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IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

STRESS CORROSION CRACKING AFFECTING SOME FRENCH REACTORS : SITUATION AFTER TWO YEARS

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MEMBRE DE ETSON

IRSN = PUBLIC EXPERT ON NUCLEAR AND RADIOLOGICAL RISKS

Assessing the risk associated with the use of ionising radiation

Our areas of intervention

NUCLEAR SAFETY	PROTECTION OF THE POPULATION AND THE ENVIRONMENT	SECURITY
Reactors, fuel cycle, waste management, transport of radioactive materials, radioactive sources	Against the risks associated with ionising radiation Public, workers, patients, environment, ecosystems	Defense Malevolence Non proliferation

OPERATIONAL SUPPORT IN THE EVENT OF RADIOLOGICAL CRISIS OR EMERGENCY SITUATIONS

SCC affecting the French nuclear fleet : the point of view of safety

1. The discovery of SCC (Autumn 2021)
2. Initial findings and actions (first half 2022)
3. Situation in 2023 and root cause analysis
4. The pillars of EDF's strategy: inspections, justification of the operation of reactors with cracks, and massive repairs
5. Long-term lessons learned

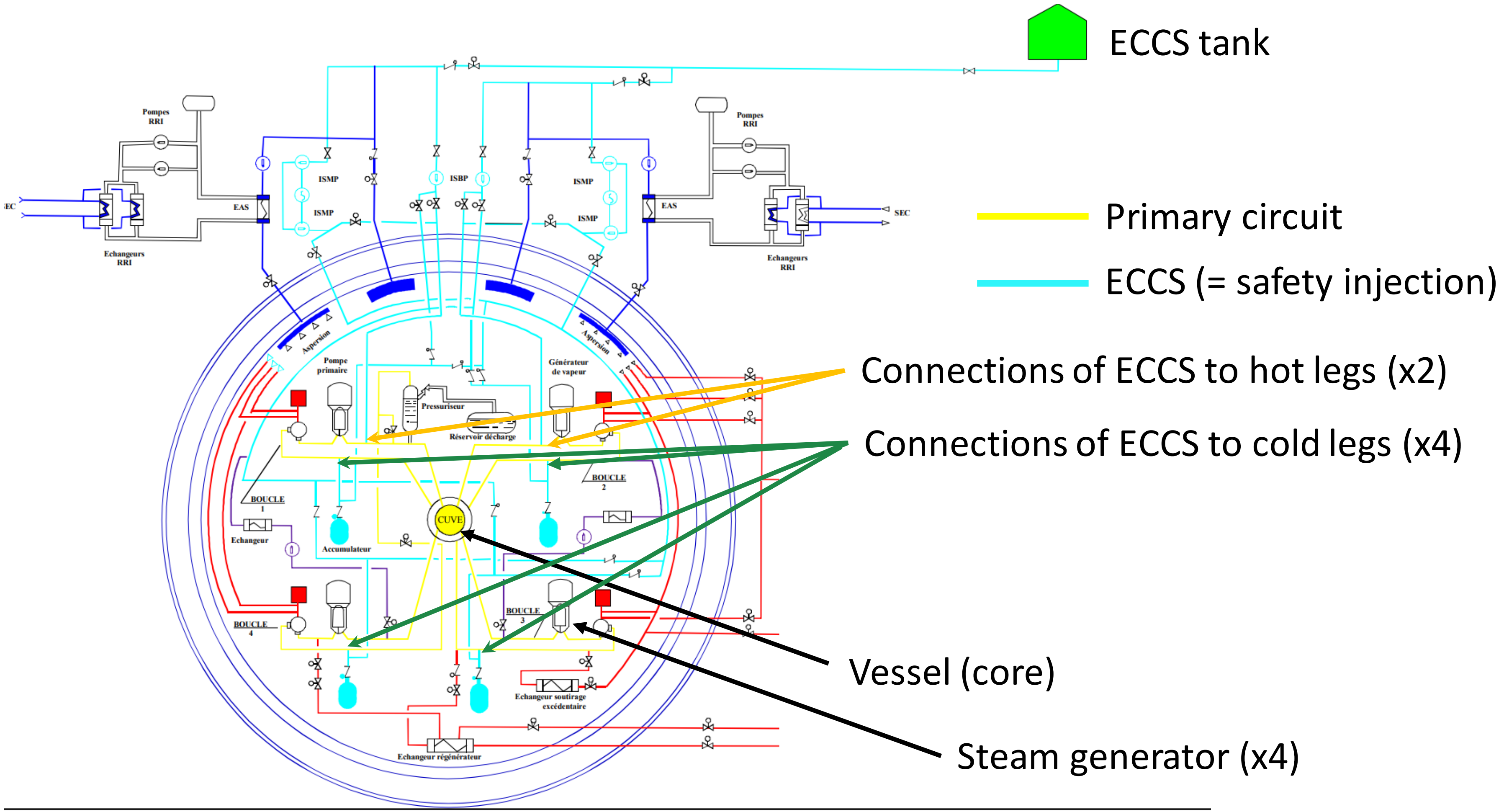
1. The discovery of SCC (Autumn 2021)

- August 2021 : the ten-yearly periodic review of Civaux 1 reactor is underway

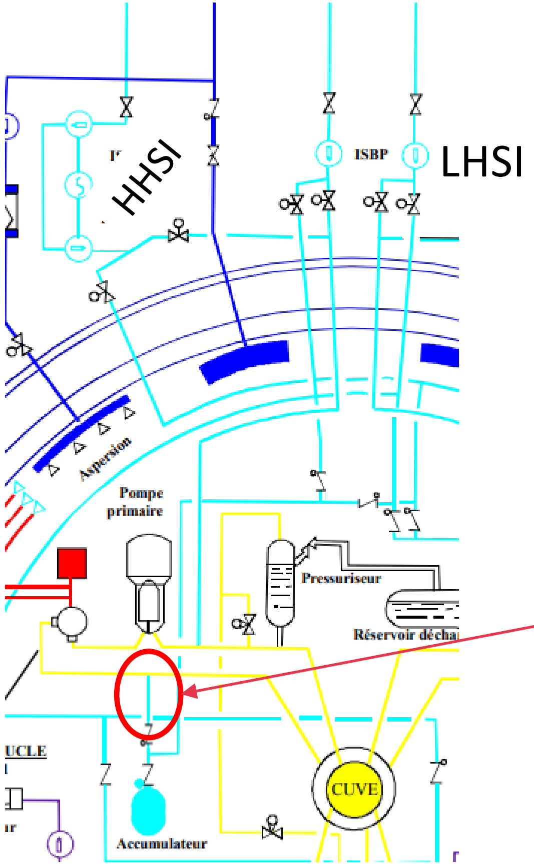
- Ultrasonic examinations of the Emergency Core Cooling System (ECCS), performed to detect defects due to thermal fatigue, show large and unexpected indications

- EDF decided to cut some elbows and perform destructive examinations in its Chinon laboratory (LIDEC, a lab specialising in the analysis of radioactive materials)

- December 2021 : LIDEC analyses revealed that defects are not due to thermal fatigue, but to stress corrosion cracking (Intergranular SCC)



ECCS tank
Primary circuit
ECCS (= safety injection)
Connections of ECCS to hot legs (x2)
Connections of ECCS to cold legs (x4)
Vessel (core)
Steam generator (x4)
Pompes RRI
Echangeurs RRI
EAS
ISMP
ISBP
SEC
Asperion
Pompe primaire
Générateur de vapeur
Pressuriseur
Réservoir décharge
BOUCLE 1
BOUCLE 2
BOUCLE 3
BOUCLE 4
CUVE
Echangeur
Accumulateur
Echangeur soutirage excédentaire
Echangeur régénérateur



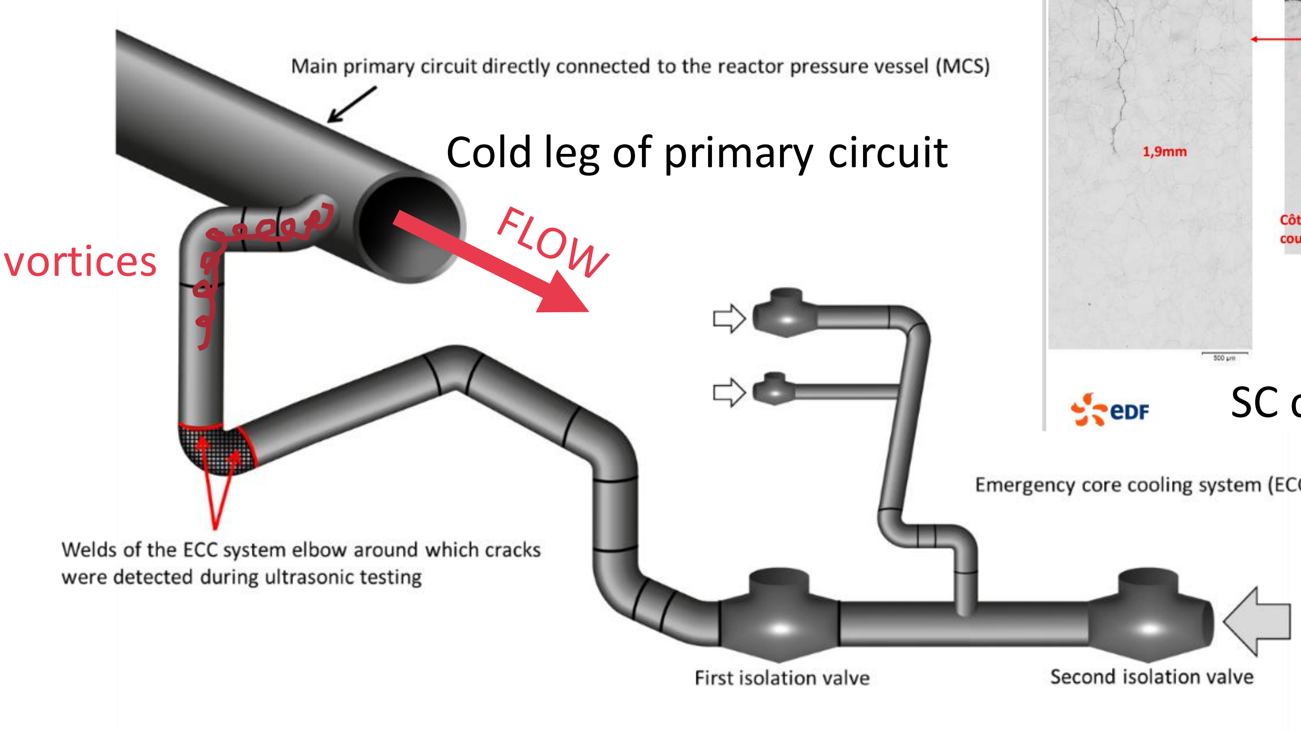
Primary circuit (~300°C)

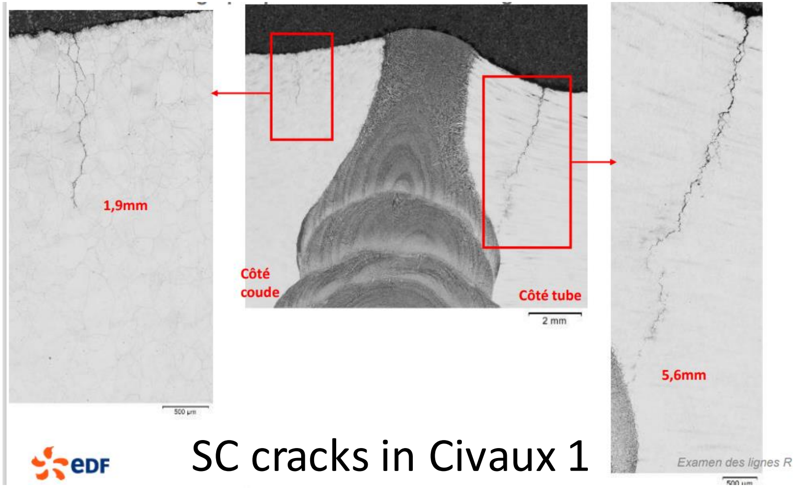
ECCS

Line between the "first" isolation valve and the primary circuit

Pipes are heat-insulated

1. The discovery of SCC (Autumn 2021)



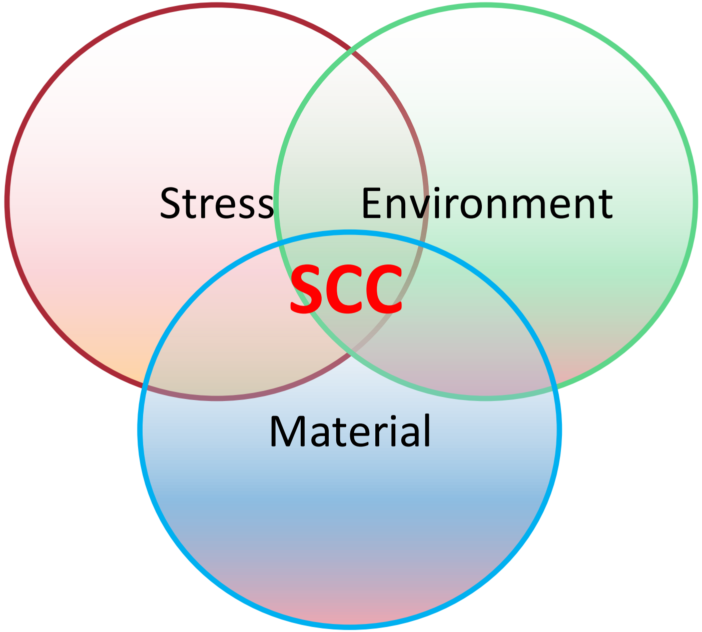


There are several ECCS lines connected to the primary circuit

1. The discovery of SCC (Autumn 2021)

- SCC is a complex phenomenon resulting from the interaction of three factors :

1. **Stresses** : residual welding stress, in-service stress…
2. **Material** : hardness, composition…
3. **Environment** : chemistry of the fluid, temperature…



SC cracks occur close to the welds because of welding (hardness, residual stress…)

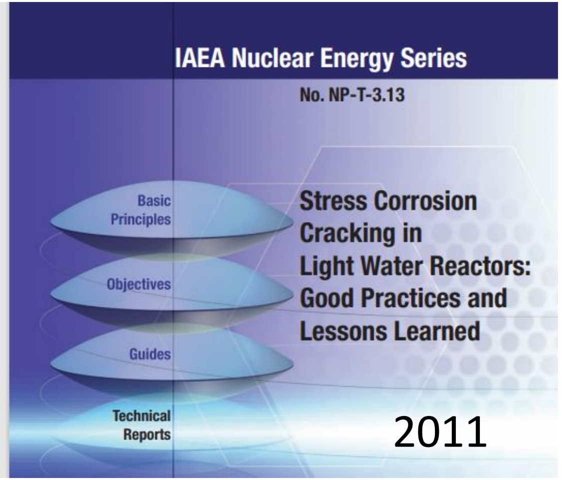
Considering the design of the lines, the material chosen and the chemistry of the fluid, SCC was not expected where it was discovered

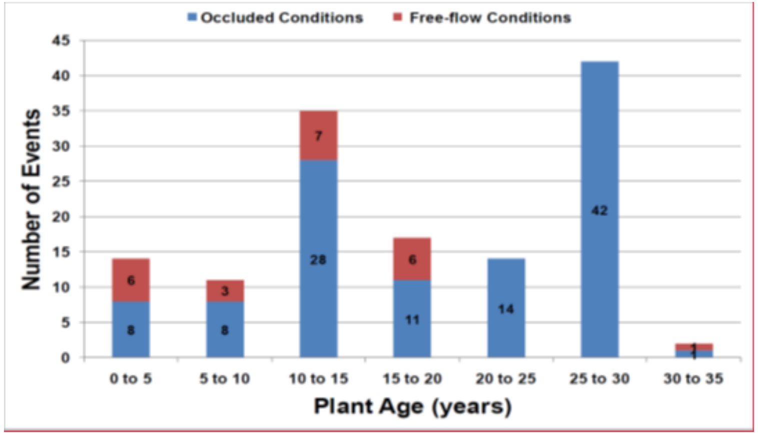
1. The discovery of SCC (Autumn 2021)

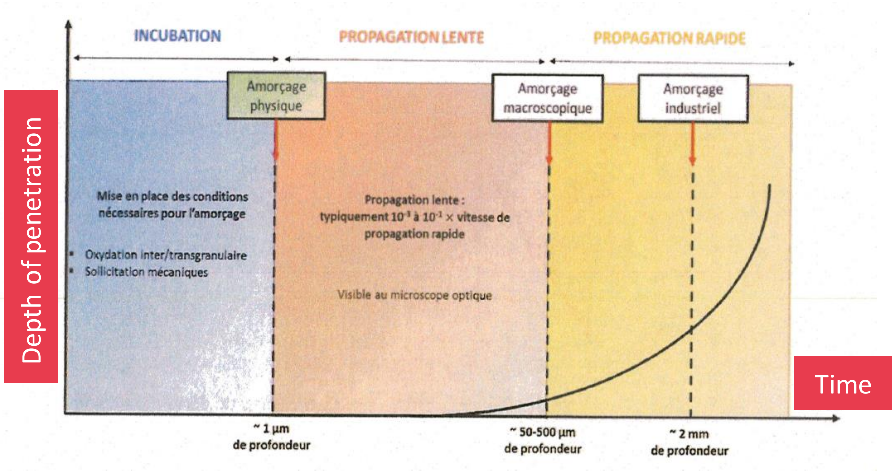
- Well known phenomenon in industry, but not frequent in PWR reactors for stainless steel 304L and 316L (~150 events between 1983 and 2022), mostly in “occluded conditions”

- Cracks appear after an incubation period, they can’t be detected before, and the crack growth rate varies widely

- Temperature is a predominant factor

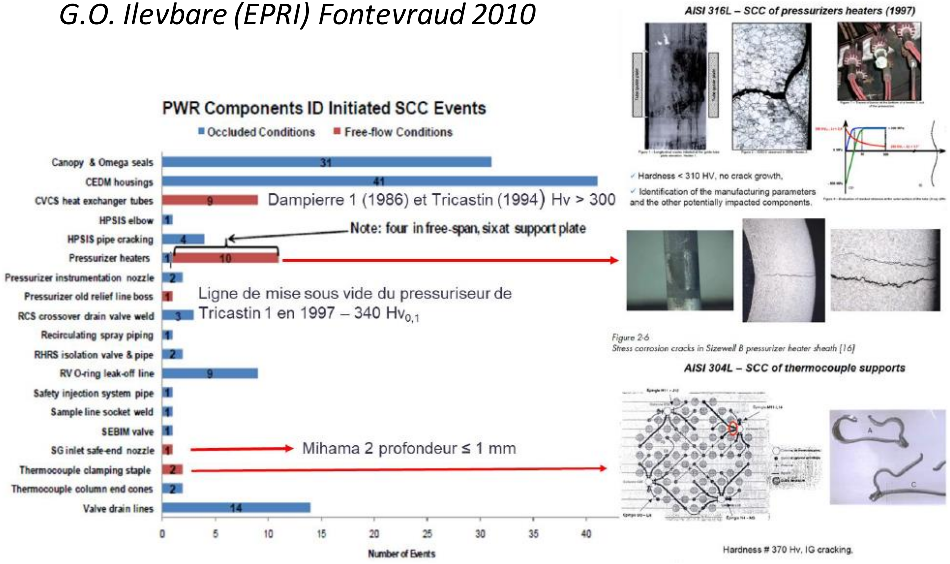




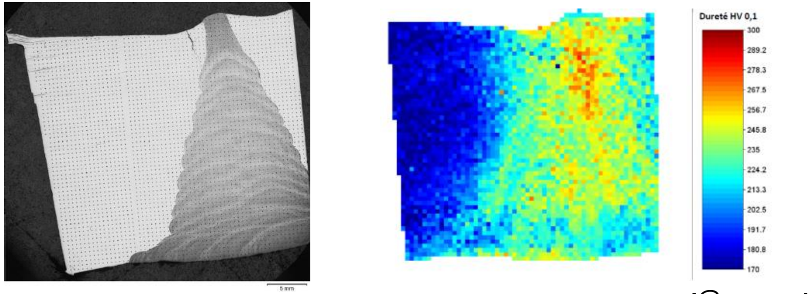


1. The discovery of SCC (Autumn 2021)

SCC of stainless steels under PWR service conditions
G.O. Ilevbare (EPRI) Fontevraud 2010



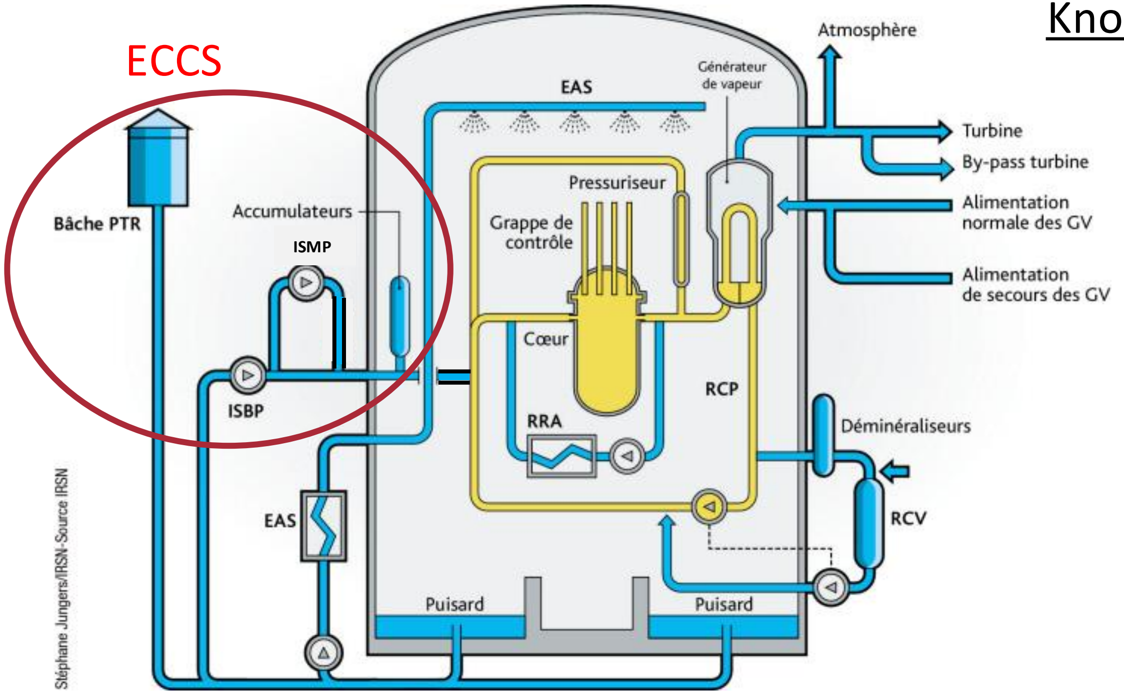
- The analyses concluded to Intergranular SCC (IGSCC)
- No evidence of pollution detected
- Conformity of the chemical control of the primary cooling system
- Conformity of the procurements of the base metal
- Degradation not expected, not in accordance with the international operating experience
- Share some similarities with a crack detected in a weld of a pressuriser spray line at Ohi 3 in 2020 (Japan)
- Higher level of hardness detected in the vicinity of the root pass with respect to the base material



CIVAUX 1 weld A12

(©EDF)

1. The discovery of SCC (Autumn 2021)



<u>Knowledge in January 2022 :</u>

- Location of cracks:
  - on the ECCS lines (and …?)
  - after the last isolation valve
  - several lines affected
- Length of cracks:
  - almost circumferential ?
- Depth of cracks :
  - > 5 mm ? growth rate ?
- Number of welds controlled :
  - 1 per line
- Root cause :
  - unknown

Risk of instable ductile tearing in accidental conditions ? ➔ A significant issue for safety !

2. Initial findings and actions (first half 2022)

- New assessment of all the former UT results where indications had been classified as « *artefact* » (all French units)

- Extension of UT control to others welds close to the cracked welds and to other lines and systems (ECCS hot leg, RHRS) : four 1450 MWe units & PENLY 1 (1300 MWe). Optimization of UT testing by EDF, but many false positives ➔ *IRSN notice n° 2022-00066*

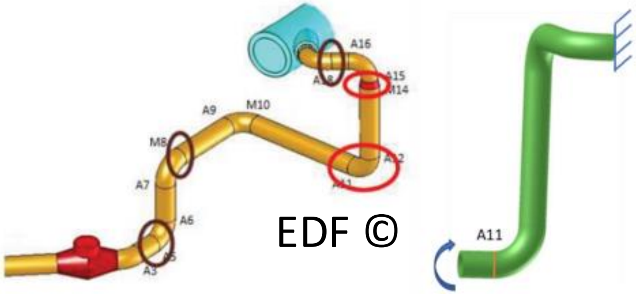
- Anticipated outage of some reactors for UT inspections (Chinon 3, Bugey 4…) and destructive examinations when indications are found. EDF chooses a "test reactor" per train of reactors

- Numerical simulation of welding and initiation/propagation of cracks (code EDF: CORIOLIS©)
➔ IRSN position : very useful tools for analyses, not yet able to fulfil the qualification requirements of software used for a safety demonstration

2. Initial findings and actions (first half 2022)

- Mechanical studies to determine the critical defect sizes ➔ *IRSN notice n° 2022-00131*

  - Codified (conservative) and more realistic calculations are performed
  - Loads resulting from postulated incidental and accidental conditions are considered



N4 ECCS line (cold leg)

- Compensatory measures: reinforcement of monitoring for potential primary leaks (water balance, fire alarm sensors), precautions in normal operations to limit thermomechanical loads on the (possibly) cracked pipes ➔ *IRSN notice n° 2022-00138*

- Extensive investigation program including many elbows removed from service for metallography

3. Situation in 2023 and root cause analysis

- The historical UT procedure (even optimized) does not perform well enough for SCC (many false positives…) ➔ it has been replaced by an improved one, that enables EDF to avoid destructive examinations

- At the end of June 2023, EDF had carried out more than 200 analyses in the laboratory and hundreds of ultrasonic tests (> 500)

- EDF defined a prioritized strategy to inspect auxiliary lines until 2025 (➔ *ASN letter CODEP-DEP-2023-007194*) in order to complete the diagnosis of the reactors fleet versus SCC

- Specific lines are susceptible to the risk of SCC: ECCS and RHRS of 1450 Mwe reactors (N4) and some 1300 MWe reactors (P'4). Ongoing investigations for pressurizer surge lines…

- 900 MWe reactors are less sensitive to the SCC risk (circuit layouts might explain the difference)

- Some repaired welds are sensitive to SCC (effect of increased residual stress ?)

- EDF carried out numerous repair

3. Situation in 2023 and root cause analysis

Root cause analysis : thermal-stratification

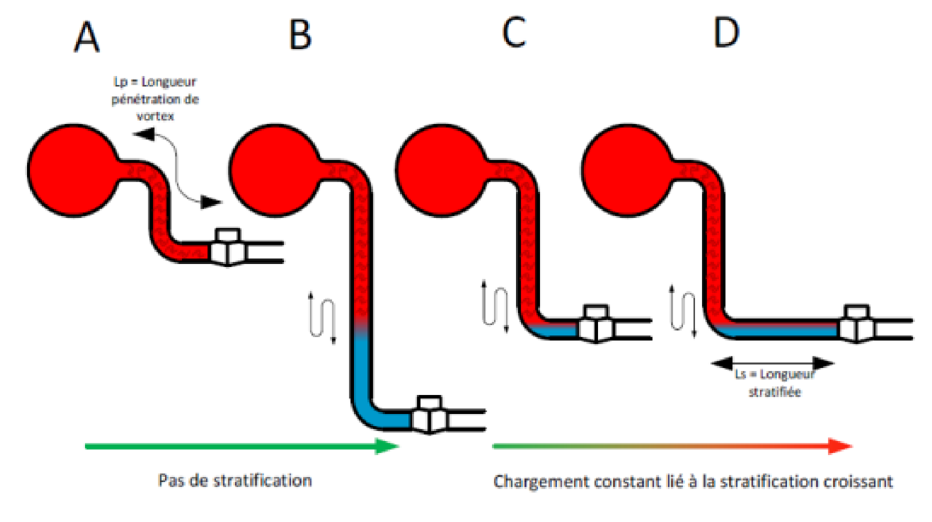


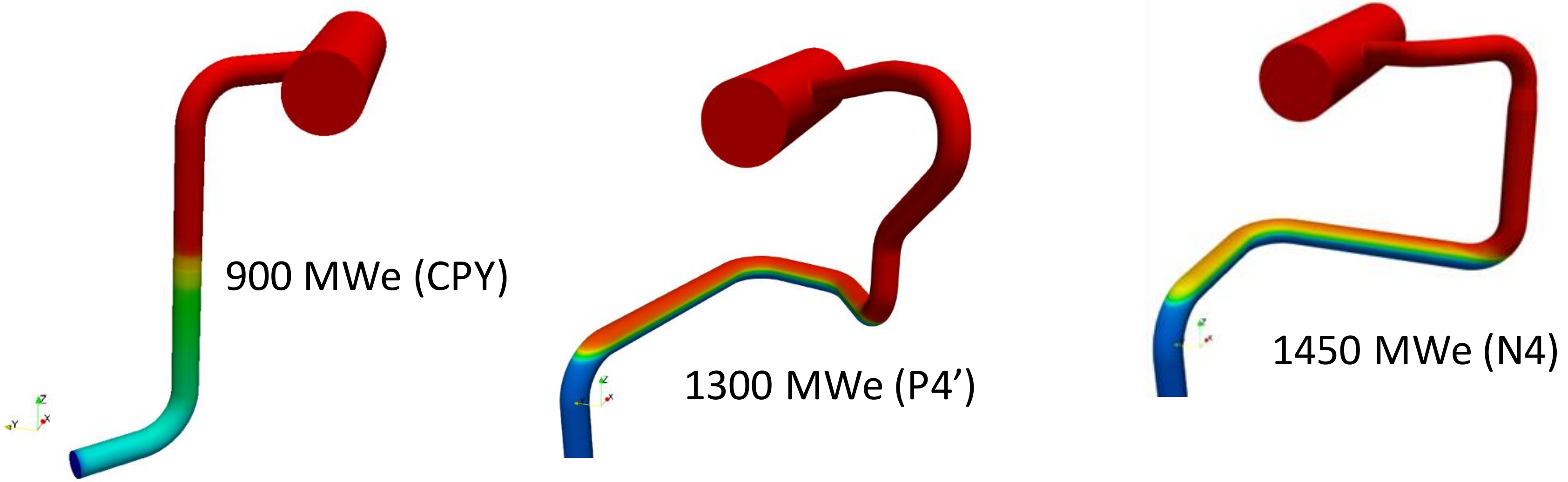
Illustration of the thermal stratification phenomenon (from EDF)

Stresses resulting from the stratification are higher in case D than in case C, as the horizontal area of the pipe is longer.

- EDF considers thermal stratification in the lines as the main cause of SCC
- The geometry of ECCS and RHRS lines in French reactors has been "optimized"
- Up to a certain point, the lines where SCC has been observed can be correlated with expected thermal-stratification effects
- Temperatures and T° fluctuations along the lines are not well known

3. Situation in 2023 and root cause analysis

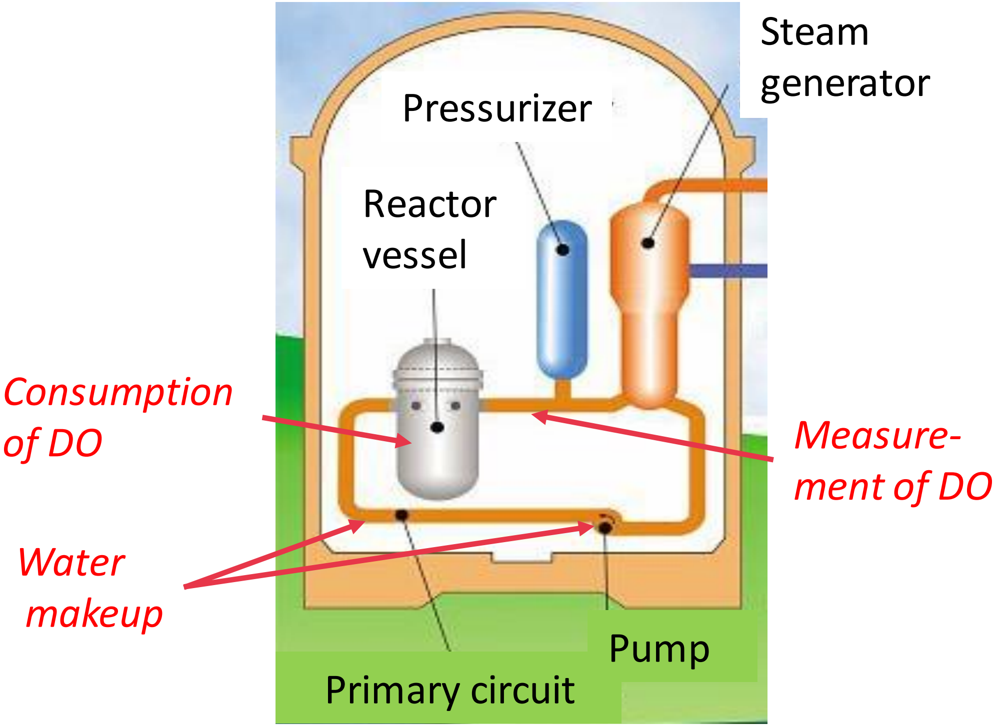
- Root cause analysis : thermal-stratification



Preliminary IRSN studies of thermal-stratification of the ECCS line connected to the cold leg of the primary circuit

3. Situation in 2023 and root cause analysis

- Root cause analysis: chemistry of the primary circuit :
  - No significant pollution regarding chlorides, fluorides, sodium, sulphites… in the primary circuits and the auxiliary circuits, no significant event regarding boron / lithium and hydrogen
  - Dissolved oxygen is a predominant parameter for the corrosion of stainless steel. Primary fluid is deaerated (when the primary circuit is closed). Possible sources of oxygen :
    - Shutdown periods when the primary circuit is open
    - Water makeup (large volume injected during each cycle, chemical and volume control system)

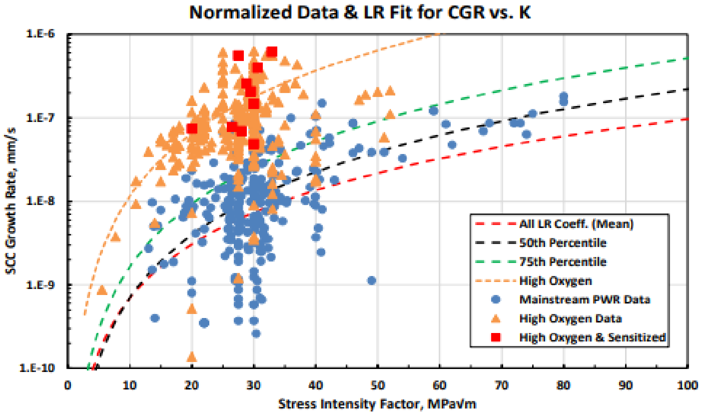


3. Situation in 2023 and root cause analysis

- Floating roof tanks cannot guarantee an injection of deaerated water

- The situation is variable depending on reactors

- Considering the position of ECCS and makeup nozzles on the cold leg of the primary circuit, IRSN considers that the presence of a DO concentration sufficient to initiate SCC cannot be ruled out ➔ *IRSN notice n° 2022-00189*



P. Andersen et al. 20th environmental degradation conference

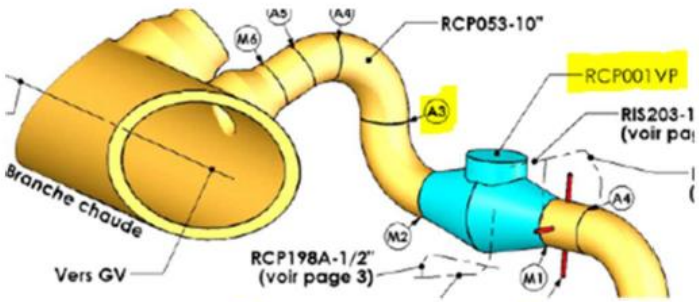
- EDF disagrees but reinforced the measurement of DO on some reactors and initiated an R&D program to study the effect of the electrochemical potential on SCC

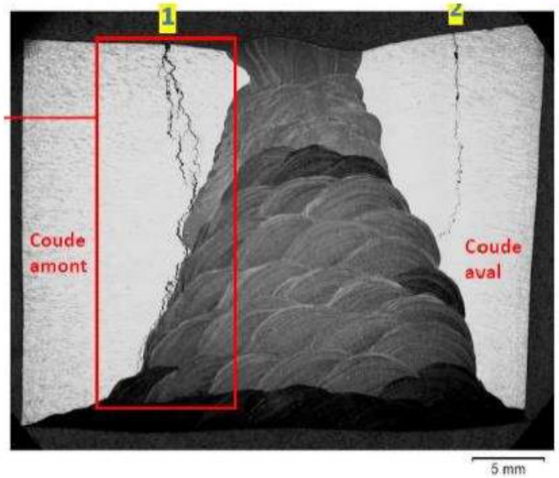
- Following IRSN assessment, ASN also asked EDF to improve the measurements of DO in RCP and to reduce DO ingress from water makeup tanks

3. Situation in 2023 and root cause analysis

Root cause analysis for weld repairs :

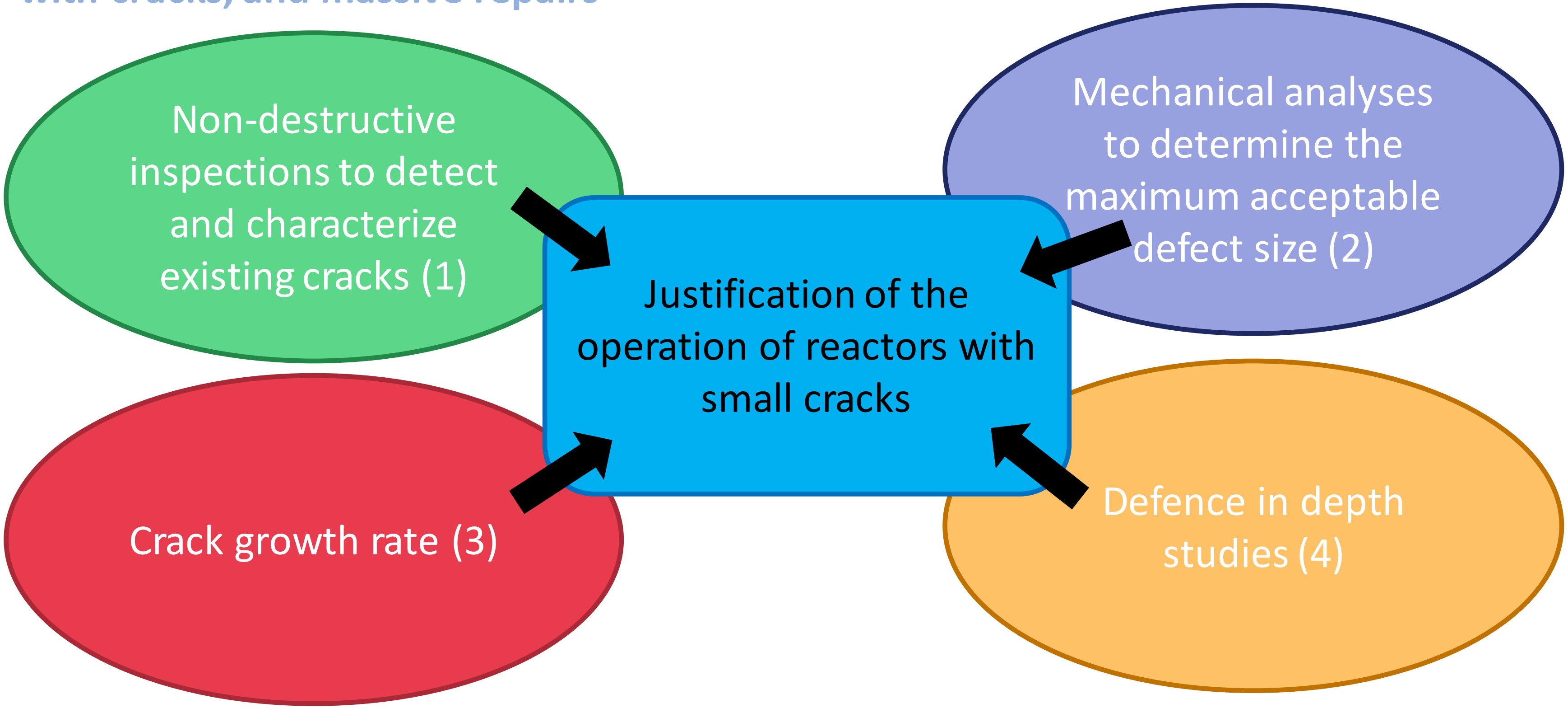
- SC cracks have been found on repaired welds, even on lines which are not sensitive to thermal-stratification
- Welds have been repaired during the construction phase of reactors either because of defects in the welds, and/or because of alignment constraints
- In Penly 1, in one of the ECCS lines connected to the hot leg n°1 of the primary circuit, a 23 mm deep and 155 mm long crack has been discovered.
- EDF defined a specific plan with priorities to control repaired welds, starting with the most sensitive ones (repaired twice…)





Penly 1 crack
The weld had been repaired twice

4.The pillars of EDF’s strategy: inspections, justification of the operation of reactors with cracks, and massive repairs



➔ *IRSN notice n° 2023-00067*

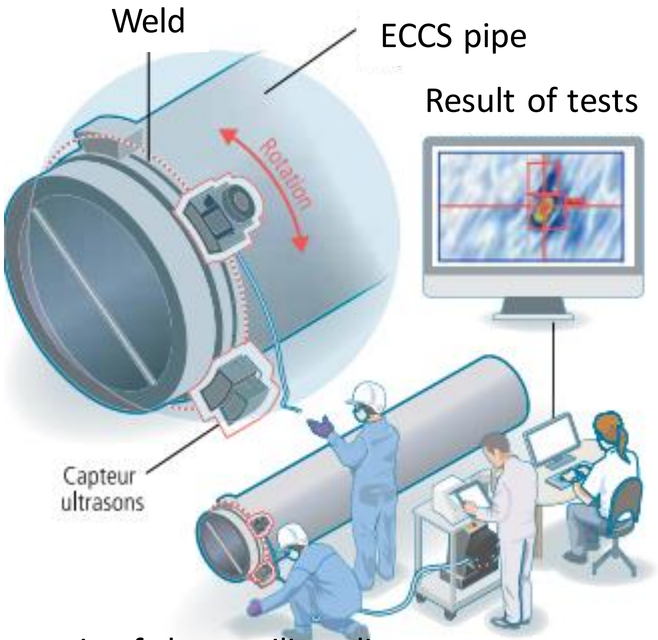
(1) Non-destructive testing to detect and characterize existing cracks

- A new UT method (Full Matrix Capture-Plane Wave Imaging Total Focusing Method) able to determine the depth of cracks (due to SC or fatigue)

- For cracks > 2mm, precision of +/- 1 mm

- A complex work of analysis of recorded signals, requiring specific training

- The possibility to supplement the UT with eddy current testing and visual testing (surface)



- The program of controls carried out by EDF in 2023 gave a partial diagnosis of the auxiliary lines. EDF will continue to carry out this program until 2025 to complete the diagnosis

- EDF is not able to replace in the short term all the lines affected by CSC (majority of cracks < 2 mm)

(1) Non-destructive testing to detect and characterize existing cracks

Typical conditions of UT inspections (EDF)

Rapport IRSN N° 2023-00286

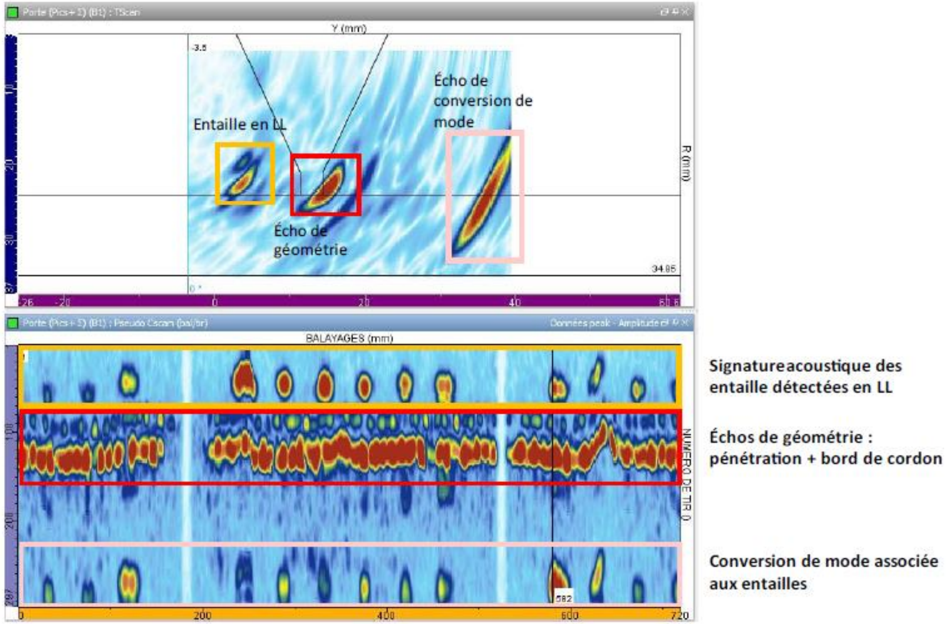


Figure 21 : Images T-Scan et C-Scan du mode direct LL de la rafale 1 obtenus sur la maquette 8''.

Analysis of EDF data by IRSN with the CIVA software

(2) Mechanical analyses to determine the maximum acceptable defect size

Geometry of defects

Axisymmetric defect
Semi-elliptical defect

Loads

Mechanical analysis of lines
Thermal hydraulics transients

Material characteristics

Stress-strain curves (for the base metal and the deposited weld metal)

J integral

Mechanical model

versus

Resistance to rupture

Deposited weld metal : RSE-M coded value
Hardened base metal : bibliography and specific tests

IRSN considered that the approach of EDF is acceptable (→*IRSN notice n° 2023-00067)*

(3) Crack growth rate

- EDF uses numerical simulation of welding and models to assess a maximum SC crack growth rate
- Model parameters adjustment relies on experimental databases

➔ Considering existing uncertainties, IRSN considers that is not possible to derive maximum SC crack growth rate with this approach. But NDE carried out on EDF's reactors will bring new elements.

- Taking into account these assessments, as well as the knowledge gained from operational feedback and from laboratory experiments, and after the assessments performed by IRSN and the advice of the "GP ESPN", ASN decided (see *CODEP-DEP-2023-036141*) to ask EDF to consider the following values for the maximum growth rate of flaws characterized as potential SCC and left in service :

	Defects < 5 mm	Defects > 5 mm
Non repaired welds	1 mm/year	1 mm/year
Repaired welds	1 mm/year	3 mm/year

"GP ESPN" = advisory committee of ASN for nuclear pressurized equipments

(4) Defence-in-depth analyses performed

- In case of primary circuit loss of pressure, the ECCS would be actuated, and "room temperature" water would flow through the safety injection lines, creating a "thermal shock" ➔ this could damage several ECCS lines at the same time

- The Safety Analysis Report of PWRs usually contains Loss of Coolant Accident (LOCA) studies: single (large) break of the primary circuit, including the loss of a safety injection train (single failure criterion)

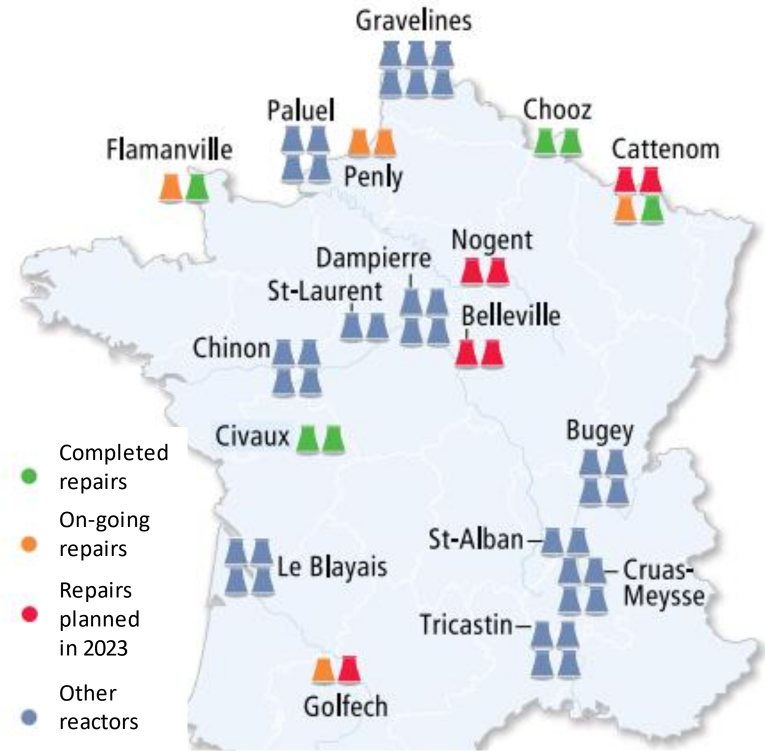
- From the point of view of the cooling of the core, several small breaks on the safety injection lines could be worse

- EDF and IRSN independently performed thermal-hydraulic analyses of the consequences of multiple small breaks (in a "realistic mode", no additional single failure) and established that the cooling of the core would still be ensured ➔ *IRSN notice n° 2022-00156*

- This analysis cannot replace the expected safety demonstration, but can be used to prioritise inspections, repairs, to supplement other analyses…

4.The pillars of EDF's strategy: inspections, justifications of the operation of reactors with cracks, and massive repairs

- Repairs :
  - EDF had to weld new elbows on reactors where destructive examinations had been necessary (Chinon 3, Bugey 4 have been restarted in Nov 2022, major concerns for power generation during fall and winter 2022)
  - In parallel, EDF decided to engage massive repair activities on ECCS and RHRS of N4 and P'4 reactors, including the replacement of long parts of the lines
  - The design (geometry, material…) of the "new lines" is identical, but precautions are taken to avoid SCC in the future ➔ IRSN and ASN agreed
  - The radiological environment is a major constraint for repairs and controls
  - Because of the scale of activities, EDF used different suppliers to carry out the repairs



Progress of EDF repair activities (March 2023)

5. Long-term lessons learned

- For existing reactors :
  - adapt the program of non-destructive tests carried out in service (frequency, number of welds…)
  - improve knowledge of thermal-hydraulic conditions, DO contents and electrochemical potential in dead legs and draw the appropriate conclusions

- For future reactors:
  - avoid designs of auxiliary lines leading to thermal-stratification
  - take precautions for welding procedures

- For long term operations (up to 80 years ??), anticipate possible degradations :
  - Maintain the defence in depth approach (perform inspections for safety significant components even if no degradation mechanism is identified and even if OEF is good)
  - Anticipative R&D
  - In-depth analysis of OEF (pay due attention to weak signals)

- At the scale of a nuclear fleet, think about the risk of common cause failure