Non-destructive Evaluation of Irradiated Nuclear Fuels and Structural Components from Indian Reactors

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Abstract

Pressurised Heavy Water Reactors (PHWRs) have been operating in India for more than four decades. These components suffer degradation during reactor operation under very hostile atmosphere of fast neutron flux, high temperature coolant corrosion and creep due to hoop stress. The liquid nitrogen-alcohol test is carried out on individual pins to identify the leaky fuel pin. The region of interest is identified by non-destructive testing like profilometry, gamma scanning, eddy current and ultrasonic testing. The change in diameter has been measured by laser technique. The ridging at pellet to pellet interfaces was observed in high burn up fuel bundles. The defects in the end cap welds were detected by immersion ultrasonic testing during post-irradiation examination. To evaluate creep in irradiated pressure tubes, internal diameter and wall thickness have been measured by UT, linear variable differential transducer and three point micrometer.Gamma scanning measurement consists of gross, isotopic, and spectrometric gamma scanning. The important PIE results are presented in this paper.

Key Words: PHWR, PIE, reactor fuels, coolant channels, NDE techniques, UT, diameter

1. Introduction

Pressurised Heavy Water Reactors(PHWRs) have been operating in India for more than four decades and play a very important role in the nuclear power programme. At present, 18 units of PHWRs with a total capacity of about 4500MWe are under operation. In addition to these, four 700MWe PHWRs are under construction and many more are planned in the near term to have an installed capacity of more than 20GWe. These operating PHWRs use natural UO_2 as fuel with an average discharge burnup of about 7 GWd/t. These fuel bundles were irradiated to more than 20 GWd/t burnup and are being examined in hot-cells at BARC. The hot pressure tube undergoes diametral, axial creep and sag leading over the life in the reactor core.

Heavy water coolant reacts with zircaloy pressure tube (PT) and fuel element cladding, producing hydrogen/deuterium (H/D) during reactor operation. Some fraction of this hydrogen is absorbed in the body throughout the length. The hydrogen/deuterium absorbed in the matrix migrates to the cooler region under thermal and stress gradients. Over a length of time, a point is reached when hydrogen concentration in the cooler region exceeds terminal solid solubility (TSS) limit and zirconium hydride platelets precipitate. The reactor fuel operates in more hostile environment like nuclear fission but it is discharged after a short duration of 1-1/2 year of operation. The pressure tubes operate under high temperature and high pressure coolant resulting in corrosion and creep over the years under fast neutrons. The reactor fuel bundle consists of 19 elements held together by spot welded to the end plates at both the ends. The pressure tube is the most important component of the coolant channel structural assembly as it has to serve for a much longer period.

2. Reactor Fuel

The cladding of the fuel element is the first boundary to contain the fission product from getting released to the coolant. The end cap welds are also the critical part in the integrity of the fuel pins. In some cases the end plugs were found to be porous which allowed permeation of coolant, resulting in clad cracking and hydriding of the end plugs on the other side of the fuel pin. This kind of defect was pre-existing in the bar used to manufacture end plugs and which escaped detection by the NDT techniques.Recently, we have examined a number of irradiated natural UO_2 fuel bundles from Kakrapar (KAPS) reactors which had seen burn up ranging from around 10,000 to 22,000 MWd/T. A number of irradiated 19 pin PHWR fuel bundles were dismantled by cutting of end platespot welds using pneumatic baby hacksaw,inside the hot-cell to separate individual elements for further investigation. The liquid nitrogen-alcohol test is carried out on individual pins to segregate the leaky fuel pin. The region of interest is identified by non-destructive testing like profilometry, gamma scanning and ultrasonic testing. None of the fuel pins had failed. The diameter measured by laser technique showed maximum ridging in the outer fuel pins as they develop higher temperature and maximum hour glassing effect between pellet to pellet interfaces. The ridging effect is local increase in clad tube diameter. The ridge region is more likely to develop an incipient crack in the clad due to PCI (pellet clad interaction) and IASCC (iodine assisted stress corrosion cracking).

2.1. Visual examination and dimensional measurement

The fuel bundles were examined under radiation resistant camera having tilting, rotation and zooming facility. Various parts of the fuel bundle were viewed under the camera in as received and after cleaning with alcohol. The bearing pads, end cap welds, coloration, presence of crud, dirt, dent, hole in the outer pins of the bundle, deformation in the bundle, marks on bundle due to handling as well as due to fuelling machines were carefully examined. Fig. 1. shows the handling marks and the fuel bundle length measured by vernier caliper.

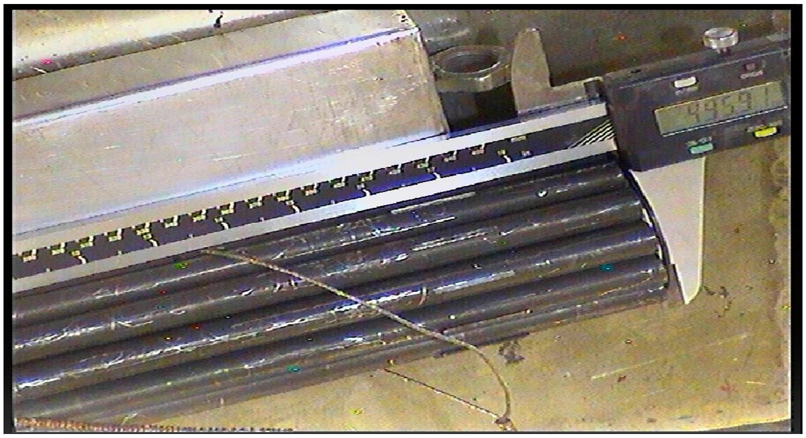

Fig. 1. Shows the fuel bundle length measurement.

The length and diameters were found to be within the specification range. The end plug welds, bearing pads and spacers were also intact.

2.2. Laser diameter measurement

In the Laser profilometry, a VFD controlled motorized stage is there on which the Laser micrometer is placed (Fig.2). The individual pins were placed in the pin holding grips and the laser micrometer is moved from one end to other end. The pin outer diameter data is recorded throughout the length of the pins in a data recorder. The diameter was measured once when the three bearing pads are in the line of laser beam. The pin was rotated by 90 degree and another set of diameter was measured where spacers were in the laser beam line. The tall peaks out of the scale in the plot are for bearing pads and spacers of the fuel pin.

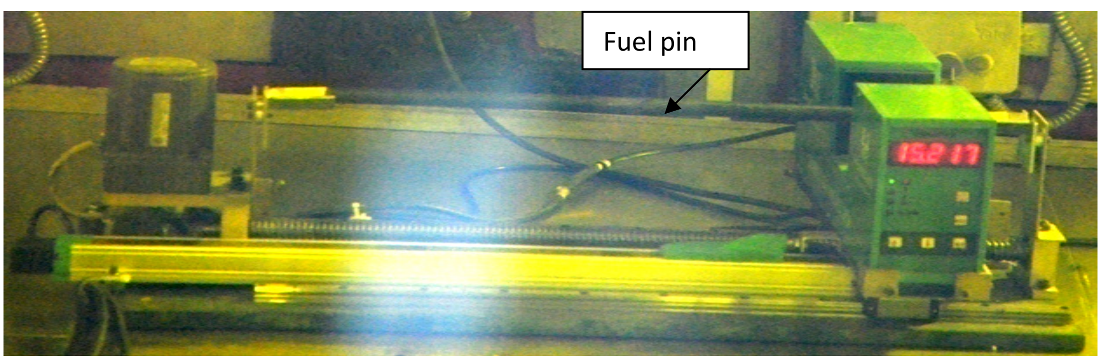

Fig.2. Laser profilometer inside the hot cell

The plot comparing the diameters of peripheral, intermediate and central pins are given in Fig. 3. which shows that the maximum ridging is observed in the outer fuel pins.

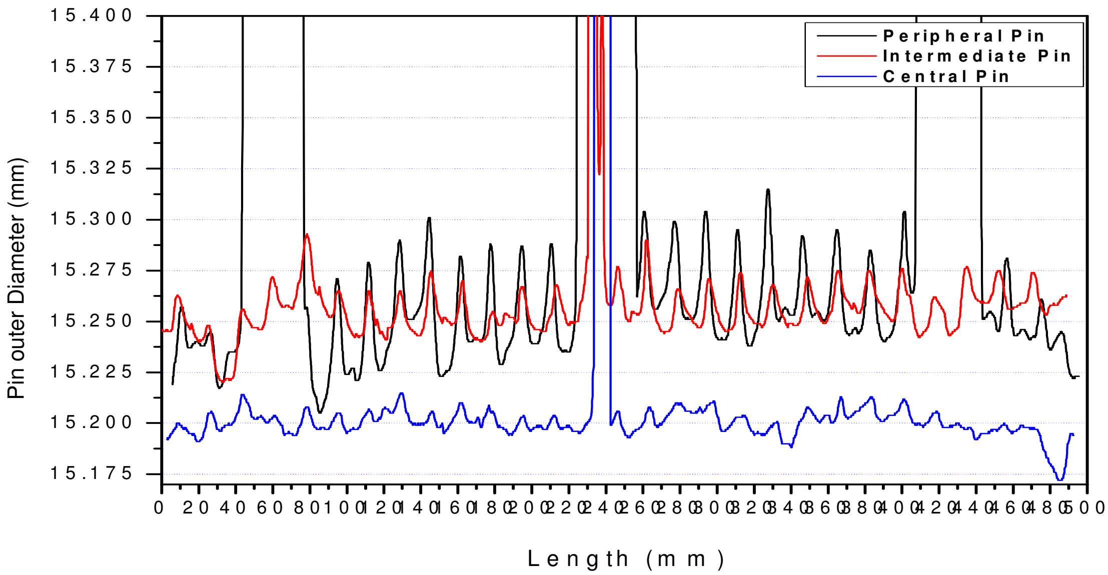

Fig.3. The peripheral pin has maximum diameter and minimum in central pin

2.3 Gamma scanning of fuel pins

During fission, the uranium atom splits into a number of different smaller atoms known as fission products. One of the fission product Cs^{137} has very high half life. The energy spectrum of irradiated UO_2 fuel showed distinct peaks of Cs^{137} (662 keV) and Cs^{134} (604 and 796 keV).

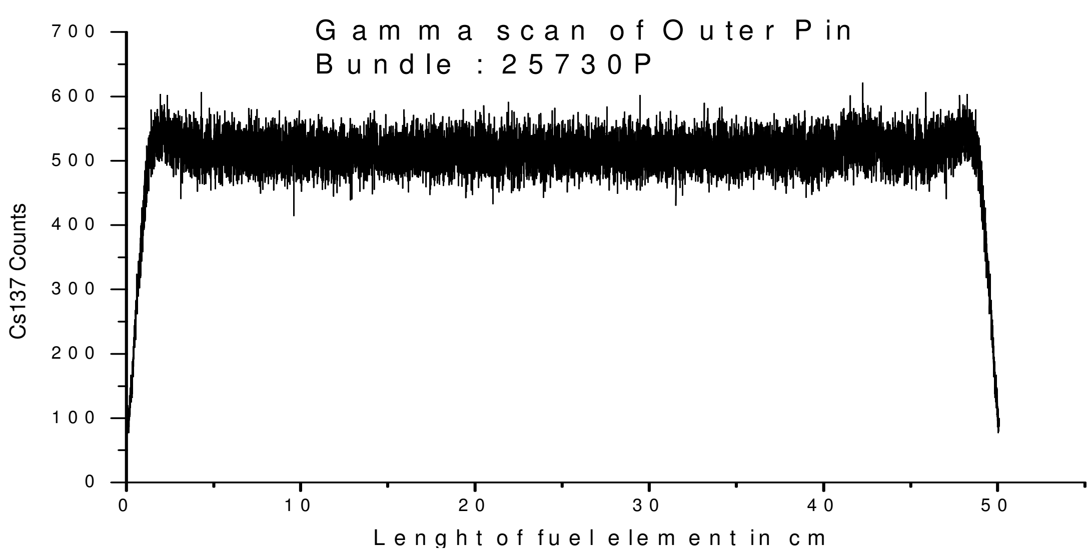

Fig.4. Gamma scanning of the irradiated fuel pin

The energy peak of Cs^{137} was selected to scan the full pin length to find out any leachingof the fuel. It was found that the outer fuel pins were showing higher activity than intermediate and central fuel pin, confirming that outer pins undergo higher burn up and produce more power. The gamma scanning also gives comparison of burn up non-destructively.

2.4. Immersion ultrasonic testing of fuel pins

Ultrasonictestingiscarriedoutto test integrityofthe clad. Fortestingthecladthefuelpinwashorizontallymountedonscanningstageinside thecell.Thestageisfittedwithtwomotors;oneforrotatingthefuelpinandother forthehorizontalmovementoftheUTprobes.Immersionultrasonicprobesof10MHzfrequencyand20m mspotfocallengthwere used.Twoprobeswereused;one forcircumferentialscanandtheotherfor axial scan.Entirestage,barringthe electricalmotorswasenclosedinatankfilled withwater(UTcouplant).

Controlanddataacquisitionsystemsarekeptintheoperatingareaand theoutputsfromtheUTprobesaretakenby10metercablethatpassesthrough theserviceplugonthecellwall.Theprobesareconnectedusingspecial adaptersinsuchawaythattheycanbeconnected/disconnectedfromthelong cable,remotelyusingthemanipulator.Waterforcouplingwassuppliedfromthe operatingareathroughtheserviceplug.Thestage, thewater tankandtheprobesaredesignedinsuchawaythattheycanbetransferredto theisolationarea,foranymaintenance, throughtheexternaltransferdrawerof thecell.Fig. 5. shows the ultrasonic scanner fitted with probes for detection of axial and circumferential incipient irradiation induced flaws in the cladding.

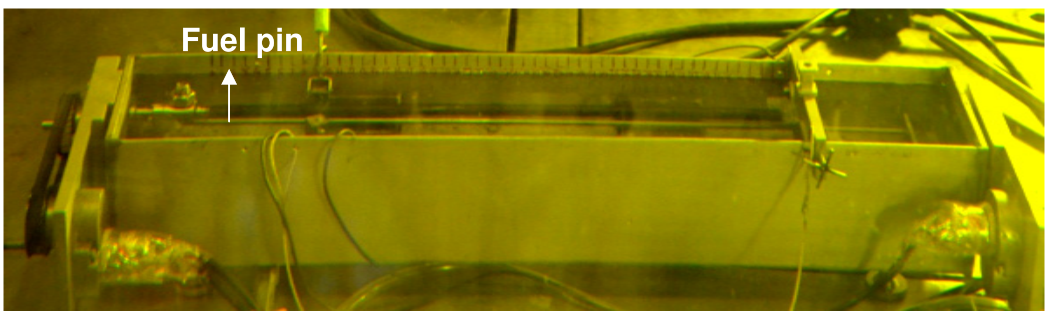

Fig. 5. Ultrasonic testing set up installed in the hot cells

All the individual pins were tested by helical scanning. Two peripheral pins and one intermediate pins were marked for the axial internal incipient flaw which are shown below in Fig.6. The intercepted defect by ultrasonic was found out to be an initiating corrosion pit in bundles above 10,000 MWd/T burn up as shown in Fig.7.

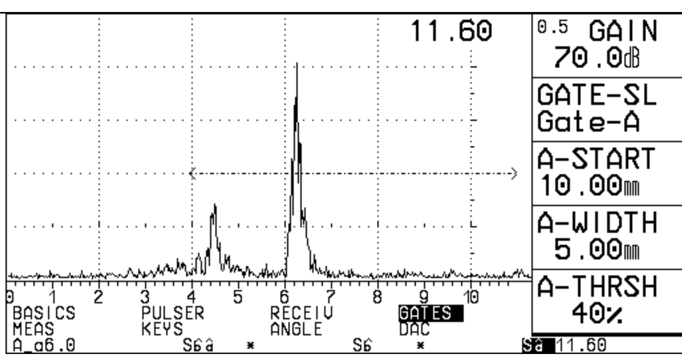

Fig. 6. Small incipient flaw signal

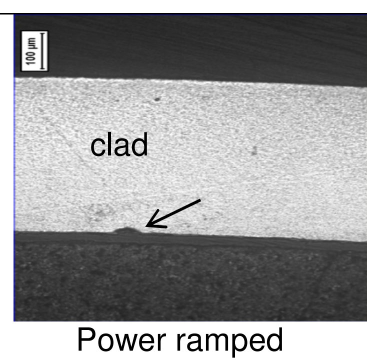

Fig. 7. Arrow shows corrosion pit

3.0 Diameter and wall thickness measurement of irradiated pressure tube

The Q-10 pressure tube (PT) was removed from the reactor after 14 effective full power year for surveillance purpose. Five point focused ultrasonic probes were fitted in an annular perspex probe holder. One probe was used to measure ultrasound velocity in water at the prevailing temperature. Rest four probes facing diametrically opposite were used for measuring water path to calculate the two perpendicular diameters. Two diameter and four wall thickness values are obtained around the same circumference which precisely defies the hoop stress. The measured thickness readings were plotted against pressure tube length. Thickness reduction is observed from inlet to outlet end in Fig. 5. Internal diameter is found to have increasing trend from inlet to outlet end with a peak in between centre and outlet end. At the peak region an increase of 2.14 mm in internal diameter was measured after 14 EFPY.

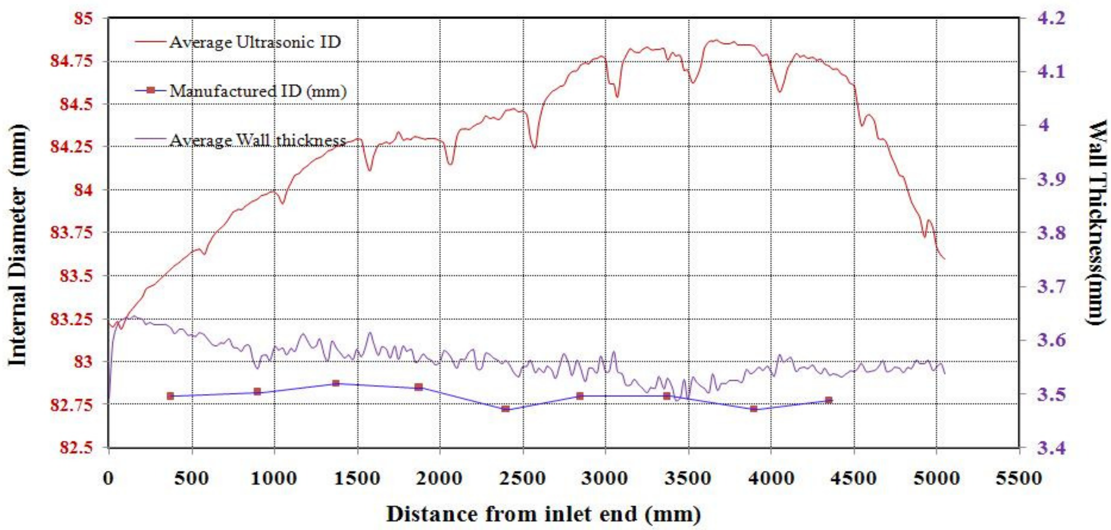

Fig.8. Measurement of internal diameter and wall thickness of irradiated PT

4.0 Conclusion

The irradiated fuel bundles from power reactors have been examined in the hotcells of BARC. The laser diameter measurement has found out the effect of ridging to be more in the outer fuel elements. It depends on a number of factors like dwelling time, linear heat rating, initial pellet clad gap and burn up of fuel bundles. Ultrasonic testing predicted that corrosion pits on the inner surface of the clad are formed on higher burn up by corrosive fission products. No crevice corrosion underneath the bearing pads were observed.

Gamma scan throws light on the burn up of the fuel pin from one end to the other end.Ultrasonic NDT has been used to measure internal diameter and wall thickness around the same circumference which is used to define precisely the hoop stress. The diametral creep was less than 3% in pressure tube Q-10 after 14 effective full power year. The NDT techniques have been used effectively to evaluate performance of reactor fuels and structural components.