Development of Advanced Techniques for Life Management and Inspection of Advanced Heavy Water Reactor (AHWR) Coolant Channel Components

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Abstract

Operating life of pressure tubes of Pressurized Heavy Water Reactor (PHWR) is limited due to the presence of various issues associated with the material like hydrogen pick up, delayed hydride cracking, axial elongation and increase in diameter due to irradiation creep and growth. Periodic monitoring of the health of the pressure tube under in-situ conditions is essential to ensure the safe operation of the reactor.

New designs of reactor call for innovative design philosophy, modification in fabrication route of pressure tube, development of reactor specific tools, both analytical and hardware for assessing the fitness for service of the pressure tube. Feedback from existing reactors has enhanced the understanding about life limiting parameters.

This paper gives an insight into the life limiting issues associated with pressure tube and the efforts pursued for development of life management techniques for coolant channel of Advanced Heavy Water Reactor (AHWR) designed in India. The tools and techniques for in-situ property/ hydrogen measurement, pulsed eddy current technique for zirconium alloy in-homogeneity characterization, horizontal shear wave EMAT system for dissimilar metal weld inspection, sliver sampling of vertical channel etc. are elaborated in the paper.

INTRODUCTION

AHWR[1] is a 300 MWe, vertical, pressure tube (PT) type, boiling light water cooled, and heavy water moderated reactor. The reactor incorporates a number of passive safety features and is associated with a fuel cycle having reduced environmental impact. It employs natural circulation for cooling the reactor core under operating and shutdown conditions. The Main Heat Transport (MHT) System transports heat from $(Th\text{-}Pu)O_2$ and $(Th^{233}\text{-}U)O_2$ fuel pins to steam drum using boiling light water as the coolant. The MHT system consists of a common circular inlet header from which feeders branch out to the coolant channels in the core. The outlets from the coolant channels are connected to tail pipes carrying steam-water mixture from the individual coolant channels to four steam drums. Steam is separated from the steam-water mixture in steam drums, and is supplied to the turbine. The condensate is heated in moderator heat exchangers and feed heaters and is returned to steam drums by feed pumps. Four down comers connect each steam drum to the inlet header.

The coolant channel houses the fuel assembly with shielding blocks and has suitable interfaces for coupling to the main heat transport system. A suitable interface is provided for coupling the fuelling machine with the coolant channel to facilitate removal of hot radioactive fuel from the reactor and introduction of fresh fuel into the reactor. The coolant channel has features to accommodate thermal expansion, and irradiation creep and growth.

The vertical coolant channel consists of pressure tube, top and bottom end fittings, and calandria tube (CT). The pressure tube, made of zirconium–niobium alloy, is located in the core portion. The core portion is extended with top and bottom end fittings made of stainless steel. The feeder pipe is connected to the bottom end fitting through a self-energized metal seal coupling which facilitates easy removal. The tail pipe is welded to the top end fitting. The light water coolant enters the coolant channel at 533.5 K, flows past the fuel assembly and hot coolant flows out as steam–water mixture at 558 K to tail pipes. The annular space between the pressure tube and calandria tube, as shown in Fig.1 provides a thermal insulation between the hot coolant and the cold moderator. The coolant channel assembly is laterally supported within the lattice tube by two bearings located at the two ends of the top end shield lattice tube.

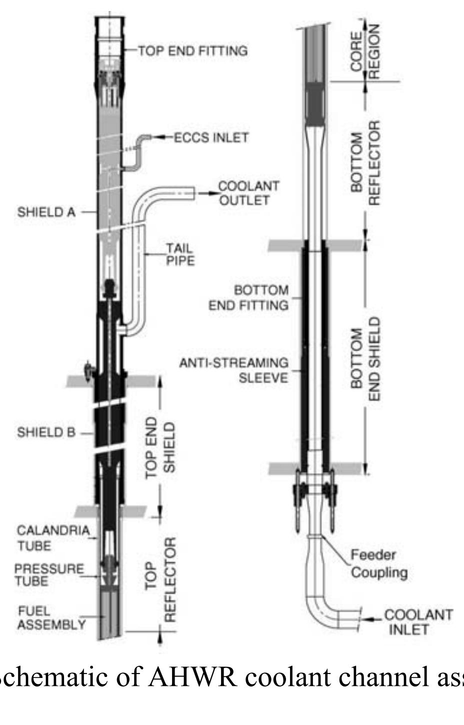

Fig.1: Schematic of AHWR coolant channel assembly

The weight of the coolant channel is supported at the top end shield. The design of coolant channel assembly is guided by the philosophy of easy replacement of pressure tubes as a part of the normal maintenance activity. This allows the individual coolant channel to be replaced at the end of its design life. The pressure tube is provided with an in-built reducer at the bottom end and a thicker walled top end. During replacement of individual channel the pressure tube is detached from the rolled joint with the top end fitting by specifically developed technique based on shock heating; and the bottom end fitting is detached from the feeder by de-coupling the bottom metal seal coupling. The pressure tube together with bottom end fitting will then be removed through the bore of the top end fitting. Top end fitting is provided with two sets of rolled joint bores. A shop assembled fresh pressure tube with bottom end fitting can be inserted through the bore of the top end fitting.

The AHWR pressure tube has an outside diameter of 133 mm and thickness of 6.1 mm at the top end and 90 mm outside diameter at the bottom end. The core region of pressure tube has 120 mm inside diameter and thickness of 3.7 mm. The schematic of pressure tube is shown in Fig.2.

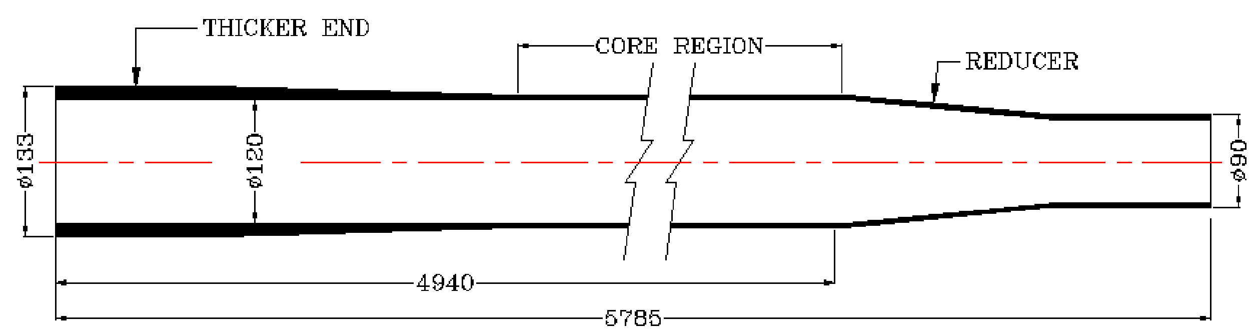

Fig. 2: Schematic of pressure tube of AHWR.

India has accumulated twelve years of operating experience with Zircaloy-2 pressure tubes and ten years of experience with Zr-2.5%Nb pressure tubes in different reactor units. The extensive experience of dealing with degradation issues relevant to Zircaloy-2 pressure tube material that had led to the development of several analytical and hardware tools and technologies for life management of these pressure tubes has helped to work on degradation models and other innovative technologies relevant for life management of Zr-2.5%Nb pressure tubes. These degradation models along with inspection and monitoring systems are also useful for similar activities in AHWR pressure tubes.

This paper discusses the life limiting issues relevant to Zr-2.5%Nb alloy pressure tube material and undergoing developments relevant for life management of Zr-2.5%Nb pressure tube material AHWR coolant channel.

DEGRADATION MECHANISMS AND ASSOCIATED LIFE LIMITING ISSUES RELATED TO AHWR PRESSURE TUBE

AHWR pressure tube operates under the environment of high pressure and temperature (typically, 7 MPa and 558 K), and fast neutron flux (typically, 3.5 x 10^{17} n/m^2 s, E > 1 MeV neutrons). Under this operating environment, the material of the PT undergoes degradation by several mechanisms and eventually needs to be assessed for fitness for continued operation without jeopardising the safety of the reactor.

These degradation mechanisms and associated life limiting issues related to zirconium alloy pressure tubes under PHWR environment have been dealt extensively in the reference [2]. Those relevant to the pressure tube operating under AHWR environment are summarised as follows:

- Dimensional changes due to neutron irradiation creep and growth
- Hydrogen ingress
- Embrittlement due to neutron irradiation and hydriding
- Service induced flaw and its propagation by delayed hydride cracking (DHC) mechanism

In AHWR pressure tube, hydrogen ingress in rolled joint will not be a safety concern because of increased pressure tube wall thickness in this region and its location away from the core region but inside diameter will be a life limiting issue as it is factored into deciding the bore of top end fitting for the easy replacement of pressure tube along with bottom end fitting assembly. Embrittlement of pressure tube material due to neutron irradiation and hydriding is a degradation mechanism but does not have potential to become a safety concern because of high starting fracture toughness of quadruple melted pressure tube material, low initial hydrogen with low in-reactor hydrogen ingress rate and operating stress being lower than threshold for hydride re-orientation. Service induced flaw and its potential to propagate by DHC mechanism will be of safety concern only in the end of service life as low starting hydrogen coupled with low in-reactor ingress rate will result in accumulation of hydrogen sufficient for hydride precipitation at operating temperature towards the end of service life of the pressure tube.

INSPECTION AND MONITORING OF DEGRADATION RELATED PARAMETERS

Along with inside diameter monitoring which appears to be the need of hour in deciding about the fitness of service of AHWR pressure tube, periodic inspection programme will include monitoring for hydrogen ingress in the main body and the rolled joint region of pressure tube, volumetric examination for flaw detection and wall thickness measurement as well.

Tools for measurement of inside diameter, hydrogen measurement by removing sliver scrape samples; wall thickness measurement and flaw detection are all ready in use in horizontal pressure tubes of Indian PHWRs [3]. These tools with suitable modification can be used for similar activities in the vertical pressure tube of AHWR. In-situ measurement tools being developed for evaluating hydrogen ingress and mechanical properties changes respectively in the AHWR pressure tube will also be used for their intended purpose in the vertical pressure tube of AHWR. In addition, tools for characterisation of in-homogeneity in zirconium alloy material, horizontal shear wave electromagnetic and acoustic transducer (EMAT) system for dissimilar metal weld inspection are also being developed. In the subsequent paragraphs, the new developments are described in brief.

Hydrogen Ingress Assessment

Hydrogen ingress will take place in both the rolled joint region and the main body of pressure tube. Monitoring and assessment of hydrogen will ingress in the both regions will be carried out by removing sliver scrape samples and analysing them for hydrogen. Two different tools namely axial scrape sampling tool and circumferential scrape sampling tool have been designed for accomplishing the intended purpose. A new tool based on conductivity measurement using eddy current probe is being developed for carrying out in-situ hydrogen measurement. Once developed, this tool will be used for the carrying of hydrogen measurement in the pressure tube.

Sliver sampling

Axial scrape sampling tool

The vertical scrape sampling tool (Fig.3) has been designed to carry out sliver scrape sampling in a vertically oriented pressure tube. Like the horizontal one it has cutters for removing oxide and metal samples. Oxide is removed first and metal afterwards. Design of cutters and their travel in axial direction are such as to get weight of metal samples in the range of 60 -100 mg. The functionality of this tool has been tested in the vertical test section installed in one of the engineering loops.

Fig. 3: Vertical Scraping tool

Circumferential scrape sampling tool [3]

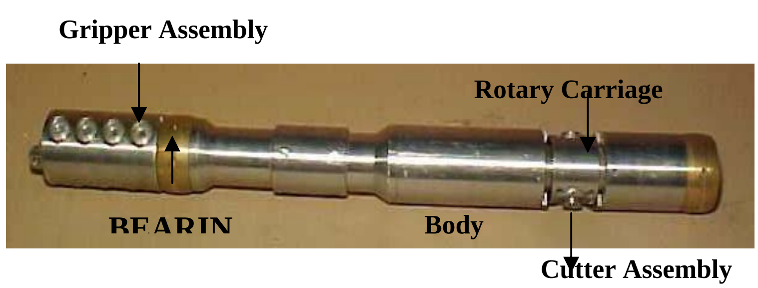

Fig. 4: Circumferential scraping tool

Rolled joint has been observed to have much higher ingress of hydrogen as compared to main body of the pressure tube. The hydrogen ingress in the rolled joint region is monitored by analysing the scrape samples removed from this region. Presence of high concentration gradient of deuterium in the axial direction requires samples to be removed by scraping in the circumferential direction. This can be accomplished with help of a specially developed scraping tool, called circumferential scraping tool (Fig. 4). It first removes 18 mm wide oxide layer of about 100 µm thickness and then 8 mm wide metal layer of 150 µm thickness.

In-Situ Measurement of Hydrogen Concentration in Pressure tube [4]

A new technique based on conductivity measurement by eddy current probe is being developed for hydrogen measurement. It consists of an eddy current probe assembly, thermocouple probe, heating module and sealing arrangement. The technique has been validated by measuring the hydrogen concentration in hydrogen charged pressure tube spool piece using the eddy current probe and later counter checked by measuring hydrogen by conventional method. The first version of tool has been assembled. It has induction heating coil to heat the pressure tube from inside and air inflated seal to isolate the region where the measurement is done. The tool head of hydrogen measurement system is shown in Fig. 5.

Fig.5: Hydrogen measurement system tool head

In-situ Monitoring of Mechanical Properties in Operating Pressure tube [5]

In-situ Property Measurement System (IProMS) based on ball indentation has been developed for estimation of mechanical properties of the pressure tube. 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. The technique has been qualified for stainless steel and cold worked Zr-2.5%Nb pressure tube materials. This technique has the potential of eliminating the removal of pressure tube for material surveillance. Fig.6 shows the tool head of IProMS and Fig.7 shows the tool head being taken inside a pressure tube. Typical results from the tests are shown in Figs. 8 &9.

Fig.6: IProMS tool head

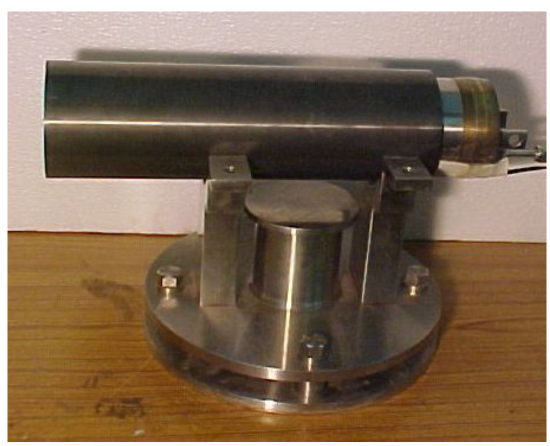

Fig.7: IProMS tool head inside a pressure tube

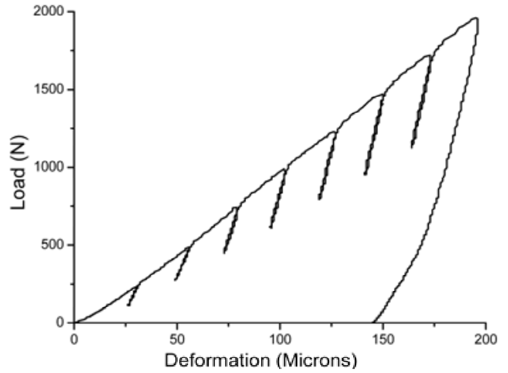

Fig.8: Typical load deformation curve obtained by IProMs during test

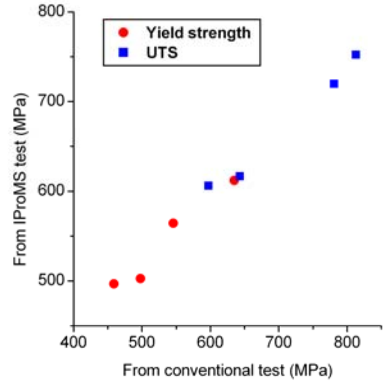

Fig.9: Comparison between properties from conventional tests and IProMS tests

In-homogeneity Characterisation by Pulsed Eddy Current Based System

As-manufactured pressure tube may have in-homogeneous zones where particular phase rich with certain alloying / impurity elements may be present. Such regions sometimes give signals when inspected by eddy current based probe, synonymous to some of those established for identifying presence of certain component (garter spring) / features during in-service inspection and create ambiguity in decision making process. Such features are sensitive to eddy current technique only. Other conventional techniques do not show any conspicuous indications or appear insensitive to them.

In order to carry out investigation for the presence of in-homogeneous zone in a fresh pressure tube, a special probe with associated signal conditioning units has been designed and fabricated. A pressure tube is first scanned with conventional technique and the in-homogeneous locations are identified. Detailed analysis using pulsed eddy current technique is carried out subsequently at the locations of interest. The signals are acquired using a high speed data acquisition system and processed using software coded wigner ville time frequency analysis. The pulsed eddy current technique being broad band technique has been used for discerning the eddy current sensitive parameters. The snapshots given in the Figs.11 (a) & (b) are the time frequency distribution of the zone of normal region of pressure tube and the zone with in-homogeneity and garter spring present at the same location.

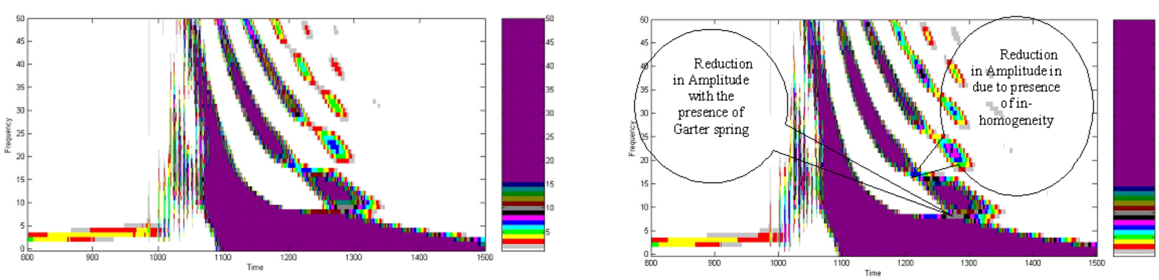

Fig.11: Time (x10^{-7} s)- frequency(x1220 Hz) analysis of (a) normal zone and (b) garter spring signal in the presence of in-homogeneity in a pressure tube

The eddy current technique being a multi-parameter sensitive technique, is quite formidable to separate any specific parameter which is contributing towards the cause of the indication. Conventional mono frequency eddy current technique is used for pressure tube inspection which has the capability to differentiate maximum two parameters out of many parameters which are subject to variation due to various metallurgical transformations under hostile and radioactive environments existing in operating nuclear power plants. In order to overcome this, pulsed eddy current technique which is a broad band technique is proposed to be employed in the excitation pulse. The various frequencies enveloped in the pulse penetrate and subside as per the skin effect phenomena in which higher frequencies subside at lower depths from the surface, where as lower frequencies have more penetration capability and subside at larger depths. This technique has the potential to segregate the indications from the multi-parameters which would otherwise get masked or lead to ambiguous state when screened by conventional mono frequency based eddy current technique.

Assessment of Dissimilar Metal Welds Integrity by Horizontal Shear Wave Electromagnetic and Acoustic Transducer (EMAT)

Inspection of dissimilar metal welds in an austenitic steel component such as the end-fitting of the AHWR is going to be challenging task due to high elastic anisotropy and high coarse grain dendritic structure of the weld metal. Conventional angle beam inspection is based on vertically polarized shear waves which scatter and skew drastically in weld metal. The horizontal polarized shear waves can propagate in a wide angle of incidence ranging from 0º to 90º without any mode conversion from refection or refraction at surfaces perpendicular to propagation direction. Further, they have good penetrating capability in the weld metal which gives improved delectability of defects in the weld. These shear waves can only be generated by EMAT.

The EMAT probe array will be capable for generation of horizontal shear waves at any angle preferably from 0º to 90º with respect to the axis normal to the surface of test object. The angle of propagation is governed by relation $\theta = \sin^{-1}(C/(\lambda f))$ where C is the shear Horizontal velocity of sound in the test object medium, λ is the track wavelength or periodicity of the magnets and f is the frequency of excitation. The probe configuration is shown in Fig. 12 and EMAT system under development is shown in Fig. 13.

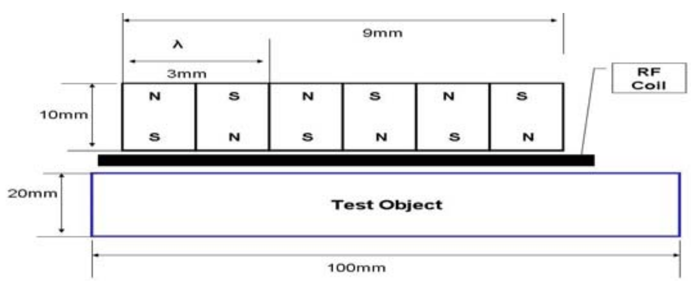

Fig. 12 : Schematic of Shear Wave Probe configuration

Fig. 13: EMAT System under development

DEVELOPMENT OF ANALYTICAL CODES FOR DEGRADATION MODELLING AND RESIDUAL LIFE ESTIMATION OF PRESSURE TUBE

Analytical models for degradation mechanisms were developed for Zirclaoy-2 and Zr-2.5%Nb pressure tubes of Indian PHWRs for residual life assessment. Except for degradation models for blister growth nucleation and growth at PT-CT contact location and irradiation enhanced bending creep which is not relevant of AHWR pressure tubes; all other models will be useful in assessing safe residual life of these pressure tubes. These analytical models have been extensively dealt in reference [3,]. For the sake of continuity, these relevant models and their capabilities are briefly described below.

Computer Code for In-reactor Diametral Expansion and Axial Elongation of Pressure tube [IDEAELP] [6]

This is an upper bound model developed using the deformation equations derived by Christodolou et. al [7] and the data obtained during in-service inspection of the operating Zr-2.5%Nb pressure tubes of the Indian PHWRs. In axial elongation synergistic nature of dimensional changes as a result of creep and growth is assumed whereas the for diametral expansion asynergistic nature of dimensional changes due to creep and growth is assumed. The axial elongation model also takes into account the effect of Iron. The model takes realistic values of channel specific operating parameters like temperature, neutron fast flux, coolant pressure; pressure tube orientation with respect to its back end and front ends and material parameters like room temperature UTS, Fe content etc. Figs.14 & 15 give the comparison of the estimated and the measured values of diametral expansion and axial elongation.

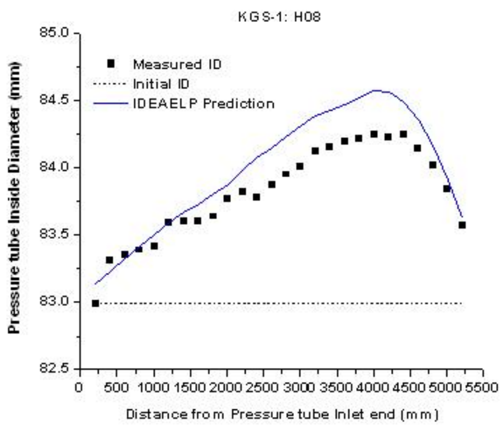

Fig. 14: Comparison of estimated and measured diameter in H08 pressure tube of unit -1 of Kaiga Nuclear Power Station

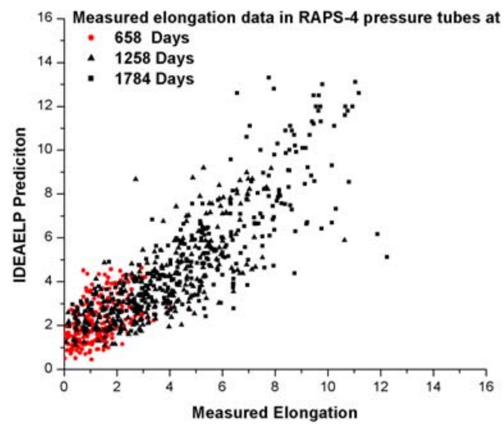

Fig. 15: comparison of estimated and measured axial elongation for different pressure tubes for three different operating periods.

Computer code for estimating hydrogen pick up in Zr 2.5 wt% Nb pressure tubes [3]

Model for estimating oxide and hydrogen pick-up in cold worked Zr-2.5%Nb pressure tube material has been developed on the basis of published PIE results of oxide thickness and hydrogen pick-up for Pickering pressure tubes [8]. Parabolic kinetics has been modelled for in-pile corrosion [9]. The model so developed has been used to estimate the hydrogen pick-up in the slivered Zr-2.5%Nb pressure tubes of unit-2 at Kakrapar Atomic Power Station. The comparison of model prediction and the measured hydrogen pick-up for one of the cases is shown in Fig. 16. The applicability of this code for the light water coolant and partial boiling condition existing in the AHWR coolant channel will be established through out-of-pile corrosion tests.

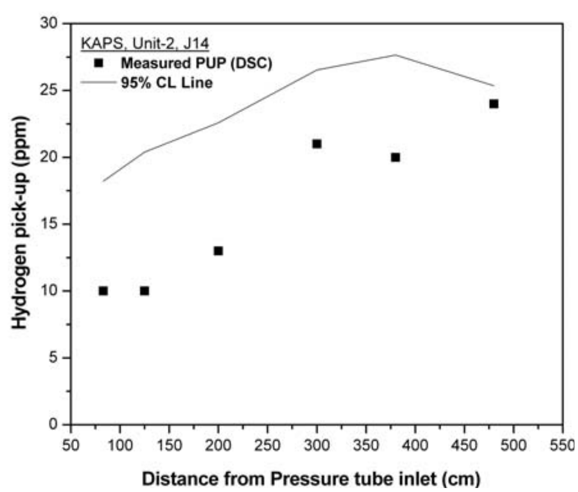

Fig. 16: Comparison of measured and estimated hydrogen

Computer Code to Study the Crack Propagation by Delayed Hydride Cracking (DELHYC) Mechanism [3]

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 references [10, 11]. The model has the capability to simulate delayed hydride cracking under

- isothermal condition where the test temperature is achieved by either heating or cooling,
- effect of direction of approach to test temperature and
- effect of thermal cycling on delayed hydride cracking mechanism.

Some typical studies of estimating crack propagation velocity in a 220 MWe Indian PHWR pressure tube with through wall crack during the process of reactor cold shutting down and hot shutting down and subsequent start-up have been carried out using this code. The results of these studies are shown in the Figs.17 &18.

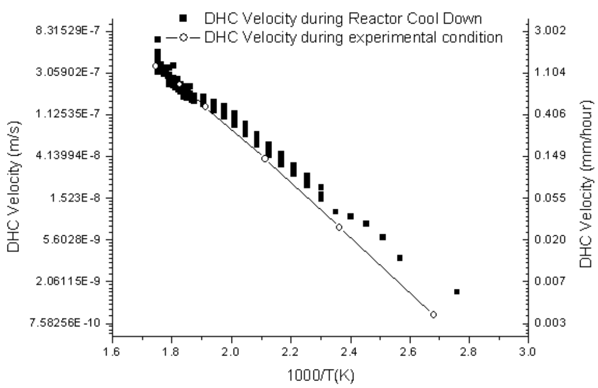

Fig. 17: DHC velocity at the outlet end during cold shutting down

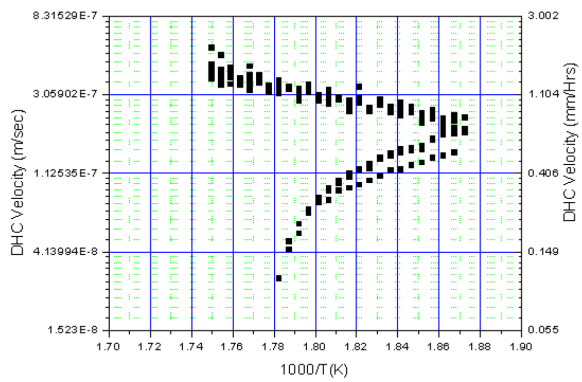

Fig.18: DHC velocity at the outlet end during hot shutting down and subsequent start-up

METHODOLOGIES FOR EVALUATION OF SAFE RESIDUAL LIFE OF ZR 2.5 WT% NB PRESSURE TUBE IN AHWR

Methodologies in the form of acceptance criteria have been developed for evaluating the safe residual life of Zr-2.5%Nb pressure tubes of Indian PHWR considering the different safety concerns. These acceptance criteria, in philosophically are also applicable for AHWR pressure tubes with modification in limiting values of the relevant parameters. The table-1 given below describes the acceptance criteria.

Table 1: 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	➢ 3.7 mm
4	High hydrogen 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.
5	% change in inside diameter as a result of creep and growth	➢ 4.5%of initial inside diameter

LIFE MANAGEMENT STRATEGY

The strategy for life management of AHWR pressure tubes will be centred on diametral change as a result of creep and growth. In general the limiting value of diametral expansion will be around 4.5% of the initial inside diameter but the actual service life of a pressure tube will be governed by the relevant dimensions of pressure tube, top and bottom end fittings and the pressure tube specific expansion rate. As the design of coolant channel provides opportunity for replacement of pressure tube in AHWR as a regular maintenance job, tube specific service life will be assessed for maximising its in-reactor residence time.

CONCLUSION

Present R&D activities have been focussed to cater to the requirement of dealing with the life management issues relevant to Zr-2.5%Nb pressure tubes of AHWR. New developments are being carried out with the objective of making the design of the inspection tools simpler and keeping the reactor outage minimum.

Considering the difficulties involved in removal and replacement of a pressure tube in PHWR, easy replaceability of a coolant channel in Advanced Heavy Water Reactor (AHWR) has been the central objective in its design. Such a design will also help in reducing the inspection burden on a pressure tube life management programme.

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