Fuel technology evolution for Indian PHWRs

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ABSTRACT

Twelve units of 220 MWe PHWRs, one unit of 540 MWe PHWR and two units of 160 MWe BWRs are currently operating in India. Additional 3920 MWe capacity is under construction in form of 4 units of 220 MWe PHWRs, one unit of 540 MWe PHWR, two units of 1000MWe VVERs and one unit of 500 MWe FBR.

The fuel bundle being used for 220 MWe and 540 MWe Indian PHWRs are of 19-element and 37 element type respectively. The current 19-element split spacer design is evolved from the Canadian 19-element wire wrap spacer bundle. In the process of design evolution of PHWR fuel, India developed, 22-element natural U bundles, 19-element thorium bundles, and 19 element MOX bundles apart from the regular natural U bundles. These types of bundles were developed, fabricated and irradiated to fulfill the various needs of Indian nuclear power program.

The guiding philosophy for fuel technology evolution in India has been the optimum utilization of limited uranium resources to generate the fissile plutonium, which in turn, is to be used in fast reactors, along with the fertile thorium to generate the power as well as additional fissile material. This paper discusses, the different developmental activities carried out as part of fuel bundle design and manufacturing.

1.0 Introduction

Twelve units of 220 MWe PHWRs, one unit of 540 MWe PHWR, and two units of 160 MWe BWRs are currently operating in India. Additional 3900 MWe capacity is under construction in form of 4 units of 220 MWe PHWRs, one unit of 540 MWe PHWR, two units of 1000MWe VVERs and one unit of 500 MWe FBR. The Department of Atomic Energy (DAE) is having plans to increase the installed capacity further by adding PHWRs, Light Water Reactors (LWR) including VVERs, Fast Breeder Reactors and Advanced Heavy Water Reactor (AHWR).

For all 220 MWe reactors, 19-element split spacer fuel bundle design is used. This design is evolved from Canadian 19-element wire wrap fuel bundle. The design has been improved continuously based on the operation and fabrication feedback. Apart from 19-element fuel bundle, a 22-element fuel bundle was also designed, and developed for 220 MWe reactor. Subsequently bundles based on this design were test irradiated in NAPS reactor. For 540 MWe PHWR 37-element fuel bundle configuration has been selected, designed and out-of-pile testing has been completed. Use of short length fuel bundles and

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on power refueling in PHWRs provides flexibility to use variety of fuel loading patterns and different fuel types. Consequently, this permits optimum utilization of fuel and full power reactor operation all the time. Using this flexibility, alternative fuel concepts like depleted Uranium, mixed oxide and thorium bundle are tried and implemented based on requirements.

This paper brings out the fuel technology evolution of Indian PHWR fuel in terms of design, manufacturing, and fuel management improvements. It also describes the effects of above improvements on fuel performance and utilization in recent years. The alternative fuel concepts are also covered briefly.

2.0 Fuel bundle and related system description in PHWR

The 19 element fuel bundle has fuel elements arranged in a circular array of 1,6, and, 12 elements to form the assembly held together by end plates resistance welded at the two ends of the elements (shown in fig-1). Each fuel element consists of natural uranium oxide sintered pellets loaded inside graphite-coated tubes, with a diameter of 15.2 mm and thickness of 0.4 mm. The tubes are closed by resistance welded end caps at both the ends. The assembled bundle has an overall length of 500mm and diameter of 82 mm. In 220 MWe PHWR such twelve bundles are located in each of the 306 channels in the calandria which forms the reactor core. Comparison of 37 element and 19 element bundle fabrication data is given in table-2.

The On-power bi-directional fuelling is performed on the channels by latching two fuelling machines on to the end fittings at each end of the coolant channel. Eight bundle fuelling scheme is adopted for fuelling operating in both 220 MWe and 540 MWe reactors. Over a sequence of fuelling operation, a pair of fresh fuel bundles is loaded on upstream side of the channel and simultaneously irradiated pair of spent fuel is discharged into the down stream fuelling machine. Spent fuel bundles are then sent to the spent fuel bay through a fuel transport system.

3.0 Salient design features of PHWR fuel

The fuel bundle for PHWRs is designed to reside in any of the position in the core in any channel and produce required power. The bundle is designed for maximum content of fissile material and minimum content of parasitic absorption material, especially in view of use of natural uranium as fuel material. During the fuel bundle residence period in core, the bundle has to be compatible with coolant system and fuel handling system. Fuel bundle operating details are given in Table-1.

Element of 220 MWe fuel bundle is designed [Ref.1] to operate at Linear Heat Ratings (LHR) of 57.5 kW/m and to a burnup of 15000 MWD/TeU, without any specific plenum volume. LHR of 57.5 kW/m is higher as compared to that of BWR and PWR fuel, hence fuel temperature in PHWR is generally higher as compared to that of BWR and PWR. That leads to higher fission gas release rate to fuel-clad gap, however lesser burnup leads to lower gas pressure in fuel element.

PHWR fuel bundle structural components consist of cladding, end plugs, spacers, bearing pads and end plates. The selection for cladding material is governed by coolant conditions and the fuel bundle service life. Required corrosion and hydriding characteristics and mechanical properties are derived based on these service conditions. Material selected for these components in PHWR fuel is Zircaloy-4, due to its low neutron absorption, and good hydriding and corrosion resistance along with adequate structural strength. To take care of high neutron economy requirement in PHWR, cladding is quite thin and therefore is of collapsible type. For such a cladding the parameters namely the yield strength, ductility, thickness and pellet sheath diametrical clearance are optimized to avoid permanent collapse of clad at the beginning of life and also to retain enough ductility at the end of life. Spacers and bearing pads maintain the inter element and element to coolant channel gap. The element with sheath and end cap forms the barrier against release of radioactive fission products to the coolant.

The PHWR fuel pellet is designed for high density (96 -98%) for increasing the natural uranium content in the element and providing support to the collapsible clad. The pellet shape and size with respect to sheath ID is also specific due the same reason. The pellet sheath diametrical clearance, the pellet surface defects are controlled in a narrow range.

4.0 Improvements for 220 MWe fuel

Fuel bundle fabrication has been evolving over the years resulting in many improvements and consequent improved fuel performance in the reactors. Fuel material and component specifications have also been revised from time to time based on the operation and manufacturing feedback. The overall review and reissue of the specifications have been carried out as and when required. Some salient activities in this regard are:

4.1 Wire wrap to split spacer design [Ref.2]

The 19-element wire wrapped fuel bundle design was replaced by the present spacer pad design to overcome the concern of clad fretting damage by wire wrap. This also led to decrease in zircaloy inventory by 8-9% and subsequent burnup gain of about 60 MWD/TeU.

4.2 Graphitized fuel bundle [Ref.2]

The inside surface of the fuel sheath is coated with around 5 micron thick layer of graphite which acts as a barrier to the chemical attack of zircaloy sheath by fission product iodine which otherwise can result into stress corrosion cracking of highly stressed sheath during a fuel power ramp. The learning experience in this regard was NAPS-1 incidence, during 1992 in which 25% power ramp resulted in 28 suspected failed bundles. These all bundles were found to be non-graphitized bundles loaded prior to 1990. After implementation of graphite technology, fuel failures due to power ramp have not been reported.

4.3 Modified scooped end cap [Ref.2]

A central conical portion has been scooped from the end cap, which otherwise was flat surface in the original design. This modification avoids the high temperature gradient in the end cap due to contact between central surfaces of the high temperature pellet and end cap surface. 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. This modification also reduces the zircaloy content by about 25 gms per bundle, resulting in burnup increase by about 20 MWD/TeU [Ref.3].

4.4 Chamfered and double dished pellet

The double dish pellet design leads to improved pellet recovery during fabrication, facilitates automation of pellet stacking and improves fuel performance by decreasing the clad strain. The chamfered pellets also result in decreased clad strain and improved pellet recovery.

4.5 Curved bearing pads

Presently the bearing pads are punched and coined with top surface flat, then they are welded on to the element and then the bearing pad top surface is machined to suit coolant tube radius. It is now planned to coin the bearing pads to the required size and curvature, and then weld on to the tubes. This will eliminate the bur milling operation and sharp corners at edges.

4.6 Empty tube welding

The bearing pads and spacer pads are first resistance-welded on the zircaloy-4 fuel cladding tube. Next, the inner surface of the tube is coated with approximately 6 micron of graphite after which the uranium oxide pellets are loaded and encapsulated. This manufacturing path will avoid the possibility of pellet chipping during appendage welding.

5.0 Fuel material other than natural-U in PHWR fuel bundle

5.1 MOX-7 bundle

It is proposed to load MOX fuel in one of the operating PHWRs. For this purpose, MOX-7 bundle design will be adopted, which is same as 19-element cluster being used in 220 MWe reactor, with inner seven natural UO_2 elements having additional 0.4 wt % Plutonium as fissile material [Ref.4]. Large-scale utilization of such bundles leads to substantial savings in the usage of natural uranium bundles. An optimized loading pattern and refuelling scheme has been evolved, such that reactor can be operated at full power, without crossing permissible limit on bundle power and channel outlet temperature. Worth of the shutdown systems come down marginally, but enough sub-criticality margins exist for all normal shutdowns and anticipated accidental scenarios. Relevant reactor physics parameters for this type of core have been evaluated [Ref.5].

Core average discharge burnup will to 9000 MWD/TeHE, subsequently fuelling rate will come down from 9 bundles / FPD in the case of Natural Uranium core to 7 bundles/FPD in the proposed MOX-7 / Natural Uranium core.

The fuel bundle drawings and fabrication specifications have been prepared for MOX fuel. For initial trial irradiation, 50 number of MOX-7 bundles have been fabricated. Special bundle transport package and storage racks have been developed such that criticality accidents do not occur. These bundles were loaded in the KAPS-1 reactor in different locations. Some of the bundles have been reshuffled to see their power ramp performance. The first four bundles, after 16 months of irradiation with a burnup of 11000 MWD/TeHE, have been discharged recently as part of normal refuelling.

5.2 Thorium Bundles

Currently, in the 220 MWe PHWRs, 35 THO_2 bundles have been used for flux flattening in the initial core, such that the reactor can be operated at rated full power without exceeding specified channel power and bundle power limits. The locations of these bundles were such that in addition to flux flattening, the worth of the shutdown systems was also unaffected. This loading was successfully demonstrated in KAPS-1 and subsequently adopted in the initial cores of KAPS-2, KAIGA-1 & 2 and RAPP 3&4. So far more than 232 THO_2bundles have been successfully irradiated in different reactors. The maximum fuel bundle power and burnups seen are 408 kW and 13000 MWd/TeTh respectively.

Manufacturing and irradiation experience of thorium bundles are also crucial baby steps towards bigger aim of thorium utilization in Indian nuclear power program.

6.0 37-element Fuel Bundle for TAPP-3&4 540 MWe PHWR

For 540 MWe PHWR TAPP-3&4 units, fuel bundle design chosen is that of 37-element fuel bundle type, with element diameter of 13.1mm. This design has been evolved from 19-element and 22-element fuel bundle types. The fuel bundle design has been evaluated by theoretical analysis using computer code FUDA MODE-2[Ref.6]. As a part of acceptance of new fuel design, a number of specific tests were conducted, to satisfy requirements like wear, fretting, strength, impact strength, fuelling machine compatibility, pressure drop, sub-channel flow behavior, vibration and in-pile performance etc. The tests include evaluation of fundamental material properties, development tests, semi-prototype tests in which major influencing parameters are simulated and prototype tests in which reactor conditions are simulated. From the parametric data obtained from the prototype tests, variation of the parameter in reactor conditions is derived. In addition, results of tests conducted on 19-element fuel bundle and their performance in reactors are also utilized to qualify the present design. The fuel bundle fabrication and operation specifications are derived based on this.

Irradiation experience of similar size elements as that of 37-element bundle was already available from the successful irradiation experience of 22-element fuel bundles in 220 MWe rector. Outer ring of this bundle consists of 13.1 mm diameter elements (Fig-2).

The initial charge fuel of 37-element fuel bundles, for TAPP-4 reactor was fabricated by Nuclear Fuel Complex, Hyderabad. TAPS-4 went critical in march-2005 with the above fuel charge.

7.0 High Burnup Fuel Development

Indian nuclear power program is guided by the limited available natural uranium and the vast amount thorium resources available. Therefore the fuel design, development and fuel utilization are planned accordingly and fuel bundle design using thorium and mixed oxide fuel materials which can be irradiated to burnups of 20000 to 50000 MWD/TeHE are being developed. The fuel bundle design in use at present is limited to irradiation up to 15000 MWD/TeU burnup.

7.1 Design Studies:

The fuel element design analysis has been carried out using Fuel Design Analysis code FUDA MODE0-2 to check the limiting parameters at higher burnups like fission gas release, internal gas pressures, plenum volume requirements etc,. The studies indicated that, present fuel design is suitable up-to 20000 MWD/TeU with minor modifications like use of higher grain size, more dish depth etc. For burnups beyond that, either annular pellets or the earlier developed 22-element fuel bundle [Ref.7], shown in Figure-2 is being considered. The fuel materials, which are being considered for use, are MOX and Thorium [Ref.8]. The optimized zircaloy with low Tin and higher Iron content are being investigated by R&D Units for this purpose [Ref.9].

7.2 Fuel Bundle Irradiation to High Burnup:

To investigate fuel behavior at high burnup with regard to fission gas release, fuel swelling and sheath material behavior, fuel bundle integrity and power ramp performance, it was decided to irradiate few present natural uranium bundles to higher burnups. For this purpose natural uranium bundles in two channels (H-13 and O-08 of KAPS-2 core) were selected and irradiated up-to a discharge burnup of 20000 MWD/TeU. Bundles in these channels were irradiated to about 1100 FPD, which is about 35% more as compared to normal irradiation time. Performance of these channels was assessed by Delayed Neutron Monitoring (DNM) system and by comparing the measured Channel Outlet Temperature (COT) with the estimated values. The variation of DN counts of these channels during operation and refueling ,indicated successful performance of the fuel bundles. Fourteen fuel bundles of these two channels have seen burnups more than 15000 MWd/TeU the maximum being 22300 MWD/TeU.

8.0 Improved fuel utilization by new fuel management concepts

In last few years number of actions has been taken to improve the fuel bundle utilization in the operating PHWRs. A decision has been taken to operate the reactor with minimum load (negative reactivity worth) of adjusters i.e. by keeping the devices out of core as far as possible. The axial fuel bundle reshuffling is also further optimized for increasing fuel burnup. The moderator purity also has been improved. All the schemes have contributed in increasing the fuel discharge burnup. The discharge burnup of all the reactors have increased in the last 3 years.

9.0 Fuel Performance

In India the performance of Nuclear Power Plants has continuously improved over the years[Ref.10]. So far, more than 70 full power (FP) years of PHWR operation and 40 FP years of BWR operational experience has been accumulated.

Till date, more than 2, 80,000 fuel bundles have been irradiated in the 12 PHWRs. 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 from 6300 to around 7500 MWD/TeU in the last 3 year.

Fuel Performance can be gauged by the fuel failure rate and also by the iodine activities in the coolant. Close monitoring of the Iodine activity in coolant system is done routinely in operating stations. 10 micro Ci/litre of I-131 is adopted as operational alert level for the reactors. The iodine activities in coolant circuits are usually less than 5 micro Ci/litre.

The fuel failure rate has been in the range of 1 bundle per 1000 bundles discharged. Efforts are underway to bring down further the fuel failures. The fuel failures are random in nature as seen by the operational history of suspected / failed bundle burnup and power.

10.0 Conclusion

Fuel technology evolution in Indian PHWRs is guided by the principle of optimum utilization of limited uranium resources and vast resources of thorium to generate the power as well as additional fissile material. The short term goals of improved fuel performance and utilization arise out of above principle have been met with success, due to continuously evolving design, manufacturing and management of fuel. In addition, Indian PHWR program has also achieved some important objectives towards the long-term goals of thorium utilization.

11.0 References

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Table-1: Operating condition for 220 MWe PHWR fuel

Maximum Linear Heat Rate	57.5 kw/m
Burnup	15000MWD/TeU
Fuel Centre Temperature	2100^{O} C
Sheath Temperature	320^{O} C
Coolant Temperature	$260\text{-}304^{O}$ C
Coolant Pressure	105 Kg/cm^2
Coolant PH	10-10.5
Coolant Velocity	9.3 m/sec.
Bundle Residence Period	200-750 days
Axial Loads on Bundle	650 Kg
Total Bundle Sliding movement in reactor	45.7 m

Table-2: 19-Element and 37-Element Fuel Bundle Details

DETAILS	**220 MWe**	**540 MWe**
Fuel	pressed and sintered natural UO_2 pellets	pressed and sintered natural UO_2 pellets
No of fuel elements	19	37
Clad and other structural Material	Zircaloy-4	Zircaloy-4
Outside clad Diameter (mm)	15.2	13.1
Clad thickness, mm	0.38	0.38
Fuel clad Diametral clearance(mm)	0.09(ave)	0.09(ave)
End-caps to sheath weld	Resistance Welded	Resistance Welded
Bearing pads to sheath weld	Spot Weld	Spot Weld
Spacer pads to sheath weld	Spot Weld	Spot Weld
Weight of Zircaloy per bundle Kg	1.4	2.2
Quantity of Fuel Bundles In Reactor	3672	5096

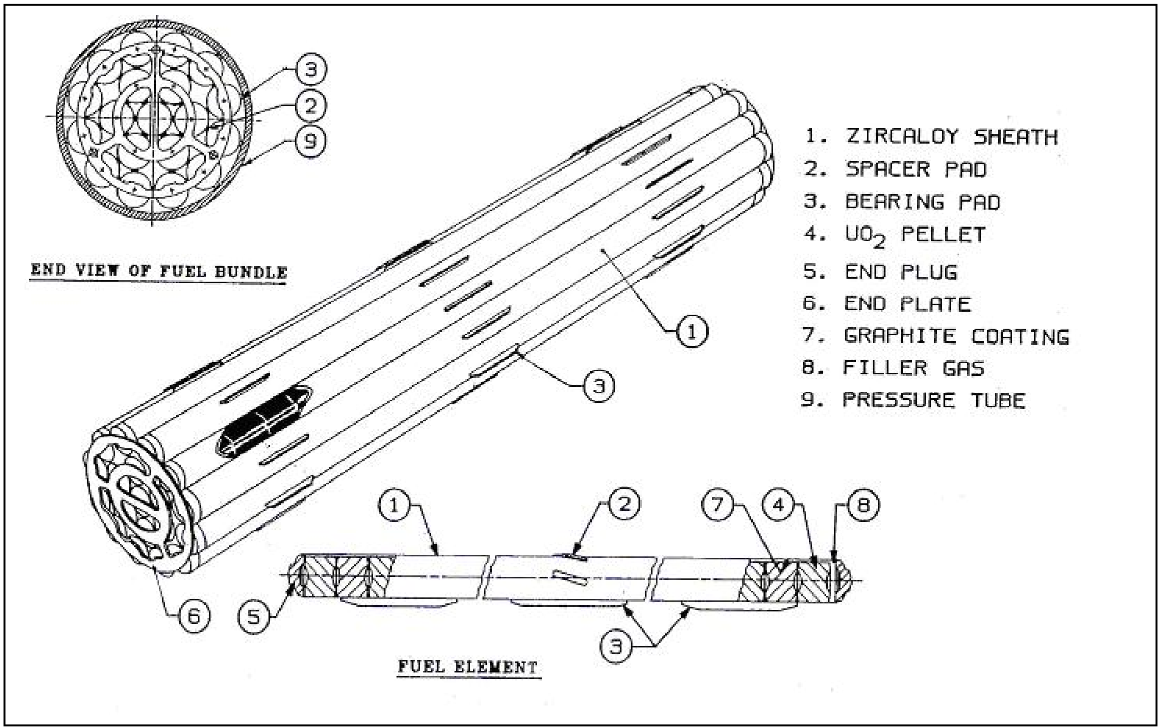

Fig-1: 19-element fuel bundle

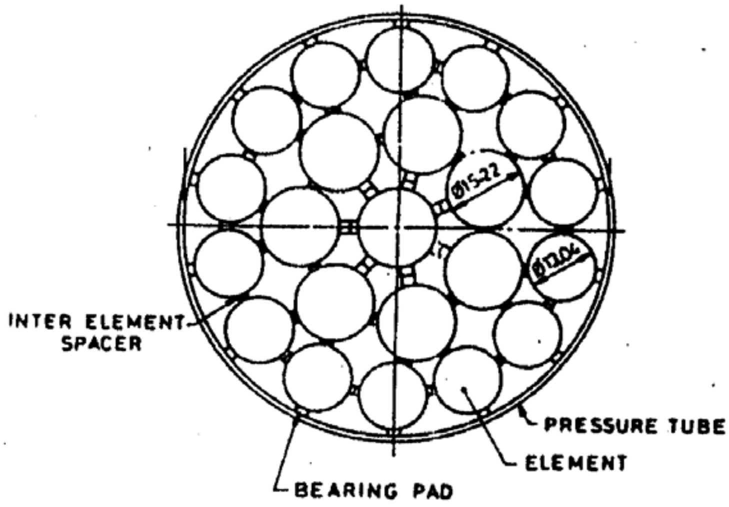

Fig-2: Cross section of 22-element fuel bundle