DEVELOPMENT OF REMOTE FIELD EDDY CURRENT TECHNOLOGY FOR STRUCTURAL INTEGRITY ASSESSMENT OF STEAM GENERATORS OF PFBR

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ABSTRACT

This paper discusses the development of remote field eddy current (RFEC) testing technology for in-service inspection (ISI) of steam generator (SG) tubes of 500 MWe Indian prototype fast breeder reactor (PFBR). This involves development of RFEC instrument and probe after numerical modeling using finite element method followed by experimental investigations to study the influence of sodium deposits on defect detection and development of wavelet transform based advanced signal processing technique for elimination of strong signals in the expansion bend regions of the SG tubes. This technology has been demonstrated on a full scale mock up test facility and also been innovatively used to assess the structural integrity of outer peripheral tubes of the SGs subsequent to welding of circumferential shells.

Keywords: Steam generator, structural integrity, in-service inspection, non-destructive evaluation, remote field eddy current.

INTRODUCTION

Steam generators are the most critical components in any nuclear power plant. The SGs of the Indian PFBR are vertical (25 m) countercurrent shell-and-tube type heat exchangers with sodium on shell side flowing from top to bottom and water/steam on the tube side. There are a total of eight SGs in PFBR and modified 9Cr-1Mo steel has been chosen as the structural material for the SG tubes [1-2]. The SGs are provided with expansion bends (bend radius 375 mm with a developed length of 1178 mm) to accommodate differential thermal expansion. Any leakage in the tube (wall thickness 2.3 mm) would be catastrophic as sodium-water reaction is violent and exothermic. In view of this, periodic in-service inspection during shutdown using non-destructive evaluation (NDE) techniques is essential to ensure safe and reliable operation of SGs and for achieving high plant availability factors. The conventional eddy current technique used for ISI of non-magnetic tubes and the saturation based eddy current technique employed for quality assurance of the tubes can't be used for NDE of installed SG tubes. The major challenges for development of NDE technique for ISI of SG tubes include the following:

- *Ferromagnetic nature of tube material with very small skin-depth,*
- *Expansion bends requiring design and development of flexible probes,*
- *Electrically conducting sodium filling the defects on OD side, if any, disturbing the eddy current signals,*
- *Disturbing signals from permeability variations, stresses, probe wobble and bend regions, requiring development of digital signal processing techniques and*
- *One-side access requiring development of robot device for automated inspection.*

As a solution to the above challenges, advanced remote field eddy current (RFEC) testing technology has been developed in-house after systematic finite element (FE) modeling, validation, and experimental studies in a sodium test vessel. This technology has been successfully demonstrated in a full-scale SG test facility available at the authors' center. This paper discusses the RFEC technique, instrument, probes, finite element models, digital signal processing methods, robotic devices etc. developed towards realizing comprehensive technology for ISI of SGs of PFBR. This paper also highlights the future directions for enhancing the capability of this technology to image defects through array sensing and to increase the speed of inspection for reducing the downtime of the SGs.

PRINCIPLE OF REMOTE FIELD EDDY CURRENT TESTING TECHNIQUE

The RFEC technique is mainly applicable to NDE of metallic tubes with probe scanning from tube side. This technique uses separate exciter and receiver coils that are kept inside the tube as shown in Fig. 1. The exciter

coil is powered by a low frequency sinusoidal current source (less than 2 kHz). The magnetic field inside the tube falls exponentially along the tube length up to certain distance and again increases and then decreases, due to the influence of secondary indirect magnetic fields travelling through the tube wall. This region where the field increases is characterized by the reentry of the indirect magnetic field. The indirect magnetic field couples the receiver coil through the tube wall at a characteristic distance (approximately 2-3 times the tube inner diameter) to induce voltage whose amplitude and phase lag (with reference to exciter voltage) is measured and correlated with the defect depth or wall loss. The exciter and receiver coils are moved in tandem and as a result, the typical RFEC signal for a defect exhibits characteristic double peak response; one when the exciter coil moves over the defect and the other when the receiver coil moves over the defect. The RFEC technique has been modeled extensively using finite element methods by several research groups and its theory is well understood [3-7].

The RFEC instrument and probes have been designed and developed in-house [8]. The RFEC instrument as shown in Fig. 2 consists of a high power sinusoidal source for excitation and a lock-in amplifier to pick-up weak magnetic fields in the remote field region after signal conditioning. During RFEC testing, the probe is retrieved from the SG tube at a constant speed of 1 mm/s using a servo motor and the analog output from the lock-in amplifier is digitized using a 12-bit analog to digital converter card interfaced to a personal computer.

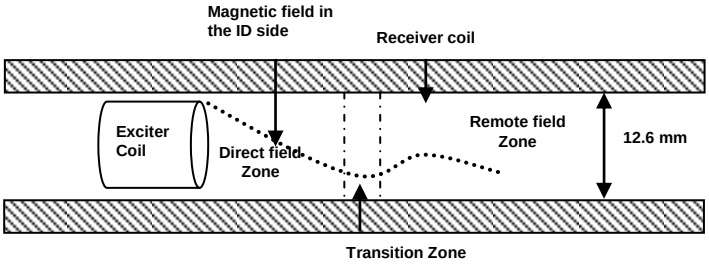

Fig. 1 Principle of RFEC technique for testing SG tubes.

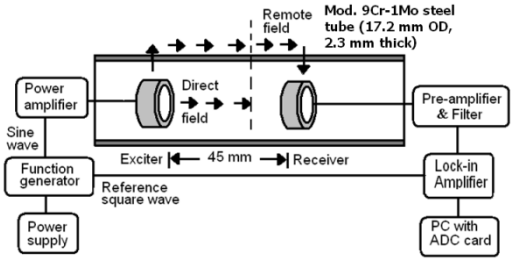

Fig. 2 Schematic of the RFEC instrument.

FINITE ELEMENT MODELING OF RFEC TECHNIQUE

Design of RFEC probe requires a thorough understanding of direct, transition and remote field regions in the tube at different frequencies, for optimizing the test frequency and the spacing between the exciter and the receiver coils. This has been performed using 3-D FE modeling. The governing partial differential equation (PDE) for RFEC technique is given by

$$\nabla \times \nabla \times \vec{A}_{\varphi} = \mu \vec{J}_S - j\omega\mu\sigma\vec{A}_{\varphi} \qquad (1)$$

where A, J_s, σ and μ are magnetic vector potential, current density, magnetic permeability, electrical conductivity of the tube material respectively. The FE method consists of discretization (meshing) of the solution domain consisting of tube, probe and defect and assuming a trial solution within each element using basis or shape functions and substituting the solution in the PDE and minimization of error due to the assumed solution to finally arrive at the variable of interest i.e. A in each element.

Fig. 3 shows the 3-D model predicted induced voltage in a receiver coil as a function of axial distance of a receiver coil for frequencies from 700 Hz to 1500 Hz. The intensity of back entered remote field (with respect to transition minimum) has been found to be maximum at 1100 Hz at around 2.5 times the inner diameter of the tube (approximately 31.5 mm). This frequency and the inter-coil spacing are taken as optimum for the tube dimensions, materials properties and exciter coil dimensions considered. Based on the model predictions, an RFEC probe comprising of exciter and receiver coils has been designed and fabricated. The probe (Fig. 4) has been made flexible to readily negotiate the expansion bend regions.

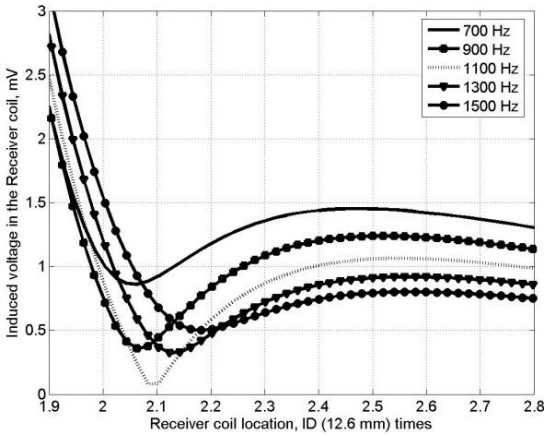

Figure 3 3-D FE model predicted receiver coil voltage as a function of axial distance.

Figure 4 In-house developed flexible RFEC probe with exciter and receiver coils.

Reference defects with 10%, 20% 30% and 40% wall loss (WL) grooves (width 2 mm) have been machined in SG tube and typical RFEC signals obtained by scanning the RFEC probe are shown in Fig. 5. The characteristic double peaks are observed in signals as expected and a near-linear relationship is observed between RFEC signal phase and wall loss.

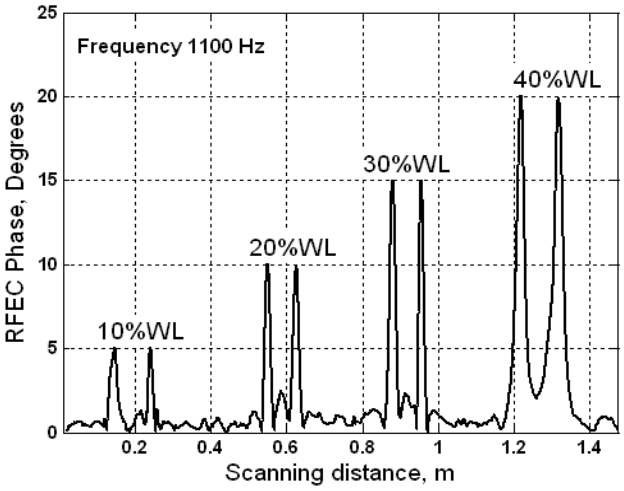

Fig. 5 Experimentally obtained RFEC signals of reference defects in SG tube of PFBR.

STUDIES ON THE INFLUENCE SODIUM DEPOSITS IN THE DEFECTS

It is envisaged that remnant sodium deposits in the defects, if any, on the outer surface of the tubes will influence the RFEC signals due to the electrical conductivity of sodium. Systematic experimental studies were carried out in this regard by simulating machined grooves in SG tubes and exposing five tubes (1200 mm length) in a specially designed stainless steel test vessel replicating the actual ISI conditions of the SG tubes. In these tubes, circumferential grooves of 10%, 20%, 30% and 40% wall loss (width 3 mm and 2 mm) were machined on the tube outer surface. One tube was left defect-free to obtain baseline data and to visually examine the sodium deposits. These five tubes were welded to a 233 mm diameter circular flange. The bottoms of the tubes were hermetically sealed to prevent entry of sodium into the tubes. The flange was kept inside a test vessel (height 1248 mm and diameter 417 mm). Hot sodium at 500° C was pumped into the test vessel to about 600 mm height to ensure complete immersion of the grooves in the tubes and then, the sodium was drained after 2 hours. This step was repeated for five times to simulate the actual SG conditions and the RFEC signals from tubes were acquired before

and after the sodium exposure. Fig. 6 shows the photograph of the flange after it was removed from the test vessel. Visual examination confirmed build-up of sodium deposits on the outer surface and also in the grooves. A definite change in the form of formation of a valley between the characteristic peaks of the RFEC signals was observed in the signals as typically shown in Fig. 7. This was found to be due to the presence of sodium deposits in the grooves. Detailed studies revealed that the signal peak-to-peak amplitude remained unchanged before and after the sodium exposure. This has been effectively used for reliable identification and sizing of defects in the SG tubes despite the presence of sodium [10].

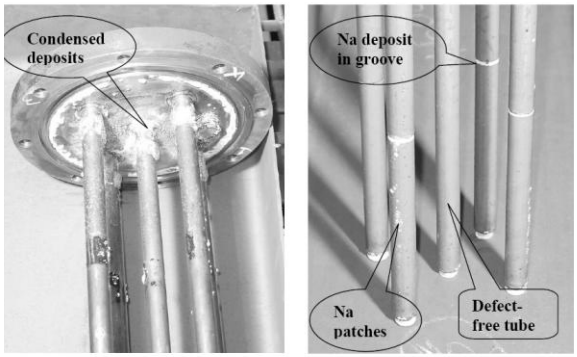

Figure 6 Flange and tubes after exposure to sodium.

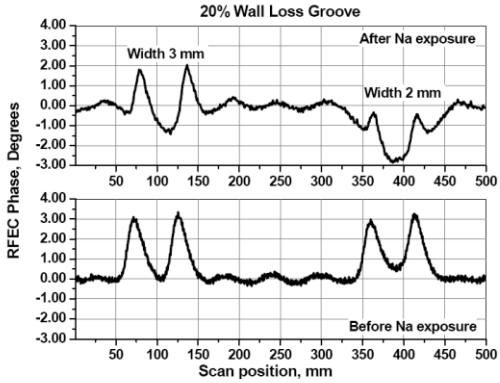

Figure 7 RFEC signals of 20% wall loss groove in the SG tubes before and after sodium exposure.

DEVELOPMENT OF ADVANCED SIGNALS PROCESSING TECHNQIUE

Detection of defects by the RFEC technique in expansion bend regions is influenced by disturbing variables such as changes in electromagnetic coupling due to exciter-receiver coil misalignment, bending stresses, magnetic permeability variations and probe wobble. It is observed that RFEC response due to misalignment of coils, bending stresses and probe wobble is slowly varying (extended) in nature, contributing to shift in the baseline. The response due to permeability variations is of higher frequency and distributed. On the contrary, the response for wall loss defects is highly localized and of intermediate frequencies, depending on the type and size of the defects. Utilising the time-frequency localization property of the wavelets and using them as band-pass filters, an advanced signal processing technique has been developed.

RFEC signals of 10%, 20% and 30% wall loss grooves in the bend regions have been obtained and processed using wavelet transform technique. Gaussian like wavelets such as Second derivative of Gaussian (Gaus2), Mexican hat (Mexh), Biorthoganal (Bior2.8) and Daubechies (DB5) wavelets have been attempted. In order to identify the optimal wavelet and the scale factor of the wavelet to be used for denoising, signal to noise ratio (SNR) has been determined. The SNR is found to be maximum for the Bior2.8 wavelet at a scale factor 19. This wavelet is also found to retain the double-peak behavior of the RFEC signals and hence is chosen [11]. Fig. 8 shows the RFEC signals processed by Bior2.8 wavelet. Application of the wavelet transform technique has resulted in 7dB improvement in the SNR as typically shown in Fig. 8. It is possible to detect defects deeper than 10% wall thickness, present anywhere in the bend regions of the SG tubes using this technique. The sizing performance of the wavelet transform technique has been analyzed for defects in bend regions as well as straight regions of the SG tube. Fig. 9 shows the mean peak amplitude of RFEC signals for grooves in straight regions and bend regions after the wavelet transform processing. It is observed that the mean amplitudes of the signals of grooves in the bend regions are always higher than that of the straight regions. Based on this observation, use of separate calibration graphs has been proposed for accurately sizing the defects in straight and bend regions of the SG tubes.

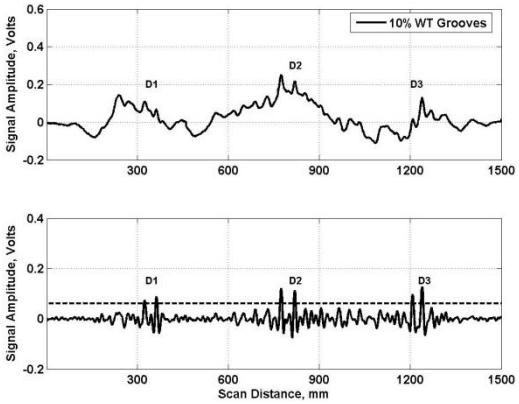

Figure 8 Raw RFEC signals of 10% wall loss defects in bend regions (top) and signals after wavelet transform processing (bottom).

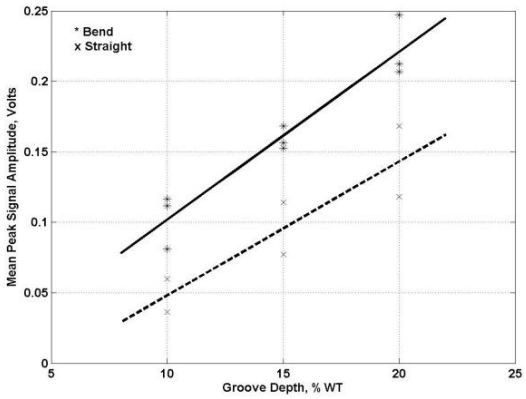

Figure 9 Calibration graph for groove sizing in bend as well as straight SG tubes.

Demonstration of RFEC Technology

The RFEC technology has been demonstrated for ISI of Steam Generator Test Facility (SGTF) available at the authors' center. The SGTF is a vertically mounted 1:1 steam generator with 19 nos. of 23 m long tubes. RFEC probe having a few 15 mm long high density depleted Uranium rings with central hole has been specially developed to enable easy lowering and negotiation through bend regions by gravity. The probe's outer diameter, effective length, fill-factor, dead-weight, and cable length are 11.5 mm, 60 mm, 90%, 200g, and 27 m, respectively. The ISI has been carried out from the top tube sheet. A specially designed, computer controlled winch shown in Fig. 10 with a coil drum has been used for retrieval of the probe at a constant speed of 25 mm/s. The RFEC data has been acquired at 900 Hz and 1100 Hz frequencies, at 200 samples/s and stored in binary format and with unique file names. Typical data acquired for a tube B1 in SGTF at 1100 Hz is shown in Fig. 11. The locations of the support plates and bend regions have been identified and matched well with the drawings. From the inspection data, presence of any characteristic double-peak signal typical of a localized wall loss or defect, if any, has been looked for [12]. Analysis revealed that none of the 19 tubes had any defect comparable to the 10% wall loss reference defect.

The RFEC testing technology has been recently applied innovatively for structural integrity assessment of outer peripheral tubes of the SGs by way of detection of arc-strike, spatter and fusion of tube wall with SG shell, if any, occurred during the final circumferential shell welding. Systematic research investigations have been carried out on six numbers of calibration mock-up specimens with low, medium and high levels of 1) arc strike 2) spatter globules and 3) fusion types of defects introduced by varying the welding parameters (welding current, root gap length) as detailed in Table 1. Studies revealed that RFEC signals due to arc strike, spatter, and fusion are unique and distinguishable from each other and also from the Inconel-718 support structures. A new methodology that uses RFEC technique for defect detection from tube side and ultrasonic technique for detection of weld defects from shell side with automated K-Means clustering algorithm has been developed (refer Fig. 12) and successfully implemented at the manufacturing site [13]. This methodology also has been successfully validated for tubes having defects. In addition to ensuring the structural integrity of the SG, this approach has also enabled to qualify the welding procedure adopted for shell welding.

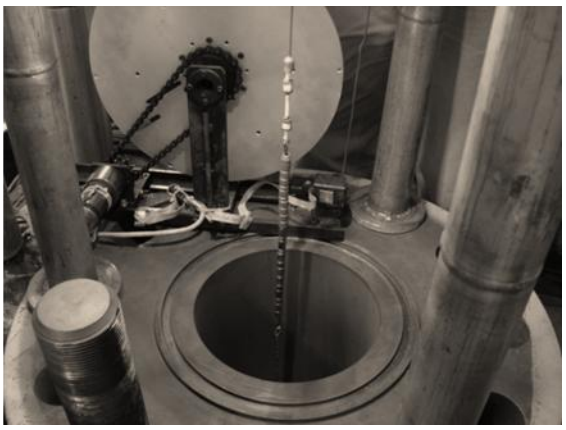

Figure 10 Specially designed computer controlled winch with cable drum for retrieving RFEC probe during ISI of SG tubes.

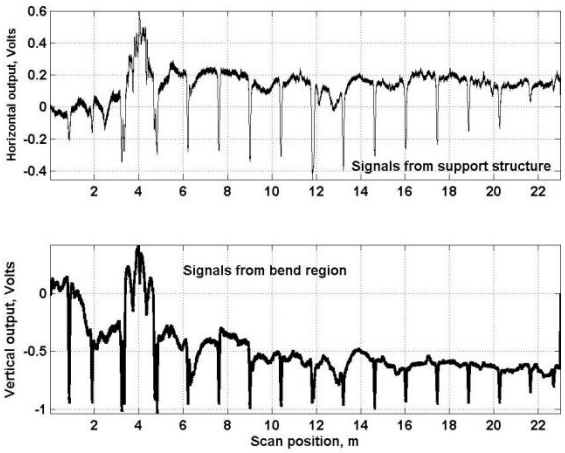

Figure 11 RFEC signals at 1100 Hz obtained from tube B1 in SGTF.

Table 1 Welding parameters used for introducing the reference defects.

Specimen No.	Type of defect	Variability in the welding parameters
1	Without defects	Nil
2	Low arc strike	Welding current (I) = 60 A
	Medium arc strike	I =100 A
	High arc strike	I =120 A
3	Low spatter	Spatter globule size (S) 0-0.5 mm
	Medium spatter	S = 0.5-1.0 mm
	High spatter	S =1.0-2.0 mm
4	Low fusion	0.5-1 mm root gap length
5	Medium fusion	1-2.5 mm root gap length
6	High fusion	2.5-4.0 mm root gap length

FUTURE DIRECTIONS

In the RFEC technique when single circumferential receiver coil is used, the detection sensitivity for localized defects is poor due to limited linkages of magnetic field with receiver coil and also defect location identification is not possible. Use of localized receiver coils is advantageous and in this direction, two types of receiver coils viz. radial and axial are being studied. Preliminary studies using the finite element model reveal that radial receiver coils show higher sensitivity for detection of localized defects than the axial receiver coils. Further work is in progress to fabricate RFEC probe with an array of radial sensors and to validate the same. Studies are also in progress to use Giant Magneto-resistive (GMR) array sensors for detection of leakage magnetic flux from defects and development of suitable magnetizing unit inside the tube without the need for demagnetization. Use of array sensors allows the possibility of imaging defects as well as application of standard image processing techniques for enhanced quantitative characterisation of defects.

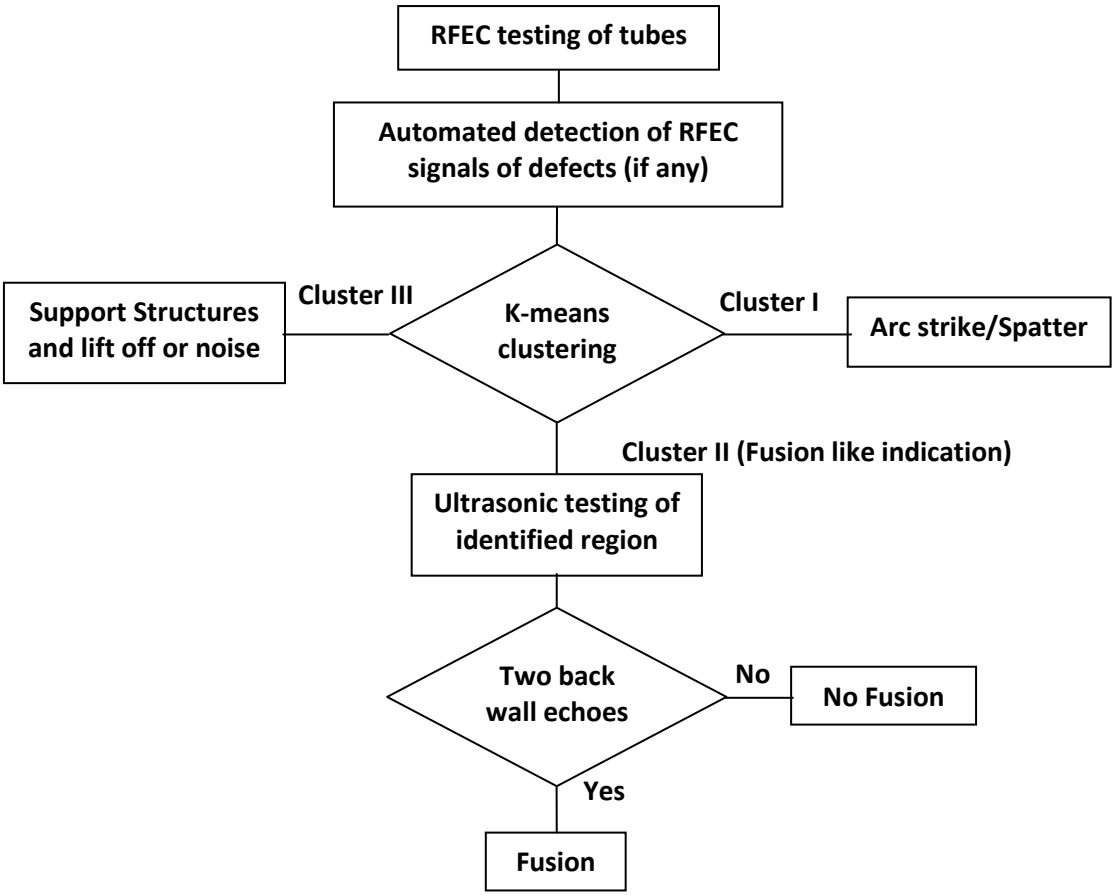

Fig. 12 New methodology that uses RFEC and ultrasonic techniques developed for detection of defects after circumferential welding of SG shells at manufacturing site.

CONCLUSION

Remote field eddy current technology has been developed for in-service inspection of modified 9Cr-1Mo SG tubes of the PFBR. Flexible RFEC probes capable of negotiating the bend regions of the SG tubes have been designed and developed after systematic numerical modeling and experimental validation. Necessary high-sensitive instrumentation also has been developed in-house. The parameters of the RFEC probe such as the spacing between the receiver and exciter coils (30 mm) and the operating frequency (1100 Hz) have been optimised based on the FE modeling. Experimental investigations to study the influence of sodium deposits on defect detection revealed that signal peak-to-peak amplitude remained unchanged before and after the sodium exposure which enables reliable detection and sizing of defects in SG tubes despite the presence of sodium. Wavelet transform based signal processing technique enabled the detection of even 10% wall thickness deep defects anywhere in the bend regions of the SG tubes. The RFEC technology has been successfully demonstrated on a full scale mock-up SG test facility. Further, this has been used along with ultrasonic technique for assessment of structural integrity of SGs after circumferential shell welding.

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