OVERVIEW OF EDDY CURRENT INSPECTION METHODS FOR PRIMARY CIRCUIT COMPONENTS OF NUCLEAR POWER PLANTS

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ABSTRACT

Non-destructive examinations are common practice for ensuring the safe and reliable operation of primary circuit components of nuclear power plants. All primary circuit critical components must be inspected during refueling outages and one of selected non-destructive methods of testing is eddy current method.

Eddy current inspection method is based on measuring of changes of magnetic field caused by changes in material in which eddy currents are induced. Field of application are non-ferromagnetic materials. Wide range of eddy current sensors are developed for applications in nuclear industry.

Among primary circuit components, the steam generator tubing is component for which eddy current examination are mandatory practice. Besides steam generators, certain components like reactor pressure vessel and vessel head J-welds also require examination by eddy current surface method. Reactor pressure vessel threaded holes, bolts and nuts can be also subjected to eddy current depending on the requirements.

Development of more advanced solutions in all fields of technology enable improvement of eddy current inspection solutions, providing, more information about condition of inspected components. All improvements in design of eddy current probes must be validated through qualification process.

This paper will present INETEC experience and modern solutions for eddy current examination applications.

INTRODUCTION

Primary circuit components of nuclear power plants represent reactor coolant boundary and maintaining of the structural integrity of these components is essential for safe and reliable operation of nuclear power plants. If integrity of primary circuit components is lost, the risk of introduction of radioactivity into environment would increase and power plant would lose ability to produce electrical energy, due to undesired outages. To ensure safe and reliable operation of nuclear power plant, international standards related to nuclear power plant safety require that primary circuit components are periodically monitored and inspected during refueling outages. Activities related to the inspection of primary components are in literature referred to as in-service inspections. Most common methods of component inspection and monitoring are through application of non-destructive examination methods, which leave the inspected component in same condition as on beginning of inspection but provide information about the component and it's condition. A number of different non-destructive techniques are used in nuclear industry like ultrasonic testing, magnetic particle testing, liquid penetrant testing, radiographic testing and eddy current testing.

EDDY CURRENT TESTING METHOD PHYSHCAL BACKGROUND

Eddy current testing is based on the principle that when coil powered by alternating current is placed near conductive material of interest, electromagnetic field or primary filed of coil will induce eddy current in material of interest. In accordance with Lenz law, induced eddy current and secondary electromagnetic field opposes the changes in primary field. Creation of eddy currents will result in change of primary field. Change of electromagnetic field of coil manifests itself as change of coil's reactance and resistance. When flaws in inspected material exist, secondary field is changed in different manner compared with changes of field when material is non-flawed and consequently, primary electromagnetic changes and related coil impedance changes are of different character when material is flawed compared with coil impedance changes when material is without flaw. Fig. 1 presents concept of material testing by application of eddy currents.

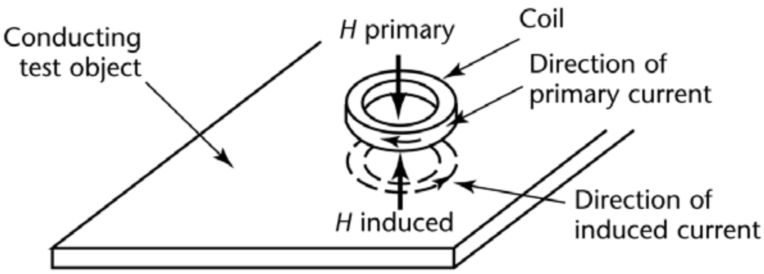


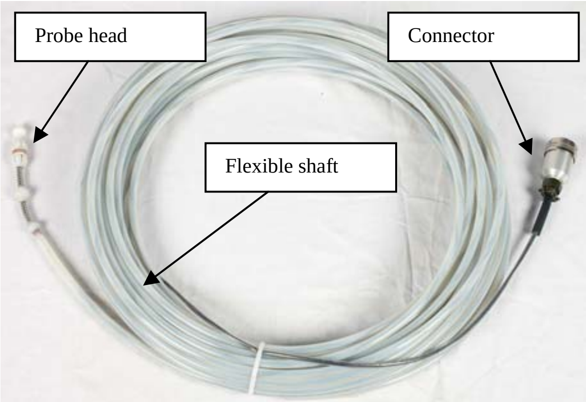
Fig.1: Concept of eddy current material testing

Common practice when designing the eddy current sensors, called eddy current probes is use of bridge circuits, because value of change in coil impedance can be very small compared to total value of coil impedance. Depending on purpose of application, different arrangement can be made for eddy current probe. Three most common arrangements or modes of operation are differential mode, absolute mode and transmit-receive mode. Detailed descriptions and explanations of each mode can be found in [1].

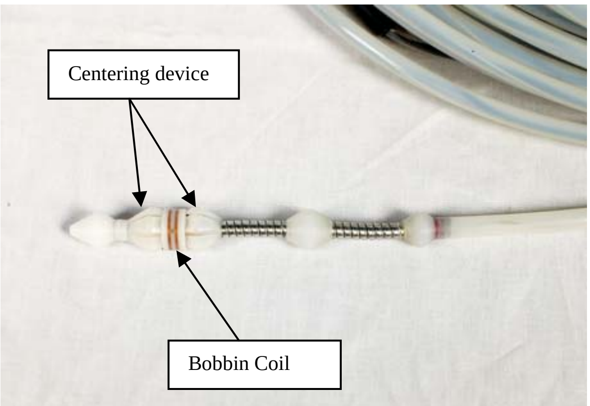
EDDY CURRENT INSPECTION OF STEAM GENERATORS

Application of eddy current inspection method is most common solution for inspection of steam generator tubing. Steam generator tubing is inspected by various types of probes that are inserted into tubing, and response of eddy current sensor is recorded along tube length. Three most common types of eddy current tubing probes are: bobbin probe, rotating probe and array probe.

Eddy current bobbin probe is used for basic inspection of steam generator tubing. This type of probe is very reliable and offers high speed of inspection capability. Bobbin probe is comprised of flexible shaft usually made of nylon with cables and probe head. Probe head is assembly where centering devices and coils are placed. Bobbin probe utilizes bobbin coil, wound circumferential around probe axis, which is of same direction as tube axis. Two coils are wound and connected opposing one another, so response of such system would be only the difference between responses of coils. Fig. 2a) and 2b) shows INETEC's bobbin probe, model IPVI 183, designed for inspection of PWR Inconel 690TT 0.875″ OD tubing.



a) Bobbin probe elements

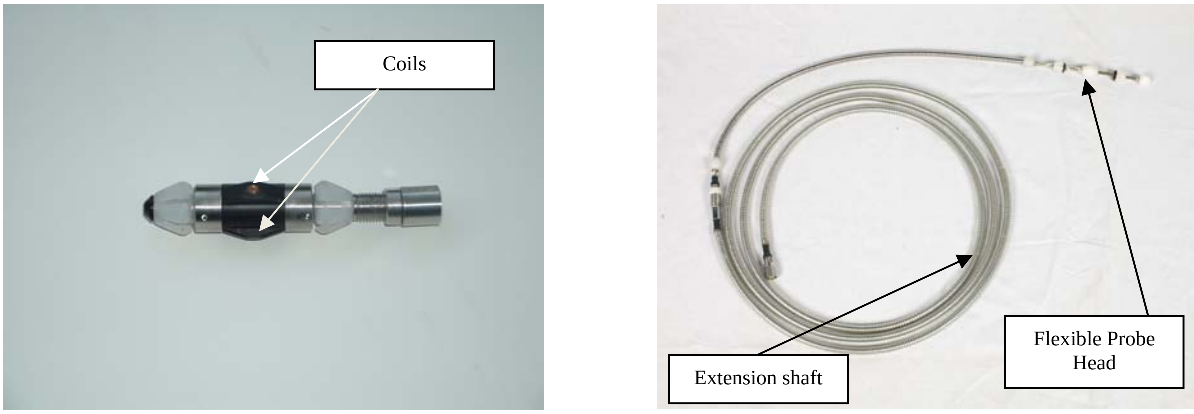


b) Probe head assembly

Fig.2: Eddy current bobbin probe for PWR tubing, probe model INETEC IPVI 183 m

Despite advantages regarding speed and reliability of bobbin probes, this inspection method has limited detection and sizing capabilities. Due to orientation of bobbin coil(s) and generated eddy currents, bobbin probe is not sensitive to circumferential flaws in tubing material. Rotating probe is used for more accurate inspection of specific areas of tubing. Depending on results of basic inspection with bobbin probe, signals of interest detected by bobbin probe as well as areas of tubing known to be susceptible to specific modes of degradation are examined by rotating probe.

Rotating probe is comprised of probe head, flexible shaft and extension shaft (optional) and rotating motor unit. In probe head one or more coils are mounted, while motor unit provides rotation of the entire assembly, while pulling or pushing. By this way, helicoid pattern of movement of probe is achieved. Standard speed of rotation is from 300 rpm to 2400 rpm, for new advanced motor units. Coupled with these speeds of rotation, pulling speed must be very low, from 5 mm/s to 35 mm/s. Low pulling speeds are necessary for achieving adequate quality of response recording. Fig. 3a) shows typical rotating probe head with three coils, INETEC 15-3C probe. Three coils mounted are: 1) middle range frequency pancake coil, 2) middle range cross-wound coil, 3) high frequency cross-wound coil. Fig. 3b) shows probe for examination of tubing U-bends, INETEC 15-1C with single cross wound coil. U-bend rotating probes have flexible head assembly necessary for U-bend examinations and in certain cases extension shaft is also used.



a) Rotating probe head, with 3 coils b) U-bend rotating probe with extension shaft

Fig.3: Eddy current rotating probe for PWR tubing,

With development of computer technology, advanced solution for tubing material became available. Array probe is solution that combines detection and sizing capabilities of rotating probe with high speeds of inspection characteristic for bobbin probe inspection. Steam generator array probe design is based on the use of larger number of coils, either cross-wound or pancake, placed circumferential around probe head.

In case that pancake coils are used in array probe, operational mode is transmit-receive mode, where one coil transmits, creates electromagnetic field, while other only register changes of field, operating as receiver. Due to character of this mode of operation, special attention must be placed to spacing of coils, that optimal spacing is achieved. In case that coils are spaced too far, signals will have low amplitude, while if too close, undesired interference will occur. Number of coil depends on inspected tube circumference and coil configurations can be in two or three rows i.e. 12x2 coil configurations consists of two rows of 12 coils, spaced half of coil width circumferentially. Detailed transmit-receive concept is shown in Fig. 4.

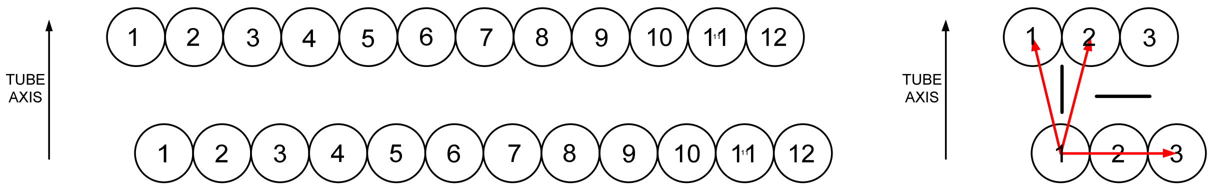


Fig.4: Array probe operation principle, 12 x 2 example

For one coil that operates as transmitter, three coils operate as receiver. As seen in Fig 4, when coil 1 operates as transmit, coils 1 and 2 in upper row register changes as well as coil 3 in lower row. Pairs 1-1 and 1-2 are oriented along tube axis, and their response will detect material degradation oriented along tube axis. These types of responses or channels are referred to as axial channels. Pair 1-3 in lower row is oriented in direction of tube circumference and this type of response will be sensitive to degradation oriented along tube circumference. This type of response and channels are referred as circumferential channels. Volumetric degradation has both axial and circumferential character, and is detected with both types of channels.

Common practice during steam generator eddy current inspection is multi frequency inspection technique. Coil is usually excited with four different frequencies of alternating current. For each frequency, eddy current will produce one channel per coil, so for X frequency and N coils number of channels is:

Total number of channels = X*N*2 [axial channels] + X*N [circumferential channels] *(1)*

For 12x2 channels, and 4-freqency technique, total number of channels would be 144. To control the triggering sequence of coils, special electronic device called multiplexer is utilized. Multiplexer controls sequence of excitation of coils ensuring that only designated coils operate as receiver. This also reduces undesired interference. Fig. 5 presents INETEC array probe, APV 12x2 model which is designated for application in VVER steam generator tubing, and includes 24 coils, in two rows of 12 coils.

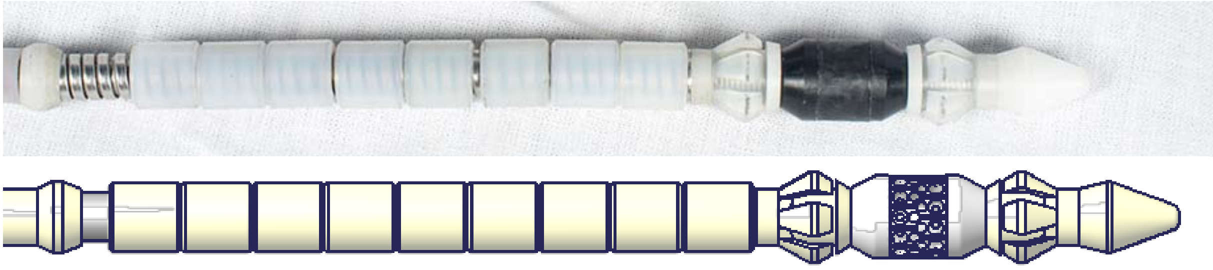
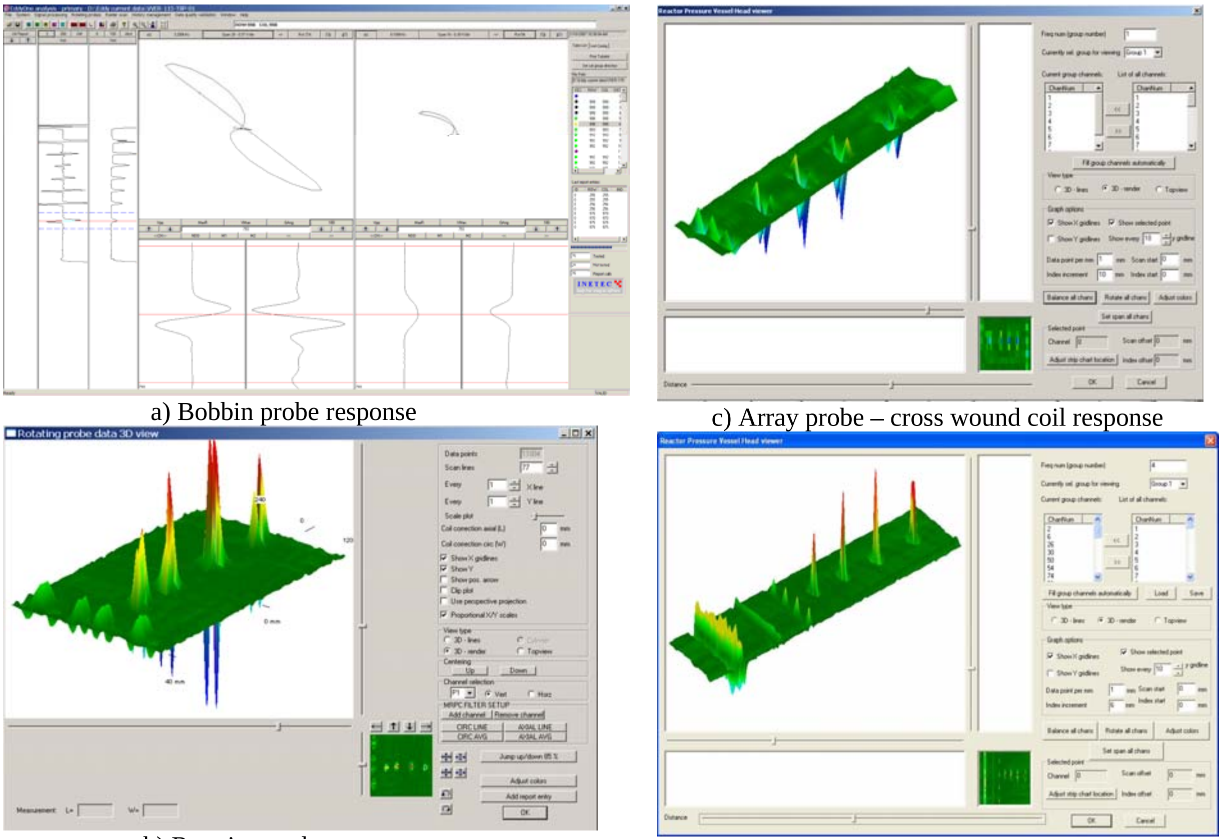


Fig.5: Array probe, INETEC APV 12x2 array probe for VVER tubing examinations

If array probe is designed with cross-wound coils, operational mode of such probe is differential mode. Single row of cross-wound coils is mounted around tube circumference and each coils covers part of circumference i.e. for 8 coils, each coil covers 45° of tube circumference. Cross-wound coils have characteristic that its response is sensitive to all orientations of degradation: axial, circumferential or volumetric. Due to this, for each coil there is single channel per frequency, resulting in lesser number of channels compared to array probes with pancake coils. Fig. 6 shows close view of array probe with cross-wound coils, INETEC ACV probe model.

Fig.6: Array probe, INETEC ACV array probe with 8 cross-wound coils for VVER collector material examinations

Due to the large number of channels produced by array probe, monitoring of gathered eddy current data must be done by using specialized viewers. Raster scan viewer merges responses from all coils around circumference, for same frequency. This way entire circumference is presented and easier, more practical evaluation is achieved. Typical presentations for each steam generator probe type are presented in Fig.7



a) Bobbin probe response

b) Rotating probe response

c) Array probe – cross wound coil response

d) Array probe - pancake coil response

Fig.7 Typical responses of steam generator probes

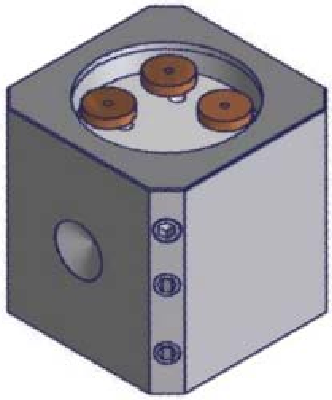
Steam generator array probes have proven as very useful and powerful tool for faster more, efficient performance of inspection. Array coils can be combined with bobbin coils in same probe, on same shaft and such concept enables reduction in number of passes through tube, because in one pass through tube, both basic, bobbin data is recorded and more detailed array data that can be used for sizing of detected degradation.

Array probe has proven to be especially efficient during VVER steam generator collector material examinations where array probe eliminates need for rotating probe use. Collector material is susceptible to axial cracking, which due to thickness of collector material is very hard to detect with bobbin coils, but possible with cross-wound coil and low operating frequency. Rotating probes have been initially used for detection and sizing of this type of degradation, but application of rotating probe required significant amount of time for inspection, increasing outage times. When using array probe, speed is increased from rotating probe’s 5mm/s to 600 mm/s for array probe insertion and pulling. This way large reduction in inspection times is achieved and detection and sizing capabilities still remain very high.

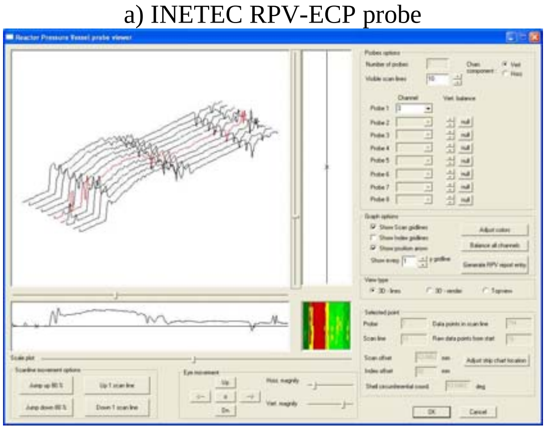
EDDY CURRENT INSPECTION OF REACTOR PRESSURE VESSEL AND REACTOR PRESSURE VESSEL HEAD

Examination of reactor pressure vessel cladding is common practice in VVER community. Inner surface of reactor pressure vessel and near surface area up to 3mm in depth are subjected to eddy current examination. Best inspection capabilities are achieved with probes using pancake coils operating in transmit-receive mode on frequencies 100kHz and lower. Example of such probe is INETEC’s RPV-ECP probe with two coil pairs sensitive to both degradation of cladding in scanning direction and perpendicular to scanning direction. Fig. 8 a) and b) present RPV-ECP probe.

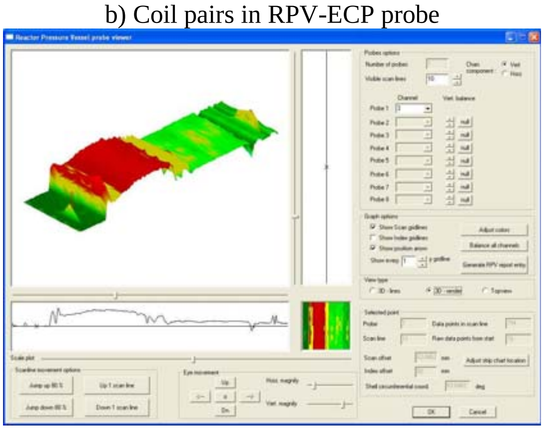
a) INETEC RPV-ECP probe



b) Coil pairs in RPV-ECP probe



c) EddyOne RPV viewer – line presentations



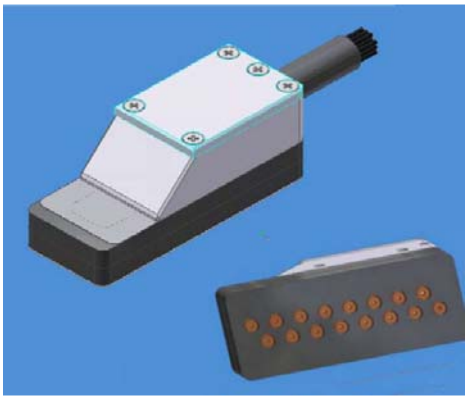
d) EddyOne RPV viewer – rendered presentation

Fig. 8 Eddy current surface array probes for RPV examination

Casing of RPV-ECP probe is 30mm x 30mm and coil spacing is optimized for scanning steps of 5 mm. Commonly used scanning step or increment for RPV scanning is 10 mm, due to crystal size of ultrasonic probes. To maintain 10 mm scanning step and better inspection times, two eddy current probes are used during scanning but spaced 5 mm in direction in which scanning steps or increments are made. This way each probes covers 5 mm of total 10 mm, which is scan line coverage. However, this method makes data evaluation difficult without special modes of presentation that merge responses from both probes. Such presentations like INETEC EddyOne RPV Viewer, are available with advanced eddy current inspection software packages. Fig. 8c) and 8d) present RPV viewer presentation modes.

Eddy current inspection of reactor pressure vessel head penetration J-welds was emphasized after the discovery of leaks and cracking on number of PWR power plants in U.S. To address this problem NRC Order EA-03-009 was issued that required performance of several different methods of examinations on RPVH. Methods were required to find solution for adequate examination of control rod penetration J-weld surface and near surface using eddy current examination method. Eddy current array surface probe is most efficient method of surface examination where multiple coils are utilized during examination with purpose of reduction of scanning enabling faster, efficient inspection.

Depending on side from which penetration J-weld is inspected different number of coils is used. For examination from nozzle side, lesser number of coils is used, like INETEC's JCW-NZL probe with three cross-wound coils. In case of inspection from shell side of penetration, larger number of coils can be used, and larger scanning area achieved. Example of such probe is INETEC's JCW-SHL probe that uses sixteen cross-wound coils mounted in flexible probe body in order to adjust to curved surface, creating detailed eddy current array which enables coverage of inspected material. Fig. 9 presents INETEC JCW-SHL probe.



a) Array probe uses 16 cross-wounded coils

b) INETEC JCW-SHL array probe

Fig.9: Eddy Current surface array probe for RPVH J-weld inspection

Examination of J-weld with such probe is done by specialized RPVH inspection tool where probes are mounted on end-effector, part of the manipulator that carries eddy current probe during scanning.

Similar to tubing array probes, large number of coils in surface array probes requires special raster scan presentation for easier monitoring of gathered data.

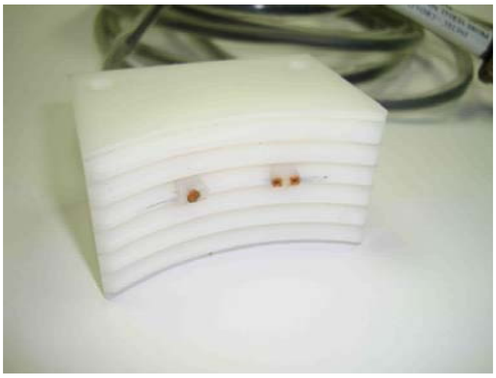
EDDY CURRENT INSPECTION OF REACTOR PRESSURE VESSEL THREADED HOLES, NUTS AND BOLTS

Reactor pressure vessel and reactor pressure vessel head connection is ensured by bolts. In case that degradation of bolt, nut or threaded hole occurs, there is possibility that radioactivity could spread outside primary circuit. To ensure integrity of these components, periodical monitoring of bolts, threads and nuts is performed. One of applied examination methods is eddy current method. Only threaded parts of these components are subjected to eddy current inspection.

Special design of probe body must be used to ensure that eddy current coils are moving along the thread and probe body is designed to maximize detection of cracks in root of the thread. Examples of solution for such purpose are INETEC probes for inspection of RPV threaded holes, bolts and nuts.

Fig. 10a) presents INETEC BLT-140 probe designed for inspection of bolts, while Fig. 10c) presents special tool designed for eddy current examination of bolts. Bolt is rotated by motor and BLT probes are moved axially along slider and this way circumferential scanning of thread is achieved. Fig. 10b) presents INETEC THR-140 probe which is used as a part of INETEC THR inspection system presented on Fig. 10d). Probe body with coils is rotated inside the threaded hole along the threads enabling scanning of thread.

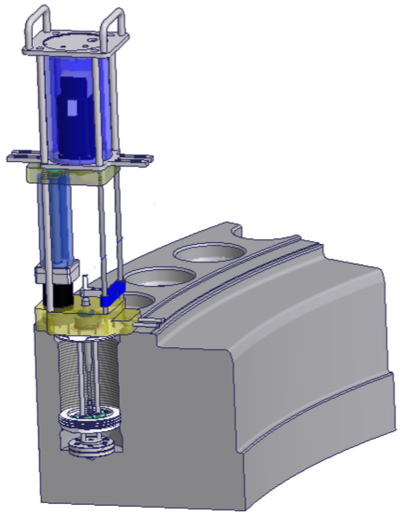
Each probe includes coil pair of pancake coils operating in transmit-receive and single cross-wound coil operated in differential mode. Pancake coil pair is oriented for detection of cracks and degradation oriented circumferentially, while cross-wounded coils are sensitive to all orientation of degradation.



a) BLT-140 probe

b) THR-140 probe

c) INETEC BOLT inspection tool



d) INETEC THR inspection tool

Fig.10 RPV M140 bolts and threaded hole inspection systems

CONCLUSION

Eddy current examination method is important tool in addressing the issues of degradation of materials of primary circuit components in nuclear power plants. Widest range of eddy current application is in use in examination of steam generator tubing, but with recent discoveries of degradation modes on other components like reactor pressure vessel head and threaded holes, eddy current has been applied on them also. Advances in computer technology and electronics provide possibilities for complex array probes and sophisticated signal presentations, but also possibilities of signal processing, and automated signal analysis which will improve performance and efficiency of eddy current inspections in future.

REFERENCES

[1] "Nondestructive testing handbook", 3rd Edition, Volume 5, "Electromagnetic testing", Columbus, OH, American Society for Non-destructive testing, 2004
[2] Matija Vavrouš, Renato Gracin.," Eddy current array probes for inspection of VVER steam generator tubing", MATEST 09, Dubrovnik, Croatia, September 2009