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ADVANCED APPROACH OF REACTOR PRESSURE VESSEL IN-SERVICE INSPECTION

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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 reactor pressure vessel 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 reactor pressure vessel tool and control systems.

This article presents remote underwater contact ultrasonic inspection equipment and developed advanced nondestructive techniques for the examination of the defined sections (reactor welds). Eddy current method applies for clad surface examinations; visual inspection is used for examination of the vessel inner surface and advanced phased array ultrasonic technique applies for base material examination. The movement of probes and data positioning are assure by using new RPV tool concept that is fully integrated with NDT systems.

The successful performance is attributed thorough pre-outage planning, training and successful performance demonstration qualification of chosen NDT techniques on the specimens with artificial and/or real defects. Furthermore, use of advanced approach of inspection through implementation the state of the art examination equipment significantly reduced the inspection time, radiation exposure to examination personnel, shortening nuclear power plant outage and cutting the total inspection costs.

1 INTRODUCTION

The reactor pressure vessel (RPV) of is an integral part of the reactor coolant pressure boundary. Ensuring safe operation of Nuclear Steam Supply Installation is a main and obligatory condition for the operation of all power units. One of the most important measures in fulfilling these requirements is periodical inspection of the condition of base metal, welded joints and RPV austenitic steel overlaying welding.

At present, INETEC has developed and is operating now the present-day systems for inspection of reactor vessel from the inside. Taking into account increasing requirements to the safety enhancement during plant operation, shortening of the inspection time, radiation exposure to examination personnel and cutting the total inspection costs, decision was to upgrade and improve existing RPV inspection system with advanced inspection techniques, such as implementation of the ultrasonic phased array probes.

2 REACTOR PRESSURE VESSEL

RPV is a vessel welded from several one-piece forged barrels. Girth joints are performed by automatic welding. Reactor bottom is usually an ellipsoid, there is from one up to several welded joints on the bottom, depends on the RPV design. Inner surface of reactor vessel has anticorrosive austenitic double layer steel overlaying welding. Primary coolant nozzles are welded to the RPV and coolant piping by automatic welding and overlaid with austenitic layer.
All RPV welded joints, austenitic overlay and core region has to be inspected on the periodical basis, depends on the operator, codes, and standards of particular country. Many manufacturers have different RPV designs and manufacturing technology, but inspection approach, equipment and non-destructive techniques (NDT) are very similar. Different RPV's consist of several types of welded joints: cylindrical welded joints between cylindrical barrels, longitudinal welded joints on the bottom, nozzle to vessel and safe end welded joints, core barrel supports and distribution ring welded joints, etc.

3 SPECIFIC INSPECTION OBJECT

This article presents advanced remote underwater contact ultrasonic inspection system and advanced nondestructive techniques for the examination of the defined sections (reactor welds) applied on VVER 1000 RPV. Eddy current method is applied for clad surface examinations; visual inspection is applied for examination of the vessel inner surface; and advanced phased array ultrasonic technique is applied for base material examination. The movement of probes and data positioning are assured by using new reactor pressure vessel tool concept that is fully integrated with NDT systems. Described equipment and NDT techniques can be applied to different types of RPV as well.

RPV VVER-1000 and core barrel are the objects of inspection. RPV is a vessel welded of solid-forged barrels (Fig. 2.1). Core barrel is a cylindrical barrel with Ø 3500 mm that has flange in upper part. Core barrel leans by this cylindrical barrel on internal nose in RPV. In lower part a core barrel has perforated bottom, in which support perforated tubes for lower end caps are installed. RPV circumferential welding are performed by automated weld under melt with welding wire (type sv.08KhGNMTA (св.08ХГНМТА)). RPV bottom has shape of ellipsoid; it can have welding performed by slag weld, welding material sv.16KhGNMAA (св.16ХГНМАА). For protection from corrosion, RPV is covered with anticorrosion overlay with thickness 7 to 12 mm from internal surface.

Thickness of VVER-1000 RPV wall with overlay is the following:

- (215 ÷ 237) mm in area of bottom (end);
- 200 mm in the area between bottom and nozzle barrels;
- 295 mm in the area of nozzle barrels.

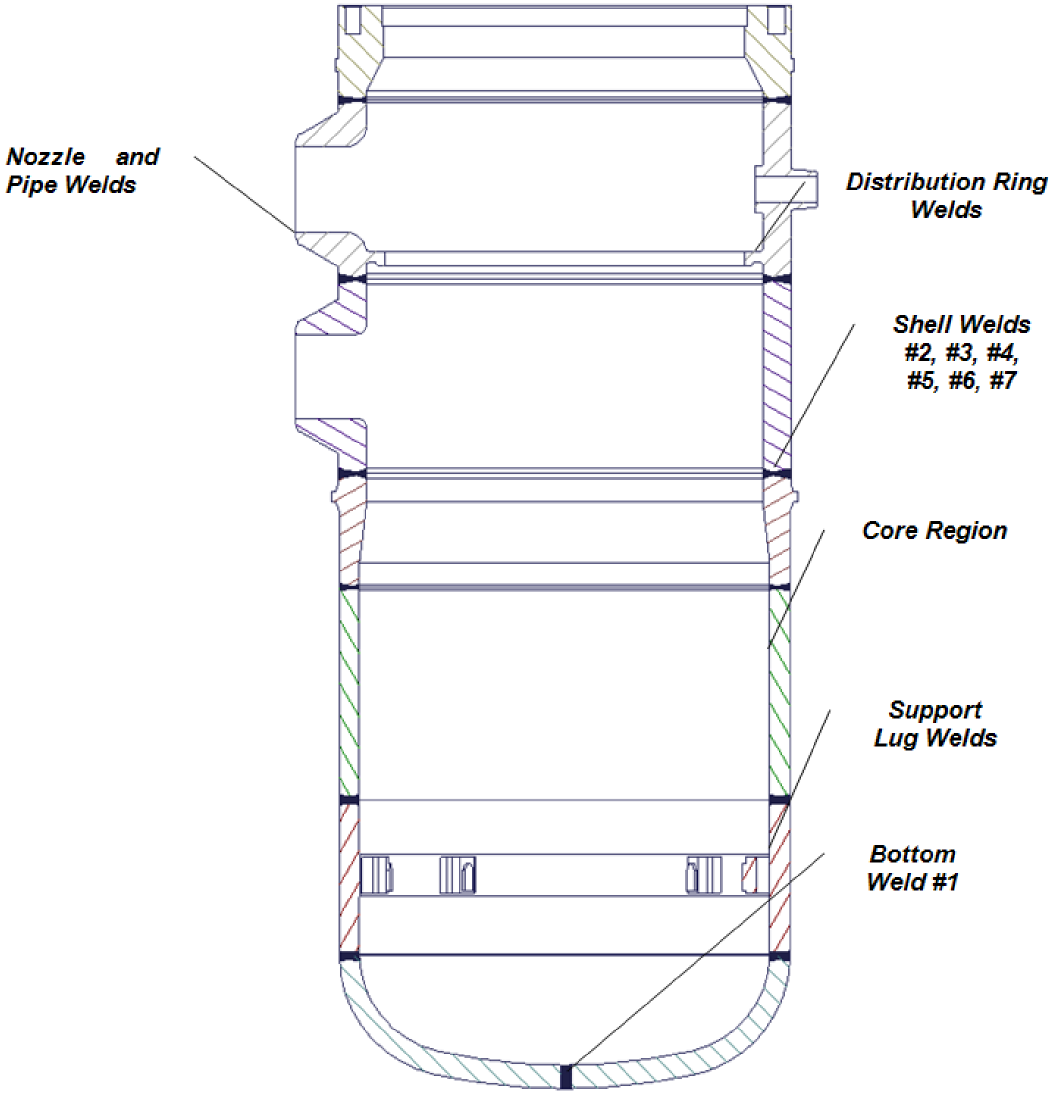

Figure 1 – VVER 1000 RPV

RPV of VVER-1000 consists of:

- pressure vessel that consists of welded barrels and bottom (total 6 circumferential welds and 1 longitude weld of bottom (weld No.1));
- 8 nozzles of primary circuit (4 "cold" and 4 "hot" loops);
- 4 nozzles of welding of emergency core cooling system (ECCS) pipes (active and passive systems);
- spreader of stream;

- circular element with brackets for installation of in-vessel equipment;
- lodgement for impulse tubes positioning;
- support flange at outside surface.

4 INSPECTION TECHNIQUES

Prior to selecting reactor vessel examinations NDT equipment, reviews have been performed of the technical requirements, the applied reference documentation (e.g. edition/addenda of the ASME Boiler and Pressure Vessel Code Section) and detailed component drawings. This review was performing to ensure that all mandatory NDT requirements are satisfied and the proposed examination techniques are in compliance with the reference documentation and good engineering judgment. The selected examination techniques that will be used during RPV inspection are evaluated against main inspection goals. These goals are:

- to achieve required inspection capabilities in regard to detection, characterization, and sizing. The techniques chosen shall have verified the total examination volume being examined. Additionally, the techniques are optimized for the use of our advanced data recording, processing and evaluation system (Dynaray).
- to arrange UT probes in the most optimized configuration to reduce inspection and preparation time. Furthermore, the scanning sequences are optimized in order to minimize preparation activities and inspection time.
- to minimize personnel radiation exposure by application of specific examination techniques and sequence of performance that reduce manipulation with equipment.

Plant specific criteria are used to define these examination techniques. The criteria, which are used, include:

- Component/weld geometry, including thickness, accessible surfaces, surface as
- cladding conditions
- Component materials
- Potential areas of concern, i.e. the inner diameter surfaces of the vessel adjacent to the fuel core, nozzle inner radius, dissimilar metal welds

Good engineering judgment factors also influence our selection of examination techniques. These factors include:

- Emphasize a multiplicity of examination techniques (multi-angle) that can be integrated to form a better picture of the examination but not allowing the techniques to become too cumbersome and unnecessary.
- Two-sided access to examination volumes.
- Optimized usage of state-of-the-art equipment and methodologies for flaw detection and sizing.
- Concentrate on known techniques but customize them to adapt to the plant specific conditions.

With these criteria as well as factors and our current knowledge of the reactor pressure vessel design, the following examination techniques have been selected.

The specialized contact ultrasonic examination techniques described in the following paragraphs requires three (3) different inspection module designs. These modules are configured on such way that probe positions are optimized in regards to examination volume coverage and that the necessary force is provided to maintain contact of the probe with the scanning surface. All ultrasonic examination data are processed by ultrasonic instrument (Dynaray) and permanently recorded on the storage media (DVD, Hard drive).

Calibration of the entire examination system shall be performed on site utilizing the generic examination procedures. During the RPV examination, the calibration shall be verified at 12-hour intervals, as a minimum. Verification of calibration, including the final calibration check, shall be performed using a combination of reflectors to confirm sensitivity and linearity throughout the entire examination range. All these verification schemes are base-lined during the initial calibrations such that the verifications during and after the examinations can be correlated back to the original calibrations.

Reference blocks (i.e. IIW, MAB, Depth Sizing, etc.) used for establishing linear screen ranges and determining actual refracted angle and exit point information shall be made of material similar to the examination base materials.

The selected technique uses calibration of the examination sensitivity based on component material noise level, which in conjunction with applied ultrasonic instrument that provides 80 dB of dynamic range, achieves the highest performance of the system regarding the examination sensitivity. In addition, the sizing of the flaws is based on tip diffraction technique which is signal amplitude independent technique that provides much more precise sizing in comparison to still commonly applied, signal amplitude dependent technique. Moreover, the technique applied is not based on any signal amplitude threshold that needs to be met in order to report the flaw but rather, it is based on the characteristic signal echo-dynamic curve.

Applied system is beneficial in that it provides a permanent record of the examinations and can be archived for future retrieval. It allows flexible manipulation of data to evaluate flaw indications with different techniques: more accurate amplitude independent as well as amplitude-based sizing techniques. The flaw information data selected by analyst may be inserted in custom design report on custom designed analysis screen by click of a mouse. The report may be edited by MS Office programs so the flaw information may be additionally processed and analyzed. On that way the flaw sizing process as well as recording of data is shorten for necessary flaw evaluation.

Examinations of the anticorrosive austenitic steel overlaying welding on the inner surface of the nozzles as well as nozzle to pipe welding is conducted within the bores of all nozzles. The scanning plan is divided in a way that all examination volumes will be subjected to four directional angle beam interrogations. This is accomplished with one simultaneous scanning routine (circumferential) for each nozzle. In order to detect the surface indication on the inner side of nozzle bore in the axial (normal to the weld) as well as in the circumferential (parallel to the weld) scan sweeps, dual phased array probes, longitudinal waves are directed towards and opposite to the vessel centerline for axial and clockwise and counter-clockwise directions for circumferential scanning. The longitudinal wave search units, also included in these scans, are similarly directed. These units are used for interrogation of the deeper volumes of the weld.

A 0° single element transducer is used for straight beam examination during performance of the nozzle scanning. Additionally, 0°, dual element, focused transducer is applied in order to detect flaws in the region of anticorrosive austenitic steel overlaying welding or its interface to base metal in the nozzles bore area.

Additionally, nozzle bore scanning is extended towards the vessel center in order to cover the furthermost parts of inner radii examination volume by nozzle bore section sleds.

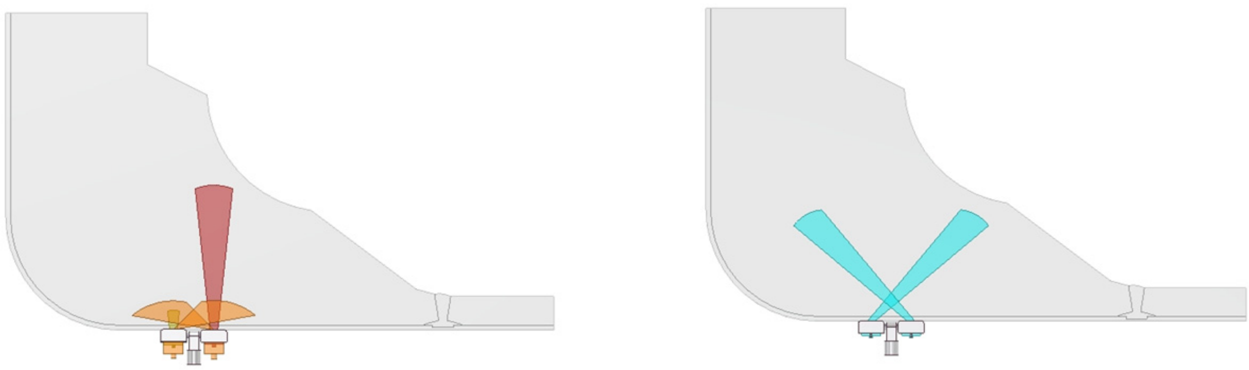

Figure 2 – Nozzle Weld Inspection PA Probes Arrangement

Nozzle inner radius transition areas are scanned by inner radius section of module (scanner arms). Two phased array probes, longitudinal waves are delivered to the inner radii examination areas by movable scanner arms operating in a circular scan path. The transducers are arranged 180° apart, with beams directed clockwise and counter-clockwise at steering angles of 50° to 75°in the primary plane and -30° - 30° in secondary plane. The transducers focal are optimized for maximum detection capabilities of near surface flaws.

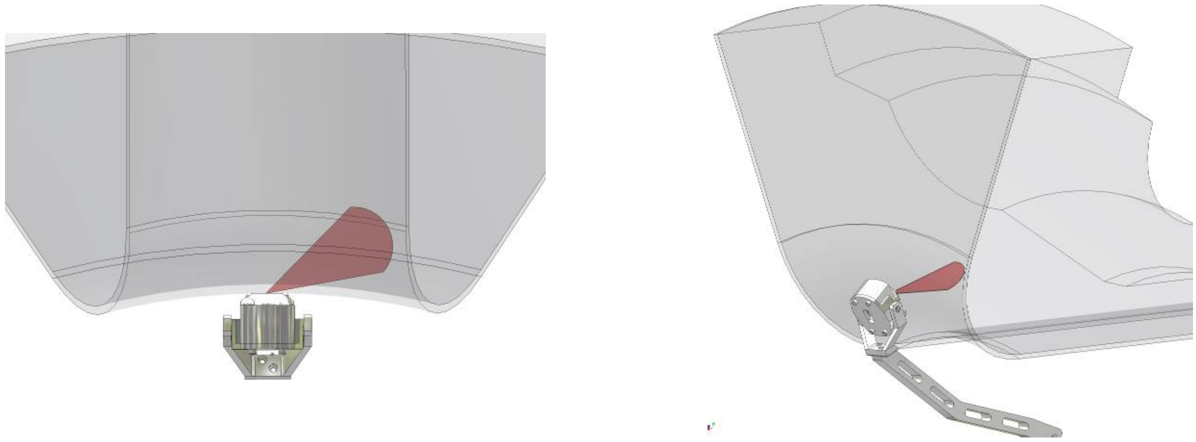

Figure 3 – Inner Radii Inspection PA Probes Arrangement

Reactor pressure vessel (RPV) base metal and anticorrosive austenitic steel overlaying welding of the vessel and bottom, as well as circumferential welding joints are simultaneously examined to the extent practical by four directional angle beam interrogation. Shear wave, phased array probes, were selected for deeper material volume inspections, while transmitter-receiver phased array probes, compression wave, are selected for supplemental near surface flaw detection. These advanced dual PA probes applies for flaw detection and sizing in base metal up to the depth of 40 mm. A 0°, transducer is used for straight beam examinations of the specified volumes. Additionally, 0°, dual element, focused transducer is applied in order to detect flaws in the region of austenitic steel overlaying welding and overlaying welding to base metal interface.

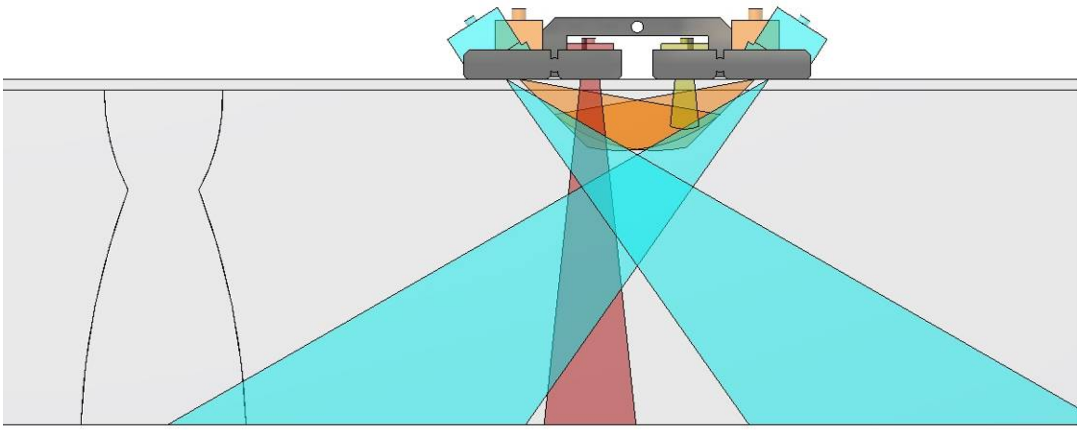

Figure 4 – Circumferential Welds Inspection PA Probes Arrangement

Designated areas of austenitic steel overlaying welding as well as inner radii surface will be inspected by the use of surface ET probes for the presence of surface penetration flaws as well as presence subsurface defects at ligaments up to 2.5 mm.

In order to achieve such detection capabilities the "Ghent G3 style" magnetic biased driver pickup probe is used. Each probe contains two sets of coils at right angles to each other and working in driver pick-up mode having separate transmit and receive coils. The probe is designed to reduce the effect of magnetic permeability variations in the clad.

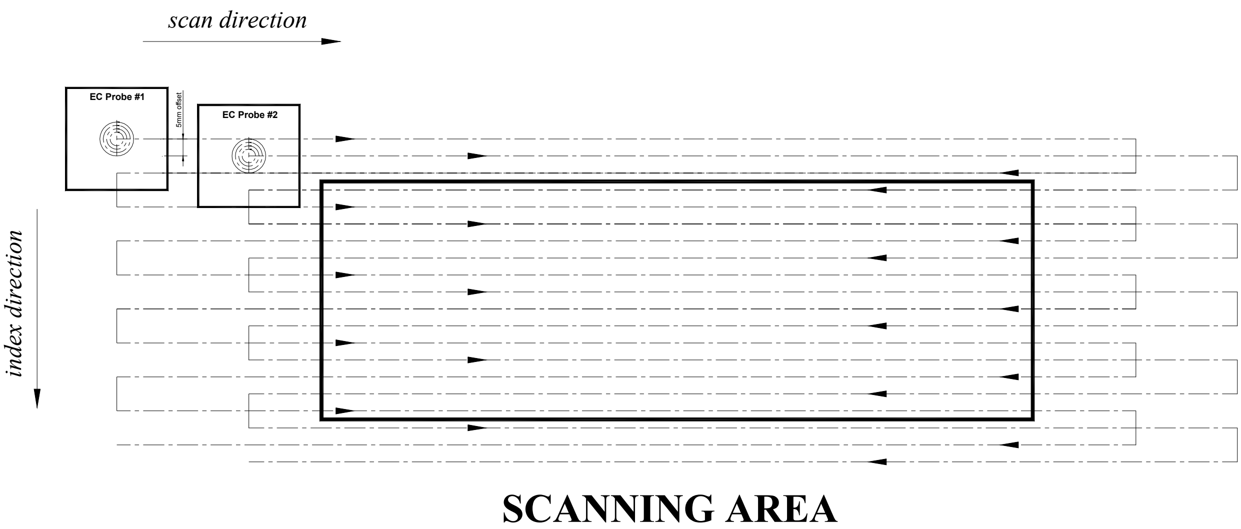

Figure 5 – Eddy Current Inspection Arrangement

The single probe covers up to ±2.5 mm towards left and right of the scan direction. In order to achieve index increment up to 10 mm, two ET probes are mounted with an offset of ½ of the increment relative to each other and used to run in parallel.

The system sensitivity of Eddy Current inspection is not lower than the sensitivity of liquid penetration method of RPV austenitic steel overlaying welding inspection, and inspection of circular bends of the nozzles. In general, a minimum surface open crack detectable by Eddy Current will be as small as (with confidence probability of 0.95) 3 mm in length and from 1 to 10μm width. Reference standard used to set sensitivity of Eddy Current system is made of material similar to 04Х20Н10Г2Б. Concerning the Eddy Current inspection technique used, the "lift off signal" recorded on the reference standard shall match "lift of signal" on RPV within 10 degrees.

At least 3 surface open grooves and 3 ligaments need to be present on the calibration standard. These are 0.5 mm, 1 mm and 2.5 mm depth surface grooves, and 0.5 mm, 2 mm, and 2.5 mm ligaments.

For surveillance and control motions of RPV-ISI tool, the color camera, pan and tilt unit with lights are mounted to the RPV Tool carriage, while during visual examination of reactor vessel interior as well as in-vessel vault camera is mounted to the specially designed visual module. The connection between camera and camera control unit is formed by composite cable with matching waterproof connectors, which provide the necessary power and remote control of focus, iris and zoom.

Resolution has been considered adequate for Visual inspections when the combination of access, lighting, angles of vision and water clarity allow the examiner to resolve a fine line 0.8 mm wide or less. For resolution demonstration, a Vision test chart which contains a fine line 0.8 mm wide and text with lower case characters without an ascender or descender (e.g., a, c, e, and o) has been used. Additionally, a Color test chart has been used for illustrating adequate color camera resolution.

5 INSPECTION EQUIPMENT

The Reactor Pressure Vessel In-service Inspection (RPV-ISI) system is employed for the full scope RPV of volumetric and surface examinations including the examinations of the circumferential welds, core region, nozzle welds, inner radius sections, vessel-to-flange weld and bottom sphere weld. A contact ultrasonic technique is applied for the examination of the defined sections as well as eddy current method is applied for clad surface examinations. DYNARAY UT acquisition instrument is applied for record, process and analyze ultrasonic data, while TC7700 system is applied for eddy current data acquisition and analysis. UT and ET data acquisition units are fully integrated with the RPV-ISI Tool to link position data with all ultrasonic and eddy current recorded data and to assess indications. In addition, the high-resolution color video system is applied to perform the visual inspection of inner surfaces of the vessel. The overall interconnection diagram of RPV-ISI System is shown below.

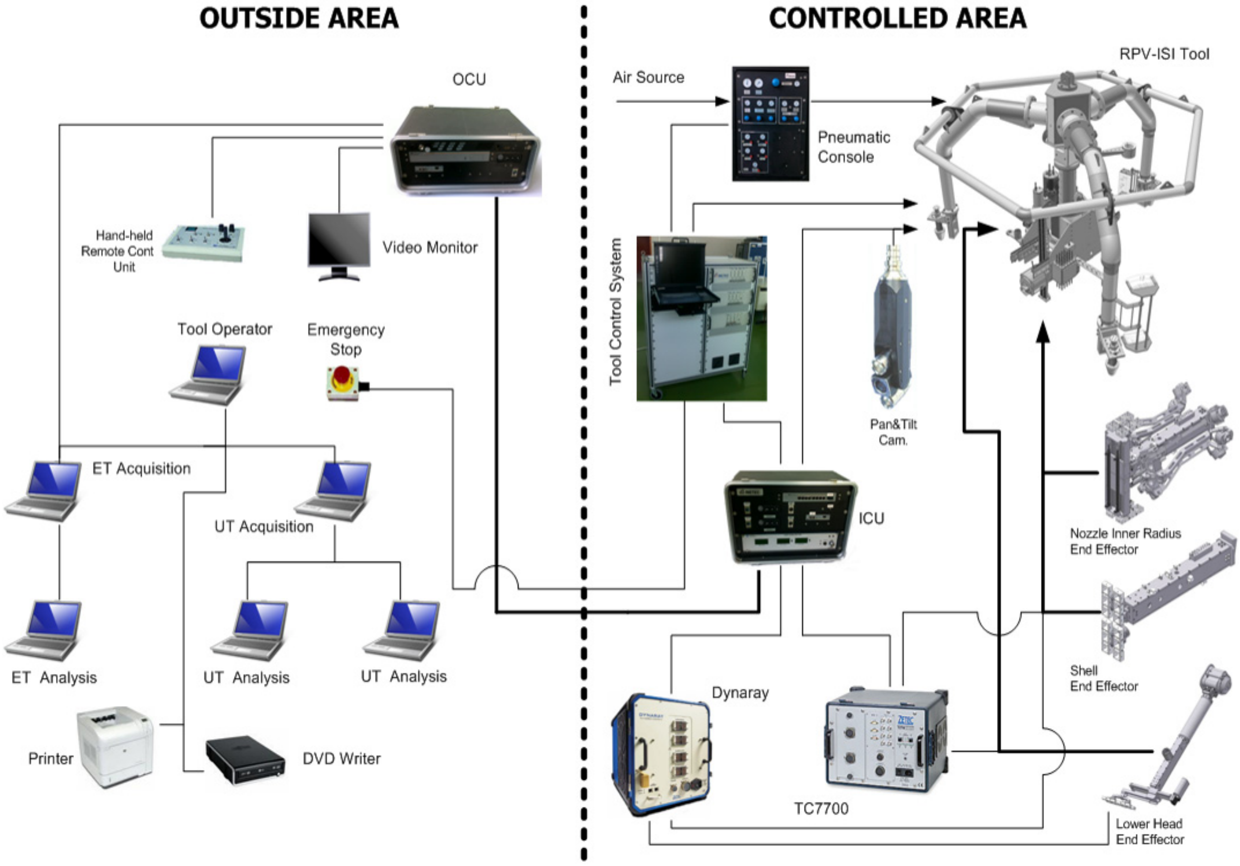

Figure 6 – RPV Inspection System Overall Schematic

Following paragraphs describes RPV inspection equipment arranged for VVER 1000 RPV inspection with single sided carriage. If required, double-sided carriage can be applied, in order to reduce inspection time. Double-sided carriage deploys two pair of inspection modules for simultaneous inspection of the vessel welds, inner radii sections and nozzle welds.

The superstructure is capable of adapting to various size reactor vessels and is used to support and align the carriage/module assembly. Changing leg support spacers can accommodate examinations of vessels of various sizes. Sections can be added to the center column to accommodate various reactor vessel depths. All underwater-motorized actuator enclosures are pressurized to prevent damage due to water leakage. Protective pads cover tool superstructure mating surfaces to prevent damage to critical reactor vessel surfaces.

The tapered support feet with tool centering mechanism, which fasten to the tool legs, act to precisely align the tool and reactor vessel vertical centerlines during the seating operation. All tool superstructure components are made of corrosion resistant stainless steel for durability and ease of decontamination, and can be assembled in a few hours using a light duty jib crane or overhead crane.

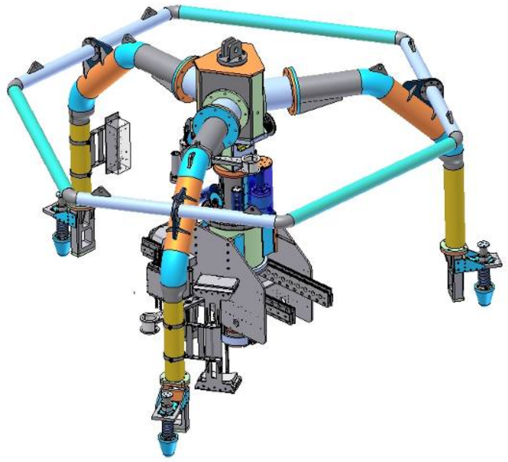

Figure 7 – RPV Inspection Tool Mainframe

The tool carriage assembly delivers simultaneously two pair of the modules to the work point in the reactor vessel. The carriage travels along and rotates around the sectional vertical center column. The carriage features a backup pneumatic brake to insure safe vertical travel.

The carriage features eight axes of movement, namely the "Z" (vertical drive), "Y" and "X" (linear drive in horizontal plane), "A" (angular displacement about the tool center column), "B" and "G" (angular displacement around the +Y axis), “C” and “D” vertical drive

For the purpose of reactor lower head inspection the additional two axes module can be mounted to the carriage. The module accommodates up to 12 UT or ECT transducers to fulfill coverage of the lower head weld to be examined.

The motorized actuators providing the eight axes of carriage motion and two axes of lower head module motion feature harmonic drive power transmissions and resolvers to minimize mechanical backlash and insure precise position feedback data. The actuators are primarily composed of strong, lightweight anodized aluminum alloy. A pneumatic distribution console supplies dry, filtered, regulated compressed air or nitrogen to all underwater motor enclosures to prevent damage due to water leakage. This distribution console features an internal shuttle valve which automatically the switches gas supply should one supply deplete.

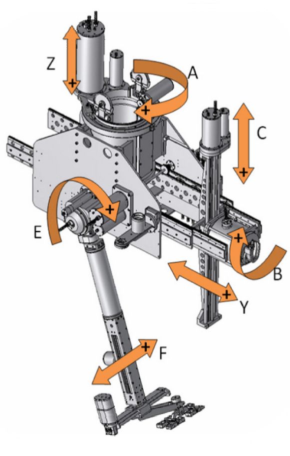

Figure 8 – RPV Tool 7 DOF Carriage

Operation and coordination of the RPV-ISI Tool is controlled through the drive position system. The controller itself comprises RISK-based axis processor together with P4 processor. The servo amplifier rack and power distribution unit are placed in the same cabinet called Multi Axis Controller (MAC)

Figure 9 - MAC

The RISK-based axis processor is primarily responsible for controlling and monitoring (in the real time) the reactor vessel inspection tool position, velocity, direction and programmable axis limits. Motor current, servo drives voltage and temperature is also continually monitored. During the inspection the tool is controlled remotely from the PC workstation. From the operators point of view the same Elvis software is running both on the MAC and on the remote workstation. This system operates under manual or computer control and utilizes built-in verification to determine the status of the system. The remote workstation control computer is housed in a remote control trailer while the tool controller is staged in containment near the RPV cavity.

A pneumatic contact type module is designed for use in examining nozzle safe-end welds, nozzle safe-end pipe welds, nozzle inside surface and nozzle inner radius areas. Air cylinders actuate different transducer holders and deliver UT transducers into contact with the surface. Each transducer is mounted into the 6-DOF gimbals sled or into the inner radius arm respectively to adapt the surface irregularities. Each module is able to carry up to 18 UT or ECT transducers to fulfill coverage of examined surface. The simultaneous scanning with two modules reduces inspection time for 50%.

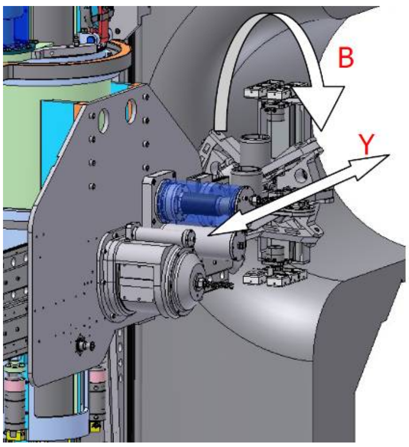

Figure 10 – Nozzle Welds and Inner Radii Inspection Module

A pneumatic contact type module is designed for use in examining shell circumferential welds and core region. Air cylinder actuates transducer holder and delivers UT transducers into contact with the reactor pressure vessel inner surface. Each transducer is mounted into the 6-DOF gimbals sled to adapt the surface irregularities. Each module is able to carry up to 12 UT or ECT transducers to fulfill coverage of examined surface. The simultaneous scanning with two modules reduces inspection time for 50%.

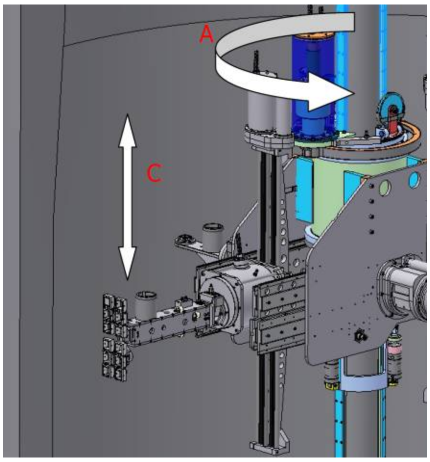

Figure 11 – Circumferential Welds Inspection module

A pneumatic contact type module is designed for use in examining reactor lower head weld. This two axes module uses E-axis motorized delivery arm to bring the transducers to the exam surface. Air cylinders actuate transducer holders and provide permanent contact between transducers and the lower head inner surface. F-axis motorized linear actuator provides transducers motion perpendicular to the weld. Each transducer is mounted into the 6-DOF gimbals sled to adapt the surface irregularities. The module is able to carry up to 12 UT or ECT transducers to fulfill coverage of examined surface.

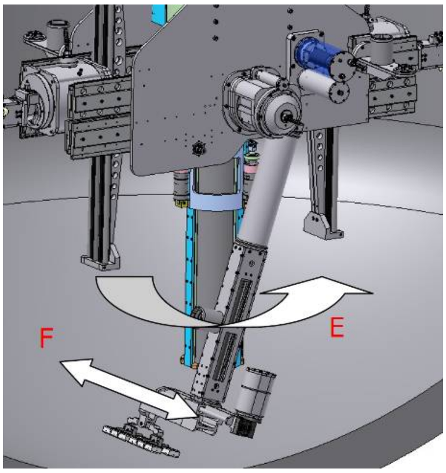

Figure 12 – Bottom Weld Inspection Module

6 QUALIFICATION

The qualification includes technical justification and open trials designed to measure the equipment essential parameters, identified during the analysis of the influential parameters. In this case the NDT procedure identifies the essential parameters and specifies allowable values and tolerances. During the open trials, the practical application of the NDT equipment is monitored. This will ensure that the equipment can be set-up and applied to components, to be inspected, and that its design is such as to minimize errors and ensure the quality of the ultrasonic, eddy current and visual data collected.

The assessment of the NDT procedure has performed in different steps:

- As first, NDT procedure must be fully written in a clear unambiguous way and provide useful systematic guidance for the user (preliminary assessment).

- Secondly, it must be technically adequate to meet the requirements of the inspection. The assessment of the technical capability of the inspection procedure will be the result of the combination of a review of the technical justification and the practical work carried out using the inspection procedure during open practical trials on test blocks.

The NDT procedure for detection and depth sizing is qualified through both open trials and technical justification.

The procedure is assessed to ensure that it contains all the points listed. It is also assessed to determine whether it is written as a logical sequence of instructions. Revision of the procedure shall perform, if changes are required.

The purpose of the open trials is to verify that the NDT procedure/equipment proposed is fit for purpose. The number of defects during open trials should be large enough to allow assessing all necessary aspect of the NDT procedure/equipment.

The open trial is a practical demonstration using the procedure and equipment to inspect the test pieces. The objective is to collect ultrasonic, eddy current and visual data to demonstrate that the procedure and equipment are capable of meeting the defect detection and sizing performance claimed in the input technical specification.

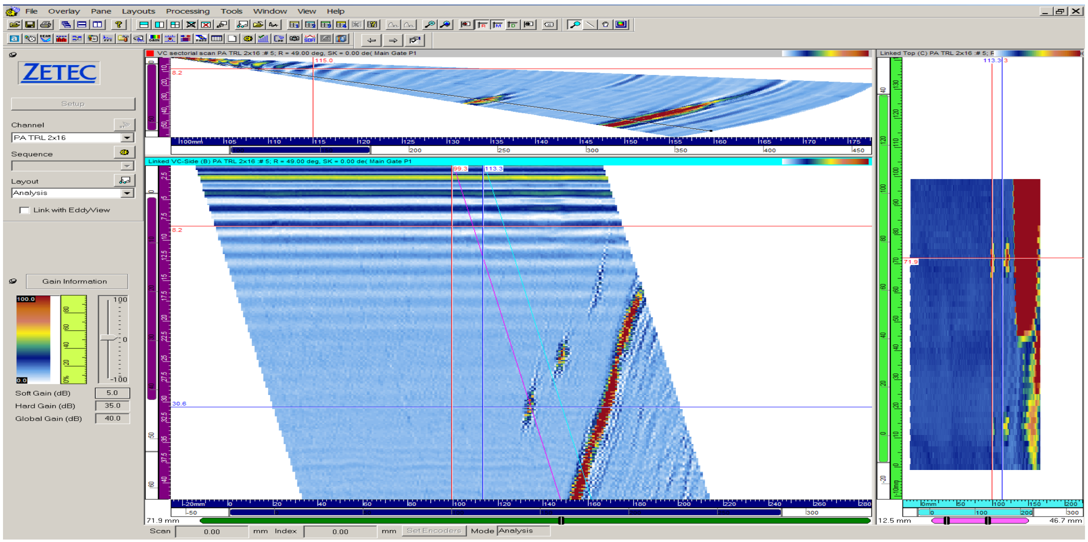

Figure 13 - PA UT probe, (45 deg) at depth 16, 23 and 30 mm flaws respond at UT trial test block

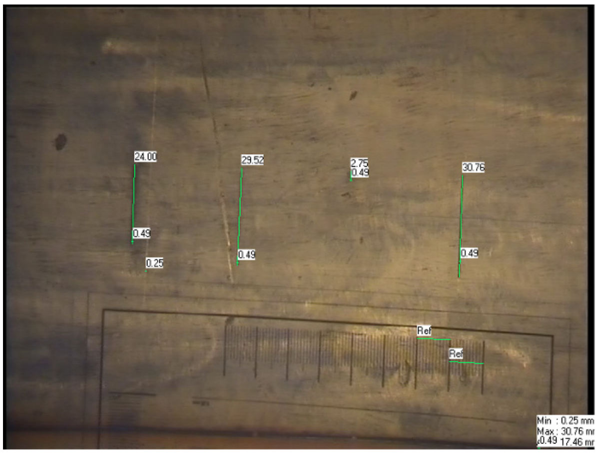

Figure 14 - wire Ø approximately 0,05 mm, length approximately 100 mm, vertically oriented at VT trial test block

The purpose of the blind trials is to verify that the inspection procedure qualified during the open trials is correctly applied by the inspector under industrial conditions. The defects for the blind trials are of the general type. As basis for the number of defects to be considered for the blind trials is the number of defects used in the framework of national personnel qualification schemes.

Blind trials are necessary to verify that the inspection personnel, in industrial conditions, correctly apply the NDT procedure and NDT equipment qualified during open trials. The analysis results are compared with the definitive defect data to evaluate the performance of the procedures and equipment.

The results and ultrasonic data records will be compared with the definitive defect data to evaluate the performance of the sizing procedure and the personnel.

7 CONCLUSION

The reactor pressure vessel (RPV) as an integral part of the reactor coolant pressure boundary requires periodical inspection of the condition of base metal, welded joints and RPV austenitic steel overlaying welding.

Implementation of the state-of-the-art equipment and inspection techniques fulfills all inspection requirements. Furthermore, such system reduces personnel radiation exposure and overall inspection time as well as plant outage time and outage costs. Qualification of the equipment, procedures and personnel and performed personnel training and education, assure safe plant operation for a long period.

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