Qualification of NDT Techniques for In-Service Inspections in Nuclear Power Plants In Accordance With Eniq - Examples and Lessons- Learned -

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Abstract. ENIQ (European Network for Inspection and Qualification) has developed regulations on how to qualify non-destructive testing (NDT) methods and techniques in a standardized and structured manner. Two major innovative qualifications were carried out and reviewed with regard to implementation, according to the recommended German practice of ENIQ. The conclusions were drawn after performing the ENIQ qualification procedure for in-service inspections (ISI) of real components in nuclear power plants (NPP). The first example covers the qualification of NDT methods for the detection and characterization of surface, subsurface and underclad cracks in the area of the austenitic cladded RPV surface. Open and blind tests were conducted applying UT and ET (from the ID) and UT (from the OD) on realistic flaws (artificially induced IGSCC, hot cracks and fatigue cracks) in the cladding of a full scale RPV mock-up from MPA Stuttgart. The second example covers the qualification of mechanised RT in combination with tomography (developed by the BAM) for the sizing of cracks in pipe welds. For both qualification procedures TUEV NORD SysTec experts were part of the qualification body. The proposed NDT procedures have been qualified within defined limits of application. Recommendations were made to optimise the procedures and the techniques itself further.

1 Introduction

Basis of NDT qualification of in service inspections (ISI) of nuclear power plants (NPP) in Germany is the guideline VGB- ENIQ- R516 [1] which has been edited by the Technical Association of Plant Operators VGB. This guideline transfers the European ENIQ- Guideline "European Methodology for Qualification of Non- Destructive Tests" [2] to the German practice. The structured approach of inspection qualification intended by ENIQ has been adopted appropriately and every step is clearly defined taking into consideration the different tasks and responsibilities of the partners involved (plant operator, NDT company and independent expert). The German guideline reflects that the expert who is authorized by the regulatory administration has to assess the NDT methods chosen for ISI, to be present during ISI and to evaluate the results independently in order to confirm the integrity of the tested components before the NPP resumes operation.

Before publication of the ENIQ- Guideline it had been common practice that descriptions of NDT procedure, equipment, test specimens and test defects had to be submitted, that test piece trials had to be evaluated by the expert and that the NDT company had to present a report of the results and to submit an inspection procedure. On the basis of these documents the expert had to confirm to the regulatory administration that – in the case of positive results-the NDT method is qualified, often giving recommendations for further improvements of the inspection procedure and technique.

In Germany in recent years several qualifications of test equipment and of modified test techniques have been accomplished following the ENIQ methodology in a more or less strict manner. In this paper two exemplary inspection qualifications are described and evaluated which were carried out executing consequently and in full the single steps in the course of an inspection qualification according the ENIQ- Guideline [1]. In the following the implementation of these qualification steps and the practicability of the ENIQ- procedure will be commented.

2 Qualification of a NDT- Procedure for Detection and Characterization of Defects in the Austenitic Cladding of Reactor Pressure Vessels (RPV)

The investigations, the manufacture of realistic test flaws and the test trials were carried out in the framework of an R&D project BMU-SR 2318 financed by the federal government. Project leader was the MPA Stuttgart where a full-scale mock-up RPV is available. The MPA developed a technique to produce test specimens with corrosion cracking in the cladding. The mechanized NDT was carried out by IntelligeNDT, Erlangen (UT) and by IzfP, Saarbrücken (ET) with equipment used in ISI of RPV. The task of the experts of TUEV Sued and of TUEV Nord was to evaluate the qualification plan, the realisation of the qualification trials and the results and finally to give recommendations for implementation NDT of cladding in the forthcoming revision of the German nuclear safety standard KTA 3201.4 [3].

Step 1: Definition of task, goal and scope of inspection qualification

These were

- Qualifying NDT of austenitic claddings and of the adjacent ferritic material of RPV
    - Inspection from inside with UT and ET in combination,
    - Inspection from outside with UT.
- Detection of surface, subsurface and underclad cracking and characterisation, whether the
    - detected flaw is open or not open to surface or reaches into the ferrite only.
- NDT of one ore more layered claddings with typical thickness 4 mm till 8 mm.

Step 2: Definition of the category of qualification

The qualification was carried out at the mock- up RPV of MPA Stuttgart and at test pieces. These contain realistic flaws like cracks, lack of fusion and slag inclusions as well as artificial flaws (notches) within and under the cladding. The corrosion cracks in the cladding were artificially produced. Real cracks in the cladding caused by stress corrosion cracking are not known in German RPV until yet. According to the definition of the ENIQ- guideline [1] this qualification corresponds to qualification category 2.

Step 3: Collection of input information

According to KTA 3201.4 [3] the surface and near surface regions and the volume of the RPV has to be inspected with UT at ISI. Ultrasonic testing of the cladding is not prescribed explicitly, but with the UT techniques applied, these are

- 70° TR longitudinal wave probes with a focus length 33 mm at the inspection from inside,

- 45° shear wave probes at the inspection from the outer RPV diameter,
the cladding is inspected inevitably too.

Earlier investigation have shown [4][5], that with the registration threshold at ISI prescribed by KTA 3201.4 (Echo height of a 3 mm notch minus 6 dB, determined on an unclad calibration block, plus a sensitivity surcharge of 2 till 6 dB which takes into account the influence of the cladding) flaws within and under the cladding are detected. A special inspection of the RPV of the older power plants Stade and Obrigheim with UT and ET in combination [6], [7] had been performed successfully in order to prove the integrity of the cladding. This experience was the base of the qualification project.

Step 4: Preparation of a Technical Justification

A detailed report has been compiled by MPA Stuttgart, which describes and reviews the essential inspection parameters for UT and ET of austenitic claddings. As essential parameters for UT were defined:
- Acoustic anisotropy of the grain structure; strong scattering at grain boundaries; deformation of the sound beam; sound reflection at the ferrite- austenite interface,
- with the consequence of a small signal to noise ratio; spurious indications influenced by grain structure which are difficult to interpret; indications due to mode conversation; varying ultrasound coupling at rough surfaces.

As essential parameters for ET were identified:
- Magnetic permeability and electrical conductivity of the cladding, which has to be homogenous regarding these material characteristics,
- evenness of the surface to have a constant distance of ET- probe,
- eddy current frequency which defines the depth of penetration in the cladding,
- interaction length of the ET probe which defines the resolution of sizing and the raster of probe shift for a complete inspection,
- sensitivity of the probe for longitudinal, transversal and diagonal oriented flaws,
- disturbing factors are a varying delta- ferrite content in the cladding; uneven surface; probe lift off; different cladding materials (e.g. in repair areas); thickness changes of cladding.

As a result of the experience at ET inspections of RPV claddings in the NPP Stade and Obrigheim the following techniques were chosen:
- Low frequency ET with four frequencies between 0.5 KHz and 20 KHz and
- high frequency ET with three frequencies between 50 KHz and 600 KHz.

With these test frequencies and their combinations ET indications should be characterised as open to surface, within or under the cladding.

Step 5: Preparation of a qualification plan

The steps and the conduct of the qualification had been laid down in a qualification plan that was coordinated and adjusted in regular meetings by the parties involved.

Phase 1: Evaluation of input information, development of a flaw catalogue, collecting and producing test pieces, preparation of an inspection procedure, conducting open trials on test pieces, verification of test flaws by destructive investigation, analysis of NDT results.

Phase 2: Implementation of test flaws in the mock- up RPV, submission of revised qualification procedures, conduction of blind tests, preparation of reports by the NDT companies, analysis and discussion of results, evaluation of the qualification and the practicability of the ENIQ- guideline by the independent experts, recommendations for further optimisation of the inspection procedure, proposals for implementation of NDT of cladding in the forthcoming revision of the German nuclear safety standard KTA 3201.4.

Step 6: Conduct of qualification tests

The tests were performed as open trials at test pieces with known realistic flaws and as blind trials at the mock- up RPV in the presence of independent experts. Altogether seven different flaw types were produced in test pieces (see table 1 and fig.1 and 2).These test pieces were first used for open trials. For the blind tests implants containing the flaw types were welded into the mock- up RPV. Around the implants a two- layer cladding was welded manually. The surface was ground. The flaw dimensions were measured at the test coupons before they were inserted.

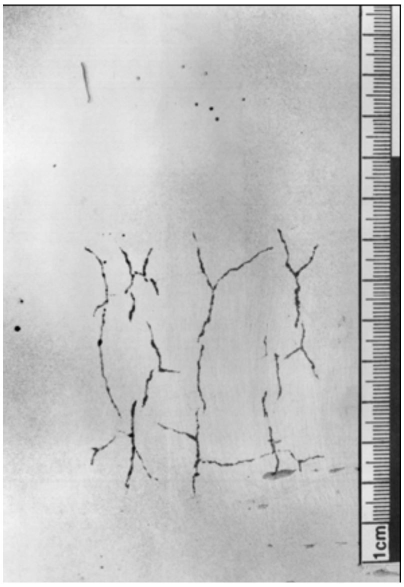


Fig.1: IGSCC field in the cladding

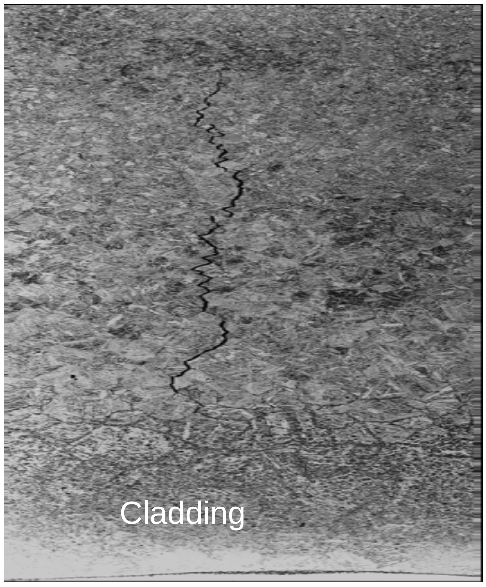


Fig. 2: Underclad crack, 4 mm deep

	Type of Flaw	Dimensions (length x depth) [mm]	Depth [mm]	Detection UT (ID)	ET (ID)	UT (OD)
1	Underclad cracking	10 till 15 x 2.5 till 4	7 - 11	+	-	-
2	Slag line	100 x 2	3 - 5	+	-	+
3	Hot crack (open)	60 x 7	0 - 7	+	+	+
4	Fatigue crack	45 x 18	2 - 20	+	+	+
5	Underclad cracking	10 till 15 x 2.5 till 4	7 - 11	+	-	-
6	IGSSC (field 40 x 90)	90 x 5	0 - 5	+	+	+
7	Hot crack (closed)	60 x 3	4 - 7	+	+	+

Tab.1: Flaws in the RPV- cladding for blind test and detection results (+: yes - : no)

Step 7: Analysis of the test results

The results are described in reports by the NDT companies and compiled in a comprehensive report by MPA. The UT was conducted with techniques applied in ISI of RPV using phased array probes with an integrated separate 70° TR longitudinal wave probe.

Inspection from inside

Ultrasonic Testing	*70° TR longitudinal wave probe*
Recording threshold acc. KTA 3201.4	notch 3 mm **minus 6 dB** (till 10mm depth) in an unclad calibration block
Sensitivity surcharge	+ 9 dB (Influence of cladding)
Eddy current testing	low frequency (0.5, 5, 10 and 20 KHz), high frequency (50, 278, 588 KHz) method
Recording threshold	surface: notch 2 mm subsurface: notch with 3 mm ligament

Inspection from outside

	Ultrasonic Testing 45° and 60° shear wave, phased array probe, 1.5 MHz
Registration threshold	notch 3mm **minus 11 dB** in an unclad calibration block
Sensitivity surcharge	+ 9 dB (influence of cladding)

The test results showed that a great lot of reflectors were found at the boundaries of the implants and in the cladding welded manually due to unintentionally produced imperfections. These imperfections were not investigated destructively because the test mock- up shall be used for further NDT qualifications. For that reason an evaluation regarding false calls was not possible.

Inspection from inside: With UT all test flaws with dimensions in depth of 3 mm ore more (i.e. one layer of cladding) were recorded above the registration threshold and characterised as relevant indications according to KTA 3201.4. With UT standard technique a characterisation (flaw open to surface or not) is not possible but UT indications, which extend into the ferritic material, are shown in the projection images correspondingly. With ET all flaws open to the surface were registrated. Both the underclad cracks were not found. The hot crack in the first layer was registrated and characterised correctly as not open to the surface.

Inspection from outside: The cladded inner zone was inspected by UT with an increased sensitivity. The recording threshold had been chosen 5 dB lower than at the inspection from inside. This value had been measured on a cladded reference block with notches as reference reflectors and had been laid down by INDT for evaluation of UT indication. All flaws in the cladded zone were detected and characterised as relevant reflectors with the exception of the under- clad cracks. The results have to be interpreted that in the case of an OD RPV-inspection a specific sensitivity surcharge has to be applied which takes into account the influence of the cladding. In this qualification trial an 1.5 MHz- phased array probe with relatively small dimensions (25 mm x 17 mm) had been used. Usually 1 MHz- transducers with greater dimensions (44 mm x 36 mm ore 25 mm x 23 mm) are applied. With such a probe the flaw detection ability of underclad flaws seems to be better [5].

Step 8: Summary of technical evidence

The applied NDT techniques for ID inspection (UT: 70° T/R, ET: multifrequency combination technique) are qualified for testing the cladded zone of RPV. UT/ET in combination is capable to detect and to characterise flaws in the cladded surface zone. For the sensitivity setting a reference block shall be used which possesses a cladding comparable with that of the RPV to be tested regarding surface condition, number of layers, material, thickness and curvature.

Our conclusions regarding OD inspection are that the applied 45° transversal wave phased array probe is not qualified for detection of underclad flaws. Instead of the small phased array transducers used in this qualification it is suggested applying transducers with greater dimensions in a further qualification trial.

3. Qualification of a NDT Procedure applying Mechanised RT in Combination with Tomography

The BAM, Berlin has developed a mechanised radiometric weld inspection system “Tomocar” [8, 9]. The device consists of a radiometric line camera assembled together with a manipulator adapted from a mechanised UT pipe inspection system and a mobile 225 KeV x-ray tube (see fig 1). With this system circumferential welds can be scanned with a pixel resolution of 50 µm for 2048 pixel per line. Corresponding to fig. 3 the camera and the x- ray tube are separated by an angle of 180°. They are moved line by line around the weld to acquire the radiometric image. This enables a central projection technique all over the weld.

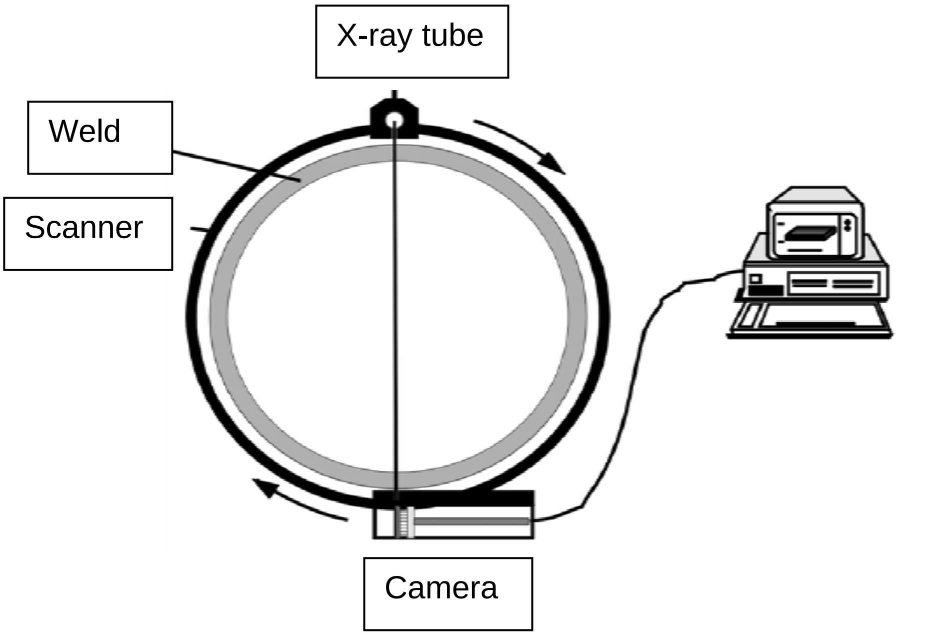


Fig.3: Radiometric weld inspection system "Tomocar"

A further advantage in comparison with film radiography is that a slit collimator integrated in the camera reduces the scattered radiation substantially. The radiometric system can especially be applied to analyse RT indications to get information about their form and their depth by x-raying the weld under different angles. For flaw analysis the camera is fixed while the x-ray tube is shifted parallel to the weld axis. During the movement of the x-ray tube the camera measures the radiographic intensity of 200 till 400 projections in a radiation angle up to ± 30°. With the planar tomography algorithm an image reconstruction of the weld cross section is provided which allows the sizing of crack- like RT indications. This method had been tested in laboratory. In an R+D project financed by VGB the radiometric weld inspection system had to be qualified in accordance with the ENIQ- Guideline [1] for application in ISI of pipe welds in NPP. The qualification body consisted of the NDT vendors BAM and Compra, of VGB and of independent experts of TUV Sued and TUV Nord. The experts had been authorized by the regulating administration.

Step 1: Definition of task, goal and scope of inspection qualification

These were

- qualification of a mechanized weld inspection system for analysing RT indications,
- characterization and sizing of planar defects oriented circumferentially in pipe welds.
- The sizing shall have an accuracy of ± 1 mm ore less. The method shall be applicable for sizing of flaws up to ± 40° oblique to the surface.
- RT of emptied pipes with wall thickness between 6 mm and 25 mm (radiographed thickness 12 mm till 50 mm).

Step 2: Definition of the category of qualification

The tests were carried out on pipe welds containing realistic flaws like lack of fusion, slag inclusions and especially real IGSCC- cracks from removed NPP piping. According to the definition of the ENIQ- Guideline [1] this corresponds with the qualification category 3.

Step 3: Collection of input information

The proposed method had been tested and further developed on several test pieces of austenitic and ferrite piping in the laboratory and on a round robin test before [8]. Information on weld configurations, dimensions of power plant piping and of possible flaw types are known and well documented.

Step 4: Preparation of a Technical Justification

A detailed technical justification had been compiled by BAM. The qualification, originally planned with an inspection system containing a radiometric line camera only, was extended to a system with a new radiometric array camera. The essential parameters were evaluated and divided into three groups:

a) Parameters that describe the testing conditions: Weld geometry, wall thickness, flaw type (planar, voluminous), flaw size (length, depth and width),
b) parameters that establish a high standard regarding flaw detection and evaluation: Radiographic testing parameters applied in accordance with the recommended practice and RT standards.
c) Parameters that describe the equipment:
Radiometric detector, x-ray technique, manipulator, data acquisition.

Step 5: Preparation of a qualification plan

The qualification plans had been prepared which have been coordinated and adjusted in regular meetings by the parties involved, both for a qualification of the inspection system with the linear and with the array radiographic camera. A first trial had to be carried out on three test pieces containing intentionally produced realistic flaws. After conducting the RT these specimens were investigated destructively and the results had been evaluated to improve the testing method further. In a second trial five test pieces had to be examined in a blind test. The test pieces came from original NPP pipes and contained circumferential welds with real flaws (IGSCC). The pipes had outer diameters between 150 mm and 275 mm; the wall thickness was between 11 mm and 20 mm. To realise a radiographed wall thickness of 50 mm a plate 10 mm thick had been put into the 20 mm thick pipe. The weld positions containing flaws which had to be analysed by the inspection system Tomocar where determined by evaluation of conventional radiographs.

Step 6: Conduct of qualification test

In the first trial altogether 15 weld positions with crack like indications were analysed. In the second trial on welds containing IGSSC eight weld positions were analysed. The test pieces of the second trial consisted of joints between straight pipes and elbows. The rotation and shifting of the x-ray tube was limited by the geometry of the elbow so that an asymmetric range of radiation angles had to be used for image reconstruction. The wall thickness of the test object needed for calibration of the tomographs had been determined by UT.

Step 7: Analysis of the test results

The results of the RT image reconstruction were compared with the results of metallography regarding flaw type, position and dimension of depth. The conclusions ere:

- The shape of flaw (planar or voluminous) has been determined correctly.

- Sizing of flaws and determination of the residual wall thickness have been exact within a range of ± 1 mm (see fig 4).
- In the presence of grooves at the weld root conical artefacts are produced in the reconstructed images, which reduce the flaw detection ability in these weld areas. The discrimination between cracks and grooves is possible only above a detection threshold of 10% of wall thickness or above 1 mm.
- Planar defects with a flaw width much smaller than the pixel size of 100 µm of the array camera can be resolved. The lower limit of flaw width is 20 µm for a reliable detection and sizing of defects.

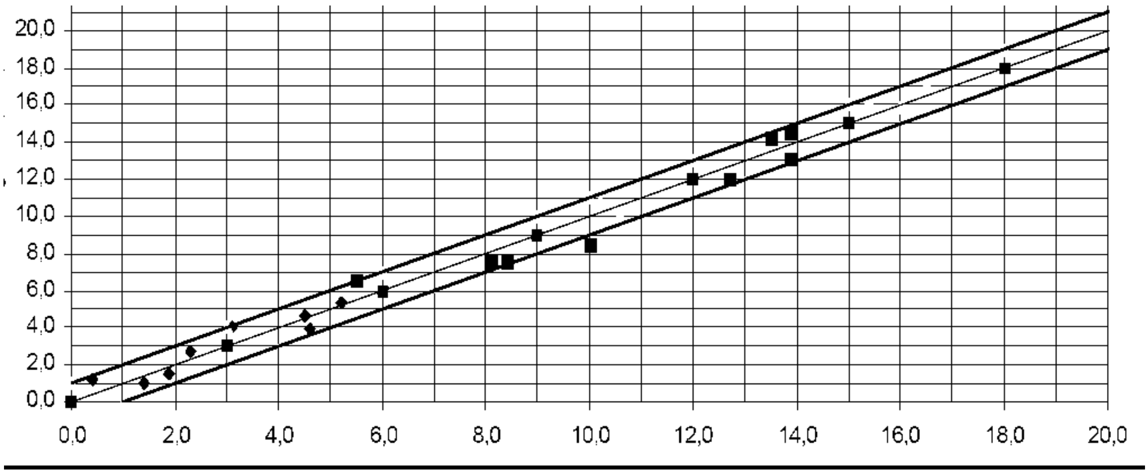
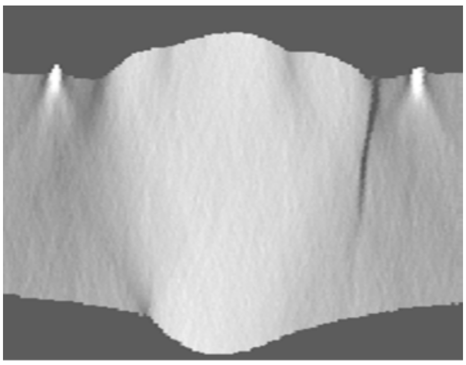


Fig.4: Sizing results (metallography vs. tomography); data from wall thickness, flaw depth and flaw size (mm)

Step 8: Summary of technical evidence

The mechanised radiometric weld inspection system Tomocar, which applies a multiple angle beam technique in combination with tomography, has been qualified to analyse crack like indications in pipe welds with wall thickness between 6 mm and 25 mm. The method allows sizing of defects with dimensions above 1 mm in depth and 20 µm in width with an accuracy of ± 1 mm. The condition is that there is enough space (ca. 500 mm along the pipe axis and ca. 250 mm in height) to mount the manipulator and to rotate the x-ray tube around the weld freely. With the array detector a tomographic image reconstruction can be produced for different layers of the weld, which can be analysed in detail. The method allows the reconstruction of a 3D cross sectional image of the weld comparable with a metallographic image, which can be interpreted clearly (see fig.: 5).



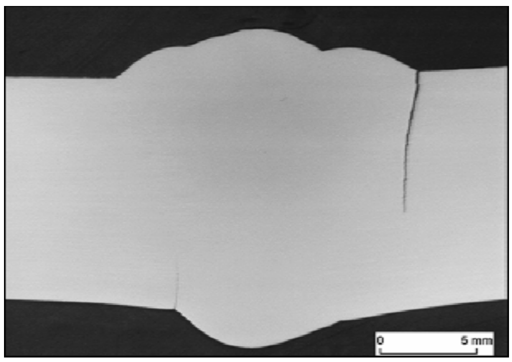


Fig. 5: Planartomogramm

Metallographical cross section

4. Conclusions

The two exemplary inspection qualifications described here showed that the ENIQ methodology adapted to the German practice is practicable. In the first example the most important step was that realistic crack- like flaws could be produced by MPA Stuttgart and implemented into the mock- up RPV for use in blind trials. The goal of the qualification was to show if the UT techniques used normally in ISI are capable to detect flaws in and under the cladding and how far ET from inside is reliable to detect and to characterize flaws open to the surface and under the surface. For ID inspection the qualification goals could be achieved. In the case of OD inspection the phased array probe applied in this trial could not detect the underclad cracks 15 mm long and 4 mm deep. We suggest applying transducers with greater dimensions in a further qualification trial. For sensitivity setting the influence of the cladding has to be evaluated carefully. The second example covers the application of a new NDT technique, a mechanised RT in combination with tomography, for sizing of cracklike indications in pipe welds. The trial was conducted as a blind test on pipe welds containing real IGSSC flaws. By this method it is possible to produce cross sectional images of the weld where the position and the dimensions of crack indications can be measured with a high accuracy (± 1mm).

Both the proposed NDT procedures have been qualified within defined limits of application. It seems evident that complex and ambitious qualification procedures cannot be prepared faultlessly by the applicant before starting the qualification procedure. It should be possible that testing parameters are changed and optimized during qualification. The main objective is, that based on reliable test results, an improved and applicable final NDT method is achieved.

5 Literature

[1] VGB Power Tech (Editor), „Methodik für das Vorgehen bei der Qualifizierung von zerstörungsfreien Prüfungen (VGB-ENIQ- Richtlinie VGB – R516)“, Essen, Mai 2001

[2] European Commission, “European Methodology for Qualification of NDT: Second Issue”, ENIQ Report N°2 EUR 17299 EN, DC Joint Research Centre, Petten, Netherlands 1997

[3] Nuclear Safety Standards Commission (KTA), Safety Standard KTA 3201.4 (6/99), “Components of the Reactor Coolant Pressure Boundary of Light Water Reactors, Part 4: In service Inspections and Operational Monitoring”

[4] T. Just, „Flaw Detectability of NDT- Techniques of Clad Surfaces of Reactor Pressure Vessels“, Nuclear Engineering and Design 151 (1994), p. 531-537

[5] B. Neundorf, G. Csapo, A. Erhard, „Optimising of the NDT of Boiling Water Reactors by Using Realistic Flaws in the Cladding“, 7th ECNDT, Copenhagen,
26. – 29. Mai 1998, Conf. Proc. p. 1429 – 1433

[6] Csapo, G.; Becker, R.; Kröning, M.; Lucht, B.,“Die Anwendung des Niederfrequenz-Wirbelstromverfahrens als diversitäre Prüftechnik für die Plattierungsprüfung von Reaktordruckbehältern“, DACH- Jahrestagung, Lindau 1996, DGZfP- Berichtsband

[7] Erhard, A.; Thomas, H., Prüfung der Plattierung mit Impuls- Wirbelstrom- und mit Ultraschallverfahren, Materialprüfung 38 (1996)

[8] B. Redmer, U. Ewert, A.V.Likatchov, V.V. Pickalov; Y.Onel, Zheng Li, V.A. Baranov
Sensitive Detection of Planar Defects by a Mechanised RadiometricWeld Inspection System, 15th WCNDT, Rome 2000

[9] B. Redmer, U. Ewert, B. Neundorf, M. Jakob
Tomographic 3 D- Radiometry for the Visualisation and Measurement of Defects of Girth Seams, 9. ECNDT, Berlin 25.- 29. Sep. 2006