EDDY CURRENT INSPECTION OF CLADDING MATERIAL ON VVER 440 REACTOR PRESSURE VESSELS

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Abstract: Reactor Pressure Vessel (RPV) is classified as a safety related component and continued operation of the NPP for an additional fuel cycle is contingent upon the Nuclear Regulator approving the in-service inspection (ISI) performance. In accordance with applicable Finish regulative the integrity of cladding material on reactor pressure vessel is part of the interest and has to be included in examination scope. Comprehensive deterministic safety analyses have been performed by Fortum Loviisa Power Plant in order to define the critical size of defects which have to be detected, as well as, requirements for their sizing. These analyses included surface breaking and subsurface flaws. On the basis of these specifications INETEC developed eddy current technique which is capable to fulfill the requirements for such examination. The aim was to developed reliable eddy current technique which can be applied in parallel with standard ultrasonic examination. As a common project between Loviisa Power Plant and INETEC, developed technique has been qualified in accordance with ENIQ Methodology.
The article will present the requirements on inspection, capabilities of developed eddy current technique and mode of its application. Also, the methodology and results of qualification process will be presented.

Introduction: Loviisa NPP has two VVER-440 units of six loop design with reactor pressure vessels (RPV) having a cladding which height is ~9mm. In accordance with applicable Finish regulative the examination of cladding material is of importance from safety point of view and have to be included in the scope of In-service inspection (ISI) of RPV. To insure the integrity of the reactor pressure vessel during operation and during severe accident conditions, it is important that there are no flaws exceeding the plant specific requirements. The flaw type information was based on the manufacturing documents, experiences and engineering judgment on the most potential flaw mechanisms. The flaw types are classified as:

a) Specific flaws – flaws specific for inspection areas such as: subsurface volumetric (slag, porosity) and planar welding flaws parallel (also transverse) to welding direction; bonding flaws in cladding/base metal (weld) interface, solidification cracks above wide slag inclusions and slag lines parallel and transverse to welding direction, fatigue cracks (stress cycles in cladding break thin porous cladding ligaments above welding flaws and grow a solidification crack to surface breaking).
b) Postulated flaws **-** flaws induced by expected damage mechanism or manufacturing – such as radial fatigue cracks in nozzle inside radius section (pressure and thermal stress cycling increased by nozzle concentration).
c) Unspecified flaws - these flaw types are neither detected nor postulated for inspection areas of RPV, damage mechanism or process is not identified.

Requirements on detection and qualification of flaws are set in accordance with the results of comprehensive deterministic safety analysis for various types of flaws specified above. This included analysis of allowable flaw sizes, taking into account flaw's position with respect to surface, flaw orientation and morphology. For determination of the different flaw sizes the assessed flaw growth during one inspection interval has been taken into account. Engineering judgment or worst case conditions was used for describing flaw information for qualification and inspection.

Requirements on Eddy Current Technique: Due to certain limitations of ultrasonic and visual testing, the eddy current method has been selected as appropriate technique for examination of cladding surface. The general idea for application of eddy current testing was to be used as complementary method to ultrasonic method. Since ultrasonic technique applied for standard RPV examination has a limited capability in characterizing the defects in near surface area, the aim of eddy current was to detect and size the flaws in region 0 – 4 mm from surface. The main goal of eddy current was to define the position of flaw with regard to surface. The flaws are classified as surface in the case that they are breaking surface, or subsurface if flaws do not break the surface. The convention was made that flaws which has ligament ≥ 1mm between the flaw tip and surface will be classified as subsurface flaws. These two types of flaws are presented in Figure 1.

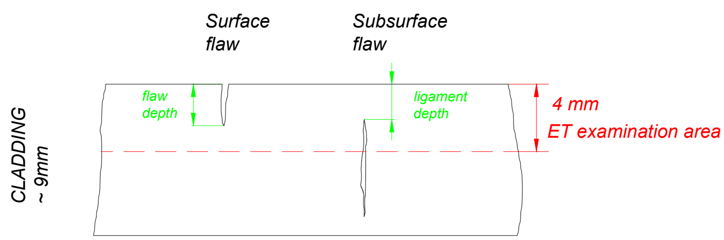

Figure 1. Eddy current task description

The requirements on eddy current technique for inspection of cladding material on Loviisa NPP reactor pressure vessels may be summarized as follows:

- to detect defects in cladding material to depth of 4mm as minimum;
- to have low sensitivity to surface roughness (consequence of grinding);
- to have equal sensibility for flaws parallel and perpendicular to probe movement;
- to distinguish surface and subsurface defects;
- to provide length sizing of defects;
- to provide depth sizing of surface defects;
- to provide sizing of remaining ligament for subsurface defects;
- to have wide field of coverage because of inspection time;
- to be integrated in standard RPV system.

The requirements which have been put on eddy current method were not applied up to now for inspections of reactor pressure vessels, so INETEC, as selected Supplier for RPV examination, had to develop and to qualify technique in compliance with plants specific requirements.

Description of Eddy Current Technique:

<u>1. ET Probe:</u> Selection of ET technique was based on INETEC previous experience in eddy current examination of cladding on RPVs. This technique has been additionally confirmed by subsequent penetrant testing of indications detected by eddy current method. However, previous ET examination was related to detection of surface flaws only, without requirements on depth sizing. The principle of old ET probe has been applied for this new task as well.

In accordance with the theoretical assumption about application of various coil settings, the pancake coils arranged in transmit-receive mode have been selected as appropriate examination technique. The probe contains two–transmit-receive circuit, where each circuit can operate individually or two can be operated simultaneously. Basically, the probe comprises two coil configurations which yield signals in the absolute mode from defects aligned with either axis of the square outer shell of probe. Two pairs of pancake coils have been used for detection in two perpendicular directions, providing that probe has equal sensitivity to axially, as well as to circumferentially oriented flaws. Both probe configuration responses to flaws are matched what is achieved by performing identical setups on both configuration (i.e. setting gains and phase rotation) within tolerances defined in inspection procedure.

Site experience proved that "probe shielding" with a permanent magnet minimize influence of extraneous test variables (like permeability variations) that may lead to false indication signals. Since the probe is intended for detection of flaws in weld region in stainless steel, the assumption is that the welds and parent material are deemed to have ferromagnetic properties. Therefore, the probe has a strong magnetic bias that suppresses permeability variations in strongly ferromagnetic, while in the case of mildly ferromagnetic stainless steel it will magnetically saturate the material. In addition, the magnetic attraction to ferromagnetic material will assist in maintaining probe to surface contact.

2. Laboratory testing: In order to evaluate and confirm the theoretical presumptions of capabilities for proposed eddy current technique, the comprehensive laboratory investigations and testing has been performed. The specimen made of stainless steel of similar conductivity to original cladding material has been used. It includes numerous EDM flaws of various dimensions: lengths: 5 to 15 mm, widths: 0.2 to 1mm, depths of surface flaws: 1 to 7 mm, depths of ligaments: 1 to 4 mm. Beside notches, examples of holes have been manufactured, as well. They vary in diameters, depths and positions with respect to surface. The various types of analyses were performed in order to justify the applicability and efficiency of developed technique. Some of the analysis are described in following chapters. The test results have been used for determination of inspection procedure including detection and sizing approach.

3. Analysis of Surface Flaws Signal Response: The surface flaws which are defined as ISI objectives have been scanned with the examination system selected for this inspection. Figure 2 presents the signal of surface flaws (1, 2, 3 and 4 mm depth) on various frequencies selected for cladding material examination (100kHz, 50kHz, 20kHz, 10kHz). Lift-off signal is adjoined to flaw signals in order to define its position in relation to flaw signal. As may be concluded from the Figure, the resolution is poor for low frequency (10kHz), but frequencies greater than 20kHz have almost the same resolution. Additional investigations confirmed that further increase in frequency (over 100kHz) do not provide better resolution, while smaller frequency decrease the quality of signal. Furthermore, higher frequency “moves” signal of indication below the lift off curve that jeopardizes flaws detectability. With respect to separation of lift-off and flaw signals and with respect to resolution between flaws the optimum frequency selected for sizing was 50kHz.

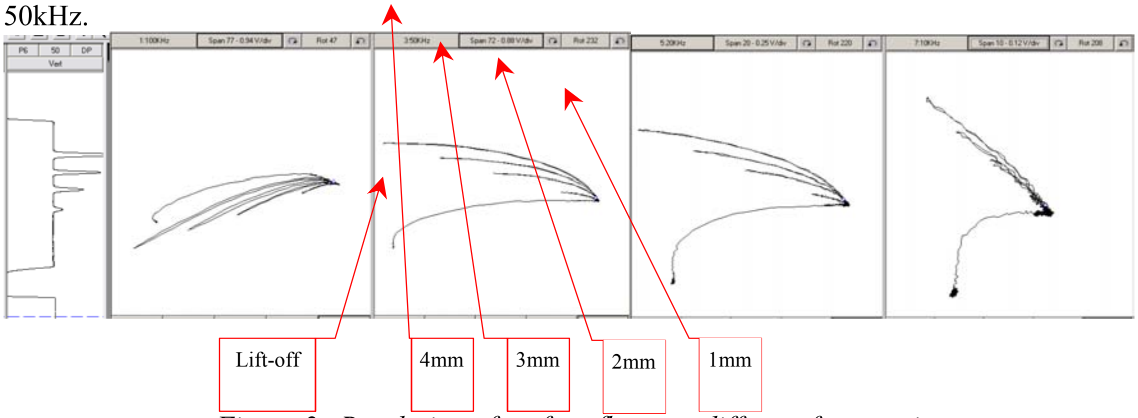

Figure 2. Resolution of surface flaws on different frequencies

4. Measurement of Depth for Surface Flaws: As has been predicted by theory and confirmed by experiments, phase variation in relation to flaw depth is negligible for surface flaws. Therefore, the calibration curve for depth measurement was established on the basis of signal magnitude. The channel selected for curve establishments was 50 kHz because of optimum resolution and signal phase with regard to lift-off signal, as explained previously.

5. Analysis of Subsurface Flaws Signal Response: Eddy current signal responses to subsurface flaws are presented in Figure 3. The flaws are located below the surface such that their ligaments are: 1, 2, 2.5, 3 and 3.5mm. As was expected, the decrease of frequency decreases the resolution between the 1 and 3.5 mm ligament depth. On the other hand, responses at higher frequency are such that a lift-off signal in the same direction as signals of flaws located deeper below the surface. This effect has a negative influence on flaw detectability. In accordance with this observation, 20kHz has been selected as optimum frequency for detection and sizing of subsurface defects.

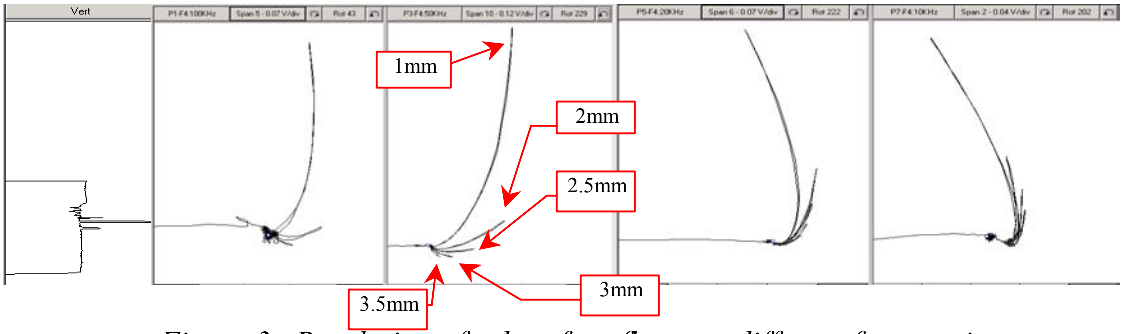

Figure 3. Resolution of subsurface flaws on different frequencies

<u>6. Measurement of Ligament Depth for Subsurface Flaws:</u> Measurement of depth of ligament between surface and tip of subsurface flaw is made on the basis of phase-depth calibration curve. 20 kHz frequency has been selected as appropriate frequency for curve set-up. Such formed curve has the 59° phase difference between 1 and 3mm ligament depth what means that each degree represents 0.033mm - this is an excellent resolution with respect to inspection requirements.
<u>7. Analysis of Relation Between Surface and Subsurface Flaws:</u> In order to define the procedure for definition of flaw position with regard to surface, signal response on 20kHz for surface flaws of 1 mm depth and subsurface flaw of 1mm ligament depth are given together in Figure 4. As may be seen, phase angle of surface flaw signals is around ~20º. As has been shown previously it doesn't grow with the depth of flaw. Subsurface flaw with ligament of 1mm have a phase angle of ~80º, while deeper flaws have a greater phase angle. Since inspection convention was that flaw shall be assumed as subsurface if ligament depth is ≥1mm, it may be concluded that very good resolution between surface and subsurface flaws is achieved.
Classification of subsurface flaws having ligament depth < 1mm as surface flaws has a consequence on measurement accuracy. In the case of surface flaws, eddy current examination has to provide information about flaw depth on the basis of signal magnitude. However, the magnitude of signal decreases with the distance from surface. This implies that estimation of depth for subsurface flaws having ligament 0<ligament<1mm will be underestimated. Final characterization of such flaws shall be made on case-by-case basis, where eddy current parameters shall be evaluated in conjunction with the UT findings.

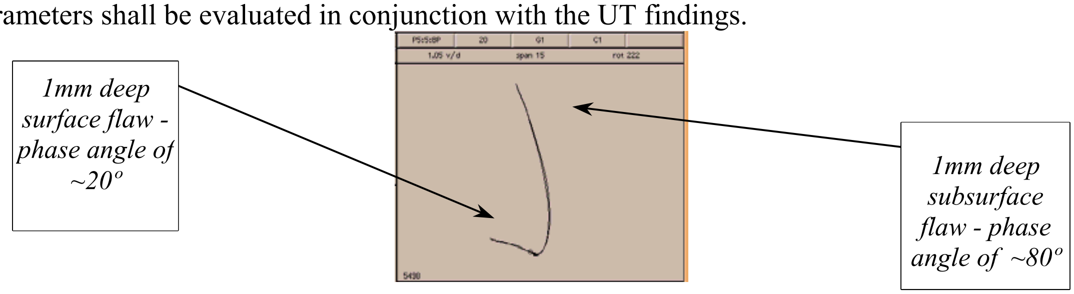

Figure 4. Phase angles of surface and subsurface flaws on 20kH

<u>8. C-Scan presentation:</u> Analysis of eddy current data only by lissajoues and strip charts is extremely inconvenient because all scan lines are represented in one straight line. This means that position of flaw, its orientation, and number of influenced scans is very hard to define. One of the very powerful tools for better visibility and easier analysis process is so-called "C-scan" where all scans are put together and presentation of scanned area can be obtained. Such presentation provides very quick and efficient analysis especially for large size data. Example of C-scan presentation for surface and subsurface flaws on specimen with 2 flaws is given in Figure 5.

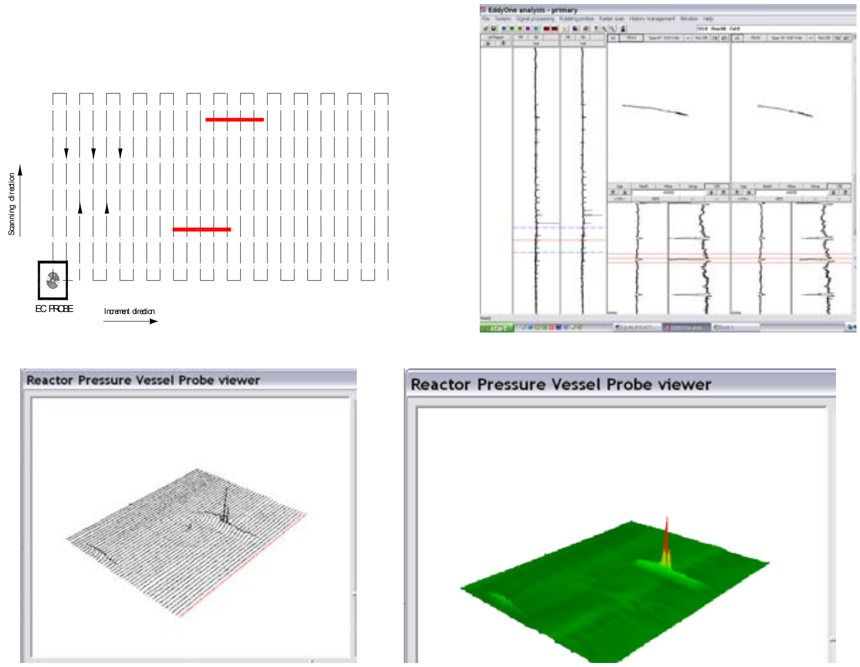

Figure 5 Efficiency of C-scan presentation on specimen with two flaws

<u>9. Influence of Scan Direction on Flaw Detection and Presentation:</u> In accordance with probe coil constitution one of coil pairs is sensitive to flaws perpendicular to scan direction, while another coil pair is sensitive to flaws parallel to scan direction. This considers that scanning in any of two orthogonal directions is sensitive for both flaw orientations. Examples of scanning of same specimen in two orthogonal directions are given in Figure 6. As may be concluded, very clear presentation and very good detectability is achieved in both scanning directions.

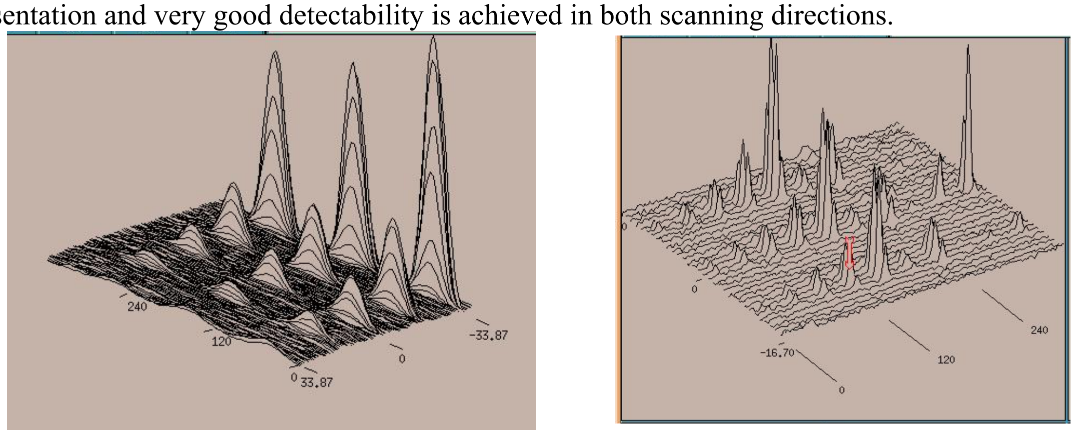

Figure 6. C-scans of scanning same specimen in two orthogonal directions

<u>10. Parametric studies:</u> Beside laboratory testing described above, comprehensive and extensive parametric testing has been performed in order to evaluate the influence of variation of various parameters that may have an influence on detection and sizing of eddy current technique. Some of examples of parametric analysis are as follows:

- influence of lift-off;
- skew angle of flaw;
- influence of scanning pattern on measurement accuracy;
- width of notches and some others.

Results of these analysis have been used to establish the procedure essential variables. As it is foreseen by qualification procedure, these analysis become a part of Technical Justification.

11.Capabilities of Developed Technique: Through the testing on various types of flaws the following capabilities of developed technique with regard to flaw detection and sizing has been demonstrated:

a) surface flaws

- detection of surface flaws deeper than 0.5 mm and having length ≥ 10mm;
- depth accuracy is within 2mm
- length accuracy is within ±5mm.

b) subsurface flaws

- detection of subsurface flaws up to 3.5 mm below surface and having length ≥ 10mm;
- ligament depth accuracy is within 1mm
- length accuracy is within ±5mm.
- These capabilities are in compliance with plant specific requirements for this particular inspection.

Qualification program: The application of eddy current method required laboratory testing and parametric analysis in order to develop reliable technique capable to achieve inspection goals. However, final confirmation for technique applicability for inspection of RPV on Loviisa NPP required performance of successful qualification. Finish regulatory body established qualification program in accordance with ENIQ methodology and IAEA methodology for qualifying ISI of WWER plant. The qualification was a common project of Finish regulatory Body, Loviisa NPP and INETEC. Basically, the program included following basic activities:

a) Determination of Technical Specification: - This part of qualification program included evaluation and determination of Code requirements, component/area-essential parameters, NDT Method, inspection conditions, expected/postulated flaws, flaw parameters to be measured, inspection effectiveness and QA requirements.
b) Preparation of Inspection Procedure – Through the preparation of procedure for inspection of RPV cladding material by ET method it was necessary to provide description of technique, to determine operational condition of equipment, to establish calibration process, to define flaw discrimination and reporting criteria, to determine of essential parameters, checks and acceptable values for equipment and software and to specify the applicable standards. The procedure preparation was based on results of laboratory testing and parametric analysis described in previous chapters.
c) Qualification – Qualification itself considers confirmation of technique capabilities to satisfy input requirements. It includes preparation of Technical Justification as an evidence of all performed testing including theoretical assumptions and modeling for proposed technique. In first phase developed technique and proposed procedure was demonstrated through the open test on known positions and characteristics of flaws. In second phase, the blind test was performed were position and dimensions of flaws were unknown for inspection personnel. Criteria for qualification evaluation regarding flaw of dimension, probability of detection, measurement accuracy, false call rate have been defined on the basis of structural integrity analysis of RPV, engineering judgment, experience in similar processes and applicable Codes. One of the most comprehensive task in this was to prepare the appropriate specimens for open and blind test what was successfully accomplished by Finish organization.
d) Evaluation of qualification results – as a final stage in qualification program, evaluation of achieved results have been made. On the basis of convincing Technical Justification and results of qualification testing which satisfies defined evaluation criteria, the certification of inspection, procedure, equipment and personnel has been performed.

At the end of the qualification process, the qualification dossier was prepared as a written evidence of performed qualification program and final approval that inspections system may be assumed as qualified for RPV inspection performance.

On-site Application: After successful qualification, developed eddy current technique has been applied for examination of reactor pressure vessel on Loviisa Unit#2 ISI 2002. The eddy current probe has been mounted on so-called Uni-end effector (Figure 7) which is part of INETEC standard manipulator for RPV examination. This considers that eddy current examination has been performed in parallel with UT examination. In order to provide the information about the probe position, eddy current instruments has been integrated in inspection system and triggered by manipulator control system.

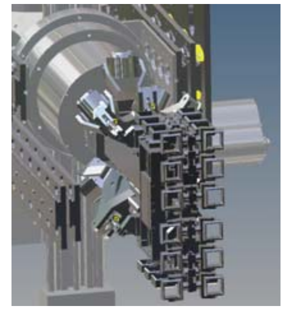

Fig. 7- Uni-end Effector

Since area coverage of ET probe is smaller than UT probe there was a request to limit the scan increment to maximum of 5mm. With respect to probe characteristics this increments assures overlapping required for coverage of examination area. Such small increment would have significant influence on inspection time, so decision has been made to perform inspection simultaneously with two probes "running in parallel". In such arrangement two probes were mounted 5mm offset (measured perpendicular to scan movement) from each other. The scanning pattern for such probe arrangement is presented in Figure 8. In conjunction with C-scan presentation of acquired data which has been presented in Chapter 2, very powerful feature for simple presentation of simultaneous scanning of several probes "in parallel" has been added to software.

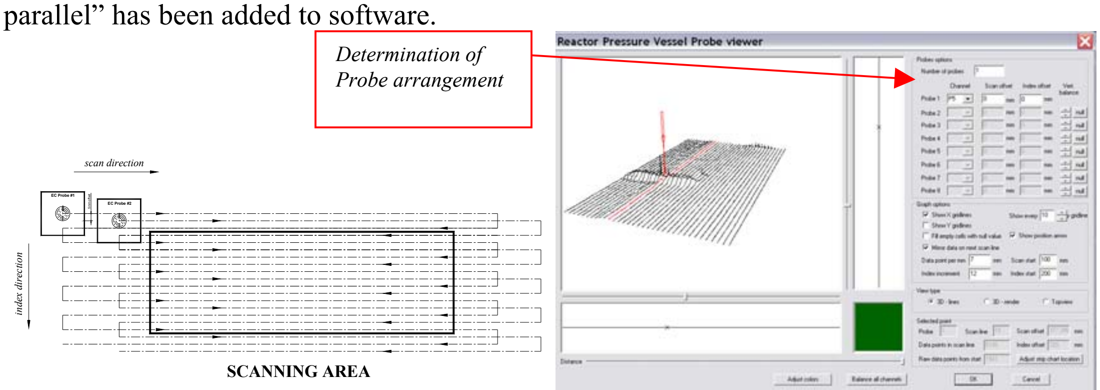

Figure 8. Presentation of multiprobe application

In accordance with the Scan Examination plans each section was examined in two orthogonal directions. This approach assures greater reliability of inspection since the ET probe coil has an equal sensitivity to both axial and circumferential flaws. It considers that each indication is detected in both scans and final judgment is based on two scanned ET data for each detected flaw.

Conclusion: Examination of cladding material on reactor pressure vessels at Lovvisa NPP Units was a new task which required development of appropriate inspection technique and procedures. Comprehensive theoretical and laboratory investigations had to reveal that technique is capable to satisfy the plant specific requirements for this particular inspections. After successful development, qualification process based on ENIQ methodology has been performed as an confirmation of technique efficiency. On the basis of qualification results inspection system has been qualified and applied for on-site examination. The RPV examination showed high reliability in application of developed eddy current techniques.

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