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Fitness for service assessment of coolant channels of Indian PHWRs

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ABSTRACT

A typical coolant channel assembly of pressurised heavy water reactors mainly consists of pressure tube, calandria tube, garter spring spacers, all made of zirconium alloys and end fittings made of SS 403. The pressure tube is rolled at both its ends to the end fittings and is located concentrically inside the calandria tube with the help of garter spring spacers. Pressure tube houses the fuel bundles, which are cooled by means of pressurised heavy water. It, thus, operates under the environment of high pressure and temperature (typically 10 MPa and 573 K), and fast neutron flux (typically 3×10^{17} n/m^2 s, $E > 1$ MeV neutrons). Under this operating environment, the material of the pressure tube undergoes degradation over a period of time, and eventually needs to be assessed for fitness for continued operation, without jeopardising the safety of the reactor. The other components of the coolant channel assembly, which are inaccessible for any in-service inspection, are assessed for their fitness, whenever a pressure tube is removed for either surveillance purpose or any other reasons. This paper, while describing the latest developments taking place to address the issue of fitness for service of the Zr–2.5 wt% Nb pressure tubes, also dwells briefly upon the developments taken place, to address the issues of life management and extension of zircaloy-2 pressure tubes in the earlier generation of Indian pressurised heavy water reactors.

1. Introduction

The coolant channel assembly is central to the design of Indian pressurised heavy water reactors (PHWRs). A typical coolant channel assembly, shown schematically in Fig. 1, mainly consists of pressure tube (PT), calandria tube (CT), and garter spring spacers, all made of zirconium alloys, and end fittings made of SS 403. The pressure tube is rolled at both its ends to the end fittings and is located concentrically inside the calandria tube. Heavy water moderator at low temperature surrounds the calandria tube and an open/CO_2 filled annulus, along with axially spaced garter springs, insulates the hot pressure tube from the cold calandria tube. High pressure, high temperature heavy water coolant is pumped through the pressure tube to extract the nuclear heat generated by the fission of natural uranium fuel and transport this to the steam generators. Amongst the coolant channel components, it is mainly the pressure tube that is vulnerable to a number of degradation mechanisms during reactor operation. Degradation issues related to other components of coolant channel are dealt in detail in [1] and are not a part of this paper.

By progressively improving the design of the coolant channel, some of its degradation mechanisms have been addressed completely, while in the case of others; the effects have been minimised. These improvements have been in terms of changes in material, specification, and design of the coolant channel assembly. Pressure tube degradation is also addressed to a great extent by a multi-pronged programme involving inspection and monitoring, assessment of degradation, material surveillance and fitness for service guidelines evolved over the years to present mature stage.

India had originally seven 220 MWe units operating with cold worked zircaloy-2 pressure tubes. Of these seven units four have been retubed with Zr–2.5 wt% Nb pressure tubes after operating successfully for a period of 8.5–10.23 EFPYs (i.e., 10–12 hot years of operation). Other two units, which have till now operated for 10.8 EFPYs (i.e., 11 hot years of operation) are due for retubing. All the new units commissioned after KAPS-1 have cold worked Zr–2.5 wt% Nb as the pressure tube material and have seen operation for a period in the range of 5–9 hot years. Besides the 220 MWe units, India has two 540 MWe units as well, which have started commercial operation recently.

It is to be acknowledged that, India is the only country in the world, which had operated a number of reactors with cold worked zircaloy-2 pressure tubes, with the help of an indigenously developed programme for assessment of fitness for service. This experience is being utilised to develop a similar programme for Zr–2.5 wt% Nb pressure tube as well. This paper discusses the life limiting issues and the systems in place for assessment of fitness for service for zircaloy-2 pressure tubes. It also throws light on

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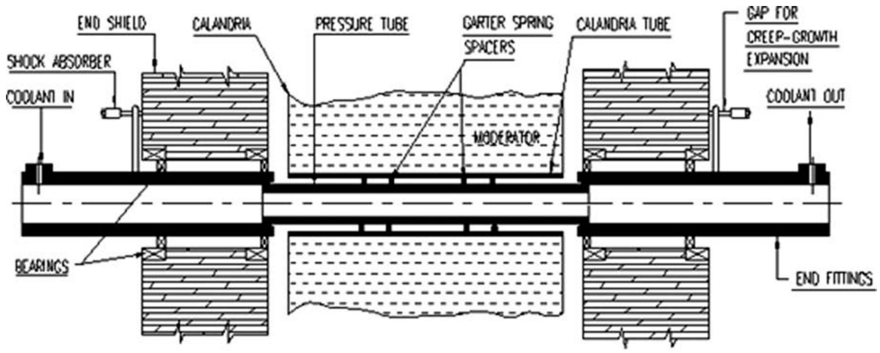

Fig. 1. Schematic of coolant channel assembly of PHWR.

the developments related to addressing the issues associated with Zr–2.5 wt% Nb pressure tubes.

2. Degradation issues related to pressure tubes

Pressure tubes operate in an environment of high pressure and temperature (typically, 10 MPa and 573 K), and fast neutron flux (typically, 3.0×10^{17} n/m^2 s, $E > 1$ MeV neutrons). Under this operating environment, the material of the pressure tube undergoes degradation over a period of time, and eventually needs to be assessed for fitness for continued operation, without jeopardising the safety of the reactor.

2.1. Degradation issues

The degradation issues [1], related to the operating zirconium alloy pressure tube are summarised as follows:

- In-service flaw generation.
- Mechanism of in situ flaw propagation.
- Dimensional changes due to irradiation creep and growth.
- Creep sag.
- PT–CT contact and hydride blister formation.
- Deuterium ingress.
- Embrittlement due to neutron irradiation and hydriding.
- Increase in delayed hydride crack (DHC) velocity.

Diametral expansion, elongation, PT–CT contact and hydride blister formation had been the life limiting mechanisms of the Indian PHWRs of earlier generation (now retubed), which employed zircaloy-2 pressure tubes with two garter springs. In the present scenario, when the Indian PHWRs operating with zircaloy-2 pressure tubes are at the end of their life, safe operation is ensured by meeting a leak before break (LBB) requirement, in the light of material degradation associated with accelerated deuterium ingress and reduced fracture toughness.

For the new generation of Indian PHWRs with Zr–2.5 wt% Nb pressure tubes, where the expected core life is in the range of 20–25 years, the LBB criteria are critical near the rolled joint in the light of increased deuterium ingress at this location as compared to the pressure tube body. The higher deuterium concentration will increase the propensity for DHC. In addition, the fracture toughness will be reduced as a result of both the hydrogen ingress and neutron embrittlement.

3. Assessment of fitness for service of pressure tubes

The assessment of fitness for service of a pressure tube is carried out through a systematic approach developed over the years. This approach requires identification of the inspection parameters, development of hardware tools, and analytical models for assessment of the extent of degradation. Assessment of the pressure tube is carried out based on the inspection parameters and methodologies, and satisfying the guidelines for fitness for service. The approach followed is described in detail in the subsequent sections.

3.1. Zircaloy-2 pressure tubes

3.1.1. Over view of life management activities

In order to assess the fitness for service of the zircaloy-2 pressure tubes in the early generation of PHWRs, where PT–CT contact had been the main concern in the case of large number of coolant channels, innovative techniques based on: non-intrusive vibration diagnostics (NIVDT) for detecting PT–CT contact [2], the channel inspection system (BARCIS) for the measurement of tube deformation and detection of flaws [3], sliver scrape sampling tool (SSST) for the measurement of hydrogen ingress [4] and integrated garter spring repositioning system (INGRES) for rehabilitating a contacting channel, were developed indigenously [5].

Along with the hardware for inspection and rehabilitation, mathematical models have also been developed for the degradation mechanisms like irradiation-induced creep deformation, in-service deuterium pick-up and blister nucleation and growth (see Fig. 2).

All the hardware and mathematical models mentioned in Table 1 have undergone several refinements based on the feed back from inspection and post-irradiation examination (PIE) received from time to time. Understanding the degradation mechanisms, along with experiences from the inspection and PIE, have helped in the development of fitness criteria and a life management strategy. All of them together have contributed towards the safe operation of early generation of Indian PHWRs.

3.1.2. Acceptance criteria for fitness for service

The acceptance criteria for disposition of coolant channels are given in Table 2.

3.1.3. Strategy followed for contacting channels [11–13]

The strategy followed for life management of contacting coolant channels of zircaloy-2 pressure tubes is shown in Fig. 3.

3.1.4. Current life management strategy

Currently, the safety of reactor cores operating with zircaloy-2 pressure tubes is being assured through their ability to meet the LBB criterion. For this purpose, sliver scrape samples are removed from the outlet half of a few pressure tubes identified by the computer code HYCON (recently updated for precise estimate of deuterium pick-up at peak location, Fig. 4(a) and (b) for assessment of deuterium pick-up. Based on this measured value of deuterium

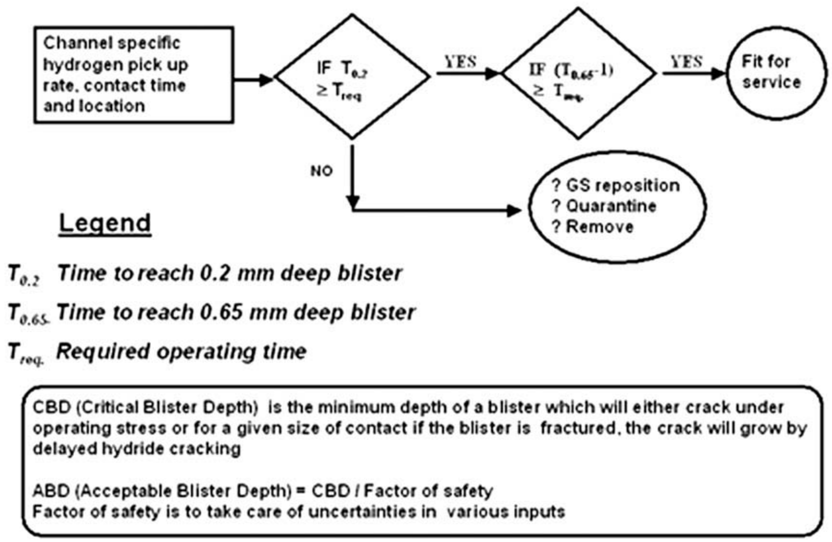

Fig. 2. Blister depth criteria for contacting zircaloy-2 pressure tubes.

Table 1
Tools and mathematical models developed for life management of zircaloy-2 pressure tubes

Sl. no.	Description of tools and mathematical models	Capabilities	Current status
1	Non-intrusive vibration diagnostic technique (NIVDT)	Ability to diagnose the PT–CT contact by analysing the channel vibration signature recorded	
2	BARC inspection system (BARCIS)	PT–CT gap measurement, wall thickness measurement, garter spring position measurement, flaw detection	Being equipped with ID measurement module and sag measurement module
3	Sliver sampling scraping tool (SSST)	Remove sliver samples of requisite weight by longitudinal scraping on inside surface at 12'O clock position	Multi-head scraping tool is designed and getting fabricated
4	Integrated garter spring repositioning system (INGRES)	Detection of garter springs and its position, Un-pinching of garter spring, repositioning using electro motive force	
5	Static and creep analysis of pressure tube and calandria tube assembly (SCAPCA) [6]	Modelling of irradiation-induced creep related deformation	
6	Hydrogen concentration (HYCON) estimation [7]	Modelling of hydrogen ingress in PT material during service life	
7	BLIST [8]	Modelling of nucleation and growth of hydride blisters at the contact spot	

Table 2
Acceptance criteria for disposition of channels [9,10]

Sl. no.	Safety concern	Acceptance criteria
1	Flaw	<3% of wall thickness
2	Minimum wall thickness	3.7 mm for zircaloy-2
3	PT–CT contact	Bliste Blister depth criteria (described in Fig. 2) applied when contact is established
4	High deuterium content and low fracture toughness	Safe residual life of an operating pressure tube is worked out on the basis of its ability to satisfy LBB criterion

concentration, conservative estimate of available operator response time is calculated using the upper bound value of DHC velocity and lower bound value of CCL. The computer code DELHYC (described later) is also used to estimate a realistic value of this operator response time. Comparison of the conservative and the realistic estimates of this parameter, and the actual time required for shutting down and depressurising the PHT, gives the confidence to operate this unit further.

3.2. Zr–2.5 wt% Nb pressure tubes

3.2.1. Inspection and monitoring of degradation related parameters

In the present scenario, where PT–CT contact is no longer a life limiting issue in the operating Indian PHWRs, monitoring of dimensional changes, garter spring position and hydrogen ingress, both in the pressure tube body and the rolled joint region is required to be carried out periodically. Tools for measurement of the inside diameter, pressure tube sag, hydrogen measurement near the rolled joint by removing sliver samples in the circumferential direction, and inspection of the scraped region are in an advanced stage of development. Additionally, two new tools are being developed for in situ measurement of hydrogen ingress and mechanical properties, respectively.

All the tools developed to date, or to be developed in future, should have provisions for cables for transmission of power and data, pneumatic lines for activating some interlocks and collapsible extension rods for driving the tools to the far end of the pressure tube. As the inside diameter of pressure tube of 220 MWe PHWR is 82 mm, the external diameter of the of the inspection system shall be a maximum of 80 mm. Meeting this constraint, without

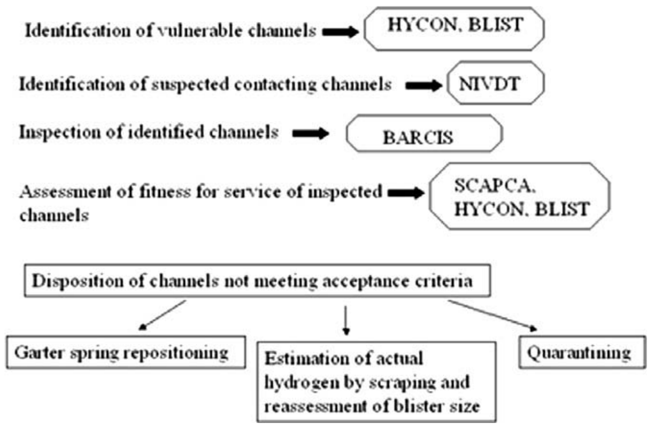

Fig. 3. Strategy followed for life management of contacting coolant channels.

jeopardising the performance of the tool, has been the major challenge involved. An attempt is being made towards developing a system for wireless communication with the inspection gadgets, so that future inspection tools will not require any cable for data transmission.

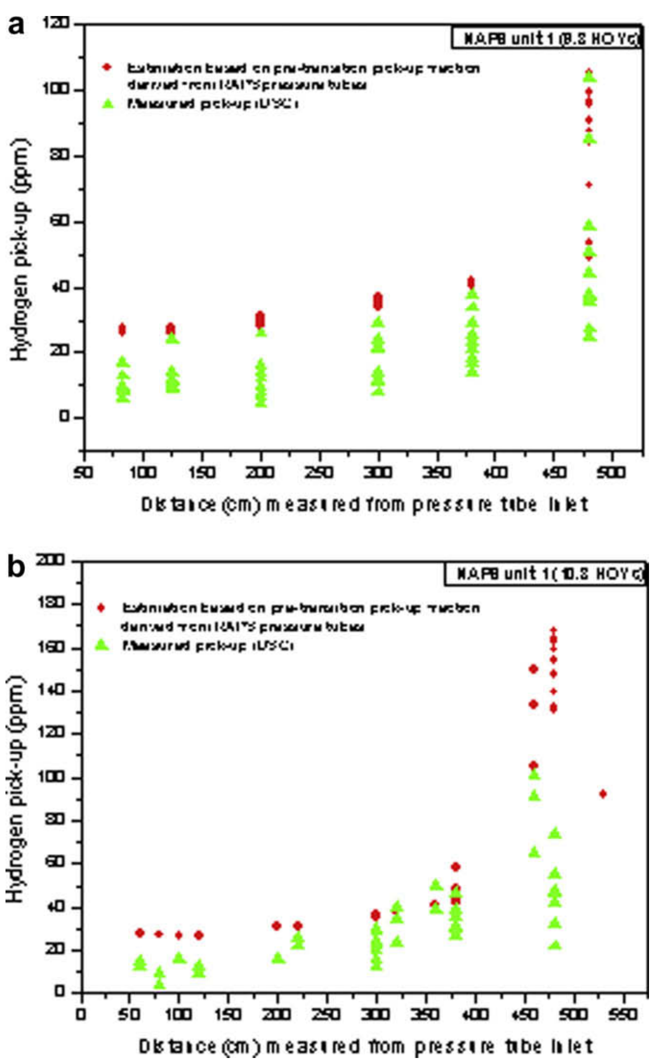

Fig. 4. Comparison of estimated and measured hydrogen pick-up in pressure tubes of NAPS unit (a) 1 at 9.8 HOYs and (b) at 10.8 HOYs.

The future inspection programme expected to start shortly will have the following parameters monitored:

- Axial elongation.
- Pressure tube wall thickness and PT–CT gap at 6'O clock.
- Location of garter spring.
- Service induced flaws.
- Deuterium concentration profile.
- Deuterium concentration in the rolled joint area.
- Rolled joint inspection for flaws.
- PT sag.
- PT inside diameter.

In situ measurement of mechanical properties and hydrogen concentration will take some more time before they are incorporated into regular inspection programme.

3.2.1.1. Assessment of integrity of rolled joint area

3.2.1.1.1. Circumferential scrape sampling tool. The rolled joints have been observed to have much higher ingress of deuterium as compared to main body of the pressure tube. The deuterium ingress in the rolled joint region is measured by analysing the sliver scrape samples removed from this region. Considering the high concentration gradient of deuterium in the axial direction, samples are removed by scraping in the circumferential direction with the help of a specially developed circumferential scraping tool (CST). It first removes an oxide layer 40 mm long, 18 mm wide and of about 100 μm depth. Once the oxide layer is removed, then a 40 mm long and 8 mm wide metal layer of about 150 μm depth is removed. Both the samples are then extracted from the coolant channel. A dedicated control system provides complete automatic operation and on-line monitoring of tool functions.

3.2.1.1.2. Rolled joint inspection for flaws [14]. Inspection of rolled joint area both in the circumferential and axial directions is done using an ultrasonic immersion technique. The circumferential angle beam scanning uses 45° refracted shear waves generated by an offset method. Calibration of the equipment is achieved by the use of a reference standard. The reference notch is 6 mm in length, 0.15 mm in width and 0.15 mm in depth. The inspection head forms a part of the BARCIS for precise scanning process.

3.2.1.2. Inspection for assessment of pressure tube (excluding rolled joint) integrity

3.2.1.2.1. Longitudinal sliver scrape sampling [15]. A wet scraping tool is used to take samples at 12'O clock position by making a lon-

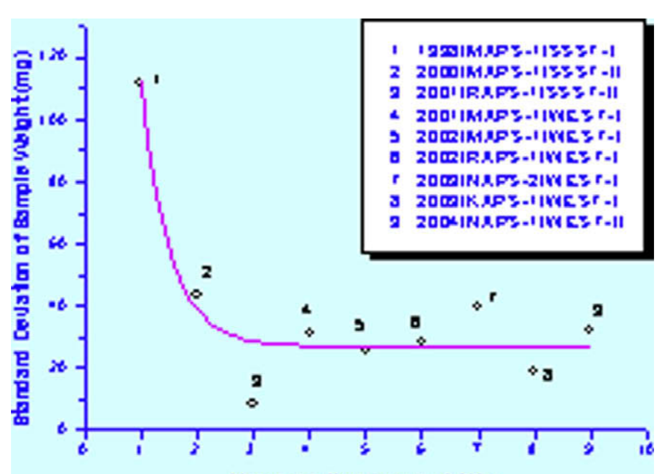

Fig. 5. Performance evaluation of scraping.

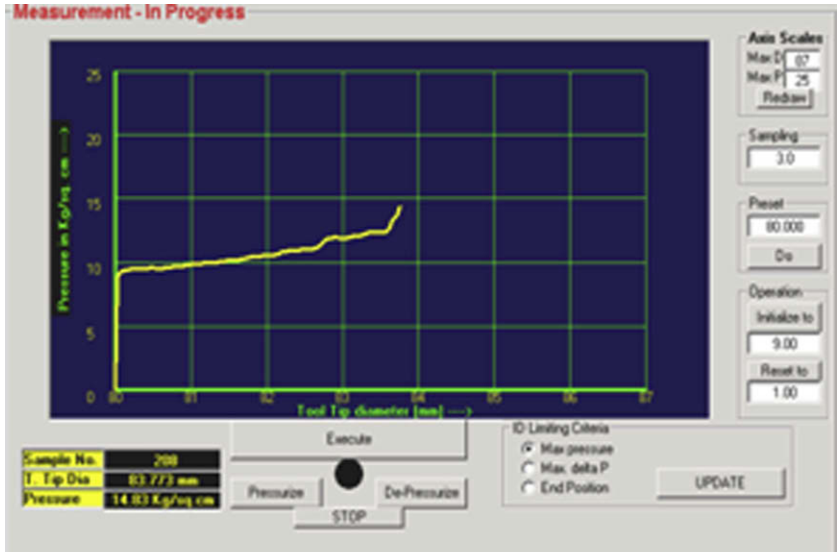

Fig. 6. Operating curve of HYRIM.

gitudinal cut from the inside surface of the pressure tube. The entire operation of tool positioning, sample removal and tool withdrawal is controlled through the fuelling machine.

The average weight of metal samples removed is 90 mg. A spring-loaded housing helps in maintaining the cutting force nearly constant and thus improves the performance of the tool in obtaining the required weight of sample. It has a provision for injection of light water near the tool bit to avoid the pick-up of deuterium during the scraping operation. Fig. 5 shows the improvement in the performance of the tool with successive modifications in design.

3.2.1.2.2. Inside diameter measurement. A hydraulically operated system (HYRIM) has been designed and developed for remote measurement of inside diameter of pressure tube [16]. The system has been developed with a targeted accuracy of 50 μm for the range of inside diameter from 82 to 86 mm. It consists of two modules, namely, an inspection head and a pressurising unit, connected using a hydraulic hose. It has fully automated features with a computer interface to reduce the measurement time. A performance trial of the tool at reactor site was carried out successfully. A typical operating curve of the system is shown in Fig. 6.

In another version of the tool developed, the inside diameter is measured by an ultrasonic technique. This tool is being tested for its performance.

3.2.1.3. Tools under development for in situ application

3.2.1.3.1. Measurement of equivalent hydrogen concentration in pressure tube [17]. A new technique based on resistivity measurement has been developed for measurement of equivalent hydrogen concentration in pressure tube. It consists of an eddy current probe assembly, thermocouple probes, heating module and sealing arrangement. This technique eliminates the need for removal of a sliver scrape samples and can be engineered for in situ measurement. Further, repetitive measurement at the same location over a period of time is possible to estimate the deuterium pick-up rate.

3.2.1.3.2. Monitoring of mechanical properties of pressure tube [15]. An in situ property measurement system (IProMS) based on ball indentation has been developed for estimation of mechanical properties of the pressure tube. It is based on multiple indentation cycles at the same penetration location on the inside surface of the pressure tube by a spherical indenter. The load and corresponding deformation are recorded during the test. Post-processing of the data recorded gives an estimate of mechanical properties of the material. The system consists of a tool head, which can go inside the pressure tube and do the cyclic indentation. Presently, qualification trials using the system are in progress. This technique has the potential of eliminating the removal of pressure tube for material surveillance (Fig. 7).

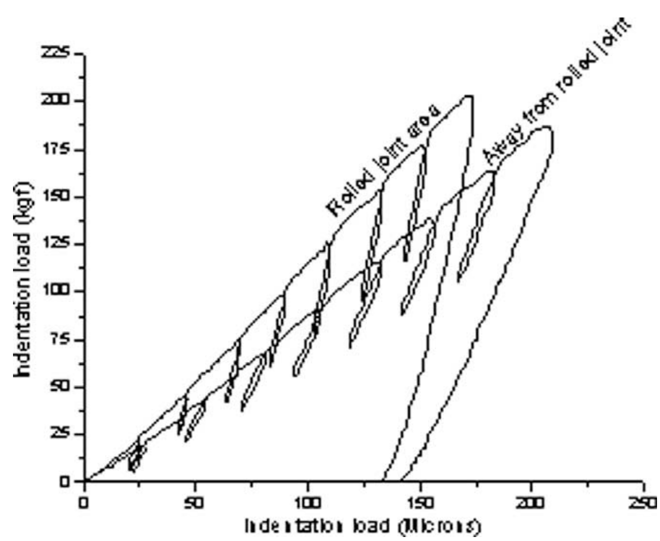

Fig. 7. Trial using IproMs.

3.2.1.4. Future of inspection gadgets

3.2.1.4.1. Telemetric transducer system. In order to carry out remote wireless inspection of coolant channels, a telemetric transducer system is being designed and developed. The system basically consists of an in-channel device module (ICDM), and repeater and receiver modules. The in-channel device module is excited to obtain information of channel parameters of interest and transmits the same through water. The signal is picked up by an ultrasonic receiver mounted on the end fitting. The output of the ultrasonic receiver signal is demodulated and sent to the control room for further processing. A prototype ICDM, and repeater and receiver modules are shown in Fig. 8(a) and (b).

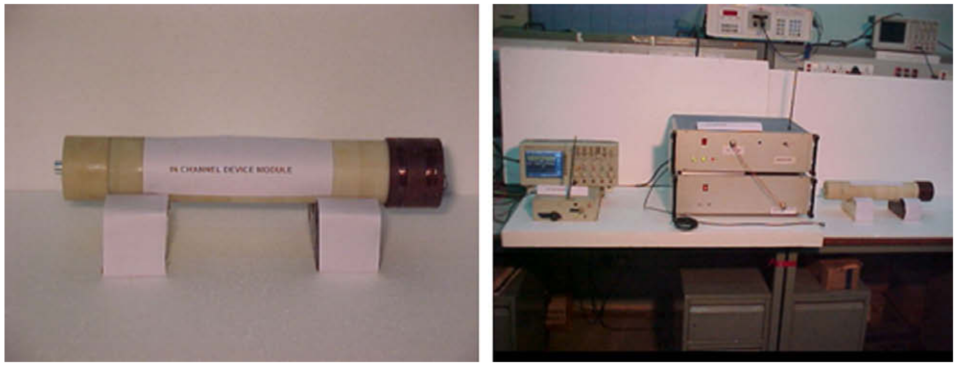

Fig. 8. (a) Prototype in-channel device module. (b) Repeater and receiver modules.

3.2.2. Development of analytical codes for degradation modelling and residual life estimation of pressure tube

A brief overview of the indigenously developed analytical codes that are used for residual life assessment of Zr–2.5 wt% Nb pressure tubes is covered in the following sections.

3.2.2.1. Computer code for static and creep analysis of pressure tube and calandria tube assembly (SCAPCA). Computer code SCAPCA is used to simulate the creep-growth and creep-sag behaviour of the coolant channel assembly. It estimates the dimensional changes in coolant channels and the creep-growth limited life on the basis of channel specific design, operation, environment and material inputs. The mathematical formulation and other relevant details are covered in [6]. SCAPCA has been used extensively for life management of zircaloy-2 pressure tubes. The creep laws used in SCAPCA have been modified for Zr–2.5 wt% Nb pressure tubes.

3.2.2.2. Computer code for estimation of hydrogen pick-up in Zr–2.5 wt% Nb pressure tubes. A new model for estimation of oxide and hydrogen pick-up has been developed on the basis of published PIE results of oxide thickness and hydrogen pick-up for Pickering pressure tubes. Parabolic kinetics has been modelled for in-pile corrosion. The model that was developed has been used to estimate the deuterium pick-up in the slivered pressure tubes of KAPS-2. The comparison of model prediction and the measured deuterium pick-up for one of the cases is shown in Fig. 9.

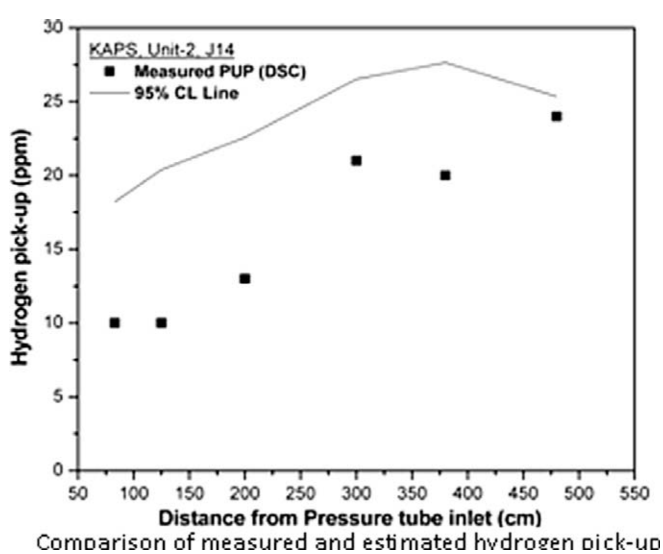

Fig. 9. Comparison of measured and estimated hydrogen pick-up.

3.2.2.3. Computer code to study the crack propagation by delayed hydride cracking (DELHYC) mechanism [18]. The computer code 'DELHYC' uses finite difference numerical technique to solve the differential equation of hydrogen diffusion under stress and concentration gradients. The basic concept of the model has been derived from the published works described in [19,20]. The model has the capability to simulate: (a) DHC under isothermal condition

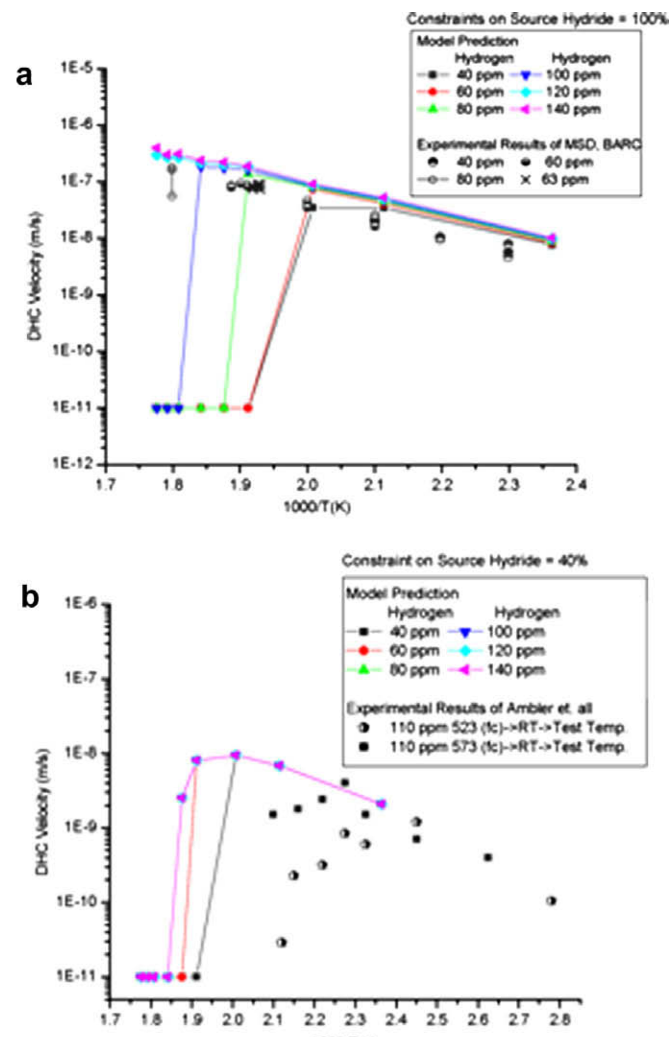

Fig. 10. Comparison of DELHYC predictions of crack growth velocity with published experimental results.

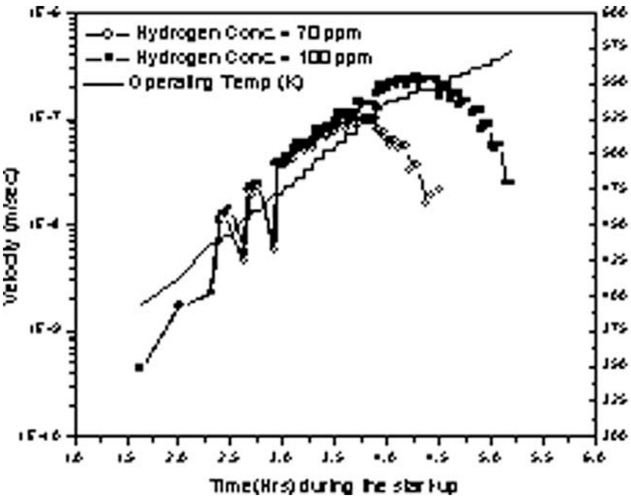

Fig. 11. Maximum DHC crack velocity at the outlet end during reactor start-up.

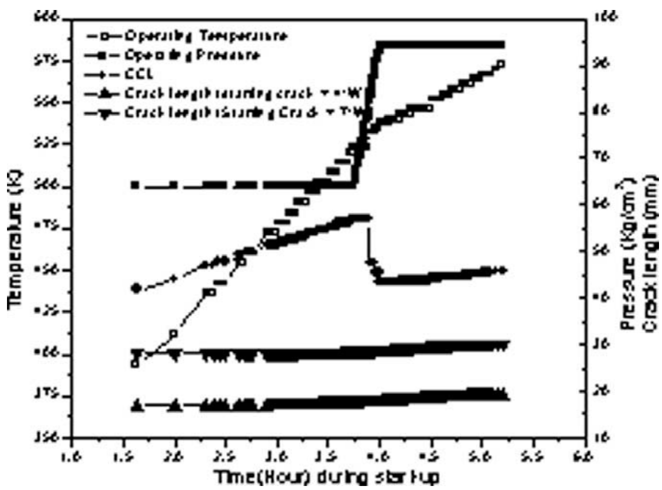

Fig. 12. Comparison of crack (aspect ratios of 4w and 7w) propagation with the critical crack length at the outlet end during the reactor start-up.

where the test temperature is achieved by either heating or cooling, (b) the effect of direction of approach to test temperature and (c) the effect of thermal cycling on the DHC mechanism. Some typical studies (Fig. 10(a) and (b)) carried out using this code for the published experimental works [19,21], have shown excellent match.

A cold pressurisation scheme for start-up of Indian PHWRs with Zr–2.5 wt% Nb pressure tubes has been conservatively studied using the code for evaluating DHC velocity and growth of a through wall crack during the start-up period. The results are presented in Figs. 11 and 12. From the code results it appears that, for hydrogen concentration of 70 ppm, the crack velocity increases up to 250 °C (0.36 mm/h) and then decreases to a negligibly small value. Similarly for 100 ppm hydrogen; the crack velocity increases with temperature up to 280 °C (0.72 mm/h) and then decreases to a negligibly small value. With this rate of crack growth, cracks of aspect ratios of 4w and 7w do not become critical during the start-up period.

3.2.2.4. Methodologies for evaluation of safe residual life of Zr–2.5 wt% Nb pressure tube. Methodologies in the form of acceptance criteria have been developed for evaluating the safe residual life of pressure tubes, considering the different safety concerns. These are described in Table 3 given below.

Table 3
Acceptance criteria currently being adapted to address different safety concerns

Sl. no.	Safety concern	Acceptance criteria
1	Flaw detection	<2% of wall thickness Pressure tube with flaw greater than the above limiting values is disposed based on an analysis for its possibility of growth by DHC and an estimate of the time/number of thermal cycles required to reach the unacceptable depth
2	Minimum wall thickness	3.32 mm
4	High deuterium content and low fracture toughness	Safe residual life of an operating pressure tube is worked out on the basis of its ability to satisfy LBB criterion

This criteria is currently being adopted. However, they are not mentioned in any regulatory documents.

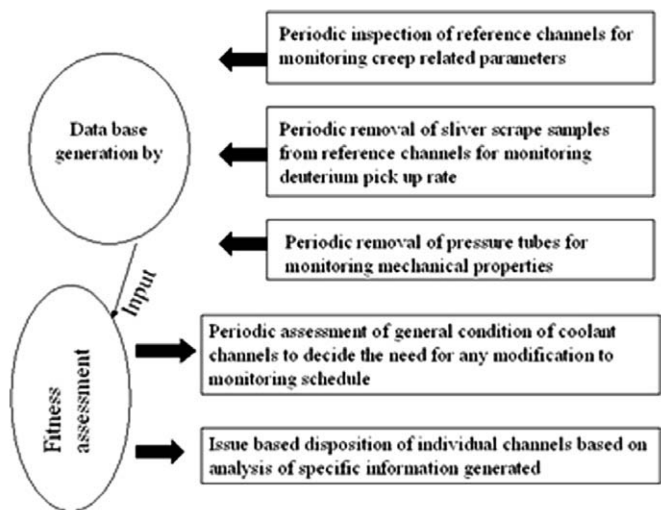

Fig. 13. Life management strategy for Zr–2.5 wt% Nb pressure tubes.

3.2.3. Life management strategy

In the case of reactors with Zr–2.5 wt% Nb pressure tubes, the inclusion of four tight fit garter spring spacers has reduced the probability for PT–CT contact considerably. In the new generation of PHWRs the material specification of pressure tube has been modified. New limits have been specified on the concentration of chlorine, and phosphorous to improve the fracture toughness. Specification limit on initial hydrogen concentration has been reduced from 25 to 5 ppm. Considering these aspects, the strategy followed for life management of coolant channels with Zr–2.5 wt% Nb pressure tubes is shown in Fig. 13.

4. Conclusion

The research and development activities in the field of life management of zircaloy-2 pressure tubes of Indian PHWRs have progressed hand-in-hand with the operation and inspection experience. Timely solutions have been delivered to take safety related decisions based on sound understanding of active degradation mechanisms. Tools and technologies developed have performed satisfactorily in achieving the targeted life of the component. Presently, the research and development activities are being pursued to cater to the need of Zr–2.5 wt% Nb pressure tubes with the objective of making the design of the inspection tools simpler and keeping the reactor outage to a minimum. Well thought-out pressure tube inspection and material surveillance programme for periodically monitoring the performance and the degradation of the material properties is in place to help in the safe operation of the component till the desired service life. Considering the difficulties involved in removal and replacement of a pressure tube in PHWR, replaceability has been a major objective in designing the coolant channel of the advanced heavy water reactor (AHWR). The design being adopted accomplishes the task of removal and replacement of coolant channel with minimum effort.

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