Updated Report
Activities in WENRA countries following the Recommendation regarding flaw indications found in Belgian reactors (2017)

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Western European
WENRA
Nuclear Regulators Association

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01
Background

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01.1 The findings in Doel-3 and Tihange-2

In 2012 a new type of in-service inspection (ISI) of the reactor pressure vessel (RPV) by ultrasonic testing (UT) was introduced in Belgian nuclear power plants. These inspections were introduced earlier in France to search for underclad cracks that may be present in the base metal directly below the interface to the cladding. These underclad cracks, if present, have perpendicular orientation to the surface and were created by the welding process of the austenitic strip cladding onto the ferritic base metal.

Yet, in the RPV wall of Doel-3 and Tihange-2 these inspections did not find any underclad cracks but a large number of flaw indications, located at different distances from the surface in the lower and upper vessel forged rings. As this technique is not suitable to find any flaws far from and nearly parallel to the surface, additional UT with straight beam (0°) was applied. With this technique, thousands of nearly laminar indications were found at larger depths of the base metal, mostly planar and nearly parallel to the surface of the RPV.

Following a number of investigations and evaluations, the UT indications in the RPV of Doel-3 and Tihange 2 were unambiguously assigned to hydrogen induced flaws (“hydrogen flakes“).

01.2 Metallurgical considerations

According to current knowledge hydrogen flakes may only form during manufacturing of the base metal. The formation of hydrogen flakes is a phenomenon well known to the steel manufacturers and may happen after cooling down the steel from high to ambient temperature, e.g. in the ingot after pouring or in the forged part after the forging operation and heat treatment. Flake formation is driven by the accumulation of hydrogen at segregations or inclusions in the metal. This accumulation of hydrogen is diffusion controlled, so the formation of flakes may have an incubation time of some days or even a couple of weeks at room temperature.

Due to the main deformation direction during the forging operation, these segregations or inclusions are preferentially stretched in planes parallel to the surface of the forging leading to the formation of laminar hydrogen flakes of the same orientation. The formation of hydrogen flakes depends on a number of factors, the most important being the hydrogen concentration and the size of the ingot, both determining the possible accumulation of hydrogen. This makes large forgings most prone to flaking. Further important factors are a “sensitive” microstructure and the stress state. Despite these known dependences it appears difficult to exclude the formation of flakes in a large forging on the basis of these factors. Therefore, acceptance tests of the base material including appropriate UT is considered the most important step to assure that the parts are free of hydrogen flakes. Therefore the WENRA recommendations as well as the WENRA questionnaire specifically asked for the results of these tests.

Plate material is generally considered much less prone due to smaller ingot sizes and higher degrees of deformation during the rolling operation compared to forging. This results in a less sensitive microstructure. Therefore, components made from plates are outside the scope of further analyses and are not addressed in the recommendations by WENRA referred to below.

The “flakes” are not considered as “cracks” however they represent a detachment or separation within the material that is assumed to have a similar detrimental effect on the mechanical behaviour of the component. In assessments of the structural integrity of the RPV the flakes are always modelled as cracks.

01.3 The role of different inspections

According to international practice, semi-finished products, i.e. “forgings” or “plates”, are subjected to an acceptance tests before they are assembled (mainly welded) to a component. Considering the possible incubation time of the formation of flakes the acceptance tests of forgings are generally not performed before one month after completion of the forging operation and the “quality heat treatment”. According to international practice of the manufacturers parts showing clear indications of flakes are discarded and will not be assembled.

These acceptance tests generally comprise UT with different inclinations of the beam to find flaws of any orientation or character. UT with straight beam (0°) is the most appropriate to find planar flaws parallel to the RPV surface such as hydrogen flakes. Besides, UT with angle beam, surface testing (e.g. with magnetic particles) and destructive mechanical tests are performed. This testing appears to be common practice of all manufacturers, at least since the 70ies.

In general, more UT is performed after each welding operation, e.g. after joining the forgings by circumferential butt welds and after welding of the cladding onto the internal surface of the RPV. These post-weld tests aim to check for flaws in the welding, including the interfaces and the heat affected zones in the adjacent base materials. These inspections do not repeat testing the full volume of the base metal again as no change is expected compared to the acceptance test of the semi-finished parts.

After completion of the components more inspections by UT are performed in the framework of ISI. In all countries the full volume of all axial and circumferential welds and the adjacent heat-affected zones are inspected. In general the volume of the base metal is not inspected again during ISI, except at VVER plants, where some parts of the base metal are covered by UT (see chapter General Observations).

Regarding the UT techniques, different inclinations of the beam may be used in order to find planar flaws in different orientations. UT with angle/straight beam is applied to search for flaws orientated nearly perpendicular/parallel to the RPV surface. Furthermore, the techniques may focus on certain zones within the component, e.g. zones close to the surfaces or close to mid-wall. Any of the special techniques applied may also find flaws in other orientations or other zones not focussed on, however with lower sensitivity and probability.

In case of Doel-3, the UT dedicated to find underclad cracks with angle beam and focus near the interface to the cladding accidentally found some of the hydrogen flakes that were relatively close to this interface. Yet, it did find only a minor part of all the flakes found later by the dedicated UT using straight beam focussing on various depths. The latter is the technique of choice to find hydrogen flakes and was also used for the acceptance tests of the semi-finished parts. Other techniques are considered less appropriate to find any flaws parallel to the RPV surface and in the centre of the wall, where most of the hydrogen flakes are expected, if any. This has to be born in mind when evaluating the UT results of the pre- and in-service inspections (PSI and ISI).

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02
The WENRA recommendation

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In response to the findings in the Belgian reactors, WENRA recommended in 2013 the nuclear safety authorities in Europe to request the licensees to verify the material quality and integrity of the RPV in a 2-step approach:

1. A comprehensive review of the manufacturing and inspection records of the forgings of the RPV
2. Examination of the base material of the vessels if considered necessary.

Furthermore, it may be considered by the national regulators to extend the scope of analysis to large forgings of other primary equipment.

Early in 2014, the WENRA Technical Secretariat sent out a questionnaire to the nuclear safety authorities in order to receive some feedback on the actions taken in the member countries. After receiving information from all relevant member countries the status of the actions taken has been summarized. A report was published in December 2014.

In spring 2017 WENRA decided to update the report. WENRA Technical Secretariat collected feedback about actions taken since the last report was published. The report was updated accordingly.

03
Feedback of the member countries

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03.1 General observations

The following member countries sent answers to the WENRA questionnaire.

- Belgium
- Bulgaria
- Czech Republic
- Finland
- France
- Germany
- Hungary
- The Netherlands
- Slovak Republic
- Slovenia
- Spain
- Sweden
- Switzerland
- United Kingdom

The issue has no relevance for NPP in Romania (pressure-tube reactor) as well as for Lithuania and Italy (no NPP in operation). Ukraine has not been WENRA member at the time the original report was created.

The following general conclusions can be drawn from the different answers.

Regarding step 1, a comprehensive review of the manufacturing and inspection records of the forgings of the RPV:

- Member countries had the manufacturing records checked for all or some of those RPV made from forgings. In those case the records of some RPV were not checked until December 2014 – the check was done in the meantime and results were included in the report 2017.

- Some operators checked the records of all forgings of the RPV, others only those of the cylindrical rings of the RPV beltline.

- In all cases where the final documentation was checked, it contained sufficient information to conclude that acceptance tests were performed that were capable to find hydrogen flakes. For one NPP a large zone of indications was reported in an intermediate UT report before heat treatment.

From all other documents that have been checked, member countries responded that either “no flaws”, “no notable (registered) indications”, “no notable indications similar to flakes” or “no unacceptable indications” were documented or found during UT.

Regarding step 2, from an additional examination of the base material of the vessels can be concluded that:

- Most member countries performed or planned to perform some kind of additional inspections in response to the findings in Doel-3 during the upcoming regular ISI taking place every 4 to 10 years.
- Most member countries decided to have inspected some sample of the cylindrical rings.
- As far as the inspections were already performed, in most countries no indications similar to flakes were found with the engaged inspection technique. Some countries reported findings of indications, leading to further analysis.

Exceptions were Slovakia and Bulgaria operating VVER units with different kind of ISI programs covering also some parts of the base metal. Slovakia also performed additional UT inspections of core region (base metal and weld) at RPV of all units in commercial operation. Apparent differences in the ISI program of these countries with respect those following Western regulations are addressed in the following.

From the information received from Bulgaria and Slovakia, it appears that there is some significant difference in the scope and periodicity of the ISI performed at RPV of VVER plants (and possibly still following the original inspection plans) on the one hand and of Western PWR plants and those following Western regulations on the other hand:

- While UT at RPV of Western type reactors is either performed from the inside (PWR plants) or from the outside (BWR plants) (with periodicity 4 to 10 years), UT is performed from the inside <u>and</u> outside in VVER plants. Periodicity at VVER 440 units is every 8 years for both sides with 4 year shift between both inspections, periodicity at VVER 1000 units is every 6 or 8 years from the inside and every 6 or 4 years from the outside.
- Even more important appear the differences in the area covered by the UT: While all circumferential welds and the adjacent heat-affected zones are inspected at the RPV of all units, some parts of the base metal are also covered in Slovak and Bulgarian VVER type units.

In the following section 03.2 an overview of the activities is given country by country. A plant specific overview can be found in Annex 1.

03.2 Review of answers from the member countries

BELGIUM

- **Plants:** Doel-1, -2, -3, -4, Tihange-1, -2, -3 (all PWR)

  - **Availability of manufacturing documentation:** Documentation is available and was extensively checked for all forging rings of the RPV of all plants. For only the Doel-3 unit, a large zone of indications in the upper core shell was manually reported only in one intermediate UT report before heat treatment, yet not in the official final UT report.

    Additionally, documentation of other forged components of the primary circuit was compiled. There were only a few indications, but no hints of flakes. Hydrogen content of forgings is available for most of components, and if it is mostly normal for the steam generators (0.6 ~ 1.2 ppm), it may be rather high (1.2 to 1.8 ppm) for some other components like nozzles.

  - **Scope and results of PSI (UT) of forgings:** In accordance with the standards (ASME III) at the time of manufacturing, UT with straight (from the inside and outside, top and bottom) and angle beam (from the inside and outside) was manually carried out on 100% of the forgings.

  - **Scope and results of regular ISI:** Belgium strictly follows ASME XI, 1992 edition, for the regular ISI (VT and UT).

  - **Scope and results of additional ISI:**

    - UT with straight beam of the two cylindrical beltline rings of the RPV of all other units (Tihange-1 and -3, Doel-1,-2, and -4) has shown no indications similar to flakes.

    - At Doel-3 and Tihange-2, repetitive UT with straight beam in 2013, 2014 and 2016-2017 on the two cylindrical beltline rings has shown no evolution of the hydrogen flakes.

    - Additional UT on all other forged components from the primary circuits (RPV nozzles and pressurizer parts) of all units show no hydrogen flaking. No additional investigations of the steam generators is regarded necessary as they were replaced in the last years and documentation was judged sufficient.

BULGARIA

- **Plant:** Kozloduy-5 and -6 (Type: VVER 1000)

  - **Availability of manufacturing documentation:** Basic data are available from RPV passport, including results of final inspections of the assembled RPV. Vacuum casting and anti-flake heat treatment were applied. Detailed information on manufacturing process is available at the manufacturer only, yet the whole documentation including NDT was checked by a team from the NPP before mounting the RPV.

  - **Scope and results of PSI (UT) of forgings:** UT of 100% of the forgings was carried out with straight and angle (45°, 60°, and 70°) beam. According to Russian norms, the recording limit was Ø = 2.2 mm, the acceptance limit for individual indications was Ø = 5.2 mm. No indications of hydrogen flakes were found during the UT inspections. After cladding, UT was performed with straight and angle beam with the same registration and acceptance levels. It covered 100% of the upper core ring and samples of 500x500 mm, located at the 4 axes of all other RPV rings, including the interface with the cladding. The UT with straight beam was calibrated for flat reflectors, simulating hydrogen flakes.
  - **Scope and results of regular ISI**: UT is qualified in accordance with ENIQ methodology. UT is performed every 4 years from the outer surface and every 8 years from the inner surface with straight and angle beam as well. The scope of the UT always comprises the circular butt welds, including the HAZ and 200mm of base metal of the upper and lower core rings adjacent to the welds. In addition, UT from the inner surface covers a height of 1000mm of the upper core ring and UT from the outer surface covers 40% of the lower ring adjacent to the core barrel supports (700mm height).

  - **Scope and results of additional ISI:** UT of 100% of base metal of the lower and 80% of the upper core ring was performed in 2002 in Kozloduy-6 from the outer surface. No further additional ISI is planned.

CZECH REPUBLIC

- **Plants: Dukovany-1 to -4** (Type: VVER 440) and **Temelín-1, -2** (Type: VVER 1000)

  - **Availability of manufacturing documentation:** The manufacturing documentation was checked and is available for all parts of RPVs.

  - **Scope and results of PSI (UT) of forgings:** Vacuum casting was used as a special manufacturing process assuring the elimination of gas and inclusions. Anti-flake heat treatment was conducted after forging for both NPPs and was followed by the UT inspections. Other UT inspections were carried out during the manufacturing process on machined surface in whole volume of the RPV material after preliminary and final heat treatment. No indications of hydrogen flakes were found during the UT inspections.

  - **Scope and results of regular ISI:** The scope of the inspections in compliance with standards for VVER type reactors goes beyond the scope of ASME XI. UT from inner and outer surfaces using Phased Array and Time-of-Flight Diffraction techniques were qualified in accordance with ENIQ methodology. Welds and base metal are inspected from both surfaces. Cladding is inspected from both surfaces. No unacceptable indications were found during ISI. At the **NPP Temelín** the inspection period is 6 years from inner and outer surfaces with 3 years shift between both inspections. At the **NPP Dukovany** the inspection period is 8 years from inner and outer surfaces with 4 years shift between both inspections.

  - **Scope and results of additional ISI:** At the **NPP Dukovany** the scope for base metal inspection of the upper ring and beltline region from the outer surface was extended. At the **NPP Temelín** no additional ISI will be performed, as the scope of the ISI is considered sufficient.

FINLAND

- **Plant:** Loviisa-1 and -2 (VVER 440/V-213)

  - **Check of manufacturing documentation:** Information on forging, heat treatment, and PSI is available and was checked for rings of the core region. Degassing during casting and some hydrogen removal annealing immediately after forging before cooling to ambient temperature were carried out.

  - **Scope and results of PSI (UT) of forgings:** UT with straight and angle beam was carried out on 100% of the forgings. Recording limit was Ø = 2.2 mm, acceptance limit for individual indications was Ø = 5 mm.

  - **Scope and results of regular ISI:** Not reported.

  - **Scope and results of additional ISI:** Inspection for Loviisa 2 was performed in 2014 for full base metal thickness with a qualified UT-method (normal probe). The RPV was inspected by full 360 degrees around the RPV vessel. In vertical direction the inspection height was about 3.2 m. The inspection area reached 2.6 m above and 0.6 m below the circumferential beltline weld (W04) that belongs to normal in-service inspection program. The reference reflector size used in the UT equipment calibration was 6 mm in diameter. No indications were detected.
    At the upper region of the inspection area the concrete structures limited the inspection areas (due to probe accessibility). The final inspection scope was about 90% of that of planned. The base metal area could be inspected according to the inspection plans.

  - A corresponding UT-inspection to Loviisa Unit 1 has been carried out on annual outage of 2016. No indications were detected.

- **Plant: Olkiluoto-1 and -2** (BWR 2500)

  - **Check of manufacturing documentation:** Documentation is fully available, was checked for rings of the core region.

  - **Scope and results of PSI (UT) of forgings:** RPV are made of plates which have much higher “forging ratio” than forgings and are considered less susceptible to hydrogen flaking. UT with straight beam was performed on 100% of the plates with recording limit of Ø = 7 – 11 mm.

  - **Scope and results of regular ISI:** Not reported.

  - **Scope and results of additional ISI:** UT with straight beam of the base metal of 1 m^2 of the bottom shell (not related to Doel-3 findings). No additional inspection is seen necessary.

- **Plant:** Olkiluoto-3 (EPR, not yet in operation)
  - **Check of manufacturing documentation:** Documentation is fully available, was checked for rings of the core region. No further measures required.
  - **Scope and results of UT-inspection of forgings and the RPV (after manufacturing):** UT with straight and angle beam was carried out on 100% of the forgings. Acceptance limit was Ø = 5 mm for individual indications and Ø = 3 mm for groups. PSI to be carried out before start of operation and ISI during operation.

FRANCE

- **Plant:** all French plants
  - **Check of manufacturing documentation:** Documentation is available and was checked for all forging rings of the RPV of all plants. EDF has verified that all required examinations and treatments were carried out during manufacture.
  - **Scope and results of PSI (UT) of forgings:** In accordance with the standards (ASME, CPFC, RCC-M) at the time of manufacturing, UT with straight beam (from the inside and outside, top and bottom) and angle beam (from the inside and outside) was manually carried out on 100% of the forgings.
  - **Scope and results of regular ISI:** All RPV in the French fleet were examined in order to detect flaws under clad and the absence of defects in the welds. None of these tests has highlighted defects identical to that observed at Doel 3 and Tihange 2.
  - **Scope and results of additional ISI:** Two types of tests were implemented:
    - All RPVs in the French NPPs, with the exception of the reactor RPVs at Chooz and Civaux (which will be examined during their second decennial visits, which are planned between 2019 and 2021), were examined with the classic method allowing the detection of defects due to hydrogen on the first 80 mm of the thickness of the RPV. These examinations confirm the absence of defects similar to those found in the RPV of Doel 3 and Tihange 2.
    - Examining of six RPV with method allowing the detection of defects due to hydrogen throughout the whole thickness. EDF carried out an examination of the entire thickness of the core zone for the 6 RPVs at Blayais 2, Bugey 3, Cruas 3, Dampierre-en-Burly 3, Gravelines 4, and Penly 2. No defects identical to those detected in the RPV of Doel 3 and Tihange 2 were found. These examinations were completed in 2014.

- In order to complete the knowledge of the condition of the RPVs, ASN asked EDF to examine the entire thickness of some 1300 MWe RPV. EDF has proposed to carry out this examination on the RPV of Cattenom 4 and Golfech 2. The choice of these RPVs was made in order to take into account the manufacturing process of the shell which is different between these two reactors.

None of these tests has highlighted defects due to hydrogen in RPV.

GERMANY

- **Plants:** Brokdorf, Emsland, Grohnde, Isar-2, Neckarwestheim-2, Phillipsburg-2 (PWR), Gundremmingen II-B, II-C (BWR twin units)

  - **Check of manufacturing documentation:** The documentation is available and was checked for all forgings of the RPV.

  - **Scope and results of PSI (UT) of forgings:** UT with straight beam (from the inside and outside, top and bottom) and with angle beam (from the inside and outside, top and bottom) was carried out on 100% of the forgings. Additional UT using both beam types was independently performed by German TÜV inspectors. Recording limit for straight beam was Ø = 6 mm, if wall thickness is above 240 mm (applicable to the PWR rings) and Ø = 4 mm, if wall thickness is between 120 and 240 mm (applicable to the BWR rings). In addition sampling of back wall loss. No notable indications similar to flakes were found.

  - **Scope and results of regular ISI:** UT with angle beam of all welds (incl. 50 mm of base metal next to welds) for PWR units every 4 or 5 years from the RPV inside, for BWR units every 4 years from the RPV outside. No notable indications similar to flakes were found.

  - **Scope and results of additional ISI:** In connection with the regular ISI additional representative UT with straight beam of the forgings in the core region was performed in all PWR plants (a sector of 30° to 37.7° from the inside) and in one BWR (a sector of 45° from the outside at Gundremmingen II-B). The latter is representative also for the twin BWR unit. No notable indications were found.

HUNGARY

- **Plant:** Paks-1 to -4 (VVER 440/V-213)

  - **Check of manufacturing documentation:** The manufacturing documentation is available for RPVs of all four Units. The revision of manufacturing documentation has been performed in the frame of operational licence renewal process. Recently the procedure for renewal (extension) of operational licence of Paks Unit 4 is in progress. The application for renewal of operational licence for Paks Units 1-3 has already been approved.

    Passport data and the results of the PSI are available and were checked regarding the base metal adjacent to the butt welds and in the core region.

  - **Scope and results of PSI (UT) of forgings:** Vacuum casting was used as a special manufacturing process assuring the elimination of gas and inclusions. Anti-flake heat treatment was conducted after forging that was followed by the UT inspections. Other UT inspections were carried out during the manufacturing process on machined surface in whole volume of the RPV material after preliminary and final heat treatment. No indications of hydrogen flakes were found during the UT inspections.

- **Scope and results of regular ISI:** Mechanized UT are performed from both outer and inner surface. The inspection scope includes all welds and adjacent base metal in extended volume, as it is required by ASME BPVC Section XI. In addition, the base metal of the whole core region is also part of the ISI scope. The cladding is inspected by UT and ET from inner surface and by UT from outer surface. Both UT and ET techniques are qualified according to ENIQ methodology. The inspection period is 10 years for both for OD and ID inspections. Earlier (before 2012) 4 years inspection period was used. At the end of each inspection cycle, an acoustic emission test of RPVs has been performed during the hydrostatic pressure test of the primary circuit.

  No indications of hydrogen flakes were found during the UT inspections.

- **Scope and results of additional ISI:** At Paks NPP the UT scope, from the beginning includes the significant part of the base metal of the RPV as well. Based on ISI results gained up to the present the extension of the ISI scope is not justified.

NETHERLANDS

- **Plant**: Borssele (PWR)

  - **Check of manufacturing documentation:** The complete fabrication documentation including all inspections and heat treatments is available. The documentation was checked for all forgings of the RPV. Based on metallurgy (fabrication technology, the used alloy, material compositions, low hydrogen content, relative small ingot sizes (Borssele is a 480 MWe unit)) it can be concluded that the forgings have a very low susceptibility to hydrogen flaking. Also with current day knowledge, no indication for the presence of hydrogen flaking in the forgings was found.

    Scope and results of PSI (UT) of forgings: The supplier performed a straight beam 100% UT inspection with +6dB sensitivity before the heat treatment. After heat treatment the regular 100% UT inspection with straight and 45° beam according to ASME was performed. The inspection of all forgings was supervised by the independent inspectorate TÜV. No relevant flaw indications were found. Other independently supervised UT inspections were performed: after cladding, welding and pressure testing. No relevant flaw indications were found.

  - **Scope and results of regular ISI:** The ISI programme for NPP Borssele is based on the ASME XI code and follows the requirements of the Dutch regulator.

  - **Scope and results of additional ISI:** For in-service inspection, the inspection can be performed from the inside of the vessel only (cladded surface). A qualified UT inspection technique for the detection of hydrogen flakes in the Borssele RPV was developed. Part of the qualification was the inspection with new and original UT techniques of archive material (cut offs) from all the Borssele RPV forgings. The Doodewaard ring" (cladded forging produced by RDM for the NPP Doodewaard RPV) was also part of the qualification. The original and new inspection method proved to be very sensitive to planar defects and no hydrogen flaking was found in these pieces.

– In 2013 more than 40% of the RPV surface was inspected by the qualified multiple UT straight beam techniques. The inspected area consisted of 4 vertical sectors, each 1m wide over the full accessible height of the RPV rings and the bottom shell. No reportable flaw indications were found. It was concluded that the hydrogen flaking phenomena is not present in the Borssele RPV.

SLOVAK REPUBLIC

- **Plants:** Bohunice-3, -4 and Mochovce-1, -2 (VVER 440)

  – **Check of manufacturing documentation:** All reactor pressure vessels in Slovakia have been manufactured by SKODA Nuclear Machinery in Czech Republic. Description of manufacturing process was obtained. According to this information, various strict measures were applied in order to keep impurities and hydrogen contents in reactor forgings on very low level. In the opinion /of experts from Skoda, as well as independent experts/, the occurrence of hydrogen flaking in these reactors is not probable and likely impossible.

  – **Scope and results of PSI (UT) of forgings:** During manufacturing, ultrasonic examination of full volume of forgings was performed in several stages of manufacturing process.

  Scope and results of regular ISI: Periodicity is every 8 years for both sides with 4 year shift between inspection from the outside and from the inside. Registration level corresponds to Ø=3.8 mm. However, all signals down to the noise level are recorded. This allows to detect indications much smaller than those corresponding to registration level UT qualified for flaws perpendicular to surface, also comprises techniques for laminar flaws parallel to surface. Some laminar flaws were found in the interface with the cladding (probably due to lack of fusion), in the base and the weld metal; all were just a few mm large and acceptable. Besides, underclad cracks were found. They did not show any propagation so far.

  – **Scope and results of additional ISI:** One time UT inspections of core region of RPV performed from the outer surface during 2013 to 2016 consequently:

    - 2013 – Mochovce -1 (inspection of 600 mm wide perimeter of core region)
    - 2014 – Mochovce -2 (inspection of whole core region)
    - 2015 – Bohunice - 3 (inspection of whole core region)

- 2016 – Bohunice - 4 (inspection of whole core region)

Results of inspections showed indications characteristic by laminar flaws. Substitute size is in range Dn=0.5 – 0.1mm. Indications are distributed in clusters which are oriented mainly vertical direction. Indications are allowed for operation according to report ŠKODA Ae 12522 / Dok rev.2 and will be submitted for next analyses in frame of project "Assessment of occurrence of laminar flaws in RPV shell". Analyses will be performed on samples of non-irradiated material from RPV Greifswald.

- **Plants:** Mochovce-3, -4 (VVER 440, in commissioning phase)

  – **Scope and results of additional ISI:** Inspections of the entire RPV wall (including core region) are planned in frame of PSI.

SLOVENIA

- **Plant:** Krsko (PWR)

  – **Check of manufacturing documentation:** General information of the material including heat treatment and results of the UT. The RPV is made of plate material.

  – **Scope and results of PSI (UT) of forgings**: UT of 54% of the base metal from the outer surface. UT of all welds including the adjacent base metal in a zone of 510-695 mm at each side of the weld.

  – **Scope and results of regular ISI:** Not reported.

  – **Scope and results of additional ISI:** Not foreseen.

Additional information after the inspection of the Krško NPP on 8th of May 2014: Preventive inspection of the calibration blocks for the reactor pressure vessel with UT method has been conducted by the Krško NPP in 2013. They were using UT probes, that were sensitive enough to discover possible hydrogen flaking. There were no indications found. Specifications of the material of the calibration blocks were the same as the material of the Krško NPP reactor vessel (SA 533 Grade B, Class 1) according to the standard.

SPAIN

- **Plants:** Trillo (PWR) and Santa Maria de Garoňa (BWR out of service)

  – **Check of manufacturing documentation:** The available documentation of the RPV of Trillo and Garoña NPP was checked. All other RPV in Spain are made of plates and their documentation will not be checked.

  – **Scope and results of PSI (UT) of forgings:** UT was performed in Trillo NPP with straight (from the inside and outside, top and bottom) and angle beam (from the inside and outside) on 100% of the forgings. Recording limit for straight beam was Ø = 6 mm. In case of Garoña NPP UT was performed with straight beam from the outside on all forgings. Recording limit was 50% of back wall loss. In both cases, no remarkable indications similar to flakes were found.

- **Scope and results of regular ISI:** In Trillo NPP, UT with both straight and angle beam of all welds (incl. ½ thickness of RPV at each side of welds) is performed every 10 years from the inside. No remarkable indications similar to flakes were found.

- **Scope and results of additional ISI:** In case of Garoña NPP, at the end of 2014, different samples of base material from all RPV rings were examined by UT from the inside with both straight beam and angle beam (45°), using recording and acceptance criteria, according to manufacturing code (ASME III). No remarkable indications similar to flakes were found. Related to Trillo NPP, it is planned to inspect the base metal area during the next outage in spring 2018, by UT techniques with capability to detect flaws similar to the flakes that were found in Döel and Tihange.

SWEDEN

- **Plants:** Ringhals-2 to -4 (PWR), Forsmark-3, Oskarshamn-3 (BWR)

  - **Check of manufacturing documentation:** All the documentation is available. It was checked for all forged rings of the lower part of the RPV of Ringhals-2 (flange, nozzle, upper core, lower core rings). A cursory review was performed for Ringhals-3 and -4. A full review have been carried out for Forsmark-3 and Oskarshamn-3. The RPV of the other 5 units in Sweden are made of plates and their documentation will not be checked.

  - **Scope and results of PSI (UT) of forgings:** UT with strait beam FBH Ø 8 mm, FBH Ø 12 mm and angle beam 45°. No reportable indications similar to flakes.

  - **Scope and results of regular ISI:** Until 1994 the following UT was performed from the inside with straight and angle beams (0°, 45°, 60° and 70°): all vessel welds including half of the wall thickness on each side of the welds, inner radius of forgings, nozzle to safe end welds, and safe end to pipe welds. The thickness range covered was: full thickness with straight beam, 20mm to full thickness with 45 and 60° angle beams and 0-20mm with 70° angle beam. After 1994 the UT performed covered welds and HAZ up to 50mm of the thickness. Since 1996 all ISI methods were qualified according to NRWG/ENIQ.

  - **Scope and results of additional ISI:** A 25% sector of the nozzle, upper core, and lower core rings was inspected by UT with straight beam in Ringhals-2, -3 and -4. For Forsmark-3 and Oskarshamn-3 no additional ISI is planned.

SWITZERLAND

- **Plants**: Mühleberg (BWR), Beznau-1, -2 (PWR), Gösgen (PWR)
  - **Check of manufacturing documentation:** The documentation is available and was checked for all forgings of the RPV for PWR (Beznau-1, -2, Gösgen) as well as BWR (Mühleberg, Leibstadt). The documentation was checked for heat treatments, hydrogen content and UT reporting criteria. The information does not indicate a hydrogen flaking issue. The heat treatment procedure for the Beznau-1 unit has not been found in detail. It was assumed the same process was used for unit 1 as it was for unit 2.
  - **Scope and results of PSI (UT) of forgings:** UT with straight beam and angle beam at least from the inside was carried out on 100% of the forgings. Additional UT using both beam types was independently performed by Swiss SVTI inspectors. Recording limit for straight beam was Ø = 6 mm. In addition sampling of back wall loss was performed. No notable indications similar to flakes were found.
  - **Scope and results of regular ISI:** UT with angle beam of all welds (incl. 50 mm of base metal next to welds) for PWR and BWR units every 10 years. No notable indications similar to flakes were found.
  - **Scope and results of additional ISI:**
    - Mühleberg (BWR): Additional representative UT with straight beam was carried out in 2012 for a sector of 30° from the inside. No notable indications similar to flakes were found.
    - Beznau-1 and -2 (PWR): In connection with the regular ISI 2015 additional UT was performed at the two RPV of Beznau units. At both units the intermediate and lower shells as well as the upper shell (nozzle ring) were 100% inspected (covering almost the entire volume of the beltline and nozzle rings). Additionally, the bottom shell of Beznau-1 was also inspected. Only at RPV of Beznau-1 numerous relative small indications, probably caused by non-metallic inclusions, were detected. The assessment of the indications is still ongoing. The utility has a Safety Case in preparation. No relevant indications were found at RPV of Beznau unit-2.
    - Gösgen: In connection with the regular ISI 2015 additional representative UT with a Phased Array system was performed for a sample of the beltline ring (120°), no relevant indications similar to flakes were found.

UNITED KINGDOM

- **Plant**: Sizewell B (PWR)

  - **Check of manufacturing documentation:** The check resulted in confidence that the precautions taken during the manufacture of the RPV for Sizewell B has minimised the likelihood of hydrogen-induced defects. The levels of hydrogen reported for forgings during product analysis are, generally, below the 0.8 ppm level.

  - **Scope and results of PSI (UT) of forgings:** UT with straight (from inside and outside) and angle beam was carried out; inspections by three independent agencies; no significant or reportable indications found. Inspection sensitivity and recording threshold was Ø = 2 mm for straight beams and 10% ASME DAC for angle beams. The acceptance limit for individual indications was Ø = 5 mm (in critical regions 3 mm). A review of the results of the PSI was conducted by the licensee prior to the outage in spring 2016.

  - **Scope and results of regular ISI:** Inspection of the welds and 25% of the core shell forging axial length. The core shell forging is 4000mm in length.

  - **Scope and results of additional ISI:** The licensee planned and performed inspection of the core shell region during the outage in spring 2016 with the capability to detect flaws of size 10 mm x 10 mm laminar planar similar to those found in the Doel-3 vessel. This again was based on ASME 10% DAC for straight and angle beams based on an 11 mm Side Drilled Hole, covering the full length of the core shell region (and adjacent welds). No significant indications were reported, and the inspection results aligned with expectations from the PSI findings.

- **Plants:** Hinkley Point C (twin unit of UK EPR under construction)

  - **Check of manufacturing documentation:** The RPV for Unit 1 is being made. Hydrogen levels in the forgings have been less than 0.8 ppm.

  - **Scope and results of PSI (UT) of forgings:** The scope of the PSI (used to set the baseline for the ISI) of the RPVs is not finalized. Volumetric (ultrasonic) and surface inspections are performed at several stages of manufacture. A capability statement has been produced for the final NDE inspection (performed after the quality heat treatment) to ensure that the ultrasonic techniques are capable of detecting and rejecting defects of concern (which includes hydrogen flakes). Each RPV forging is subject to a full repeat ultrasonic inspection implemented by an independent NDE organisation. The initial and repeat inspections are subject to surveillance by the licensee and by an Independent third party inspection agency (ITPIA).

- **Scope and results of regular ISI:** The scope of regular ISI is to be finalized.
- **Scope and results of additional ISI:** The scope of additional ISI is to be finalized.

Annex: Activities with regard to WENRA recommendation plant by plant

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
Belgium						
Doel	1	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Doel	2	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Doel	3	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Doel	4	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Tihange	1	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Tihange	2	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Tihange	3	PWR	All forging rings of RPV	- - -	Beltline rings	- - -
Bulgaria						
Kozloduy	5	VVER-1000/320	All forging rings of RPV	- - -	No[1)]	- - -
Kozloduy	6	VVER-1000/320	All forging rings of RPV	- - -	No[1)]	- - -
Germany						
Brokdorf	-	PWR	All forging rings of RPV	- - -	Sample of beltline	- - -
Emsland (KKE)	-	PWR	All forging rings of RPV	- - -	Sample of beltline	
Grohnde (KWG)	-	PWR	All forging rings of RPV	- - -	Sample of beltline	- - -
Gundremmingen (KRB B)	B	BWR	All forging rings of RPV	- - -	Sample of beltline	- - -
Gundremmingen (KRB C)	C	BWR	All forging rings of RPV	- - -	No, KRB B add. ISI representative for KRB C	---
Isar (KKI 2)	2	PWR	All forging rings of RPV	- - -	Sample of beltline	
Neckarwestheim (GKN 2)	2	PWR	All forging rings of RPV	- - -	Sample of beltline	- - -
Philippsburg (KKP 2)	2	PWR	All forging rings of RPV	- - -	Sample of beltline	

[1)] Some areas of the base metal are included in the original ISI schedule. UT is performed from the inside and outside.

[2]) RPV made of plates, that are considered not susceptible to hydrogen flaking.

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
Finland						
Loviisa	1	VVER-440/311	Beltline	- - -	Beltline rings (2016)	- - -
Loviisa	2	VVER-440/311	Beltline	- - -	Beltline rings (2014)	- - -
Olkiluoto	1	BWR	Beltline	- - -	No[2)]	- - -
Olkiluoto	2	BWR	Beltline	- - -	No[2)]	- - -
Olkiluoto	3	EPR	All forging rings of RPV	- - -	not yet in operation, UT-inspections of the forgings and the RPV after manufacturing	
France						
Belleville	1	PWR	All forging rings of RPV	- - -	Beltline for UCC	- - -
Belleville	2	PWR	-“-	- - -		
Blayais	1	PWR	-“-	- - -		
Blayais	2	PWR				
Blayais	3	PWR				
Blayais	4	PWR				
Bugey	2	PWR				
Bugey	3	PWR				
Bugey	4	PWR				
Bugey	5	PWR				
Cattenom	1	PWR				
Cattenom	2	PWR				
Cattenom	3	PWR				
Cattenom	4	PWR				

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Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
France						
Chinon	B1	PWR				
Chinon	B2	PWR				
Chinon	B3	PWR				
Chinon	B4	PWR				
Chooz	B1	PWR				
Chooz	B2	PWR				
Civaux	1	PWR				
Civaux	2	PWR				
Cruas	1	PWR				
Cruas	2	PWR				
Cruas	3	PWR				
Cruas	4	PWR				
Dampierre	1	PWR				
Dampierre	2	PWR				
Dampierre	3	PWR				
Dampierre	4	PWR				
Fessenheim	1	PWR				
Fessenheim	2	PWR				
Flamanville	1	PWR				
Flamanville	2	PWR				
Golfech	1	PWR				
Golfech	2	PWR				

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[2]) RPV made of plates, that are considered not susceptible to hydrogen flaking.

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
France						
Gravelines	1	PWR				
Gravelines	2	PWR				
Gravelines	3	PWR				
Gravelines	4	PWR				
Gravelines	5	PWR				
Gravelines	6	PWR				
Nogent	1	PWR				
Nogent	2	PWR				
Paluel	1	PWR				
Paluel	2	PWR				
Paluel	3	PWR				
Paluel	4	PWR				
Penly	1	PWR				
Penly	2	PWR				
Saint-Alban	1	PWR				
Saint-Alban	2	PWR				
Saint-Laurent	B1	PWR				
Saint-Laurent	B2	PWR				
Tricastin	1	PWR				
Tricastin	2	PWR				
Tricastin	3	PWR				
Tricastin	4	PWR				

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2) RPV made of plates, that are considered not susceptible to hydrogen flaking.

Annex: Activities with regard to WENRA recommendation plant by plant

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
Netherlands						
Borssele (KCB)	-	PWR	All forgings of RPV	- - -	Sample of beltline including nozzle ring and bottom shell	- - -
Romania						
Cernavodă	1	CANDU-6	Not relevant	- - -	Not relevant	- - -
Cernavodă	2	CANDU-6	Not relevant	- - -	Not relevant	- - -
Sweden						
Forsmark	1	BWR	No	- - -	No[2)]	- - -
Forsmark	2	BWR	No	- - -	No[2)]	- - -
Forsmark	3	BWR	Flange, Nozzle and beltline rings (2015)	- - -	No additional ISI is judged to be necessary.	- - -
Oskarshamn	1	BWR	No	- - -	No[2)]	- - -
Oskarshamn	2	BWR	No	- - -	No[2)]	- - -
Oskarshamn	3	BWR	Flange, Nozzle and beltline rings (2015)	- - -	No additional ISI is judged to be necessary.	- - -
Ringhals	1	BWR	No	- - -	No[2)]	- - -
Ringhals	2	PWR	Flange, Nozzle and beltline rings	- - -	Sample of beltline and nozzle ring	- - -
Ringhals	3	PWR	cursory review	- - -	Sample of beltline and nozzle ring (2016)	
Ringhals	4	PWR	cursory review	- - -	Sample of beltline and nozzle ring (2014)	

[1)] Some areas of the base metal are included in the original ISI schedule. UT is performed from the inside and outside.

[2]) RPV made of plates, that are considered not susceptible to hydrogen flaking.

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
Switzerland						
Beznau (KKB)	1	PWR	All forgings of RPV	- - -	Beltline rings including nozzle ring and bottom shell	
Beznau (KKB)	2	PWR	All forgings of RPV	- - -	Beltline rings including nozzle ring	
Gösgen (KKG)	-	PWR	All forgings of RPV	- - -	Sample of beltline rings	
Leibstadt (KKL)	-	BWR	All forgings of RPV		No[2)]	
Mühleberg (KKM)	-	BWR	All forgings of RPV	- -	Sample of beltline rings	
Slovak Republic						
Bohunice (EBO)	V2-3	VVER-440/213	Yes, in cooperation with ŠKODA	- - -	UT inspection of whole core region	- - -
Bohunice (EBO)	V2-4	VVER-440/213	Yes, in cooperation with ŠKODA	- - -	UT inspection of whole core region	- - -
Mochovce (EMO)	1	VVER-440/213	Yes, in cooperation with ŠKODA	- - -	UT inspection of 600 mm wide perimeter of core region	- - -
Mochovce (EMO)	2	VVER-440/213	Yes, in cooperation with ŠKODA	- - -	UT inspection of whole core region	- - -
Mochovce (EMO)	3	VVER-440	Yes, in cooperation with ŠKODA			During commissioning
Mochovce (EMO)	4	VVER-440	Yes, in cooperation with ŠKODA			During commissioning
Slovenia						
Krško (JEK/NEK)	-	PWR	General info of UT		No[2)]	

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[2)] RPV made of plates, that are considered not susceptible to hydrogen flaking.

Annex: Activities with regard to WENRA recommendation plant by plant

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
Spain						
Almaraz	1	PWR	No	- - -	No[2)]	- - -
Almaraz	2	PWR	No	- - -	No[2)]	- - -
Ascó	1	PWR	No	- - -	No[2)]	- - -
Ascó	2	PWR	No	- - -	No[2)]	- - -
Cofrentes (CNC)	-	BWR	No	- - -	No[2)]	- - -
Trillo (CNT)	1	PWR	All forgings of RPV	- - -		2018 Outage
Santa María de Garoña (currently out of service)	-	BWR	All forgings of RPV		Sample of all rings	
Vandellòs (CNV)	2	PWR	No	- - -	No[2)]	- - -
Czech Republic						
Dukovany ([J]EDU)	1	VVER-440/213	All forgings of RPV	- - -	Sample of beltline and upper ring	- - -
Dukovany ([J]EDU)	2	VVER-440/213	All forgings of RPV	- - -	Sample of beltline and upper ring	- - -
Dukovany ([J]EDU)	3	VVER-440/213	All forgings of RPV	- - -	Sample of beltline and upper ring	- - -
Dukovany ([J]EDU)	4	VVER-440/213	All forgings of RPV	- - -	Sample of beltline and upper ring	- - -
Temelín ([J]ETE)	1	VVER-1000/320	All forgings of RPV	- - -	No[1)]	- - -
Temelín ([J]ETE)	2	VVER-1000/320	All forgings of RPV	- - -	No[1)]	- - -
Hungary						
Paks	1	VVER-440/213	Beltline area	- - -	No[1)]	- - -
Paks	2	VVER-440/213	Beltline area	- - -	No[1)]	- - -
Paks	3	VVER-440/213	Beltline area	- - -	No[1)]	- - -
Paks	4	VVER-440/213	Beltline area	- - -	No[1)]	- - -

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[2]) RPV made of plates, that are considered not susceptible to hydrogen flaking.

Name	Unit	Reactor type	Step 1: check of documentation		Add ISI	
			performed	planned	performed	planned
United Kingdom						
Dungeness	B1	AGR	Not relevant	- - -	Not relevant	- - -
Dungeness	B2	AGR	Not relevant	- - -	Not relevant	- - -
Hartlepool	A1	AGR	Not relevant	- - -	Not relevant	- - -
Hartlepool	A2	AGR	Not relevant	- - -	Not relevant	- - -
Heysham	A1	AGR	Not relevant	- - -	Not relevant	- - -
Heysham	A2	AGR	Not relevant	- - -	Not relevant	- - -
Heysham	B1	AGR	Not relevant	- - -	Not relevant	- - -
Heysham	B2	AGR	Not relevant	- - -	Not relevant	- - -
Hinkley Point	B1	AGR	Not relevant	- - -	Not relevant	- - -
Hinkley Point	B2	AGR	Not relevant	- - -	Not relevant	- - -
Hunterston	B1	AGR	Not relevant	- - -	Not relevant	- - -
Hunterston	B2	AGR	Not relevant	- - -	Not relevant	- - -
Sizewell	B	PWR	All forgings of RPV	- - -	Beltline (2016)	
Torness	1	AGR	Not relevant	- - -	Not relevant	- - -
Torness	2	AGR	Not relevant	- - -	Not relevant	- - -
Wylfa	1	Magnox-Reactor	Not relevant	- - -	Not relevant	- - -

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[2]) RPV made of plates, that are considered not susceptible to hydrogen flaking.