Large scale utilisation of such bundles leads to substantial savings in the usage of natural uranium bundles (Ref 7). The core average discharge burnup increases to 9000 MWD/TeHE[9] with this scheme. Due to this, the fuelling rate comes down from 9 bundles / FPD in the case of Natural Uranium core to 7 bundles/FPD in the proposed MOX-7 / Natural Uranium core.

Based on detailed studies, an optimised loading pattern and refuelling scheme has been evolved for loading initially 50 lead MOX bundles in an existing operating reactor.

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5. Madras Atomic Power Station Unit 1
6. Kakrapar Atomic Power Station Units 1&2
7. Kaiga generating Station Units 1&2

8. Rajasthan Atomic Power Station Units 1-4
9. Burnup of MOX bundles is specified in MWD/TeHE (Tonne of Heavy Element)

The scheme evolved was to load a combination of MOX-7 bundles and natural UO_2 fuel bundles in each refuelling. Relevant reactor physics parameters for this type of core have been evaluated. The reactivity worths of the shutdown systems are calculated and found acceptable as sufficient subcriticality margins exist between the negative reactivity requirements and availability for all normal shutdowns and anticipated accidental scenarios.

The MOX-7 fuel bundle design has been carried out. The maximum Linear Heat Rating (LHR) for MOX bundle occurs for the inner ring MOX elements. The LHR for these elements are maintained similar to the 19-element natural uranium bundle outer elements. Based on this concept, the fuel bundle power burnup envelope for MOX-7 bundle was evolved. The variation of plutonium content possible in MOX lots is taken into account in this. Figure-1 shows the Bundle power envelope for MOX-7 bundles.

The fuel bundle subchannel analysis has been carried out to check for dryout margins (Ref. 8) for channel loaded with 12 MOX fuel bundles. One of the fuel design limits for normal reactor operation condition is that the ratio of Critical Heat Flux (CHF) to normal heat flux shall be more than 1.30. CHF value for a bundle in a channel depends on the channel/bundle and reactor coolant conditions. Even though (MOX) fuel bundle configuration is similar to 19-element natural uranium fuel bundles, fissile material and its quantity in inner 7 elements is different from natural uranium bundle. Inner elements of a MOX bundle produce higher power where coolant flow is less compared to outer elements. For channel loaded with MOX bundles, the maximum sub-channel coolant temperature and sheath temperatures increased when compared to UO_2 fuel channel. MOX (0.4% PuO_2) fuel bundles sheath temperature is higher by 10^o C compared to natural UO_2 fuel bundles. However, this temperature is lower than 350^o C, which is the limiting temperature. The CHFR is about 3.8. Hence, adequate margin exists for MOX bundles to reach limiting sheath temperature and limiting CHFR.

The fuel bundle thermo-mechanical analysis has been carried out for MOX fuel elements and different parameters like fuel temperatures, sheath strain and fission gas releases are checked for acceptance.

The structural design of end plates has been evaluated with respect to strains induced due to difference in power ratings of inner ring of MOX bearing elements as compared to present all natural uranium elements (Ref. 9). Due to this, the different elements of bundle expand differently in axial direction. These elements with differential expansion will try to bend the end plates. This gives rise to bending stresses on the end plates of the bundle. There will be cyclic variation of these bending stresses because of bundle power cycling. Analysis was carried out to estimate the stresses in end plate and calculate the number of fatigue cycles, which the fuel bundle can withstand. It was found that present bundle design qualifies the analysis.

MOX elements of similar dimensions as PHWR fuel bundle were earlier fabricated and test irradiated in CIRUS research reactor. BWR MOX fuel bundles have also been fabricated and irradiated in the two TAPS 1&2[10] BWRs (Ref 10).

Subsequently the fuel bundle drawings and fabrication specifications have been prepared. Provision for identification of bundles provided. The specific requirements for MOX fuel pellet and element fabrication were included. Earlier experience of MOX fuel fabrication and irradiation experience in the BWRs has provided valuable feed back for this purpose. For initial trial irradiation 50 number of MOX-7 bundles have been fabricated by BARC and NFC. Unlike natural uranium bundles, elements of these bundles are seal welded by TIG welding. The pellets are of single dish pellets. For loading these bundles in one of the PHWR, regulatory permission has been obtained. Special bundle transport package and storage racks have been developed such that criticality accidents do not occur.

These 50 MOX bundles were loaded in the KAPS-1 reactor in different locations in the year 2004 (Ref.11). In each refueling four MOX, bundles are loaded in the bundle locations 5 to 8 of the channel. In few channels MOX bundles were loaded in 4^{th} location and subsequently shuffled to 8^{th} location in the same channel. Figure-3 shows typical bundle power variation of a MOX bundle loaded in channel N-08 fourth location. In order to obtain higher bundle power production from MOX bundles and achieve desired burn up at the earliest, bundles producing about 300 KW in low power channels like K-03 were recycled (Figure-4) to central channels at a burnup of about 2000 MWD/TeHE. These bundles successfully withstood the power ramps. The first four bundles, after 16 months of irradiation and accumulating a burnup of 11000 MWD/TeHE, have been discharged recently as a part of normal refuelling. The performance is so far good. The DN counts of these channels are steady, indicating good fuel performance of these bundles. The DN data of channel N-08 is shown in Figure-5. The iodine activity in the coolant is maintaining 1-2 micro Ci/ lit. The four discharged bundles were sniffed in spent fuel bay and found nondefective.

4. CONCLUSION

Indian nuclear power programme is based on optimum utilisation of available uranium and thorium resources in the country. The fuel designs and fuel usage strategies are evolved based on this objective. In addition to natural uranium bundles, the different alternative fuel designs irradiated namely Thorium bundles and MOX bundles have performed well.

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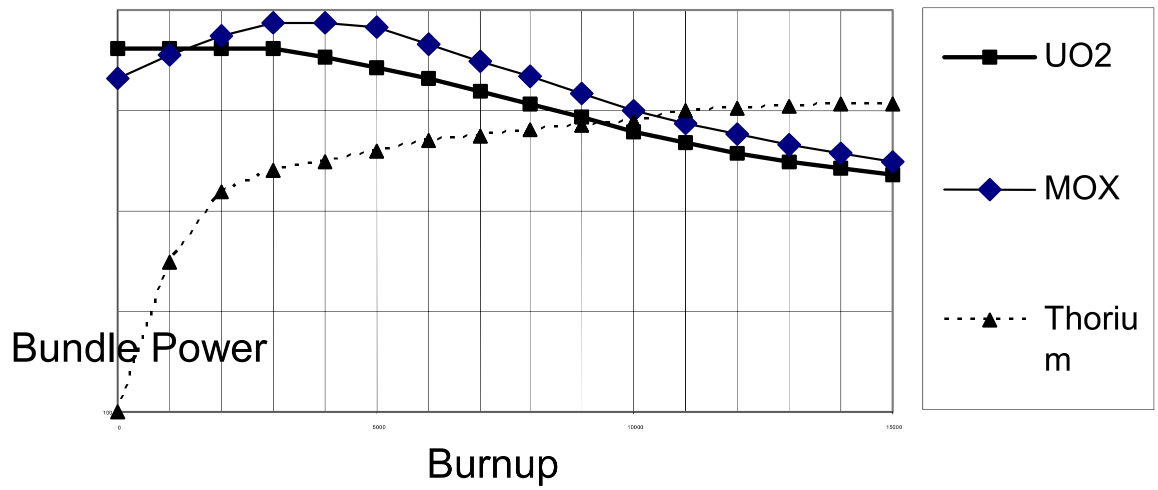

FIGURE 1. Bundle Power Envelopes for Different Fuel Types

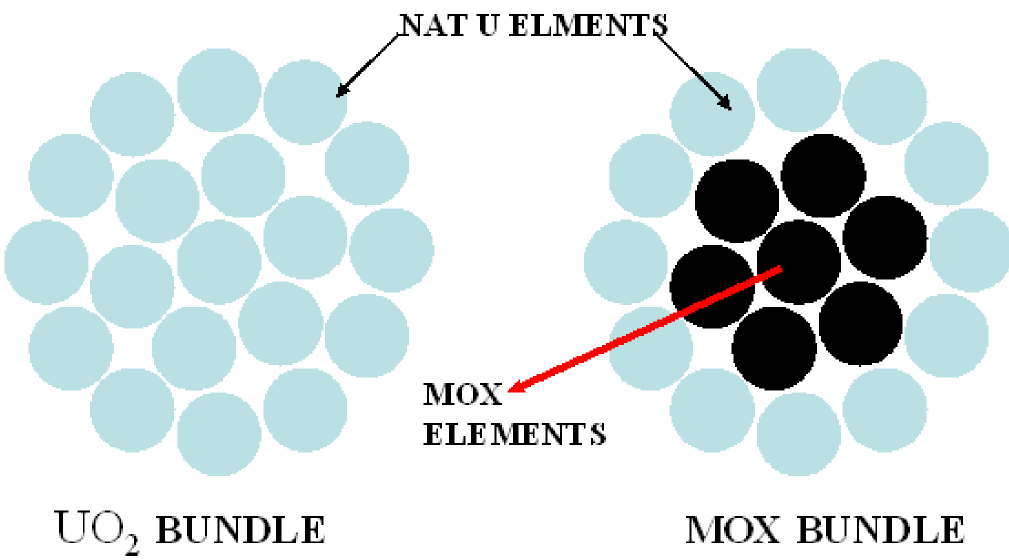

Figure - 2 Natural Uranium and MOX 19-element fuel bundles

FIGURE -3 BUNDLE POWER VARIATION FOR CH N-08 (MOX-7 BUNDLE AT STRING 4TH & 8TH POSITION)

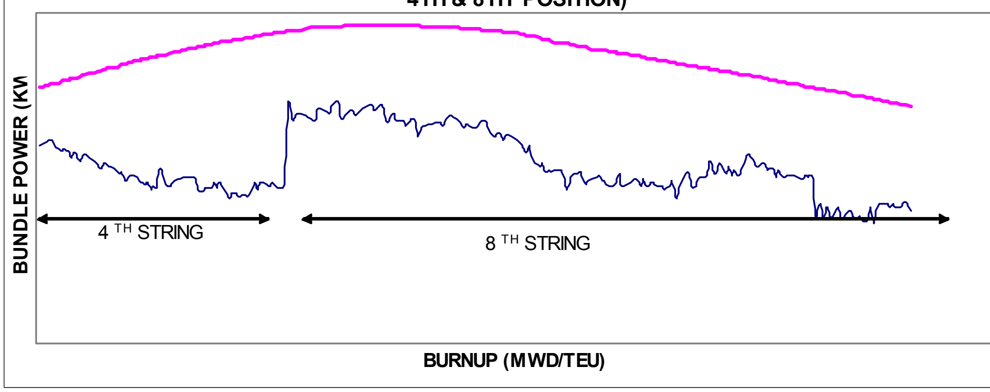

FIGURE -4 BUNDLE POWER VARIATION FOR CH K-03 AND G-09 (MOX-7 BUNDLE AT STRING 5TH POSITION)

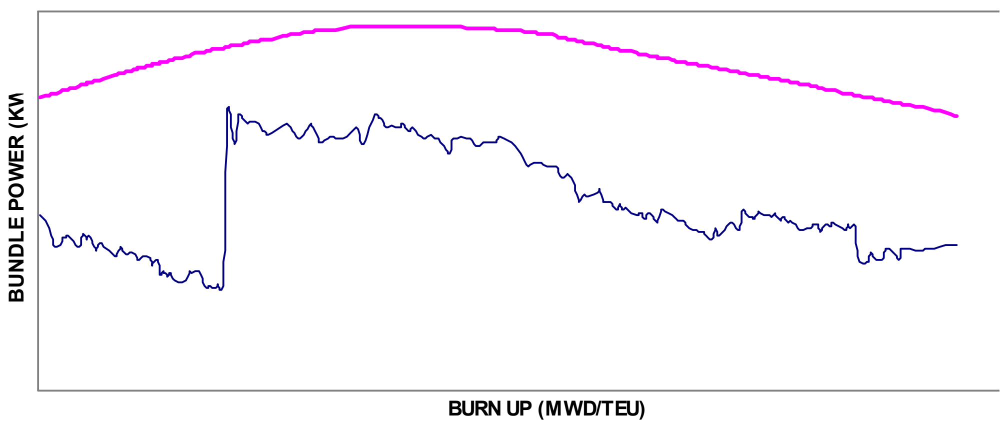

FIGURE - 5 DN COUNTS IN CPS VARIATION FOR DIFFERENT CHANNELS INCLUDING N-08 WHICH CONTAINS ONE MOX-7 BUNDLE