ABSTRACT

The steam generator (SG) is a critical component in nuclear power plants (NPP) with the largest surface area in the primary reactor coolant system, and its integrity is essential for avoiding possible radioactivity release to the environment. SG tube walls are susceptible to aging, i.e., various degradation mechanisms take place in its structural material, such as volumetric material loss due to fretting wear, stress corrosion cracking (SCC), pitting corrosion, flaw accelerated corrosion, intergranular attack (IGA) etc.

New more strict regulatory requirements request plant management to assure the safety of the public and the environment, as well as better SG life management strategies. Therefore, those requirements forced specialized inspection companies to develop advanced probe technologies, more reliable instruments and robotics, and improve training and knowledge of personnel involved in the inspection process.

Thanks to intensive evolution of electronics and computers in the last decade, inspection systems have evolved to a much higher level of automation, efficiency and reliability. Tools based on the eddy current examination techniques were subject to continuous development - from a simple detection tools to advanced diagnostic tools that provide input for decision making based on the integrity assessment.

Forerunner is a part of INETEC’s inspection system for PWR plants, primarily used for quick and accurate positioning of the tube guide on the SG tube sheet, and efficient performance SG tube walls inspection. It is a light mobile robot, adjustable for different tube sheet configurations and inner tube diameters. Integrated electronics based on the EtherCAT technology increases the speed of operation and simplifies the cable management. Using the strongest grippers currently available at the market, the FORERUNNER is a reliable and robust system, highly automated with a machine vision, and built-in smart algorithms for optimal movement.

Forerunner is controlled by PC-based software, which is synchronized with INETEC EddyOne software package. The complete scope of inspection activities, the planning, examination, data analysis and final report, became a highly automated process, which makes the inspection much easier and more reliable.

1 INTRODUCTION

Steam generators are heat exchangers used to convert water into steam from heat produced in a nuclear reactor core. They are used in pressurized water reactors between the primary and secondary coolant loops. These loops have an important safety role because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant as the primary coolant becomes radioactive from its exposure to the core. For this reason, the integrity of the tubing is essential in minimizing the leakage of water between the two sides of the plant. Steam generator tubes are susceptible to several degradation mechanisms like outer diameter stress-corrosion cracking (ODSCC), either circumferential or axial or intergranular attack (IGA) which can result with cracking. Crack defects can also be initiated from primary side in form of primary water stress corrosion cracking (PWSCC). An other common degradation form is volumetric loss of tube material due to wear, wastage, pitting corrosion and impingement. There is a potential that, if a tube bursts while a plant is operating, contaminated steam could escape directly to the secondary cooling loop.
Thus during scheduled maintenance outages or shutdowns, some or all of the steam generator tubes are inspected by eddy current testing (ECT).

Recently, INETEC has developed a new generation of the PWR steam generator inspection system, using modern technologies and great experience from the previous inspections. New inspection system consists of three sub-systems: manipulator, probe pusher with ECT instrument and advanced software solution for PWR steam generators inspection. All of the features of the new system will be described in detail in the paper.

2 PWR STEAM GENERATOR INSPECTION SYSTEM

INETEC’s new system for PWR steam generator inspection has been designed as modular system with a light mobile robot called Forerunner. Its role is to position the guide tube at the exact coordinates in the tube sheet according to the inspection plan. In order to perform the data acquisition and obtain all inspection requirements, the Forerunner is linked with other devices in the system.

Usher is a probe pusher used for testing the integrity of the pipes wall by the eddy current method. It is primarily developed for the testing of steam generators in nuclear power plants, but it can also be used for testing other heat exchangers on the balance-of-plant side of the nuclear power plant. It is a link between the Forerunner and the ECT instrument. In the case of manual positioning of the probe Usher can work as a standalone device. These two devices are connected via communication link with operator’s workstation where control software is installed. Operator performs inspection process with EddyOne software package that consists of several modules that will be presented later.
On the site, equipment is set on two locations as shown in Figure 2. Manipulators and ECT instruments are installed in reactor building. Pressurized air and 110/220VAC power supply are required on site to perform the inspection. On the other hand, workstations with EddyOne software installed are located in operator’s room. In order to connect these two locations and exchange audio, video and control data, special communication system is designed. With only one optical fiber all data are transferred to central control system.

2.1 Forerunner

![Forerunner](image)

Forerunner is a polyvalent device designed to perform different tasks in steam generators with the aim of positioning, movement and working with a variety of tools. Primarily, Forerunner works with probes for NDT testing, but it can also carry plugging tool in order to do corrective operations. Moving is achieved by translating the main axis and sticking fingers (grippers) in the tubes of the steam generator tube sheet. The device has a capability for spider-like movements in all working positions on horizontal, or vertical tubesheets, and easy adaptation to different parameters of heat exchangers.

Forerunner is designed as finger-walker and it has two pairs of fingers to hold the manipulator in contact with the tubesheet. The manipulator has five degrees of freedom, two for moving across the tubesheet and three degrees of freedom for tool positioning. In that way, the manipulator can reach and perform inspection of all tubes in the tubesheet, which means there are no exclusion zones.

As it is shown in Figure 3, Forerunner has three main parts: control system unit, main axes unit and auxiliary axes unit. Control system unit is consists of motion control electronics and actuators that are used to generate forces needed for manipulator movement. Main axes unit perform manipulator movement and positioning on the tube sheet according the inspection plan. In order to assure independent position verification, Machine Vision is integrated in the system. Auxiliary axes are in charge of accurate positioning of various tools that can be used during inspection. The great advantage of employment of the auxiliary axes is high speed of inspection because Forerunner’s main axes remain idle with grippers (A, B, C and D) locked while the auxiliary axes can inspect up to 72 tubes before the next movement of the manipulator.
2.2 Performances and features

Forerunner requires 110/220 V AC power supply. However, the operating voltage is 48 V DC for motors and 24 V DC for sensors and control electronics. It means that Forerunner is low-voltage device that can be used in areas with high humidity without any harm. Motion control system can reach linear speed up to 95 mm/s and over 45 degrees per second during rotation. In addition, the maximal force that can be achieved in motion is over 550 N, which means that Forerunner can easily operate on vertical tubesheets.

During motion, Forerunner uses grippers to keep the contact with tubesheet. Forerunner’s grippers are specially designed to withstand all forces that can occur during inspection with dual probe pusher system. Each gripper is pneumatically actuated with total force up to 1700 N. Also, it has specially designed mechanical locking system that is used while gripper is in the tube. With this mechanical system, Forerunner can be locked in the steam generator tubesheet as long as needed even in case of loss of pressurized air or power supply. To unlock the gripper air supply should be present and all safety requirements have to be met which is controlled by fail-safe logic. Additional function that is used in the grippers operation is active self-leveling, which is used to maintain the permanent contact of all grippers with the tubesheet. It is done by monitoring the tubesheet contact sensors on every pair of grippers and performing self-leveling function in case of lost contact. Self-leveling function uses a pair of grippers that are in contact with the tubesheet to pull the manipulator to the tubesheet while contact sensors on grippers that lost contact are activated.

From safety side of view, there is one more subject that has to be resolved when working with finger-walker type of manipulator in the steam generator. It is extremely important to keep the manipulator on the tubesheet without any damage caused to any tube. Forerunner’s grippers are currently the strongest grippers on the market. However, they do not make any damage to the steam generator tubes because of large contact surface and carefully chosen materials that are used as finger coating. For that purpose, numerous experiments were carried out, all with satisfactory results.

In order to test contact with inner surface of tube and determine possible damage to tube, INETEC has made a tubing model and a procedure to load fingers on tubing. When all test phases have been performed, INETEC made eddy current examination of the tubing. Grippers testing model is presented in Figure 1.
Tubes are inspected by bobbin coil and rotating probe technique in accordance with INETEC procedure for in-service inspection of vertical steam generators tubes by using multi-frequency eddy current examination techniques.

Tubes are recorded 5 times after 5 phases of load per procedure. After the latest phase, bobbin technique and rotating probe technique did not find any damage that could be detected by performed inspection technique. Visual examination has detected areas on the tube inside diameter surface, spread in axial direction, and which disappeared after cleaning process made by dry textile.

On tube No. 3 (where severe load was made per procedure) pancake coil detected signal initiated from inside tube diameter, axially oriented, with small volume that did not allow any sizing procedure. It has to be added that pancake coil is very sensitive to changes in geometry. Cross wound coil did not find any response on this particular location, what indicates that there is neglected change in geometry. Further, visual examination detected small change in tube surface color, spread in axial direction which did not disappear by using cleaning process with dry textile. By using magnifying glass, no damage was detected. Also, a needle with curved end was used; no change on inside diameter surface of tube was detected as well. Therefore, it might be concluded that EC examination did not find any damage in the tubes on the model, which were loaded per defined procedure.

2.3 Control system

Forerunner control system is designed as 3-level control system with precisely defined functions. Low level is in charge of motion control for particular degree of freedom, and it monitors all sensor activity. Middle level is used to synchronize independent motions of each degree of freedom in a way that is needed to carry out planned trajectory. High level control system is link between operator and the manipulator. It can plan the movement trajectory according the inspection plan, monitor all activities that have been performed, and run the diagnostics algorithm in case of any unplanned situation. General schematics of Forerunner control system is given in Figure 6.
This control system is able to manage the whole inspection process automatically after it has all information about the steam generator to be inspected (e.g. SG type, tubesheet scheme, plugged tubes …) and scope of inspection. It has to be emphasized, that trajectory planning algorithm is based on optimal control using several criteria. Criteria that can be used in trajectory planning include, but are not limited to estimated inspection time, inspection plan, position of installed plugs in specific steam generator, presence of other Forerunner or any other device that is used in inspection, and any other constraint.

2.4 Usher

Usher is used to push the cable shaped probe inside the tube with controlled speed and position. Combining the years of experience from the field and the modern technology, numerous new features are built in the Usher, which makes this device fast, reliable and easy to operate with. The all-in-one design means that the control electronics are integrated inside the device increasing the speed, simplifying cable management and reducing the noise of the measuring signal. A single Ethernet connection from the host acquisition computer provides all of the control communication. Usher architecture supports simultaneous usage of multiple devices through a common interface. This option is used to reduce the inspection time.

Like Forerunner, Usher is also based on the 3-level control system: the first level consists of servo drives and input/output unit, in the second level is the main controller, and in the third level is PC application directly controlled by the operator. Most operations are carried out in the first and second level, which makes the Usher highly automated device.
As it is shown in Figure 7, the Usher can be easily disassembled by the clip-on connection into two main parts: pusher drive unit and controller unit. This is useful during manipulation when the mass is equally distributed in the both hands. Usher can work even in disassembled mode, when additional conduit and extension cable should be inserted between separated units. This mode is used in the narrow space when only pusher drive unit is close to the tube sheet while the probe could be exchanged at up to 10 m remote location.

The pusher drive unit consists of a drive mechanism, driving wheels and the housing with all electrical and pneumatic components. For the practical reasons air supply and two connectors for sensing coils are placed in the front of the unit below the drive mechanism. Driving wheels are pushed by two pneumatic cylinders against the probe ensuring the traction force. Contact pressure between the wheels and the probe is regulated according to the working conditions. The wheels are driven by a special torque motor whose dimensions and a power/weight ratio are the most convenient to this application. Probe speed inside the tube can be set in the range within 0.5 mm/s to 2.6 m/s, while the pushing force can be set in range between 100 N and 1000 N. The exact location of the probe inside the tube is measured by the linear encoder. Comparing the data from the linear encoder and the motor encoder wheel slippage can be detected. In that case Anti Slipping Control (ASC) progressively increases the wheels pressure to a maximum value. If the slippage is still present, control system will give up on pushing and notify the operator. This function assures optimal pushing force during inspection and increases the probe lifetime.

Controller unit consists of take up reel and housing for the main control unit. The reel is also driven by torque motor controlled with algorithm that controls the torque and the winding speed according to operating conditions. On the reel there is a slip ring that is used to transmit the signal from the probe to the instrument next to the device. Special instruments that are embedded into the take up reel digitize signals before passing through the slip ring and thus further reduce the measuring noise. Usher supports many different types of instruments including these one.

Interaction with Eddy Current instrument includes exchange probe position data and start/stop signals. Remote control features include remotely operated emergency stop that can be arranged to stop all devices if more than one Usher is used in inspection. On the other hand, there is possibility to use remote control accessories in order to operate each device.

Due to harsh work conditions in the high radiation zone in nuclear power plants, where operators wear special suits and multiple layers of protective gloves, special attention is paid to safety and ergonomics issues. The emergency stop button is placed at an easily accessible location with optional remote button near the operator. The entire device is powered with low voltage (48 V DC) in order to reduce the possibility of electric shock. Front-wheel drive can be set up with protective cover which minimizes the possibility of injury from mechanical parts.

From the ergonomic point of view the Usher is suitable for handling particularly due to significantly less weight than other similar devices. All surfaces are very smooth with no pockets in which radioactive dust might be deposited. Because of its shape and IP protection level Usher is very suitable for decontamination after usage.

2.5 EddyOne

EddyOne Software Package is a complete solution for eddy current inspection of nuclear power plant components. EddyOne software package is consisted of: Inspection Management, Manipulator Control, Acquisition and Analysis. Inspection Management is a central database for modeling of the steam generator (tubesheet, landmarks…), inspection planning and progress tracking. After the inspection it’s used for interpretation of results and generating of the required reports. INETEC’s manipulators are driven using the Manipulator control software. It is used to control the manipulators and track their status. It supports the automatic acquisition mode where the predefined inspection plan is used to automatically perform the inspection. The Acquisition software is used to record the eddy current data and track the inspection procedure, while Analysis software is used for offline analysis of the recorded data.
Automatic analysis further simplifies the analysis procedure by reducing time and costs required for data analysis. All the software is available in multiple languages and can be customized according to the user’s needs.

3 CONCLUSION

In order to reduce outage time of nuclear power plant, development of new inspection systems is needed. They have to provide faster inspection, be compact for easier installation and be able to bring more information about steam generator condition. All these requirements have to be met to perform better structural integrity assessment and fulfill ALARA recommendations at the same time.

New generation of INETEC’s steam generator inspection system is designed to satisfy all regulatory requirements and give the best inspection results at the same time. This system has been designed as modular system with a light mobile robot called Forerunner. Its role is to position the guide tube at the exact coordinates in the tube sheet according to the inspection plan. In order to perform data acquisition and obtain all inspection requirements, the Forerunner is linked with other devices in the system, primarily probe pusher and ECT instrument. All inspection data are collected and managed by EddyOne software package that is a complete solution for eddy current inspection of nuclear power plant components.

REFERENCES

3) A. Bakić, “PWR Steam Generator Inspection System”, Workshop on advanced NDE applications, China Nuclear Operation Technology Corporation, Wuhan, China
4) A.Bakić, P.Mateljak, D.Rohde, “Advanced System for VVER Steam Generator Inspection”, 8 ISTC Safety Assurance of NPP with VVER OKB GIDROPRESS, Podolsk, Russia
5) M. Vavrouš, „Advanced system for VVER SG tubing inspection“, The III International Forum of Nuclear Industry Suppliers ATOMEX 2011, December 6–8, 2011, Moscow