AUTORITÉ DE SÛRETÉ NUCLÉAIRE

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STRESS CORROSION CRACKING IN FRENCH REACTORS

NRC PUBLIC MEETING ON PIPING STRESS CORROSION CRACKING EXPERIENCE

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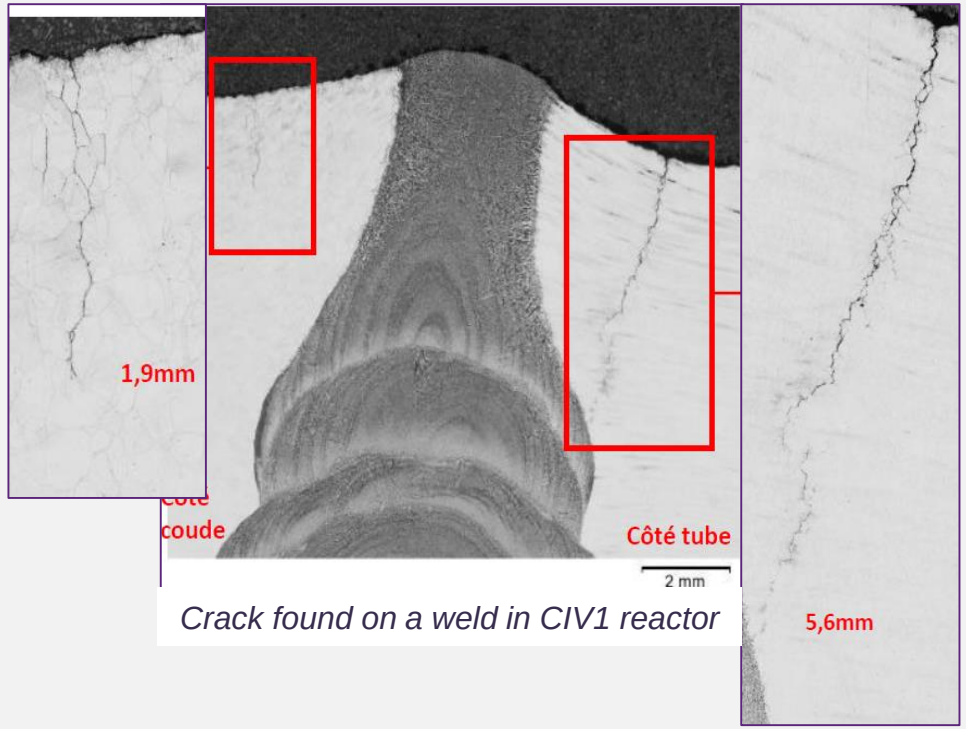
CONTENTS

1. **FINDINGS BETWEEN SINCE 2021**
2. UNDERSTANDING OF THE PHENOMENON
3. CURRENT INSPECTION PROGRAMME AND PERSPECTIVES FOR 2024-2026
4. RECOMMENDATIONS FOR THE DESIGN OF NEW PARTS OR NEW NUCLEAR REACTORS

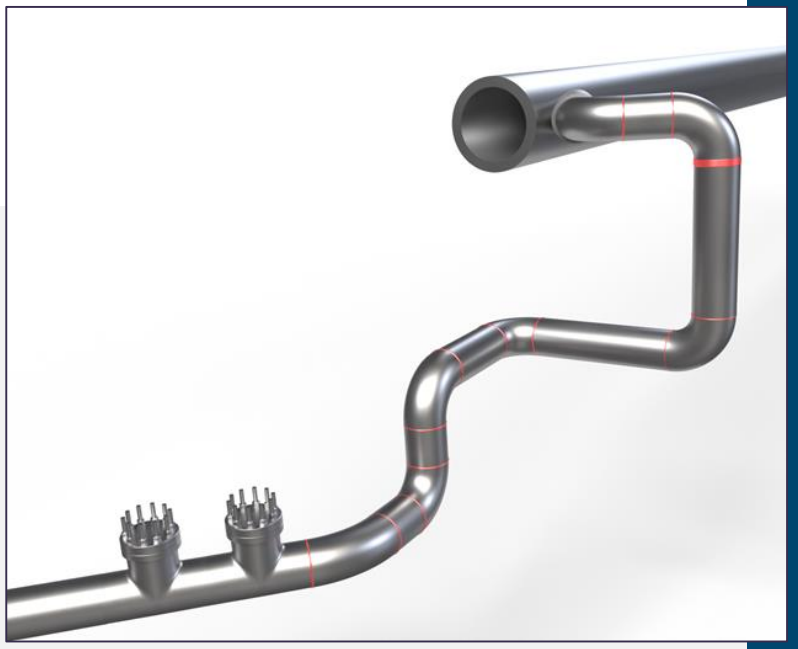
BRIEF SUMMARY OF THE DISCOVERED CRACKS

- **First SCC cracks accidentally discovered at the end of 2021** during the 3rd ten yearly inspection of reactor 1 of Civaux NPP.
  - This weld was part of the inspection program on thermal fatigue, inspection was conducted using manual UT probes.
- SCC was known to affect stainless steel, but not expected on the auxiliary piping of the main primary system
- Previous experience in France on stainless steel pipes was in between isolation valves, where chemistry conditions can be locally affected.



Crack found on a weld in CIV1 reactor

BRIEF SUMMARY OF THE DISCOVERED CRACKS

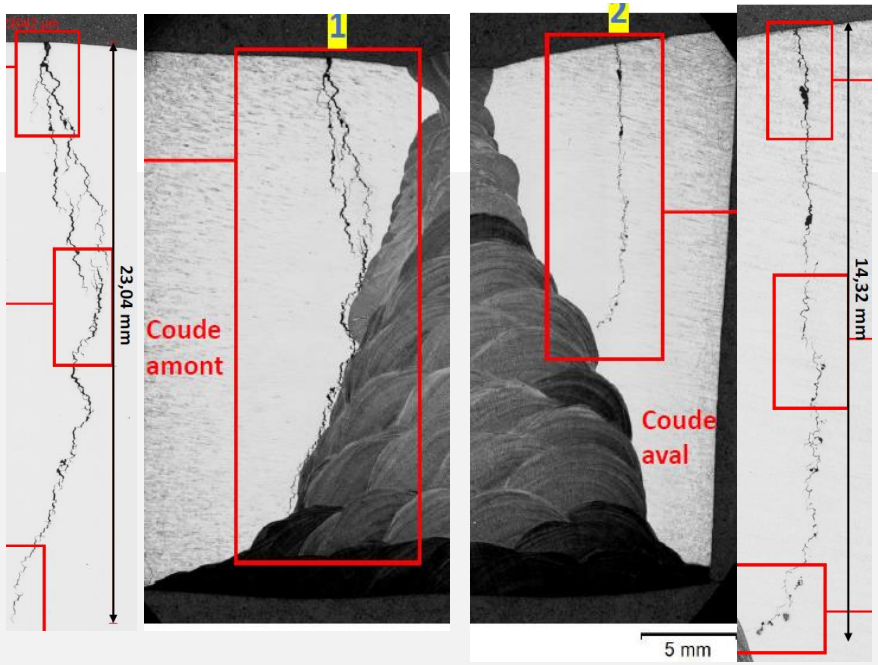


Typical location of affected welds

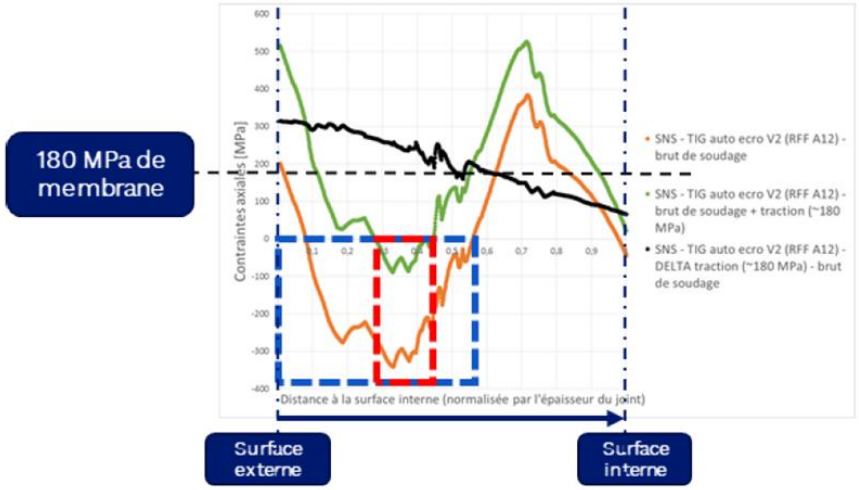
- **Cracks located in the thermally affected areas of the welds on stainless steel pipes, in the non-isolable part of the main primary circuit**
- Concerned systems: **safety injection system and reactor heat removal system** (10 to 12 inches piping, piping wall 20 to 25 mm thick)
- **Low carbon stainless steel pipes** (304L and 316L)
- **972 weld inspections conducted since the end of 2021**, mainly using advanced UT methods
- **54 cracks above 2 mm in depth** detected
  - ➢ All welds with cracks that could threaten the piping integrity have been repaired by replacing the affected pipes (critical flaw depth has been assessed using conservative fracture mechanics computations, based on the RSE-M code, and is around 5 to 7 mm)
  - ➢ Most detected **cracks below 6 mm in depth** (1/4 of the pipe thickness), but **a few very deep cracks discovered**

DEEP CRACKS FOUND ON WELDS REPAIRED DURING MANUFACTURING

- **23 mm deep crack found early 2023 in a weld of a safety injection pipe of reactor 1 of Penly NPP**
- **Weld repaired during the construction** of the plant (the weld was locally grinded to eliminate a flaw and welded again)
- Deep SCC cracks discovered in a few other repaired welds. **All the cracks measured ≥ 6 mm in depth found in repaired welds**
- **Local weld repairs affect the distribution and intensity of residual stresses, and could increase the risk of SCC initiation.**
- **Typical welding residual stresses could limit the crack propagation after reaching a ¼ of the wall thickness, but the beneficial effect of these compressive residual stresses can be lost with some repair configurations.**



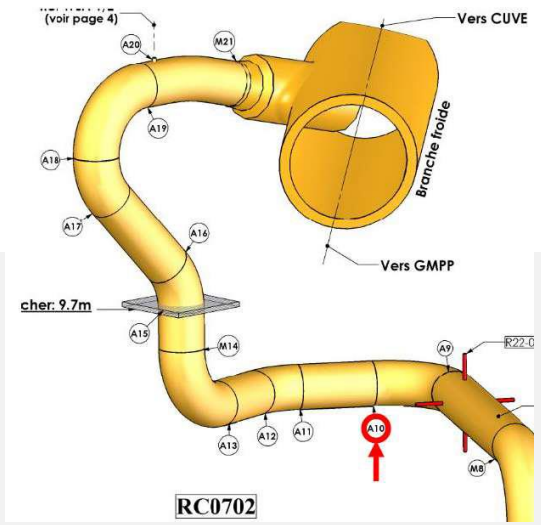
Above : SCC crack found in Penly 1 in 2023 ;
Below : welding residual stresses without weld repairs

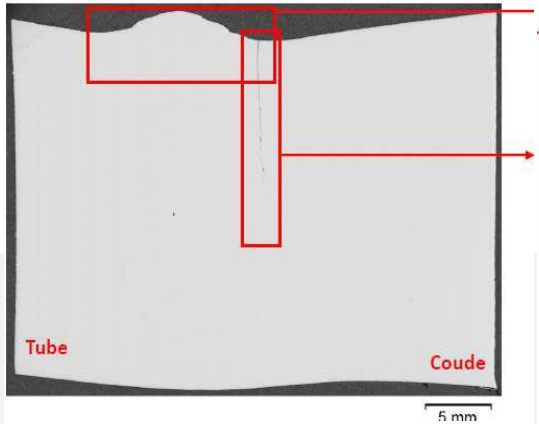


THERMAL FATIGUE CRACKS

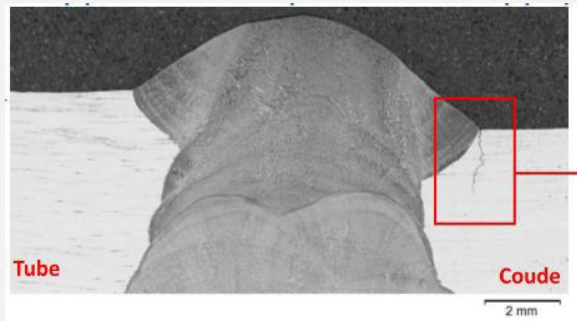
- **A few thermal fatigue cracks (up to 12 mm) also discovered on some pipes subject to thermal stratification loads and susceptible to SCC ;**
- **1 mixed SCC/thermal fatigue crack also observed in 2023.**

Theses discoveries are challenging the current understanding of thermal apparition (these welds were not considered as the most sensible to thermal fatigue within the pipe) and also the understanding of the competition between fatigue and SCC.

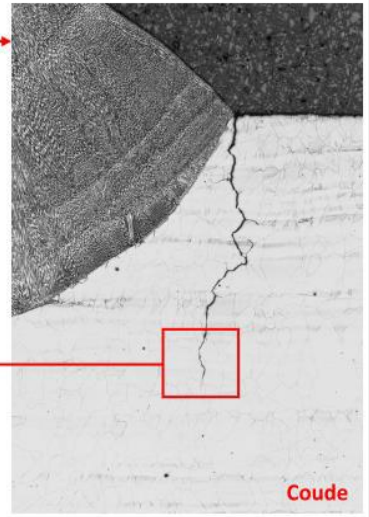




Thermal fatigue crack found on a weld of PEN2 reactor



Mixed crack found on a weld of CHZB2 reactor



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UNDERSTANDING OF THE CURRENT SCC PHENOMENON

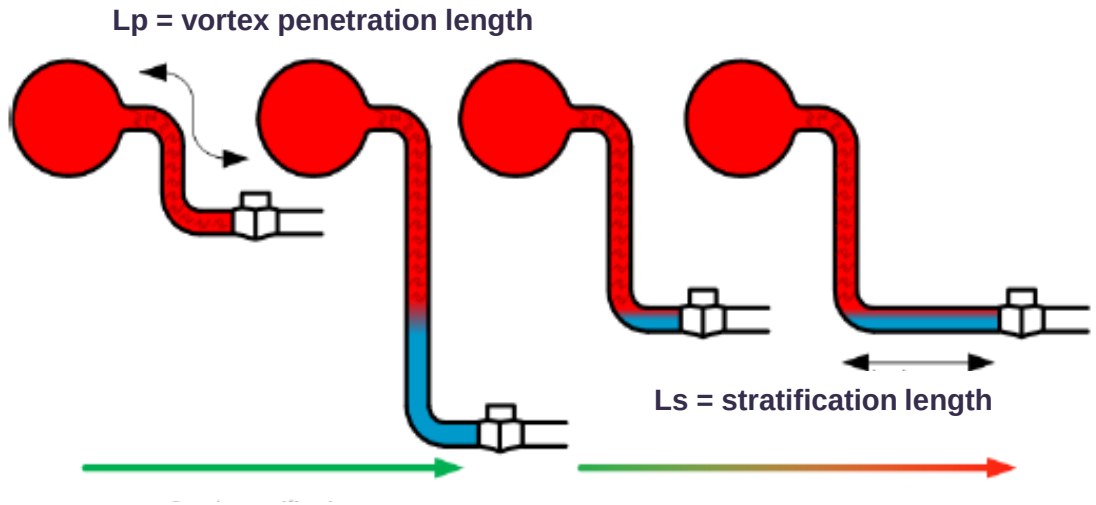
- **IGSCC = a complex phenomenon**, resulting from the combination of three factors:
  - Stress (welding residual stress, in-service stress)
  - Susceptibility of the material (material composition, hardness,…)
  - Influence of the environment (temperature, chemical composition of the fluid…)

➡ **Root cause of the cracks very difficult to understand ; and most probably several factors are influencing the developpement of the cracks that were found.**

SUSCEPTIBILITY FACTORS CURRENTLY IDENTIFIED
1/ THERMAL STRATIFICATION

- **Some specific design of auxiliary pipes seem to be** more susceptible to SCC as they were the ones that presented the most important number of crack. **These pipes are subject to thermal stratification, a thermal phenomenon inducing additional stresses on the welds.**
- However there are other susceptibility factors. **Some cracks were found on pipes that are not sensible to thermal stratification** (typically, pipes that are short in length that are entirely at the main coolant line temperature). These cracks were mostly detected on welds repaired at the manufacturing, but there are some occurrences concerning welds that were not repaired.

Vortex and stratification



SUSCEPTIBILITY FACTORS CURRENTLY IDENTIFIED
2/ OTHER SUSCEPTIBILITY FACTORS

- **Welds repaired during the manufacturing**

There is undeniable evidence that some repairs are increasing the risk of SCC initiation and propagation.

However, a lot of repaired welds have also been inspected and show no sign of SCC cracks.

The type of repairs that are presenting a risk is still under investigation (extension and deepness of the area that is repaired is probably a factor).

- **Environmental factors (temperature, chemistry)**

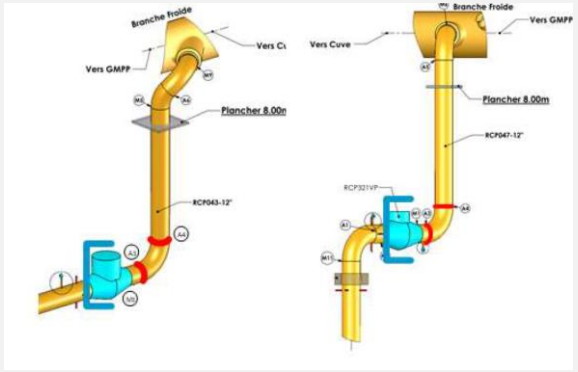
Laboratory tests and international experience show that high temperature and high oxygen content increase the risk of SCC.

The role of oxygen and temperature in the development of cracks in France is not completely understood yet. Indeed, investigations conducted since 2021 show that the temperature distribution within auxiliary lines is not well known (and subject to variation between plants with the same design), and there are questions raised by some experts regarding the oxygen concentration in areas with no regular water circulation.

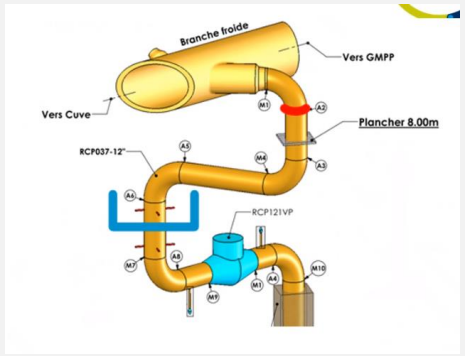
THE SUSCEPTIBILITY FACTORS CURRENTLY IDENTIFIED
1/ THERMAL STRATIFICATION

- **Considerations for an assessment on the sensibility of the auxiliary lines, based on their geometry**

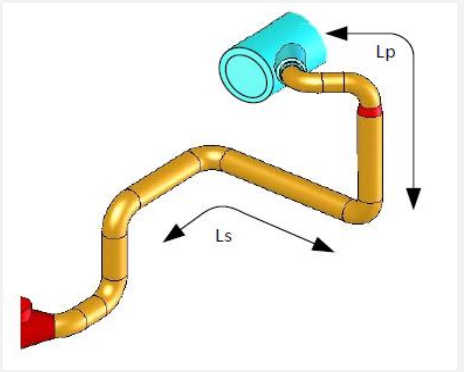
➔ one of the basis of the next years inspection programme by EDF on ECCS and RHRS lines



Low risk of stratification (?)



Limited risk of stratification (?)



High risk of stratification

- However, knowledge of the thermohydraulic effects within these lines still not precise enough according to ASN

➢ **Assessment to be confirmed**

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FOCUS OF THE 2023-2025 INSPECTION PROGRAM TARGETING SAFETY INJECTION AND RESIDUAL HEAT REMOVAL PIPES

- Inspections targeting the welds on all pipes of the safety injection and reactor heat removal systems (not isolable from the main primary circuit) on all French reactors
  - **Repaired welds: inspection of all welds repaired during the construction on these systems**, because of the higher risk of developing deep SCC cracks
  - **Other welds: programme based on a sample of welds**, with a sampling rate
    - higher on the pipes considered susceptible to develop SCC according to the current understanding
    - A minimal sampling rate is included on other lines to confirm this understanding.
- **ASN still monitors closely the results of these inspections, and this program shall be adapted in case of an evolution of the understanding of susceptibility factors.**
- **More than 300 welds still to be inspected by 2025 under this programme**
- **Some instrumentation programs about the temperature distribution, and a closer monitoring of oxygen levels in main coolant lines, has also been requested by the ASN**

ADDITIONAL 2024-2026 PROGRAM ON OTHER AUXILIARY PIPING SYSTEMS

According to current French experience, SCC is still not expected on other auxiliary piping systems than safety injection and residual heat removal pipes. However, factors as weld repairs (or other unknown factors) could still lead to some cracks and ASN now considers that the risk of SCC cracks on 304L/316L welds under nominal PWR conditions cannot be entirely excluded. In addition, some parts of these piping systems are not well covered by standard 10-yearly inspection programs.

➔ ASN considered it was also **important to check whether the other stainless steel pipes of the main primary circuit were affected or not**

Preliminary investigations, conducted on the pressurizer surge line and some parts of the main coolant lines: no SCC cracks detected.

2024-2026 program:

- Controls on some components of the main coolant lines replaced after 40 years of operation
- Advanced UT inspections on welds of the pressurizer surge line and other stainless steel lines below 8 inches in diameter, targeting a sample of welds

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FOCUS ON WENRA RECOMMENDATIONS BASED ON CURRENT FRENCH EXPERIENCE

The ASN chaired a WENRA (Western European Nuclear Regulators Association) working group on the current lessons learned from French operating experience.

The group issued some recommendations accessible at https://www.wenra.eu/node/224

The recommendations concern PWRs and are structured in 5 categories :

- **Inspections to be performed on PWR stainless steel welds :** recommendation to take into account the risk of SCC development when conducting inspection programs on all stainless steel welds ; and about the sampling of the welds targeted by the inspections :
- **Monitoring of the parameters that may influence the development of IGSCC :** a monitoring of influent parameters (mainly temperature and oxygen) is recommended at *appropriate* locations of a PWR piping system. Operating conditions and inspection programs shall take into account the results of this monitoring.
- NDT methodology recommended for the detection of IGSCC : Multi-element UT seem to be the most precise way of detecting and sizing SCC cracks. Single element, under proper qualification, may also show some good performance especially on cracks above a few mm in depth. The recommendation focuses on the qualification of the processes, and underlines the challenges raised by austenitic welds inspection, and the fact that qualifying a process on real SCC cracks (rather than notches or fatigue

FOCUS ON WENRA RECOMMENDATIONS BASED ON CURRENT FRENCH EXPERIENCE

- **NDT methodology recommended for the detection of IGSCC :** Multi-element UT seem to be the most precise way of detecting and sizing SCC cracks. Single element, under proper qualification, may also show some good performance especially on cracks above a few mm in depth. The recommendation focuses on the qualification of the processes, and underlines the challenges raised by austenitic welds inspection, and the fact that qualifying a process on real SCC cracks (rather than notches or fatigue specimens) is a good practice.
- **Repairs and mitigations on IGSCC susceptible or affected welds :** the WENRA report show that there is a strong international experience on SCC mitigation and repair (such as the methods developed after the discovery of SCC in the US BWR fleet) and that the subject is well documented. The report simply emphasizes the need for qualification of these methods according to applicable standards.

FOCUS ON WENRA RECOMMENDATIONS BASED ON CURRENT FRENCH EXPERIENCE

- **Recommendations regarding the design and manufacturing of stainless steel piping on new PWRs:**

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. [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;

FOCUS ON WENRA RECOMMENDATIONS BASED ON CURRENT FRENCH EXPERIENCE

- **Recommendations regarding the design and manufacturing of stainless steel piping on new PWRs:**

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.

ASN is monitoring the application of these recommendations by the EPR2 project, as EDF is currently planning the construction of 6 (and possibly 8 more) EPR2 reactors.

Currently, contracts for the piping manufacturing have not yet been passed, and the design of the piping is not completely achieved, which allows to take into account most of these recommandations.

Thank you for your attention!

Any questions?