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SYSTEM FOR EDDY CURRENT INSPECTION OF VVER-440/1000 SG'S TUBES

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ABSTRACT

The most important task of every utility operating a nuclear power plant is the continuously keeping of the desired safety and reliability level. This is achieved by the performance of numerous inspections of the components, equipment and system of the nuclear power plant in operation and in particular during the scheduled maintenance periods at re-fueling time. Periodic non-destructive in-service inspections provide most relevant criteria of the integrity of primary circuit pressure components. The task is to reliably detect defects and realistically size and characterize them.

One of most important and the most extensive examination is a Steam Generator (SG) in-service inspection. That inspection demand high standards of technology and quality and continual innovation in the field of non-destructive testing (NDT) advanced technology as well as regarding SG inspection tools, control systems and techniques.

This article presents overview of the system for SG examination with focus on bobbin and array probes eddy current of the tubes, ultrasonic examination of SG collector welds and service - mechanical plugging of the tubes.

1 INTRODUCTION

VVER SG tubes have a number of important safety functions. These tubes are an integral part of the reactor coolant pressure boundary and, as such, are relied upon to maintain the primary system's pressure and inventory. As part of the reactor coolant pressure boundary, the SG tubes are unique in that they are also relied upon as a heat transfer surface between the primary and secondary systems such that residual heat can be removed from the primary system; the SG tubes are also relied upon to isolate the radioactive fission products in the primary coolant from the secondary system. [1]

Integrity assessment of SG tubes of VVER nuclear power plant was based, at the beginning, on the following leakage tests:

- Water under very high pressure on secondary side (Hydro test). Monitoring appearance of water on primary side; detection of leaking tubes.
- Water with tracer elements (for example fluorescent) on secondary side under pressure. Monitoring appearance of water with tracer on primary side using in some cases halogen lamps or other tools depending on the type of tracer.
- Bubble test. Water in collector, air under pressure on secondary side, bubbles show position of leaking tubes.
- Helium test. Helium pumped on secondary side and sniffing device(s) on primary side.

After determination of leaking tubes such tubes on VVER SGs were plugged with various types of plugs (welded and mechanical).

Previous methods are still very popular and on some VVER nuclear power plants they are still the only methods used for integrity assessment of SG tubes. With development of eddy current examination techniques at the beginning of seventies, for use on PWR SGs and at the end of seventies on VVER SGs, integrity assessment was performed using eddy current testing method based on bobbin probes. [1]

Use of eddy current examination techniques allowed detection of tubes with degradation(s) of various sizes what is much better than results of leakage test(s) which can detect only tube(s) with through wall hole(s). In other words with eddy current method the degradations which can potentially leak before next examination can be detected and sized. [1]

Because the eddy current method with bobbin coil is giving the depth of degradation as the main result of examination on some particular axial location in the tube, the first repair (plugging criteria) were related only on the depth of degradation.

The first plugging criteria were calculated for PWR SGs with:

- Inconel 600 tubes,
- Tube diameters 3/4” and 7/8”,
- ASME safety factors,

- Wastage degradation process,
- One fuel cycle to next examination.

With time the eddy current techniques were developed and many advanced probes were used (starting at the end of eighties on PWR and at the end of nineties on VVER) for examination of SG tubes as rotating probes (cross wounded, pancake, plus point) as well as different array probes (8x1, 16x1, 32x1, X probe). These probes allowed the use of other parameters besides depth and voltage (results of bobbin probe use) like length and orientation. More information about degradation allowed more accurate integrity assessment of SG tubes.

For the purpose of integrity conserving, faster inspection examination and increasing of inspection quality, Inetec developed new system for complete inspection and repair of VVER SG. Specificity of this system is tube inspection on VVER type of SG with array probe besides standard Bobbin probe, and that makes it unique System of that kind. Technique of VVER SG tubes inspection using array probe provides replacement of inspection of tubes and collector materials with rotating probes which results in reducing of inspection time.

Inspection System (further IMEC) has modular type of construction, which provides very easy transformation from VVER 440 to VVER 1000 inspection system, as well as quick conversion for use of SG Collector Material UT or Tube Plugging Modules.

This article presents overview of the system for VVER SG inspection, with focus on bobbin and array eddy current probes, ultrasonic examination of SG collector welds and repair - mechanical plugging of the tubes.

2 INSPECTION SYSTEM DESCRIPTION

2.1 System overview

INETEC developed the remote controlled manipulator to be used for remotely operated eddy current inspection of tubes by the use of DPS (double pusher system), that mounts the manipulator carriage. In addition, DPS module can be easily replaced with other modules such as PLG or SGU, through Quick Release Coupling System (QRS). Manipulator can be easily configured for VVER 440 or VVER 1000 SG inspection.

Installation of the IMEC Manipulator into the steam generator is performed without personnel entering in the steam generator. Instead, the manipulator is inserted through collector flange and mounted to collector flange bolt holes. Manipulator lower flange is covered with plastic material in order to protect SG flange from damage.

The remote manipulator provides independent two axis of movement, by using motors equipped with gear boxes and encoders needed for manipulator location verification. It means that manipulator can be calibrated by using reference locations and after that driven by created database loaded into computer memory. For accurate, smooth and quiet drive of assemblies, little maintenance with minimum tools is required. INETEC remote manipulator incorporates high-quality machine parts, and most aluminum surfaces are hard-anodized or made from stainless steel, to prevent pitting from harsh environments.

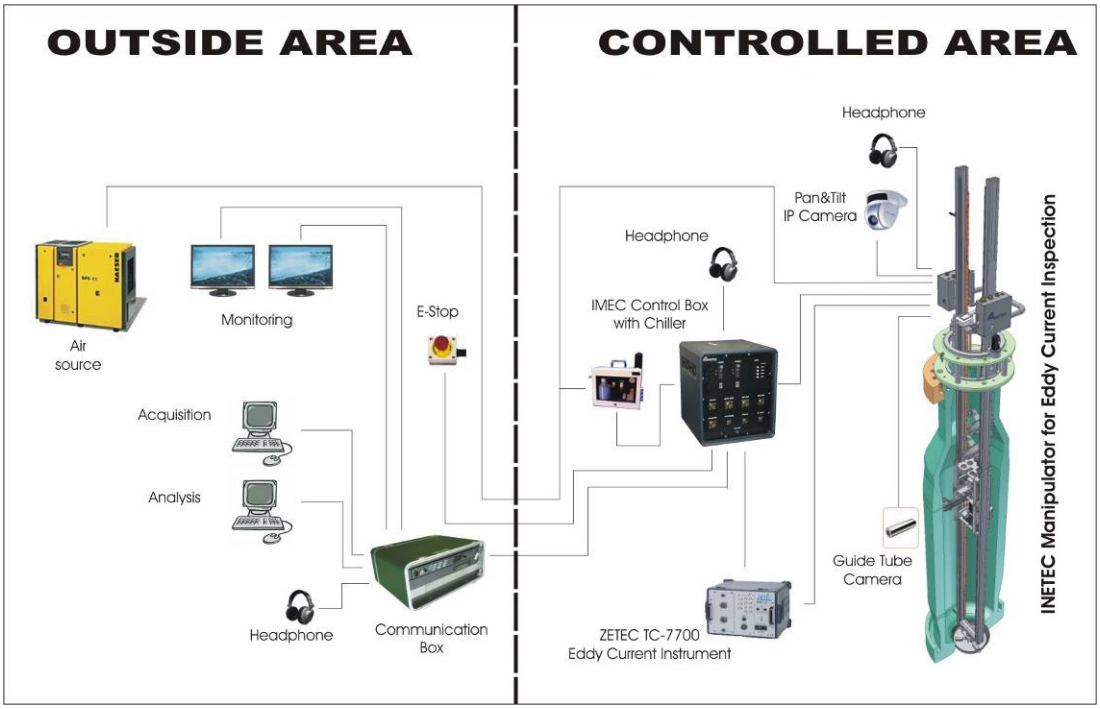

Figure 1: System for Eddy Current Inspection of VVER-440/1000 SG's Tubes.

Service Spacer Subassembly provides manipulator rotational movement around steam generator centerline. Two stainless steel bearings with gears are mounted in the hard anodized aluminum housing. Bottom of the Spacer is covered with DELRIN layer, in order to protect steam generator sealing surface of damage. Spacer is clamped to the SG flange with SS bolts. Spacer can be adapted to both VVER 440 and VVER 1000 steam generators.

Adjustable limit switches provides 380° of manipulator rotational movement. Maximal horizontal speed is limited to 130 mm/s (3 r/min) with accuracy of ± 0.5 mm. On the top of spacer, junction box is located, where harness cable is connected. Junction box, except main connectors, includes also audio connection for platform support worker.

Mast Subassembly is separable pair of bars made from hard anodized aluminum frame. Through the hinge system, mast assembly can be gathered, to fit transportation box. Cable chain as part of the mast assembly protects all cables and air hoses during manipulator movements. Mast Assembly is connected to the Spacer Assembly on the top and to the centering device with debris catching basket on the bottom. Vertical position of the Spacer Assembly attached to the Mast Assembly, defines manipulator height in order to be adapted to VVER440 or VVER1000 steam generator. Stainless steel linear slide with gear rack are attached to the mast, providing Carriage vertical movement. Motor with reducer are attached to the Driving Carriage. This Assembly contains Carriage with Quick Release Coupling System (QRS) used for quick module replacement, Motor and Reducer for vertical drive, Cable Chain, Aluminum Hinged Mast and Gear Rack with Linear Slide.

Centering device Subassembly, which is mounted to the bottom of the Mast Subassembly, features two functions: manipulator centering and foreign material catching basket. Pneumatically driven cylinder extends three pins while getting into the contact with steam generator. Protective rubber ring closely fits to the steam generator bottom, which protects primary circuit of foreign material objects.

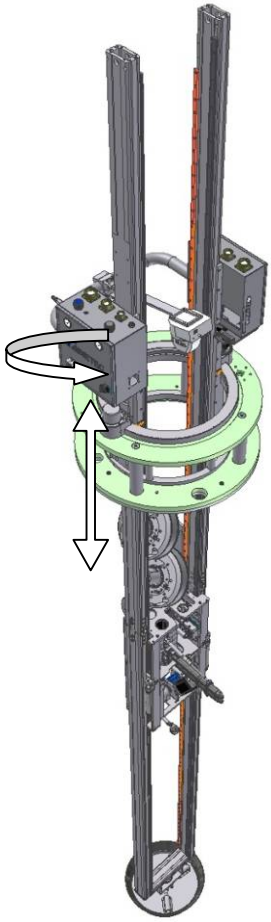

Figure 2 – IMEC Manipulator

2.2 Eddy Current Module

INETEC double pusher system (DPS) is used for Eddy Current inspections of VVER steam generators. It mounts onto the Mast Carriage. During the inspection (i.e. in “working position”), it is located inside steam generator collector and provides simultaneous, independent pushing drive for two probes. It consists of two identical pusher units powered by electric motors. It is controlled by EC control box (drive wheels functions), which is connected to the acquisition PC workstation through the LAN. Each of units can be run together or separately. When connected together, Control unit software allows running in single or double mode. DPS is powered by DC motor and probe speeds can be controlled remotely through PC workstation.

The probe speed for pushing/pulling regulation ranges from 2 mm/s to 2300 mm/s. All other pusher functions, for example: opening and closing of wheels; setting pushers to a “service position” (i.e. separating pushers) as well as extend and retract of guide tubes are provided by pneumatics and controlled by EC control.

Several ways for probe automatic stopping is implemented: Encoder integrated on the pushing/pulling Motor, Linear encoder used for measuring absolute inspection length, optical sensor and sensing coil placed between DPS and Conduit entrance. A motor encoder precisely measure motor rotation. In the case of slipping of the rubber rollers over the probe, linear encoder measures absolute position of the probe in the tube and stops the probe at the desired position (i.e. tube support, known position, guide tube, etc). In addition to that, guide tubes are equipped with an

optical sensor and sensing coil which stops the probe while pulling from the tube. Signal from eddy current probe through the EC Tester is deployed by Ethernet cable to the workstation.

The speed of the probe pusher is variable, allowing operator to adjust the speed in order to pass tube bends with smaller, or straight section of the tube with higher speed.

Guide tubes are equipped with calibration standards for bobbin probe. Bobbin probe calibration standards can be easily replaced with rotating probe calibration standards if required. DPS System has been designed for many different types and sizes of eddy current probes such as: Bobbin Poly probe, Bobbin Pearl probe, Rotation Probe, Array Probe, X-probe, etc.

Probe winding system (PWS) is a part of double pusher system. PWS enable winding of probes on the drum during probes pulling from generator tube and it does not permit uncontrolled probe unwinding and it is always active, no matter of pushing or pulling the probe within the tube. Guide tube centers the probe in front of tube to be inspected and contains bobbin and array calibration blocks, s well as photo sensors and sensing coils for probe stopping. Probe Drum Subassembly is mounted on the top of DPS. The shape and position of the drums provides probe self winding inside the drums. By adjusting angle and position of the drums, different type of probes could be used. Self winding system (SWS) is a part of double pusher system. SWS enable probe winding on the drum during probe pulling from generator tube and it does not permit uncontrolled probe unwinding. SWS assembly consists of drum assemblies and the winding mechanism. SWS can support different probe types and lengths. Probe Drum Subassembly contains Upper and Lower Probe Drum, Rotating Mechanism, Drum Carriage and MIZ-80ID ECT Tester.

Advanced eddy current instrument MIZ-80 has been integrated into the system. MIZ-80 is chosen as the latest development of eddy current remote data acquisition unit. Integration of MIZ-80 eddy current instrument is provided on both hardware and software levels, which means that instrument incorporated into IMEC assembly is fully controlled by EddyOne Software Package used for manipulator control, eddy current data acquisition, management and analysis. MIZ-80 ET includes advanced logic and circuitry systems which simplifies setup and improves data quality and noise immunity and it can operate with all types of probes.

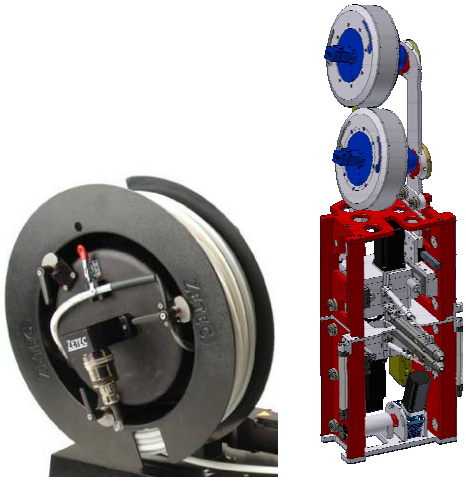

Figure 3 – Eddy Current Module with MIZ-80 integrated

MIZ®-80iD represents a break-through in technology to provide highly efficient and cost effective eddy current inspections of steam generator and condenser tubing in nuclear and conventional power plants. It combines a powerful eddy current instrument plus controllers for MRPC® probes, probe driver, and power supplies into one compact modular package. Together these modules maintain nearly the same footprint as the widely-used 10D Probe Pusher.

Each module is lightweight, easy to connect, and configurable in either left or right hand setups. When left and right units are combined, the MIZ-80iD supports dual probe acquisition. One operator can easily install and remove the entire system.

MIZ-80iD electronics are neatly packaged into the probe pusher drive head and take-up reel modules. A single Ethernet connection from the host acquisition computer operating with EddyOne software provides all of the control communication to the entire MIZ-80iD system.

The integrated acquisition instrument includes advanced logic circuitry that eliminates the need for probe extensions, probe adapters, analog slip rings, and reference probes. Integration simplifies setup as well as improves data quality and noise immunity. Cabling connections require one air line, one Ethernet cable, and two AC cables—a significant cable reduction compared to other systems.

Conventional testing methods with the bobbin technology provide very good detection and high speed testing, but can only measure the depth of the damage. Up to today, rotating probes have been used on VVER SG's in order to determine the other two dimensions of the flaw. Inspection with rotating probes is reliable, but very time-consuming.

The main advantage of the concept of the array probe is the ability to connect high-speed testing with the possibility of determining all dimensions of the damage. Array probes have a large number of coils in the probe body which is in contact of the pipe inner surface. Since the complexity of the array probe, advanced eddy current instrument that will support such a probe is required. Probe and eddy current instrument are connected with associated electronic system (multiplexer) that performs the task of sequential or individual coil triggering. Since this is a complex system that collects a large amount of information, latest state-of-the-art technology presentation of data is used, a three-dimensional presentation.

Inetec developed array probe for VVER steam generator tubes. Difference to the X-probe is in fact that instead of pancake coils, cross wounded coils are mounted inside probe body. Coils are optimized for VVER tubing to be sensitive to all type of damages – volumetric, axial or circumferential, inside and outside diameter initiated. Application of array probe combined with standard bobbin coils in the same probe provides increased sensitivity of inspection system. Array coils replace need for using rotating eddy current probe, which would be significant improvement in time needed for inspection. Tube is analyzed by using bobbin coils, and in case of doubt in data interpretation, data obtained from array coils field shall be used to resolve evaluation process. Further, array coils are giving us tool for additional characterization of found indications like orientation and sizing of indication.

Another application of array probe is eddy current examination of VVER steam generator collector material. So far, this type of examination is conducted by using rotating probes. Taking into account probe linear speed of 300 mm/s, inspection time of collector material is rapidly decreased.

All the improvements achieved so far are fully compatible with existing eddy current instruments, mechanical and other devices. Array probe has been already successfully applied on VVER 1000 steam generator inspection.

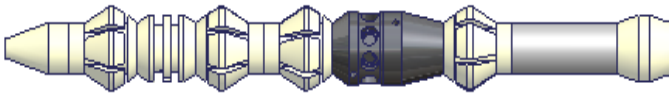

Figure 4 – Bobbin - Array Probe

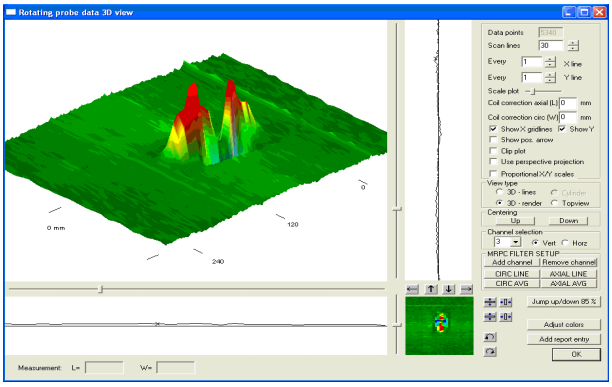

Figure 5 - Rotating probe C scan screen with gridlines

2.3 Ultrasonic Module

INETEC's Ultrasonic Module (SGU) is designed and developed for inspections of VVER steam generators collector welds, utilizing ultrasonic method. SGU is capable of accommodating up to 8 ultrasonic probes in specially designed sleds, regarding the requirement for ultrasonic probes to correspond to the scanning surface and provide full freedom of motions in conformity with inclination and unevenness of scanning surface. SGU has two Sled assemblies mounted on each sled arm. Each sled assembly comprises 4 sled subassemblies. Both of these subassemblies are capable of 360 deg rotation by use of integrated swivel module. Tin water film between ultrasonic probe and collector sheet is supplied by means of water pipes indented through the Manipulator and SGU. Two versions of SGU have been developed to accommodate INETEC older design of SG ECT Manipulator with central mast (IMD), and new manipulator design (IMEC). SGU, as well as other modules, can be mounted to the IMEC Manipulator very fast and very easy through the Quick Release Coupling System (QRS). Rotation and elevation of SGU are managed by rotation and elevation functions of IMEC Manipulator.

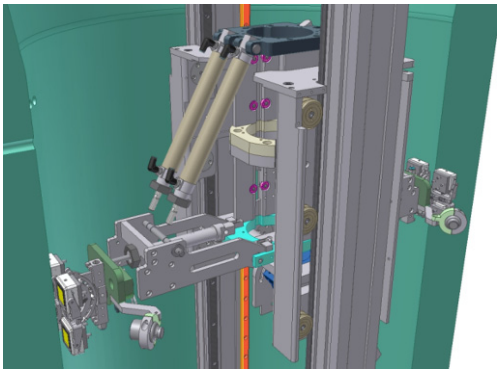

Figure 6 – Ultrasonic Module

SGU module has been applied on VVER steam generator UT inspections, with excellent feedback results.

2.4 Mechanical plugging Module

INETEC's existing plugging module have been redesigned and modified, so it can be attached to the new IMEC system. Quick Release Coupling System provides fast module replacement. Attached to the new IMEC Manipulator with integrated Machine Vision, plugging activities becomes much faster and more accurate. New Plugging Software has been developed to eliminate any human errors and to improve speed and quality during plugging performance

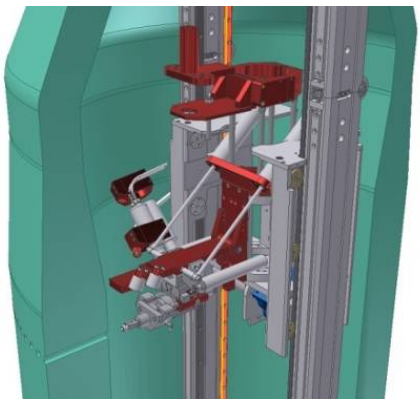

Figure 7 – Mechanical Plugging Module

2.5 IMEC Control Unit

The IMEC Control System, inspection controller is a precise control instrument designed for use with INETEC's Double Pusher Unit and Ultra Sonic Unit. It is completely controlled and displayed at the PC workstation running Microsoft Windows operating system. The IMEC Control System is connected with the workstation with 10/100Mbit Ethernet connection. Inside containment IMEC Control System unit contains both control and power unit and communication equipment in a single housing, and outside containment there is a Communication Box for connecting audio, video and Ethernet. All units and features are sealed, electronically cooled enclosure for environmental protection. The enclosure features a removable bottom and top cover to safeguard hardware during shipment and storage.

Integral parts of IMEC Control System are extension cable and tool harness. The IMEC Control System is a control system for eddy-current and ultrasonic testing of SGs on VVER440 and

VVER1000 nuclear power plants. It combines the selected features from Galil motion control system, INETEC designed I/O units, and motor power drives from Advanced Motion Controls. Up to five axes of motion is supported, two for manipulator control, rotation and elevation of the tool, two for motors on double probe pusher (DPS), and one for DC brushed motor on rotating probe. The control system consists of one 19" 12U height units (control box) and one 19" 3U unit (communication box) placed in separate cases for easier handling.

The control box contains CPU board, Relay board, Sense-coil and Rotating probe control board, power supplies and power amplifiers.

Figure 6 – Control Unit

2.6 Software

EddyOne, Windows based, software package integrate all modules needed for complete eddy current inspection of heat exchanger. Three modules communicate with each other in the real time.

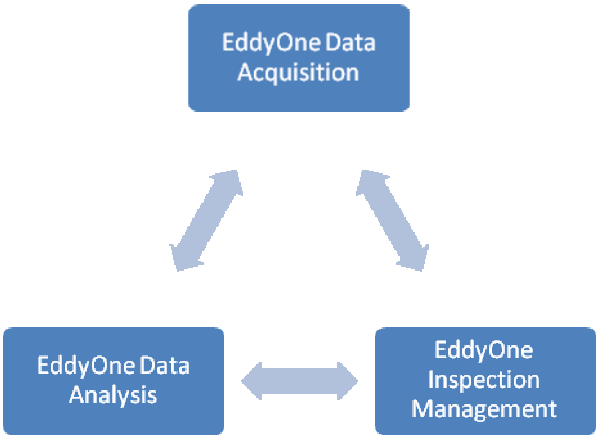

Figure 8 – EddyOne Software Package

EddyOne Data Acquisition and Manipulator Control

EddyOne Data Acquisition is software used to acquire data from TC-7700, MIZ-70, MIZ-30 or MIZ-8. EddyOne Manipulator Control is software used to observe the position and control the movement of the IMEC manipulator and different modules.

Four modes of testing are available:

- Free run (Operator can reach any tube just by pressing four direction arrows)
- Manual mode (Operator has to write coordinates of tube which he wants to reach. Computer automatically find requested tube)
- Test mode (Operator load the test plan with particular number of tubes and computer is reaching those tubes in the same order. Operator still has to submit to computer information like: to go to the next tube, to enter the tube, to start recording the data during pulling)
- Total automatic mode (Computer in accordance with loaded test plan inspect the tubes totally by itself. Operator has only to watch the process of data collection with the aim to act in some irregular situations)

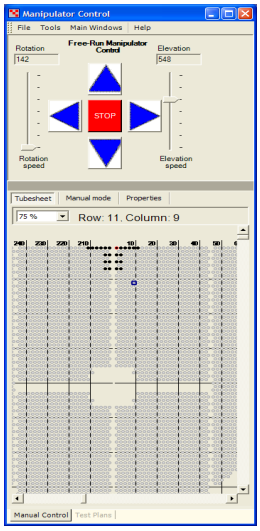

Figure 9 – Manipulator Control Widget

Data Analysis

All recorded data are transferred to data analysis room and analyzed in order to find reportable indications. Criteria for reporting indications are in accordance with appropriate standards and guidelines (i.e. ASME code, EPRI PWR Steam Generator Guidelines Rev.5), Customer's special requests. In order to determine the depth and volume of detected flaws, calibration standard are used. For bobbin coil examination ASME Calibration Standard is installed inside the manipulator. The standard is made of tube with the same dimensions (outside diameter and wall thickness) as the original tubes installed in the steam generator. All calibration standards are made from the material as tube bundle of the VVER steam generators.

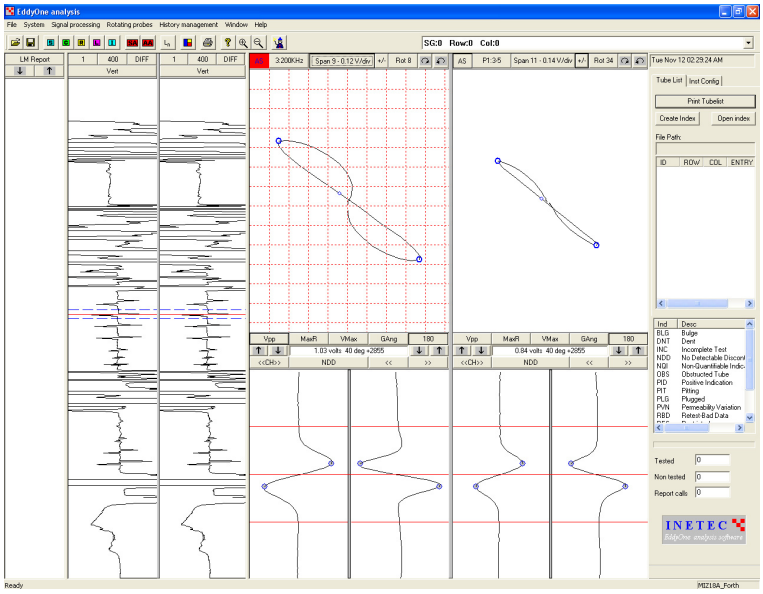

Figure 10 – EddyOne Analysis Main Widget

On the basis of calibration block defects, calibration curves are established on particular channels. Volume and depth of detected indication may be determined by comparison with artificial defects on calibration standard. Smallest flaw on ASME calibration standard is 4×20%, what provides sizing the defects found on steam generator tubes in the range of 20 – 100%, meaning the percentage of tube wall degradation.

Planning and Data Management

The inspection planning and data management consider performance of the following activities:

- Creation of inspection plans which contain all information necessary for inspection performance (list of tubes, type of probe, required extent),
- Preparation of inspection plans should consider steam generator geometry, its condition and contracted scope of inspection.
- Monitoring fulfillment of inspection activities according to schedule,
- Consideration of sorting of EC results by different parameters
- Data management is on-line with data analysis and provides simultaneous review of data analysis results.

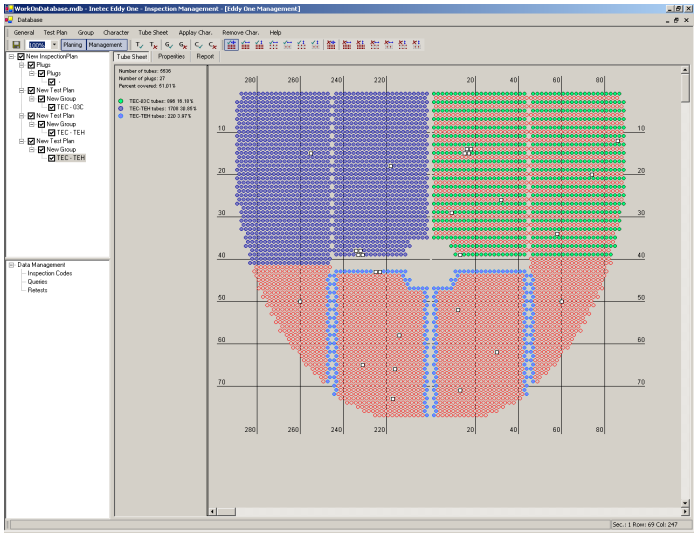

Figure 11 – EddyOne Data Management Widget

3 CONCLUSION

For the purpose of integrity conserving, faster inspection examination and increasing of inspection quality, Inetec developed new system for complete inspection and repair of VVER SG. Specificity of this system is tube inspection on VVER type of SG with array probe besides standard Bobbin probe, and that makes it unique system of that kind. Technique of VVER SG tubes inspection using array probe provides replacement of inspection of tubes and collector materials with rotating probes which results in reducing of inspection time.

As described system incorporates complete SG inspection (ECT and UT) and repair (plugging), it is ideal solution for nuclear power plant NDT divisions, as well as for NDT companies.

REFERENCES

[1] IAEA-TECDOC-1577, Steam Generator Tube Integrity Strategy for Assessment of WWER, December 2007