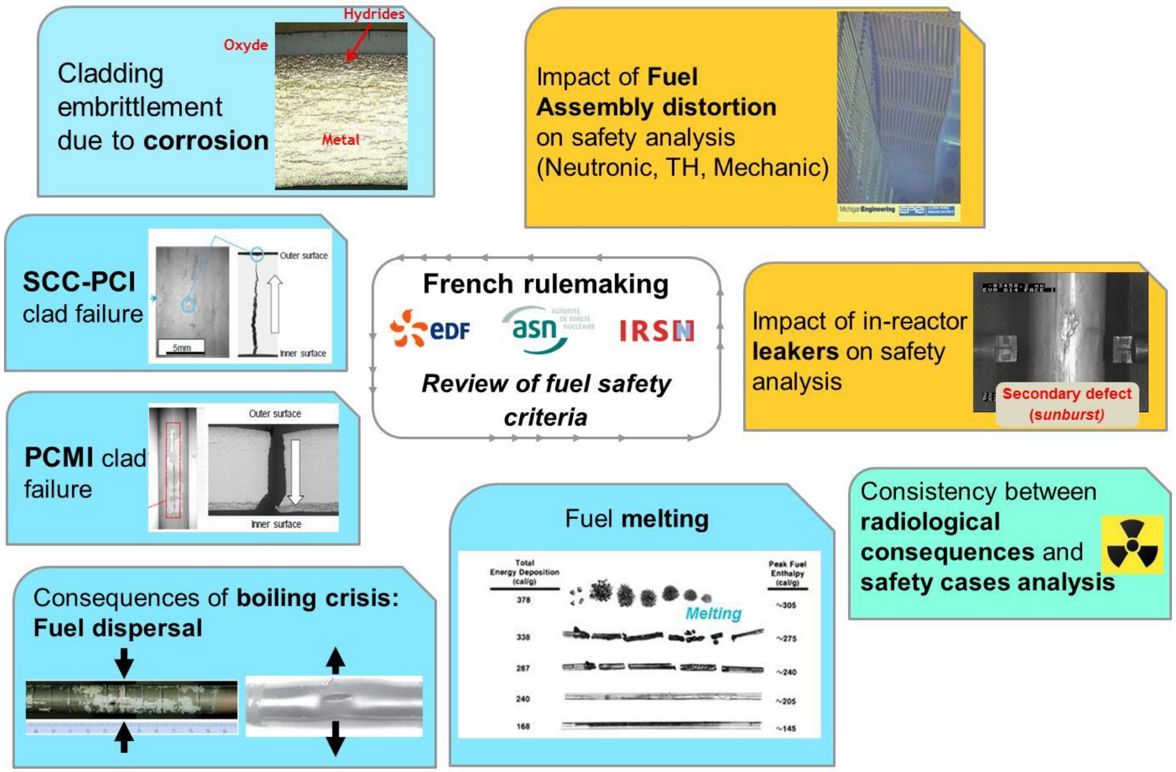
Sandrine BOUTIN *– Stéphanie GRAFF – Aude TAISNE – Olivier DUBOIS*

REVIEW OF FUEL SAFETY CRITERIA IN FRANCE



AGENDA

1. **About French rulemaking**
2. **Review of all acceptance criteria in France**
3. **Summary**

ABOUT FRENCH RULEMAKING

- **US requirements** were adopted in France **at the start of the French PWR nuclear program**
- **Numerous international research programs** have addressed the fuel behavior especially during Loss Of Coolant Accident (LOCA) and Reactivity Initiated Accident (RIA) conditions

  ➲ **improving the calculation methods and knowledge**
- The **discharge burn-up** of the fuel rods **has increased notably** compared to the situation forty years ago (FA BU_{limit} = 52 GWd/tU except for EPR : 58 GWd/tU)

  ➲ increasing oxide thickness and higher hydrogen pick-up in the cladding material which **influence fuel rod behavior under incidental and accidental conditions**

ABOUT FRENCH RULEMAKING

- **New cladding materials** characterized by **enhanced performances** (i.e. cladding corrosion in normal operating conditions) have been introduced in French reactors ➲ **M5** (AREVA), **ZIRLO** and **Optimized ZIRLO** (Westinghouse)

- **Fresh Zy-4 is no longer loaded in EDF's reactors**

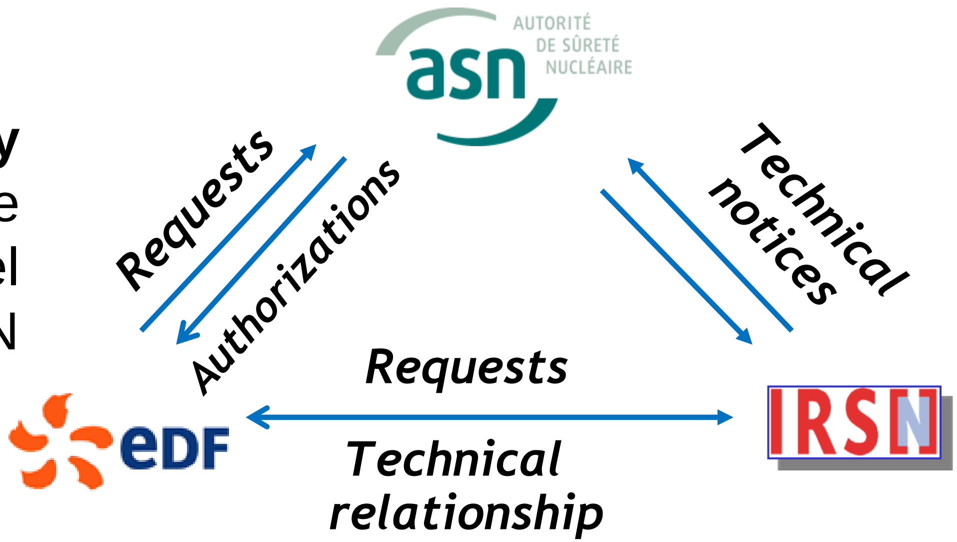
Clad material	First Reloads	Generalization
M5	2000	2014
ZIRLO	∅	2006
Optimized ZIRLO	2009	In 2017, EDF has asked for authorization

- **Operating conditions of French plants have changed,** notably by stretch-out operating conditions

ABOUT FRENCH RULEMAKING

- Because of these evolutions, the **French Nuclear Safety Authority** (**ASN**) decided to review fuel safety criteria especially those addressing LOCA and RIA

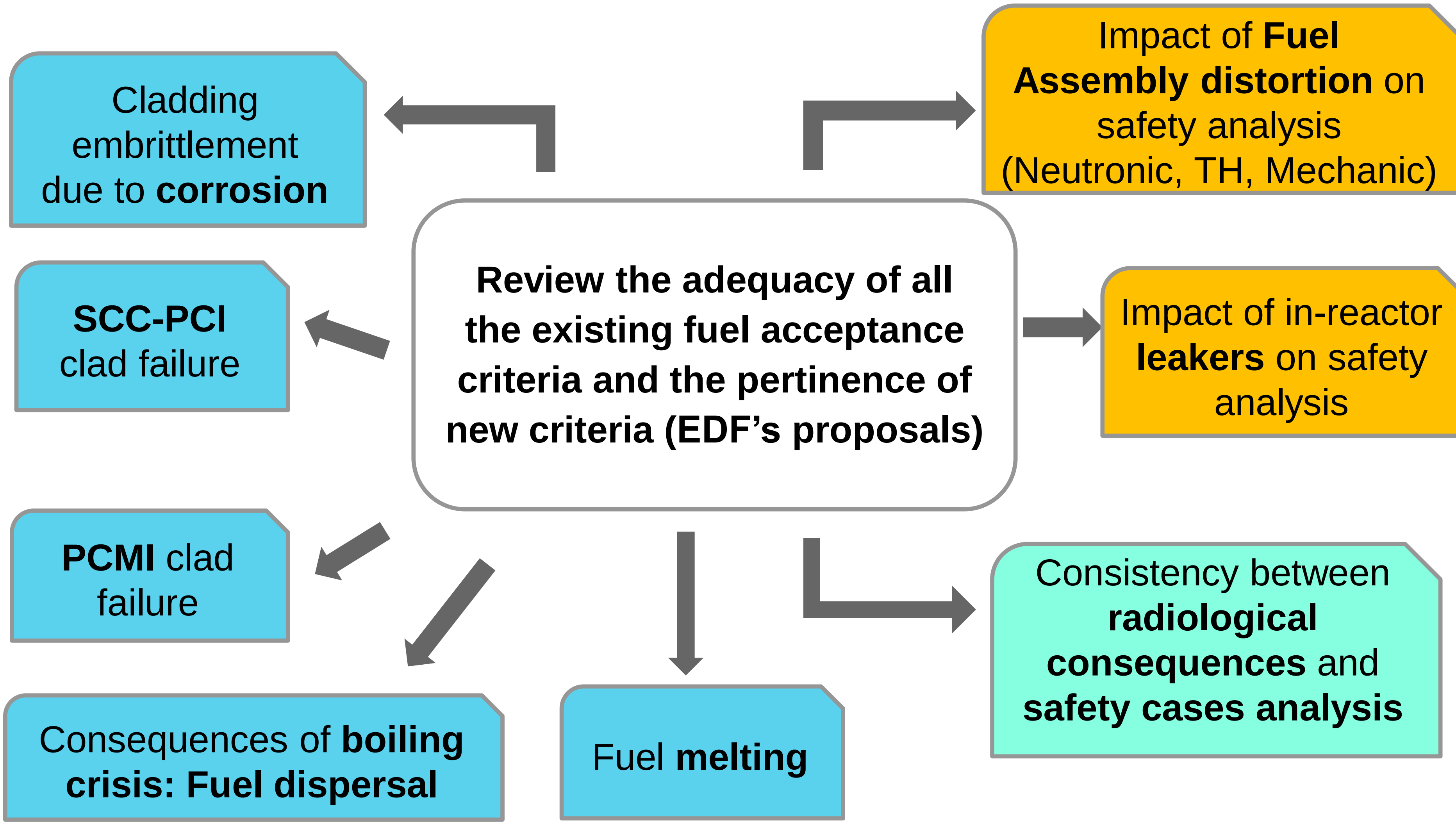
- The **French regulatory framework** is specific: the French utility **EDF** proposed fuel safety criteria submitted to ASN which were assessed by **IRSN**



- The **review** of **fuel safety criteria** took place from 2011 to 2017 except for LOCA *(review from 2008 to 2014 - see* ***Eurosafe 2016****)*

- **June 2017**: meeting of the **Advisory Committee for Reactors Safety** of ASN about the **French rulemaking on fuel safety criteria** related to PCC-1, PCC-2, PCC-3 and PCC-4

REVIEW OF ALL FUEL ACCEPTANCE CRITERIA IN FRANCE



REVIEW OF ALL FUEL ACCEPTANCE CRITERIA IN FRANCE

Review the adequacy of all the existing fuel acceptance criteria and the pertinence of new criteria (EDF's proposals)

- Cladding embrittlement due to **corrosion**
- **SCC-PCI** clad failure

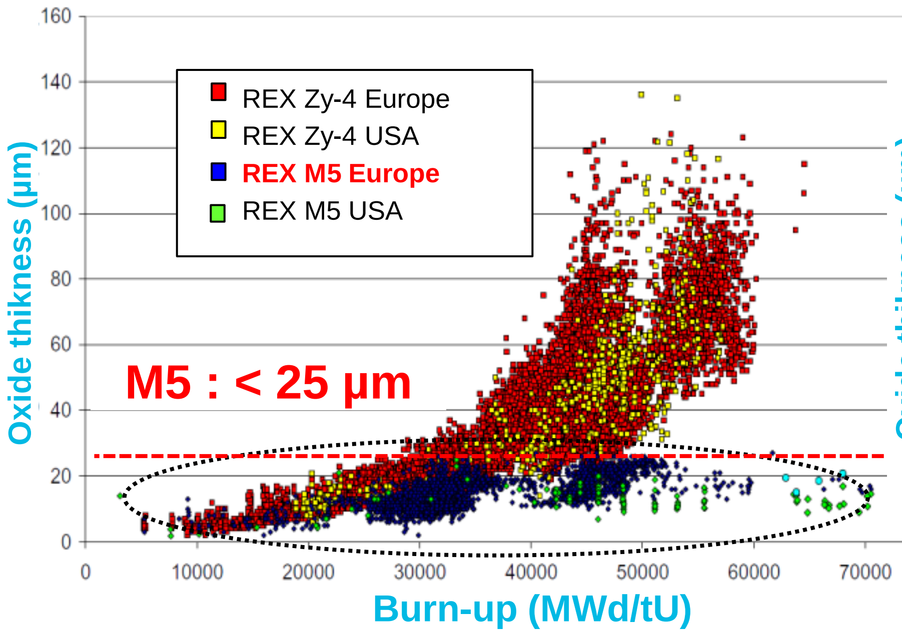
  See N. Waeckel presentation at FSRM 2017
- **PCMI** clad failure
- Consequences of **boiling crisis: Fuel dispersal**
- Fuel **melting**
- Consistency between **radiological consequences** and **safety cases analysis**
- Impact of in-reactor **leakers** on safety analysis

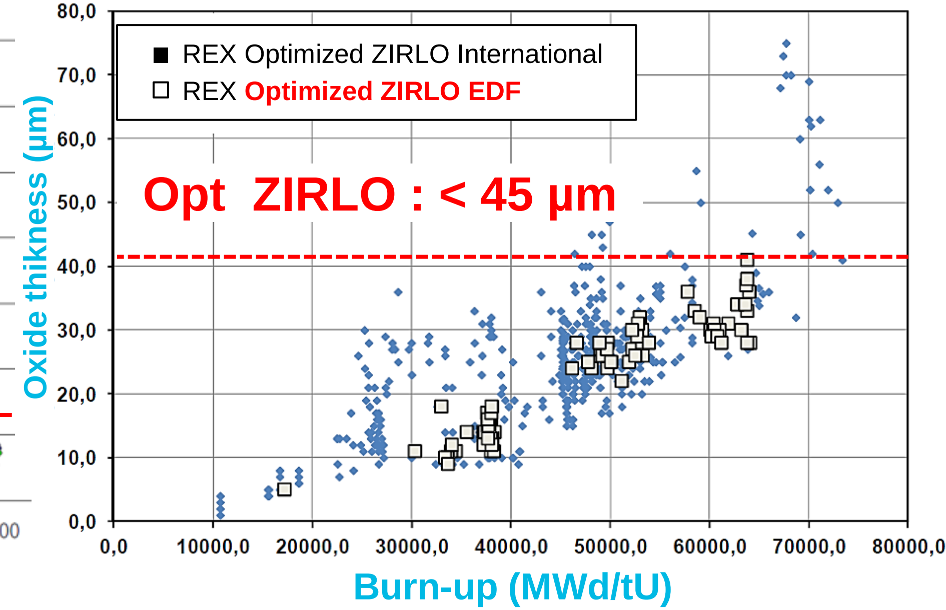
  See N. Waeckel presentation at FSRM 2017
- Impact of **Fuel Assembly distortion** on safety analysis (Neutronic, TH, Mechanic)

Corrosion

IN-REACTOR CORROSION LIMIT

- **Advanced alloys** (M5, Opt ZIRLO) exhibit EOL oxide thickness < 45 µm





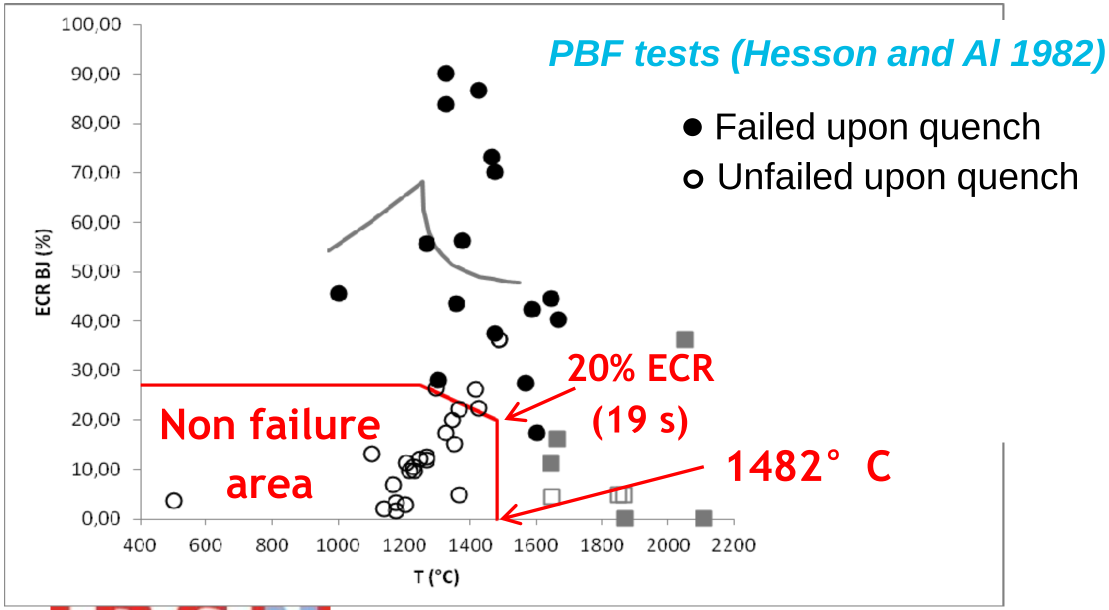
- Question: **Is the standard 100 µm corrosion limit still relevant ?**
- Mechanical tests show cladding ductility is not affected if zirconia remains low
- **IRSN** considers it is **no longer necessary** to verify the oxide thickness criterion for advanced alloys in France ➲ **associated hydrogen content is the key parameter regarding PCMI clad behavior** (in the future, IRSN will assess EDF's correlations *[H] = f(oxyde thickness)*)

TRANSIENT CLAD TEMPERATURE CRITERION

(PCC-3 AND PCC-4 – except for LOCA)

Corrosion

- Historically: **1482°C** (2700°F) comes from LOCA experiments and is appropriate for short transients (less than ≈ 30s) - This clad temperature limit ensures core coolability (clad non-failure during rewetting)
- Question: Is this criterion **appropriate to long time range transients** such as uncontrolled control rod assembly withdrawal initiated at power (PCC-3) ?
- **EDF proposed a new criterion as a transient "Equivalent Cladding Reacted" (ECR) limit** depending on maximum clad temperature and based on PBF PCM tests database



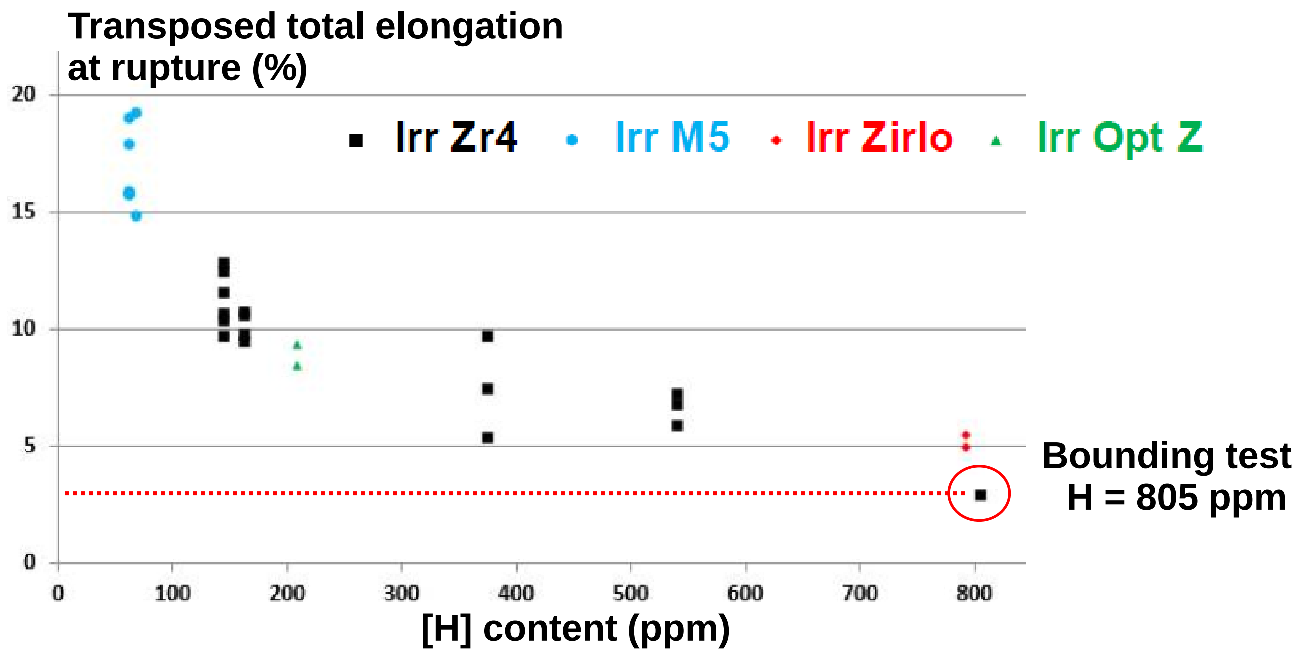
- **IRSN** recommends taking into account **experiments which integrate clad ballooning and burst after boiling crisis and secondary hydriding phenomenon**

PCMI CLAD FAILURE: PCC-2 POWER PULSE

PCMI

- Up to now, no criterion for the **PCC-2 power pulse**: uncontrolled withdrawal of control rod assembly bank(s) at zero power level
- Question: Is the **historical 1% clad strain** acceptance criterion for PCC-2 ramps also applicable to this transient ?

Mechanical property tests
280-400°C
10^{-2}/s



- EDF's proposal: the **1% plastic circumferential strain criterion** is applicable to PCC-2 power pulse for M5, ZIRLO and Opt ZIRLO
- IRSN considers this **clad non-failure criterion relevant**

PCMI CLAD FAILURE DURING REA (AT ZERO POWER LEVEL)

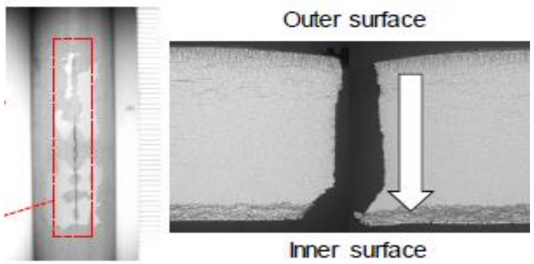
PCMI

Before the rulemaking → *The new French criteria*

Requirement

No fuel rod failure due to **PCMI** and **ballooning** during boiling crisis

No clad failure due to **PCMI**



Fuel safety criteria

Before the rulemaking:

$BU_{fuel\ assembly}$ > ***47 GWd/tU***

Oxide thickness < 108 µm

ΔH < 57 cal/g

$L_{1/2}$ > 30 ms

T_{clad} < 700°C

The new French criteria:

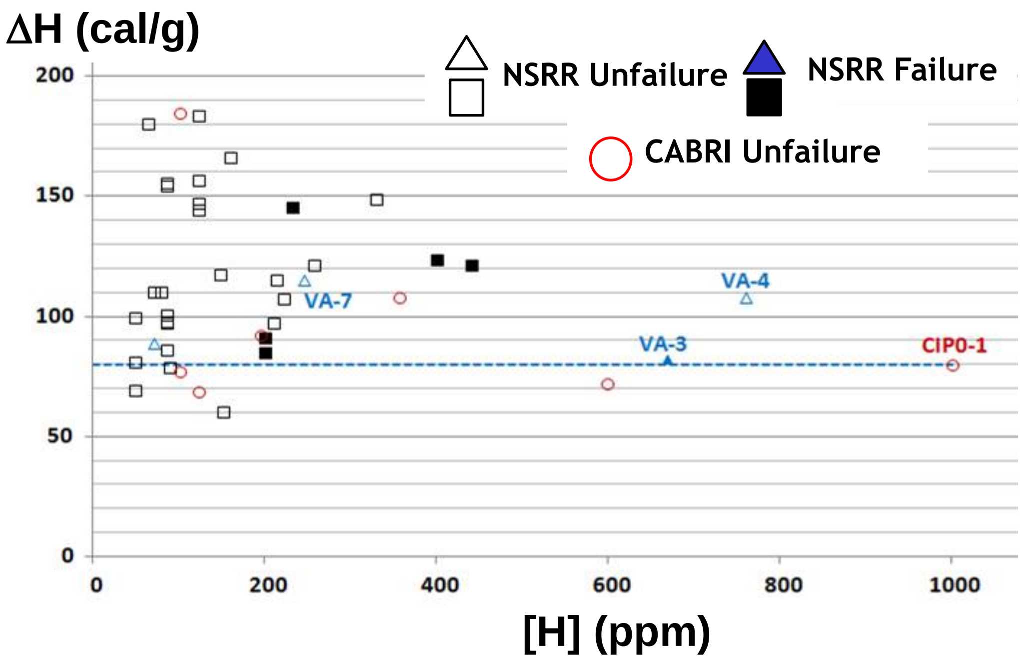
$BU_{fuel\ assembly}$ > ***33 GWd/tU***

New criteria expressed by ΔH and $L_{1/2}$ whose limits depend on cladding corrosion performances : **in reactor hydrogen content**

PCMI CLAD FAILURE DURING REA (AT ZERO POWER LEVEL): BU_{FA} > 33 GWD/TU

PCMI

- **IRSN analysis** focused on the validity of EDF's approaches which depend on fuel rod design:



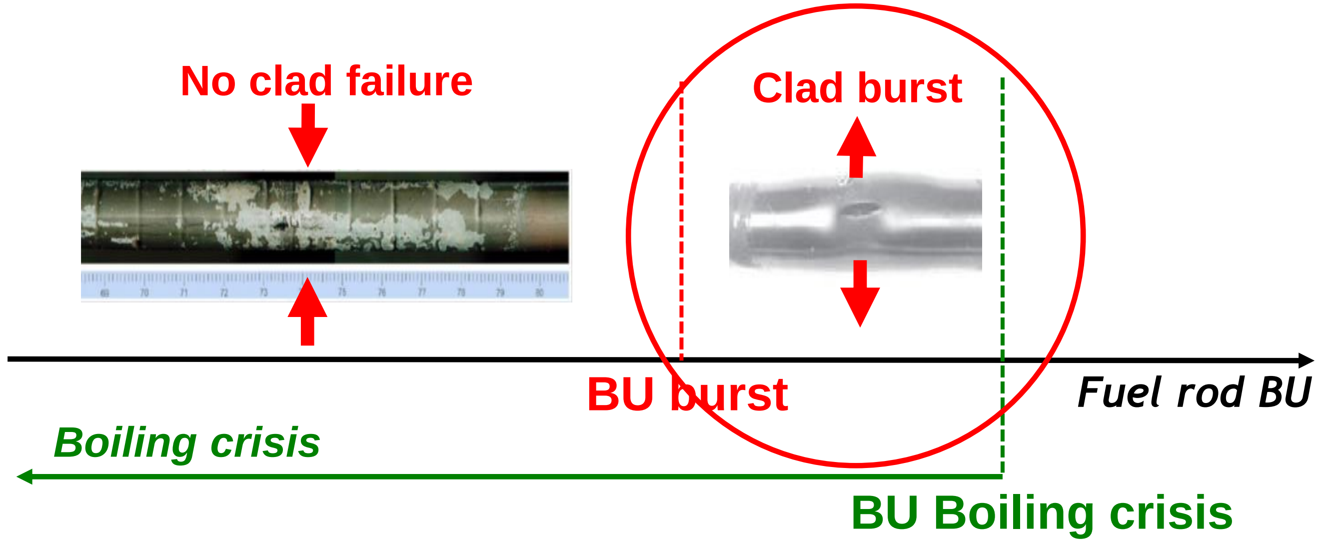
- ➢ ***UO_2+ ZIRLO/Opt ZIRLO***: **No uncertainty** concerning experimental data taken into account to define the fuel enthalpy rise limit (EDF's proposal ΔH<80 cal/g) based on the restrictive test (**CIP0-1**)

  ➲ EDF should take into account **uncertainties concerning experimental data to define the criterion**

- ➢ ***UO_2 + M5***: **ΔH<150 cal/g acceptable** + definition of $L_{1/2}$ limit in progress
- ➢ ***MOX + M5***: EDF will **apply an approach based on the interpretation of RIA full-scale tests devoted to MOX fuel**, in place of transposition calculations with SCANAIR V6.7 code (EDF's proposal ΔH<113 cal/g)

CONSEQUENCES OF BOILING CRISIS

- To calculate radiological doses, the **current conservative assumption** considers that **all fuel rod** entering into boiling crisis **is failed**
- **EDF** suggests **to consider only fuel rods susceptible to burst**: by applying a **fuel rod burn-up threshold** (*BU burst*) calculated with SCANAIR code, some fraction of fuel rods can be excluded from the counting of failed rods

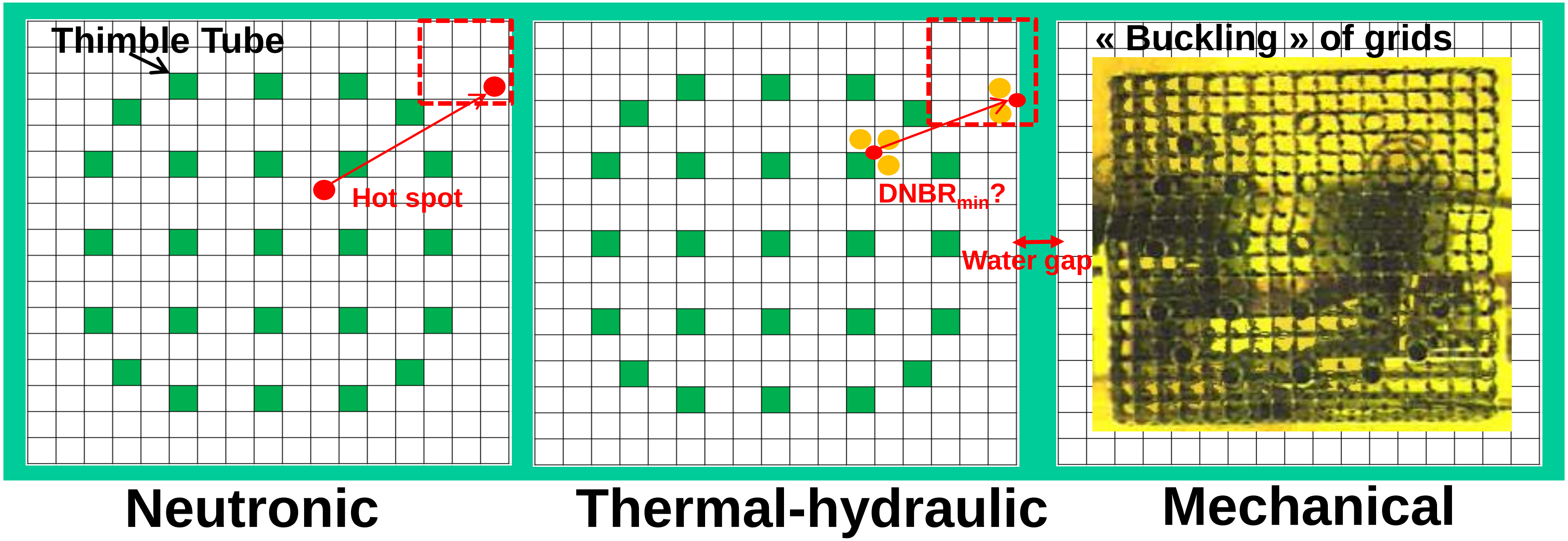


- **In case of plant operating conditions modifications** (for the future), **EDF's evolution could lead to increase radiological consequences**, which is **not acceptable for IRSN**

FUEL ASSEMBLY BOWING EFFECTS

Fuel Assembly distortion

- Phenomenon observed through incomplete/delayed control rods insertion during reactor trip
- Can be measured/evaluated with DAMAC measurements during **refueling outages** for some PWRs (from few mm to 20 mm)
- **FA distortion** potentially leads to the following impacts on **safety demonstration:**

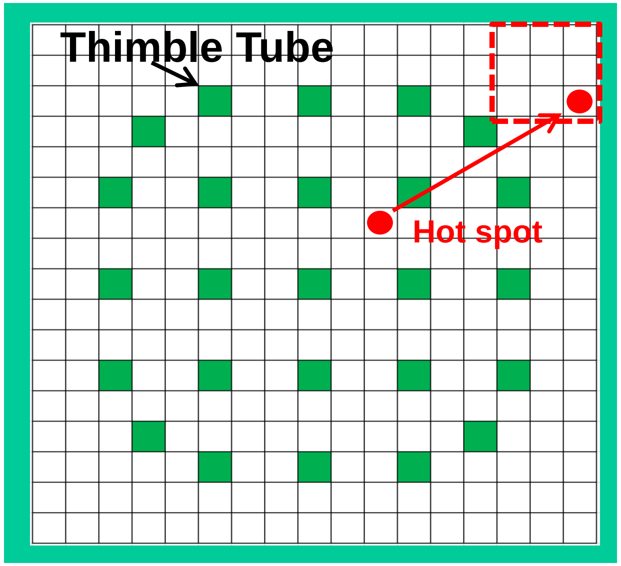


FUEL ASSEMBLY BOWING EFFECTS

Fuel Assembly distortion

- **Neutronic effect:** the presence of larger inter-assembly gaps causes **power distribution modification** which can cause the hot spot value to move to peripheral pins and/or increase
- EDF developed a **new methodology** for quantifying and taking into account this effect in the safety demonstration
- **EDF** proposed to consider this impact directly by means of a **modification in the power distribution evaluation uncertainty**

Neutronic



- **IRSN** assessed neutronic calculations, hypothesis of methodology: **IRSN considers this methodology satisfactory**

SUMMARY

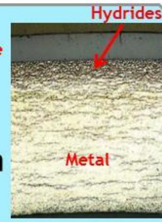
- **Most (if not all) fuel acceptance criteria** or fuel design limits have been **reviewed** to take into account:
  - current **fuel design**
  - more **demanding conditions**
  - current state of the French reactors regarding **leakers** (not presented here – see paper Eurosafe 2017) and **fuel assembly bow**
  - the **state-of-the-art** concerning physical phenomena: PCMI, cladding embrittlement due to corrosion, clad ballooning and burst during boiling crisis and fuel melting
- This review lead to a **big commitment in terms of methodologies development, carrying out and interpretation of experiments and technical exchanges between EDF and IRSN**

SUMMARY

- **Some** of fuel acceptance criteria may be **relaxed** (not presented here – see paper Eurosafe 2017)
- **Some** of fuel acceptance criteria have **evolved** (**in-reactor hydrogen content** instead of oxide thickness) or **should be complemented:**
  - clad temperature limit of **1482°C**
  - **centerline melting temperature**
  - correlations [H] = function (oxide thickness)
- **New approaches and fuel acceptance criteria** have been defined in order **to complete the safety demonstration:**
  - **fuel dispersal** after clad ballooning-burst during **boiling crisis**
  - **PCMI** during **PCC-2 power pulse** and **REA**
  - **SCC-PCI** during **PCC-3** and **PCC-4** (see paper Eurosafe 2017)

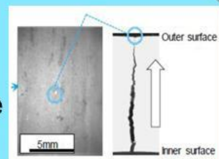
THANK YOU FOR YOUR ATTENTION !

Cladding embrittlement due to **corrosion**



Impact of **Fuel Assembly distortion** on safety analysis (Neutronic, TH, Mechanic)

SCC-PCI clad failure

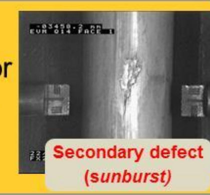


French rulemaking

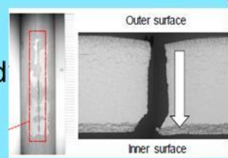
EDF asn IRSN

Review of fuel safety criteria

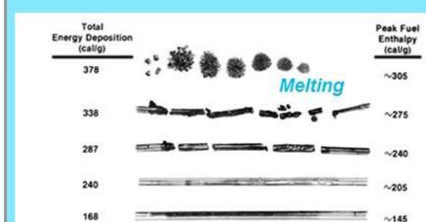
Impact of in-reactor **leakers** on safety analysis



PCMI clad failure



Fuel **melting**



Consistency between **radiological consequences** and **safety cases analysis**

Consequences of **boiling crisis: Fuel dispersal**