Note:
This is a translation of the RSK recommendation entitled
"Ergebnisse des ENSREG Topical Peer Review zum Alterungsmanagement
Anforderung zur Prüfung des RDB-Grundwerkstoffes"
In case of discrepancies between the English translation and the German original, the original shall prevail.

Annex 3 to the minutes of the 512th meeting of the Reactor Safety Commission (RSK) on 22./23.10.2019

Results of the ENSREG Topical Peer Review on ageing management
Requirement of examining the RPV base material

RECOMMENDATION

1 Advisory request of the BMU and consultations

In October 2018, the European Nuclear Safety Regulators Group (ENSREG) presented its report on the first Topical Peer Review (TPR) [1] dedicated to ageing management. The TPR report deals, among other things, with ageing management for reactor pressure vessels. In the country specific findings (Annex [2] resulting from the report [1]), an area for improvement has been identified for Germany regarding the examination of the base material of the reactor pressure vessel (RPVs). The corresponding action expected by ENSREG to meet the requirements of the TPR is as follows (Expected level of Performance):

Comprehensive NDE is performed in the base material of the beltline[1] region in order to detect defects.

In a letter dated 18.03.2019 [3], the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) requested the RSK to discuss the results of the ENSREG Topical Peer Review and to assess whether, in the light of the state of the art in science and technology, additional measures are required to examine the base material of the RPVs of the German nuclear power plants. A second question of the BMU is dealt with in the statement on ageing management of electrical cables from the 511th meeting on 04.09.2019.

At the 176th meeting of the Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW) on 13.06.2019, the advisory request of the BMU was discussed and the draft of the recommendation prepared. At a video conference on 21.08.2019, the draft recommendation was revised and then submitted to the RSK. The RSK discussed the recommendation at the 511th meeting on 04.09.2019. At the 177th meeting of the RSK Committee DKW, remaining questions from the RSK meeting were addressed and the draft was subsequently supplemented. The RSK discussed the amended recommendation and adopted it at its 512th meeting on 22./23.10.2019.

[1] ENSREG defines the "beltline region" as the region where the material accumulates a fluence of more than 10^{17} n/cm^2. This corresponds to the range in which neutron embrittlement of the material is to be taken into account in accordance with safety standard KTA 3201.2.

2 Background

The reason for ENSREG to require a comprehensive examination of the RPV base material in the beltline region are the flaw indications in the base material of the reactor pressure vessels of the Belgian nuclear power plants Doel-3 and Tihange-2 (which are e.g. described in the RSK statement from the 503rd RSK meeting [4]) as well as the flaw indications in the reactor pressure vessel of the Swiss nuclear power plant Beznau-1 (information is given in the report [5]).

In its report [1], ENSREG refers to recent operating experience feedback according to which some manufacturing defects were not detected in the base material during fabrication or previous inspections. In this context, reference is made to underclad defects in France in the late 1990s, hydrogen flakes in Belgium in 2012 and non-metallic inclusions in Switzerland in 2015 detected during in-service inspections. These findings did not indicate ageing-related degradation, but they had been found by non-destructive examination (NDE) using the most recent techniques.

In 2014, WENRA (Western European Nuclear Regulators Association) had recommended a comprehensive review of the manufacturing and inspection records of the RPV forgings and an examination of the RPV base material if this was considered necessary. According to WENRA, most countries considered at that time that comprehensive examination of the base material is not necessary, based on the manufacturing and inspection records.

However, taking into account the experience from the Beznau-1 nuclear power plant, where another type of defect was discovered than in the Belgian reactors, ENSREG considers it in the framework of the TPR as insufficient not to perform a comprehensive examination of the base material of the beltline region at least once in order "to detect any defects". ENSREG highlights that standard qualified techniques for cracking type defect detection in the welded zones are not necessarily suitable for detecting defects in the beltline region. The use of qualified techniques and adequate recording limits for NDE were necessary for comprehensive NDE of the base material of the beltline region in order to detect defects. From this, ENSREG derives the expectation described above.

The RSK already dealt with the flaw indications at the Belgian Doel-3 nuclear power plant and the conclusions to be drawn from it for the German plants in its statement at the 454th meeting on 17.01.2013 [6]. Based on the state of knowledge at that time, the RSK came to the conclusion that the inspection concept currently required in the KTA safety standards and implemented in the plants, which is focused on in-service inspections of the welds and the adjacent heat-affected zones and highly stressed areas (e.g. nozzle edges), but does not provide for in-service volumetric inspections of the base metal, was appropriate. In the opinion of the RSK, extension with respect to the technique or the scope of examinations due to the indications in Doel-3 is not necessary. Furthermore, the RSK stated that the quality assurance and documentation during the fabrication of the RPV forgings of the German plants in operation was such that specific manufacturing process parameters that could have caused such indications as in Doel-3 would have been identified, especially if the defect sizes described for Doel-3 were used as a basis. With the confirmation of flawlessness by an evaluation of the documentation, such defects could be excluded. Therefore, the RSK recommended to evaluate the manufacturing documentation of all RPV forgings (i.e. not only the cylindrical area) of the German nuclear power plants in operation with regard to the flaw indications in the cylindrical part of the RPV of Doel-3.

The measures subsequently implemented are documented, for example, in the WENRA report [7]. Accordingly, the manufacturing documentation was checked for all German nuclear power plants in operation. Furthermore, additional ultrasonic testing of the forged rings in the beltline region was performed in all German pressurised water reactor (PWR) plants in operation in a sector of 30° to 38° from the inside. At the boiling water reactor (BWR) Gundremmingen, Unit B, ultrasonic testing was performed in a sector of 45° from the outside. No indications requiring recording were found. The RSK Committee DKW was informed about the special tests at its 123rd meeting on 09.10.2012, 132nd meeting on 16.10.2013 and 141st meeting on 10.12.2014. According to the presentation at the 123rd DKW meeting using the example of GKN-2, the sensitivities of the ultrasonic testing technology were adjusted in these tests as they had been adjusted in the course of the manufacturing test [8].

Knowing the situation as presented by the BMU within the framework of the TPR, ENSREG submitted the country specific assessment that there is a need for improvement for Germany with regard to the comprehensive examination of the base material of the reactor pressure vessels in the beltline region.

3 Assessment criteria

This recommendation answers the question of the BMU whether, against the background of the assessment in the ENSREG Topical Peer Review and in the light of the state of the art in science and technology, additional measures for the examination of the RPV base material are necessary in German nuclear power plants.

The ENSREG requirement for comprehensive NDE of the base material in the beltline region goes beyond the recommendation of WENRA in 2014, which first of all recommended a review of the manufacturing and inspection records. ENSREG's argumentation for deriving this requirement is based on the following two aspects:

- In the Swiss nuclear power plant Beznau, another type of defect was discovered than in Doel-3 and Tihange-2.

- The techniques for defect detection in the welded zones are not necessarily suitable for detecting defects in the base material in the beltline region.

ENSREG acknowledges that the defects in the RPV are due to manufacturing and not to ageing effects.

To answer the BMU question, the RSK deals with the following individual aspects:

- Suitability of the manufacturing methods to avoid defects as in Beznau. In this respect, the RSK refers to its statement [4] of 2013.

- Assessment as to whether the tests performed during the manufacture of the German RPVs were suitable, also against the background of the current findings, for reliably identifying deviations that are unacceptable from a safety point of view.

The RSK is not aware of any further requirements from the international rules and regulations or of any new findings from operating experience which, according to the state of the art in science and technology, would have to be taken into account for answering the question of the BMU.

4 Statement

According to the RSK's understanding, the tests and inspections at nuclear power plants are correlated with each other in order to ensure that the structures, systems and components have the required properties and that these are maintained over the service life:

- Tests during manufacture shall demonstrate that the components supplied to the operator meet the specified requirements.

- Regular in-service inspections serve to demonstrate that degradation during operation does not impair the required quality of the structures, systems and components over the operating life of the plants. For the RPV, these inspections comprise the weld seams and heat-affected zones but not the base material.

- Special tests are required if new findings indicate that the manufacturing tests were not suitable to demonstrate the required quality, or if ageing effects previously not taken into account in the tests may lead to the loss of the required properties during operation. In this case, the new findings may require the permanent adaption of the in-service inspections.

In accordance with this concept, the RSK examined whether new findings were available that would require additional testing.

As described above, ENSREG bases its argumentation on the flaw indications at the Swiss Beznau-1 nuclear power plant. In the safety case review [5], which is based on the report by the operator axpo [9], ENSI describes these indications as follows:

In total, 3,632 indications were found in the Beznau-1 RPV in three forged rings. The large majority of them, i.e. 3,511 indications, were found in Ring C in the beltline region. Of these, the majority (2,689 indications) were agglomerated, referred to as "extended areas" by the operator. The operator's report [9] shows that the indications in Ring C extend over the entire circumference, with areas with a very low density of indications being located between the extended areas. In Ring B, where 119 indications were identified, these are distributed unevenly across the circumference. In Ring A, there were two indications. In addition, indications were found in the bottom dome, whose number, according to ENSI [5], is not comparable with the results for the forged rings due to another test technique not qualified for this application. These indications are also distributed unevenly.

The indications were attributed to non-metallic inclusions of aluminium oxide (Al_2O_3) from the manufacturing process. For the majority of the indications, a size between 3 mm and 5 mm (in axial and circumferential direction) was determined. An area of 1 mm² was indicated as the detectable defect size [9].

According to [9], the aluminium oxide inclusions were caused by the manufacturing process. In accordance with the documentation, aluminium was added to the melt during the casting process to remove oxygen from the melt. In the case of Ring C, the vacuum could probably not be completely maintained during the casting of the ingot. The ingots of rings B, C and E affected by indications had a relatively large height to diameter ratio, so they were relatively slim. The diameter of the cut out inner part was small compared to the other RPV rings where no indications were found. Based on this, ENSI confirms that the indications are caused by aluminium oxide inclusion agglomerated in the sedimentation cone in the centre bottom of the ingot [5].

In its safety case review, ENSI points out that vacuum pouring and a sufficient ingot discard are required by the applied ASTM standard A-508[2] in order to avoid the occurrence of flaws in the final forging, such as clusters of non-metallic inclusions. Several RPVs in different countries were tested with the same UT inspection technique as the Beznau-1 RPV. These tests had not shown indications with a characteristic comparable to the Beznau-1 RPV. This observation would confirm that the manufacturing practices based on steelmakers' internal expertise around the time of the fabrication of the Beznau-1 RPV were able to prevent the formation of such clusters. In this context, ENSI notes that the Beznau-1 RPV was one of the first vessels fabricated.

According to the ENSI review, the manufacturing documentation confirms that the manufacturer of the Beznau-1 RPV himself was aware of the need to discard and cut out respectively a sufficient part of the segregated regions of the cast ingot. However, the UT indications from 2015 showed that the zone with negative segregations at the bottom of the ingot was probably insufficiently cut out.

All in all, ENSI considers it reasonable to interpret some indications in the manufacturing documentation of the Beznau-1 RPV as deviations from the then best practices. This may have contributed to the deviations, in particular in Ring C.

In addition, a replica of Ring C ("Replica C") was fabricated with process parameters as close as possible to those used for the fabrication of Ring C. The process parameters were determined on the basis of the existing Ring C manufacturing documentation. The replica has the same indication characteristics as Ring C. Furthermore, the aluminium oxide inclusions formed are located in the zone with negative segregations. This provides additional evidence that the indications are due to specific manufacturing process parameters that are recorded in the manufacturing documentation.

[2] The ENSI document states SA-508, but to the knowledge of the RSK this should be A-508 as an ASTM specification, since SA is the ASME variant of the corresponding ASTM standard.

In its safety case review, ENSI concludes that the aluminium oxide inclusions do not significantly influence the macroscopic material properties relevant for the integrity or neutron embrittlement. This is supported by the assessment by an international review panel appointed by ENSI [5].

In its statement of 2013 [6], the RSK dealt with the manufacturing processes for the RPV of the plants in operation in order to examine whether manufacturing-related defects as in the Doel-3 NPP can be reliably excluded.

Based on the statement [6], the RSK states: The forgings for the cylindrical part of the RPVs of the German plants in operation (Grafenrheinfeld nuclear power plant and younger) have been manufactured exclusively at Japan Steel Works (JSW, Japan) since the mid-1970s. At that time, JSW was qualified by the responsible experts for the production of large forging ingots for German plants.

Manufacture was carried out in accordance with the manufacturing documents (manufacturing and test sequence plans, heat treatment plans, NDE instructions, etc.) which were reviewed and approved by the plant supplier Siemens/KWU and the responsible authorised expert. This differs from the manufacture of the RPVs of the plants in Doel, Tihange and Beznau, which were manufactured in accordance with the American ASME/ASTM specifications. The manufacturing documents for the German plants described all monitoring and testing steps that had to be performed during the manufacturing process from melting to delivery of the components. The execution of the individual steps has been confirmed by the manufacturer and, as required, also by the plant supplier Siemens/KWU and by the authorised expert for the final documentation by stamp and signature. In the case of components that were not yet assigned to a project at the time of manufacture (so-called "prefabrication"), the expert consulted for the plant additionally assessed the components within the framework of the take-over acceptance report.

The steel was melted in electric furnaces; the casting of the ingots (partly using the "multiple-pouring method" to improve homogeneity of the melt and to reduce segregations) was carried out under vacuum to reduce the hydrogen and oxygen content. After forging, so-called "hot depositing" was carried out allowing the effusion of hydrogen and thus to prevent hydrogen flake cracking. Subsequent to this hot depositing, the forging blank was mechanically treated to allow the first ultrasonic volume inspection of the part by the manufacturer in a condition with as little contour as possible. Only parts that revealed no abnormalities in this inspection were further processed and, after final heat treatment, subjected to further independent ultrasonic testing by the manufacturer, plant supplier, and authorised expert. To demonstrate that the forgings were free of inadmissible segregations, chemical analyses were carried out at the top and bottom of the ingot after "discarding" and for cylindrical parts along three surface lines offset by 120° (both face areas, inner and outer surface) in accordance with the specifications of the plant supplier Siemens/KWU. These analyses served to determine the content of all relevant alloying and steel accompanying elements. The results were documented. For the same reason, hardness tests and sulphur prints (Baumann method) were made on the face areas and in some cases over the entire length of the finished inner and outer surfaces of the cylindrical rings. These material tests are not required according to the ASME Code.

With regard to the deviations found in the Beznau-1 RPV, it should be noted that the addition of small quantities of aluminium to bind oxygen is common practice and was also used in the fabrication of the German RPVs.

The resulting aluminium oxides are concentrated in the segregation zones. As described above, the manufacturing process at JSW was aimed at minimising segregations and non-metallic inclusions in the further processed forgings. Compared to the fabrication of the RPVs of Doel-3, Tihange-2 and Beznau-1, larger cast ingots were used from which larger top and bottom parts as well as the central area of the rings could be discarded and cut out respectively before the forging process. The separated areas of the ingot have a significantly increased content of non-metallic inclusions compared to the parts of the ingot used to produce the forgings. Overall, material homogeneity was ensured to a higher degree compared to other manufacturers.

VGB POWERTECH compiled the differences in the manufacturing processes at JSW compared to other manufacturers and presented information on research projects carried out in Germany to ensure a high, requirement-compliant quality of the forgings for the reactor pressure vessels of the German nuclear power plants in operation for the 168th meeting of the RSK Committee DKW on 22.02.2018 [10]. Numerous investigations on RPV materials were carried out within the framework of research programmes in the 1970s and 80s. These investigations included an evaluation of the influence of macro- and micro-segregations as well as hydrogen flakes on the structural integrity of RPV materials. In connection with the issue discussed here, research programme BMI-TB SR 76 on fundamental investigations of the segregation behaviour of reactor steel 20 MnMoNi 5 5 on a 180 t ingot *(Grundlegende Untersuchungen des Seigerungsverhaltens des Reaktorstahls 20 MnMoNi 5 5 an einem 180 t-Block)* is to be mentioned in particular. According to [10], different types of macro-segregations were described in the research project, including negative segregations and non-metallic inclusions, which mostly occurred in the bottom area. The corresponding remedial measures were presented: reduction of P and S contents, effective degassing, improvement of mould geometry, multiple pouring method and cap heating. In addition, the presentation described the tests performed during the manufacture.

With regard to manufacture and quality assurance of product forms of the reactor coolant system, the VGB summarised the following:

- The product check analyses of top and bottom scrap and on the forging of top and bottom of the original ingot (in particular carbon and sulphur content) would have revealed segregations. The product check analyses could therefore exclude relevant segregations.

- Testing of tensile specimens and notched bar impact specimens in longitudinal direction (in parallel to the main deformation direction), in transverse direction (transverse to the main deformation direction) and in the radial direction (thickness direction) and the tests over the cross-section ensure that the mechanical properties comply with the specifications. Segregations which would have negatively influenced the mechanical properties could therefore also be excluded in the tested parts.

- Segregations would have been detected by the sulphur prints (Baumann method) of the finished parts from the top and bottom areas of the original ingot. Thus, segregations could also be ruled out via the sulphur prints.

As described in Chapter 2, the manufacturing documentation for the RPVs [7] of the German nuclear power plants in operation was reviewed again. In doing so, deviations during the manufacturing process could have been detected. Here, there is a significant difference to the manufacture of the RPV for Beznau-1, for which,

according to the ENSI review, at least some forgings deviated from the then best practices. Specific manufacturing process parameters in the manufacture of the Beznau-1 RPV, such as the late addition of aluminium in the fabrication of Ring C, can be seen from the documentation.
From the RSK's point of view, in summary, there is no indication that during the manufacturing process of the RPVs for the German nuclear power plants the formation of inadmissible non-metallic inclusions, such as aluminium oxides, not removed during the manufacturing process, could have occurred.

With regard to the sensitivity of the manufacturing tests, the RSK explains in its statement [6] that regarding the detectability of defect sizes and in comparison to the defects found in Doel-3, the results as measured according to [11] and documented during the manufacturing test of heavy forgings for the nuclear applications of the manufacturer Japan Steel Works (JSW) are taken as a basis. There it is stated that the detection limits for wall thicknesses up to 200 mm can be specified with a reference reflector size of 0.5 mm (reflectivity of a circular disk measured as echo height) at a test frequency of 2 MHz. Also, individual flaw indications were detected with this reference reflector size. Thus, defect sizes having a significant influence on the integrity of the RPV, i.e. in particular crack-like defects of a technically relevant size, are clearly identifiable.

However, the reflection behaviour of a circular disk is different from that of more spherical, round non-metallic inclusions. Therefore, no statement can be made on the basis of the available information as to whether these non-destructive examinations could have reliably identified defects such as those in the Beznau-1 RPV.

The special tests of the RPVs of the German nuclear power plants in operation were performed with the same sensitivity as the manufacturing tests. So, it is not ensured for these tests either that defects such as those detected on the RPV of Beznau-1 would have been reliably identified.

Thus, the question arises as to the necessity of detecting such deviations by means of ultrasonic testing during manufacture. In this respect, two aspects are important:

- The manufacturing process ensured that no inadmissible segregations or non-metallic inclusions remained in the forgings.

- The manufacturing tests were suitable for detecting inadmissible segregations and non-metallic inclusions. Here, the entirety of the material tests and non-destructive examinations performed shall be considered; the ultrasonic tests shall not be considered isolated.

In summary, it can be stated that the deviations in the RPVs of Doel-3, Tihange-2 and Beznau-1 are due to effects (pronounced segregations, inadmissible non-metallic inclusions and excessively high concentrations of hydrogen not removed during the manufacturing process, as well as insufficient degassing during casting) which were sufficiently well known when producing the forgings for the German RPVs. These were avoided in the manufacturing process and taken into account in the manufacturing tests. The independent monitoring by authorised experts provides additional safety. For reasons of verification, the manufacturing documentation was reviewed again after the findings from Doel-3 and Tihange-2. Manufacturing and testing in compliance with the defined specifications and requirements was confirmed. There are no new findings which would make additional special tests necessary.

For the reasons described above, the RSK concludes that no need for a comprehensive examination of the base material of the RPVs of the German nuclear power plants can be derived from the manufacturing-related deviations detected in the cylindrical rings of the RPVs of Doel-3, Tihange-2 and Beznau-1.

5 Conclusion

The RSK does not consider it necessary in the light of the state of the art in science and technology to carry out further measures for examining the base material of the RPVs in the German nuclear power plants.

6 References

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