Note:
This is a translation of the RSK Recommendation entitled
"Schäden an Dampferzeuger(DE)-Heizrohren durch Spannungsrisskorrosion – Maßnahmen zur Sicherstellung der Integrität der Heizrohre."
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK Recommendation
(512th meeting of the Reactor Safety Commission (RSK) on 22/23 October 2019)

**Damage on steam generator (SG) tubes caused by stress corrosion cracking –
Measures to ensure the integrity of the tubes**

RECOMMENDATION

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1 Introduction

During the 2018 overall maintenance and refuelling outage (hereinafter referred to as "outage"), eddy current tests performed at the Neckarwestheim 2 nuclear power plant (GKN-2) revealed linear, circumferential indications in SG tubes in the hot leg of steam generators (SG) 20 and 40. Here, hot leg refers to the side where the primary coolant enters the SG tubes. A total of 101 tubes were identified to show linear, circumferentially oriented indications, 99 of them in SG 20 and two in SG 40. Wall thinning was of different depths (maximum local wall thinning on one pipe 91 %). The indications were located in the area of the tube sheet that separates the primary from the secondary side and into which the tubes are mechanically expanded.

At the request of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the RSK Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW) dealt at its 172nd meeting on 05 November 2018 with the plant-specific issues with regard to the restart of the GKN-2 plant after the 2018 outage.

In addition, the RSK identified the need to evaluate the findings at GKN-2 with regard to generic conclusions for all German nuclear power plants (NPP) with pressurised water reactors (PWR) since circumferential indications to such an extent had not been found in German NPPs before. So far, the RSK had only been aware of circumferential indications on SG tubes from the Unterweser nuclear power plant, where such findings were detected on seven SG tubes in 2007 [1].

In previous years, the RSK has already dealt with the question of the integrity of the SG tubes, caused by linear and mainly axial indications on SG tubes of the Biblis A and Unterweser plants. It submitted two statements on this issue in 2010 and 2012:

- Damage to steam generator (SG) tubes caused by stress corrosion cracking - cause and detection; adopted at the 428th meeting of the Reactor Safety Commission on 15 July 2010 [1]:
  In this statement, recommendations were made regarding the in-service inspections of SG tubes, the monitoring of the water chemistry with so-called hide-out-return (HOR) analyses and the procedure to be followed if crack-like indications on SG tubes are detected.

- Leakages from steam generator (SG) tubes to be postulated: multiple tube rupture/leak opening of wall thickness-reduced SG tubes; adopted at the 447th meeting of the Reactor Safety Commission on 03 May 2012 [2]:
  This statement dealt with the leakage rate to be assumed in case of axial cracks in SG tubes and, on this basis, derived a recommendation for the inclusion of an operating procedure for the shutdown of the plant in case a leakage of > 40 kg/d is detected.

Against the background of the findings at GKN-2, the RSK considers it necessary to review and supplement the two statements. The result of the consultations is documented in the recommendation at hand.

2 Course of discussions

At the 166th meeting of the RSK Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW) on 12 October 2017, a committee member reported on eddy current test results showing indications on SG tubes at the GKN-2 plant [3]. The consultations were resumed at the 168th DKW committee meeting on 22 February 2018 and the 171st DKW committee meeting on 28 June 2018 [4]. At the 172nd DKW committee meeting on 05 November 2018 [5], the utility, manufacturer, authorised experts and regulatory authority (Länder) delivered presentations on the indications detected by the eddy current testing of SG tubes at GKN-2 (reportable events ME 03/2017 and ME 04/2018). At this meeting, the committee looked in particular at plant-specific aspects. At the 173rd DKW committee meeting on 22 November 2018 [6], the generic aspects of the indications on SG tubes were discussed. Also at that meeting, the results of a survey conducted by the BMU among the Länder [7] regarding condenser leakages and in-service inspections of SG tubes in German nuclear power plants with pressurised water reactors were presented.

At the 174th DKW committee meeting on 12.12.2018 [8], the Information Notice (WLN) 2018/06 "Indications upon eddy current testing of steam generator tubes at the Neckarwestheim-2 nuclear power plant (GKN-2), reported on 25 September 2017 and 14 September 2018" [9] was discussed and a draft statement was prepared. GRS[1] reported on the calculation of crack opening areas and leakage rates. The demonstrability of the leak-before-break behaviour was discussed.

The draft statement was adopted at the 175th DKW committee meeting on 14 February 2019 [10] and submitted to the RSK for further discussion. The document was discussed at the 510th meeting of the RSK on 05 June 2019.

At the 511th meeting of the RSK on 04 September 2019, the DKW committee was requested to consider further findings from the 2019 outage at GKN-2. Thereupon, the draft was revised at the 177th meeting of the RSK's DKW committee on 26 September 2019 [11] and again submitted to the RSK. The RSK discussed and adopted the recommendation at its 512th meeting on 22/23 October 2019.

3 Background

At the 166th meeting of the RSK DKW committee on 12 October 2017, a committee member reported on eddy current tests showing findings on SG tubes at the GKN-2 plant [3]. During the September 2017 outage, SG tubes from two SGs in GKN-2 were subjected to eddy current testing according to KTA 3201.4 [12] and the existing in-service inspection concept. One SG showed indications of volumetric (shallow-pit-like) damage, predominantly close above top of the tube sheet (TTS). The subsequent 100% inspection of the SG tubes on the exit side of this SG (cold leg) revealed a total of 31[2] affected tubes. The depth of the indications ranged from approx. 15 % to approx. 60 % of the wall thickness, starting from the outside of the SG tubes, which are immersed in secondary cooling water. 13 of the affected tubes had already been inspected in 2007 or 2012 and

1 GRS is the abbreviation for the German TSO Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH.
2 In subsequent reviews, the number of tubes with findings was corrected to 32.

revealed no findings at that time and were not conspicuous. Since 2012, minimal condenser leakages that could not be localised have been detected several times, which could have an influence on the degradation. The Action Level 1 specified by VGB[3] in the Guideline for Water in Nuclear Power Plants with Light Water Reactors (VGB R 401 J) with regard to secondary-side water chemistry was not reached and no indications were found on the SG tubes in the other SG that was inspected.

In the 2017 outage, 13 tube positions with relevant indications (evaluation limit of ≥ 30 % wall thinning) and one tube position with one recordable indication (recording level of ≥ 20 % wall thinning) were plugged (rolled plugs). Two pipes with relevant indications (each with wall thinning of more than 30 %) were not plugged in order to obtain information on the kinetics of the underlying damage mechanism. The manufacturer was involved in the investigation of the root cause.

During the 2018 revision, in light of the findings in 2017, eddy current tests were carried out on all four SGs of the plant. With these tests, new indications on steam generator tubes were detected. According to the description in Information Notice WLN 2018/06 of GRS [9], a total of 23 further SG tubes with volumetric indications were found in the four SGs in addition to the 32 SG tubes detected in the 2017 revision. The new volumetric indications fit into the characteristic known from 2017 with regard to their axial position on the tube and their depth. With the exception of one SG tube, for which an increase in wall thinning of approx. 20 % was observed in 2018, the change in the volumetric indications already found in 2017 was small. No changes were found in the two unsealed tubes with relevant indications above the evaluation limit.

In contrast to 2017, however, volumetric indications were also found on the primary inlet side or hot leg of the SG (two tubes in SG 10, one tube in SG 20). In addition, linear indications oriented in circumferential direction of the SG tubes were found for the first time. The majority of the SG tubes affected show single indications and in some cases also multiple indications. The linear indications are interpreted as outer diameter circumferential surface planar flaws (hereinafter referred to as "circumferential indications"). SG 20 (99 tubes) and SG 40 (two tubes) are affected by circumferential indications. The circumferential indications are located exclusively on the hot leg side of the two SGs and, in contrast to the volumetric indications, they are in a range from approx. -2 mm to approx. +7 mm relative to the upper roll-in edge of the SG tubes and thus close to the top of tube sheet. The depth is very uneven over the length of the indications and on one SG tube locally reaches a maximum value of 91 % of the wall thickness.

All SG tubes affected are made of Alloy 800 mod., have an outer diameter of 22 mm and a wall thickness of 1.2 mm. The SG tubes were shot peened with glass beads before mounting, to induce compressive stresses in a surface layer in order to improve their resistance to stress corrosion cracking, for which tensile stresses are necessary.

In [9], GRS refers to investigations by the manufacturer and the licensee to clarify the root cause. According to them, the following primary damage root causes are responsible for the degradation:

- A large input of iron oxide into the SG and its deposition in the flow dead zones. Since 2010, iron oxide from the water separator reheater (WAZÜ) has been increasingly flushed into the SG. The cause of the

3 VGB is the abbreviation for the technical association of power plant operators in Germany.

iron oxide input was the dosing of oxygen into the heating steam of the water separator reheater, which has been in operation since the 2010 outage. The iron oxides flushed into the SGs could deposit on the tube sheets in flow dead zones and, over time, form hard deposits there. Further corrosion products, foreign materials and impurities could in turn deposit on these in loose form (soft deposits). In fact, during the mechanical tube sheet cleaning in the 2018 outage, significantly larger masses of corrosion products were extruded than during the previous tube sheet cleaning in 2010. However, significantly lower deposition masses were found in SG 20 than in the other SGs. For this asymmetrical load of the SGs with corrosion products from the water-steam cycle, only a hypothesis is available so far.

- The deterioration of water chemical parameters. Since 2013, there have been repeated micro-leakages from various chambers of the condenser, not all of which could be identified and eliminated. The values for the control parameters "sodium" and "conductivity in steam generator water" have been temporarily above the normal operational values since 2016, but still clearly below Action Level 1 according to the relevant VGB Guideline, from when on measures have to be taken to quickly identify and eliminate the root cause of the deviation without reducing power output.

- The hide-out return analyses have shown increasing values for calcium and sulphate and slightly increased values for chloride over the years. In addition, comparatively high values were found for copper. The impurities were able to concentrate in the crevices between the SG tubes and the tube sheet, in the transition area between hard and soft deposits above the top of tube sheet as well as in the deposits on the SG tubes, which allowed locally strongly acidic conditions to form under which even the material Alloy 800 mod. is susceptible to corrosion. Furthermore, these conditions lead to increased corrosion of the tube sheet made of the ferritic material 20 MnMoNi 5 5.

Based on the findings from the GKN-2 plant and from destructive tests on pulled SG tubes of other plants, Framatome attributes the findings to the following damage mechanisms as described in the Information Notice [9]:

- The volumetric indications found in the 2017 and 2018 outages are due to pitting corrosion and/or intergranular attack (IGA) under strongly acidic conditions, caused by the ingress of sulphate and chloride into the SGs and their concentration in the transition area between hard and soft deposits or in the deposits on the tubes.

- The circumferential indications identified in the 2018 outage are due to intergranular stress corrosion cracking under strongly acidic conditions in areas with axial tensile stresses on the outer surface of the tube. Axial tensile stresses are present in the roll expansion transition where the effect of shot peening is largely eliminated due to the roll expansion. Due to this fact, the lower height of deposits in SG20 compared to the other SGs has led to the concentration of corrosive impurities (especially sulphate) in the crevice between the tube and the tube sheet. This also led to increased corrosion of the tube sheet, with an increase of the crevice depth between tube and tube sheet over time. The crevice could reach as far as below the upper rolling edge in some of the affected SG tubes, where the axial tensile stresses are particularly high. In addition, the evaluation of the eddy current data in GKN-2 also points at a slight

denting of the SG tubes by corrosion products of the tube sheet in some SG tubes. This could have induced additional axial tensile stresses in the SG tube.

According to the findings of the RSK Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW), it can meanwhile be assumed that for all SG tubes affected by stress corrosion cracking, the roll expansion close below the upper transition has been exposed.

At the 177th meeting of the RSK Committee on DKW, the licensee and the authorised expert reported on the findings in the steam generators in GKN-2 in the 2019 outage [13]. According to these reports, new insights from the re-evaluation of the already available test results from GKN-2 and from the test results obtained in another German plant were submitted by the plant manufacturer to the plant operator prior to the outage. Within the framework of the re-evaluation of the inspection data from 2018 and in response to WLN 2018/06 "Indications during eddy-current inspections of steam generator tubes", it was shown that a significantly higher detection probability can be achieved with the motorized rotating pancake coil (MRPC) than with the combination of array probe (X-Probe) and bobbin coil, if there is a high interference level in the crevice area between the upper roll expansion and the top of tube sheet. According to the authorised expert, high interference levels are caused in particular by corrosion-related changes in the conditions in the crevice (geometric changes, deposits) between SG tube and tube sheet.

As a result of these new findings, the inspection and evaluation strategy for the upcoming outage was changed. In the 2019 outage, volumetric and circumferential indications were then found in all four steam generators during eddy current testing upon renewed inspections of the SG tubes. Of the tubes with volumetric indications, 20 were plugged, four of them in SG10 and 16 in SG20. Circumferential indications on 191 tubes were detected in all four SGs on the hot leg side, with the majority (147) found in SG20. The evaluations of the eddy current tests showed that about half of the circumferential indications had already been present in 2018 but were not detected during the evaluation in the 2018 outage. Some of the indications found in 2019 were only detected with the MRPC probe, not during the test using the combination of array probe and bobbin coil.

The DKW Committee found it could follow the presentations of the licensees and experts. The findings identified in 2019 are consistent with the damage hypothesis developed in 2018. The detection of the new findings in 2019 is due, on the one hand, to the improved evaluation and the extension of the scope of examination of the SG tubes tested with the MRPC probe and, on the other hand, to a still active corrosive potential in the steam generators of GKN-2. With the various flushing treatments carried out and the elimination of the condenser leakages, it was possible to improve the water chemical conditions in the steam generators, as is shown by the analysis data of the water chemical investigations during the 2018 - 2019 operating cycle and during the 2019 outage. The overall lower number of new indications also proves the effectiveness of these measures. However, it was not possible to remove all corrosive impurities from the crevices and deposits.

The RSK has no further information on the root cause of the described damage. In the following recommendation, it therefore proceeds from the presented damage hypothesis.

4 Safety significance

The SG tubes are components of the reactor coolant pressure boundary. The tubes represent the interface between the primary circuit and the secondary water-steam circuit in a PWR. The heat exchange between the two circuits takes place via these tubes. Due to the different pressure conditions, wall-penetrating damage to individual tubes during power operation leads to the transfer of primary coolant into the water-steam cycle and is thus relevant with regard to safety. In case of any SG tube damage, systems on defence-in-depth level of protection 2 or systems for design basis accident control (defence-in-depth level of protection 3) may be challenged. A simultaneous failure of several SG tubes (> 2A rupture) is not postulated in the design.

SG tubes made of Alloy 800 mod. are used in all German PWR in operation. The occurrence of pitting corrosion/intergranular attack and stress corrosion cracking on these tubes in the roll expansion areas in the tube sheet, between top of tube sheet and first spacer as well as the spacer grids are damage mechanisms that had previously only been postulated under very unfavourable water chemical conditions.

5 Assessment criterion

The safety-related requirements for SG tubes ensue from their functions of heat removal from the primary circuit and as barrier for the confinement of radioactive materials as a component of the reactor coolant pressure boundary. According to the Safety Requirements for Nuclear Power Plants (SiAnf) [14], Section 3.4 (1), the reactor coolant pressure boundary shall be designed, arranged and operated such that the occurrence of rapidly propagating cracks and brittle fractures need not be postulated. SG tube ruptures have to be prevented accordingly. Hence operating modes that could lead to stress corrosion cracking of the SG tubes must be avoided. However, SG tubes are excluded from the requirements of the SiAnf for basis safety (see SiAnf, Section 3.4 (3)) and for components with small nominal diameter (see SiAnf, Interpretation 2, Section 4.1). Otherwise, the general technical requirements according to SiAnf, Section 3.1, apply, especially with regard to complete testability according to Section 3.1 (12).

According to SiAnf, Annex 2, the failure of a SG tube with a leakage rate above the operationally permissible rate up to the maximum SG tube leak cross-section of 2A has to be treated as a design basis accident. In ageing management in accordance with KTA 1403 [15], the SG tubes have to be assigned to group M2, for which preventive maintenance has to be carried out. This is to prevent ageing-related failures due to systematic effects. This also results in the requirement to avoid operating conditions that may lead to stress corrosion cracking of the SG tubes. If there is still degradation of SG tubes, this must be detected in good time by suitable non-destructive testing methods so that a failure of SG tubes need not be postulated until the next inspection. A SG tube leakage that is greater than the operationally permissible leakage is considered to be a failure. In this context, the damage mechanisms affecting SG tubes that are known so far have to be taken into account. Non-destructive testing plays an important role in predicting the integrity of the SG tubes.

6 Results of the discussion

Based on the available findings, the RSK comes to the conclusions described in the following:

In the years 2005 and 2007 [1], crack-like indications due to stress corrosion cracking were detected in older German PWRs. Thereupon the two RSK Statements mentioned above were prepared. The recommendations from the RSK Statements have to be supplemented on the basis of the new state of knowledge.

To ensure the integrity of the SG tubes in the German nuclear power plants with pressurised water reactor, additional precautions have to be taken to ensure compliance with the requirement of SiAnf, Section 3.4 (1), according to which the reactor coolant pressure boundary has to be operated in such a way that the occurrence of rapidly propagating cracks need not to be postulated.

To this end, priority must be given to avoiding operating conditions that could lead to corrosive conditions and thus, with regard to the medium, to the precondition for the occurrence of stress corrosion cracking of the SG tubes. The event in GKN-2 has shown that the previous specifications in the operating rules of the plant, but also the requirements of the VGB Guideline for Water in Nuclear Power Plants with Light Water Reactors R 401 J, were not sufficient in this respect. In case of any prolonged entry of even small amounts of ionic impurities such as sulphates or chlorides, local conditions can arise due to concentration within deposits on the SG tube sheet under which the SG tubes are susceptible to corrosion.

The control parameters for continuous operation defined in the Guideline for Water in Nuclear Power Plants with Light Water Reactors R 401 J of VGB PowerTech do not sufficiently consider such low long-term entry as it may occur, for example, in case of micro leakages from the piping of the main condenser. Corrosive conditions for the SG tubes due to concentration can also occur in particular if the values for the control parameters "sodium" and "conductivity downstream of strongly acidic cation exchanger" in the SG water in the SG blowdown system for continuous operation are still significantly below the action threshold values. By introducing integral control parameters such as "integral conductivity downstream of strongly acidic cation exchanger" or "integral sodium concentration" in SG water for continuous operation, the amount of ionic impurities introduced per operating cycle can be limited. Action levels should be defined, linked to corresponding measures to minimise the integral ionic load of the SGs. These action levels should be determined in the light of recent operating experience.

Corresponding requirements therefore have to be included in the operating rules, taking current knowledge into account. In addition, the VGB Guideline R 401 J (PWR) should be updated accordingly. **[R-1]**

As explained above, condenser leakages may lead to corrosive conditions in the secondary circuit due to the introduction of impurities. Hence, frequent condenser leakages and prolonged operation with condenser leakages should be avoided. The RSK therefore recommends that if condenser leakages are detected, measures for their elimination should be taken at an early stage. Preventive measures against condenser leakages, such as regular inspections and plugging of condenser tubes in areas frequently affected by leakages, should also be taken. **[R-2]**

Hide-out-return analyses can provide information on the accumulation of corrosive impurities in the tube sheet area of the SG. They allow an overview of the contamination of the SG with dissolved impurities. This was already the topic of the two previous RSK Statements [1] and [2]. In continuation of these Statements, the RSK recommends performing hide-out return analyses for trending with respect to the risk of stress corrosion cracking. In addition, the sampling of SG water (drain samples) is useful if SGs are drained for the outage. It should be taken into account that not only intergranular stress corrosion cracking under acidic conditions but also – as shown by the results of laboratory tests [16] – transgranular stress corrosion cracking under alkaline conditions may occur. In case of any abnormalities of the secondary water chemistry, additional data on the input of impurities into the SG as well as on their discharge through SG blowdown has to be recorded and evaluated. In case of any abnormalities with regard to the ion contents determined in HOR analyses or drain samples, calculations of the pH(T) values, i.e. the pH values at operating temperature, also have to be carried out. **[R-3]**

In case of any indications of corrosive conditions affecting the SG tubes, the RSK recommends draining the SG after cooldown and carrying out an appropriate flushing programme in order to neutralise the conditions in the crevices and deposits as far as possible. Water samples have to be taken for analysis in order to monitor the effectiveness of the flushing programme. **[R-4]**

At GKN-2, the input of iron oxide has led to considerable deposits on the SG tube sheet in the area of the flow dead zones. It has to be assumed, among other things due to the results of the hide-out-return analyses, that the impurities introduced as a result of the condenser leakages were able to concentrate in the deposits and lead to pitting corrosion/IGA. Against this background, excessive deposits have to be avoided. If this has nevertheless occurred, deposits on the SG tube sheet should be removed, using appropriate methods. **[R-5]**

In accordance with the requirements of KTA 1403 [15], the damage mechanism of stress corrosion cracking of SG tubes has to be considered in the non-destructive examinations. The concept for in-service inspection has to be suitable to detect such damage in time to be able to predict the integrity of the SG tubes at least for one inspection cycle.

The application of the conventional eddy current technique (bobbin coil) for the tubes as a whole and the additional use of the array probe for the area up to the first spacers correspond to common practice in the plants after 2010. The inspection results from the 2019 outage at GKN-2 have shown that in the area between the upper roll expansion and the top of tube sheet, interference signals may impair the reliable detection of cracks by the array probe, especially when there are corrosion-related changes in the conditions in the crevice between tube sheet and SG tube. Against this background, additional inspections with the motorized rotating pancake coil (MRPC) probe have to be carried out for steam generator tubes where a clear detection of cracks by the array probe is not possible due to existing interference signals. **[R-6]**

Operating experience with axial and circumferential indications on SG tubes made of Alloy 800 mod. that are attributed to intergranular stress corrosion cracking shows different rates of crack propagation. In some cases, “fast propagators” with high crack growth rates have been observed [16]. From the data listed in [16], wall thinning rates of more than 20 % to approx. 40 % per year would be determined, assuming a constant crack growth rate. Due to the limited operational experience and the crack propagation rate which cannot be assumed to be constant, however, the RSK considers it impossible to reliably derive a maximum crack propagation rate

from the data of the non-destructive examinations. In addition, in the case of the damage mechanism of stress corrosion cracking, rapid crack propagation is principally possible.

Against this background, it cannot be ruled out that the damage mechanism of stress corrosion cracking can lead to local through-wall cracks during one operating cycle. To ensure that a local through-wall crack is detected during operation, the RSK recommends the determination of the crack opening areas and the resulting leakages in case of local through-wall cracks below the critical crack length at which a SG tube rupture can no longer be reliably excluded. The operating rules have to contain provisions to ensure that SG tube leakages are detected with certainty before any cracks reach a critical length and that in this case, the plant is shut down immediately. Uncertainties in the determination of the leakage rate also have to be taken into account. **[R-7]**

It can be deduced from the findings in GKN-2 that corrosion occurred on the SG tube sheet prior to the crack indications on the SG tubes. The corrosion of the tube sheet in GKN-2 exposed areas of the SG tubes where tensile stresses were present on the outside of the tube as a result of the deformations during the roll expansion process. Thus, all conditions for stress corrosion cracking prevailed in the hot leg of the affected SG: sufficiently high temperatures, tensile stresses, and a corrosive environment. Therefore, the RSK recommends as one element of the package of measures to prevent damage to the SG tubes by stress corrosion cracking to evaluate the results of the last and of future non-destructive tests of the SG tubes for any changes in the crevice depth between the SG tubes and the tube sheet. This should also include a check for any indications of denting. **[R-8]**

If during in-service inspections of SG tubes in a nuclear power plant with pressurised water reactor any indications are found for the operational damage mechanisms of pitting corrosion, IGA, stress corrosion cracking or tube sheet corrosion, the recommendation is to proceed as follows:

- During the discussions in the RSK's DKW Committee it was explained that corrosion-induced damage such as pitting corrosion and stress corrosion cracking had already occurred in the past in steam generators with secondary water chemistry conditions similar to those of the German PWRs. A description of this can be found e.g. in "Steam Generators for Nuclear Power Plants", 2017 [17]. In retrospect, the volumetric findings in GKN-2 in the 2017 outage can be classified into the pattern of damage caused by corrosion-related damage mechanisms. Against this background, the RSK recommends that if indications for corrosion-induced damage mechanisms are found, it has to be evaluated how the detected indications fit into the known secondary-side corrosion mechanisms affecting SGs.

- In order to clarify the root cause of the damage and to define remedial measures, all information on specific operational conditions of the SG, on the results of mechanical and chemical SG cleaning and on the extent and frequency of condenser leakages has to be compiled. For the purpose of the validation of the damage hypothesis and defining effective remedial measures, it is recommended to compare indication characteristics and the chemical conditions in the areas affected by the findings with those in other plants with proven damage due to pitting corrosion, IGA or stress corrosion cracking. In case of doubt, SG tube sections with linear indications should be cut out for damage analysis. When assessing

the need for pulling SG tube sections, the knowledge of the damage mechanism, the possible damage progression and the possible impacts have to be taken into account.

- In all SGs, the critical sections of the tubes in the potentially affected areas of the SG according to the findings have to be inspected.

- For the SG tubes on which stress corrosion cracking has been detected, the dimensions (length, depth) and the orientation (axial, circumferential) of the defects have to be determined.

- SG tubes affected by stress corrosion cracking have to be plugged. If there is an accumulation of SG tubes with crack findings that can be correlated with corrosion-related changes in the crevice between tube and tube sheet, it should be checked whether additional tubes without crack findings in positions with tube sheet corrosion should be plugged as a preventive measure.

- In the case of circumferentially oriented crack findings, the SG tubes to be plugged additionally have to be stabilised in such a way that subsequent damage is avoided even in the case of a complete rupture.

- Appropriate measures have to be taken to eliminate the corrosive conditions.

- After the first occurrence of such a finding, the inspection has to be repeated during the next refuelling outage.

- If similar findings continue to occur during the recurrent inspection, a new assessment has to be performed. **[R-9]**

  This recommendation updates and replaces the corresponding recommendations from [1].

To enable the RSK to monitor the implementation of the recommendations and the further developments, VGB is requested to give presentations on the following topics in due course

- implementation of WLN [9] in the plants,
- monitoring of the SG condition in the plants,
- development of the VGB Guideline for Water in Nuclear Power Plants with Light Water Reactors.

7 Recommendations

Recommendation 1: Priority must be given to avoid environmental conditions in the water-steam cycle that could lead to stress corrosion cracking of SG tubes. Corresponding requirements therefore have to be included in the operating rules, taking current knowledge into account. In addition, the VGB Guideline VGB R 401 J (PWR) should be updated accordingly.

Recommendation 2: If repeated condenser leakages occur in a system, it is recommended that, in addition to the early elimination of leakages, preventive measures against condenser leakages should be taken to avoid long-term deviations of the water chemistry from the normal operating values. This includes periodic inspections and preventive plugging of condenser tubes in areas frequently affected by leakages.

Recommendation 3: Hide-out-return analyses are recommended for trending with respect to the risk of stress corrosion cracking. In addition, the sampling of SG water (drain samples) is useful if SGs are drained for the outage. These samples provide a general overview of the contamination of SGs by dissolved impurities. In case of plant-specific abnormalities of the secondary water chemistry, additional data on the input of impurities into the SG as well as on their discharge through SG blowdown has to be recorded and evaluated. In case of any abnormalities with regard to the ion contents determined in HOR analyses or drain samples, calculations of the pH(T) values, i.e. the pH values at operating temperature, also have to be carried out.

Recommendation 4: If there are any indications that the SG tubes are at risk from secondary-side corrosion mechanisms, in particular stress corrosion cracking, it is recommended to drain the SG after cooldown and to carry out an appropriate flushing programme in order to neutralise the conditions in the crevices and deposits as far as possible. Water samples have to be taken for analysis to monitor the effectiveness of the flushing programme.

Recommendation 5: Excessive deposits have to be avoided. An appropriate method has to be chosen to remove deposits on the tube sheet.

Recommendation 6: When inspecting steam generator tubes where interference signals may impair the reliable detection of cracks in the crevice area between SG tube and tube sheet by the array probe, additional inspections with the motorized rotating pancake coil (MRPC) probe have to be carried out in the crevice area.

Recommendation 7: In order to ensure that a local through-wall crack is detected during operation, it is recommended to determine the crack opening areas and the resulting leakages in case of local through-wall cracks below the critical crack length. The operating rules have to contain provisions to ensure that SG tube leakages are detected with certainty before any cracks reach a critical length and that in this case, the plant is shut down immediately. Here, uncertainties in the determination of the leakage rate also have to be taken into account.

Recommendation 8: For early detection of corrosive conditions in the SGs, the results of the last and of future non-destructive tests of the SG tubes have to be evaluated for any changes in the crevice depth between the SG tubes and tube sheet and also with regard to denting.

Recommendation 9: If during in-service inspections of SG tubes in a nuclear power plant with pressurised water reactor any indications are found for the operational damage mechanisms of pitting corrosion, intergranular attack (IGA), stress corrosion cracking or tube sheet corrosion, it is recommended to proceed as follows:

a) It has to be evaluated how the detected indications fit into the known secondary-side corrosion mechanisms affecting SGs.

b) In order to clarify the root cause of the damage and to define remedial measures, all information on specific operational conditions of the SG, on the results of mechanical and chemical SG cleaning and on the extent and frequency of condenser leakages has to be compiled. For the purpose of the validation of the damage hypothesis and defining effective remedial measures, it is recommended to compare indication characteristics and the chemical conditions in the areas affected by the findings with those in other plants with proven damage due to pitting corrosion, IGA or stress corrosion cracking. In case of doubt, SG tube sections with linear indications should be pulled for damage analysis. When assessing the need for pulling SG tube sections, the knowledge of the damage mechanism, the possible damage progression and the possible impacts have to be taken into account.

c) In all SGs, the critical sections of the tubes in the potentially affected areas of the SG according to the findings have to be inspected.

d) For the SG tubes on which stress corrosion cracking has been detected, the dimensions (length, depth) and the orientation (axial, circumferential) of the defects have to be determined.

e) SG tubes affected by stress corrosion cracking have to be plugged. If there is an accumulation of SG tubes with crack findings that can be correlated with corrosion-related changes in the crevice between tube and tube sheet, it should be checked whether additional tubes without crack findings in positions with tube sheet corrosion should be plugged as a preventive measure.

f) In the case of circumferentially oriented crack findings, the SG tubes to be plugged additionally have to be stabilised in such a way that subsequent damage is avoided even in the case of a complete rupture.

g) Appropriate measures have to be taken to eliminate the corrosive conditions.

h) After the first occurrence of such a finding, the inspection has to be repeated during the next refuelling outage.

i) If similar findings continue to occur during the recurrent inspection, a new assessment has to be performed.

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