FUEL PERFORMANCE IN INDIAN PRESSURISED HEAVY WATER REACTORS (PHWRs)

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ABSTRACT

At present India has eight 220 MWe Pressurised Heavy Water Reactors (PHWRs) in operation and four under different stages of construction. The operating PHWRs RAPS, MAPS, NAPS and KAPS use natural uranium dioxide nineteen element fuel bundles. We have accumulated more than 35 years of full power operating experience of these PHWRs. This covers irradiation of more than 125 thousand fuel bundles. Based on the reactor operating experience, the fuel design, manufacturing and the reactor operating practices are under continuous evolution in order to improve the fuel performance. This paper discusses the changes introduced in the fuel design, various steps taken for improving the manufacturing and quality control plan and plant operation to improve fuel performance. The paper also reviews the consequent fuel performance data from the operating plants.

1.0 INTRODUCTION

Indian Pressurised Heavy Water Reactor (PHWR) of 220 MWe capacity is a pressure tube type reactor with heavy water as moderator and coolant and natural uranium dioxide as fuel. Pressure tubes, numbering in all 306 and made of zirconium alloys are arranged horizontally in a square lattice pitch of 22.86 cm inside a large cylindrical vessel referred to as calandria. These pressure tubes contain fuel and heavy water coolant at high temperature and pressure. The fuel bundle is about 500 mm in length and 81.7 mm in diameter. The bundle is a cluster of 19 elements arranged in a circular configuration of 1, 6 & 12 elements as shown in Figure-1. There are 12 bundles per channel. Only 10 bundles lie within the active region of the core.

2.0 REACTORS IN OPERATION AND UNDER CONSTRUCTION

The first PHWR reactor in India went critical way back in 1972 at Kota, Rajasthan. The second unit at Kota, Rajasthan went critical in 1980. These reactors were a collaborative project with Atomic Energy Canada Limited (AECL), Canada. Subsequently, 6 more reactors have been made operational. The details of their criticality are given in Table-1. We have gained more than 35 years of full power operating experience of these reactors and irradiation experience of more than 125 thousand PHWR fuel bundles.

Four more units, two each at Kaiga, Karnataka and at Kota, Rajasthan are under construction, to be commissioned by the year 1999.

3.0 FUEL DESIGN

3.1 Design Improvements

The present nineteen element fuel bundle design being used in our operating plants is an improved version of the wire wrap fuel bundle as was used in Douglas Point Reactor in Canada. The salient design changes are split spacer design, graphite coating and modified scooped end cap (1).

Split Spacer Design : In the earlier design, the inter element gap and gap between pressure tube and elements was maintained by helical wire wrapped and spot welded around elements. In order to avoid the possible fretting damage by these wires to the neighbouring elements sheath surface, split spacer design has been adopted. Skewed split spacers in this design maintain gap between the fuel elements. Short bearing pads on outer elements as shown in Figure-1 are used to provide desired gap between fuel bundle and pressure tube. The spacers and bearing pads are attached to fuel elements by spot welding. In this process the zircaloy inventory is also reduced by about 8-9% which is equivalent to a gain in burnup of about 60 MWd/TeU (1).

Graphite Coating : In order to overcome the fuel failure, if any, induced due to power ramps or stress corrosion cracking of zircaloy and in general to increase the potential of the fuel element to resist the power ramp failures, development of the graphite coating on the inside surface of the sheath was accomplished at Bhabha Atomic Research Centre (BARC). The production of the graphite coated fuel bundles was introduced in our manufacturing plant at Nuclear Fuel Complex (NFC) in the year 1989.

Modified Scooped End Cap : The end plug design parameters are either specified from compatibility with the reactor fuelling machine or from manufacturing considerations eg. overall form, contact with sheath and end plate for satisfactory welding etc. The only other significant dimension to be specified is the thickness of the end cap. After providing the minimum thickness based on axial strength consideration, the modified end cap design has been provided with a scooped out conical portion (Figure-2), which otherwise was flat surface in the original design. The modification avoids the high temperature gradient in the end cap due to its possible contact with flat end of the fuel pellet. This modification further increases the free volume available for accommodation of fission gases, which in turn reduces the internal fission gas pressure by about 10% at the end of the life of the fuel bundle in the core. In the end cap design the zircaloy content per bundle is reduced by about 25 gms, giving rise to increase in the burnup by about 20 MWd/TeU (2).

3.2 Thorium Oxide Fuel

Thorium bundles in general are identical to 19 element natural UO2 pellet fuel bundles except that the UO2 pellets have been replaced by ThO2 pellets. Based on the properties of the thorium fuel, the fuel bundle design was prepared, engineered and fabricated. The first hand operational experience of this design was gained by irradiating four thorium bundles in Madras Atomic Power Station (MAPS) Unit-1(1). Based on this experience 35 thorium bundles were loaded in the initial cores of Kakrapar Atomic Power Station (KAPS) Unit-1&2 for flux flattening and to achieve full power in the initial phase of reactor operation.

4.0 FUEL MANUFACTURING AND QUALITY CONTROL

The fuel used in our reactors is manufactured at NFC, Hyderabad. The improvements in fuel fabrication and quality control plan is a continuous process. The major change in the PHWR design was use of graphite coating on the inner surface of the fuel sheath and was introduced in the regular production in the year 1989. The standardised fuel now being manufactured at NFC is a result of number of steps which have been taken in the fabrication of UO_2 pellet, sheath, end cap to sheath weld joint, fuel bundle assembly, etc. to ensure consistent quality (3).

5.0 REACTOR OPERATION

The number of steps have been taken to reduce the fuel failures due to power ramps. Since the beginning of our nuclear power programme, we have been using 8 bundle shuffling refuelling scheme. Apart from this, following operating procedures have been introduced to reduce power ramp failures(4).

5.1 Core Simulations

Physics core simulations are performed to provide the guidance for routine on load fuel scheduling. In earlier days dedicated computers were not available at each station and simulations were performed at a central point in BARC. Moreover, because of long distance between station and the central place, the simulations were planned to be at an interval of one month. Many a times, refuelling was done based on experience and on thumb rules, which might have caused some fuel failures. To reduce such uncertainties, dedicated computers were installed at each station. In India, the reactor physics simulations and fuel scheduling are done by physicists stationed at each station prior to each refuelling.

5.2 Criteria For Refuelling

Apart from other reactor operating considerations, flux shape, power and power ramps to the bundles of the refuelled channel and also the neighbouring channels are considered before refuelling.

5.3 Regularity In Refuelling

Due to non availability of fuelling machines, if the excess reactivity has been lost from the core, the excess reactivity is regained gradually with due care to the flux shape, control rod positions and consequent power ramps to fuel.

5.4 Thorium Fuel For Initial Flux Flattening

The thorium fuel bundles are used in the initial core for initial flux flattening to achieve full power operation in initial phase of reactor operation. The selection of the number of bundles and their locations in the core is based on the detailed physics and fuel management studies of the reactor. The performance of the reactor and the reactivity devices during the irradiation period of these thorium bundles in the reactor is assessed by performing prior physics simulations. Based on the operational experience of the thorium fuel bundles in the initial core of KAPS-1&2, similar initial fuel loading pattern is being adopted for future PHWRs.

5.6 Detection Of Failed Fuel

Concentration of I131, I132, I133, I134, in the heat transport system are measured on a routine basis. A first order estimate of the nature of defect in fuel and the coolant contamination caused by them is made by systematic analysis of these isotopes (3). However, a particular channel with a failed fuel bundle is detected during reactor operation by the Delayed Neutron (DN) detection system which is provided for all Indian PHWRs. The suspected failed fuel is removed from the channel based on the DN ratio trend. Till 1988, a value of 1.4 as the ratio of channel DN counts to average DN counts of group of similar power channel in the DN system was considered a threshold limit to signal out a failed fuel channel. It is suspected that this DN ratio of 1.4 sometimes permitted sufficiently large residence time for the fuel defect to grow in the core, resulting into higher contamination of the core, leading to increase in iodine activity and increased background DN counts as well. During 1988, for early detection of the failed fuel bundle, the threshold DN ratio was brought down to 1.2. This has been further supplemented by the DN ratio trend monitoring. Only after observing a continuously increasing trend in the DN ratio, the channel is considered to be a suspected failed fuel channel. The DN background readings of the PHT circuit is also analysed. This method together with monitoring of I-134 is a good means of indication of deterioration in status of defect and its contribution to core contamination.

6.0 FUEL PERFORMANCE EXPERIENCE

Fuel performance can be gauged by the fuel failure rate and also by the iodine activity in the coolant. Close monitoring of the I-131 activity is done. Even though Technical Specifications for operation permit 100 micro curies per litre of I-131 in PHT, a significantly low alert level of 10 micro curies is adopted by operation.

As has been discussed above, on the basis of the fuel performance experience of our earlier plants RAPS-1&2 and MAPS-1&2, some changes have been incorporated in our fuel design, manufacturing and reactor operating guidelines (1, 2, 3, & 5). The performance of KAPS-2 unit which went critical in the year 1995 can really be used to judge the effect of all such improvements simultaneously. The fresh core of KAPS-2 had been loaded with a fuel which can be considered to be present standard 19 element fuel bundle from the consideration of the fuel design, manufacturing and also from the consideration of the reactor core operation. The reactor has shown an excellent fuel performance, with a cumulative fuel failure rate of 0.1%. The recent I-131 activity observed in KAPS-2 is given in Figure 3. It can be seen that the I-131 activity in the reactor has generally remained below 2 micro Ci/lt.

The Fuel Reliability Indicator (FRI) has been defined by WANO (World Association of Nuclear Operators). The median FRI value reported for world PHWR is 170.0 bq/gm for the year 1996. The FRI of 120 bq/gm has been achieved for KAPS-2 reactor for the first half of 1997.

Similar trend is observed in other PHWRs in India where fuel of earlier type was also present in the core for quite some time. RAPS and MAPS units showed fuel performance similar to KAPS-2. The NAPS-1 reactor which went critical in the year 1989, experienced high fuel failure rate in the year 1992 due to global power ramp (2). The power ramp experienced was due to sudden rise in reactor power after prolonged low power operation. It may be brought out here that the fuel bundles in the NAPS-1 reactor core at that instance were nongraphatised. The global power ramp gave rise to about 33 fuel failures in the core. The failed fuel channels were detected and refuelled systematically. The iodine activity which had reached to a value of 80 micro Ci/lt took almost about one full power year to come to a steady value below of 10 micro Ci/lt. NAPS-1 had a major fire incident in March 1993, and both units of NAPS remained shutdown for considerable period. The impact of the changes in fuel design and manufacturing has been experienced at these units, later on only after significant refuelling operations on their restart. At present, the fuel performance in these reactors has also converged to that in KAPS-2 and I-131 values of less than 5 micro Ci/lt are being maintained.

In Indian PHWRs thorium fuel bundles have been loaded in the initial reactor cores of KAPS-1&2. The performance of these bundles is quite satisfactory. In all 74 bundles have been irradiated. The thorium bundles have experienced a maximum burnup of 3146 n/Mb and a maximum bundle power of 433 KW.

7.0 CONCLUSIONS

The first charge of KAPS-2 reactor core was loaded with fuel manufactured with improved fuel design and manufacturing procedures. The updated reactor operating practices were followed from the initial days. Where as the earlier reactor cores were refuelled by the improved fuel during the course of the normal refuelling. Same operational guidelines have been implemented at these plants as well. All round improvements made in design, manufacture of the fuel and the operating guidelines followed at stations have resulted in improved fuel performance in all operating reactors and fuel failure rate is now steady at the value less than 0.1%.

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TABLE-1

PHWR OPERATION REACTORS

STATION	FIRST CRITICALITY	FPD*
RAPS-1	11-8-72	1898
RAPS-2	08-10-80	3203
MAPS-1	02-07-83	2418
MAPS-2	12-08-85	2048
NAPS-1	12-03-89	1033
NAPS-2	24-10-91	938
KAPS-1	03-09-92	762
KAPS-2	08-01-95	549
		12,849

* Full Power Days of reactor operation as on 31-3-97.

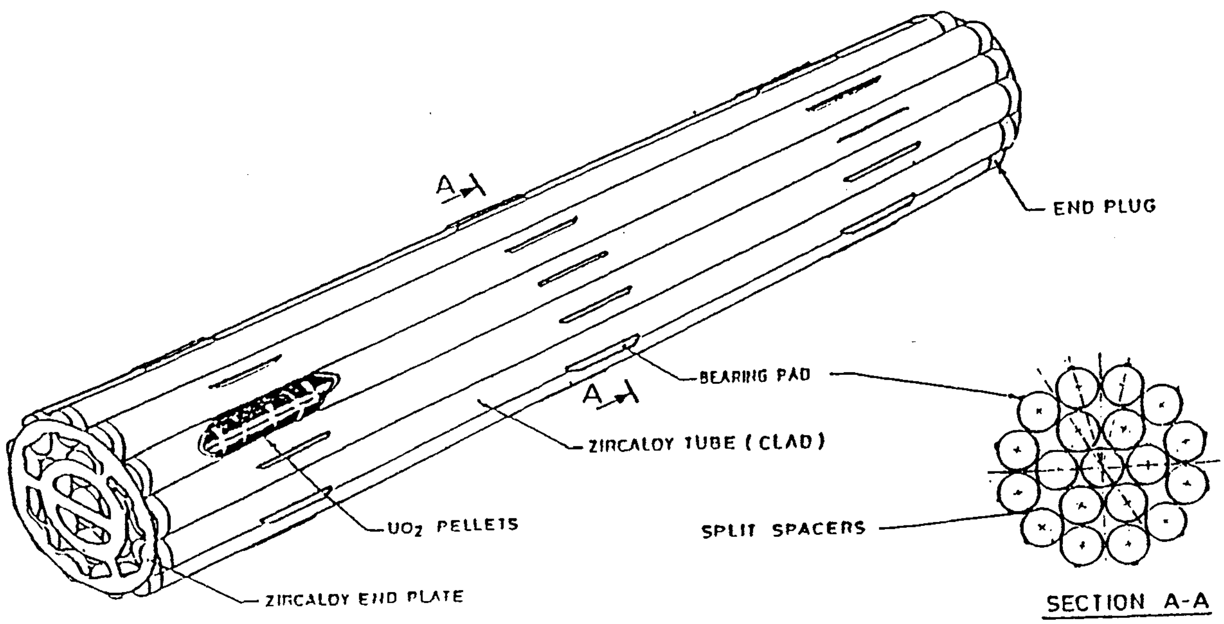

FIG. 1 NINETEEN ELEMENT FUEL BUNDLE

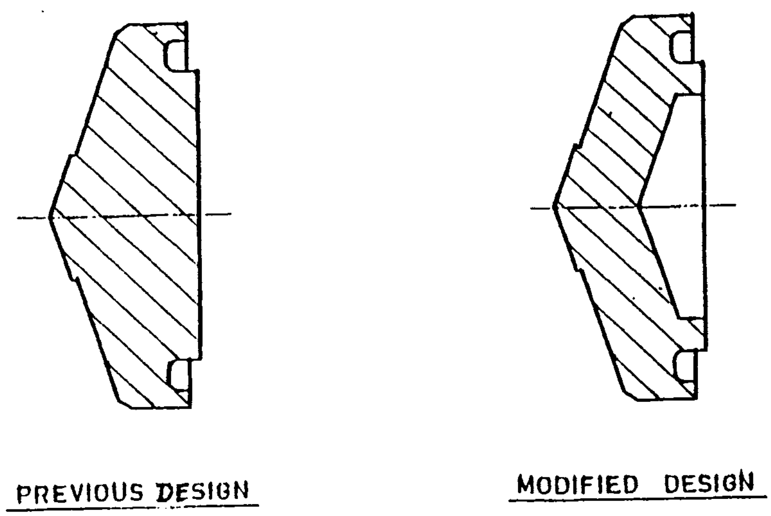

FIG. 2 END CAP

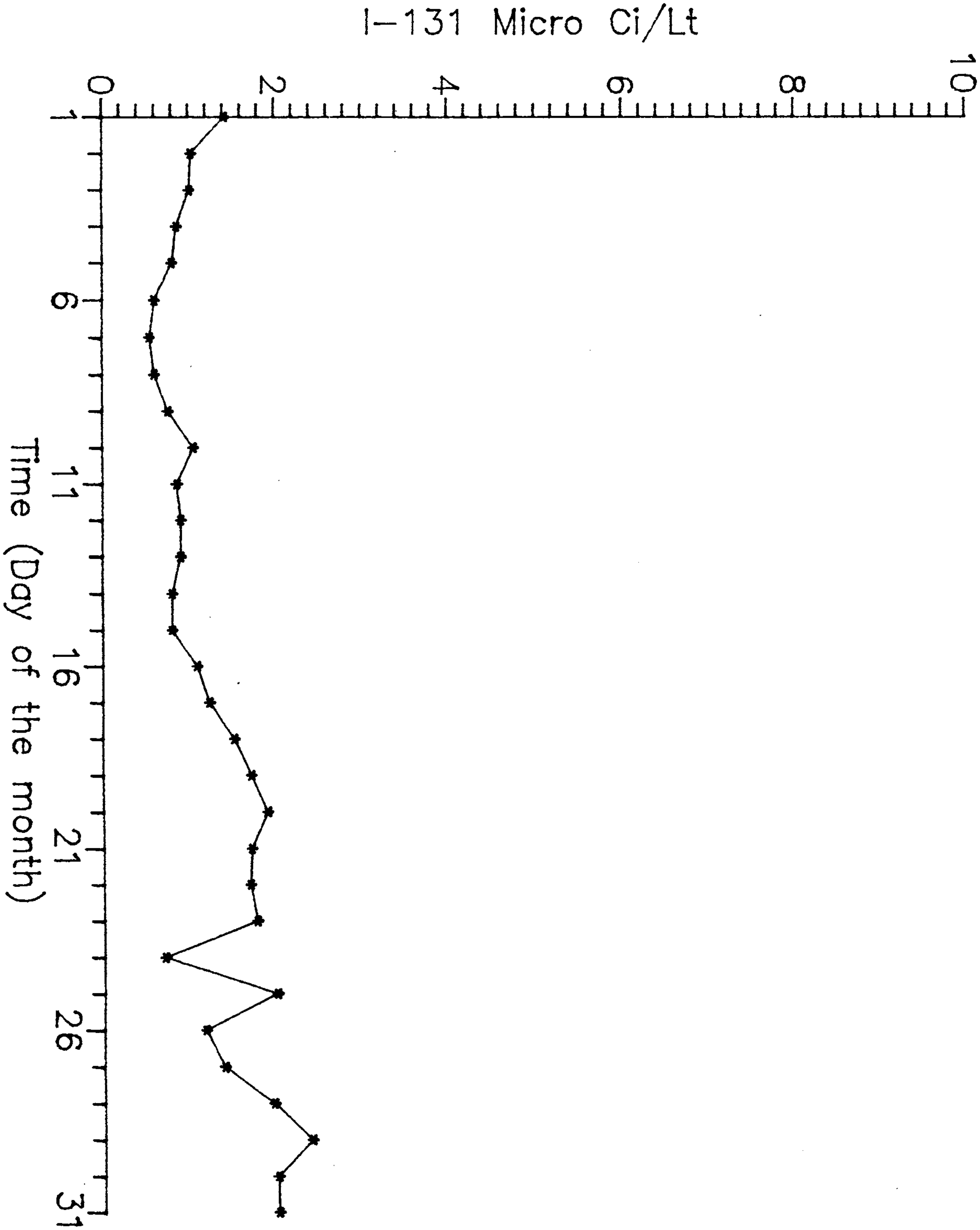

FIG.3 I-131 ACTIVITY IN COOLANT OF KAPS-2