FLAW CHARACTERIZATION IN PHWR PRESSURE TUBES BY ULTRASONICS: INDIA'S EXPERIENCE DURING IAEA CRP

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Abstract

The pressure tubes of pressurized heavy water reactor (PHWR) operate under high temperature high pressure aqueous environment and are subjected to fast neutron irradiation. In order to assure the structural integrity of pressure tube during service, it is periodically examined by non-destructive examination (NDE) techniques. The International Atomic Energy Agency (IAEA) conducted a Coordinated Research Programme (CRP) involving several countries operating heavy water reactors. The CRP involved round-robin transfer of pressure tube samples containing artificial flaws, resembling closely with real defects of concern. The paper gives details of ultarsonic testing techniques employed by India during this CRP and India's performance on flaw detection and sizing in pressure tube samples. Based on the analysis of inspection results, the most effective NDE techniques were identified for flaw characterization in PHWR pressure tubes.

1. Introduction

A typical Indian Pressurized Heavy Water Reactor (PHWR) consists of few hundred horizontally placed coolant channels. The coolant channel comprises of a Zr-2.5% Nb pressure tube encircled by a Zircaloy-4 calandria tube and four garter spring spacers (Zr-2.5 Nb-0.5 Cu), which prevents these two tubes to come in contact during their service life (Figure 1). The pressure tube carries the nuclear fuel, high temperature high pressure heavy water coolant and is subjected to fast neutron irradiation. The integrity of pressure tube is central to the safety of PHWRs. To ensure this, they are periodically subjected to in-service inspection by non-destructive examination (NDE) techniques. The International Atomic Energy Agency (IAEA) conducted a Coordinated Research Programme (CRP) titled 'Intercomparison of Techniques for Pressure Tube Inspection and Diagnostics' involving countries that operate heavy water reactors. The first phase of this CRP dealt with flaw characterization in pressure tubes by in-situ NDE techniques. This paper deals with India's experience during NDE of pressure tube samples, which were circulated as part of this CRP. The results of these investigations and the analysis of test results are discussed.

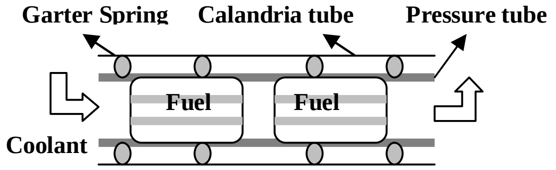


Figure 1: Simplified sketch of coolant channel

2. Pressure Tube Degradation and its Life Management

The 540 MWe Indian PHWR [1] consists of 392 coolant channels. The pressure tube, 103.4mm ID, 4.3mm wall thickness, is approximately 6.3meter long. It operates at 300^{o}C, 110 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). The BARCIS inspection head includes ultrasonic and eddy current sensors and involves four specific tasks: detection of flaw, if any, in pressure tube, measurement of pressure tube wall thickness, measurement of gap between pressure tube and the calandria tube and location of garter spring spacers [2, 3]. 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 [4]. These life management tools provide valuable inputs to designers, plant operators and the regulatory authorities on fitness-for service assessment of pressure tubes.

3. Objective of IAEA CRP

To foster international collaboration in the efficient and safe use of nuclear power, the IAEA conducted a Coordinated Research Programme (CRP) on Inter-comparison of Techniques for Heavy Water Reactor (HWR) Pressure Tube Inspection and Diagnostics. This CRP was carried out within the frame of the IAEA Department of Nuclear Energy's Technical Working Group on Advanced Technologies for HWRs (the TWG-HWR). The TWG-HWR is a group of experts nominated by their governments and designated by the Agency to provide advice and to support implementation of IAEA's Project on advanced technologies for HWRs.

The primary objective of this CRP was to arrive at the most effective NDE techniques for pressure tube inspection. It is very crucial that the NDE techniques that are employed for this purpose are very reliable in detection of all significant flaws and very accurate to characterize them in terms of their geometry and nature. In order to assess the effectiveness of these techniques for their intended purpose, it is important that they are periodically subjected to 'blind tests' on pressure tube samples containing known flaws. This CRP gave the opportunity for the participating laboratories to prepare their own pressure tube samples containing flaws and carry out blind tests on pressure tube samples prepared by others. 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 characterisation of flaws. A good detectability and accurate characterisation would strengthen the confidence in the technique(s) employed, while poor detectability and inaccurate characterisation 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 characterisation of various kinds of flaws encountered in pressure tubes. This information is useful for the heavy water reactor community to improve the tools being used for pressure tube inspection and diagnostics, by modifying the existing techniques or adapting new ones, so that the inspection is carried out in the most effective manner. The inter-comparison of NDE techniques also helps in identifying those areas where none of the existing techniques are reliable or effective to the desired level. It identifies areas of research for future collaboration in this field.

4. Conduct of IAEA CRP on Pressure Tube Inspection and Diagnostics

A total of seven laboratories from six countries, including India participated in this CRP. The participating laboratories prepared pressure tube samples containing artificial flaws resembling real defects of concern. Details on these laboratories and their samples can be found in IAEA TECDOC 1499 [5]. The flaws on the outside surface were hidden by a cover to facilitate blind testing. The CRP was conducted in a round-robin manner during which the pressure tube sample moved from one laboratory to other. All samples had to be inspected from the inside surface, as in real conditions during in-service inspection. The samples, after examination by participating laboratories, were returned to the originating laboratory, which determined 'flaw truth' in its sample by destructive means or non-destructively by using either measuring microscope or profilometry of replica. The originating laboratory analysed the sample inspection reports from investigating laboratories on its pressure tube sample and assessed their performance on flaw detection and sizing. The intercomparison of NDE techniques employed by investigating laboratories provided a very good platform to arrive at the most effective NDE technique(s) for detection and sizing of flaws in pressure tube. These findings are reported in IAEA TECDOC 1499.

5. Indian Pressure Tube Sample

The Indian pressure tube sample IND1 is 103.4mm ID, 4.3mm wall thickness and 500mm long. It contains a total of 17 flaws, including the reference flaws required for calibration of ultrasonic and eddy current examination. The reference flaws are made as per Canadian standard [6], and included axial and circumferential notches and flat bottom reflectors at different depths. In addition to these the Indian pressure tube sample contains OD notches resembling axial, circumferential and oblique delayed hydride cracking (DHC) and ID grooves resembling fretting damage due to debris and bearing pad. Table 1 gives the details of all the flaws in IND 1 sample:

Table 1: Flaws in IND1 pressure tube sample

Sr. No.	Location and Orientation	Flaw Size*			Flaw type
		Length (mm)	Width (mm)	Depth (mm)	
1	OD ,Oblique at 45˚	5.84	0.21	0.16	DHC
2	ID, equiaxed	2.50	2.3	1.15	smooth debris fret
3	OD, equiaxed	1.46	0.80	0.63	laminar flaw near OD
4	ID, axial	11.50	2.3	1.00	bearing pad fret
5	ID, axial	6.00	0.4	0.22	reference flaw
6	ID, circ.	6.00	0.3	0.21	reference flaw
7	OD, oblique at 20˚	5.81	0.24	0.16	DHC
8	OD, equiaxed	1.92	1.27	3.67	laminar flaw near ID
9	ID, axial	2.00	1.0	1.10	sharp debris fret
10	OD, circ.	5.88	0.32	0.11	shallow DHC
11	OD, axial	5.85	0.28	0.13	reference flaw
12	OD, circ.	5.76	0.27	0.14	reference flaw
13	OD, circ.	11.96	0.39	0.23	DHC
14	OD, oblique at 20˚	5.84	0.17	0.13	DHC
15	OD, equiaxed	1.62	1.15	2.14	Laminar flaw at mid-wall
16	OD, axial	5.80	0.24	0.068	shallow DHC
17	OD, axial	11.88	0.35	0.17	DHC

** In the above Table, the flaw dimensions for OD flaws are found out by measuring microscope and for ID flaws by profilometry of replica*

6. Ultrasonic Testing Techniques for Pressure Tube Examination

The selection of NDE techniques for pressure tube examination was left open to the participating laboratory. The underlying condition was that the applied techniques should be useful during in-service inspection. The CRP witnessed two NDE methods for examination of pressure tube samples: ultrasonic and eddy current. India used only ultrasonic testing for examination of pressure tube samples.

The inspection head carries six ultrasonic transducers: four for angle beam examination and the remaining two for normal beam examination. Figure 2 shows the inspection head employed during pressure tube examination

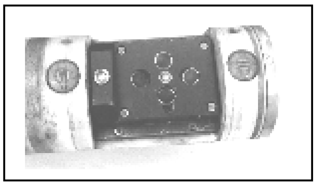


Figure 2: Inspection head for pressure tube examination

The angle beam transducers were arranged in two pairs (axial and circumferential) in which one transducer acted as transmitter and the other as receiver. They are placed on an inspection head such that the ultrasonic beam from transmitter (T) reaches the receiver (R) after travelling two skip distance in the pressure tube. One of the normal beam transducer was focused on OD while the other on ID of the pressure tube. The ultrasonic beam from four angle beam and one normal beam converged at one point in the pressure tube. The schematic arrangement of transducers for different scans is shown in Figure 3:

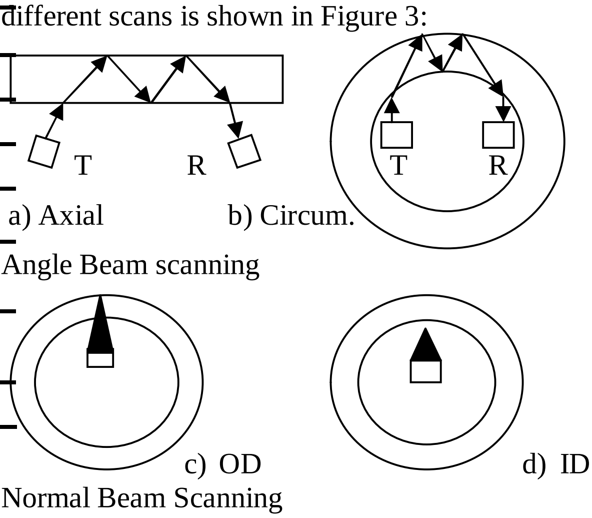


Figure 3: Angle & Normal Beam scans

The ultrasonic transducers for angle beam are 10 MHz frequency, 10 mm dia. and 30 mm focal length. The normal beam OD focused transducer is 10 MHz frequency, 6 mm diameter and 25 mm focal length, while the one focused on ID is 20 MHz frequency, 6 mm diameter and 12 mm focal length. All the transducers are point focused. The ultrasonic technique for flaw detection included pulse-echo and pitch-catch scan using angle beam and pulse-echo scan using normal beam. The angle beam pitch-catch scan is very effective for detection of flaws not favorably oriented, like oblique and tilted flaws. With such an arrangement of transducers, any flaw in the pressure tube, irrespective of its orientation and location is detected in more than one scan. This ensures high degree of reliability in flaw detection. The length and width sizing of flaws was based on 6 dB drop technique, while the depth sizing was based on time-of-flight. Tip diffraction technique was used to get the diffracted signals from flaw tip in angle beam and normal beam scan. Depth of ID flaws was found by ID focused normal beam transducer, which monitors the shift in ID signal (surface profiling). The time-of-flight is measured with a resolution of 1nanaosecond (1GHz digitizer) to get good accuracy in depth sizing. The data record included time-of-flight and amplitude plots and the B-scan images.

7. Pressure Tube Examination Set-up

The pressure tube samples are examined in a semi-automated set-up. The tube is held in fixtures and then filled with water from inside surface. The inspection head carrying ultrasonic transducers is driven by two stepper motors, one for axial and other for rotary motion. During examination, the data is collected by: angle beam pulse-echo axial and circumferential scan, angle beam pitch-catch axial and circumferential scan and normal beam pulse-echo scan. Any indication having amplitude of 6 dB over noise in angle beam pulse-echo scan and/or resulting in amplitude drop of 5% or more in reference signal in normal beam pulse-echo and angle beam pitch-catch scan is evaluated. If the indication is suspected to be from a genuine flaw, then it is evaluated for length, width and depth. The depth is found out by both, angle beam pitch-catch and normal beam. Signals from scratches and dents created in the tube due to handling are only recorded and not evaluated in details.

8. India's Performance during CRP

The Indian inspection team examined a total of seven pressure tube samples from different participating laboratories. These samples contained a total of 170 flaws. All the flaws, which are likely to be present in PHWR pressure tubes, were a part of these samples. India detected all the 170 flaws in these pressure tube samples.

With respect to the sizing, the accuracy of length sizing was very good for all the flaws, except the oblique ones. These flaws are required to be imaged in C-scan mode to get the true estimate of their length. The width of fretting damage and the lap type/laminar flaws was sized very accurately. For crack-like flaws simulated by very fine notches, the width was not reported. None of the NDE techniques employed during this CRP by various participating laboratories could give satisfactory results on width of fine notches. The accuracy of depth sizing for majority of flaws was very good.

Table 2 gives India's result on depth sizing of flaws in one of the pressure tube samples.

Table 2: Inspection results on a pressure tube sample

Flaw Type	Flaw Depth (mm)		
	True value	NDE estimate	Error (mm)
OD, DHC (Semi-elliptical)	2.40 (max.)	2.26	0.14
OD, DHC (Semi-elliptical)	1.56 (max.)	1.38	0.18
OD, DHC (Semi-elliptical)	2.95 (max.)	2.78	0.17
OD, DHC (Semi-elliptical)	0.81 (max.)	0.74	0.07
OD, DHC (Semi-elliptical)	2.05 (max.)	1.65	0.40
OD, DHC (Semi-elliptical)	1.45 (max.)	0.97	0.48
Equiaxed OD Dent	1.52	1.48	0.04
Equiaxed OD Dent	0.53	0.48	0.05
Equiaxed OD Dent	2.03	1.96	0.07
Equiaxed OD Dent	1.04	1.04	0.0
Bearing Pad Fret	1.94	2.26	0.32
Bearing Pad Fret	0.94	0.99	0.05
OD long shallow notch	0.15	0.12	0.03

The above Table indicates that the NDE estimate on depth is very accurate, except for three flaws.

It is observed that other investigating laboratories also encountered error of this order for these flaws. This indicates that the true depth reported by the originating laboratory for these flaws may not be correct.

Table 3 consolidates India's performance on flaw sizing accuracy for all the flaws in all the pressure tube samples examined during this CRP. The flaws in these samples are grouped in to six categories: (i) OD shallow DHC, (ii) OD deep DHC, (iii) ID shallow DHC, (iv) OD oblique DHC, (v) shallow fretting damage and (vi) deep fretting damage. Not included in this Table are: (i) reference notches and flat bottom reflectors as per the Canadian Standard, (ii) lap type or laminar flaws, as their depth sizing is not of interest during in-service inspection, (iii) flaws, for which it is quite likely that the true value reported by the originating laboratory is in-correct and (iv) very deep DHC. The depth sizing accuracy for the above flaw types is expressed in terms of Root Mean Square (RMS) error. It is calculated as follows:

$$\text{RMS Error} = [\Sigma (x_{it} - x_{im})^2 / (n-2)]^{0.5}, \quad i = 1 \text{ to } n$$

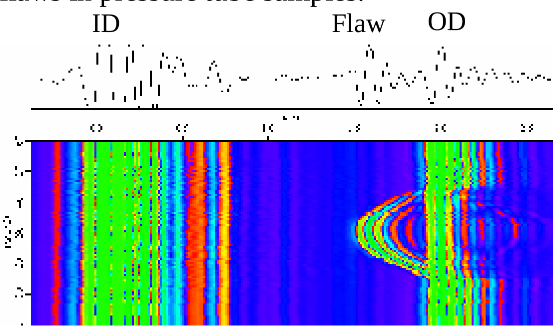
x_{it} is the true flaw depth,
x_{im} is NDE estimate on flaw depth,
n is the number of flaws

Table 3: India's Performance on flaw depth sizing

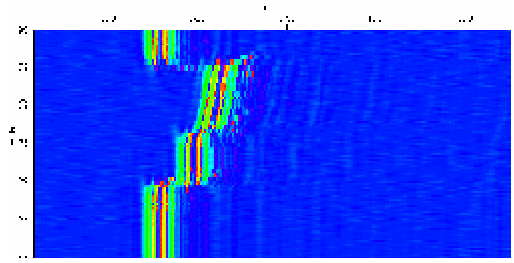
Flaw Type	Depth Range (mm)	Average Depth (mm)	RMS Error (mm)
OD shallow DHC	0.07 - 0.18	0.14	0.027
	0.23 - 0.31	0.27	0.041
OD deep DHC	0.38 - 0.81	0.65	0.113
ID shallow DHC	0.14 - 0.29	0.21	0.026
Oblique DHC	0.11 - 0.17	0.14	0.038
Shallow fretting damage on ID	0.21 - 0.25	0.24	0.045
Deep fretting damage on ID	0.78 - 1.51	1.10	0.075

Table 3 indicates that the accuracy of depth sizing for all the types of flaws in pressure tube samples was very good. For shallow ID and OD DHC, the RMS error is approximately equal to the inherent error involved in time-of-flight measurement. In view of the difficulty associated with locating the flaw-tip for such shallow flaws, the accuracy achieved in their depth sizing is extremely good. The depth of oblique flaws was also sized very well, considering their unfavorable orientation. The debris fret, shallow and deep, were sized most accurately, when seen in relation to the RMS error encountered in terms of percentage of true depth.

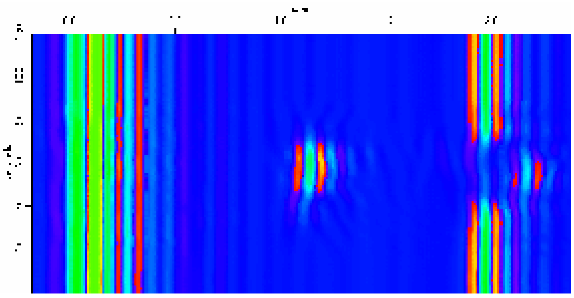
Figure 4 shows the B-scan images for some of the flaws in pressure tube samples.



(a) Simulated DHC on OD



(b) Simulated Bearing Pad Fret on ID

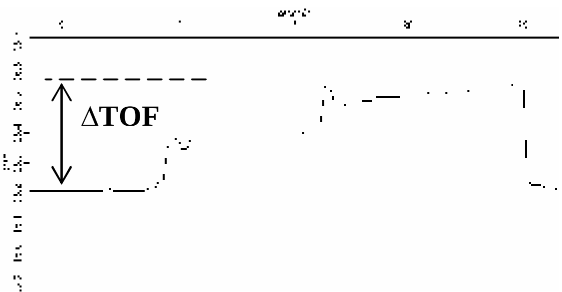


(c) Simulated laminar flaw at mid-wall

Figure 4: B-scan images of simulated flaws in pressure tube samples

Figure 4a shows the B-scan image for the DHC on OD (simulated by a fine notch). The corresponding A-scan at the flaw location is also shown. The image is collected by circumferential movement of a normal beam OD transducer. X-axis represents the time-of-flight and the Y-axis represents the transducer travel. The signal on the left is from pressure tube ID and the one on the right is from pressure tube OD. The semi-elliptical profile of the notch, which is typical of DHC, is clearly seen in the image. The time of-flight plot for this flaw is shown in Figure 5a. From this plot, one can find the maximum shift in time-of-flight (ΔTOF) of the flaw tip signal, with respect to the reference signal (OD) and get the depth estimate. In the present case this shift is 0.408microsecond and the calculated depth is 0.97mm. Figure 4b shows the B-scan image for a bearing pad fret (simulated by ID groove). The image shows the change in surface profile of the ID signal at the flaw location. This image is collected by moving the ID focused normal beam transducer along the width of the flaw. The time of-flight plot for this flaw is shown in Figure 5b. From this plot, one can find the maximum shift in time-of-flight of the reference signal (ID) at the flaw location and get the depth estimate. In the present case this shift is 0.354microsecond and the calculated depth is 0.27mm.

a) Delayed Hydride Cracking



b) Bearing Pa Fret

Figure 5: Time-of-flight plots for simulated flaws in pressure tube

Figure 4c shows the B-scan image for a laminar flaw, which is simulated by a flat bottom reflector. The flaw is at the mid-wall of the pressure tube. The image shows the signals from pressure tube ID and OD and an additional signal from the laminar flaw close to the centre of the pressure tube thickness. For these types of flaws, sizing of their through-thickness dimension is not of concern. They only need to be reliably detected and reported in terms of length, width and depth from scanning surface.

9. Analysis of Inspection Results

The Sample Inspection Reports submitted by investigating laboratories on Indian pressure tube sample were analyzed. The objective of this analysis was to assess the performance of investigating laboratories, but more importantly on the effectiveness of various NDE techniques for flaw detection and sizing. For flaw detection, this analysis was based on comparing the relative response that was observed from a particular flaw using various techniques. For example, in case of ultrasonic testing, the angle beam pulse-echo technique is based on the reflected signal, while the angle beam pitch-catch and normal beam is based on the drop in the amplitude of the transmitted and backwall signal respectively. If the flaw gives higher amplitude of reflected signal in pulse-echo mode and a lesser amplitude drop of transmitted signal in pitch-catch mode, then pulse-echo technique is adjudged the ‘Best’. Contrary to this, if the pulse-echo shows lesser response in terms of amplitude of the reflected signal and a pitch-catch or normal beam show better response in terms of drop in the amplitude of the transmitted or backwall signal, then they are adjudged as the ‘Best’ technique(s).

For flaw sizing, the analysis was based on comparing the true flaw dimensions with the ones estimated by NDE. The first step in this analysis is to find out the error encountered by individual laboratory during NDE sizing of length, width and depth for each flaw in pressure tube sample. The next step was to find out the laboratory, which encountered least error for these dimensions. Finally, the NDE technique employed by this laboratory for that particular dimension is identified. This analysis was carried out for all the flaws in Indian pressure tube sample. This analysis helped in identifying techniques, which worked consistently well for sizing flaw dimensions for different types of flaws in pressure tube sample.

The analysis of inspection results revealed that for axial and circumferential flaws the conventional pulse-echo technique in circumferential and axial direction is good enough. However, for the oblique flaws, the angle beam pitch-catch works much better. The lap-type or laminar flaws are best detected by normal beam scan. The same is also true for ID fretting damage. With respect to flaw sizing, it is observed that for the length, 6 dB or 20 dB drop technique using ultrasonic normal beam is the most suitable technique. The same is applicable for width of the flaw, if it is greater than the size of the ultrasonic beam. For fine crack-like flaws, none of the existing NDE techniques could give desired results. For depth sizing, time-of-flight measurement using normal beam and/or angle beam pitch-catch gave accurate results for OD flaws. ID flaws are best sized by time-of-flight measurement using high frequency normal beam ID focused transducer. A more detailed account of this analysis and the most effective NDE techniques for detection and sizing of various types of flaws can be found in IAEA TECDOC 1499.

10. Conclusion

The structural integrity of pressure tube is of prime importance for the safe operation of heavy water reactors. Non-destructive examination during in-service inspection plays a crucial role in this regard by providing inputs in the form of flaw characteristics. It is of utmost importance that the inspection techniques employed for in-situ pressure tube examination reliably detect all the harmful flaws and characterize them very accurately. The IAEA CRP on pressure tube inspection gave a very good opportunity to the participating laboratories to assess the effectiveness of various NDE techniques (both established and under development) by carrying out blind test on the pressure tube samples. The intercomparison of these techniques based on the results of examination helped in identifying technique(s) most suited for detection and sizing of various types of flaws encountered in heavy water reactor pressure tubes.

India’s performance on flaw detection and sizing during this CRP was excellent. The detection of all the flaws of various size, shape and orientation in all the pressure tube samples is a significant achievement. Equally noteworthy is the accuracy achieved in depth sizing of these flaws by NDE. India’s performance on flaw detection during this CRP reflects the effectiveness of ultrasonic testing techniques employed, especially the new approaches like amplitude drop in angle beam pitch-catch and normal beam examination. A very good accuracy in depth sizing of flaws could be achieved due to the use of time-of-flight based measurements.

India also carried out the detailed analysis of sample inspection reports on Indian pressure tube sample. The analysis led to the identification of most effective NDE techniques for detection and sizing of various types of flaws in heavy water reactor pressure tubes. This assessment is reported in IAEA TECDOC 1499.

12. Acknowledgement

The authors would like to acknowledge International Atomic Energy Agency for granting the permission and the financial assistance to present this work at the APCNDT 2006. The authors would like to put on record their appreciation for the members of inspection teams from various laboratories for carrying out examination of pressure tube samples, providing the inspection reports and analyzing the results of investigation.

13. References

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Abstract

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1. Introduction

A typical Indian Pressurized Heavy Water Reactor (PHWR) consists of few hundred horizontally placed coolant channels. The coolant channel comprises of a Zr-2.5% Nb pressure tube encircled by a Zircaloy-4 calandria tube and four garter spring spacers (Zr-2.5 Nb-0.5 Cu), which prevents these two tubes to come in contact during their service life (Figure 1). The pressure tube carries the nuclear fuel, high temperature high pressure heavy water coolant and is subjected to fast neutron irradiation. The integrity of pressure tube is central to the safety of PHWRs. To ensure this, they are periodically subjected to in-service inspection by non-destructive examination (NDE) techniques. The International Atomic Energy Agency (IAEA) conducted a Coordinated Research Programme (CRP) titled 'Intercomparison of Techniques for Pressure Tube Inspection and Diagnostics' involving countries that operate heavy water reactors. The first phase of this CRP dealt with flaw characterization in pressure tubes by in-situ NDE techniques. This paper deals with India's experience during NDE of pressure tube samples, which were circulated as part of this CRP. The results of these investigations and the analysis of test results are discussed.

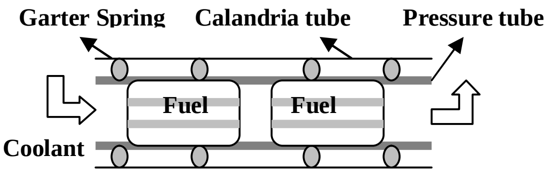

Figure 1: Simplified sketch of coolant channel

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The 540 MWe Indian PHWR [1] consists of 392 coolant channels. The pressure tube, 103.4mm ID, 4.3mm wall thickness, is approximately 6.3meter long. It operates at 300°C, 110 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). The BARCIS inspection head includes ultrasonic and eddy current sensors and involves four specific tasks: detection of flaw, if any, in pressure tube, measurement of pressure tube wall thickness, measurement of gap between pressure tube and the calandria tube and location of garter spring spacers [2, 3]. 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 [4]. These life management tools provide valuable inputs to designers, plant operators and the regulatory authorities on fitness-for service assessment of pressure tubes.

3. Objective of IAEA CRP

To foster international collaboration in the efficient and safe use of nuclear power, the IAEA conducted a Coordinated Research Programme (CRP) on Inter-comparison of Techniques for Heavy Water Reactor (HWR) Pressure Tube Inspection and Diagnostics. This CRP was carried out within the frame of the IAEA Department of Nuclear Energy's Technical Working Group on Advanced Technologies for HWRs (the TWG-HWR). The TWG-HWR is a group of experts nominated by their governments and designated by the Agency to provide advice and to support implementation of IAEA's Project on advanced technologies for HWRs.

The primary objective of this CRP was to arrive at the most effective NDE techniques for pressure tube inspection. It is very crucial that the NDE techniques that are employed for this purpose are very reliable in detection of all significant flaws and very accurate to characterize them in terms of their geometry and nature. In order to assess the effectiveness of these techniques for their intended purpose, it is important that they are periodically subjected to 'blind tests' on pressure tube samples containing known flaws. This CRP gave the opportunity for the participating laboratories to prepare their own pressure tube samples containing flaws and carry out blind tests on pressure tube samples prepared by others. 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 characterisation of flaws. A good detectability and accurate characterisation would strengthen the confidence in the technique(s) employed, while poor detectability and inaccurate characterisation 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 characterisation of various kinds of flaws encountered in pressure tubes. This information is useful for the heavy water reactor community to improve the tools being used for pressure tube inspection and diagnostics, by modifying the existing techniques or adapting new ones, so that the inspection is carried out in the most effective manner. The inter-comparison of NDE techniques also helps in identifying those areas where none of the existing techniques are reliable or effective to the desired level. It identifies areas of research for future collaboration in this field.

4. Conduct of IAEA CRP on Pressure Tube Inspection and Diagnostics

A total of seven laboratories from six countries, including India participated in this CRP. The participating laboratories prepared pressure tube samples containing artificial flaws resembling real defects of concern. Details on these laboratories and their samples can be found in IAEA TECDOC 1499 [5]. The flaws on the outside surface were hidden by a cover to facilitate blind testing. The CRP was conducted in a round-robin manner during which the pressure tube sample moved from one laboratory to other. All samples had to be inspected from the inside surface, as in real conditions during in-service inspection. The samples, after examination by participating laboratories, were returned to the originating laboratory, which determined 'flaw truth' in its sample by destructive means or non-destructively by using either measuring microscope or profilometry of replica. The originating laboratory analysed the sample inspection reports from investigating laboratories on its pressure tube sample and assessed their performance on flaw detection and sizing. The intercomparison of NDE techniques employed by investigating laboratories provided a very good platform to arrive at the most effective NDE technique(s) for detection and sizing of flaws in pressure tube. These findings are reported in IAEA TECDOC 1499.

5. Indian Pressure Tube Sample

The Indian pressure tube sample IND1 is 103.4mm ID, 4.3mm wall thickness and 500mm long. It contains a total of 17 flaws, including the reference flaws required for calibration of ultrasonic and eddy current examination. The reference flaws are made as per Canadian standard [6], and included axial and circumferential notches and flat bottom reflectors at different depths. In addition to these the Indian pressure tube sample contains OD notches resembling axial, circumferential and oblique delayed hydride cracking (DHC) and ID grooves resembling fretting damage due to debris and bearing pad. Table 1 gives the details of all the flaws in IND 1 sample:

Table 1: Flaws in IND1 pressure tube sample

Sr. No.	Location and Orientation	Flaw Size*			Flaw type
		Length (mm)	Width (mm)	Depth (mm)	
1	OD ,Oblique at 45˚	5.84	0.21	0.16	DHC
2	ID, equiaxed	2.50	2.3	1.15	smooth debris fret
3	OD, equiaxed	1.46	0.80	0.63	laminar flaw near OD
4	ID, axial	11.50	2.3	1.00	bearing pad fret
5	ID, axial	6.00	0.4	0.22	reference flaw
6	ID, circ.	6.00	0.3	0.21	reference flaw
7	OD, oblique at 20˚	5.81	0.24	0.16	DHC
8	OD, equiaxed	1.92	1.27	3.67	laminar flaw near ID
9	ID, axial	2.00	1.0	1.10	sharp debris fret
10	OD, circ.	5.88	0.32	0.11	shallow DHC
11	OD, axial	5.85	0.28	0.13	reference flaw
12	OD, circ.	5.76	0.27	0.14	reference flaw
13	OD, circ.	11.96	0.39	0.23	DHC
14	OD, oblique at 20˚	5.84	0.17	0.13	DHC
15	OD, equiaxed	1.62	1.15	2.14	Laminar flaw at mid-wall
16	OD, axial	5.80	0.24	0.068	shallow DHC
17	OD, axial	11.88	0.35	0.17	DHC

** In the above Table, the flaw dimensions for OD flaws are found out by measuring microscope and for ID flaws by profilometry of replica*

6. Ultrasonic Testing Techniques for Pressure Tube Examination

The selection of NDE techniques for pressure tube examination was left open to the participating laboratory. The underlying condition was that the applied techniques should be useful during in-service inspection. The CRP witnessed two NDE methods for examination of pressure tube samples: ultrasonic and eddy current. India used only ultrasonic testing for examination of pressure tube samples.

The inspection head carries six ultrasonic transducers: four for angle beam examination and the remaining two for normal beam examination. Figure 2 shows the inspection head employed during pressure tube examination

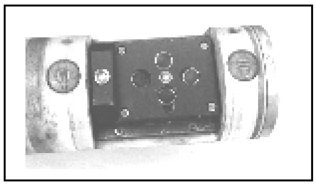


Figure 2: Inspection head for pressure tube examination

The angle beam transducers were arranged in two pairs (axial and circumferential) in which one transducer acted as transmitter and the other as receiver. They are placed on an inspection head such that the ultrasonic beam from transmitter (T) reaches the receiver (R) after travelling two skip distance in the pressure tube. One of the normal beam transducer was focused on OD while the other on ID of the pressure tube. The ultrasonic beam from four angle beam and one normal beam converged at one point in the pressure tube. The schematic arrangement of transducers for different scans is shown in Figure 3:

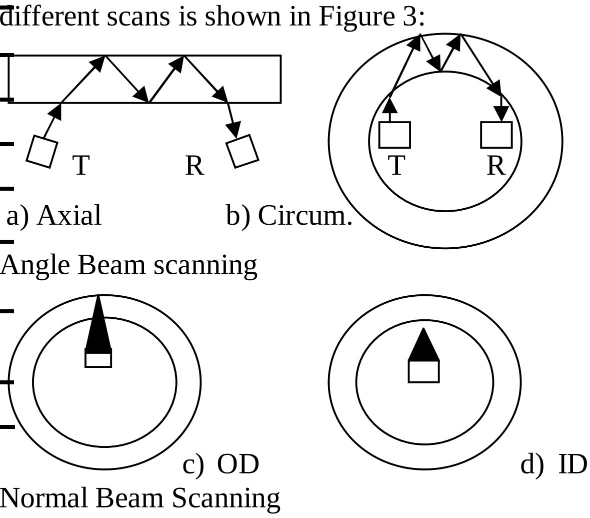


Figure 3: Angle & Normal Beam scans

The ultrasonic transducers for angle beam are 10 MHz frequency, 10 mm dia. and 30 mm focal length. The normal beam OD focused transducer is 10 MHz frequency, 6 mm diameter and 25 mm focal length, while the one focused on ID is 20 MHz frequency, 6 mm diameter and 12 mm focal length. All the transducers are point focused. The ultrasonic technique for flaw detection included pulse-echo and pitch-catch scan using angle beam and pulse-echo scan using normal beam. The angle beam pitch-catch scan is very effective for detection of flaws not favorably oriented, like oblique and tilted flaws. With such an arrangement of transducers, any flaw in the pressure tube, irrespective of its orientation and location is detected in more than one scan. This ensures high degree of reliability in flaw detection. The length and width sizing of flaws was based on 6 dB drop technique, while the depth sizing was based on time-of-flight. Tip diffraction technique was used to get the diffracted signals from flaw tip in angle beam and normal beam scan. Depth of ID flaws was found by ID focused normal beam transducer, which monitors the shift in ID signal (surface profiling). The time-of-flight is measured with a resolution of 1nanaosecond (1GHz digitizer) to get good accuracy in depth sizing. The data record included time-of-flight and amplitude plots and the B-scan images.

7. Pressure Tube Examination Set-up

The pressure tube samples are examined in a semi-automated set-up. The tube is held in fixtures and then filled with water from inside surface. The inspection head carrying ultrasonic transducers is driven by two stepper motors, one for axial and other for rotary motion. During examination, the data is collected by: angle beam pulse-echo axial and circumferential scan, angle beam pitch-catch axial and circumferential scan and normal beam pulse-echo scan. Any indication having amplitude of 6 dB over noise in angle beam pulse-echo scan and/or resulting in amplitude drop of 5% or more in reference signal in normal beam pulse-echo and angle beam pitch-catch scan is evaluated. If the indication is suspected to be from a genuine flaw, then it is evaluated for length, width and depth. The depth is found out by both, angle beam pitch-catch and normal beam. Signals from scratches and dents created in the tube due to handling are only recorded and not evaluated in details.

8. India's Performance during CRP

The Indian inspection team examined a total of seven pressure tube samples from different participating laboratories. These samples contained a total of 170 flaws. All the flaws, which are likely to be present in PHWR pressure tubes, were a part of these samples. India detected all the 170 flaws in these pressure tube samples.

With respect to the sizing, the accuracy of length sizing was very good for all the flaws, except the oblique ones. These flaws are required to be imaged in C-scan mode to get the true estimate of their length. The width of fretting damage and the lap type/laminar flaws was sized very accurately. For crack-like flaws simulated by very fine notches, the width was not reported. None of the NDE techniques employed during this CRP by various participating laboratories could give satisfactory results on width of fine notches. The accuracy of depth sizing for majority of flaws was very good.

Table 2 gives India's result on depth sizing of flaws in one of the pressure tube samples.

Table 2: Inspection results on a pressure tube sample

Flaw Type	Flaw Depth (mm)		
	True value	NDE estimate	Error (mm)
OD, DHC (Semi-elliptical)	2.40 (max.)	2.26	0.14
OD, DHC (Semi-elliptical)	1.56 (max.)	1.38	0.18
OD, DHC (Semi-elliptical)	2.95 (max.)	2.78	0.17
OD, DHC (Semi-elliptical)	0.81 (max.)	0.74	0.07
OD, DHC (Semi-elliptical)	2.05 (max.)	1.65	0.40
OD, DHC (Semi-elliptical)	1.45 (max.)	0.97	0.48
Equiaxed OD Dent	1.52	1.48	0.04
Equiaxed OD Dent	0.53	0.48	0.05
Equiaxed OD Dent	2.03	1.96	0.07
Equiaxed OD Dent	1.04	1.04	0.0
Bearing Pad Fret	1.94	2.26	0.32
Bearing Pad Fret	0.94	0.99	0.05
OD long shallow notch	0.15	0.12	0.03

The above Table indicates that the NDE estimate on depth is very accurate, except for three flaws.

It is observed that other investigating laboratories also encountered error of this order for these flaws. This indicates that the true depth reported by the originating laboratory for these flaws may not be correct.

Table 3 consolidates India's performance on flaw sizing accuracy for all the flaws in all the pressure tube samples examined during this CRP. The flaws in these samples are grouped in to six categories: (i) OD shallow DHC, (ii) OD deep DHC, (iii) ID shallow DHC, (iv) OD oblique DHC, (v) shallow fretting damage and (vi) deep fretting damage. Not included in this Table are: (i) reference notches and flat bottom reflectors as per the Canadian Standard, (ii) lap type or laminar flaws, as their depth sizing is not of interest during in-service inspection, (iii) flaws, for which it is quite likely that the true value reported by the originating laboratory is in-correct and (iv) very deep DHC. The depth sizing accuracy for the above flaw types is expressed in terms of Root Mean Square (RMS) error. It is calculated as follows:

$$\text{RMS Error} = [\Sigma\,(x_{it} - x_{im})^2 / (n-2)]^{0.5}, \quad i = 1 \text{ to } n$$

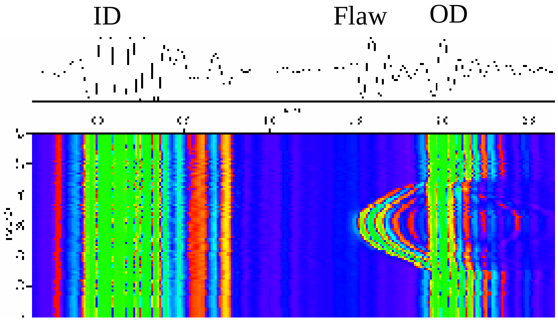
x_{it} is the true flaw depth,
x_{im} is NDE estimate on flaw depth,
n is the number of flaws

Table 3: India's Performance on flaw depth sizing

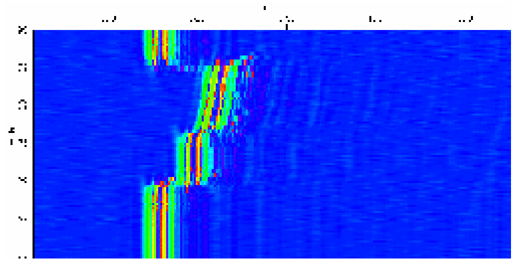
Flaw Type	Depth Range (mm)	Average Depth (mm)	RMS Error (mm)
OD shallow DHC	0.07 - 0.18	0.14	0.027
	0.23 - 0.31	0.27	0.041
OD deep DHC	0.38 - 0.81	0.65	0.113
ID shallow DHC	0.14 - 0.29	0.21	0.026
Oblique DHC	0.11 - 0.17	0.14	0.038
Shallow fretting damage on ID	0.21 - 0.25	0.24	0.045
Deep fretting damage on ID	0.78 - 1.51	1.10	0.075

Table 3 indicates that the accuracy of depth sizing for all the types of flaws in pressure tube samples was very good. For shallow ID and OD DHC, the RMS error is approximately equal to the inherent error involved in time-of-flight measurement. In view of the difficulty associated with locating the flaw-tip for such shallow flaws, the accuracy achieved in their depth sizing is extremely good. The depth of oblique flaws was also sized very well, considering their unfavorable orientation. The debris fret, shallow and deep, were sized most accurately, when seen in relation to the RMS error encountered in terms of percentage of true depth.

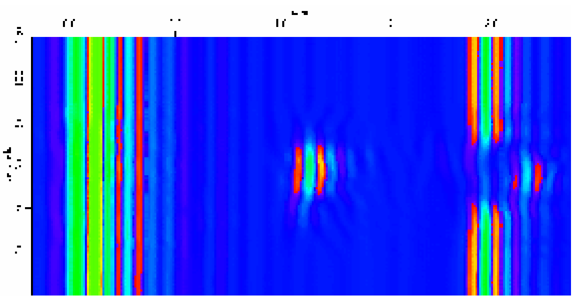
Figure 4 shows the B-scan images for some of the flaws in pressure tube samples.



(a) Simulated DHC on OD



(b) Simulated Bearing Pad Fret on ID



(c) Simulated laminar flaw at mid-wall

Figure 4: B-scan images of simulated flaws in pressure tube samples

Figure 4a shows the B-scan image for the DHC on OD (simulated by a fine notch). The corresponding A-scan at the flaw location is also shown. The image is collected by circumferential movement of a normal beam OD transducer. X-axis represents the time-of-flight and the Y-axis represents the transducer travel. The signal on the left is from pressure tube ID and the one on the right is from pressure tube OD. The semi-elliptical profile of the notch, which is typical of DHC, is clearly seen in the image. The time of-flight plot for this flaw is shown in Figure 5a. From this plot, one can find the maximum shift in time-of-flight (ΔTOF) of the flaw tip signal, with respect to the reference signal (OD) and get the depth estimate. In the present case this shift is 0.408microsecond and the calculated depth is 0.97mm. Figure 4b shows the B-scan image for a bearing pad fret (simulated by ID groove). The image shows the change in surface profile of the ID signal at the flaw location. This image is collected by moving the ID focused normal beam transducer along the width of the flaw. The time of-flight plot for this flaw is shown in Figure 5b. From this plot, one can find the maximum shift in time-of-flight of the reference signal (ID) at the flaw location and get the depth estimate. In the present case this shift is 0.354microsecond and the calculated depth is 0.27mm.

a) Delayed Hydride Cracking

b) Bearing Pa Fret

Figure 5: Time-of-flight plots for simulated flaws in pressure tube

Figure 4c shows the B-scan image for a laminar flaw, which is simulated by a flat bottom reflector. The flaw is at the mid-wall of the pressure tube. The image shows the signals from pressure tube ID and OD and an additional signal from the laminar flaw close to the centre of the pressure tube thickness. For these types of flaws, sizing of their through-thickness dimension is not of concern. They only need to be reliably detected and reported in terms of length, width and depth from scanning surface.

9. Analysis of Inspection Results

The Sample Inspection Reports submitted by investigating laboratories on Indian pressure tube sample were analyzed. The objective of this analysis was to assess the performance of investigating laboratories, but more importantly on the effectiveness of various NDE techniques for flaw detection and sizing. For flaw detection, this analysis was based on comparing the relative response that was observed from a particular flaw using various techniques. For example, in case of ultrasonic testing, the angle beam pulse-echo technique is based on the reflected signal, while the angle beam pitch-catch and normal beam is based on the drop in the amplitude of the transmitted and backwall signal respectively. If the flaw gives higher amplitude of reflected signal in pulse-echo mode and a lesser amplitude drop of transmitted signal in pitch-catch mode, then pulse-echo technique is adjudged the 'Best'. Contrary to this, if the pulse-echo shows lesser response in terms of amplitude of the reflected signal and a pitch-catch or normal beam show better response in terms of drop in the amplitude of the transmitted or backwall signal, then they are adjudged as the 'Best' technique(s).

For flaw sizing, the analysis was based on comparing the true flaw dimensions with the ones estimated by NDE. The first step in this analysis is to find out the error encountered by individual laboratory during NDE sizing of length, width and depth for each flaw in pressure tube sample. The next step was to find out the laboratory, which encountered least error for these dimensions. Finally, the NDE technique employed by this laboratory for that particular dimension is identified. This analysis was carried out for all the flaws in Indian pressure tube sample. This analysis helped in identifying techniques, which worked consistently well for sizing flaw dimensions for different types of flaws in pressure tube sample.

The analysis of inspection results revealed that for axial and circumferential flaws the conventional pulse-echo technique in circumferential and axial direction is good enough. However, for the oblique flaws, the angle beam pitch-catch works much better. The lap-type or laminar flaws are best detected by normal beam scan. The same is also true for ID fretting damage. With respect to flaw sizing, it is observed that for the length, 6 dB or 20 dB drop technique using ultrasonic normal beam is the most suitable technique. The same is applicable for width of the flaw, if it is greater than the size of the ultrasonic beam. For fine crack-like flaws, none of the existing NDE techniques could give desired results. For depth sizing, time-of-flight measurement using normal beam and/or angle beam pitch-catch gave accurate results for OD flaws. ID flaws are best sized by time-of-flight measurement using high frequency normal beam ID focused transducer. A more detailed account of this analysis and the most effective NDE techniques for detection and sizing of various types of flaws can be found in IAEA TECDOC 1499.

10. Conclusion

The structural integrity of pressure tube is of prime importance for the safe operation of heavy water reactors. Non-destructive examination during in-service inspection plays a crucial role in this regard by providing inputs in the form of flaw characteristics. It is of utmost importance that the inspection techniques employed for in-situ pressure tube examination reliably detect all the harmful flaws and characterize them very accurately. The IAEA CRP on pressure tube inspection gave a very good opportunity to the participating laboratories to assess the effectiveness of various NDE techniques (both established and under development) by carrying out blind test on the pressure tube samples. The intercomparison of these techniques based on the results of examination helped in identifying technique(s) most suited for detection and sizing of various types of flaws encountered in heavy water reactor pressure tubes.

India's performance on flaw detection and sizing during this CRP was excellent. The detection of all the flaws of various size, shape and orientation in all the pressure tube samples is a significant achievement. Equally noteworthy is the accuracy achieved in depth sizing of these flaws by NDE. India's performance on flaw detection during this CRP reflects the effectiveness of ultrasonic testing techniques employed, especially the new approaches like amplitude drop in angle beam pitch-catch and normal beam examination. A very good accuracy in depth sizing of flaws could be achieved due to the use of time-of-flight based measurements.

India also carried out the detailed analysis of sample inspection reports on Indian pressure tube sample. The analysis led to the identification of most effective NDE techniques for detection and sizing of various types of flaws in heavy water reactor pressure tubes. This assessment is reported in IAEA TECDOC 1499.

12. Acknowledgement

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