REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

WP:	**WP 6 – Knowledge dissemination**
Task:	Clad behavior modelling advancements
Speaker:	Tatiana Taurines
Affiliation:	IRSN
Event:	Short Course DBA and DEC-A for Light Water Reactors
When:	July 5th 2023
Where:	Bologna (Italy) + Teams

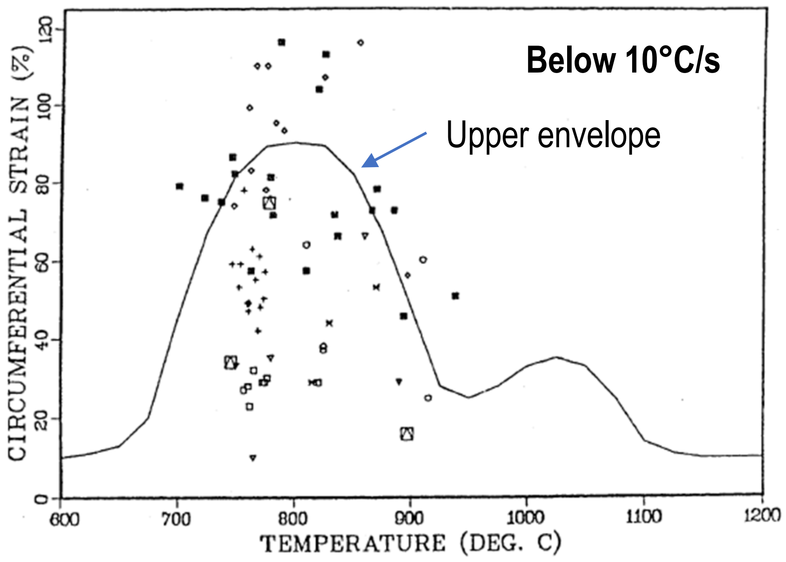
Commission européenne

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

Why developing new cladding mechanical models in the frame of R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Objective: Quantification of the radiological consequences during PWR LOCA**
- **Cladding thermomechanical behavior prediction is needed to evaluate the number of failed rods**
- **Historical burst criteria were mostly dedicated to predict flow blockage due to ballooning and were usually fitted on cladding hoop strain prediction**
- **New cladding materials are currently used or under testing in reactors**



NUREG-0630, Power D.A., Meyer, R.O., 1980

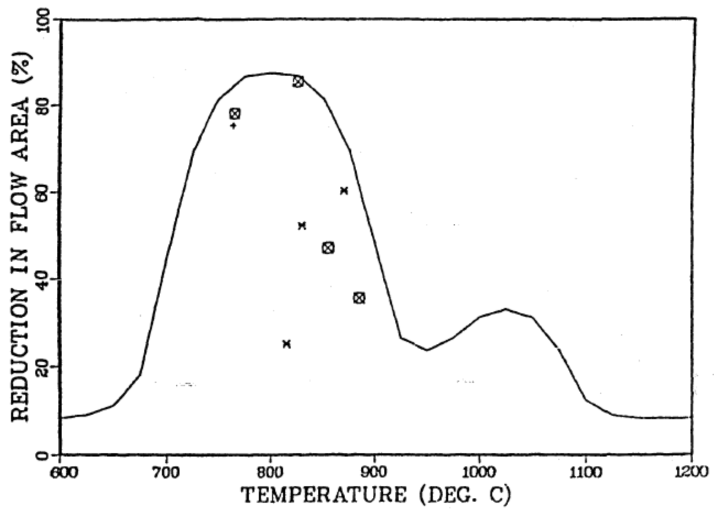


Fig. 14 Reduction in local flow area as a function of rupture temperature for internally heated Zircaloy clad bundles in aqueous atmospheres at heating rates less than or equal to 10°C/s.

Table 4-1: Chemical composition, material condition and estimated corrosion and creep behaviour of alternate Zr alloys being applied for PWR application.

Alloy	Sn %	Nb %	Fe %	Cr %	Others	Cond.*	FF**	Creep (%)+	Used since
Best Zry-4	1.3		0.22	0.1	1200 ppm O	SR[10]	~2.5	0.48	
Best Zry-4	1.3		0.22	0.1	1200 ppm O	RX[11]	~4	0.26	
E110		1	0.01		600 ppm O_2, F- impurity	RX	~0.8	0.31	
DX-ELS[12]-0.8b	0.8		0.3	0.2	1200 ppm O_2	SR	~1.1	0.48	1991
ZIRLO	1	1	0.1		1200 ppm O_2	SR	~2.5	0.37	1991
ZIRLO	1	1	0.1		1200 ppm O_2	RX	?	0.20	1991
PCA-2b	1.3		0.3	02	1200 ppm O_2	PR	1.8		1995
PCAm	1.3		0.3	02	1200 ppm O_2	RX	2.3		
DX[13]-3b	0.8		0.5		1200 ppm O_2	SR	~1		1993
DX-D4	0.5		0.5	0.2	1200 ppm O_2	SR	~1	0.48	2000
HPA[14]-4	0.5		0.5		0.3% V, 1200 ppm O_2	RX	~1.3	0.50	1999?
M5		1	0.04		1200 ppm O, 20 ppm S	RX	~0.8	0.34	1998
E635°°	1.3	1	0.4		900 ppm O_2	RX		0.18	1997
MDA	0.8	0.5	0.2	0.1	1200 ppm O_2	SR	~2.4	0.45	2004
NDA	1	0.1	0.3	0.2	1200 ppm O_2	SR	~2.4	0.71	2004
Optim. ZIRLO	0.67	1	0.1		1200 ppm O_2	PR		0.37	2008
E110-Sponge		1	0.04		800 ppm O_2,	RX	~0.8	0.28	2009

*FR cladding/structural part: SR = stress relieved, PR = partially recrystallised, RX = fully recrystallised.
** Estimated corrosion rate relative to out-of-pile Zry-4 corrosion rate by the author based on published oxide data and [Seibold & Garzarolli, 2002].
° Corrosion Rate increases in-PWR at >50 MWd/kgU
°° Only used for structural components
+ Estimated for a fluence of 3E21 n/cm² (>1MeV) and a stress of 70 MPa acc. [Adamson et al, 2009a]

ANT International, 2011

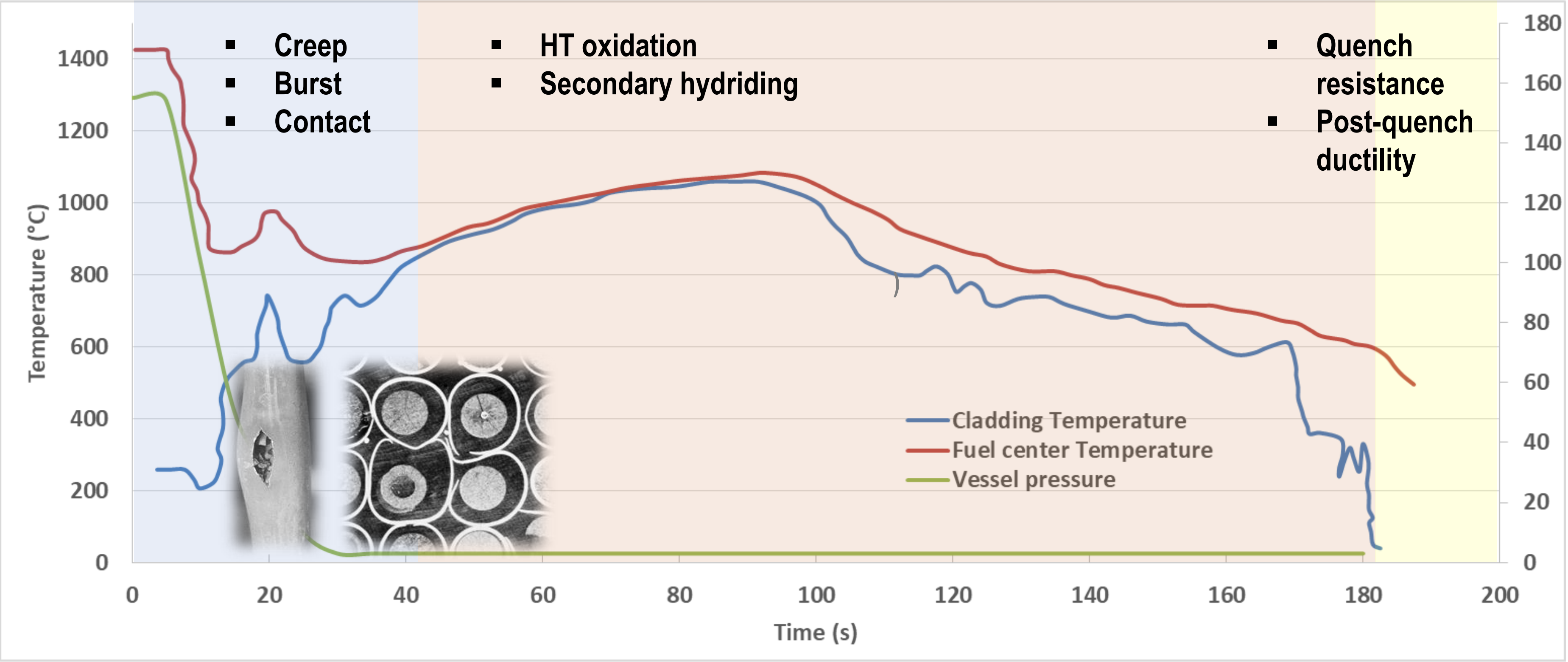
New thermomechanical models and new burst criteria are needed to better predict the number of failed rods during LOCAs

Cladding modelling in R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Cladding behavior during LOCA transients**
  - General overview of key phenomena during LOCA
  - Phase transition modelling improvements in R2CA
  - Creep modelling improvements in R2CA
  - Cladding burst improvements in R2CA

Key phenomena to model during LOCA

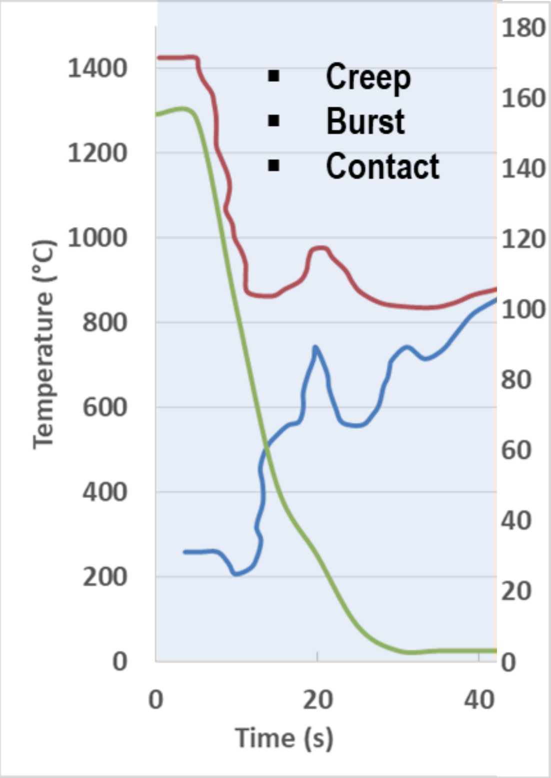


The cladding material undergoes several changes during the LOCA transient

Key phenomena to model during LOCA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Cladding alloy metalurgical changes



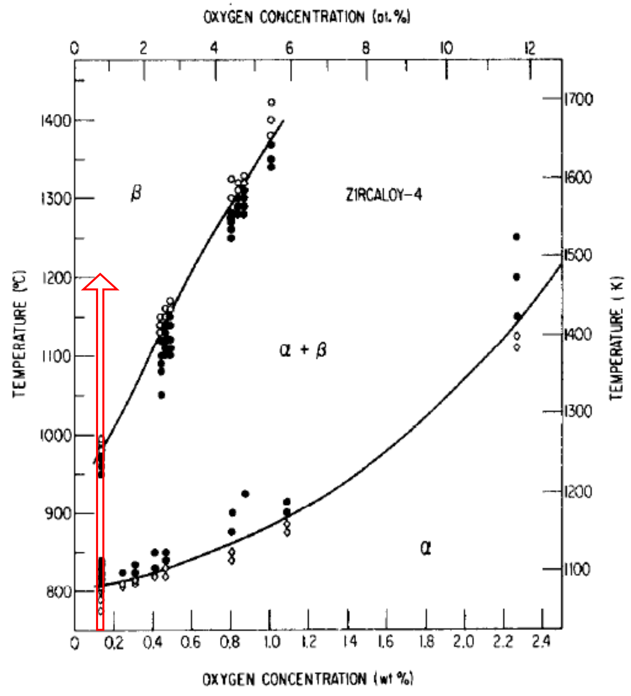
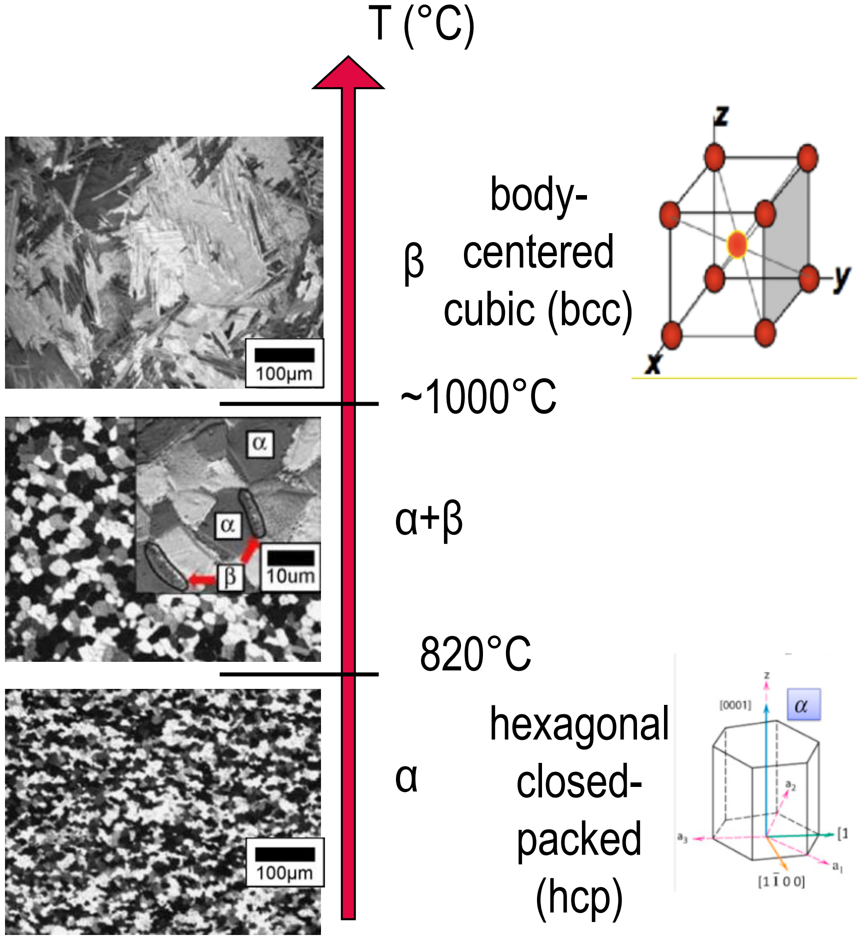


Fig. 10. α- and β-phase boundaries of the pseudobinary zircaloy-4/oxygen phase diagram determined by metallographic analyses of equilibrated and quenched specimens.



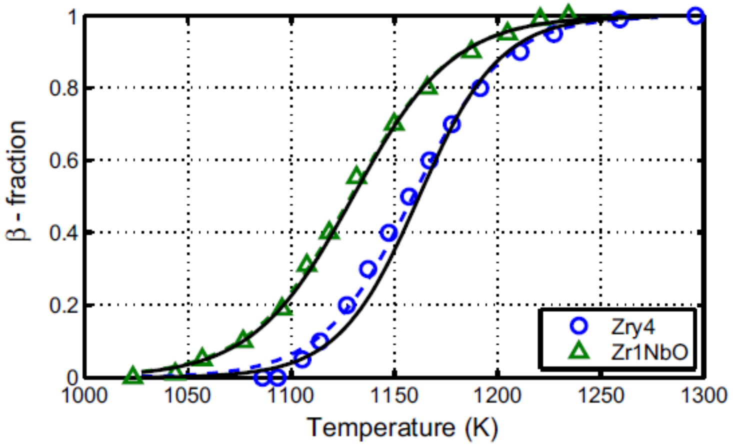
Source: H.M. Chung, Journal of Nuclear Materials 84 (1979) 327-339

During the heat-up phase the cladding undergoes metallurgical changes around 700-800°C that significantly impact thermomechanical behavior

Phase transition modelling

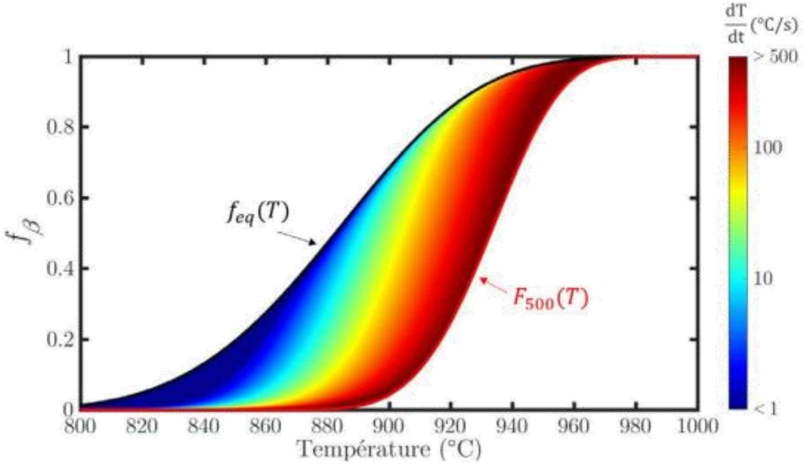
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Cladding alloy metalurgical changes



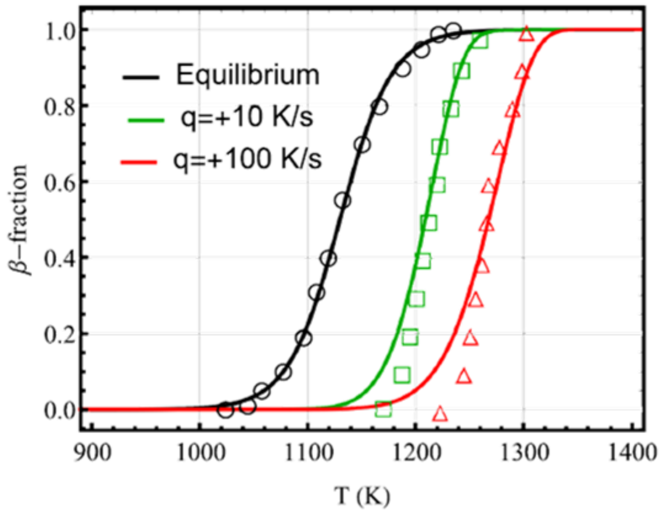
Equilibrium volume fraction of β phase as a function of temperature calculated (lines) versus measured data (markers)11 for Zircaloy-4 and Zr-1NbO alloy.

Source: A.R. Massih, L.-O. Jernkvist, “Solid state phase transformation kinetics in Zr base alloys”, Scientific Reports, Nature, 2021



Volume fraction of β phase as a function of temperature calculated for Zry-4

Source: T. Jailin, PhD Thesis, Étude expérimentale et modélisation du comportement d’un tube de gainage lors d’un accident de réactivité en phase post-crise ébullition



Volume fraction of β phase as a function of temperature calculated (lines) using model B versus measured data (markers)11 for Zr1NbO at heating rates q = dT/dt = 10 and 100 K/s and at thermal equilibrium.

Source: A.R. Massih, L.-O. Jernkvist, “Solid state phase transformation kinetics in Zr base alloys”, Scientific Reports, Nature, 2021

Strong impact of the heating rate on the α → α+β transition beginning

Phase transition modelling

Cladding alloy metalurgical changes

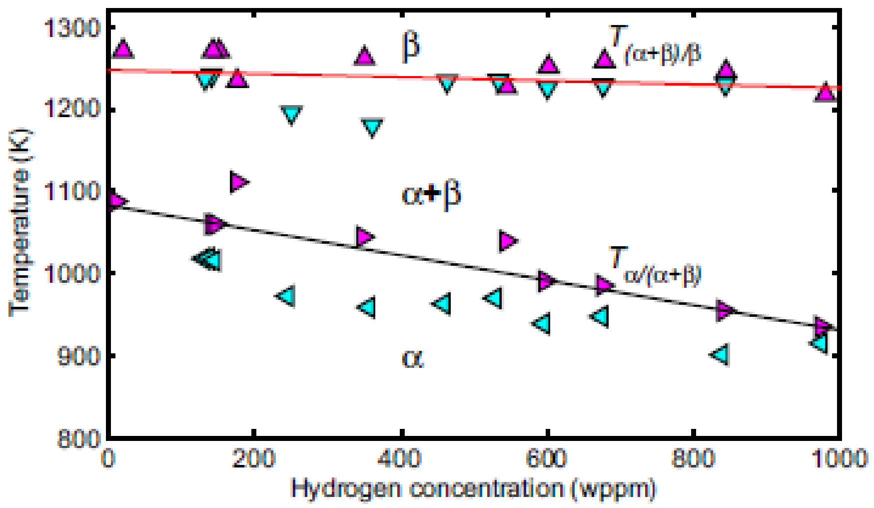
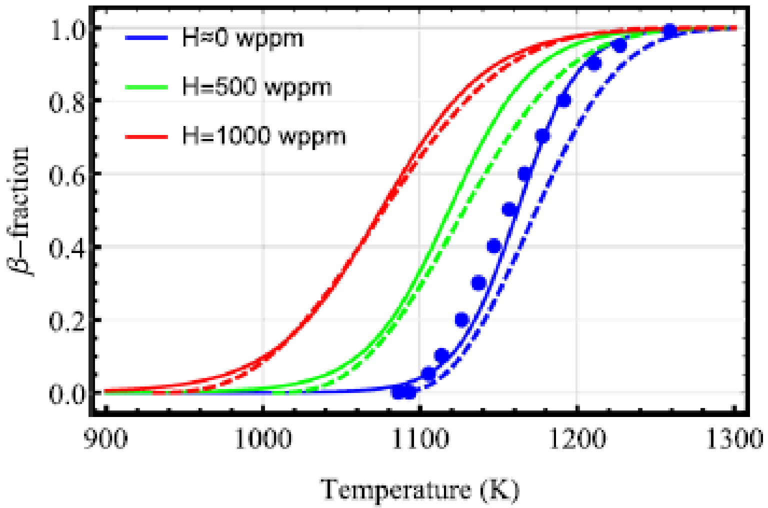


Figure 2. Phase boundary temperatures versus hydrogen concentration for Zircaloy-4L measured upon heating (Δ ▹) and cooling (∇ ◃) at ≈ 0.17 K/s. The lines (between heating and cooling) are assumed to represent the equilibrium temperatures; after Brachet et al.[20].



Equilibrium volume fraction of β phase as a function of temperature calculated for Zircaloy-4 with several concentrations of hydrogen. Solid lines are calculated whereas the dashed lines are based on analysis of experimental data.

Source: A.R. Massih, L.-O. Jernkvist, "Solid state phase transformation kinetics in Zr base alloys", Scientific Reports, Nature, 2021

Strong impact of hydrogen content on α → α+β transition beginning

Phase transition modelling improvements in R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

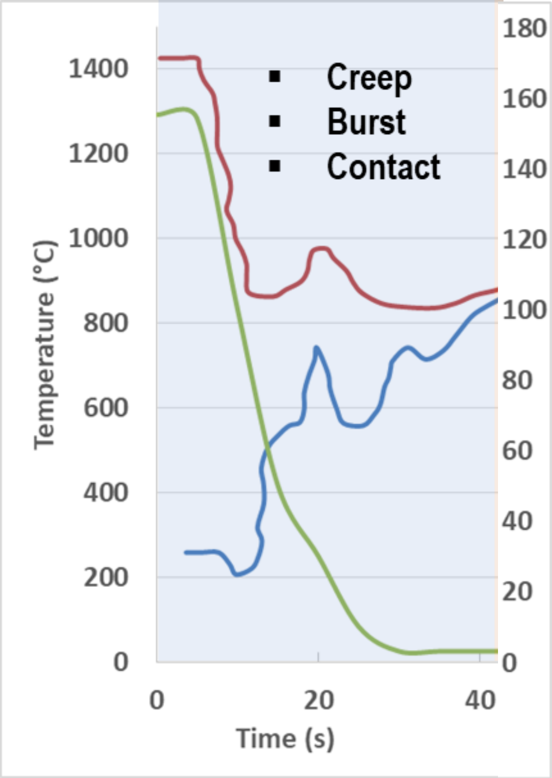
- **Identification of state-of-the-art models**

  →A.R. Massih, L.-O. Jernkvist, "Solid state phase transformation kinetics in Zr base alloys", Scientific Reports, Nature, 2021
    - Zry-4 : heating rate and hydrogen impacts
    - Zr1%Nb alloy: heating rate impact
- **Implementation of models in TRANSURANUS (ENEA-JRC)**
- **Implementation in VTT-FRAPTRAN version (VTT)**

Key phenomena to model during LOCA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Cladding ballooning and burst



Burst morphologies

Crack

Halden 650.7
1100°, 10 bars
LK3/L Zry-2

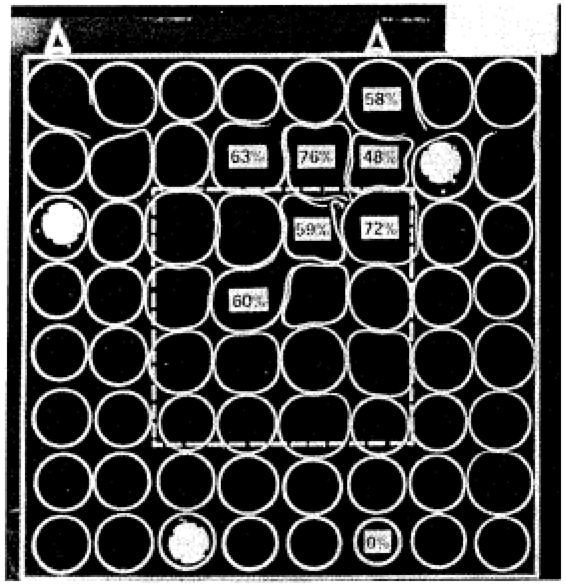
Fish mouth

Quench-L2
862°, 55 bars
M5 vierge

Open window

MT4-NRU
819°, 63 bars
Zry-4

Contact development



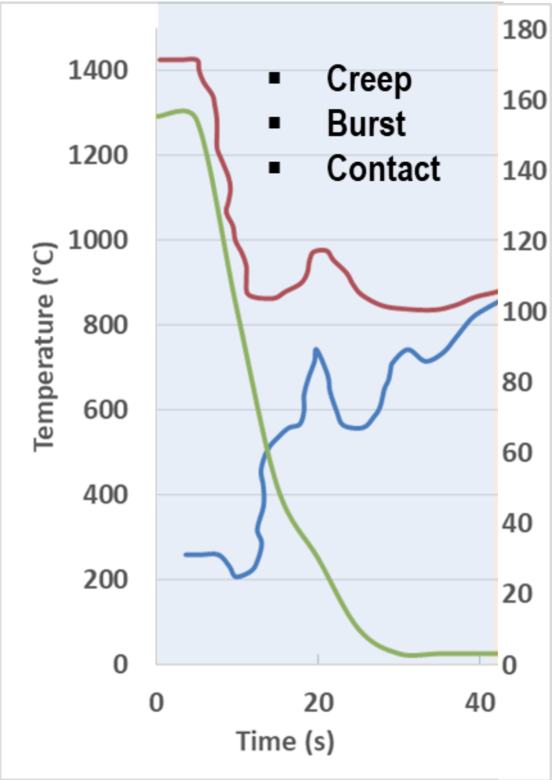
ORNL-MRBT - sections from highly deformed regions of B5

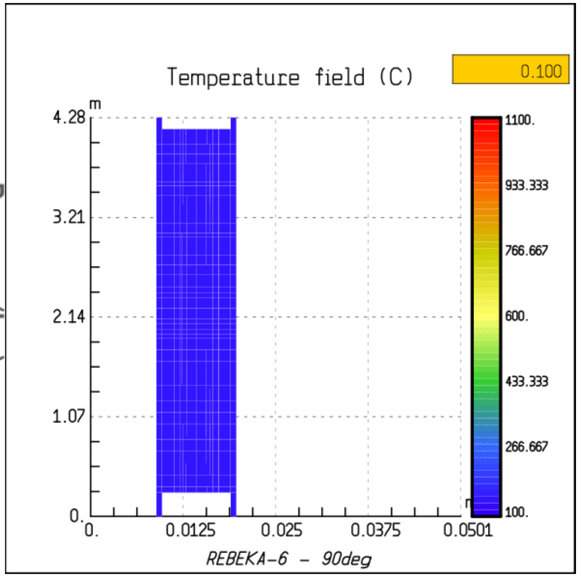
During the heat-up phase the cladding may balloon till burst →ballooning and burst predictions are needed to evaluate the fission gas release to the primary circuit

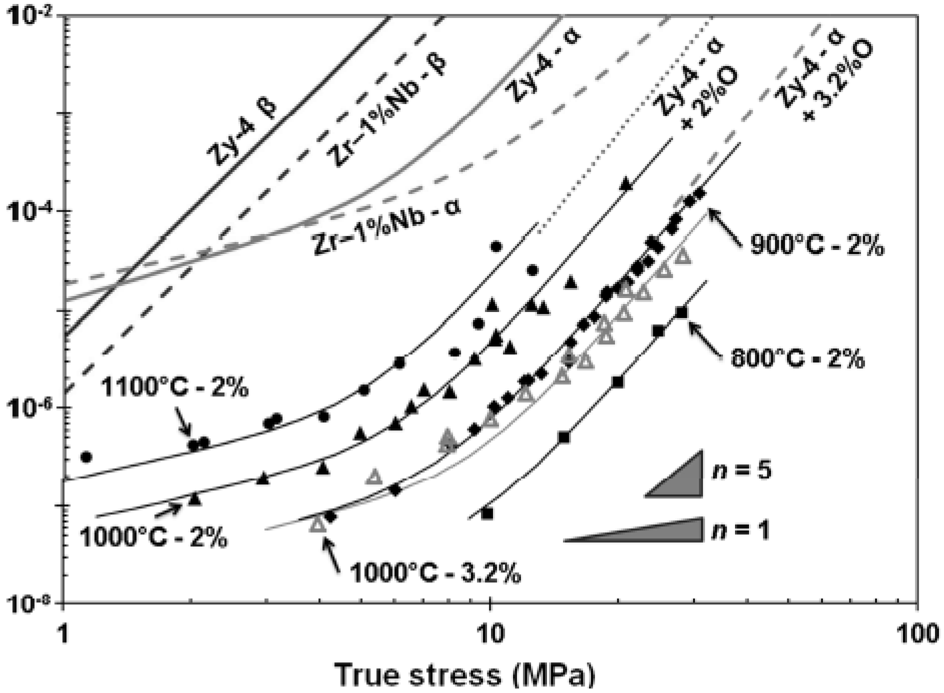
Key phenomena to model during LOCA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Cladding creep/ballooning







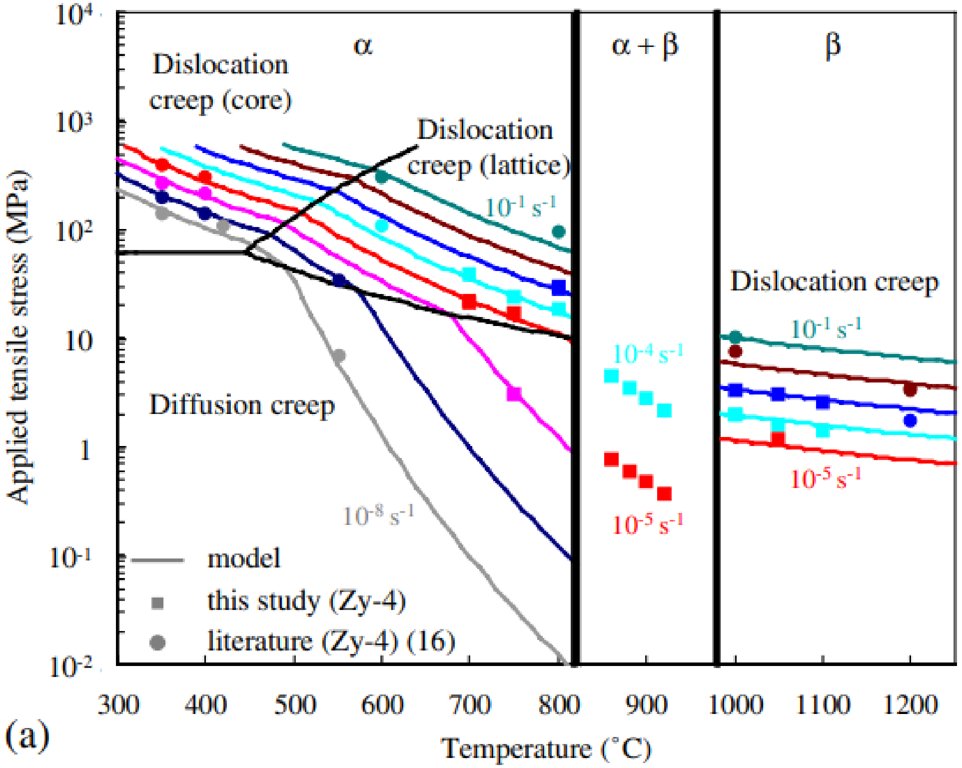
Stress sensitivity of the strain rate: present experimental results on Zr 1%Nb-2%O alloys (black symbols) and on Zr-1%Nb-3.2%O alloys (grey symbols), predictions at 1000°C for zirconium alloys which are non-enriched (color lines) [13] or enriched with oxygen (dashed and dotted grey lines) [11]. Source: R. Chosson PhD manuscript

During the heat-up phase, cladding creep occurs due to temperature increase and pressure difference increase.

Key phenomena to model during LOCA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Cladding creep/ballooning



Deformation-mechanism maps for (a) Zy-4. Lines of constant true axial strain rate are plotted using the model presented in this paper

Source D. Kaddour et al., Scripta Materialia, vol. 51, 2004, 515.:

Various creep models available in literature

Depending on diffusion regimes

- Diffusion at low stresses
- Dislocation at high stresses or high temperature

Example: Norton law

$$\dot{\varepsilon} = \frac{A}{T}\sigma^n \exp\left(-\frac{Q}{RT}\right)$$

σ true stress (Pa)
$\dot{\varepsilon}$ strain rate (–)
A, n, Q model coefficients

Creep rate depends on the metallurgical phase, temperature, stress, oxygen and hydrogen content

Creep modelling improvements in R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **Analysis of various creep models for Zirconium alloys**
- **Implementation and validation in fuel performance codes**
  - Implementation of two new models in VTT-FRAPTRAN version (VTT)
    - Rosinger[1] for Zircaloy-4 and is suitable for generic zircalloy claddings type
    - Kaddour[2] Norton creep law both for Zy-4 and Zr1%NbO (M5) types
  - Fit of existing creep model parameters in FRAPTRAN on E110 cladding after burst models identification (EK)
  - Implementation of Kadour[1] and Massih[3] models in TRANSURANUS (ENEA-JRC)

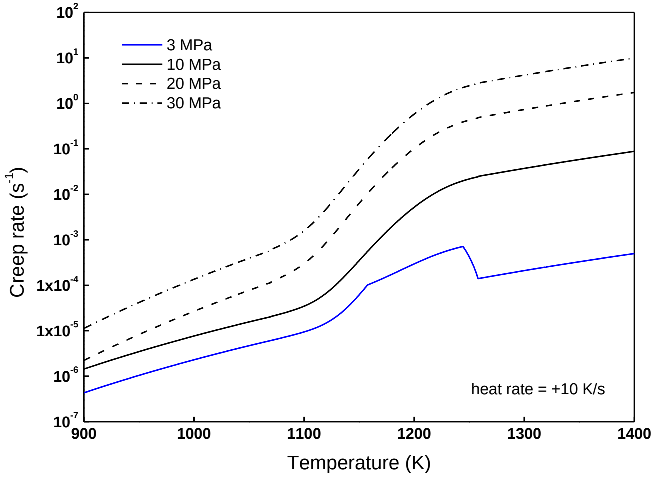


Figure 4: Creep rate of M5™ as a function of temperature and heat rate: +10 K/s

Source: R. Calabrese, NENE2022

References:

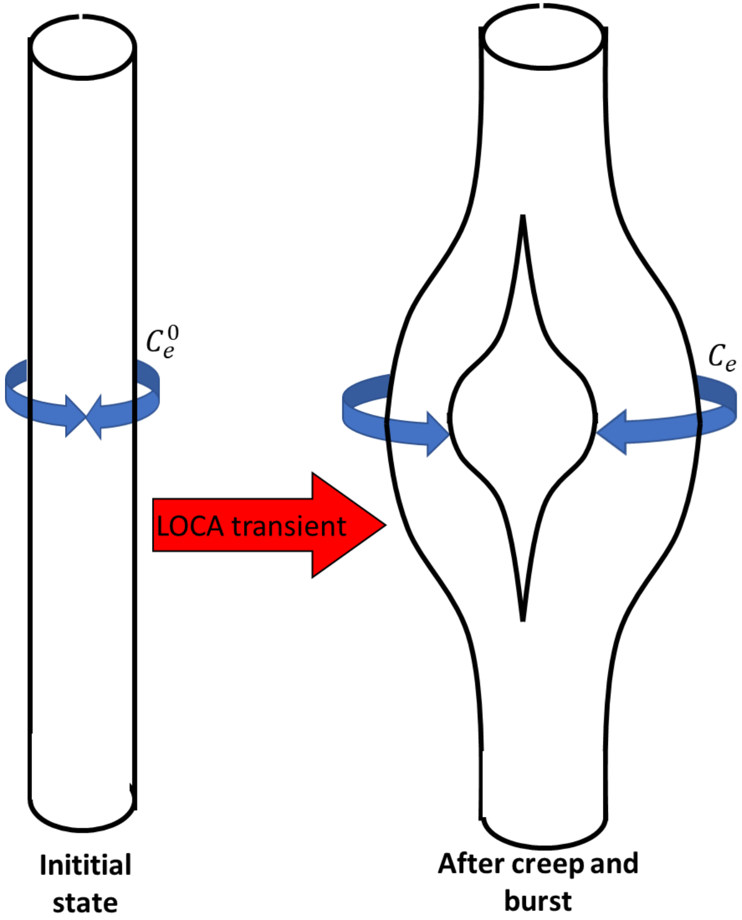
[1]H. E. Rosinger, "A Model to predict the failure of Zircaloy-4 fuel sheating during postulated LOCA conditions," Journal of Nuclear Materials, vol. 120, p. 41, 1984, doi: 10.1016/0022-3115(84)90169-7

[2]D. Kaddour, S. Frechinet, A. F. Gourgues, J. C. Brachet, L. Portier, and A. Pineau, "Experimental determination of creep properties of zirconium alloys together with phase transformation," Scr Mater, vol. 51, no. 6, pp. 515–519, 2004, doi: 10.1016/j.scriptamat.2004.05.046.

[3]A.R. Massih, "High-temperature creep and superplasticity in zirconium alloys", Journal of Nuclear Science and Technology, 50, 2013, pp. 21-34.

Burst in LOCA conditions

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



Engineering burst strain

$$\varepsilon_e = \frac{C_e - C_e^0}{C_e^0}$$

Engineering burst stress

$$\sigma_e = \frac{P_i(r_e - t_0) - P_e r_e}{t_0}$$

True burst stress

$$\sigma_T = \sigma_e.(1 + \varepsilon_e)^2$$

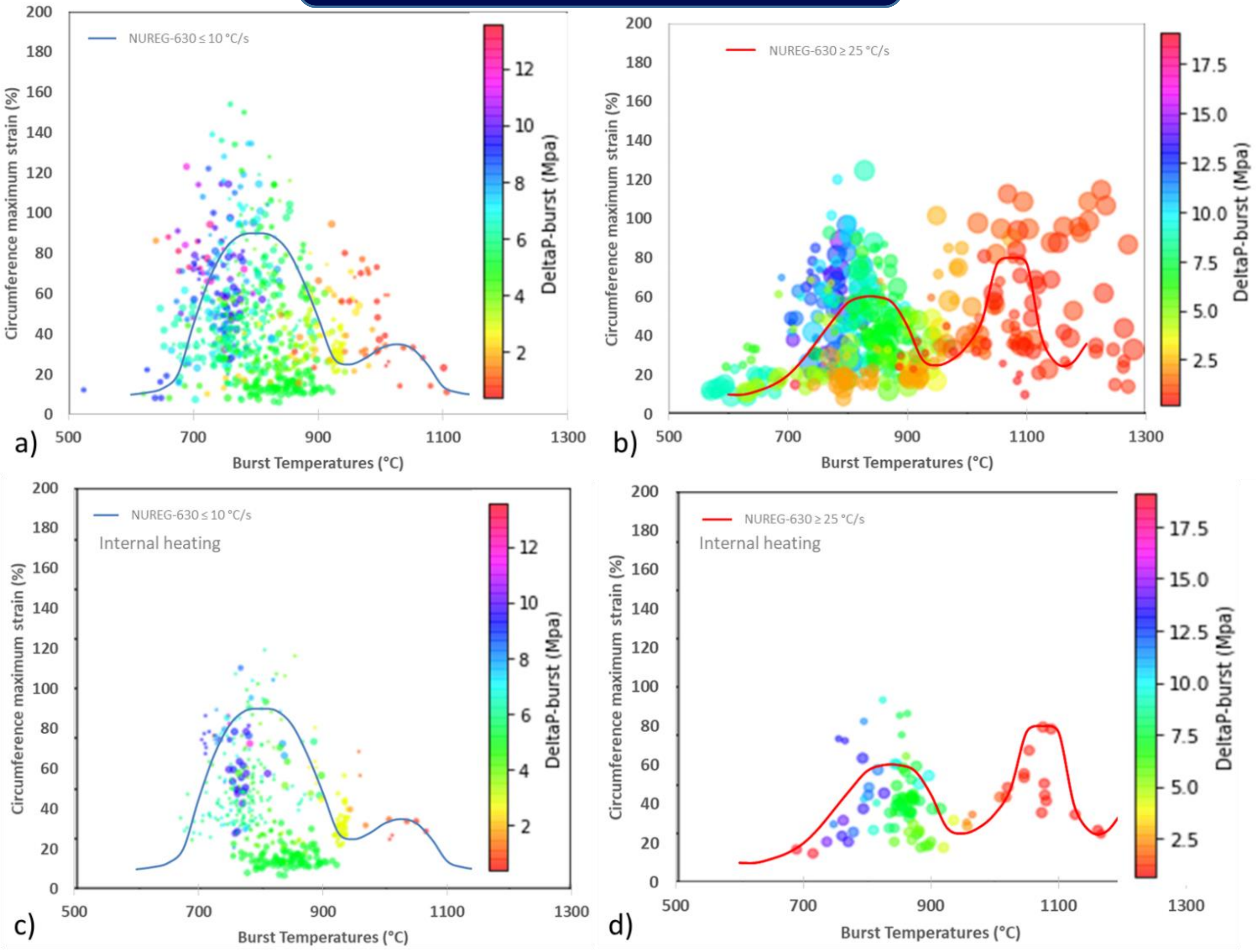
P_i internal pressure at burst time
P_e external pressure at burst time
r_e cladding external radius **at initial state**
t_0 cladding thickness **at initial state**

Various burst criteria in literature, most are based on strain or stress limits or a mix of parameters

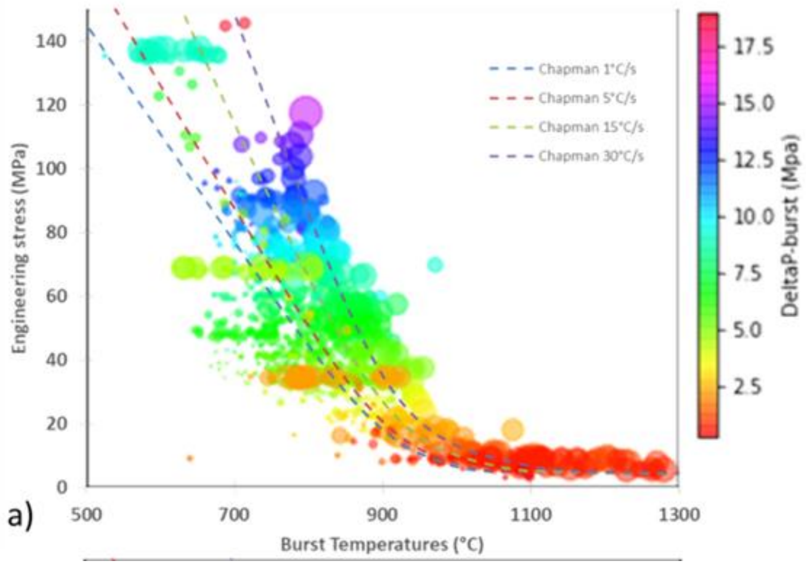
Burst in LOCA conditions

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Strain + NUREG 360 strain envelopes



Engineering stress + Chapman criterion



Strong scattering in experimental data points!

Source: T. Taurines, D3.4 T3.2 Final report – R2CA H2020 EC project

Burst in LOCA conditions

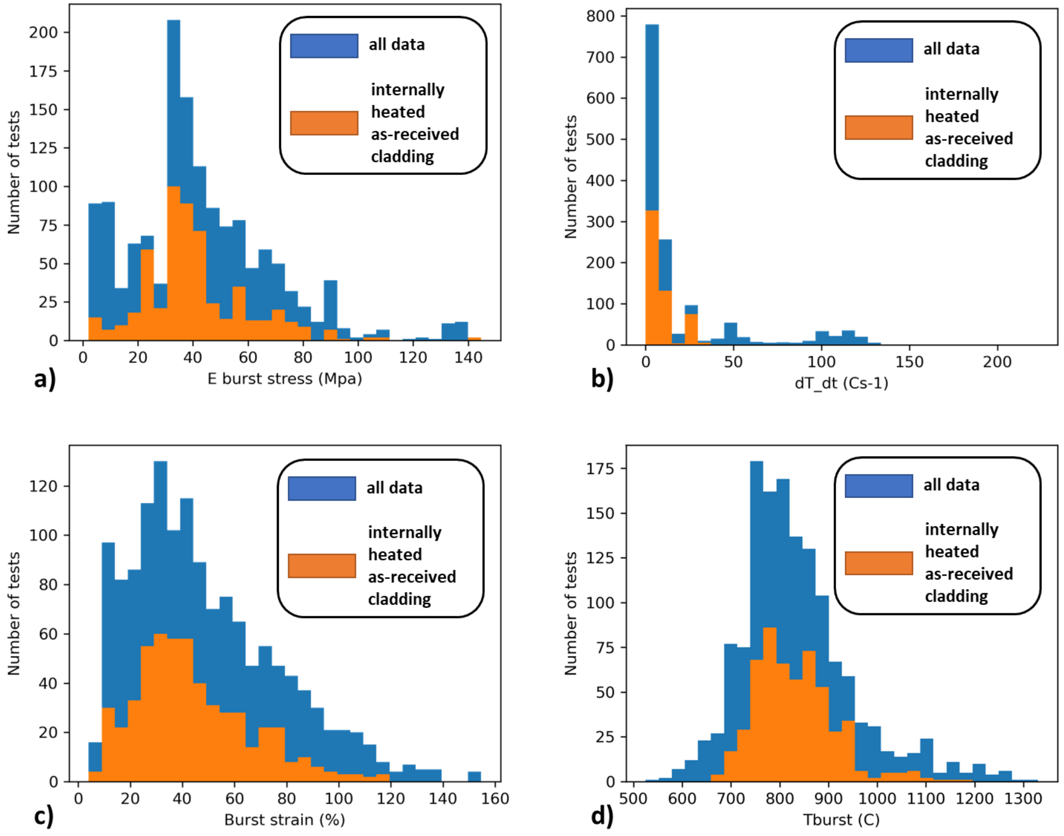
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

More than 1400 tests in LOCA conditions

Alloy / Test type	Zy-4	M5/E110/Zr-1%Nb	Zirlo/Opt Zirlo	Zy-2
Creep	78	12	0	0
T ramp	1093	55	79	12
P ramp	31	49	0	0
Total	1202	116	79	12

Table 5: General overview (cladding alloy, test type and number of tests) of complete collected burst tests.

Percentile / Parameter	0 (min)	0.1	0.25	0.5 (median)	0.75	0.9	1 (max)
Burst temperature (°C)	525	710	757	**813**	889	993	1330
Engineering Circumferential Burst Strain (%)	4	16	28	**43**	66	89	155

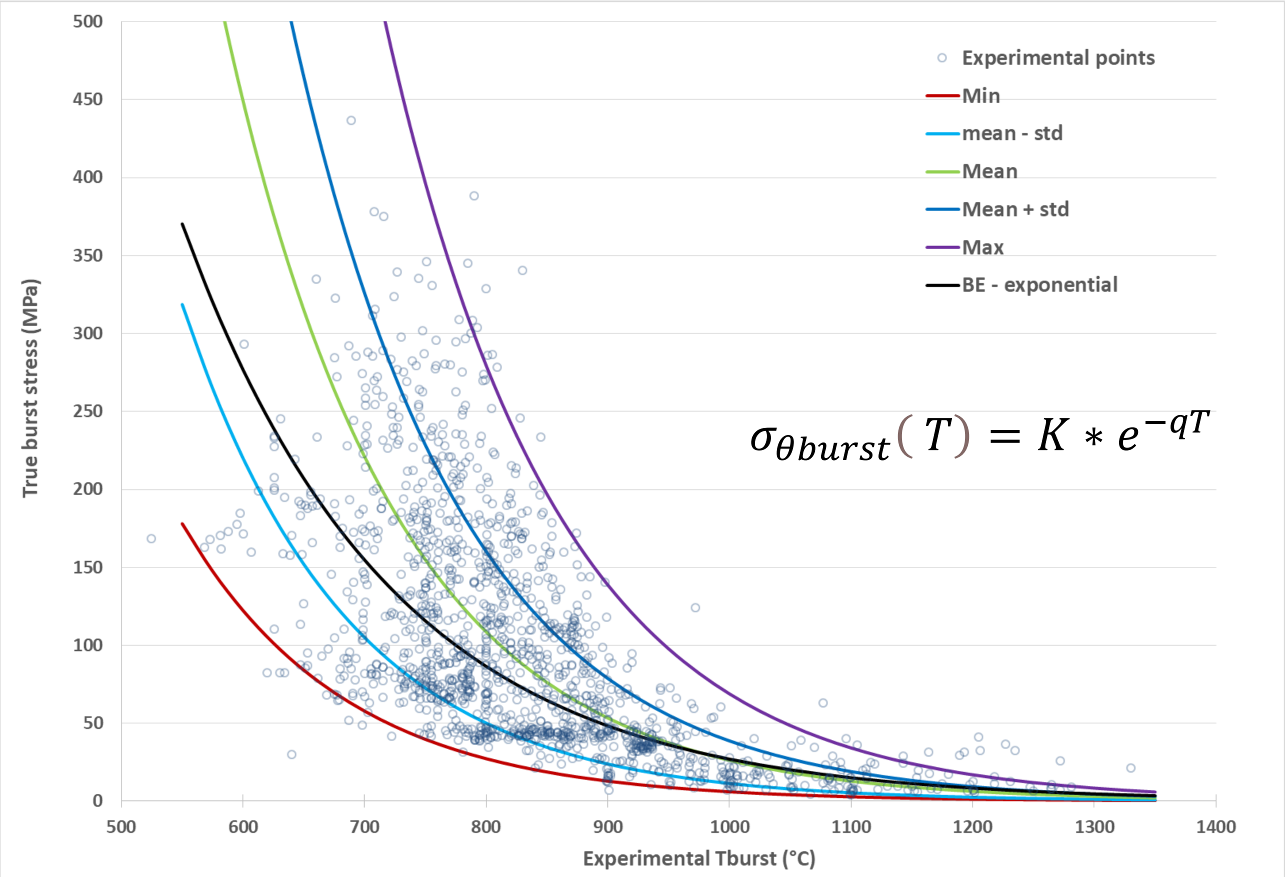


Source: T. Taurines, D3.4 T3.2 Final report – R2CA H2020 EC project

Most tests were temperature ramp tests on Zry-4, very few data on irradiated fuel rods

Burst modelling improvements in R2CA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



$$\sigma_{\theta burst}(T) = K * e^{-qT}$$

Figure 14: True burst stress versus experimental burst temperature, best estimate fit and exponential envelopes

Implementation in the DRACCAR code (Fuel+ IRSN Platform)

Source: T. Taurines, D3.4 T3.2 Final report – R2CA H2020 EC project

Envelopes on true burst stress were fitted to allow sensitivity studies for number of failed rods estimation

Burst modelling improvements in R2CA

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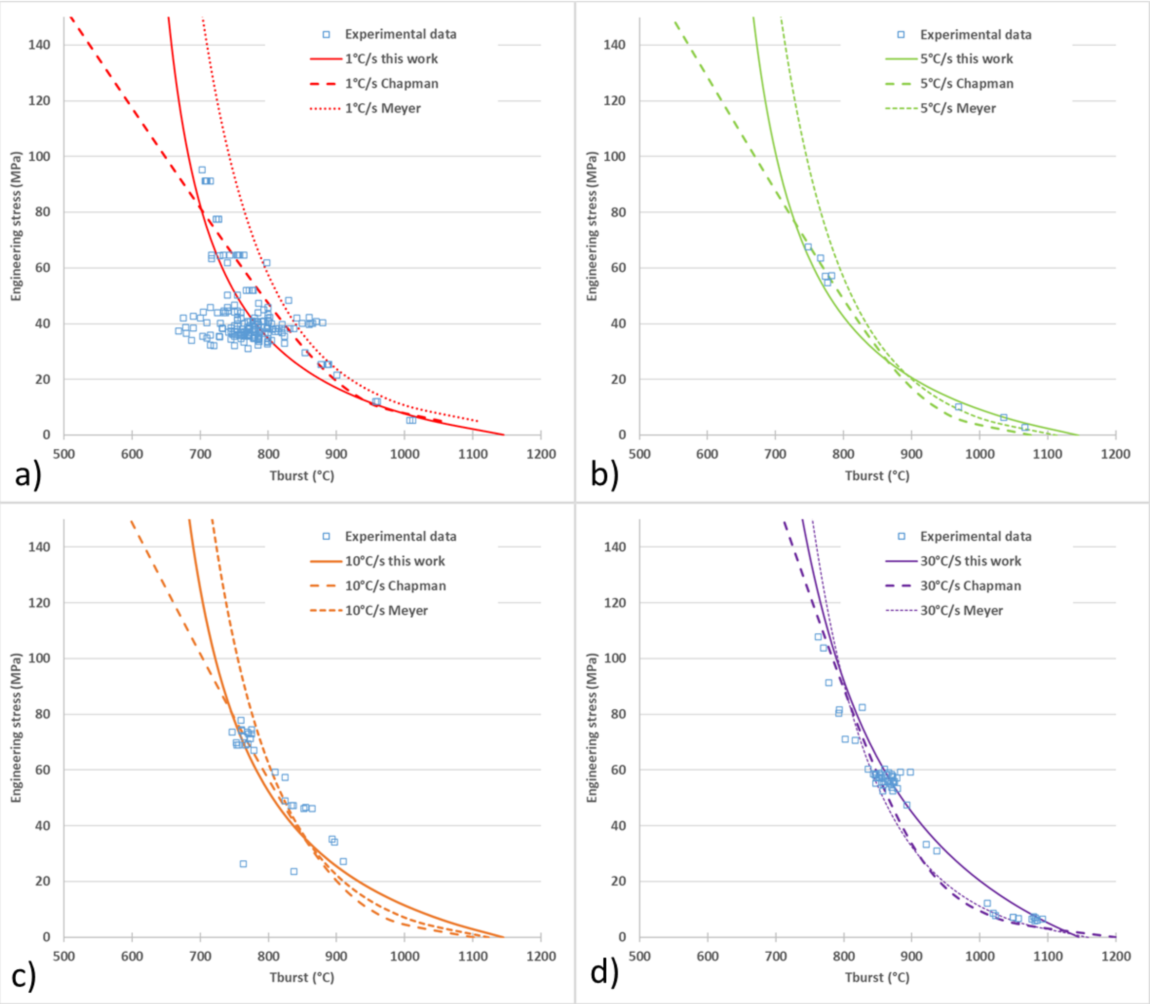

Source: T. Taurines, D3.4 T3.2 Final report – R2CA H2020 EC project

$$T_{burst}(°\mathrm{C}) = \mathrm{A} - \frac{\mathrm{B}\,\sigma_{e,\theta}}{1 + \frac{\min\left(\frac{dT}{dt}, 38\right)}{C} + \mathrm{D}\,\sigma_{e,\theta}}$$

- T_{burst} is the burst temperature (°C)
- $\sigma_{e\theta}$ the engineering hoop stress (kpsi)
- $\frac{dT}{dt}$ the heating rate (°C/s)

- New burst temperature criterion fitted considering only internally heated as-received claddings
- Comparison to other criteria shows a different trend for low burst temperatures and a similar trend at high burst temperatures
- Implementation in the DRACCAR code (Fuel+ IRSN Platform)

Burst modelling improvements in R2CA

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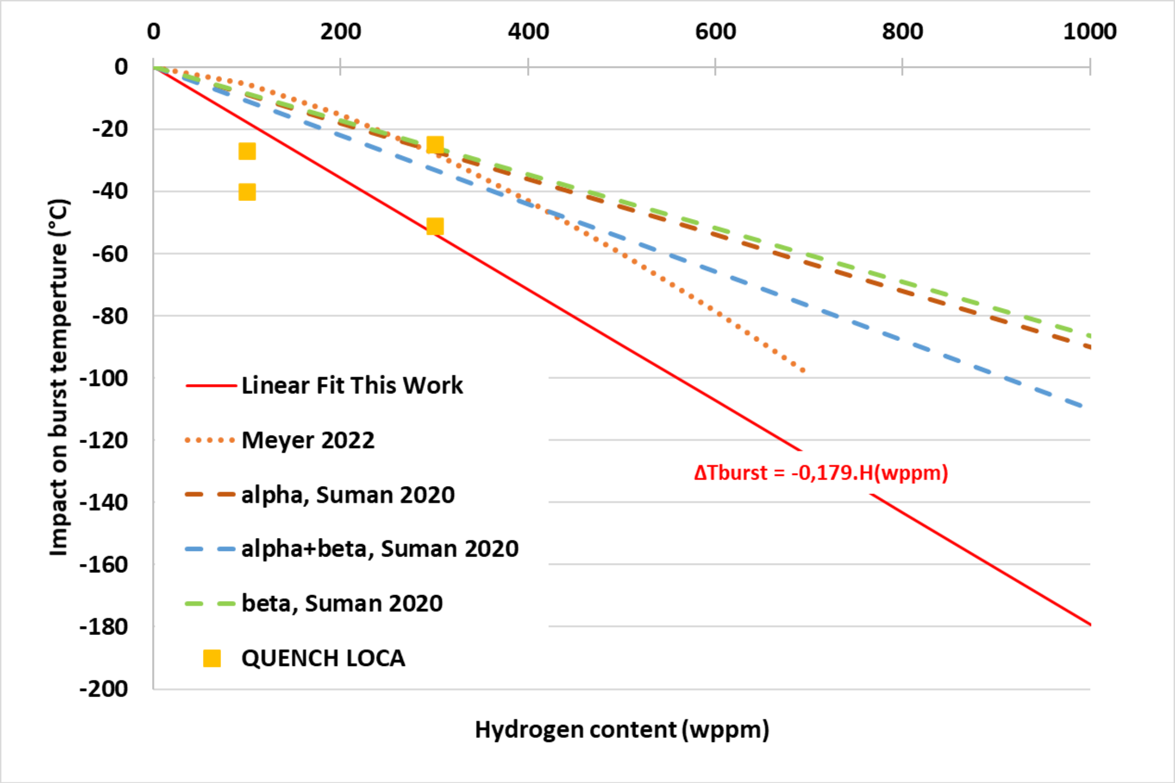

Figure 11: Impact of cladding hydrogen content on burst temperature from literature and fitted during this work

Source: T. Taurines, D3.4 T3.2 Final report – R2CA H2020 EC project

Hydrogen content leads to lower burst temperatures, a correlation has been proposed.
More data on irradiated rods are needed to improve the correlation

Burst modelling improvements in R2CA

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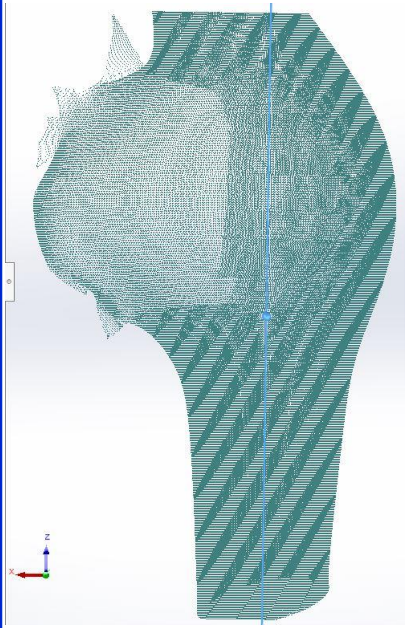
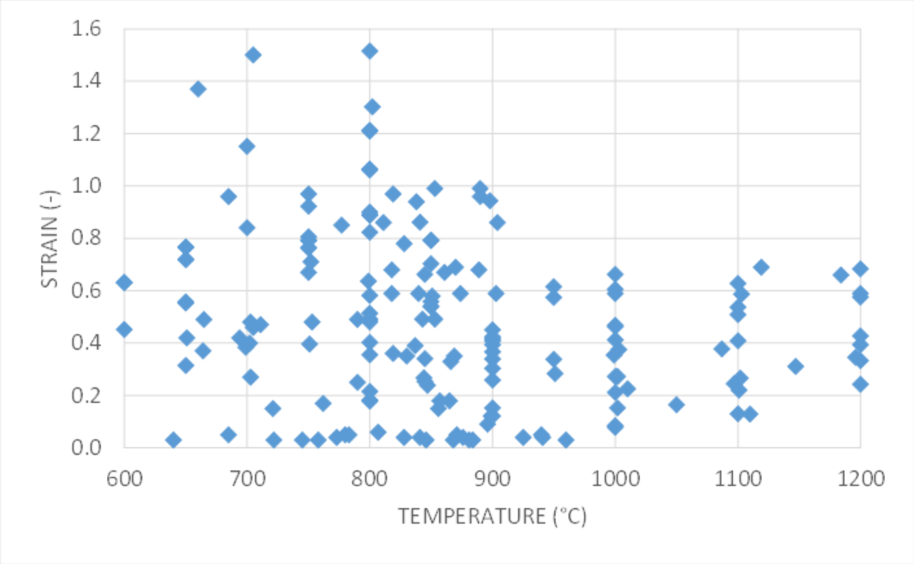
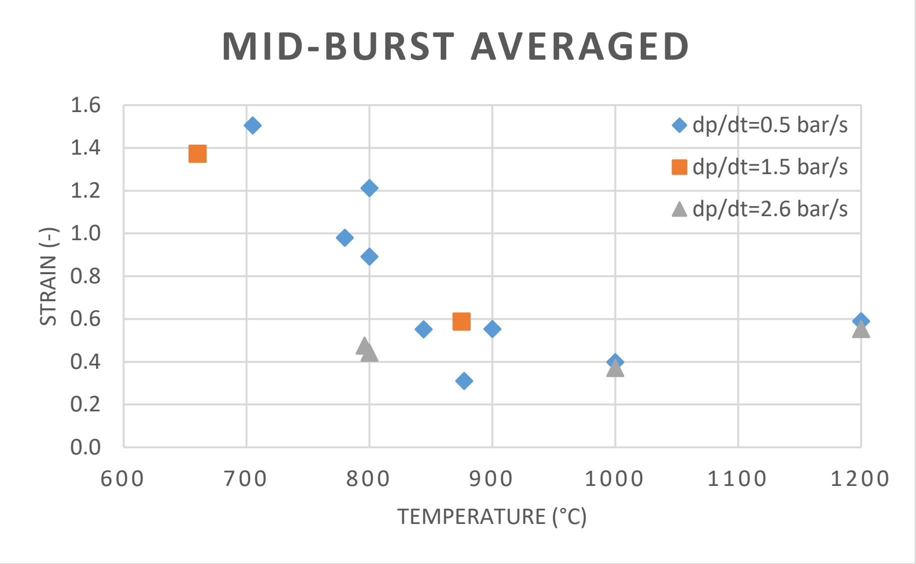


- **3D scanning measurements of previous burst tests on E110**
- **Analysis of strain at various elevations/ burst elevation**
- **Proposal of a conservative burst criterion for radiological consequences analysis**
  - A strain limit of 21% was used





Source: K. Kulacsy, D3.4 T3.2 Final report – R2CA H2020 EC project

Conclusions and prospects

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

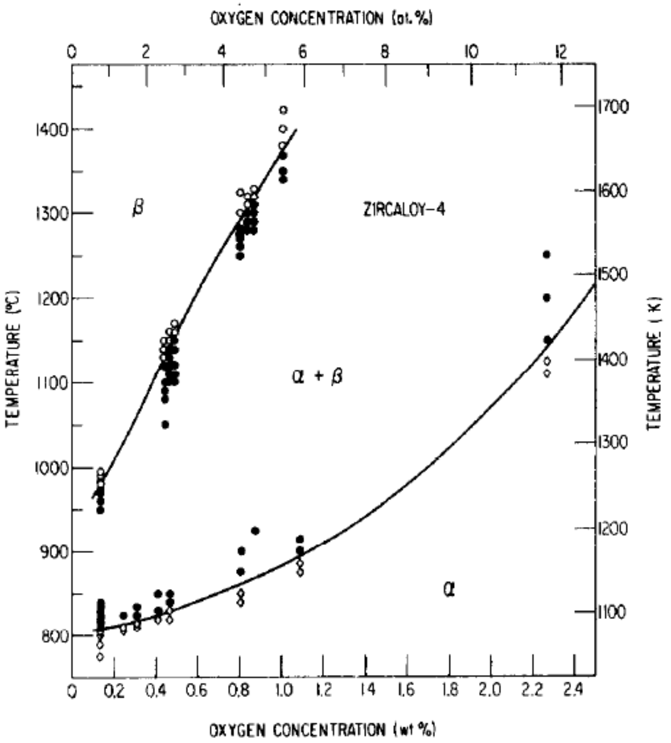
- Conclusions
  - State of the art models for phase transition and new creep laws have been implemented in the TRANSURANUS and FRAPTRAN-VTT codes
  - Very large burst database in LOCA conditions was built (more than 1400 burst tests)
  - Burst criteria
    - New engineering burst stress criteria fitted on internally heated as-received cladding rods implemented in the DRACCAR code
    - Hydrogen impact on burst temperature correlation
    - Low strain envelope for E110
- Open questions and data gaps
  - Burst data for irradiated fuel rods with impaired axial gas communication
  - Burst tests with more complex transients similar to LOCA Intermediate and small breaks transients (“Low Peak cladding temperatures” ~700-900°C)

BACK – UP for questions

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

Key phenomena to model during LOCA

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



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Source: H.M. Chung, Journal of Nuclear Materials 84 (1979) 327-339

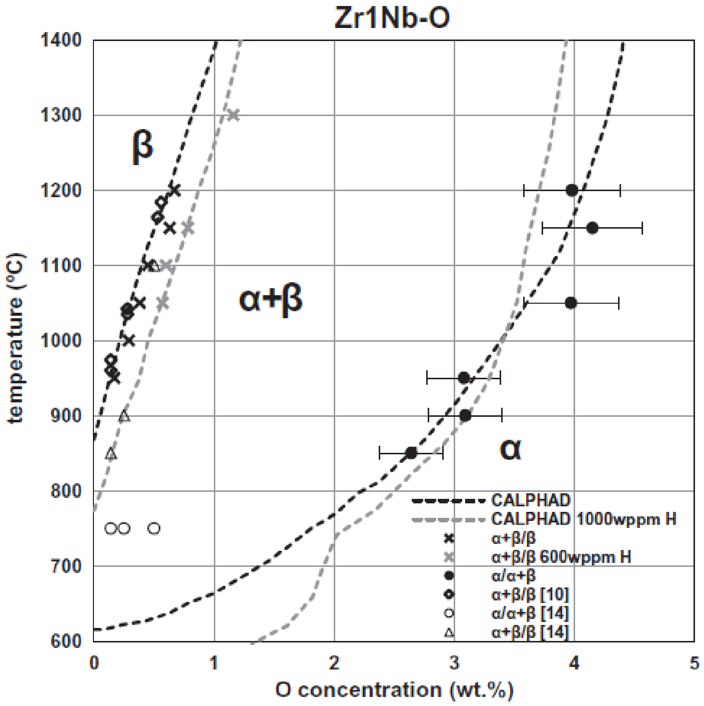

Fig. 5. Pseudobinary Zr1Nb–O phase diagram for temperatures 600–1400 °C and oxygen concentrations 0–5 wt.%. The dashed lines indicate calculated phase intefaces α/α + β and α + β/β.

Source: M. Négyesi, Journal of Nuclear Materials 420 (2012) 314–319

Impact of cladding material and hydrogen content on phase transition