Manufacture Of Fuel & Fuel Channels And Their Performance In Indian PHWRS – An Overview

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Abstract

Nuclear Fuel Complex (NFC) at Hyderabad is a conglomeration of chemical, metallurgical and mechanical plants, processing uranium and zirconium in two separate streams and culminating in the fuel assembly plant. Apart from manufacturing fuel for Pressurised Heavy Water Reactors (PHWRs) and Boiling Water Reactors (BWRs), NFC is also engaged in the manufacture of reactor core structurals for these reactors.

NFC has carried out several technological developments over the years and implemented them for the manufacture of fuel, calandria tubes and pressure tubes for PHWRs. Keeping in pace with the Nuclear Power Programme envisaged by the Department of Atomic Energy, NFC had augmented its production capacities in all these areas.

The paper highlights several actions initiated in the areas of fuel design, fuel manufacturing, manufacturing of zirconium alloy core structurals, fuel clad tubes & components and their performance in Indian PHWRs.

Introduction

Nuclear Fuel Complex (NFC) at Hyderabad, India is an industrial facility of the Department of Atomic Energy for manufacture of fuel assemblies and core structurals for all the power reactors in the country. Uranium and Zirconium are processed in two separate streams of plants engaged in chemical, metallurgical and mechanical operations and finally culminating in PHWR fuel assembly plant. The production capacities of various plants have been significantly enhanced to meet the increased fuel demand for the growth of nuclear power generation programme in India. Several technological developments carried out in production processes have resulted in improved quality of the fuel and productivity of the plants at NFC. Backed by more than three decades of fuel manufacturing experience at NFC, fuel for the first 540 MWe PHWR at Tarapur has been successfully manufactured and supplied.

In the areas of reactor core structurals too, NFC has developed unique technology for the manufacture of large diameter thin – wall calandria tubes through seamless route instead of conventional welded route. Likewise, several process improvements have been carried out for the manufacture of Zr – 2.5% Nb pressure tubes and zirconium alloy clad tubes & components resulting in improved quality.

With continual improvements in production processes coupled with strict quality assurance system in place at NFC, the performance of fuel and fuel channels in the reactors has been quite satisfactory.

The subsequent sections of the paper highlight the improvements made in the manufacture of fuel and fuel channels for PHWRs.

Nuclear Power Generation in India :

Presently, 12 PHWRs and 2 BWRs are in commercial operation in India with a total installed capacity of 2720 MWe. Two of these units viz. RAPS-II at Rajasthan and MAPS-II at Kalpakkam are operating successfully after en-masse coolant channel replacement. The first of the higher capacity 540 MWe PHWR units at Tarapur (TAPP–IV) has been successfully commissioned in March, 2005. Construction of the second 540 MWe PHWR unit at Tarapur (TAPP-III) and four additional PHWR 220 units at Kaiga (KAIGA – III & IV) and Rawatbhatta (RAPP – V & VI) is progressing well. These units which are in various stages of construction are expected to go into commercial operation during the next couple of years. Kakrapar-I surpassed record of 272 days of uninterrupted operation on June 15, 2005. Table 1 summarizes the nuclear power programme in India based on PHWRs.

TABLE 1 : NUCLEAR POWER PROGRAMME BASED ON PHWRs

PLANT	RE-RATED CAPACITY	COMMERCIAL OPERATION SINCE
PLANTS UNDER OPERATION		
RAPS - 1	1 x 100 MWe	December 16, 1973
RAPS – 2	1 x 200 MWe	April 01, 1981
MAPS – 1	1 x 220 MWe	January 27, 1984
MAPS – 2	1x 220 MWe	March 21, 1986 (Uprated to 220 MWe)
NAPS – 1 & 2	2 x 220 MWe	January 01, 1991 and July 01, 1992
KAPS – 1 & 2	2 x 220 MWe	May 06, 1993 and Sept 01, 1995
KAIGA – 2	1 x 220 MWe	March 16, 2000
RAPS – 3	1 x 220 MWe	June 01, 2000
KAIGA – 1	1 x 220 MWe	November 16, 2000
RAPS – 4	1 x 220 MWe	December 23, 2000
TAP – 4	1 x 540 MWe	Became critical in March 2005
SUB TOTAL	**3040 MWe**	

PLANTS UNDER CONSTRUCTION		
TAP – 3	1 X 540 MWe	
KAIGA – 3 & 4	2 X 220 MWe	
RAPP – 5 & 6	2 X 220 MWe	
SUB TOTAL	**1420 MWe**	
TOTAL	**4460 MWe**	

The performance of the Indian Nuclear Power Plants has been continuously improving over the years. So far, 70 full power (FP) years of PHWRs and 40 FP years of BWRs have been clocked.

3.0 PHWR fuel production in India:

3.1 Fuel manufacturing activities at NFC:

Keeping pace with the nuclear power generation profile as projected by Nuclear Power Corporation of India Ltd (NPCIL) and the consequent increase in the requirement of yellow cake, the mining and milling activities have been intensified by Uranium Corporation of India Ltd (UCIL). Likewise, the production capacities of various plants at NFC have also been significantly enhanced to ensure the supply of required quantities of fuel in time.

High density natural uranium dioxide pellets are required as fuel for PHWRs. The as -received magnesium diuranate (MDU) concentrate from UCIL is processed by dissolution in nitric acid, purification by solvent extraction using Tributyl Phosphate and precipitation of ammonium di-uranate (ADU) by ammonium hydroxide. ADU is subjected to controlled calcination, hydrogen-reduction and stabilization treatments to obtain sinterable grade UO_2 powder. High density UO_2 pellets are manufactured through classical "powder-pellet" route involving granulation of fine UO_2 powder, pelletisation, high temperature sintering in pusher-type continuous sintering furnace in reducing atmosphere and centreless grinding. The ground pellets are subjected to quality control checks and the accepted UO_2 pellets are encapsulated in zirconium alloy-4 clad tubes which are finally assembled in the form of 19-element or 37-element fuel bundles for PHWR-220 and PHWR-540 units respectively.

NFC has been expanding its fuel production capacities over the years to meet the continuously increasing fuel demand. The cumulative production of PHWR fuel bundles manufactured at NFC since its inception is given in Figure 1 below:

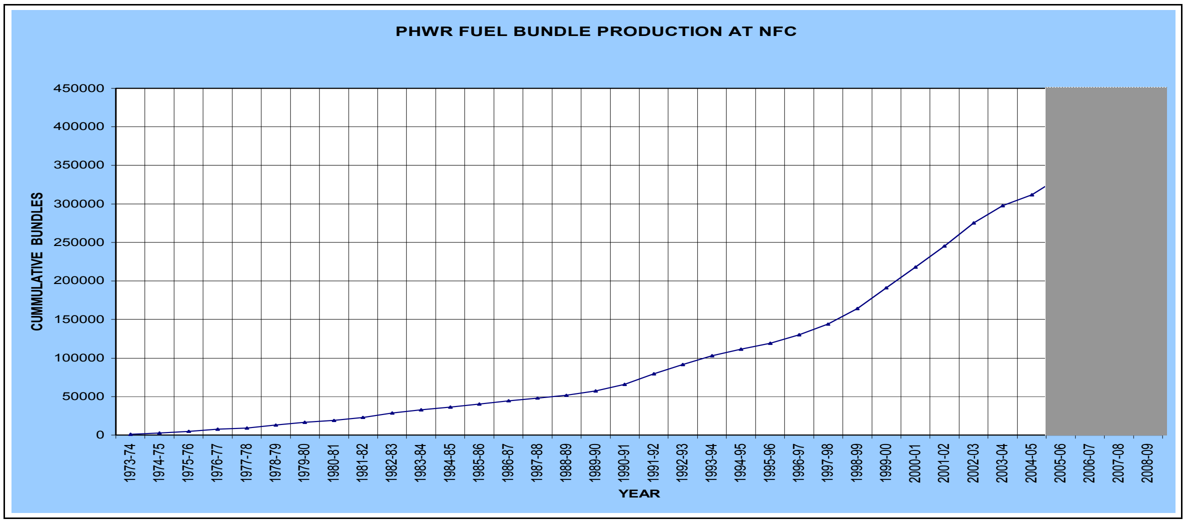

FIG. 1: CUMULATIVE PRODUCTION OF PHWR FUEL BUNDLES AT NFC

During the year 2004, NFC has crossed yet another milestone of manufacturing 300,000 PHWR fuel bundles which include natural uranium dioxide, depleted uranium dioxide and thoria as fuel. While the depleted uranium dioxide and thoria bundles have been used mostly for neutron flux flattening of the initial core of PHWRs during start up, the depleted uranium dioxide bundles are also envisaged to be used in equilibrium cores of PHWRs that enables closing of the fuel cycle and also conserving natural uranium resources.

3.2 Fabrication of fuel for PHWR 540 units :

Process flow sheets for manufacture of smaller dia UO_2 pellets, smaller dia clad tubes, appendage welding and assembly required for the first 540 MWe PHWR at Tarapur were standardized incorporating necessary quality checks at various stages of fuel manufacturing. More than 5000 nos of 37-element fuel bundles were successfully manufactured and supplied towards the initial core requirement of TAPP-IV which was commissioned during March, 2005. The in-reactor performance of these bundles during this period is reported to be quite satisfactory by which NFC has been accredited for manufacturing of new type of fuel “Right First Time”.

FIG 2: 37-ELEMENT FUEL BUNDLES FOR 540 MWe PHWRs

Compared to 19-element fuel bundle, 37-element fuel bundle has more types of elements and requires more number of precision components. Several innovative techniques, as detailed below, were adopted while manufacturing fuel for 540 MWe PHWR.

a) A noteworthy feature of these bundles is that the spacer pads and bearing pads are resistance welded on to the fuel tubes prior to loading of UO_2 pellets. This operation of attaching appendages by resistance welding is unique to India and has the distinct advantage of maintaining the integrity of the pellets during fuel bundle assembly. This process is also advantageous in that it allows easy retrieval of the pellets from rejected pins, if any, thus improving the recovery.

b) The pelletisation operations were standardized for the production of UO_2 pellets having double dish and chamfer on both edges, which were used for manufacturing fuel bundles required for initial charge of TAPP-IV. These pellets are expected to minimize “pellet-clad mechanical interaction” thus improving the performance of fuel in the reactor.

3.3 Improvements in production processes :

A number of technological innovations were carried out in the production of UO_2 powder, pelletisation and assembly operations. In the UO_2 powder production process, Uranyl Nitrate Raffinite (UNR) is a liquid effluent generated in the purification steps which contains valuable residual uranium. A new process was developed that results in avoidance of UNRC generation, which is demonstrated successfully at plant scale. After optimization of design parameters in consultation with fuel design group, regular production of UO_2 pellets, having double dish and chamfer on both edges, was carried out both for 19-element and 37-element fuel bundles. Likewise, in the fuel assembly manufacturing lines one of the most important development works carried out and implemented on industrial scale production is the introduction of curved bearing pads. As against the conventional bearing pads, these pads do not require milling operation to be carried out for achieving the required radius on the outer profile. All the 37-element fuel bundles manufactured for the initial core of TAPP-IV contained these curved bearing pads.

Quality Assurance :

Quality Management System and QA Programme at NFC have been effectively synchronized to meet the enhanced production targets. Several innovative techniques adopted in different streams of fuel production have resulted in the manufacture of 37-element fuel bundles of high quality.

Increased number of components and welds meant enhanced defect opportunities, hence emphasis was laid on capability studies for new process and development of inspection equipment. Hence Quality Assurance Systems for 37-element fuel manufacturing had to be redesigned.

In order to ameliorate operator fatigue while handling 37 element fuel bundle during dimensional check, helium leak testing and final visual inspection, material handling system based on zero gravity air balancers have been indigenously developed and put into use. Machine Vision System for inspection of fuel tube inner surface after appendage welding was developed for checking the weld defects. An accepting sampling was evolved and templates were made to facilitate random selection of pellets. Testing methods and procedures were finalised to suit the needs of new process flow sheet. Integration of process control with systematic inspection has resulted in obtaining Cp value more than 1.67.

Ultrasonic test results of end-closure welds showed the defect echo less than the specified limit of 70%. UO_2 content was also maintained above the specification limit. On-site inspections like helium leak testing on sampling basis, kinked tube and visual check on 100% basis by the customer revealed no defects.

Many advances were made in eddy current and ultrasonic evaluation to meet the stringent quality control requirement and locate the micro flaws for manufacturing of fuel clad tubing and bar for end caps. Special defect standards were developed to identify and eliminate micro-flaws and thereby ensure consistent quality product.

Ultrasonic Testing equipment for evaluating quality of fuel tubes was successfully developed indigenously and put into regular use on the shop floor.

Development of special purpose equipment :

Several special purpose equipment for welding of spacer pads and bearing pads have been successfully designed and developed at NFC, which are employed for the fabrication of 37-element fuel bundles. An Integrated Spacer and Bearing-pad Welding machine, developed for welding the appendages on empty fuel tubes, has special features like capability to weld both spacer pads and bearing pads for all the five types of fuel elements; replacable magazines for all the appendages; integrated tube loading-and-unloading system for ease of operation; automatic selection of the optimum welding parameters for the two spacer pads and bearing pads of different thickness and provision of a ‘weld sentry’ for ‘on-line’ assessment of the quality of welds. In addition, equipment like appendage weld-strength testing units, graphite coating units and baking furnaces were also designed and developed at NFC.

Several other critical process equipment were indigenously developed with the help of Indian industry which include end cap welding machine, fuel tube/fuel element machining centers, fuel element degreasing/cleaning stations, centreless grinding machines for UO_2 pellets and final assembly & end plate welding machine. In addition, high temperature sintering furnace having advanced features like automatic charging/discharging of charge carriers, data acquisition systems and controls through SCADA was also indigenously built and put into regular operation.

FIG 3: INTEGRATED SPACER AND BEARING PAD WELDING MACHINE

Manufacture of reactor core structurals :

6.1 Calandria Tubes :

During the last couple of years, NFC has put in a lot of developmental efforts that has resulted in standardizing manufacture of thin-wall calandria tubes through seamless route for the first time in the world. The zirconium alloy-4 calandria tubes for 540 MWe PHWR, though of larger diameter as compared to the one for 220 MWe PHWR, were successfully manufactured through this innovative route. Unlike the calandria tubes produced through the conventional welding route, these seamless calandria tubes have uniform micro-structure, homogeneous mechanical properties, negligible residual stresses, favourable texture and superior dimensional stability. This apart, fewer production steps, higher productivity and better recovery are the other distinct advantages of this route.

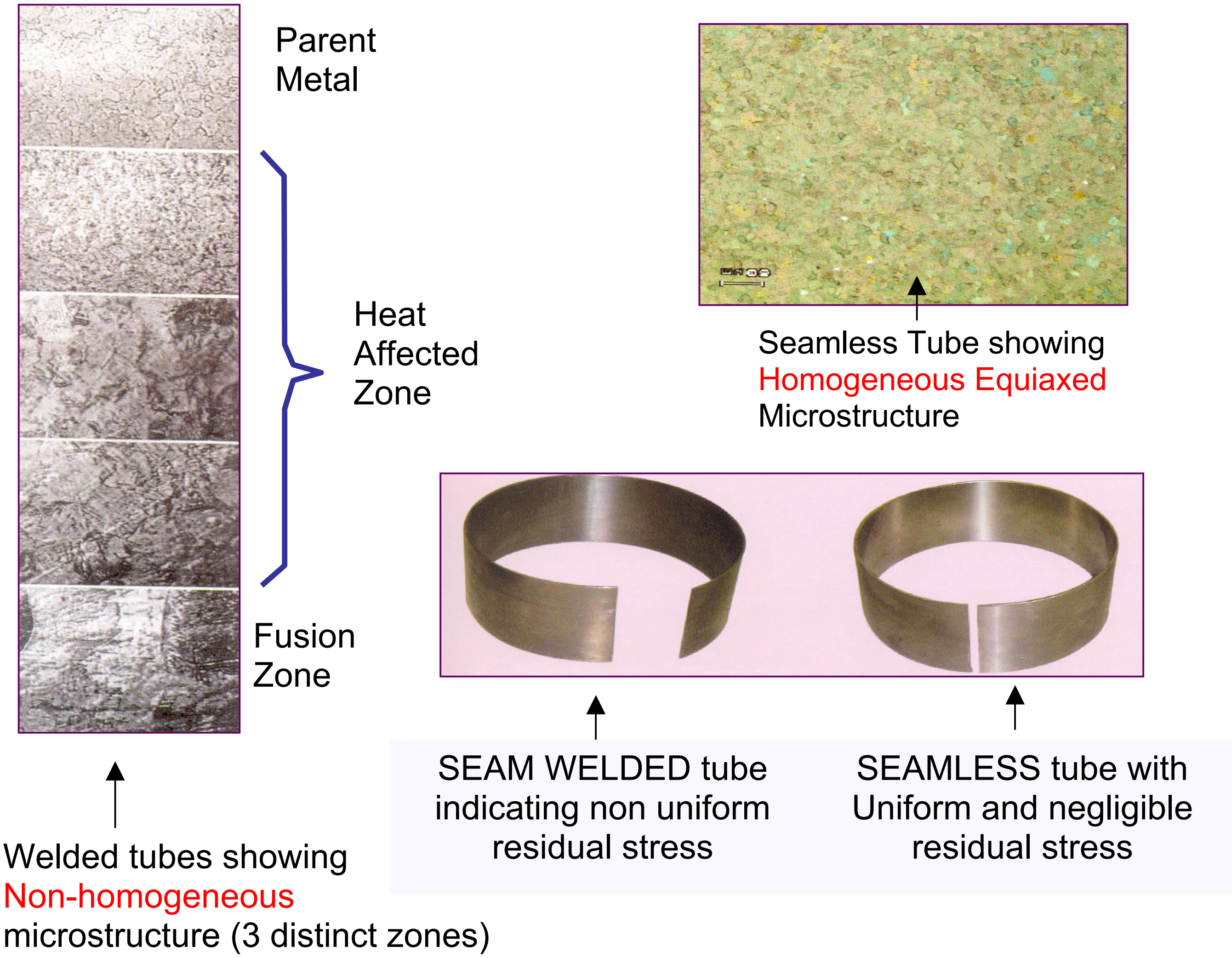

Fig 3 : Comparison of seam welded and seamless calandria tubes

6.2 Coolant Tubes :

Similarly, full core of Zr-2.5% Nb pressure tubes required for PHWR 540 units (TAPP-IV) were also successfully manufactured and supplied. These pressure tubes are produced through the process route of multiple vacuum arc melting followed by extrusion and two-pass pilgering. Quadruple melted Zr-2.5% Nb alloy ingots are expanded, beta-quenched and extruded to suitable blanks. The concentration of gaseous impurities is reduced to extremely low values due to quadruple melting (maximum of hydrogen – 5 ppm ; phosphorous – 10 ppm; chlorine 0.5 ppm and carbon 125 ppm). The fracture toughness of the tubes is more than doubled due to the control of chemical composition as a result of multiple vacuum arc melting. The fabrication process has been designed to eliminate pick-up of hydrogen during manufacturing.

The extruded blanks are finished in two cold pilger passes. The adoption of Pilgering process enabled control of texture in the finished product. The dislocation density was also closely controlled. Large reduction is employed in the initial breakdown pass to improve homogeneity and dimensional tolerances. The final pass is designed with high Q-factor and 20-25% cold work. These large size coolant tubes meant for PHWR 540 units were manufactured for the first time meeting all the stringent specifications in terms of mechanical properties and dimensional tolerances. A very high recovery of about 98% by numbers was achieved.

6.3 Reactivity and shut-off devices :

Assemblies for reactivity and shut-off mechanisms for the PHWR 540 units are more complicated than PHWR 220 units, both from design and fabrication point of view. A variety of assemblies, totaling 95 include horizontal and vertical flux units , liquid zone control, liquid poison injection tube and guide tubes consisting of adjusted rod, shut-off rod and control rod assemblies. After freezing the design aspects in consultation with the design group of NPCIL, NFC took up fabricability studies, manufacture, mock-up testing and finally supply of these intricate assemblies. High level of accuracy in manufacturing and assembling in a length of 13 m was needed to achieve zero leaks. All the welds were subjected to radiography and helium leak testing to ensure integrity.

Zirconium Alloy Fuel Cladding and components:

Quality of Zirconium Alloy Fuel Cladding and components has a direct bearing on the performance of fuel bundles. Many sophisticated and intricate processes such as vacuum arc melting, extrusion, hot working and cold working process with intermediate annealing are employed in the production of zirconium alloy fuel cladding and components. Emphasis was laid for achieving high recoveries at minimum cost.

NFC has developed necessary expertise and sophisticated manufacturing facility to meet the stringent specifications imposed by the customer in the production of zirconium alloy fuel cladding. Several creative and innovative processes were adopted particularly in the fabrication of spacers for 37 element fuel bundles. The spacers were produced through the wire route and subsequently parting them into tiny spacers which is entirely different from the conventional route of fabricating the sheets followed by blanking and coining. While manufacturing bars for end caps, specifications and testing procedures were tightened at various stages of production starting from melting of ingots and subsequent extrusion and swaging.

Fuel performance:

The fuel performance in Indian reactors has progressively improved over the years. So far, more than 280,000 fuel bundles have been irradiated and discharged from the 12 PHWRs. Efforts have been put to improve the fuel bundle utilization by increasing the fuel discharge burn-up of the natural uranium bundles. The discharge burn-up of all the reactors have increased in the last 3 years. The present average fuel discharge burn-ups are in the range of 7500 – 8000 MWD/TeU. This is against the design discharge burn-up of 6,300 MWD/TeU.

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 in operating stations. The iodine activities in coolant circuits are usually less than 5 micro Ci/litre. Typical iodine activity values in MAPS-II, since restarting of the reactor after en-mass coolant channel replacement in the year 2003, is shown in Fig.5.

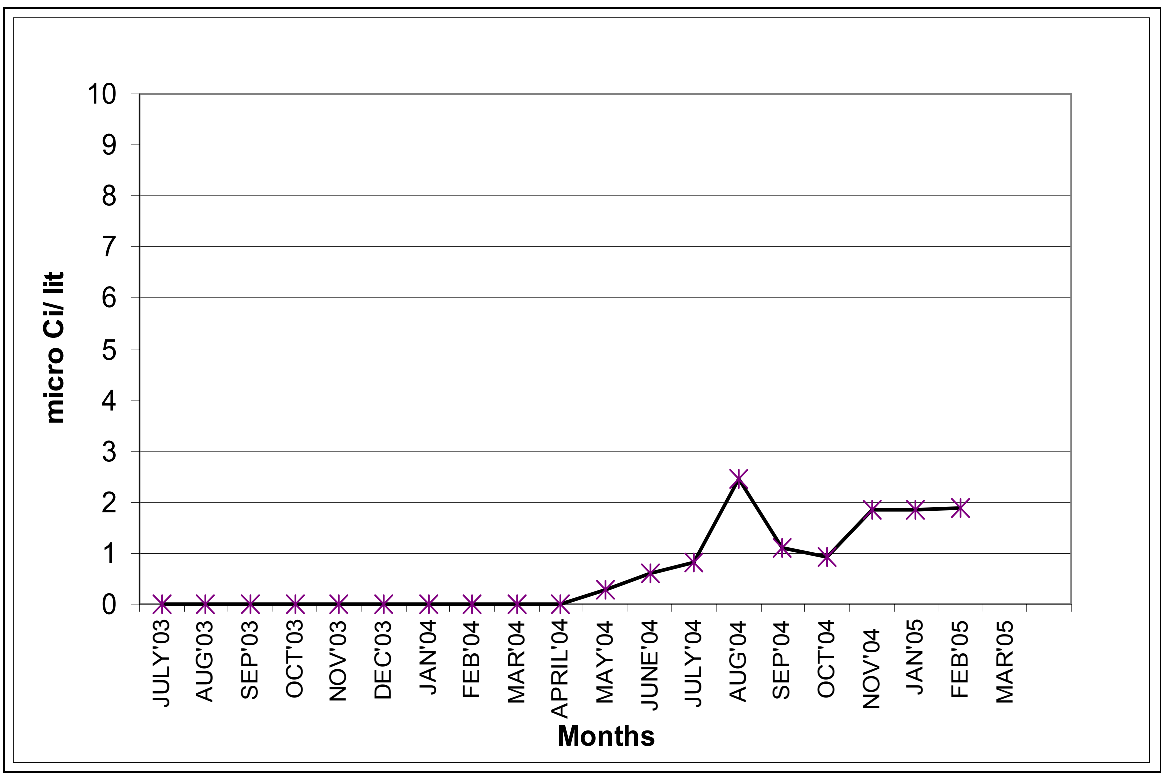

Fig 5 : Iodine activities in PHT system of MAPS-II

The fuel failure rate has been in the range of 1 bundle per 1000 bundles discharged. The fuel failure rates in the year 2003-04 and 2004-05 are 0.05 and 0.136 respectively.

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 burn-up and power.

Performance of Fuel Channels :

The pilgered coolant tubes are superior to drawn tubes in terms of wall thickness variation, homogeneity, texture etc. The coolant tubes made of Zirconium-2 are performing satisfactorily and these reactors have completed more than 10 full power-years of operation. Up to about 15 years of operation, the hydrogen concentration in Zirconium-2.5% Niobium pressure tubes have been found to be low (21 ppm at tube center) and most of the hydrides are found to be circumferential. It is also known that up to 63 ppm of hydrogen, the hydrides being circumferential, in the reactor operating range, hydrogen concentration had little effect on fracture toughness.

KAPS is the first Indian Reactor with Zirconium-2.5% Niobium alloy. This reactor has also been fitted with 4 Nos. of tight fit garter springs, which do not move from their installed positions. Hence these channels would not come into contact with calandria tubes at least till 40 years. The hydrogen pick up rate in this material is also very low with the result hydrogen embrittlement problems are expected only in the late life of the reactor. Regular examinations reveal that there are no life limiting or safety issues in any of the coolant channels in the near future. There has been no failure of any coolant tube.

10.0 Alternative fuel concepts for PHWRs :

Taking advantage of the flexibility to use variety of fuel loading patterns with different fuel types in PHWRs, fuel bundles are designed and irradiated on specific requirement/situation. This enabled the designers to evolve alternative fuel concepts that can be employed in Indian PHWRs.

10.1 Thorium bundles :

Bestowed with vast deposits of thorium, India has a long term strategy for use of thorium in its nuclear power programme. To gain experience in irradiation of thorium in power reactors, fuel designs with thorium were optimized for use in the initial cores of PHWRs for the purpose of flux flattening. The design aspects included suitably specifying the axial and radial gaps in the fuel elements and incorporating some minor modification in bearing pad positions to enable proper identification of these bundles. As per the reactor physics calculations, 35 thorium bundles have been used as a part of initial charge fuel in the 220 MWe PHWRs which are distributed in the high power and low power channels of the core. The use of these thorium fuel bundles in the initial cores was successfully demonstrated in Kakrapara Atomic Power Stations (KAPS I and II), Kaiga Atomic Power Stations (KGS I and II) and Rajasthan Atomic Power Stations (RAPS III and IV). The fabrication and irradiation of thorium bundles have provided valuable experience that can be utilized for the Advanced Heavy Water Reactor (AHWR) and Fast Breeder Reactors (FBRs).

10.2 MOX-7 bundles :

19-element bundles with inner seven elements having MOX pellets, consisting of plutonium dioxide mixed in natural uranium dioxide, and outer twelve elements having natural uranium dioxide pellets was evolved to conserve natural uranium resources. Fuel loading pattern and refueling schemes were optimized for establishing the use of these bundles in one of the operating PHWRs. As part of initial trial irradiation programme, some 50 nos of MOX-7 bundles have been fabricated by BARC and NFC and were loaded in the KAPS-I unit in the year 2004. The performance of these bundles in the reactor is found to be quite satisfactory.

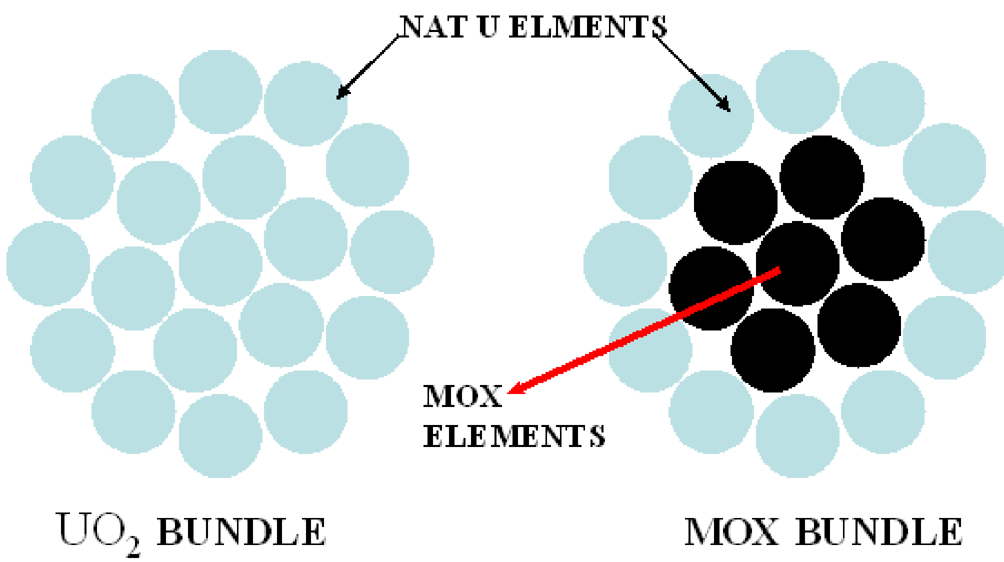

FIG 5: CONFIGURATION OF MOX-7 FUEL BUNDLE

More details about the alternative fuel concepts for PHWRs and their performance are discussed in the technical paper being presented during this Conference.

11.0 Concluding Remarks

The Nuclear Power Programme in India is poised for steep growth with five PHWRs currently under construction and many more under consideration to meet the ever increasing demand for electricity. Being the only manufacturer of fuel and fuel channels in the country, NFC is gearing up to meet the enhanced requirements. In addition to conventional fuels containing natural uranium dioxide, alternative fuel concepts with Thorium and MOX materials were also developed and irradiated to establish their usage in PHWRs. Several developmental efforts at NFC has successfully established the techniques of attachment of appendages on tubes by resistance welding and manufacture of calandria tubes through seamless route, which are unique to India.

12.0 Acknowledgements

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