Mid-term Seminar: EAF workshop

19-20 September, 2023

Santander, Spain

From R&D results to industry practice: past experiences and INCEFA-SCALE advances on modelling and assessment rules

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1. Introduction
2. French Civaux plant experience
3. RCC-M new rules for EAF
4. INCEFA-SCALE advances on modelling and assessment rules
5. Conclusions

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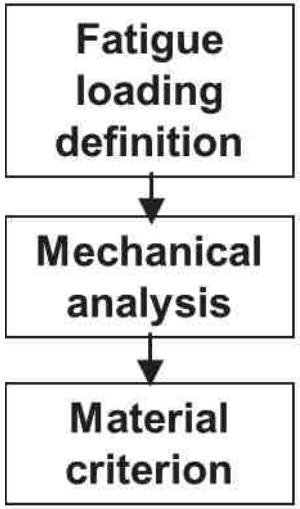
1. Introduction

Fatigue is a major industrial failure mode to avoid
and each link of the engineering fatigue analyses is important:

- Definition of the loading scenario
- Determination of the structural response
- Reference to a fatigue material criterion



R&D actions are often necessary to address industrial challenges
and R&D results must be systematically promoted in industry practice

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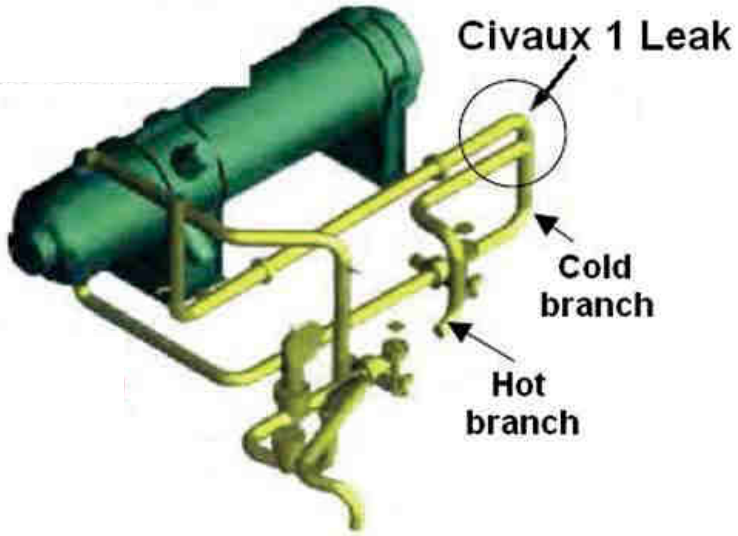
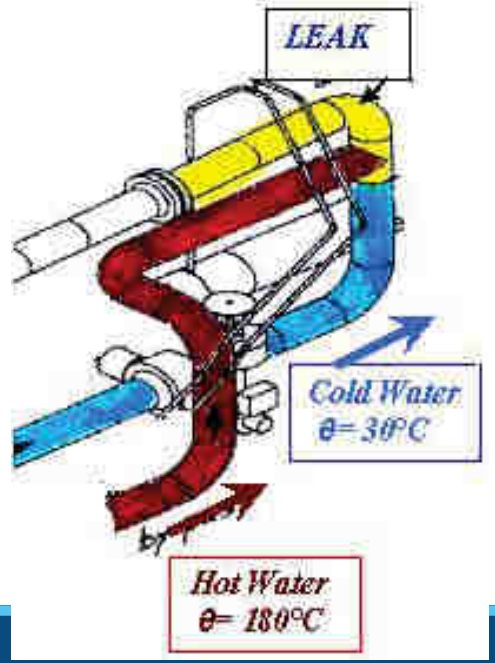
2. French Civaux plant experience

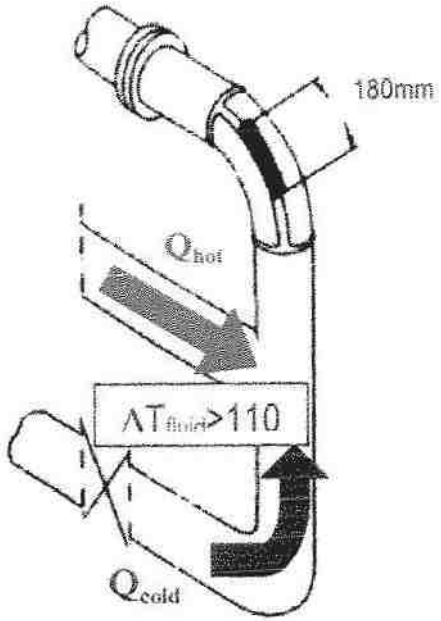
The event

10mm through wall crack in the Residual Heat Removal System (RHRS), in 1998:

- 180mm length longitudinal crack at the extrados of the bend
- Damages in the mixing tee and in the straight sections

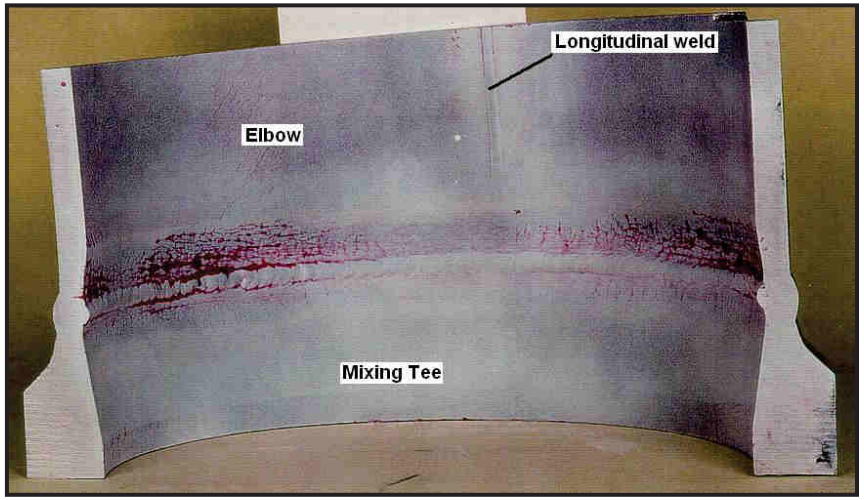


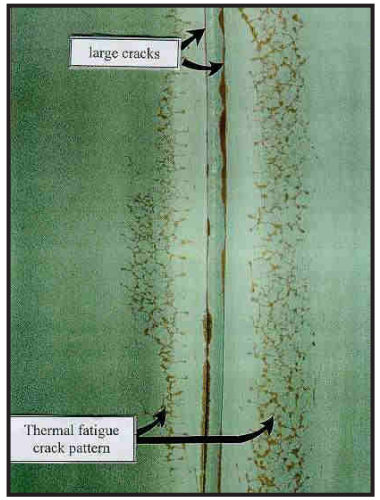


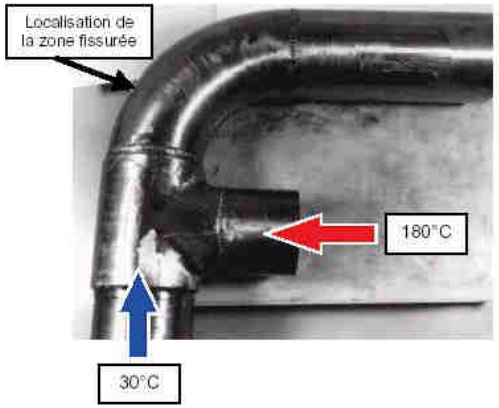


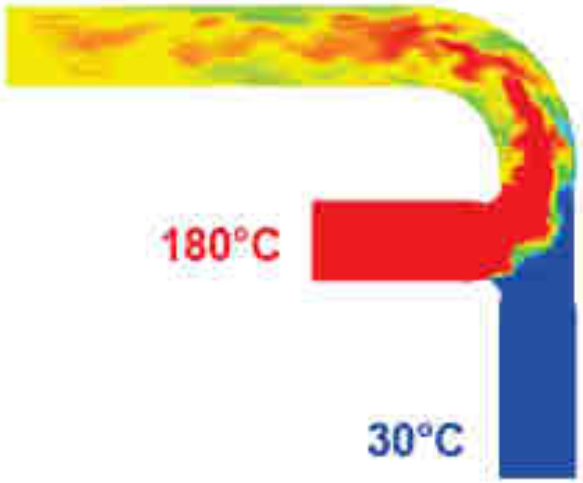
2. French Civaux plant experience

The expertises







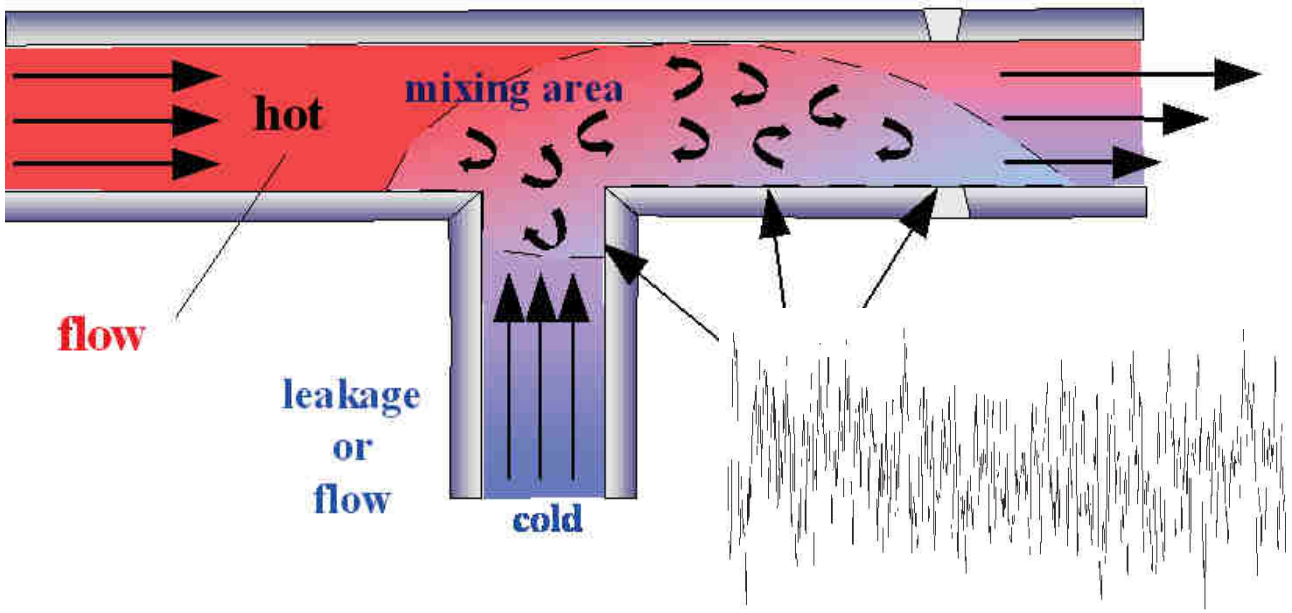


2. French Civaux plant experience

Thermal fatigue in mixing zones

Governing parameters for damage:

- Temperature difference ΔT between hot and cold fluids
- Flow rate ratio β between both fluids
- Associated time

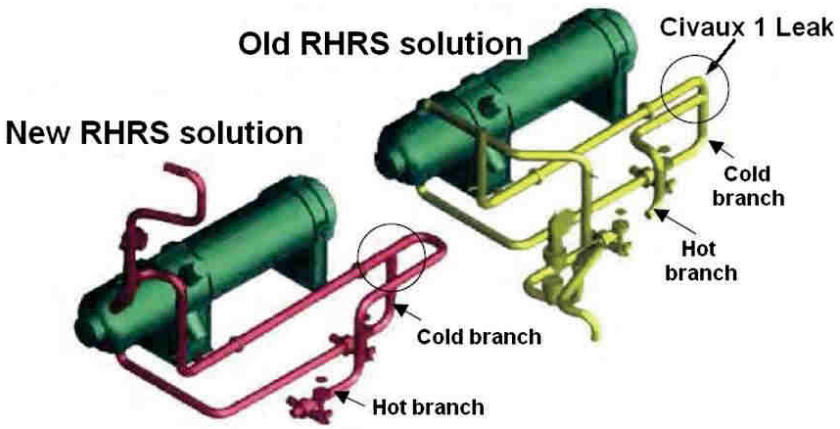


2. French Civaux plant experience

Consequences of the Civaux event

For the utility:

- Inspection of mixing areas
- Replacement of damage areas
- Definition of a maintenance program



For the designer:

- Geometrical improvements:
  flushed welds, specified surface roughness
- Specific geometrical dispositions
- Functional improvements to reduce ΔT and associated time

→ Need to be able to determine, qualitatively at least, the sensible areas

2. French Civaux plant experience

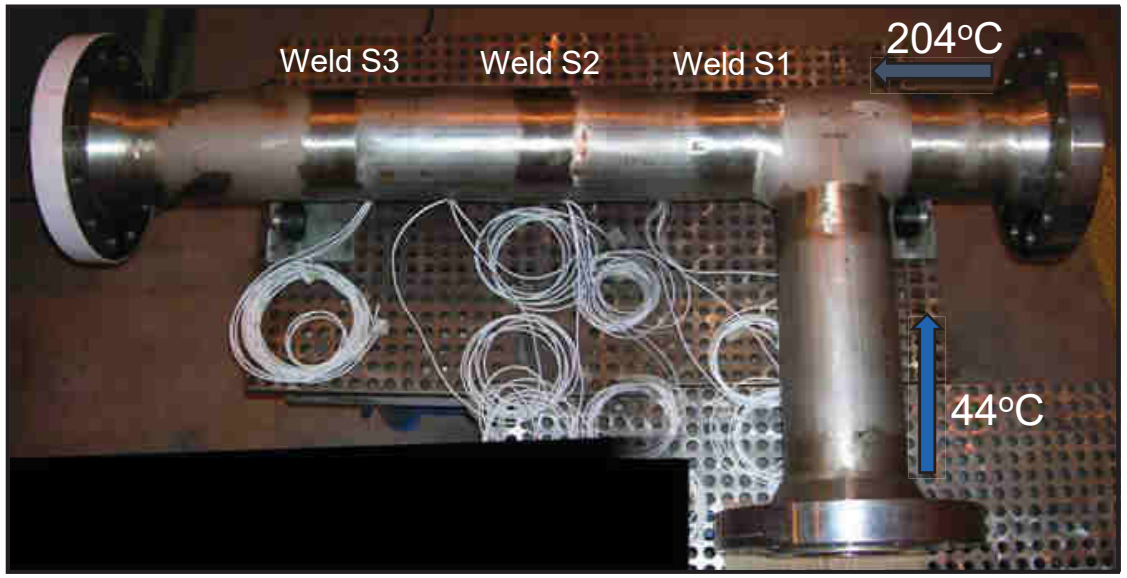
FATHER R&D program

Representative mock-up of the new RHRS mixing tee
in the framework of Framatome / CEA / EDF R&D actions

Fine analyses of surface roughness effects:
polishing, grinding,
weld grinding flush or not

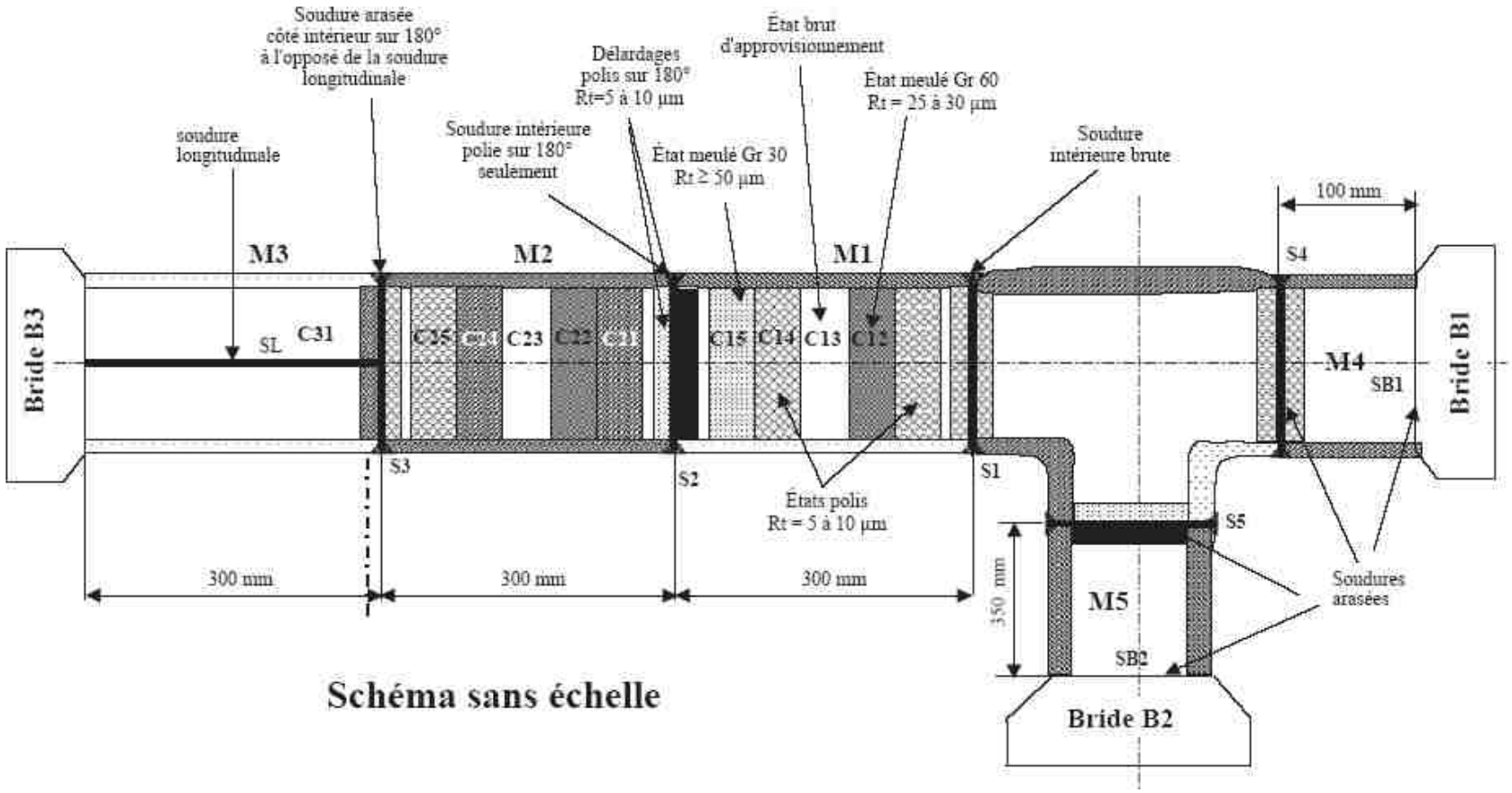
Test conditions:

- **ΔT = 160°C**
- **Flow ratio = 20%**
- **Test duration = 300h**



2. French Civaux plant experience

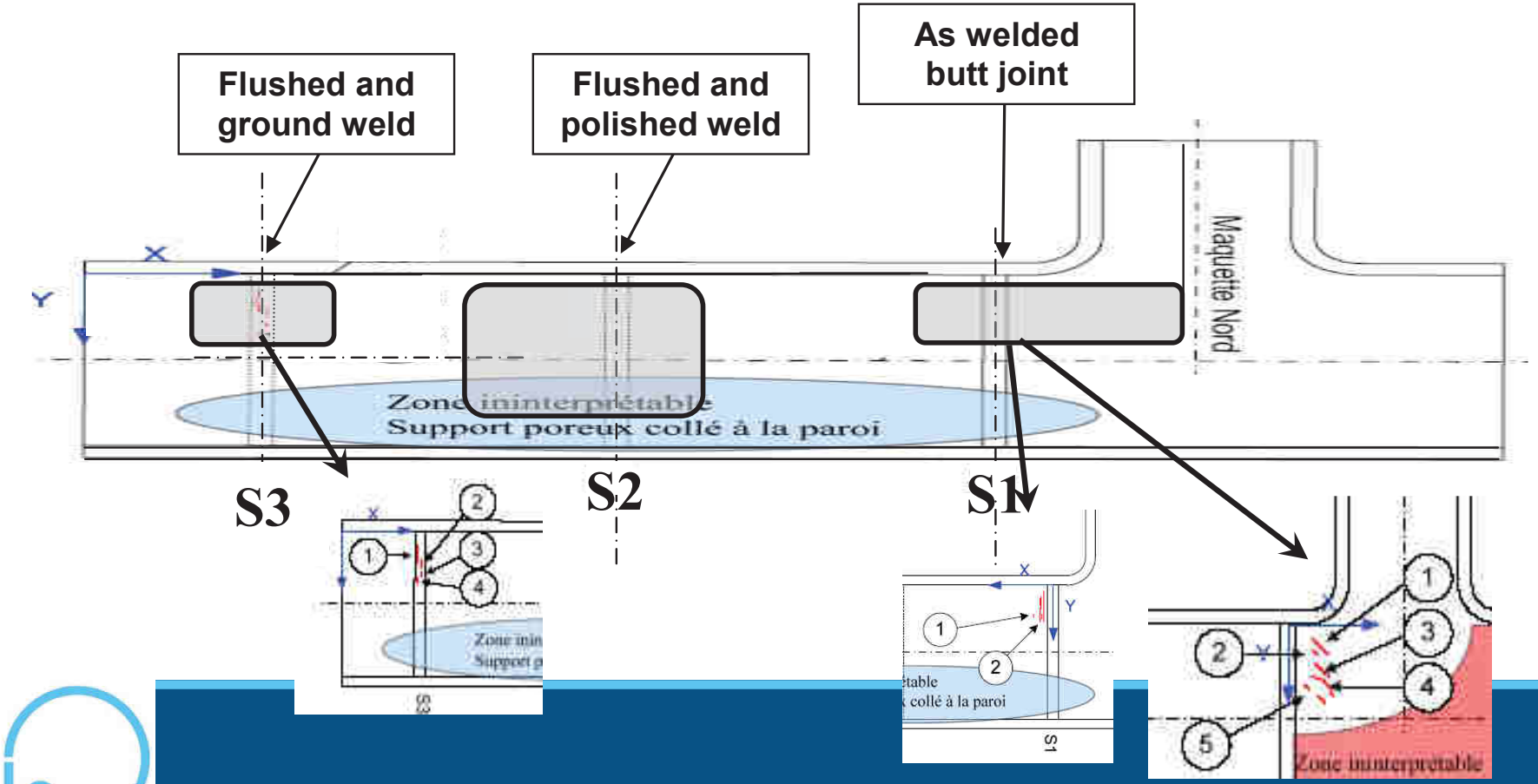
FATHER R&D program



2. French Civaux plant experience

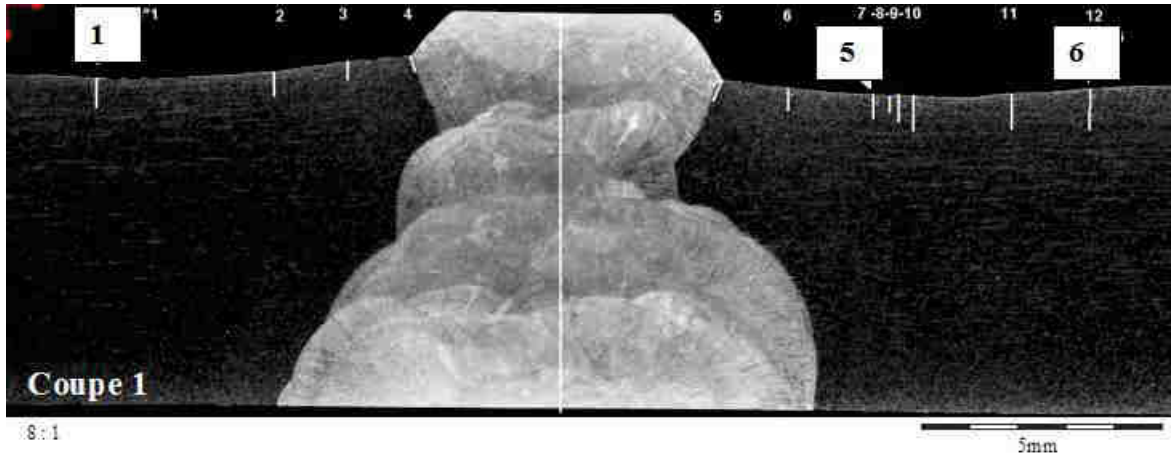
FATHER R&D program

Non destructive examination and identification of the zones with defects



2. French Civaux plant experience

FATHER R&D program



Cliché K : fissure 8

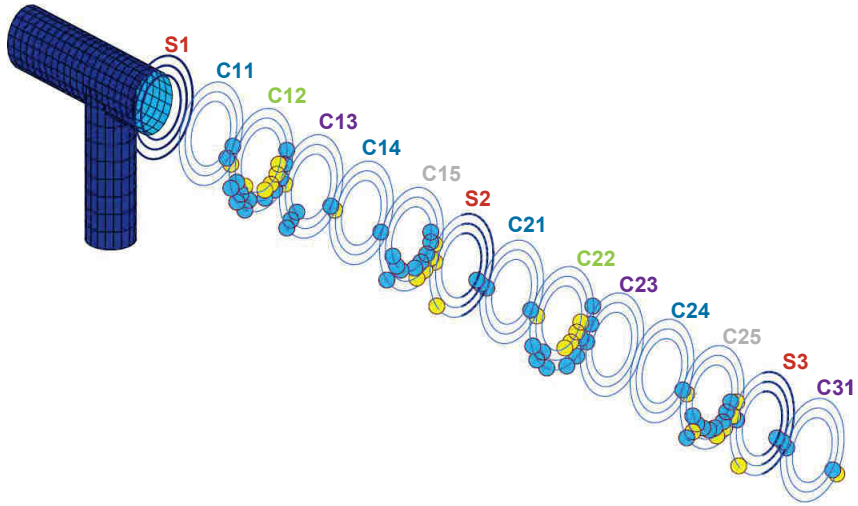
2. French Civaux plant experience

FATHER R&D program

Main results:

- Fatigue cracks in the vicinity of non flushed welds and ground zones
- No crack for polished zones (pipe and welds)

Better understanding
of the thermal-hydraulic phenomena,
particularly of the heat exchange
between the fluid and the wall



2. French Civaux plant experience

French Engineering approach for mixing zones

Objectives to simply classify the mixing areas in terms of risk and to provide an estimation of damage

Two level analysis:

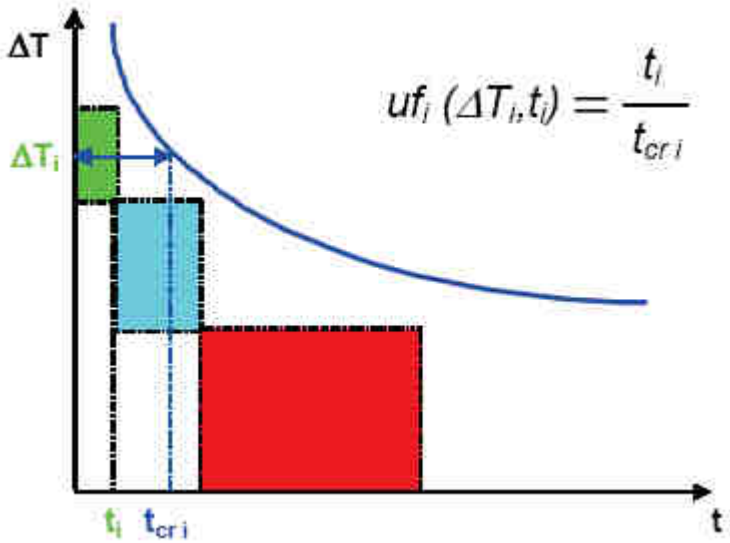
- 1st level : Screening criterion

  No risk if $\Delta T_{max} < 50°C$

- 2nd level : Engineering tool

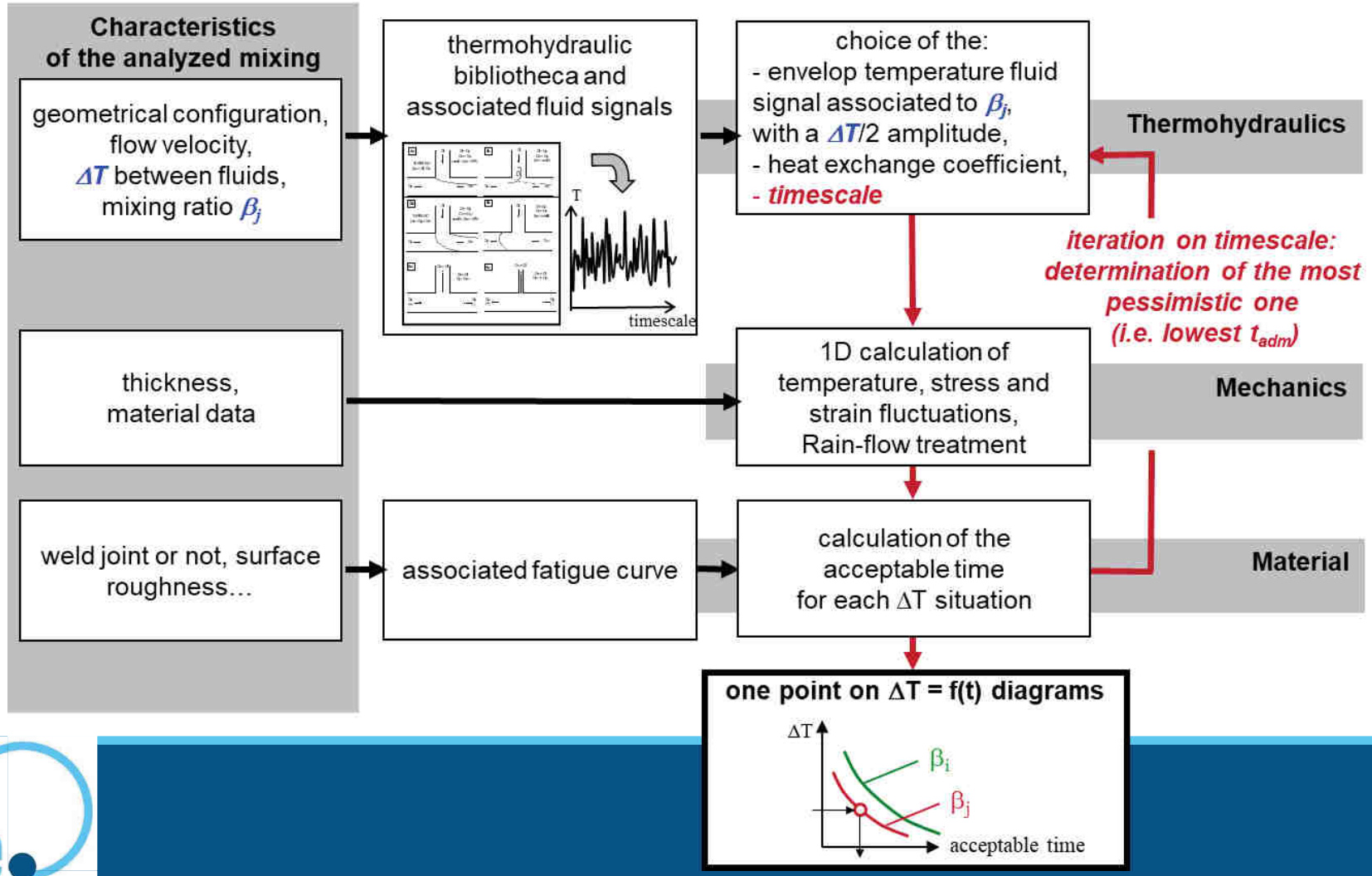
  - List of the operating conditions (ΔT and associated time)

  - Calculation of an usage factor uf(ΔT) by comparison of the operating time to the acceptable time for the same ΔT (ΔT vs time diagrams)



2. French Civaux plant experience

French Engineering approach for mixing zones



2. French Civaux plant experience

Application to the FATHER case

Assumptions:

- Conservative fluid temperature signal and heat exchange coefficient
- ΔT = 160°C during 300h

Results:

	Initiation time	Damage
Polished and finely ground surfaces (ASME A curve)	209h	1.44
As-machined and roughly ground surfaces (ASME C curve)	169h	1.78
Non-flushed welds (ASME C curve + weld reduction factor)	18h	16.67

Conservatism of the approach:

- Damage parameter much greater than 1 for non-flushed welds
- Damage parameter greater than 1 for polished zones but no crack really observed

2. French Civaux plant experience

Application to the French Civaux plant case

Assumptions:

- Conservative fluid temperature signal and heat exchange coefficient
- Conservative fatigue curve
- ΔT = 135°C during 1 500h

Damage parameter = 14
= ratio between the operating time (1 500h) and the crack initiation time predicted

→ Conservatism of the engineering approach

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3. RCC-M new rules for EAF

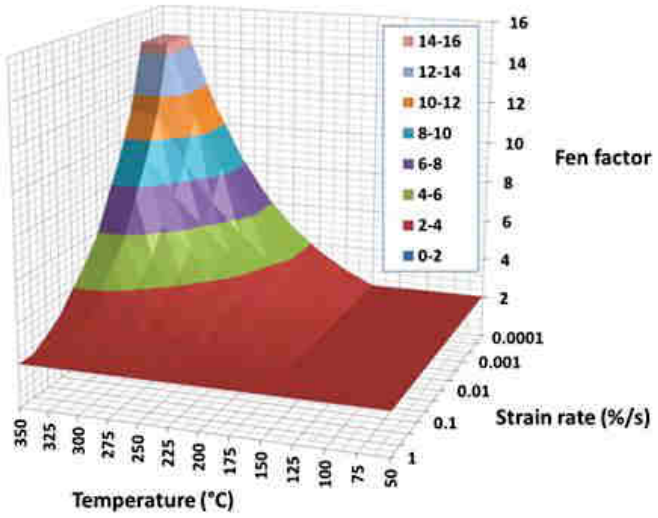
International context in 2007

Release of the Rev. 0 of the US NUREG/CR-6909 report addressing EAF issues

Fen factor proposals
to take into account fatigue lifetime reduction in PWR water observed on specimens in laboratory tests mainly for:
high temperatures, low strain rates, particular O_2 contents

$$Fen = \frac{N_{air}\ (in\ air\ lifetime)}{N_{water}\ (in\ water\ lifetime)} > 1$$

Fen values
for austenitic stainless steels



3. RCC-M new rules for EAF

International context in 2007

EAF cumulative usage factor via the multiplication
of the in-air partial usage factors
by the corresponding Fen penalty factors

$$U_{en} = \sum_{1}^{n} F_{en,i} \, U_i$$

→ For the utility and the designer,
possible significant increase in the final usage factors

→ Considering the good operating feedback,
need to better understand EAF in industrial conditions…

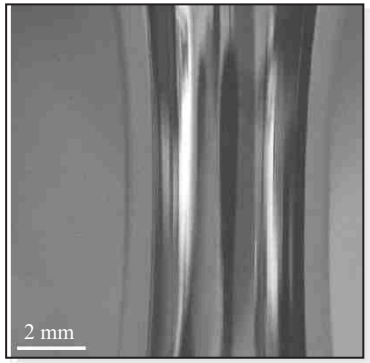
… that will lead to the Rule in Probation Phase (RPP)
addressing EAF for austenitic stainless steels in the 2016 RCC-M edition

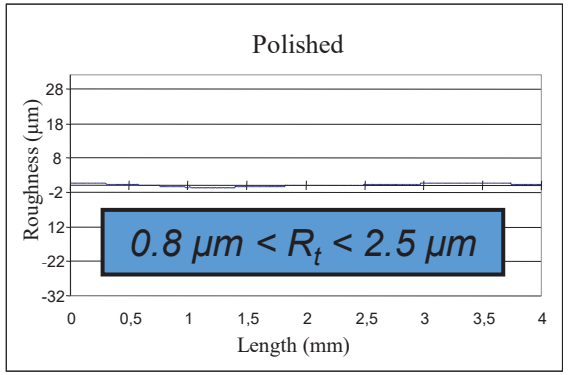
[PVP2008-61894], [PVP2009-78129], [PVP2010-26027], [PVP2015-45158], [PVP2016-63127]

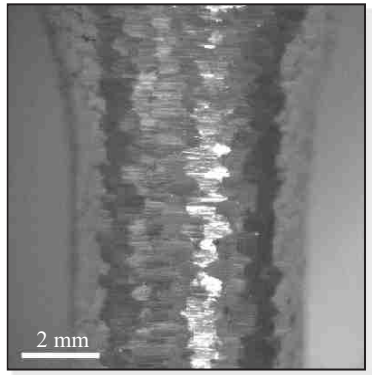
3. RCC-M new rules for EAF

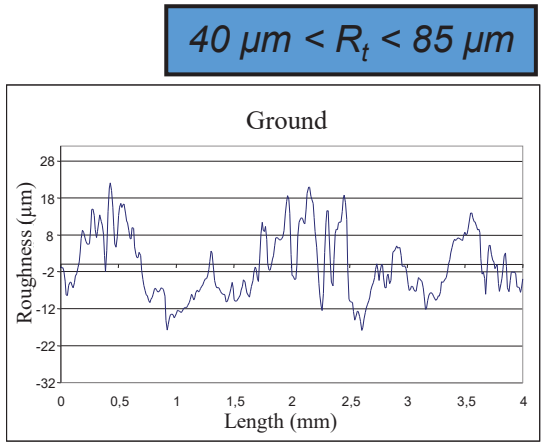
The Framatome (former AREVA) R&D EAF test campaign

Representative industrial surface finish



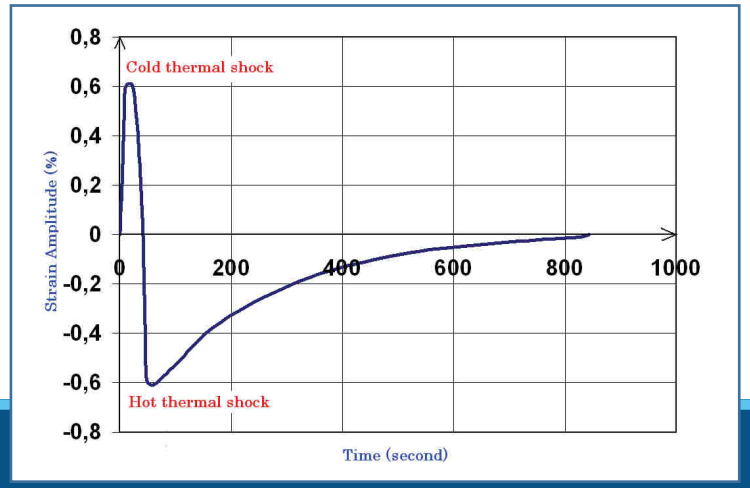






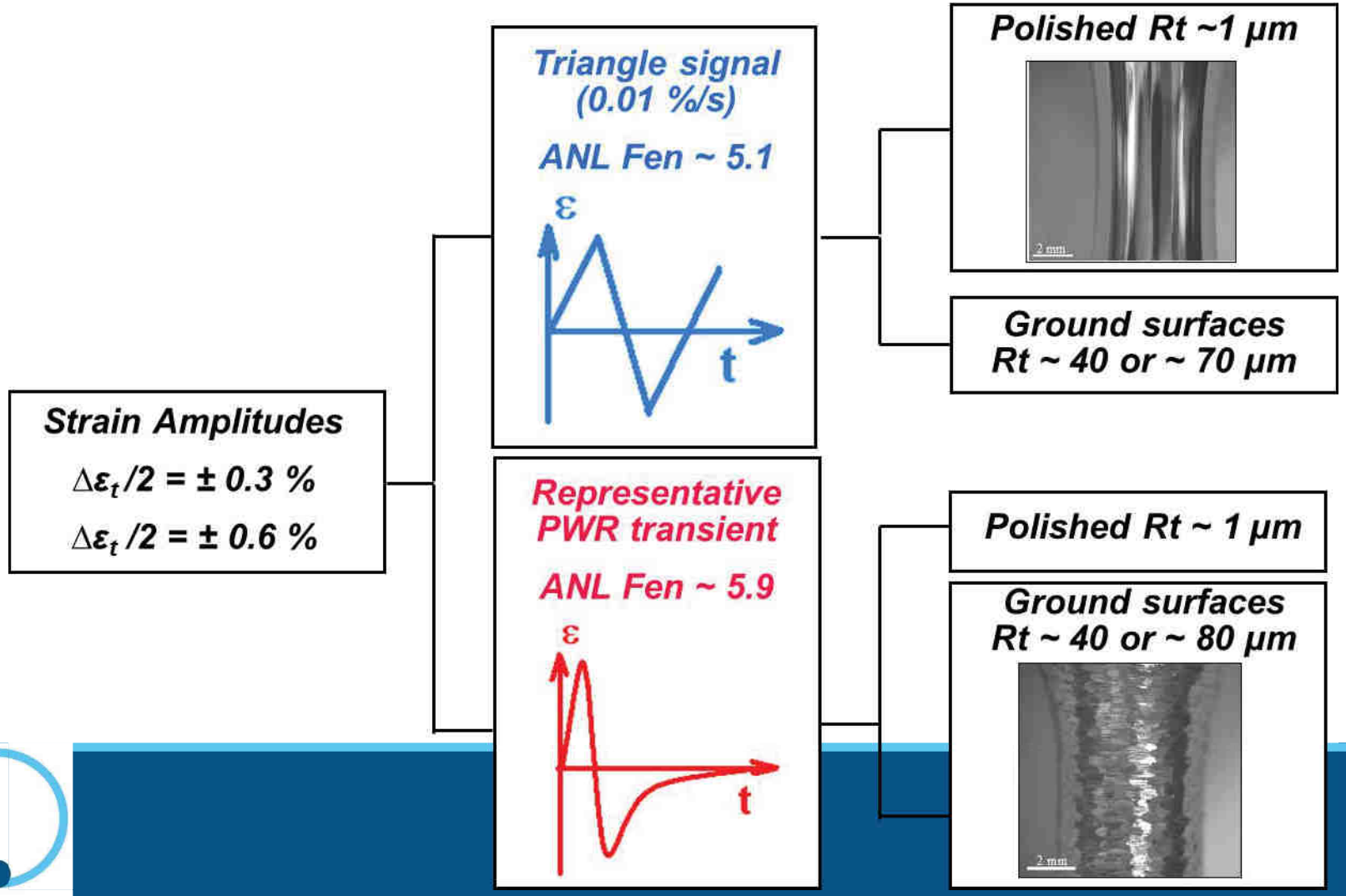
Representative loading signal
typical of operating transients

Pessimistic loading in terms of environmental effects
because of 300°C isothermal conditions



3. RCC-M new rules for EAF

The Framatome (former AREVA) R&D EAF test campaign



3. RCC-M new rules for EAF

The Framatome (former AREVA) R&D EAF test campaign

Strain-controlled LCF tests PWR environment at 300°C		Surface finishing		
Strain amplitudes $\Delta\varepsilon_t/2 = \pm 0.3\%$ or $\pm 0.6\%$		Polished	Ground	
Loading signal	Fully reverse triangle			Fen ~5.1
	Representative PWR loading			Fen ~5.9

Laboratories LCF test conditions

PWR components loading conditions

Environmental effects of the tests assessed through the NUREG/CR-6909 approach

3. RCC-M new rules for EAF

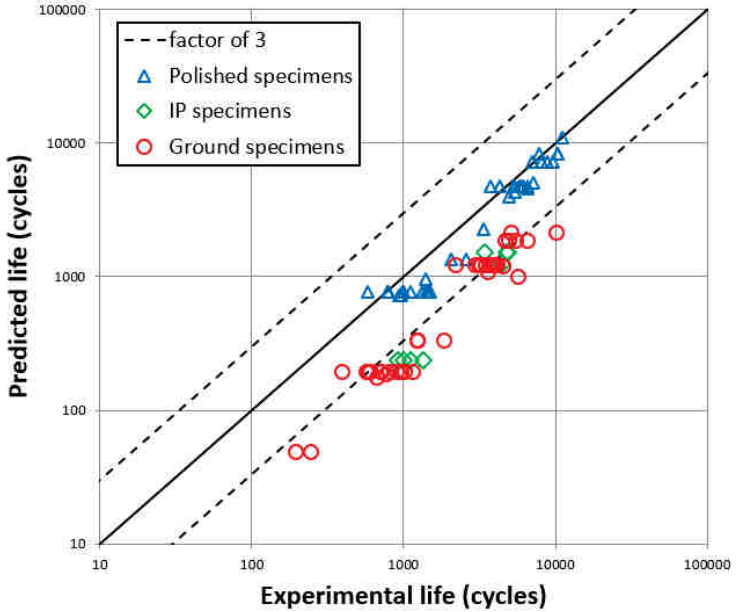
The Framatome (former AREVA) R&D EAF test campaign

Main results:

- Over-conservatism of the NUREG/CR-6909 approach for industrial conditions: surface finish, operating transients
- Appreciable part of the environmental effects already covered by the codified design curves

→ Concept of integrated Fen factor
(taken equal to 3 in the 2016 RCC-M RPP)

Similar results obtained in the INCEFA-PLUS project



3. RCC-M new rules for EAF

RCC-M RPP addressing EAF for austenitic stainless steels

Objective to follow the international state of the art
but with optimizations to propose a reasonably conservative EAF codified method

Optimizations supported by test campaigns in more representative industrial conditions

Methodology:

- 1st step: Performing conventional RCC-M fatigue analyses
- 2nd step: Using screening criteria to select the zones to treat with the EAF methodology
- 3rd step: Assessing theoretical Fen factors using a NUREG/CR-6909 type approach
- 4th step: Comparing these results with the integrated Fen values considered as covered
- Possible 5th step: Performing an environmental correction on the initial usage factor if acceptability criteria in terms of Fen factors are not fulfilled

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4. INCEFA-SCALE advances on modelling and assessment rules

The WP4 on modelling

WP4 objective to derive an environmental assisted fatigue model
from the data and mechanistic understanding obtained through others WPs,
and particularly, guidance for assessors wishing to extrapolate laboratory test results
to real plant conditions and component geometries

5 sets of analyses identified in the modelling plans:

- Test modelling, to guide test campaign and provide stress/strain fields for modelling actions
- Statistical analyses, to guide test campaign and modelling actions,
  by identifying the main parameters influencing fatigue life
- Analyses about the current codified methods, to strengthen their robustness
- Fatigue damage modelling, to propose non-codified methods
  to better address for EAF damage mechanisms
- Application to an industrial case, to consolidate the validation of the methods

4. INCEFA-SCALE advances on modelling and assessment rules

Overview of the modelling plans – Test modelling

N#	TASKS	OBJECTIVES	INPUTS	OUTPUTS	PLANNING	CONTRIBUTORS
1.1	Elastic-plastic FEA about the WP3.3 tests on solid specimens (phases 1, 2 and 3)	- Identify a simple common material modelling cyclic behavior - Obtain stress/strain fields throughout the specimen	Specimen geometries and test conditions from WP3	- Stress/strains fields for nucleation and crack growth analyses (see #4.1)	2022-2023	Each partner carrying out FEA with its own solver
1.2	Elastic-plastic FEA about the WP3.3 and WP3.4 tests on hollow specimens (phases 1, 2 and 3)	- Obtain stress/strain fields throughout the specimen - Examine the effects of geometry and internal pressure - Ratchetting evaluation		- Stress/strains fields for nucleation and crack growth analyses (see #4.2) - Guidance for the WP3.3 and WP3.4 test design and interpretation	2022-2024	- FRAMATOME France - JACOBS / ROLLS ROYCE - PSI
1.3	Elastic-plastic FEA about the WP3.4 multiaxial tests (phases 2 and 3)	- Obtain stress/strain fields throughout the specimen		- Stress/strains fields for nucleation and crack growth analyses (see #4.3) - Guidance for the WP3.4 test design and interpretation	2022-2024	- CEA - JACOBS / ROLLS ROYCE
1.4	Elastic-plastic FEA about the WP3.4 tests on notched specimens (phases 2 and 3)	- Obtain stress/strain fields throughout the specimen		- Stress/strains fields for nucleation and crack growth analyses (see #4.4) - Guidance for the WP3.4 test design and interpretation	2022-2024	- FRAMATOME France - Maybe JACOBS / ROLLS ROYCE and/or KTU

4. INCEFA-SCALE advances on modelling and assessment rules

Overview of the modelling plans – Statistical analyses

N#	TASKS	OBJECTIVES	INPUTS	OUTPUTS	PLANNING	CONTRIBUTORS
2.1	To use and to implement/modify the WP2 statistical tool	- Identify the impact of variable amplitude loading and the possible interaction with environmental and surface roughness effects	Test conditions and fatigue lives from WP3	- Support to guide WP3 phases 2 and 3 - Support to guide WP4 analyses (about the codified methods and fatigue damage modelling) - Modelling results for WP6	2022-2025	INESCO

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4. INCEFA-SCALE advances on modelling and assessment rules

Overview of the modelling plans – Codified methods

N#	TASKS	OBJECTIVES	INPUTS	OUTPUTS	PLANNING	CONTRIBUTORS
3.1	Fatigue life comparison between ASME/JSME/RCC-M predictions and experimental data (WP3.3 uniaxial and WP3.4 multiaxial tests)	- Examine the ASME/RCC-M conservatisms - Test the methods for addressing VA loading - Test the mean stress Goodman correction - Reassess the $F_{en\text{-}threshold}$ criterion in VA loading - Compare ASME with RCC-M and JSME	- Test conditions and fatigue lives from WP3 - Results of statistical analyses (see #2)	- Support to guide WP3 phases 2 and 3 - Methods for the application on an industrial case (see #5) - Modelling results for WP6	2022-2025	- CEA - EDF - JACOBS / ROLLS ROYCE - JRC
3.2	Fatigue life comparison between ASME predictions and WP3.4 tests on notched specimens	- Examine the ASME conservatisms - Review the Fatigue Strength Reduction Factor (FSRF)			2023-2025	JACOBS / ROLLS ROYCE
3.3	Fatigue life comparison between RCC-M predictions and WP3.4 tests on notched specimens	- Examine the RCC-M conservatisms			2023-2025	FRAMATOME France
3.4	Analyses on WP3.3 uniaxial tests and WP3.4 multiaxial tests using the best fit mean air fatigue curve	- Test the methods for addressing VA loading - Test the Miner linear damage accumulation rule - Test the methods for assessing the Fen factor			2022-2025	- CEA - EDF - JACOBS / ROLLS ROYCE

4. INCEFA-SCALE advances on modelling and assessment rules

Overview of the modelling plans – Fatigue damage modelling

N#	TASKS	OBJECTIVES	INPUTS	OUTPUTS	PLANNING	CONTRIBUTORS
4.1	Nucleation and crack growth analyses about the WP3.3 tests on solid specimens	- Test the methods - Identify the modelling parameters according to the approaches (nucleation or crack growth stages)	- Test conditions and fatigue lives from WP3 - Striation counting and/or DCPD measurements from WP5 - Stress and strain fields from test modelling (see #1.1 to 1.4) - Results of statistical analyses (see #2)	- Support to guide WP3 phases 2 and 3 - Methods for the application on an industrial case (see #5) - Modelling results for WP6	2023-2025	- JACOBS / ROLLS ROYCE - KTU
4.2	Nucleation and crack growth analyses about the WP3.3 and WP3.4 tests on hollow specimens				2023-2025	- FRAMATOME France - JACOBS / ROLLS ROYCE
4.3	Nucleation and crack growth analyses about the WP3.4 multiaxial tests				2023-2025	- JACOBS / ROLLS ROYCE - KTU
4.4	Nucleation and crack growth analyses about the WP3.4 tests on notched specimens				2023-2025	- JACOBS / ROLLS ROYCE - UC - Maybe EDF and/or FRAMATOME France

4. INCEFA-SCALE advances on modelling and assessment rules

Overview of the modelling plans – Industrial case

N#	TASKS	OBJECTIVES	INPUTS	OUTPUTS	PLANNING	CONTRIBUTORS
5.1	Analyses about the EPRI component test	- Validate INCEFA SCALE results on an industrial case - Benchmark between partners	- Test conditions and results from EPRI - Methods from #3 and #4 WP4 tasks	Modelling results for WP6	2024-2025	- EDF - INESCO - JACOBS / ROLLS ROYCE - KTU

4. INCEFA-SCALE advances on modelling and assessment rules

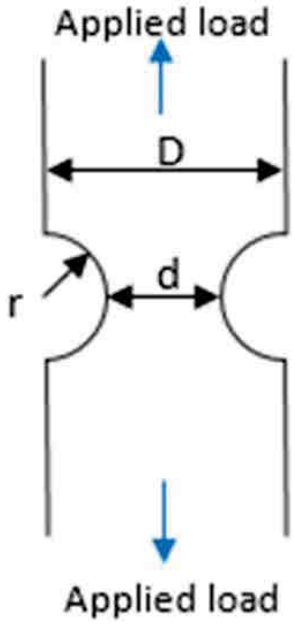
Example of the test modelling on notched specimens

To guide WP3.4 tests whose objectives are:

- To obtain better understanding of crack initiation & growth in a stress concentration area
- To determine the reliability of design rules for stress concentration areas

3 design parameters in the notched specimens:

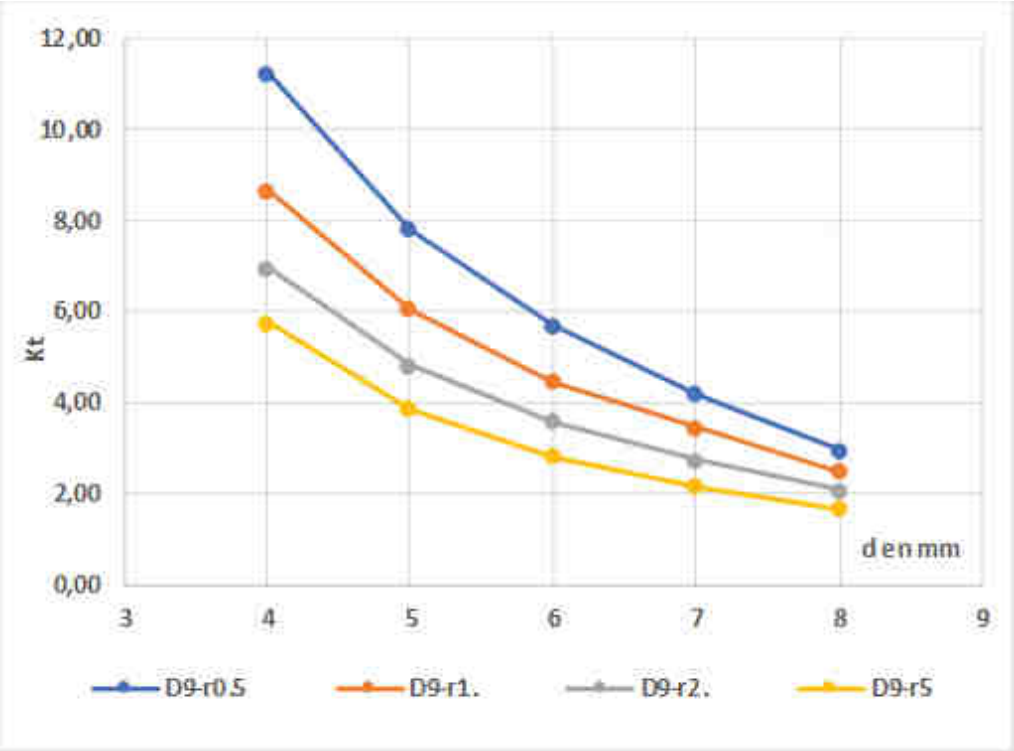
- The nominal diameter D
- The reduced diameter d, or the reduction of section $\Delta = D/d$, controlling the stress concentration Kt
- The radius of the notch r, governing the triaxiality state Tr

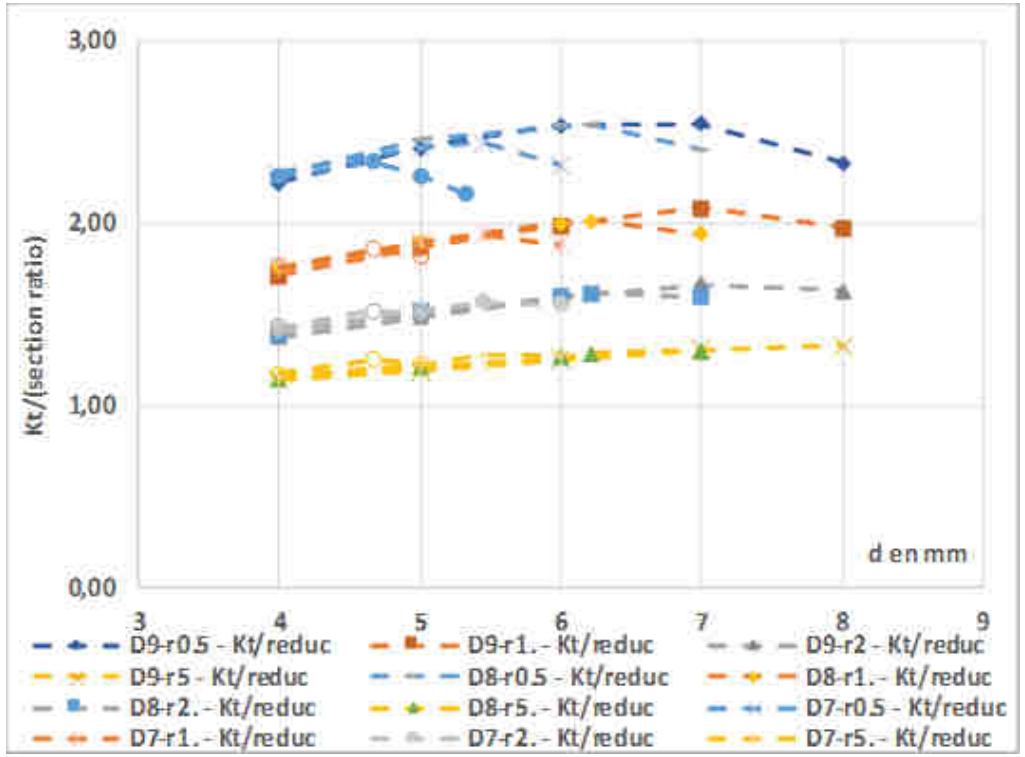


4. INCEFA-SCALE advances on modelling and assessment rules

Example of the test modelling on notched specimens

Kt and Tr assessments through elastic finite elements calculations





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4. INCEFA-SCALE advances on modelling and assessment rules

Example of the test modelling on notched specimens

Proposal of a 1st set of geometry to study the scale effect (various D diameter values):

- Δ ratio equal to 1.29
- r radius equal to 0.5 mm

→ Kt values between 3.8 and 4.2

→ Tr values between 2.3 to 2.6

D	d	r	Kt	Kt/section ratio
mm	mm	mm		
9	7	0,5	4,20	2,54
8	6,22	0,5	4,19	2,53
7	5,44	0,5	4,02	2,43
6	4,67	0,5	3,86	2,33

Proposal of a 2nd set of geometry,
also to study the scale effect, but to experimentally analyze the triaxiality effect as well:

- Δ ratio still equal to 1.29
- r radius now equal to 2 mm

→ Kt values between 2.5 and 2.7

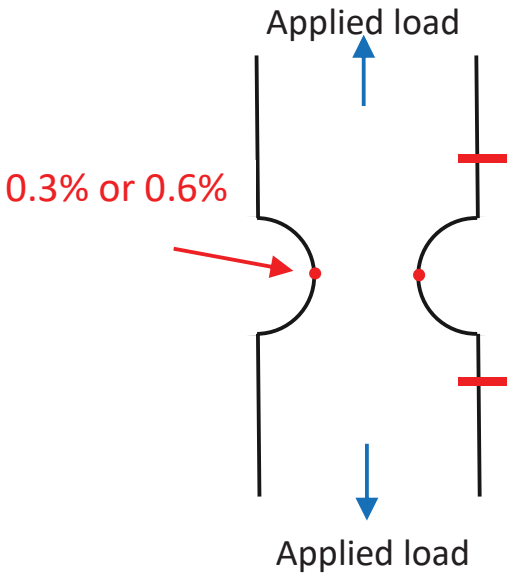
→ Tr values between 1.5 and 1.7

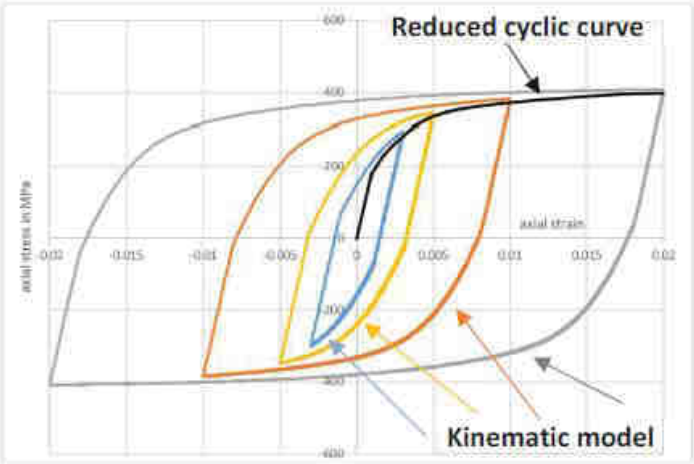
D	d	r	Kt	Kt/section ratio
mm	mm	mm		
9	7	2	2,74	1,66
8	6,22	2	2,67	1,61
7	5,44	2	2,59	1,57
6	4,67	2	2,51	1,52

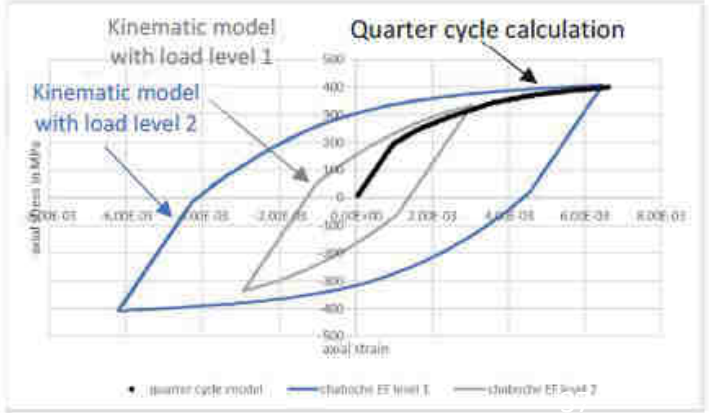
4. INCEFA-SCALE advances on modelling and assessment rules

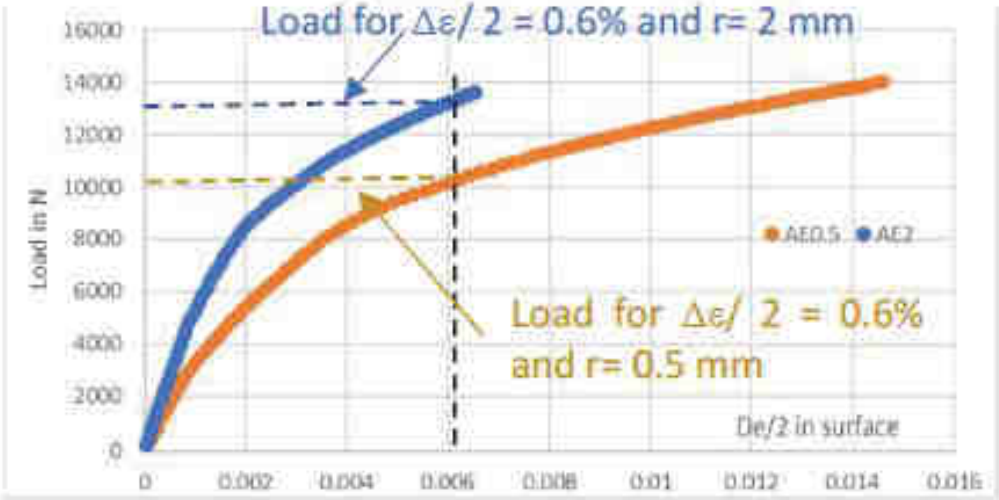
Example of the test modelling on notched specimens

Calibration of the load level to apply in the tests through elastic-plastic calculations









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5. Conclusions

5. Conclusions

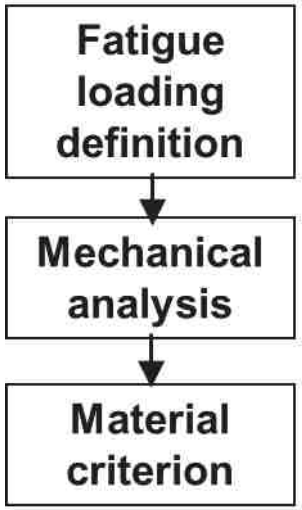
R&D results must be systematically promoted in industry practice but keep in mind the difficulties to be faced:

- The long timescale required for R&D actions to understand the mechanisms
- The emergency related to industrial issues

→ **Safety first for nuclear applications**

Recommendations:

- Multi-disciplinary exchanges between thermal-hydraulics, mechanics and materials, to optimize each link of the engineering fatigue analyses
- Multi-disciplinary exchanges to be consistent between design assumptions, manufacturing and operating



Thank you!

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