IRSN Work Program for Criteria Definition

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Background / Methodology

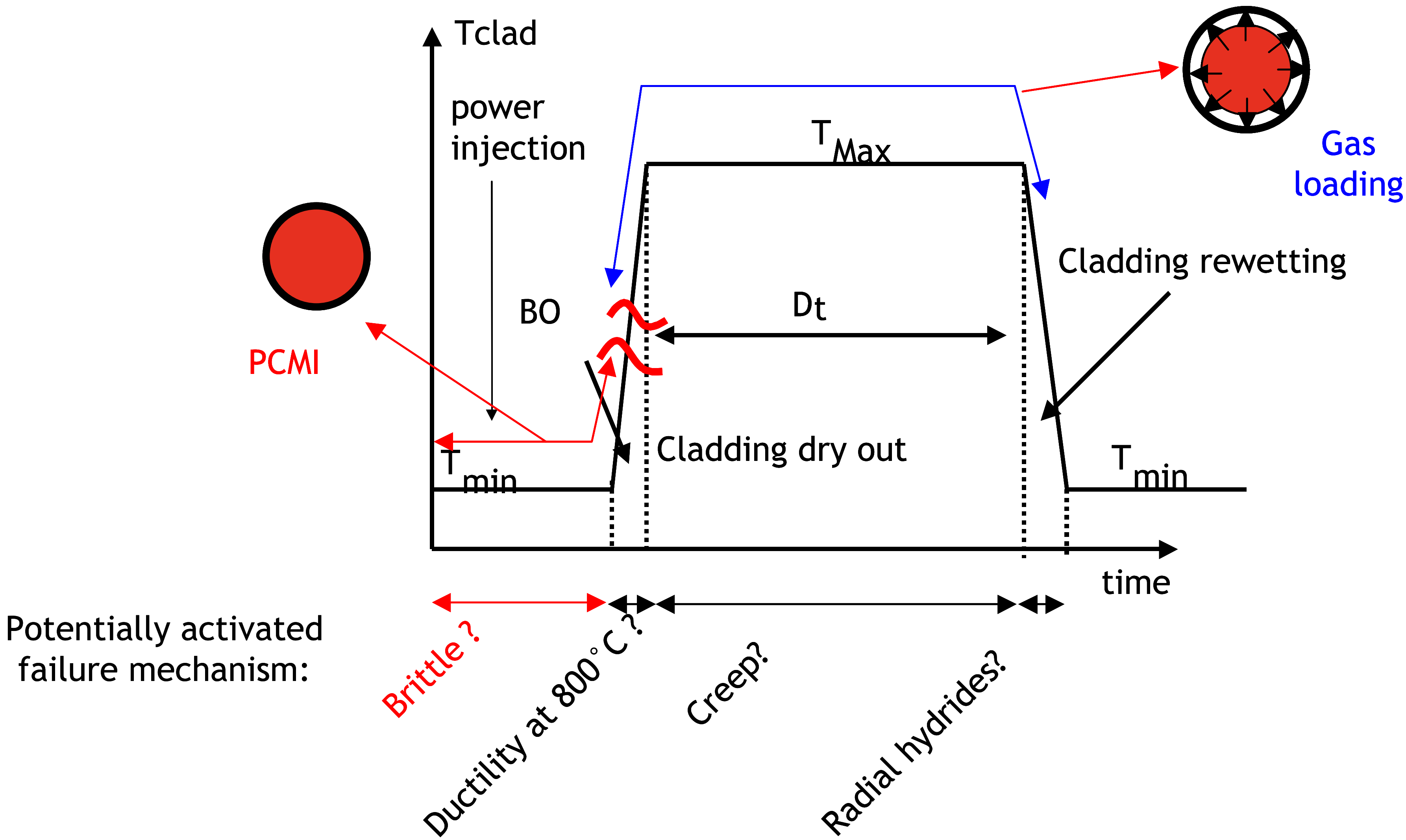
-The first part of the program is to elaborate clad failure limit criteria for RIA, as many organizations do worldwide

-Although there exist experiments to study the failure of high burnup fuel rods under reactivity insertion: PBF, SPERT, NSRR, IGR/BIGR, CABRI, none of them is fully representative of reactor conditions

- Thus there is a need to transpose the results

- Because the phenomena are complex and coupled, the transposition requires the use of computational tools

Phenomenology and failure mechanisms



Computational tools

- Initial state of the rod
- Use of **FRAPCON** and/or METEOR
- Clad corrosion, Fission gases inventory, …

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- Thermomechanical behavior under RIA
- Use of **SCANAIR**

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- Clad failure during PCMI
- **CLARIS** module as a SCANAIR post processing

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- Clad failure after boiling crisis
- **NO NAME YET** module as a SCANAIR post processing

Initial State of the Rod

- The behavior of the rod depends on the initial state

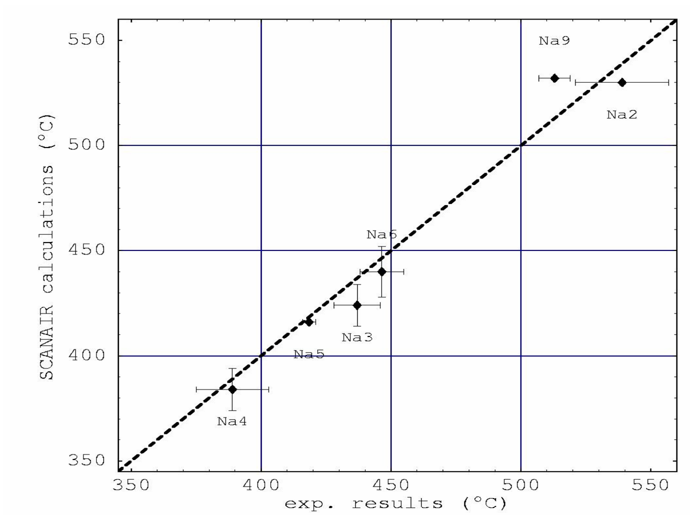
- Need to account for different cladding materials -> corrosion and for different fuel types -> fission gas content

- Studies will be conducted using FRAPCON (IRSN acquired recently) and/or METEOR; very high burnups may be a concern for these tools

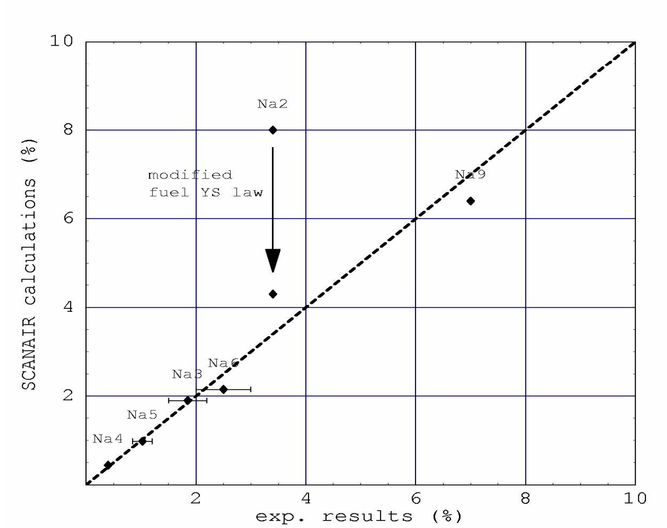
- First study to select parameters of the irradiation computation that have an influence on the rod failure

- Then use reference values for this limited set of parameters and perform sensitivity studies

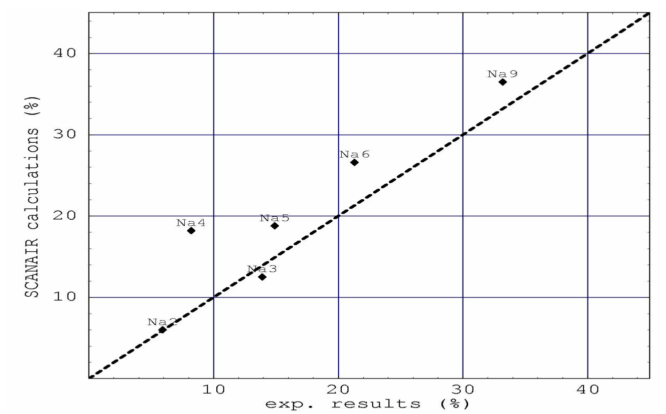
SCANAIR code



Max coolant temperature



Clad residual hoop strain



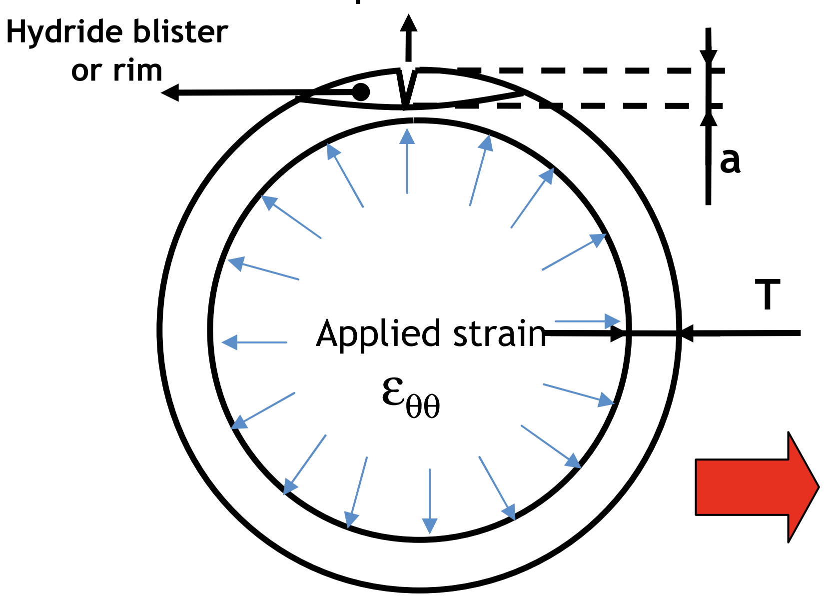
Fission gas release

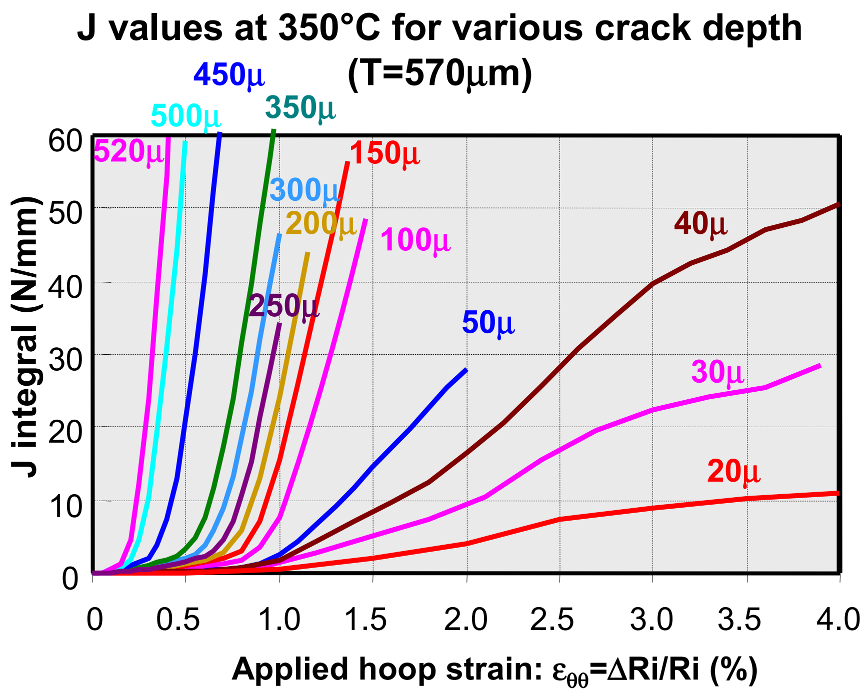
- SCANAIR mostly validated on REP-Na experiments

- Thermomechanical behavior adequately modeled

CLARIS module for failure due to hydrides

Finite element calculations of J Integral for several incipient crack length and temperatures





$$J(\varepsilon_{\theta\theta};a;T)$$

•J: Rice integral measures the loading intensity on a cracked component in terms of Elastic-Plastic Fracture Mechanics,

•J_c: critical J value, fracture toughness(=$(K_{Ic})^2/E$)

Assumption :

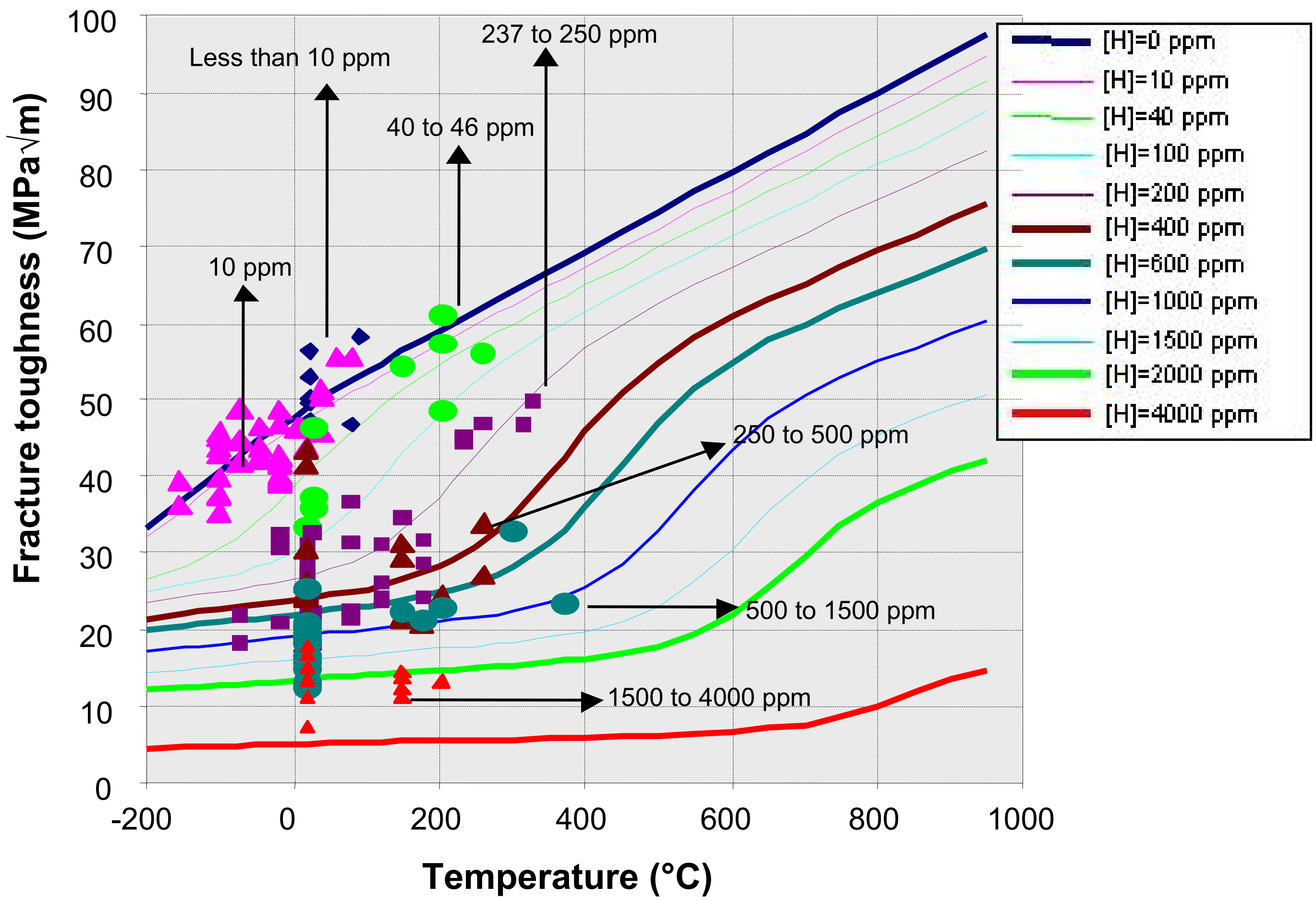
crack length = Hydride blister or rim depth

CLARIS module for failure due to hydrides

Bibliographic study:

$K_{IC} = K_{IC}(T, [H])$

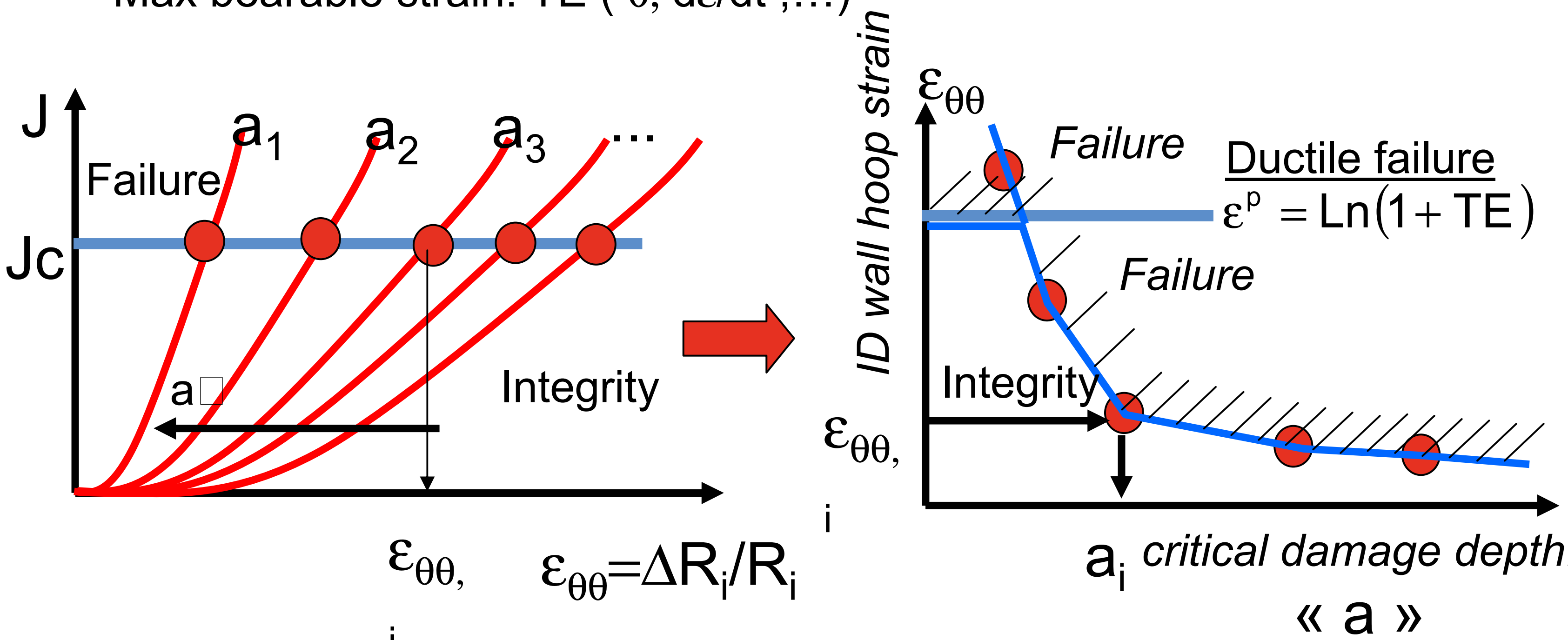
$$J_C = \frac{K_{IC}^2}{E}\left(1 - \nu^2\right)$$



CLARIS module for failure due to hydrides

At a given temperature (θ), strain rate (dε/dt),hydride content ([H]):

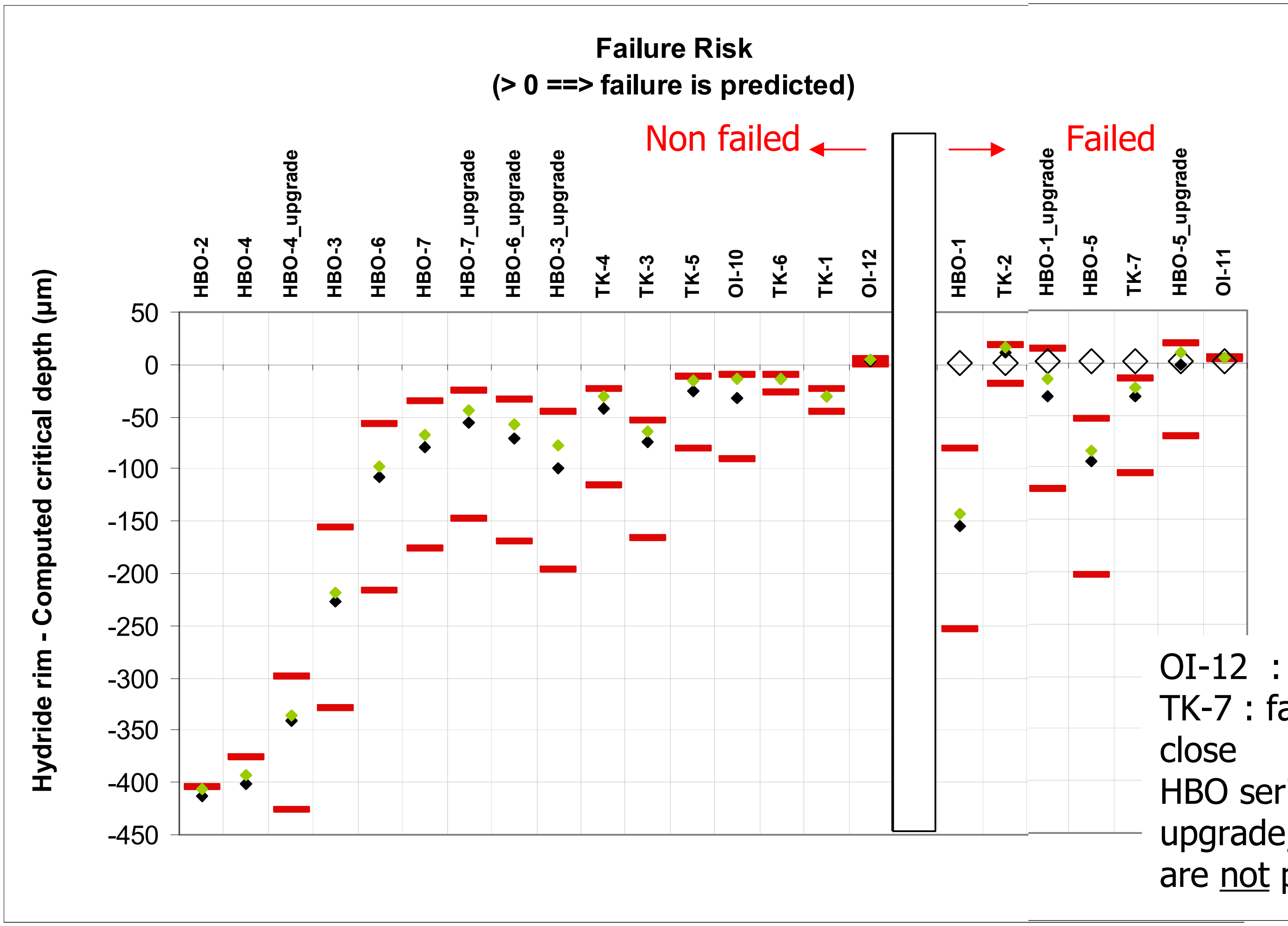
- Fracture toughness:Jc([H], θ, ...)
- Max bearable strain: TE (θ, dε/dt ,…)



Result: critical crack depth versus $\varepsilon_{\theta\theta}$ (and temperature).

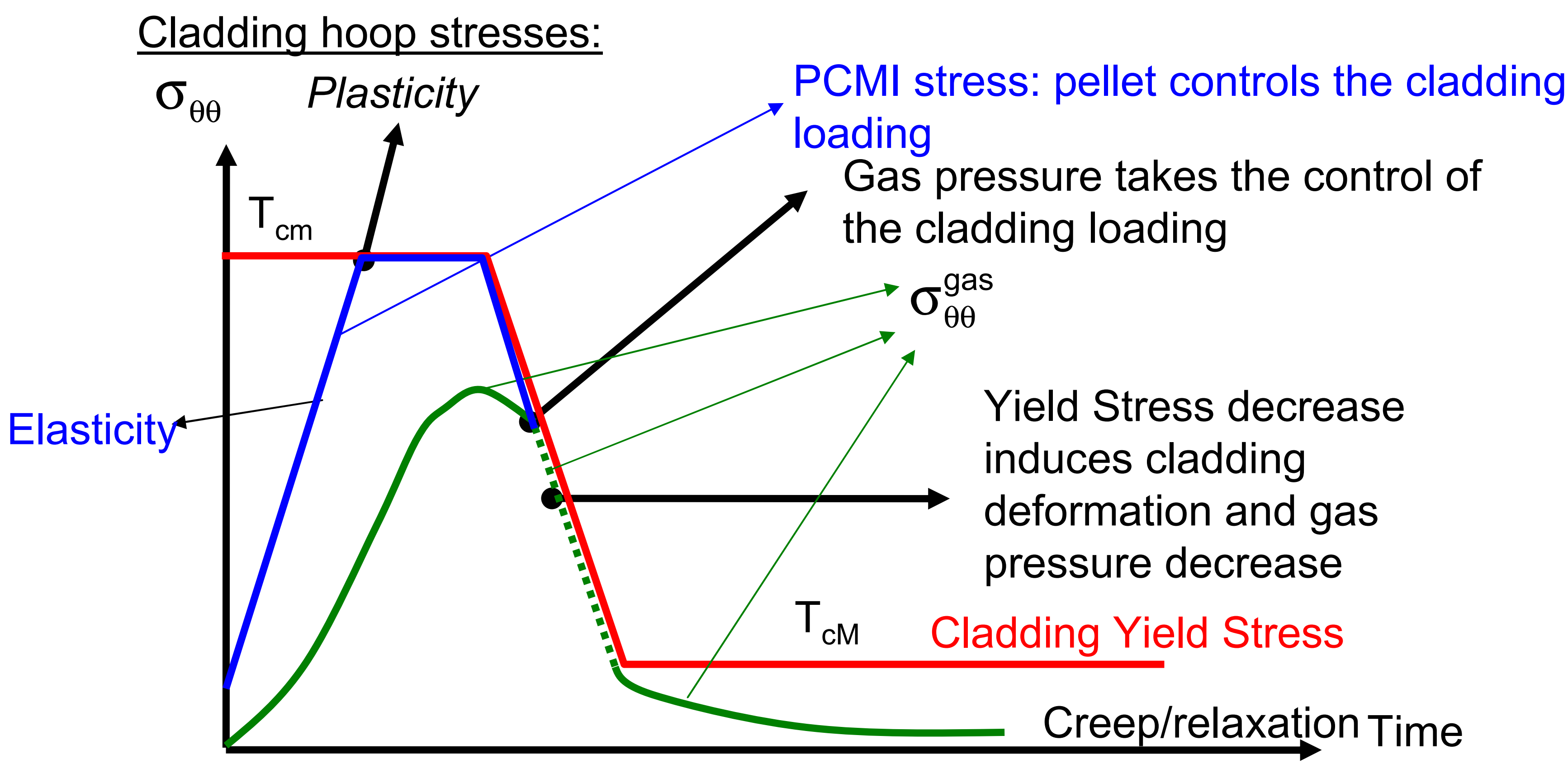
CLARIS module for failure due to hydrides

Example of application on NSRR -> global agreement



OI-12 : at the threshold of failure…
TK-7 : failure is not predicted … but close
HBO series : without energy deposit upgrade, failures of HBO-1 and HBO-5 are not predicted

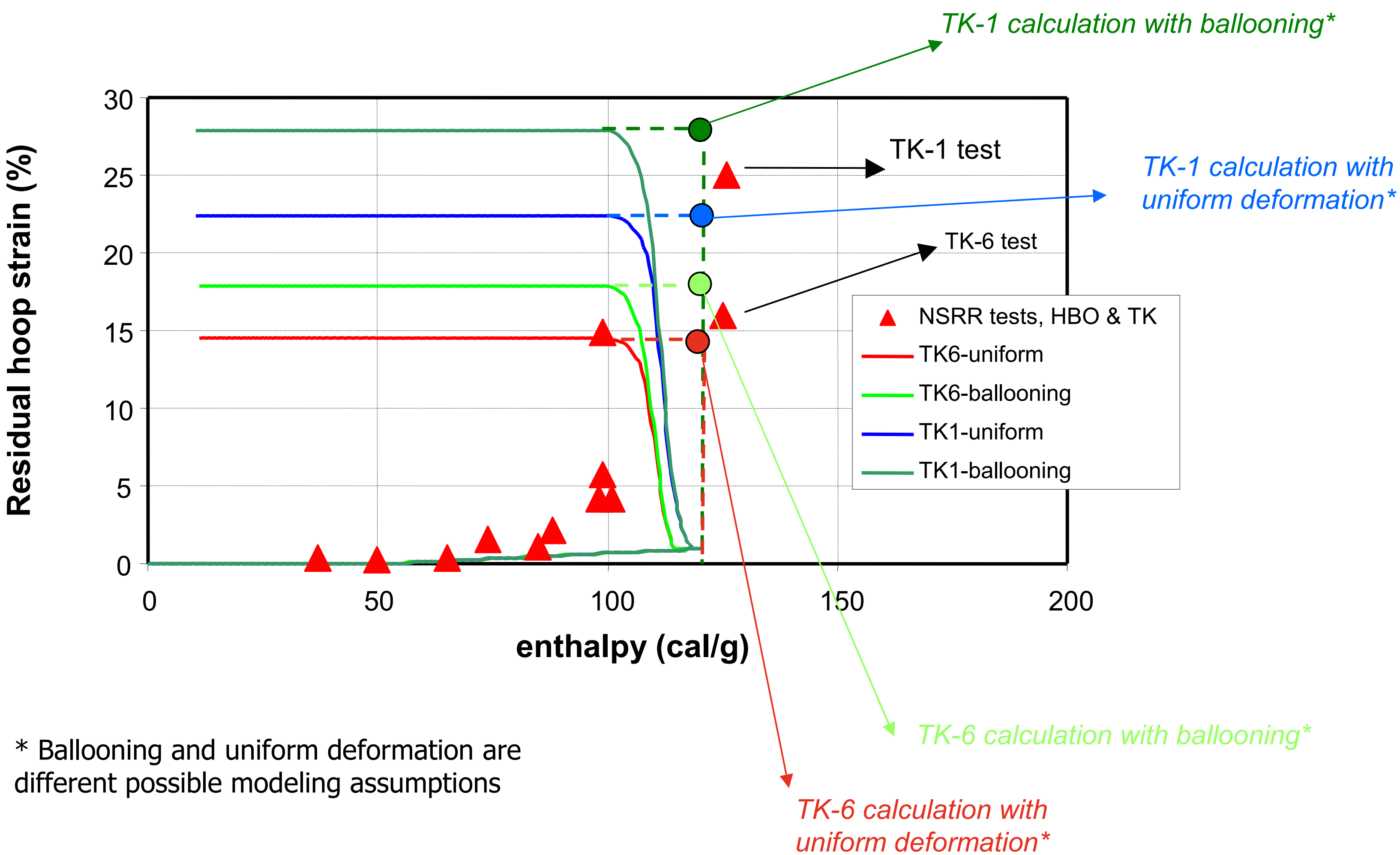
Post DNB Behavior



If the gas temperature and gas pressure are high enough a loading transition from PCMI to gas controlled loading takes place.

Post DNB Behavior

Application to NSRR TK-1 & 6 gives consistent results



* Ballooning and uniform deformation are different possible modeling assumptions

IRSN

Clad ductility at 800°C

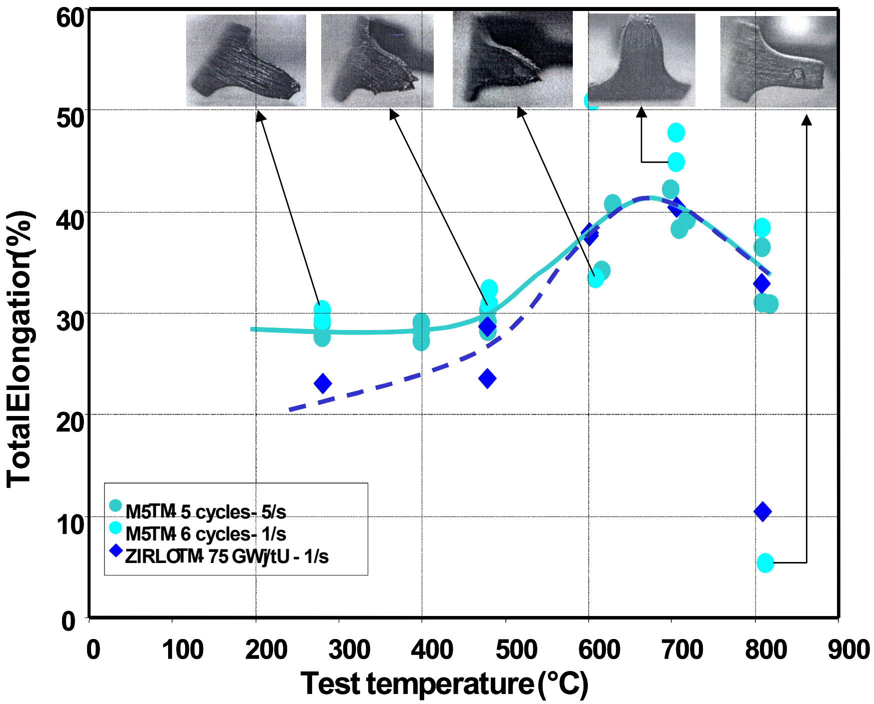


Fig. 8. M5™ and ZIRLO™ Total Elongation vs test temperature with visual examinations of 6 cycle M5™ sample

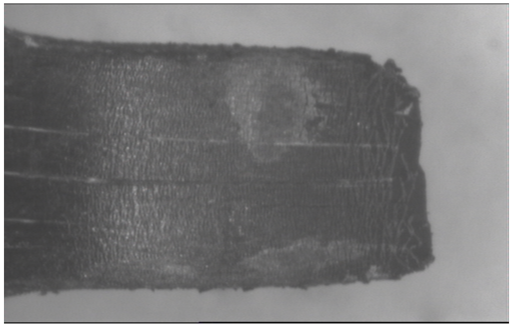


Fig. 9. Visual detail of the 6 cycle M5™ broken leg (#ABDJ3- 816 °C).

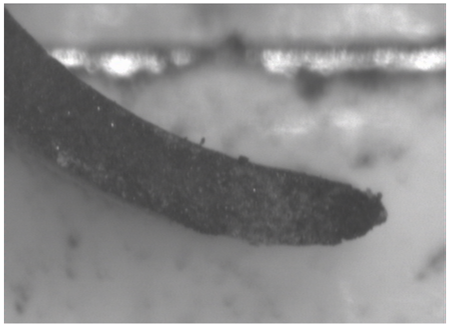


Fig. 10. Through thickness visual detail on 6 cycle M5 sample (#ABDJ3- 816 °C).

Some PROMETRA experiments show reduced ductility at 800°C
-> temp. increase at burn-out may not necessarily beneficial

Consequences of clad rupture

- Although criteria are set up to prevent clad failure, consequences of clad rupture can not be completely ruled out because it appears difficult to ensure that in the whole core not even one rod is defective

- Different studies are foreseen to address this issue
  - Determine the amount of fuel that can interact with coolant without loss of integrity of the 2nd barrier -> "acceptable" number of failed rods; because the problem is similar, methods used to assess the integrity in PSA level 2 FCI studies may be a good starting point

  - Assess whether the geometry resulting from a failure is coolable; which method to apply?

  - Evaluate whether the rupture of a rod can induce the rupture of its neighbors (cascading failure); use of fast dynamics mechanical computer code

Variables to use in the criteria

- The question of which variables to use in building the criteria is not an obvious one
    - Burn-up vs. oxide thickness vs. ?
        - The effect of burn-up depends on the cladding material with respect to failure due to embrittlement; however burn-up is a well known characteristic of a fuel management
        - Oxide thickness may be a good parameter for Zr4 (and Zirlo) but does not seem so relevant for M5; but large scatter may exist in the evaluation
        - …
    - Enthalpy vs. Enthalpy increase vs. Energy deposition vs. SED
        - Energy deposition does not require a computation of the rod response
        - Enthalpy seems a good choice for characterizing thermal behavior
        - But enthalpy increase more relevant for mechanical loading (assuming relaxation as occurred prior to power transient)
        - SED/CSED approach theoretically questionable
        - …

Schedule

- PCMI failure
  - Modeling finished
  - Validation until mid 07
  - Application, criteria elaboration end 07

- Post-DNB failure
  - First modeling available, to be improved in 07
  - First application end 07 (for illustration purposes)
  - Application, criteria elaboration in 08

- Consequences of rupture
  - First orders of magnitude and definition of future studies end 07