Overview of CEA Analytical Studies on PWR Nuclear Fuel cladding subjected to RIA Loading Conditions

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C. Sainte Catherine and P. Yvon

Context 1/2

- **Design safety studies for Reactivity Initiated Accident)**

⇨ Studies underway to raise the average burn-up of fuel assembly (ex : 1998, EDF, 47 to 52GWd/tU and 62 GWd/tU expected in the future)

⇨ Strong need for investigations of the fuel behavior under design basis reactivity accidents such as control rod ejection (failure of the control rod drive mechanism)

- **Assumption : Accidental ejection of a control rod**

⇨ Rapid increase of the local power (~ 50ms)

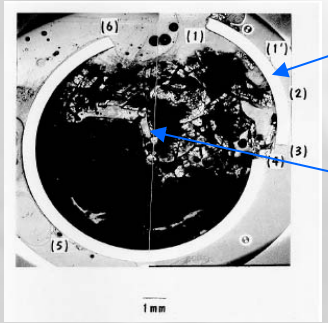
⇨ Increase of temperature (10^3 to 10^4 $K.s^{-1}$)

⇨ Fuel swelling

⇨ Clad deformations (a few %)

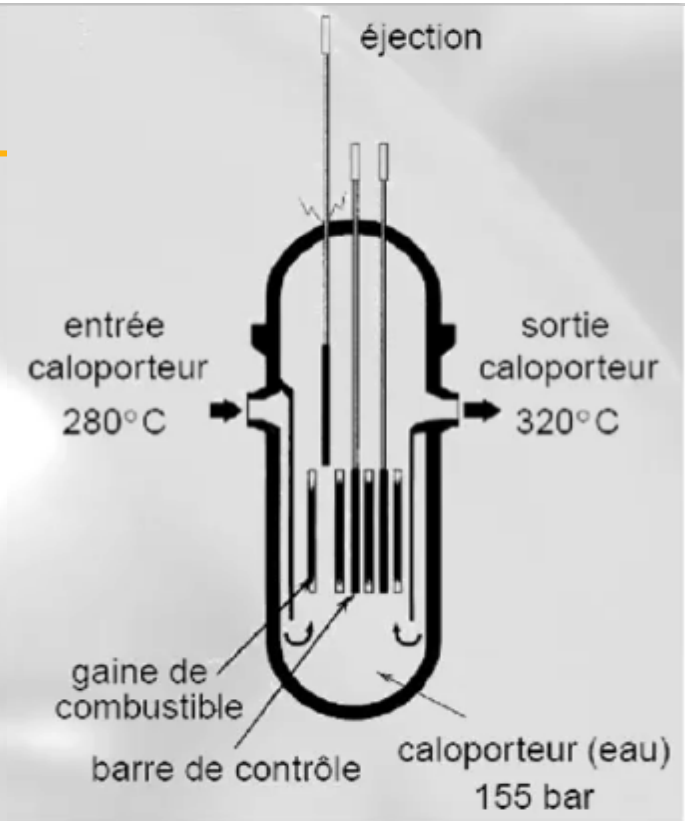
⇨ Potential for crack initiation and growth (failure criterion required)

⇨ Fuel dispersal in the coolant, boiling crisis, etc …



Failed cladding

Dispersed fuel



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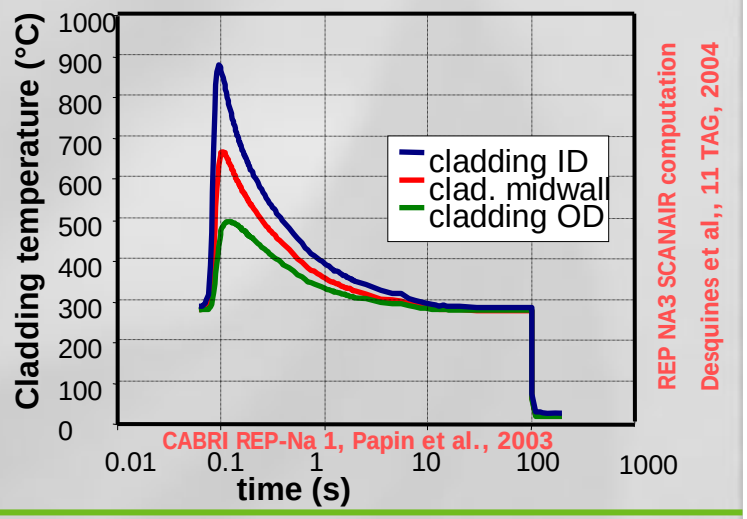
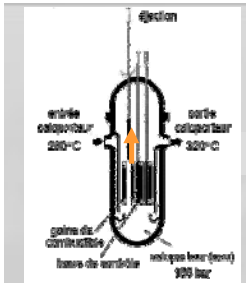
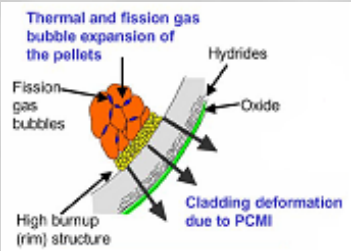


Reactivity Initiated Accident Problematic



Control rod ejection
⇒ Rapid local power increase (~50 ms)

Fast fuel temperature rise (10^4 °C/s)



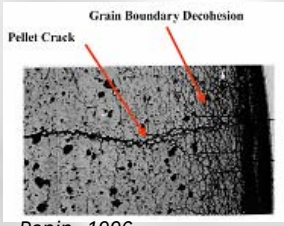
Nakamura et al., 2002

Fuel thermal expansion

Fuel expansion

Pellet-cladding gap closing

Accumulated fission gas expansion



Papin, 1996

Fuel grain decohesion

Fission gas release

Internal pressure increase

Loss of cladding ductility due to a dense hydride thickness

PCMI loading
350<T<600°C, T~10^3 °C/s, ε~1 s^{-1}

Crack initiation on outer diameter

Transient PCMI failure

First phase pre DNB failure

Departure from Nucleate Boiling (DNB)

Fast cladding temperature increase
(T<800°C)

Drop of the mechanical strength

Post-DNB failure by local ballooning

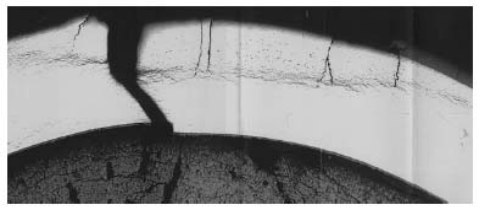
Last phase post DNB failure

Fuel fragmentation

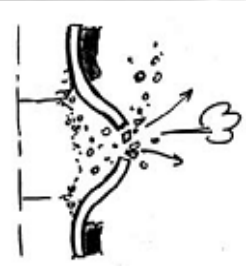
Fuel dispersal and coolant interaction

Mechanical energy production

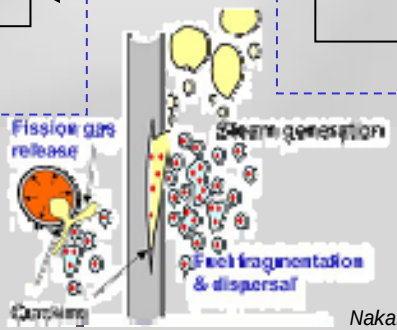
Post failure events



REP-Na 8 *(Papin et al., 2003)*



Waeckel., 1997

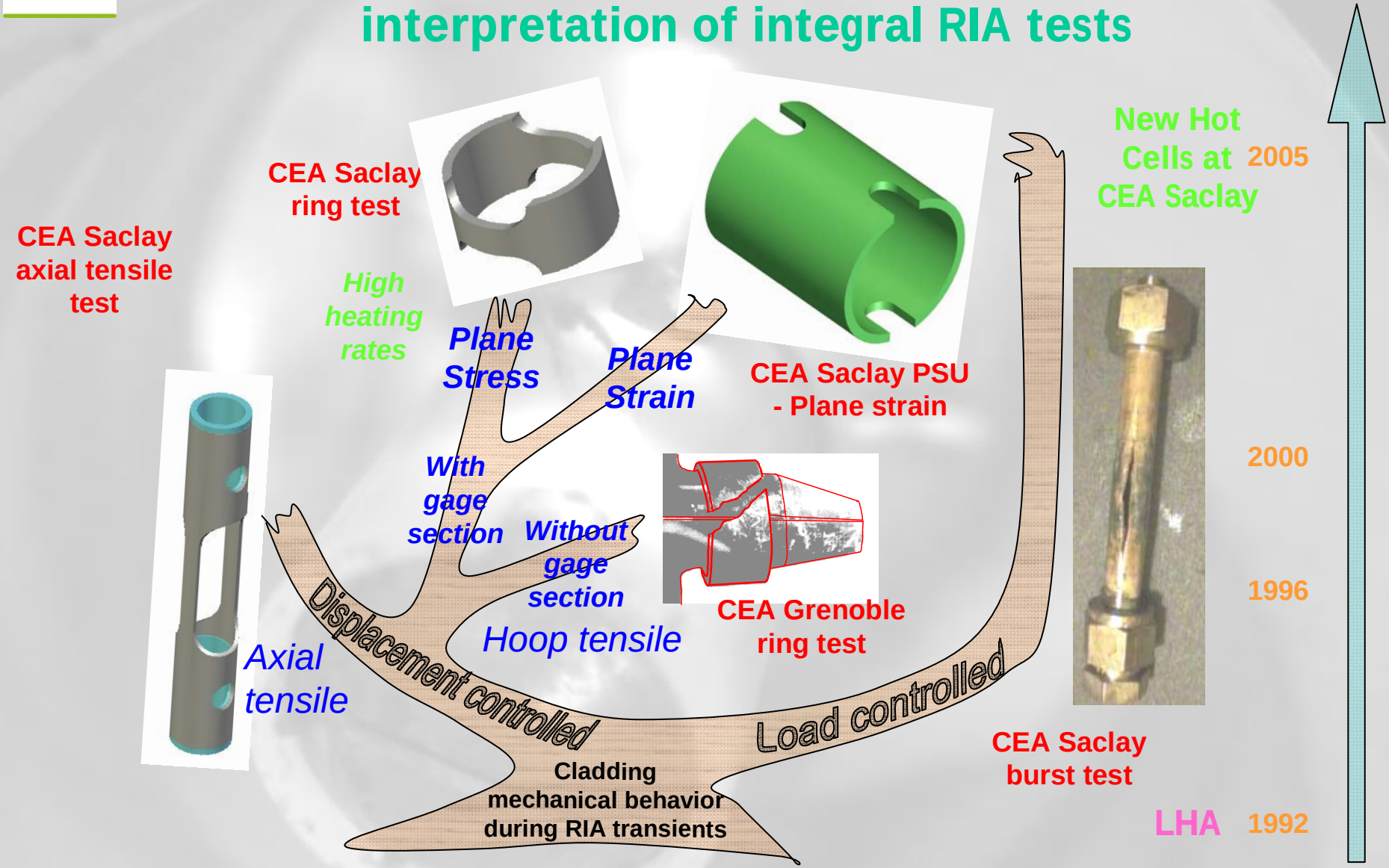


Nakamura et al., 2002

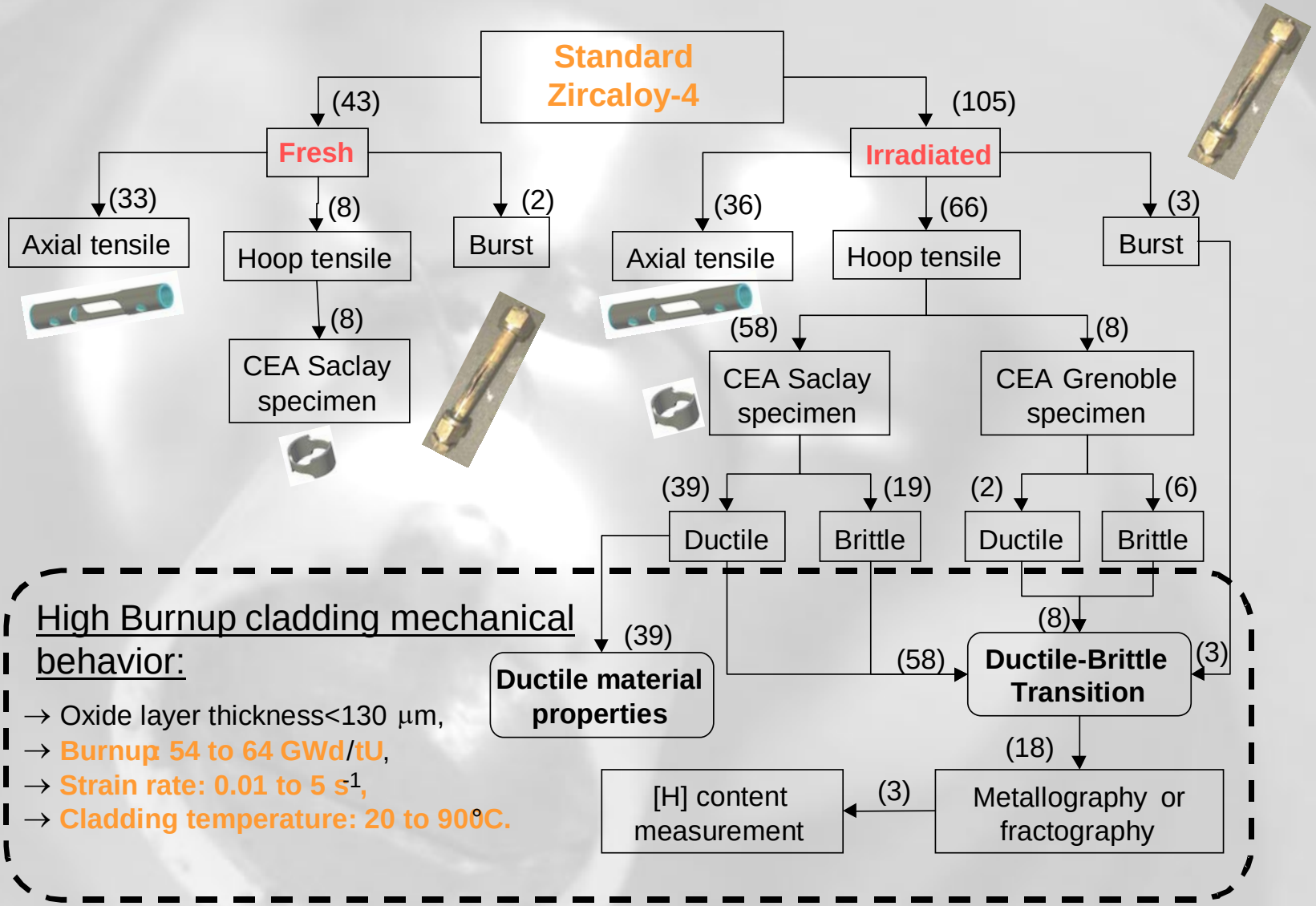
Context 2/2

- **1992 : IRSN (formerly IPSN) initiated, in partnership with EDF, a research program, the CABRI REP-Na dedicated to :**
  - ⇨ Study the behavior of highly irradiated fuel (UO_2 and MOX) under RIAs
  - ⇨ Verify the adequacy of the present safety criteria with available experimental database (SPERT, PBF, early NSSR experiments) restricted to fresh or lightly irradiated
  - ⇨ Evolution of the criteria and evaluate safety margins
- **CABRI REP-Na experimental program launched in the sodium loop reactor in France : fast power transient applied to irradiated rods**
- **Development of the SCANAIR code :**
  - ⇨ Interpret the test results, perform sensitivity studies
  - ⇨ Extrapolate to reactor conditions
  - ⇨ Process closely coupled phenomena such as rod thermics and thermal hydraulics, fuel and clad mechanics, transient behavior of fission gases
- **1992 : Initiation of a separate effects test program for the study of transient clad mechanical behavior : PROMETRA**

PROMETRA : transient mechanical testing program for high burn-up claddings in support to the interpretation of integral RIA tests



A Reliable Material Database For Highly Irradiated Fuel Claddings 1/2

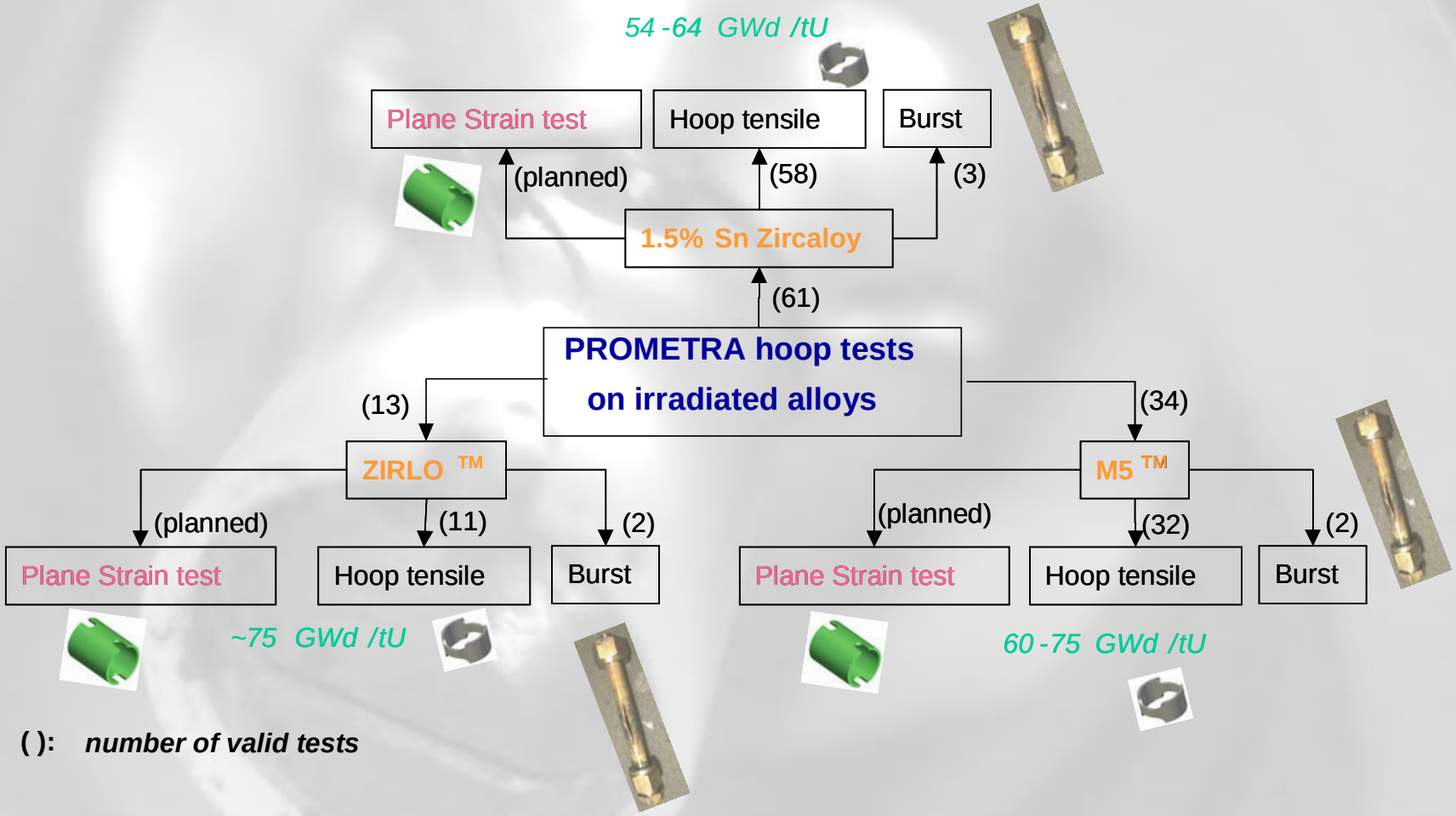


High Burnup cladding mechanical behavior:

→ Oxide layer thickness<130 µm,
→ **Burnup: 54 to 64 GWd/tU,**
→ **Strain rate: 0.01 to 5 s^{-1},**
→ **Cladding temperature: 20 to 900°C.**

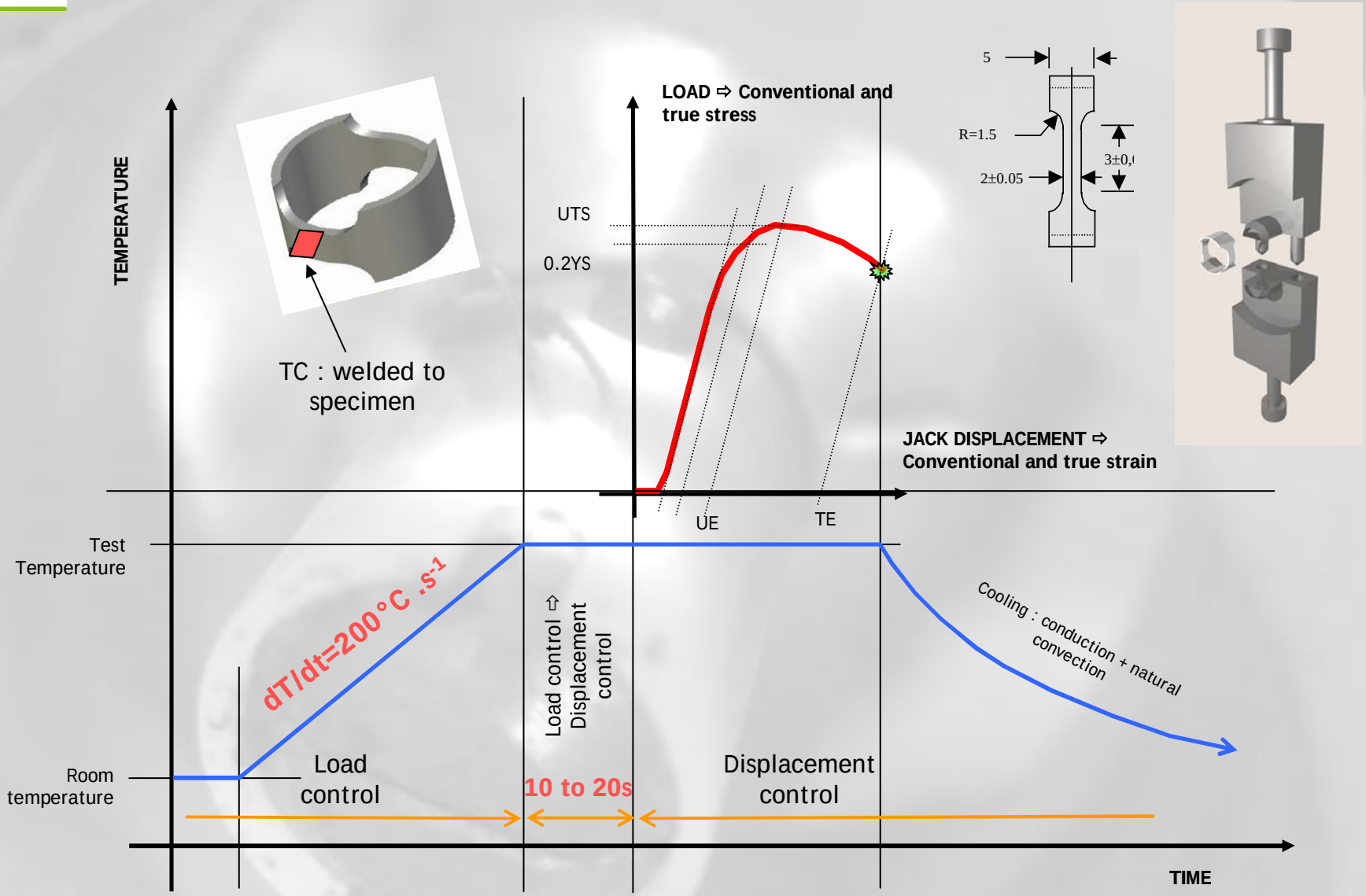
( ): *number of valid tests*

A Reliable Material Database For Highly Irradiated Fuel Claddings 2/2



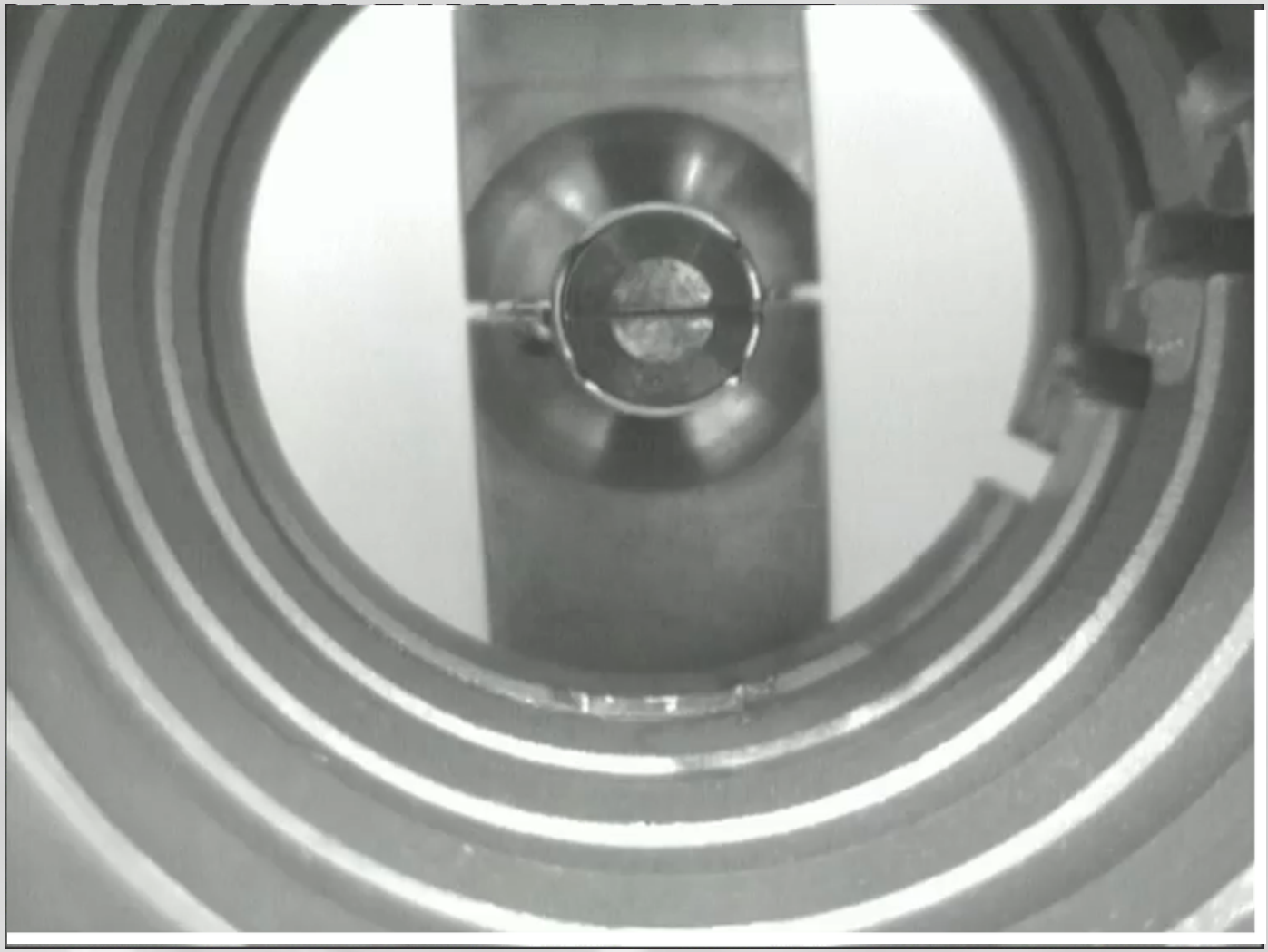
( ): *number of valid tests*

CEA testing technique for high temperature rings : (induction heating, T > 480°C up to 900°C)



PROMETRA hoop tensile test at high temperature

x2 times faster than real life

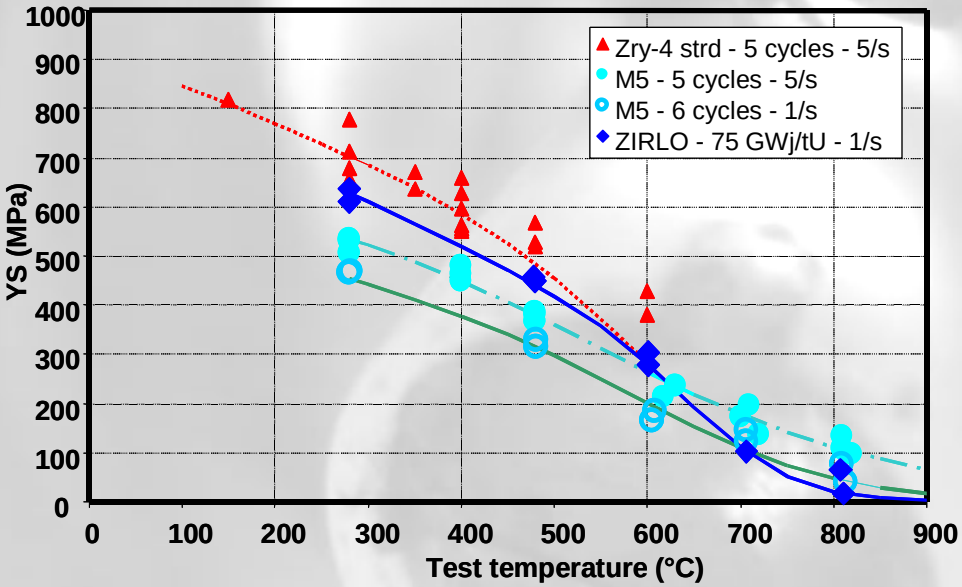


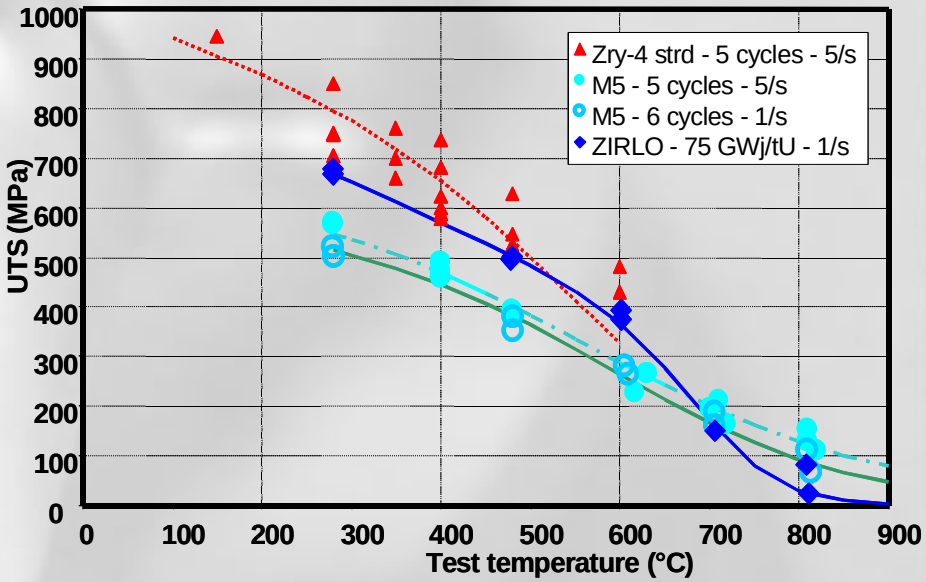
movie

Test specifications : 800°C, 1s^{-1} Test duration : 20s including induction heating @ 100°C/s

On going research : towards a better interpretation of the PROMETRA test data

- **Conventional and true stress-strain interpretation of the PROMETRA data is made :**
  - ⇨ To derive validated mechanical transient mechanical properties usable in SCANAIR
  - ⇨ To develop failure criteria





YS and UTS for irradiated Zy4, M5 and Zirlo, Cazalis et al., SMIRT 18, 2005

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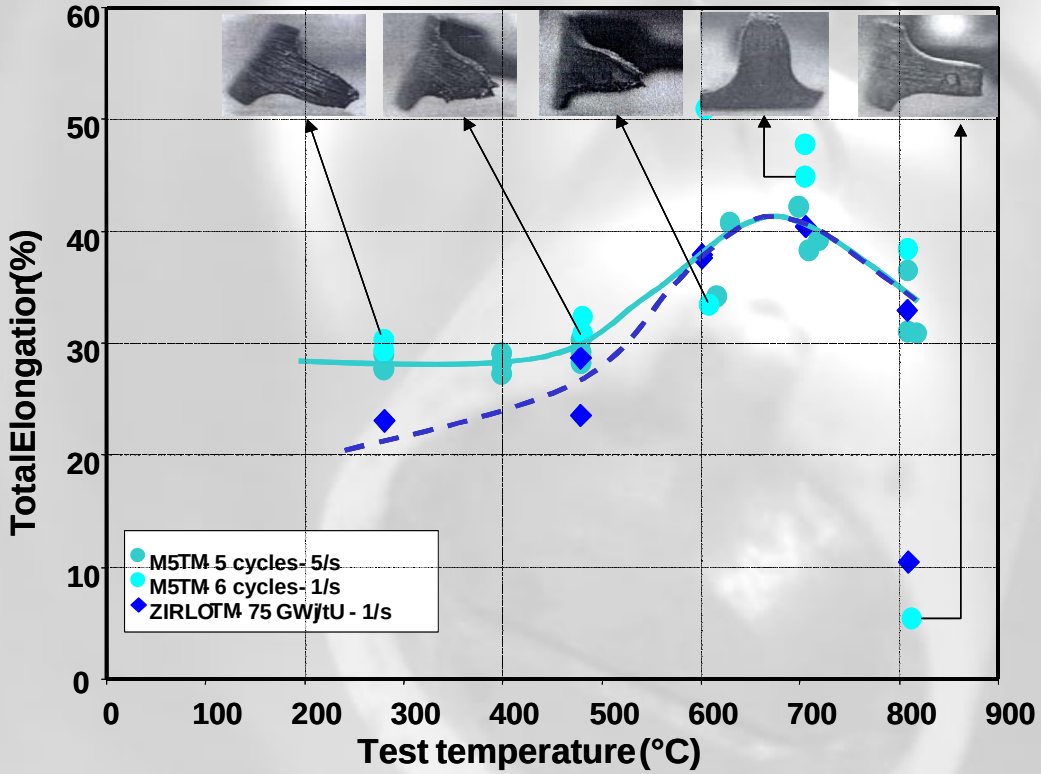
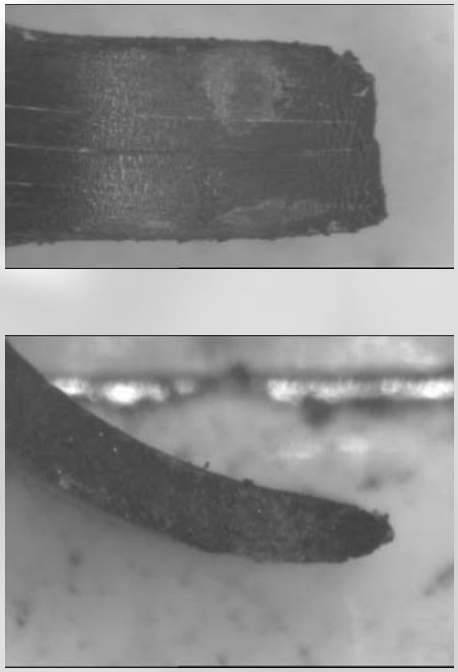


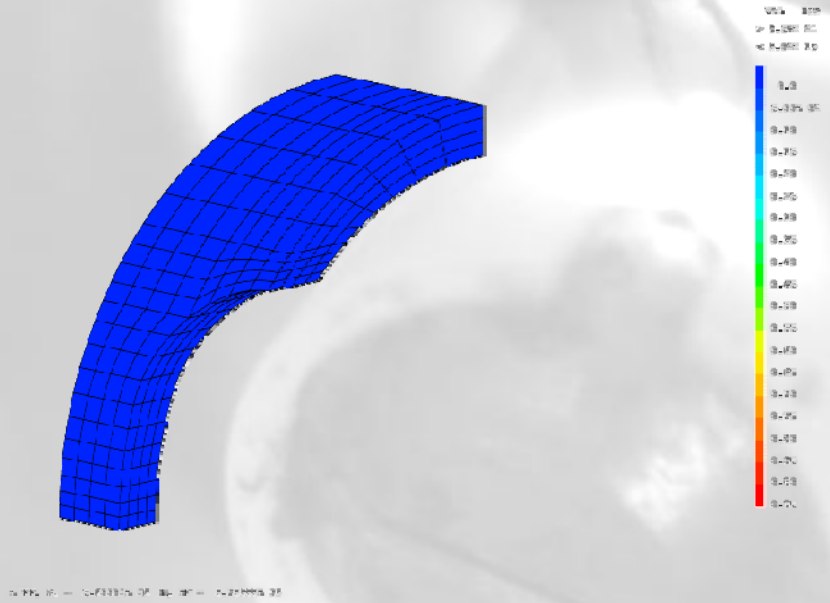


TE for irradiated M5 and Zirlo, visual view of M5TM broken leg, tested 816°C

Cazalis et al., SMIRT18, 2005

On going research : towards a better interpretation of the PROMETRA test data

- **FE modeling is achieved to deeply understand the tests data and insure that experimental artifacts, geometry (strain and stress gradients), boundary conditions (contacts and friction) do not invalidate the data**



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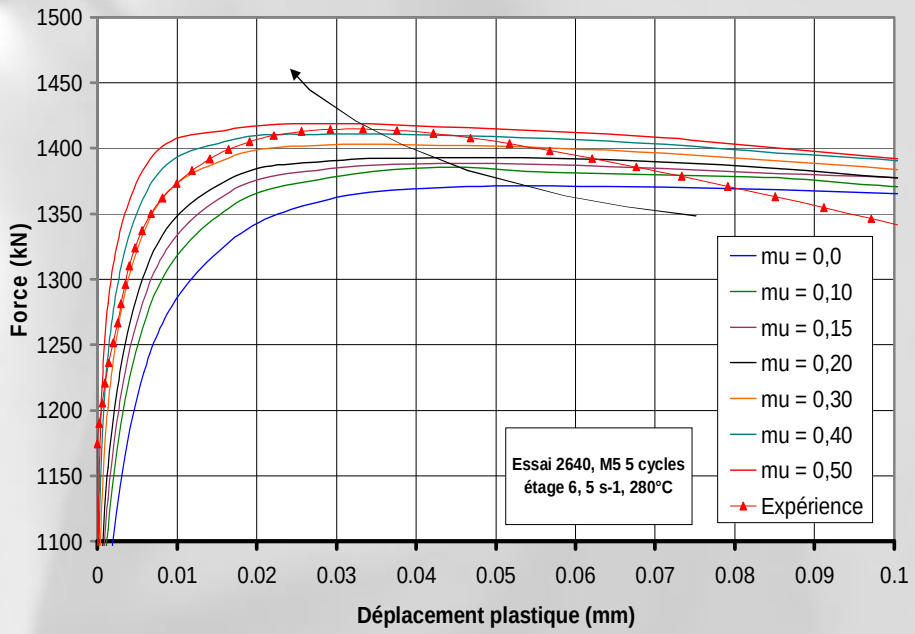


On going research : towards a better interpretation of the PROMETRA test data

- **GPL constitutive law (Goguel Poussard Limon) (Goguel et al., 2005) :**

⇨ For a better use of the PROMETRA data, a validated constitutive equation applicable to the whole temperature, strain rate and loading conditions RIA domain, compatible with structural mechanics computations codes (CAST3M, SCANAIR, …) has been identified

Jean Lemaitre formalism : $\underline{\dot{E}}^{vp} = \frac{3}{2}\dot{\bar{E}}^{vp}\,\underline{\underline{M}} : \frac{\underline{\underline{s}}}{\bar{\Sigma}}$

C. Poussard et al., FSRM 2006

with $\dot{\bar{E}}^{vp} = \dot{E}_0\left[\frac{\bar{\Sigma}}{V(T).(\bar{E}^{vp} + E_0)^{n(T)} + \varphi(T,\phi_t)}\right]^{m(T)}$

and $\bar{\Sigma} = \sqrt{\frac{3}{2}\underline{s} : \underline{\underline{M}} : \underline{s}} = \sqrt{H_r(\Sigma_\theta - \Sigma_z)^2 + H_\theta(\Sigma_z - \Sigma_r)^2 + H_z(\Sigma_r - \Sigma_\theta)^2}$

70 tests available, 20 to 800°C

80 tests available, 20 to 900°C

5 tests available, 20 to 350°C

⇨ Domain of application :

Burnup up to 64 GWd/tU),

Temperature (200 up to 800°C),

Strain rate (3.10-4 up to 5 s-1)

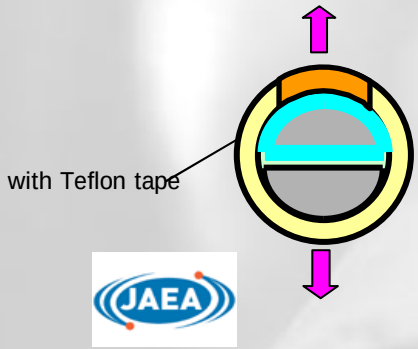
Material anisotropy (temperature and neutron flux dependant … the anisotropy decreases when the irradiation increase)

⇨ The GPL law, available in ⚙ and CAST3M can now be used to model structures

On going research : towards a better interpretation of the PROMETRA test data

- **International collaboration with ANL and Penn State University (USA), JAEA (Japan) and Studsvik (Sweden) underway since 2001:**

⇨ Experimental and analytical Round Robin to exchange and validate experimental practice and test interpretation



1 Gage ring tensile specimen

Argonne NATIONAL LABORATORY

Studsvik® Nuclear

2 gauges and dog bone ring tensile specimen

2 gauges ring tensile specimen

On going research : towards a better interpretation of the PROMETRA test data

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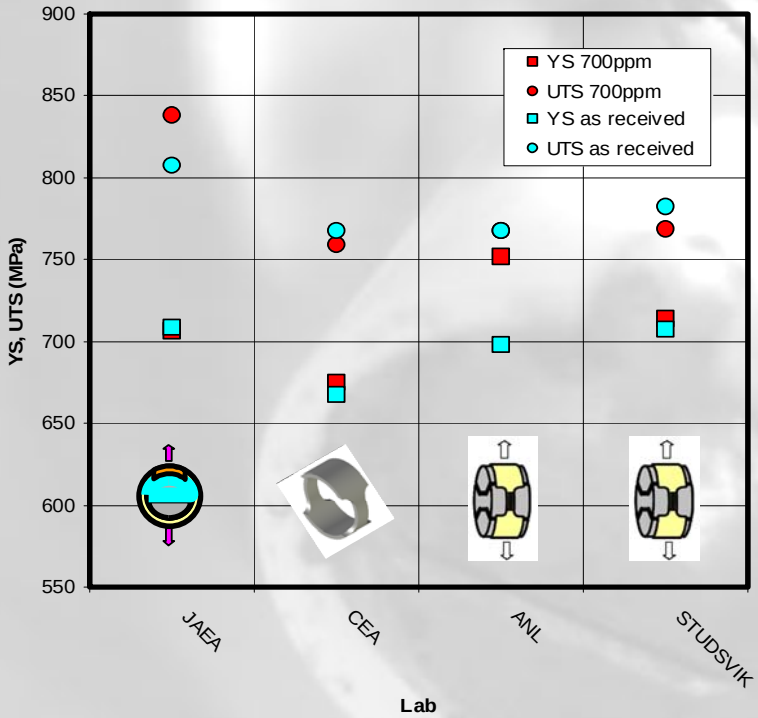
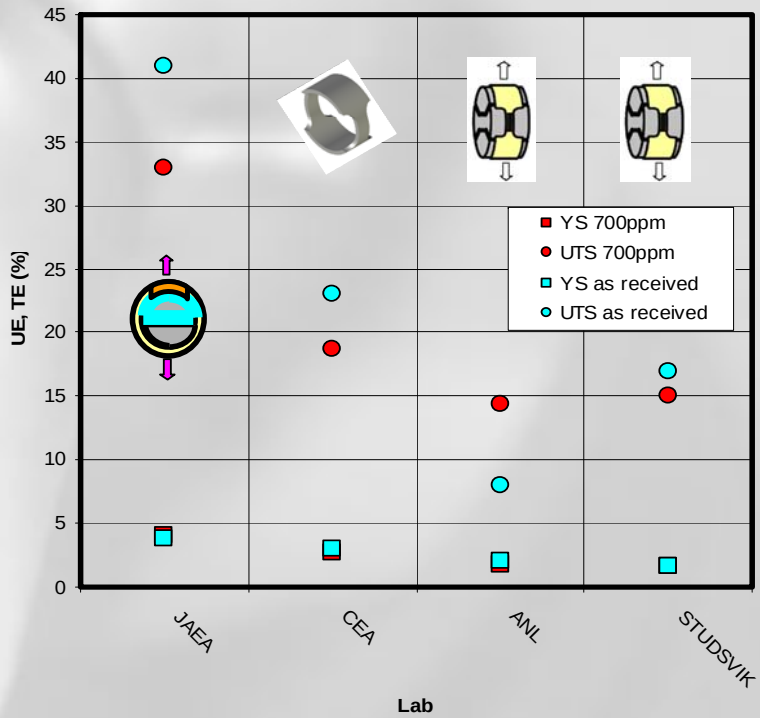
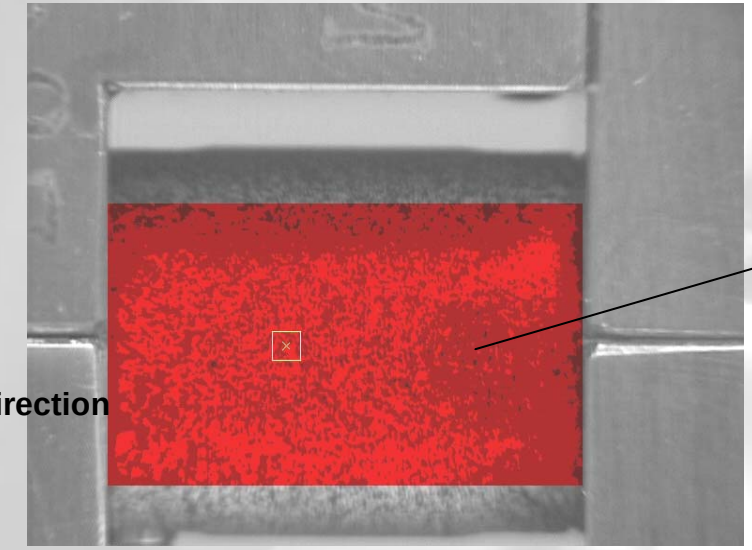




On going research : measurement of local strains

⇨ Measurement of local strain at failure from Penn State University specimens with a zero strain biaxiality between the notches

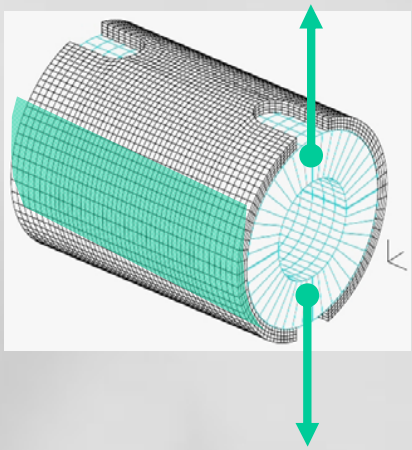


V direction

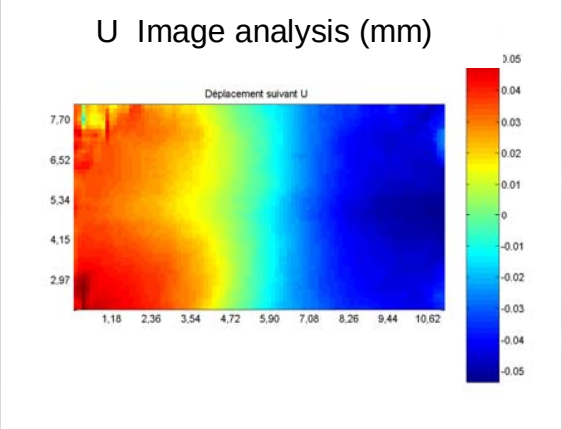
U direction

Room temperature tests

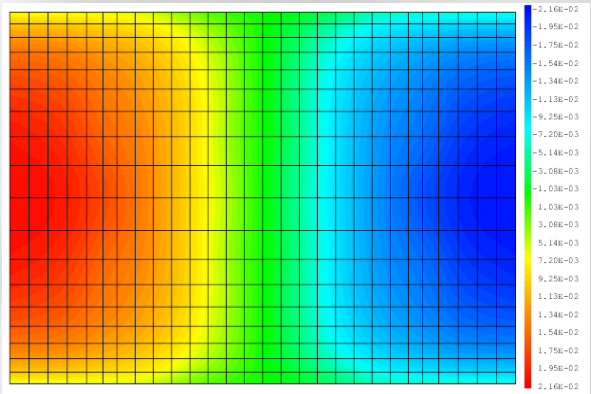
Speckle Painting + Image analysis



U Image analysis (mm)

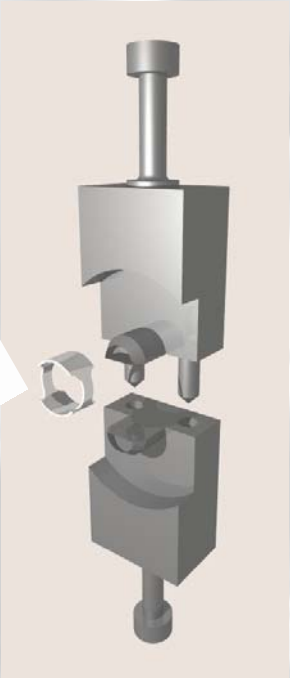


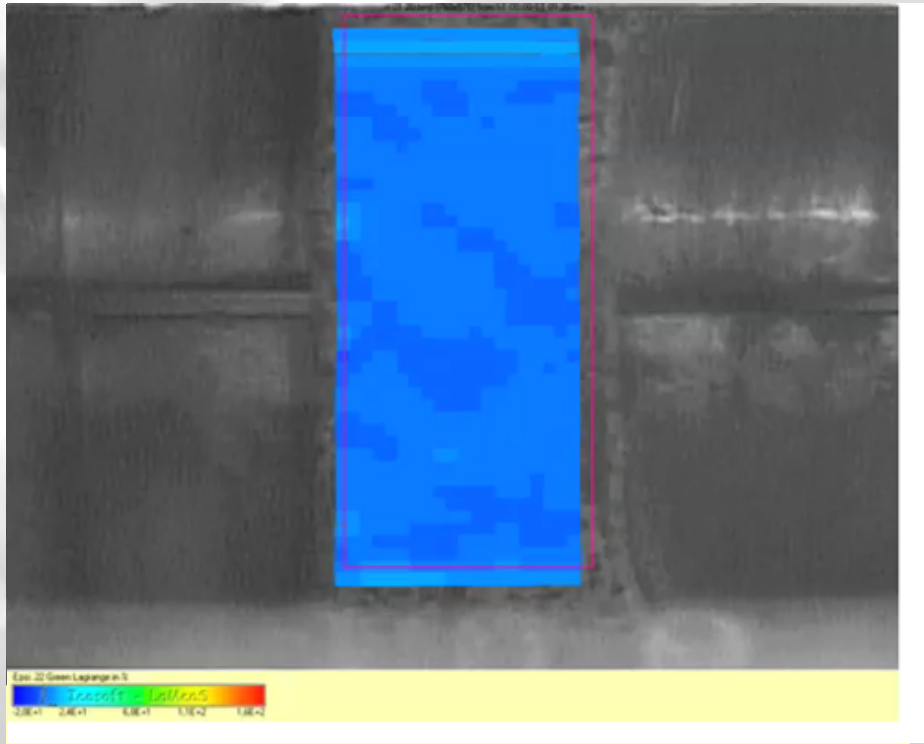
U Cast3m (mm)



On going research : measurement of local strains

⇨ Example of local strain measurements for a ring specimen **@350°C** through the window of the furnace available in M04 hot cell :





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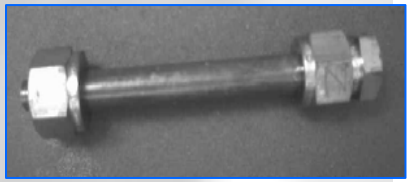
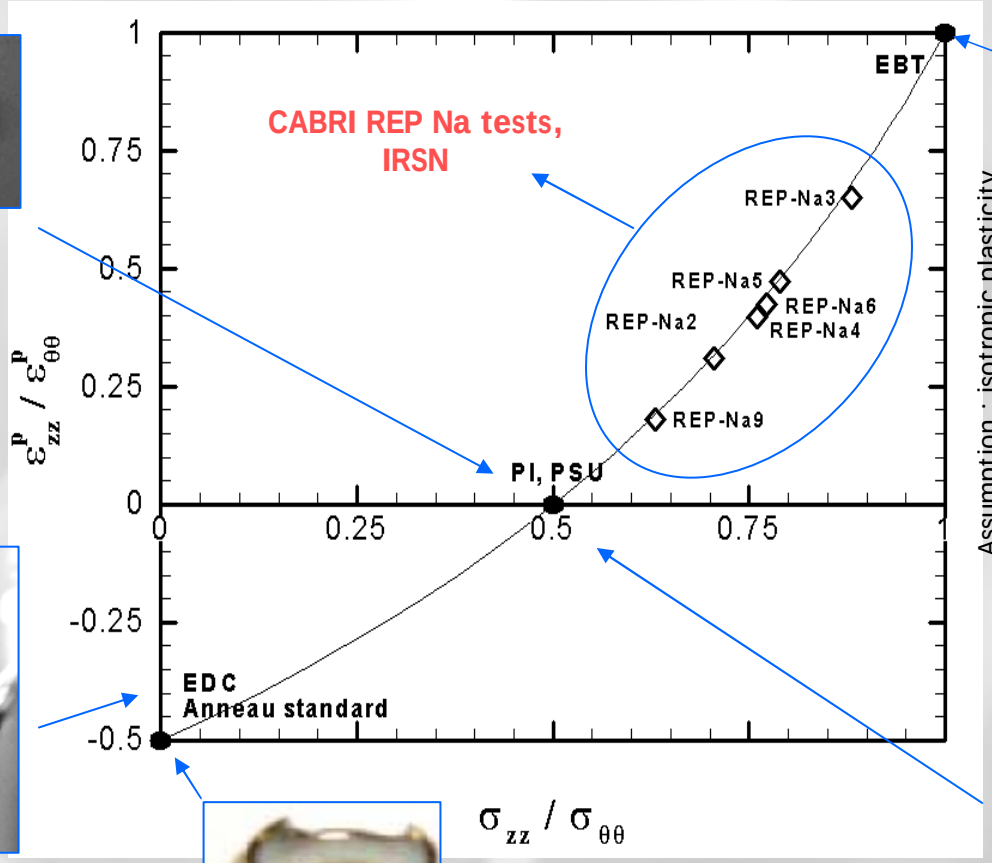
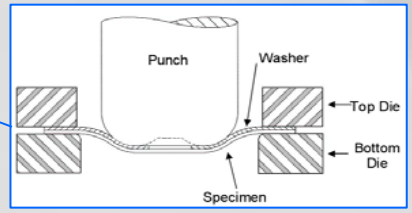
Towards a representative RIA analytical test…

- **Actual available experiments do not fully represent the biaxiality expected during an RIA :**







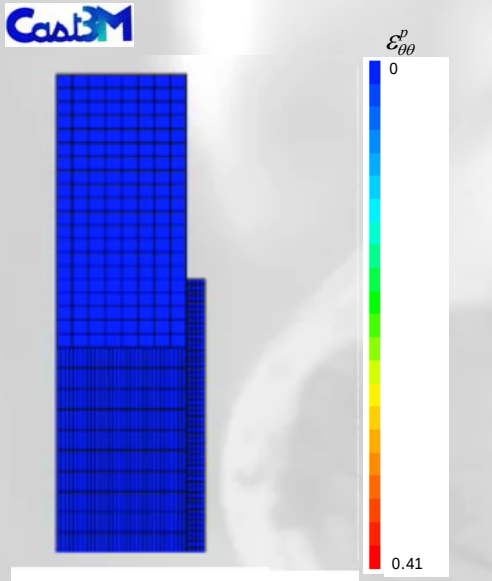
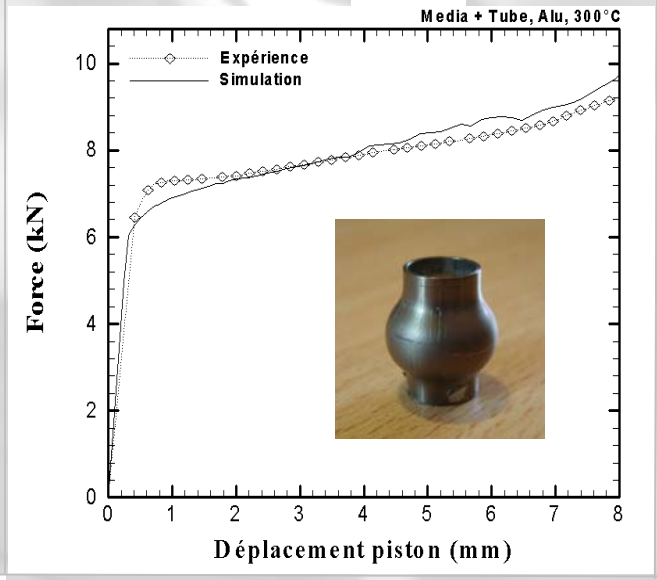
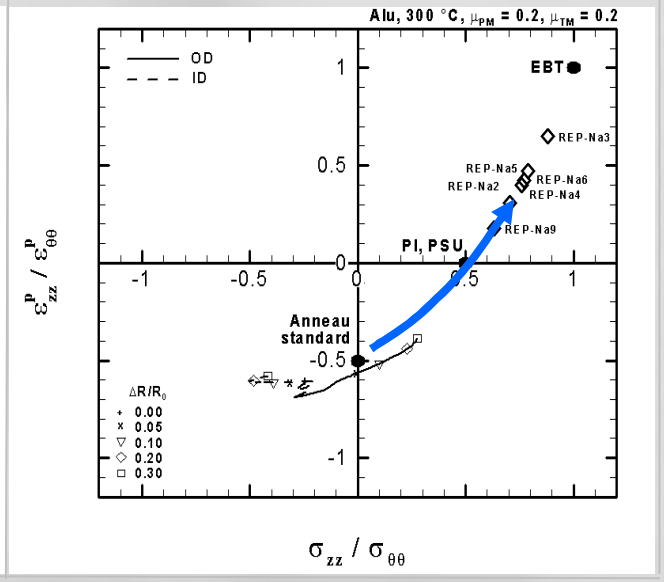
A. Motta et al., ASTM 2004

Towards a representative RIA analytical test…

- **PhD thesis (Matthieu Le Saux) underway to develop further an EDC test with a controlled biaxility**

Mechanical properties : - Media : inverse identification
- Cladding : GPL law

Inverse identification of friction coefficients (media vs. jack and media vs. cladding)

Modeling	Computation vs. experiment	Biaxiality
		

Aluminium, T = 300°C, μ_{PM} = 0, μ_{TM} = 0.2

movie

EDC ~ pure circumferential loading : ⇒ It is necessary to control the axial deformation

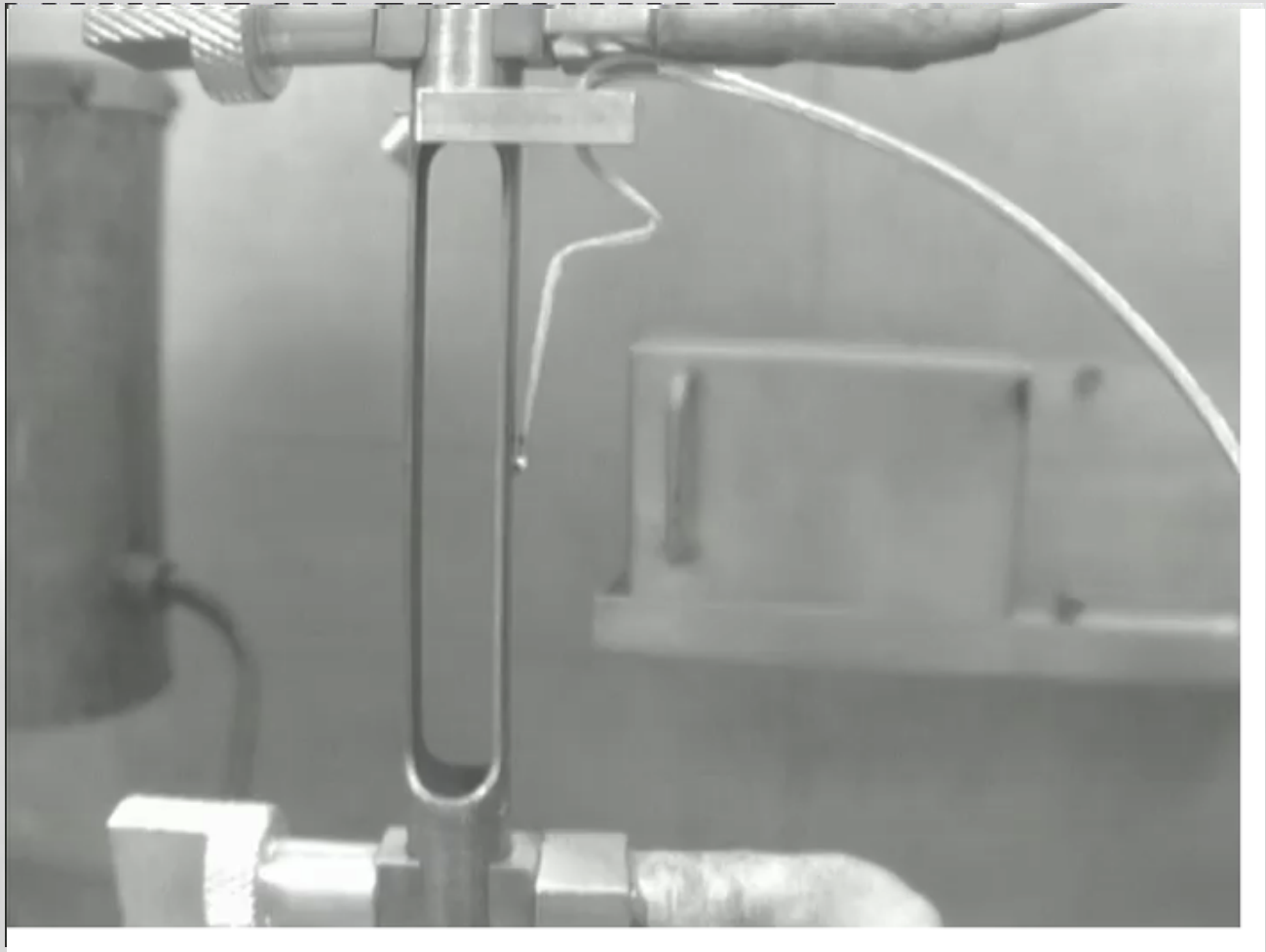
Summary and closing points

- **PROMETRA represents an extensive material database with :**
  - ⇨ over 250 validated tests results for fresh and high burnup Zircaloys, M5 and Zirlo subjected to thermomechanical transients
  - ⇨ various geometries tested with high heating rates systems and dynamic testing machines
  - ⇨ supported by full 3D modeling , indispensable for a correct interpretation of the data
  - ⇨ over 15 publications worldwide with our colleagues of EDF and IRSN

- **On-going research within PROMETRA :**
  - ⇨ new measuring techniques developed in hot cells (image analysis, acoustic emission, …)
  - ⇨ new mechanical tests prototypical of reactor biaxial loading
  - ⇨ constituve equations for a better representation of the material database
  - ⇨ development of constituve equation coupled with damage

PROMETRA axial tensile test at high temperature

x2 times faster than real life



movie

Thank you for your attention !

Any questions ?

Test specifications : 800°C, 5s^{-1} Test duration : 18s including Joule effect heating @ 100°C/s