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In-service Inspection of Nuclear Power Plant Components

B.K. Shah
Quality Assurance Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400 085

Abstract

In India, we currently have two types of nuclear power reactors: Pressurized Heavy Water Reactors (PHWRs) and Boiling Water Reactors (BWRs). The core components in these reactors operate under high temperature and pressure aqueous environment and are subjected to fast neutron irradiation. As far as the material of construction for the core components is concerned, Zirconium alloys (Zircaloy-2, Zircaloy-4 and Zr-2.5% Nb) is predominantly used in PHWRs while Stainless steel (AISI 304/304 L/ 304 LN, AISI 316/ 316 L/ 316 LN) is extensively used in BWRs. There is also a great deal of difference in terms of the chemistry of primary coolant in these two types of reactors: reducing water chemistry in PHWRs as against oxidizing water chemistry in BWRs. For both the types of reactors, it is mandatory to carry out periodic in-service inspection of core components to monitor their degradation due to various damage mechanisms that are possible depending upon the material-environment combination. For PHWRs, each plant has an in-service inspection manual, which is prepared based on various codes such as CAN CSA 285.4, ASME Boiler & Pressure Vessel Code Sec. XI, AERB Safety guides, etc. For BWRs, the in-service inspection requirements are based primarily as per the guidelines of ASME Boiler & Pressure Vessel Code Sec. XI. The in-service inspection of components in these reactors is carried out by employing variety of non-destructive examination (NDE) techniques. These inspections provide valuable inputs in the form of flaw characteristics for structural integrity assessment of these components. They form the basis for taking decisions regarding continued service or removal/quarantine/repair of these components depending on whether the flaw is present and if so, how severe it is? Several NDE techniques have been developed and implemented for use in these reactors keeping in view the degradation mechanism and the nature of flaw it can lead to. These techniques are continuously being evolved so that inspection is carried out in the most effective manner.

In PHWRs, the pressure tube is one of the most critical core components. It carries the nuclear fuel and high temperature high pressure heavy water coolant. The earlier generation of Indian PHWRs had zircaloy-2 pressure tubes, which have now been replaced with Zr-2.5% Nb. All the new generation PHWRs and the ones under construction will have Zr-2.5% Nb as the pressure tube material. The pressure tube operates at 300^{o}C, 11 MPa internal pressure and is subjected to neutron flux of the order of 10^{13} n/cm^2/s. These conditions lead to degradations in the pressure tube with respect to i) dimensional changes as a result of irradiation creep and growth, which result in increase in its diameter and length, ii) deterioration in mechanical properties due to irradiation embrittlement, thereby reducing its flaw tolerance, iii) the growth of existing flaws, which were too small or 'insignificant' at the time of installation, and iv) initiation and growth of new flaws like fretting damage due to debris and fuel element bearing pads. The pressure tube material also undergoes corrosion in heavy water aqueous environment during service. This reaction releases hydrogen, a part of

which gets absorbed in the pressure tube. The absorbed hydrogen can limit the life of a pressure tube due to the degradation mechanisms such as delayed hydride cracking (DHC), hydride blister formation and cracking and hydride embrittlement. It is a regulatory requirement to periodically subject pressure tubes to in-service inspection by employing non-destructive examination techniques. In India, these inspections are carried out by an automated tool called BARCIS (BARC Channel Inspection System). BARCIS inspection head carries ultrasonic and eddy current sensors for volumetric examination of pressure tube to detect and characterize the flaws, if any. In addition to BARCIS, there are several other indigenously developed Diagnostics tools and Analytical Models to assess and predict the health of coolant channels in Indian PHWRs. These life management tools provide valuable inputs to designers, plant operators and the regulatory authorities on fitness-for service assessment of pressure tubes.

Recently, the International Atomic Energy Agency (IAEA) conducted a Coordinated Research Programme (CRP) on Inter-comparison of Techniques for Heavy Water Reactor (HWR) Pressure Tube Inspection and Diagnostics. Seven countries, including India participated in CRP, which lasted for almost five years. The objective of the CRP was the identify the most effective and reliable NDE techniques for flaw characterization in PHWR pressure tubes. The Phase 1 of CRP dealt with flaw characterization in pressure tubes by in-situ NDE techniques. It involved round-robin transfer of pressure tube samples containing flaws that resemble closely with real defect of concern. The samples were prepared by participating laboratories and the defects were hidden to facilitate 'blind tests'. Because these were blind tests, the results of examination on pressure tube samples can be directly correlated with the effectiveness of NDE techniques for detection and characterization of flaws. A good detectability and accurate characterization would strengthen the confidence in the technique(s) employed, while poor detectability and inaccurate characterization would give a feedback to the laboratory that the existing technique needs improvements or new techniques should be developed. The inter-comparison of NDE techniques based on the results of investigation of pressure tube samples highlights the most reliable and accurate NDE method (ultrasonic, eddy-current or a combination of both) and also a specific technique for that NDE method (time-of-flight monitoring, amplitude monitoring, C-scan image, etc.) for detection and characterization of various kinds of flaws encountered in pressure tubes. This information is now available to heavy water reactor community worldwide through IAEA TECDOC 1499 (2006).

In BWRs, austenitic stainless steel is extensively used as a material of construction for core components and primary pipelines. The radiolysis of water by high energy neutrons lead to oxygenated water chemistry in BWRs. As a result intergranular stress corrosion cracking is a generic problem is these reactors. ASME B&PV Code Sec. XI provides guidelines to monitor the initiation and growth of IGSCC in primary pipelines. The code asks for ultrasonic examination of the weld joint (including the heat affected zones) using angle beam shear wave technique and 10% wall thickness deep machined notch as reference defect standard. Recording and detailed evaluation is required for any flaw indication equal to or more than the reference level. This evaluation includes determination of depth (a) by amplitude comparison and length (l) by echo amplitude drop technique. The acceptance criterion is based on the aspect ratio a/l. If this ratio exceeds the limit specified in the code, then that section of the pipe is repaired/replaced. Over the years, many IGSCC failures have been observed in these pipelines and corrective action has been taken. The old pipelines have also been replaced with the new pipelines of IGSCC resistant material. The new pipelines are inspected after installation and also periodically during re-fuelling outage for monitoring IGSCC. One of the significant failures reported in the 1990s due to IGSCC/IASCC in BWRs all over the world, is that of reactor core shroud cracking. The core shroud is a cylindrical vessel inside the main pressure vessel and surrounds the nuclear fuel assemblies. It provides structural support to the core and maintains its geometry. The core shroud welds are examined visually by using a high resolution, radiation resistant camera and by angle beam ultrasonic examination. Special manipulators were designed and fabricated for this purpose. No significant indication has been observed in any of the core shroud welds examined.

The limitation of conventional ultrasonic technique based on amplitude comparison for evaluation of IGSCC depth is well known. The difficulty arises due to the poor reflectivity of IGSCC for the incident ultrasonic waves. In order to overcome these limitations, two approaches were standardized. The first approach uses a known depth IGSCC as reference defect standard instead of machined notch. This approach takes care of the difference in reflectivity of IGSCC in the component and the reference standard. The second approach employs tip diffraction techniques for sizing IGSCC. In these techniques, sizing is based on monitoring the time of travel of the reflected/diffracted signals from the crack extremists. In order to standardize the above two approaches, IGSCC was generated in the laboratory by accelerated tests in 25 mm thick stainless steel plates. The results of the investigation indicate that, the sizing accuracy is greatly improved by following the above two approaches.

The objective of periodic in-service inspection is to detect flaws, which can affect structural integrity of components during service. These flaws can either originate during service or can result due to growth of discontinuities left in the components during fabrication. It is important from the safety point of view that the NDE techniques employed during in-service inspection are very much reliable and sensitive so that all the significant flaws are detected, and at the same time accurate so that the flaw is characterized as close to its real dimensions and its nature is identified. This can be achieved by employing NDE technique(s) which specifically address a particular degradation mechanism in a component. This paper describes the developments carried out in author's laboratory towards development of NDE techniques, which are being used for in-service inspection of primary components in Indian PHWRs and BWRs.