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Recommendations Following the Discovery of Intergranular Stress Corrosion Cracks on some French Pressurized Water Reactors

November 2023

1. Summary

The discovery of some intergranular stress corrosion cracks (IGSCC) on some non-isolable pipes of the main primary system of French pressurized water reactors (PWR) in December 2021 led to a large scale inspection programme on all French PWRs, considering the potential impact of those cracks on safety of the reactors.

In the frame of this inspection programme, more than 60 IGSCC cracks above 2mm in depth have been discovered on the welds of the emergency core cooling and the residual heat removal systems. It is important to point out that this mode of degradation was not expected on the welds PWR piping that is made of wrought austenitic stainless steel with a low carbon content.

The understanding of the root causes of IGSCC on these welds is still ongoing. However, the results of the inspections in France show that some auxiliary piping of the main primary system of the reactors are more susceptible than others. According to the current studies, the design of the pipes and the loads resulting from the variation of the water temperature are factors that could affect a pipe susceptibility to IGSCC.

In addition, inspections showed that the welds of auxiliary pipes that had been repaired during the construction of a plant may present the risk of being affected by large IGSCC cracks. The susceptibility of these repaired welds does not seem to be related to the susceptibility of the pipes: it is probably due to the higher level of residual stress and hardening induced by weld repairs. Consequently, a specific inspection programme has been implemented on French PWRs on the welds of the auxiliary pipes of the main primary systems that had been repaired according to the manufacturing reports.

These findings led WENRA to issue the recommendations that are presented in part 1 of this report. Part 2 presents further details on the IGCSC cracks discovered in France, and part 3 a concise background regarding international experience regarding IGSCC on light water reactors.

The recommendations in this paper only deal with IGSCC potentially affecting austenitic stainless steel welds in non-isolable sections of the primary systems of PWRs. Other related issues, such as IGSCC on nickel-base alloys components in PWRs, or transgranular SCC on chloride contaminated materials, etc. may provide relevant feedback, but are not in the scope of these recommendations.

2. Recommendations to WENRA members and good practices regarding the risk of IGSCC on stainless steel piping of PWRs

2.1. Inspections to be performed on PWR stainless steel welds.

It is recommended to WENRA members that the inspection programme of stainless steel welds of the non-isolable parts of the primary circuit takes into account the risk of IGSCC, and is performed in accordance. The methods used for these inspections shall follow recommendations given in 2.3.

Any sampling inspection programme shall target the welds that represent the most important risk of IGSCC development considering environment, material, and potential tensile stresses (due to fabrication and operating conditions).

When weld repairs can be identified by manufacturing records, the higher risk of IGSCC development that of these welds can present needs to be considered.

The use of different samples from one inspection interval to another, as well as fixed welds that are inspected at given inspection intervals, is a good practice especially in the context of the long term operation of a reactor.

2.2. Monitoring of the parameters that may influence the development of IGSCC

It is recommended to monitor the parameters influencing the development of IGSCC at the appropriate locations.

The monitoring of oxygen concentration is recommended in order to control the risk of IGSCC. The control of chemistry shall ensure that samples are taken at representative locations, taking into account stagnant water conditions that may disturb water chemistry control. It shall also consider all relevant operating conditions including power production, shutdown and outage conditions.

The monitoring of water temperature in the piping is also recommended as higher temperature areas can lead to a higher risk of IGSCC, and loads resulting from thermal gradients can lead to high tensile stresses and can be a cause of IGSCC or thermal fatigue cracks. The monitoring programme shall take into account horizontal sections of piping that present a risk of stratification.

The results of this monitoring shall be taken into account in the definition of the inspection programs and the definition of the operating conditions of the plants.

2.3. NDT methodology recommended for the detection of IGSCC

Qualified UT inspections methodologies and qualified testing staff operators, according to applicable codes and standards, are recommended for the detection and sizing of IGSCC. Considering the locations where IGSCC is susceptible to occur, the use of UT methods that are qualified for both the detection of IGSCC and fatigue cracks is particularly appropriate.

Qualification procedures shall take into account the different configurations of welds to be inspected and the challenges inherent to austenitic stainless steel inspections such as weld and piping geometry, counterbore, or weld metal microstructure.

Detectable flaw size shall be in accordance with the allowable flaw size in the piping according to the applicable codes and standards.

The use of real IGSCC cracks along notched sample during the qualification can be a good practice. Grinding of the outer surface of the weld can also facilitate examination.

The use of automated UT methods with the recording of inspection data is also a good practice.

2.4. Repairs and mitigations on IGSCC susceptible or affected welds

It is recommended to WENRA members to only use qualified mitigation or repair methods, recommendations given in 2.5 being applicable for these repairs

If the size of a detected IGSCC flaw implies a repair according to applicable flaw acceptance criteria, it is recommended to focus on the limitation of welding residual stresses while performing these repairs.

Regarding measured flaws that meet the applicable flaw acceptance criteria, the high uncertainties regarding IGSCC cracks growth rate shall be taken into account when studying the possibility to differ the repair, considering all the relevant parameters that may influence this growth rate.

References incorporated in part 4 may provide guidance on some mitigation methods that can be used on IGSCC susceptible welds. They refer to mitigations such as water chemistry control, material selection, stress improvement processes, overlays, welding methods or grinding.

2.5. Recommendations regarding the design and manufacturing of stainless steel piping on new PWRs.

Considering the recent discovery of IGSCC on a large scale on French PWRs, it is recommended that the risk of IGSCC on stainless steel piping shall be considered during the design and manufacturing of both BWRs and PWRs.

In particular, the following measures are recommended:

[1] Stainless steel types being more resistant to IGSCC shall be used, such as low carbon or stabilized stainless steel;
[2] Water chemistry control, including locations susceptible to have stagnant water conditions, shall be taken into account during the design;

[3] The design of piping shall limit loads resulting from thermal gradients (including thermal stratification), and any type of load that can result in a higher probability of IGSCC initiation. In the design of auxiliary piping, the number of welds, and the length of the piping up to the isolation valves, shall be limited;

[4] The elaboration of materials shall limit the amount of permanent deformation and hardening;

[5] Welding procedures and sequences shall be determined in order to limit the residual stresses and hardening at the inside surface of the wall;

[6] Welding repairs shall be minimized. When performed, welding repairs shall be done using qualified methods with focus on the limitation of residual stresses and deformation at the inside surface;

[7] All welding parameters, including welding repairs, shall be recorded during the manufacturing and records shall be kept by the licensee during all the operation of the plant;

[8] If applied, mitigations methods such as stress improvement or weld grinding shall be qualified to ensure adequate limitation of IGSCC initiation;

[9] Design shall take into account the ability to inspect welds using UT methods qualified for the detection of IGSCC, considering for example external surface preparation. Conducting pre-service measurements on some welds before the start of operation using qualified methods, to serve as a reference for later inspections, is a good practice.

3. Background in France

3.1. Findings

An intergranular stress corrosion crack (IGSCC)[1] was discovered in France on October 21st, 2021, during the ten-yearly inspection of reactor 1 of Civaux plant[2]. It was found on a weld of a 12” emergency core cooling system (ECCS) pipe, on the non-isolable part of this pipe.

The crack was extended along the whole length of the weld (360°) and its maximum depth was measured at 5.6 mm, after the removal of the weld for destructive analysis.

It was detected during the non-destructive tests that were performed as part of the standard inspection programme for this plant, originally dedicated for the detection of thermal fatigue cracks. The inspection method used was standard mono-element UT (ultrasonic testing), qualified for this type of defects.

A similar IGSCC crack, of smaller depth, was later found on the same reactor on a weld of the non-isolable part of the residual heat removal system (RHRS).

Figures 1 and 2 below show the typical location of the cracks that were found.

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[1] It was initially considered as a thermal fatigue crack, and characterized as a IGSCC crack in December 2021 after metallurgical analysis.
[2] Which is a 1450 MW pressurized water reactor (PWR).

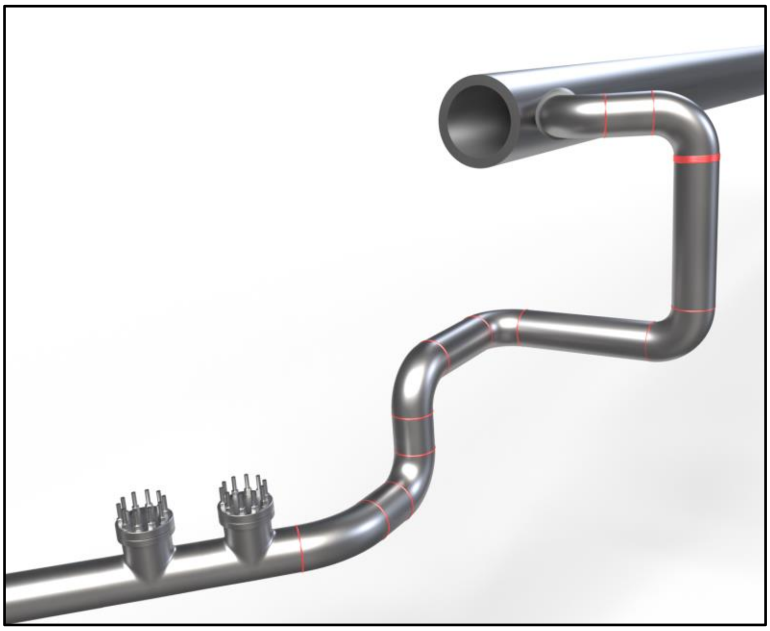

Figure 1: illustration of typical geometry of a non-isolable part of an auxiliary pipe of the main-primary system on a French pressurized water reactor. The welds that are susceptible to be affected are outlined in red.

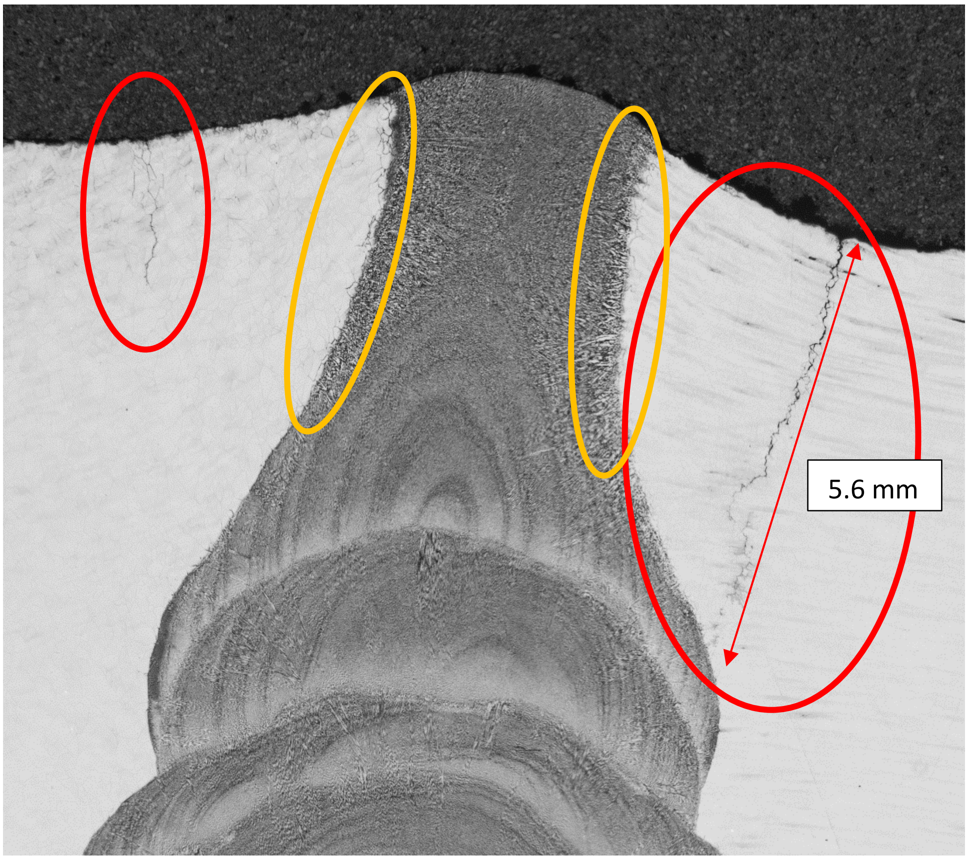

Figure 2: typical location of IGSCC cracks in the thermally affected area of a weld (cracks discovered on Civaux 1 reactor in 2021)

The extension of the inspections that followed those discoveries, further described in 3.3 below, led to the discovery of more cracks on ECCS and RHRS systems in French reactors.

3.2. Potential safety impact and definition of a dedicated inspection programme

The detected cracks were located on some non-isolable part of the main primary system, on auxiliary lines of the ECCS and RHRS systems whose diameter are mainly 10" or 12" in French reactors. The failure of these pipes would result in a loss of coolant accident that could impact the core cooling, especially in case of a failure of an ECCS pipe.

The safety demonstrations for French reactors cover the break of one auxiliary pipe of the main primary circuit. However, in reaction to the findings, ASN required the licensee to perform additional safety analyses in order to demonstrate that the core cooling could be maintained in the case of a simultaneous break of two ECCS pipes.

In addition, fracture mechanics calculations were conducted using RSE-M code criteria[3], in order to demonstrate the critical depth of an IGSCC crack, considering all possible loadings on an auxiliary pipe (in normal, accidental or faulted conditions). These calculations showed that the typical depth of an axisymetrical critical defect, on 10 to 12” auxiliary pipes, was around 5 mm.

Considering the fact that those additional safety analyses were not available at the end of 2021, and that the licensee lacked access to a non-destructive testing method that allowed the sizing of IGSCC cracks at this time, the 4 French 1450 MWe reactors were shutdown to allow a rapid extension of the inspections of the welds of the ECCS and RHRS systems of these reactors. The inspection method used was still the standard mono-element UT testing dedicated to the identification of thermal fatigue cracks which detected the first IGSCC crack.

Additional safety analyses became available in 2022. They demonstrated that French reactors could withstand the break of two ECCS lines while still maintaining the core cooling. In parallel, the licensee also developed a UT inspection method that allowed the detection and sizing of the IGSCC cracks.

Following that, ASN considered acceptable to deploy, from mid-2022, a prioritized inspection programme, to be carried out during the normal shutdown periods of all French reactors, focusing on large diameter auxiliary pipes that were considered the most susceptible to IGSCC following the first findings.

French regulations require the repair of flaws detected on the non-isolable parts of the main primary system. Accordingly, the repair of welds showing some IGSCC indications would be required. French regulations also require the immediate repair of cracks that would present the risk to be unstable under some operating conditions (following the fracture mechanics assessment conducted under the RSE-M)[4]. Those repairs were conducted by the licensee by replacing the affected parts of the pipe by new ones. They were also the opportunity to perform destructive examination of the cracks detected, to analyse the performance of the UT methods deployed for crack sizing and detection.

3.3. Description of the findings of 2021-2023 inspection programme

The inspection programme initiated after the discovery of IGSCC cracks will continue at least until 2025.

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[3] RSE-M (“Règles de Surveillance en Exploitation des Matériels Mécaniques des Ilots Nucléaires REP ») is the French code applicable for in service inspection of PWR pressure vessels and piping.

[4] The growth rate of an IGSCC crack needs to be taken into account when studying the capacity of differing a repair. Current experience in France shows that it is difficult to reliably estimate the crack growth rate as it is necessary to take into account several parameters such as the intensity of residual stresses, material hardening, water temperature and chemical condition, etc.

It will include the control of a sample of welds of the non-isolable parts of all the ECCS and RHRS systems pipes above 8” in diameter of the French PWRs in operation, in locations where the operating temperature is considered to be above 140 °C. The sampling is based on an assessment of each pipe susceptibility to IGSCC, as described in 1.5, the pipes that are considered the most susceptible being subject to a higher sampling. An extension of the sampling is required in case an IGSCC crack is found during an inspection.

Around 500 welds were inspected on these systems between the end of 2021 and June 2023, either by destructive testing (around 200 welds were removed and examined in laboratory during this period) or by using the new UT testing method developed by the licensee for IGSCC detection and sizing (see below).

IGSCC cracks were found on several pipes of the ECCS and RHRS systems of the French PWRs, with different type of reactors, systems, and susceptibility. A distribution of the measured size of the cracks is given in figure 3 below, for the cracks examined in laboratory after UT testing.

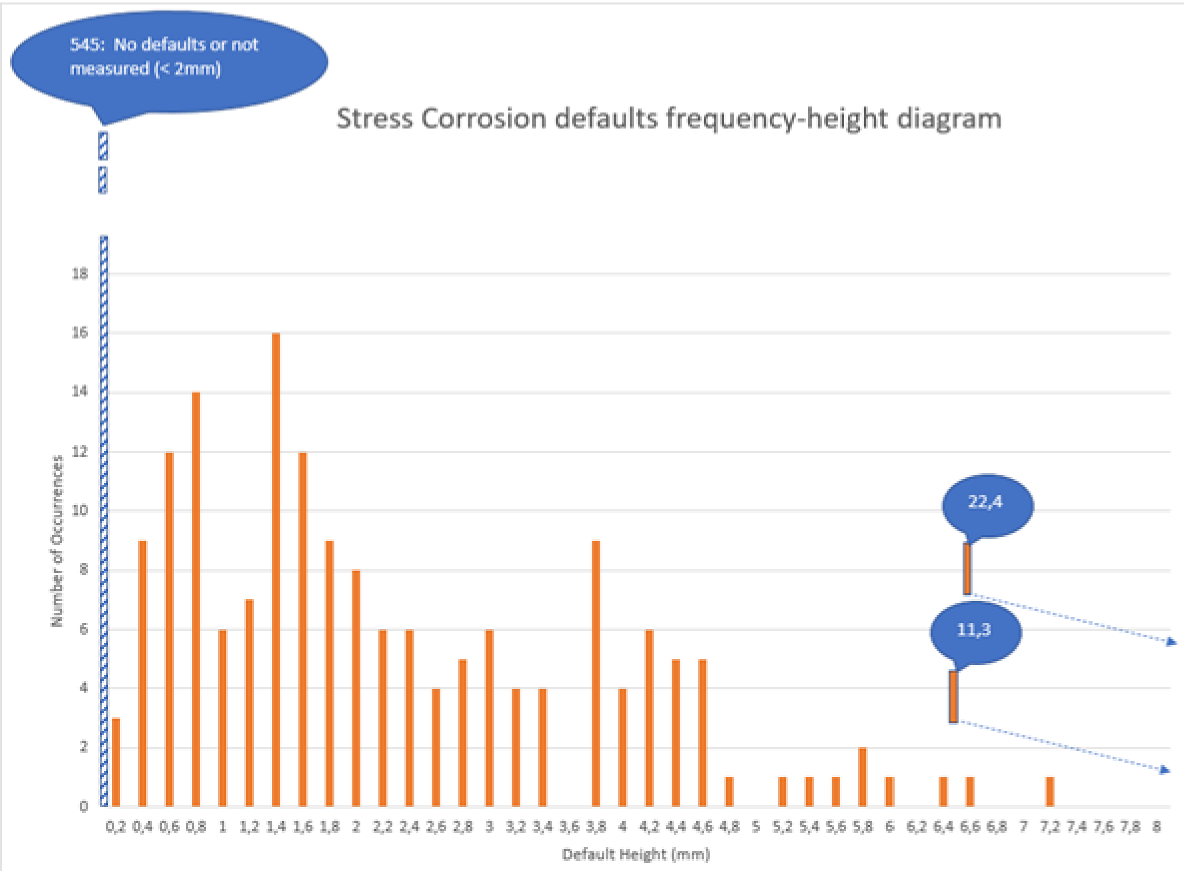

Figure 3: Distribution of IGSCC cracks depth (in mm) on ECCS and RHRS welds examined between the end of 2021 and the beginning of 2023, from licensee EDF

All the affected pipes are in 304L or 316L steel[5]. According to the manufacturing reports, various types of welding methods were used on the welds with IGSSC cracks, such as automated or tungsten inert gas welding (TIG), shielded metal arc welding (SMAW), or flux welding. On some welds, a combination of these methods were also used.

[5] Austenitic wrought stainless steel with low carbon content.

3.4. Large IGSCC cracks found on welds that were repaired at the manufacturing stage

In addition to the distribution in figure 3 showing that most of the depth of the cracks are between 0 and 6 mm[6], notable findings occurred in the beginning of 2023, when two particular cracks were discovered:

- An IGSCC crack was found on Penly 1 reactor, on a weld of a pipe of the ECCS system, limited in extension (around 150 mm which is roughly a quarter of the length of the weld) but with a very important depth (23 mm, the thickness of the pipe wall being around 25 mm). The maximum depth of this crack was not typical of the distribution observed before. The current understanding is that this weld having been repaired twice during the manufacturing stage of the reactor, at the exact same location where the crack was observed, was a contributing factor to the crack initiation and growing. Indeed, weld repairs modify the distribution and intensity of residual stress, and increase material hardening in the inner surface of the pipe.
- A 12 mm deep fatigue crack, approximately 60 mm long, was found on a weld of a pipe of the ECCS system of Penly 2 reactor. Although this line was considered to be susceptible to IGSCC, this discovery showed that fatigue cracks of important depth could also occur on these lines. This weld had also been repaired at the manufacturing stage. Thermal fatigue was not expected on this weld. This finding may question the current understanding of thermohydraulics in the main primary system auxiliary piping, and identification of areas susceptible to thermal fatigue.

[6] Pipe thickness is approximately 25mm on the pipes that were subject to the inspection program.

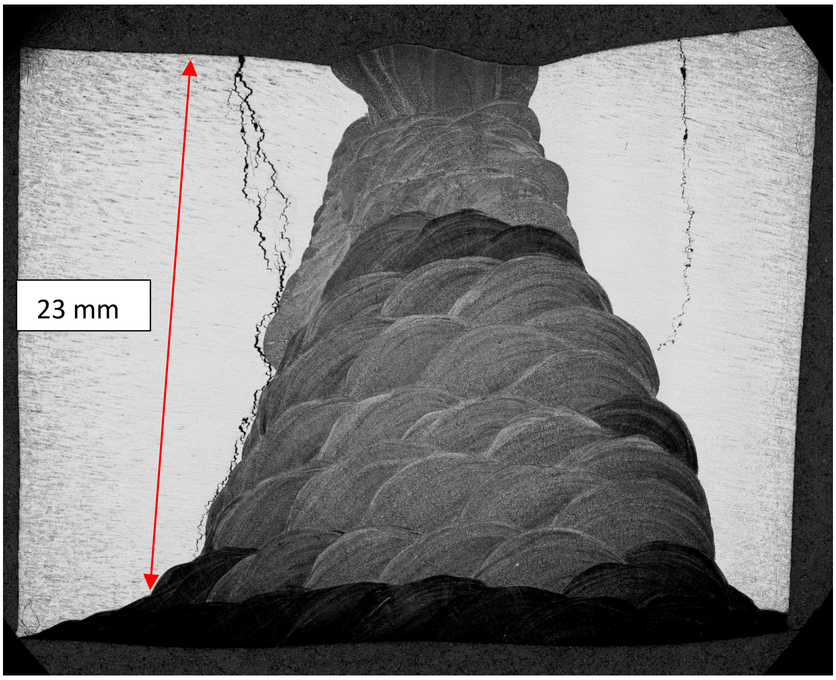

Figure 4: 23 mm deep IGSCC crack discovered on a weld of Penly reactor safety injection system, on a part of the weld that had been repaired during the manufacturing.

Current findings also show, on a limited number of cases, the occurrence of fatigue and IGSCC cracks on a same auxiliary pipe, and sometimes on the same weld showing mixed fatigue-IGSCC behaviour.

The inspection programme described in 3.2 and 3.3 was therefore completed by the scheduling of the inspection of all the welds of ECCS and RHRS systems above 8” in diameter that had been repaired according to the manufacturing reports.

3.5. Current understanding of the phenomenon

Three conditions are necessary and must be present simultaneously for IGSCC cracks to occur[7] :

- A susceptible material;
- A tensile stress;
- A favourable environment.

The material of the systems that are concerned in France is type stainless steel, either AISI 304L or AISI 316L. This material was known to present a susceptibility to IGSCC, but the cases previously encountered in PWRs were considered very specific (occurrences were typically limited to highly cold

[7] See for example Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned, IAEA Nuclear Energy Series, No. NP-T-3.13.

worked materials), and IGSCC was not considered as a potential degradation mode on the welds of the non-isolable parts of the auxiliary pipes of the main primary system.

No chemical pollution was identified on the material of the welds that were examined, nor in their environment.

Important research has been conducted by the licensee, and is still ongoing, regarding the stresses affecting the welds. Part of these stresses are the welding residual stresses that can result in axial tensile stress in the inner surface of the piping. Some studies are ongoing, using weld mock-ups and numerical simulations, showing the level of residual stresses that can be expected depending on the welding procedure and the welding parameters (such as the intensity, the number of beads…). This programme was also extended in order to reach a better understanding of the influence of welding repairs on residual stresses. However, the results of the current studies does not allow yet a reliable discrimination of welds that would be more sensible to IGSCC when considering only the manufacturing reports. Variations on the welding parameters resulting from the operator input must also be taken into account.

Studies on the pipes with the highest number of IGSCC cracks also showed that their geometry is very specific and allow the thermal stratification phenomenon to occur, as illustrated in figure 5 below. The additional stress in operation resulting from thermal stratification could explain the higher susceptibility of some particular pipe design to IGSCC or fatigue cracks.

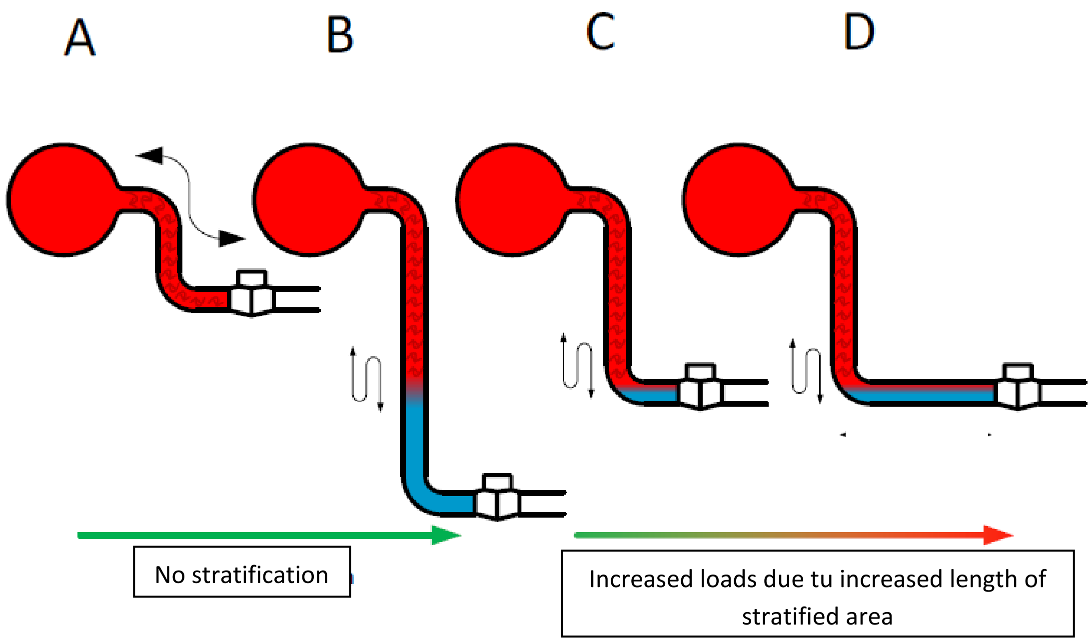

Figure 5: illustration from EDF showing the effect of an auxiliary pipe design on thermal stratification. The water circulation within the main primary pipes generates a vortex that penetrates into the

auxiliary pipe. The water in the auxiliary pipe is therefore at the same temperature as the main primary pipes in the length that is penetrated by the vortex. If the vortex ends up in a horizontal part of the pipe, there is a superposition of a cold and a hot water layers inducing a bending stress.

Regarding the environment, investigations are still ongoing for the oxygen concentration in the auxiliary systems of the primary circuit. This concentration is not expected to be at the same level on PWRs, compared to boiling water reactors that present an environment more favourable to IGSCC initiation. However, the purpose of these investigations is to assess whether an unexpected oxygen concentration can be found and could increase the risk of IGSCC in these lines.

The current understanding is therefore that the welds that have been repaired during manufacturing can be more susceptible to IGSCC, but the precise way the repairs affect the sensibility is still being studied. Moreover, some systems of the main primary system present a higher susceptibility to IGSCC: this sensibility is currently understood by the French licensee as the result of stresses generated by a thermal stratification due to the piping designs.

3.6. UT examination methodology, past and current

Previous UT testing of the welds of the ECCS and RHRS systems was performed by EDF using a standard UT examination procedure, with mono-element UT, using transversal waves at 2.25 MHz and 5 MHz, and various orientations (mainly 45° and 60°).

This process had been qualified in France for the detection of fatigue cracks, which are expected to show a better UT response than IGSCC cracks because of their shape. It was found in 2021 that this process could allow the detection of IGSCC cracks in some cases, but was not reliable for the detection of all IGSCC cracks. Furthermore, this process was not able to measure the depth of the cracks, and did not allow the recording of the UT signal, for later analysis or comparison.

A tentative improvement of this “historic” UT methodology, mainly based on an evolution of the detection threshold, was later considered non-relevant, as it was leading to a very important number of false positive results.

The current UT testing methodology that is used since the middle of 2022 by the licensee was developed by EDF and is based on a multi-element UT methodology. The process is using a 32 elements UT probe mounted on a circular rail that is clamped around the weld. A measurement is taken all along the weld circumference with 4 MHz and 2 MHz UT waves, the position of the probe being recorded through a coding wheel.

Measurements are taken at three different offsets from the centre of the weld position, on both sides of the weld and the UT signal is recorded. The analysis is conducted in office by separate teams, using imagery reconstructed using the Total Focusing Method. This process allows the detection of cracks that are above 2 mm in depth and 20 mm length, by comparing the location of the echo reflected by the root of the crack to the location of the diffraction echo originating from the tip of the crack.

This process is still under qualification by the licensee, but it was tested on a sample of around 140 welds, 60 of them affected by IGSCC cracks that were measured by destructive analysis and by the UT process. All cracks above 2 mm in depth were detected, and a good precision was achieved for the sizing of the cracks (+/-1.1 mm).

4. Brief summary of the international experience regarding IGSCC

4.1. IGSCC on BWRs stainless steel piping

There is a large international operating experience on IGSCC affecting stainless steel pipes of the boiling water reactors. A significant number of IGSCC cracks were discovered on the piping on these reactors, starting from the mid-1970s. At first, they were mainly attributed to the sensitization of stainless steel, but later on IGSCC cracks were discovered on cold worked areas of low carbon type stainless steel. These cracks affected piping of various diameter, large diameter recirculation pipes being also concerned.

These discoveries led to a high amount of studies and researches, and various corrective actions were undertaken to limit the risk of IGSCC occurrence on these types of reactors, such as water chemistry control, materials improvement, and specific mitigation techniques.

These evolutions allowed the reduction of the occurrence of IGSCC cracks on BWRs piping, even though some unpredicted IGSCC cracks could still occur.

References such as [1], [3] and [4] provide with more details on this operating experience, and the way IGSCC was dealt with by nuclear regulation authorities and licensees for BWRs.

4.2. IGSCC on PWRs stainless steel piping.

There is less international operating experience on the occurrence of IGSCC on stainless steel piping of pressurized water reactors, the chemistry of the water of the reactor coolant for those reactors being less favourable to IGSCC initiation.

Indeed, IGSCC occurrences in PWRs were initially limited to components made of materials such as nickel-base alloy 600 of steam generator tubes or of dissimilar metal welds. As stated in [1], stainless steel piping had a very good record on PWRs with IGSCC occurrences being limited to cases linked with external chloride contamination, or oxygen concentration in some occluded conditions (see for example [2]).

However, more recent discoveries were made, that showed the possible initiation of IGSCC cracks on non-occluded conditions. These cases remained rare, and were always related to an important hardening of the stainless steel resulting from the manufacturing. Two notable cases are the discovery of a through-wall crack on an elbow of an auxiliary pipe in Daya Bay power plant (2011), which was related to an important hardening resulting from the cold bending of the elbow, and the discovery of a crack next to a weld of the pressurizer spray line in Ohi-3 power plant (Japan, 2020) that was related to a high hardening along the weld boundary near the inner surface of the pipe, resulting from a high heat input during the welding and the effect of the rigidity of the pipe on the nozzle-elbow side.

Those cases remained limited, and therefore, a large scale occurrence of IGSCC on the welds of stainless steel piping in PWRs was not expected, until the first discoveries on 2021 on the French PWR fleet.

Following the discoveries in France, several countries conducted additional investigations on their PWR fleet. Without listing all the actions that were conducted, it can be cited that countries such as UK, Switzerland, or Spain conducted additional controls on their reactors fleet, targeting locations similar to the ones affected in France. At the moment, no findings similar to French findings (SCC cracks affecting stainless steel piping of some PWRs primary circuits on a large extent) were discovered in other countries.

4.3. NDT methods used for inspection of stainless steel piping in PWRs

International operating experience shows that UT of stainless steel piping is an adequate method for the detection and sizing of IGSCC cracks. In particular, various UT methods are used worldwide as part of the inspection programme of the primary system auxiliary pipes and can be appropriate for the detection of IGSCC cracks, even though those inspection programmes were mostly developed to address the risk of thermal fatigue cracks.

The inspection of austenitic stainless steel welds still remains a challenge using UT methods, for the following reasons:

- Large grains in the welds micro-structure make the examinations challenging, and single-sided examinations are therefore not recommended as they may not fulfil the codes and standards requirements for the inspection of both sides of the weld on base metal ;
- Weld crowns and outside pipe geometries may restrict access and not permit proper probe coupling ;
- The internal geometry and the presence of counterbore may mask some flaw indications ;
- In some cases, IGSCC cracks may show a smaller UT response than thermal fatigue cracks or machined notches.

UT methods used worldwide for the inspection of these welds are either mono-element UT, or phased array technologies. The inspections are either conducted manually or mechanically and several methods used allow the recording of the UT signal.

Operating experience therefore shows that UT methods are available to detect IGSCC cracks and there has been improvements regarding the availability of mechanized techniques that could be more reliable and allow UT signal record and re-analysis. However, the challenges exposed above still require thorough qualifications of UT methods and operators to provide with reliable detection of small IGSCC cracks in the various conditions that can be encountered.

Moreover, operating experience suggest that radiographic testing (RT) is less reliable for the detection of small IGSCC cracks.

4.4. Repairs and mitigations

The large operating experience of IGSCC cracks on BWRs led to important research and development of mitigations methods. Some of these methods have been largely used internationally with good results, reducing the risk of occurrence of IGSCC on stainless steel piping [1], [2].

In particular, the US NRC NUREG-0313 [3] listed the following mitigation methods that were recognized adequate to reduce the risk of IGSCC:

- Water chemistry control (hydrogen addition to reduce the oxygen concentration);
- Material improvements: the use of low carbon wrought austenitic stainless steel such are 304L, 304NG, 316L, 316NG, 347NG, to reduce the effect of the sensitization[8];
- Stress improvement: methods such as Induction Heating Stress Improvement (IHSI) or Mechanical Stress Improvement Process (MSIP) are used to impose some compressive residual stress on the inside surface of the weld;
- Solution heat treatment;
- Heat sink welding: a method of butt-welding pipes or fittings in which the major portion of the weld is produced with cooling water inside the pipe[9];
- Weld overlay which is the addition of weld metal over the original weld to improve the mechanical resistance and add compressive stress on an existing IGSCC crack.

Some of these methods were widely used in BWRs, such as heat sink welding and IHSI in Japan, MSIP in the US, Spain, etc., or weld overlays.

However, regarding the material improvement, the experience in Japan showed that stainless steel welds in low carbon stainless steel piping could still develop IGSCC in BWR operating conditions. French PWRs auxiliary pipes in 316L type steel also developed IGSCC as discussed above. Therefore, the use of low carbon stainless steel may not represent the only necessary mitigation and must be considered alongside other design or mitigation methods.

[8] The use of stabilized stainless steel, such as NB-stabilized stainless steel on German BWRs, has also been recommended in some countries.

[9] This method reduces the sensitization caused by the welding process and generates a temperature gradient through the pipe wall that can reduce the tensile residual stresses on the inside surface of the wall.

There is less international feedback on mitigations methods for IGSCC in PWRs stainless steel piping, as current experience is mostly limited to the IGSCC on nickel-base alloys and dissimilar metal welds.

In the USA, the predominant methods to mitigate and repair susceptible welds and PWRs have been weld overlays and MSIP. Some industry guidance was also incorporated into the ASME code through Section XI Code Case N-770. This code case includes the following mitigation techniques, which are for the most part derived from techniques that were already endorsed by NUREG-0313:

- Weld overlay, with two types of overlay considered, full structural weld overlay being designed so that the weld reinforcement is capable of supporting the design loads, without consideration of the piping, component, or associated weld beneath the weld reinforcement, while optimized weld overlay allows the consideration of the outer 25% of the wall thickness of the piping, component, or associated weld beneath the weld reinforcement in the design ;
- Stress improvement methods, including peening (a process that produces benefic stress conditions on a sensible surface through the application of a compressive layer) ;
- Inlay: the application of a corrosion resistant barrier applied on the inside surface, after excavation of some portion of the weld ;
- Onlay: the same as an inlay but without requiring excavation
- Weld repairs that, in the case of allay 82/182 welds, consists in the excavation of part of the weld metal, followed by weld deposit with Alloy 52/152 to restore full pipe thickness.

As exposed above, this code case was written in the context of the IGSCC on 82/182 alloys, but these methods may be of useful reference in the context of IGSCC in PWR stainless steel piping. A description of the PWSCC inspection and mitigation history in the USA can be found in NUREG/CR-7187.

References [8], [9], [10], [11] and [12] deal with the application of some of these methods in Japanese plants, as well as the grinding of the welds inner surface, which can also have an effect on the residual stresses that limit the risk of IGSCC initiation. Grinding can also eliminate small geometrical defects on the surface that may be favorable IGSCC initiation sites. The grinding must however be applied with care and after qualification, as improper grinding may have a detrimental effect on SCC initiation.

5. References

[1] Stress corrosion cracking in light water reactors: good practices and lessons learned. Vienna: International Atomic Energy Agency, 2011.p.; (IAEA nuclear energy series, ISSN 1995–7807; no. NP-T-3.13)

[2] NRC Information notice 2011-04: Contaminants and stagnant conditions affecting stress corrosion cracking in stainless steel piping in pressurised water reactors

[3] Hazelton, W., and Koo, W., "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," NUREG-0313 Revision 2, January 1992, ADAMS Accession number ML031470422

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