

HIGH TEMPERATURE OXIDATION AND CREEP BEHAVIOR OF PRE-OXIDIZED ZIRCALOY-4 CLADDINGS UNDER LOCA CONDITIONS

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Context of the study : LOCA



This work investigates the effect of oxygen and zirconia (ZrO_2) on the cladding ballooning during the ductile phase of the LOCA.



Experimental observations



Multi-physics problem: multilayer material $(ZrO_2/\alpha Zr(O)/Zy-4/\alpha Zr(O)/ZrO_2)$ with ZrO_2 cracking and oxygen diffusion during the transient.



General strategy of the study



The problem is treated with an both experimental and numerical approaches.



Oxidation test protocol



-2 studyied testing temperatures: 750°C and 820°C,

- -2 types of specimens: as-fabricated and pre-oxidized (10/10),
- -2 environments: neutral (argon) and oxidiszing (argon+steam mixture).



Optical metallography before and after HT oxidation

Optical metallography



820°C-3200s

Optical metallography



- Sample colour change, .
- oxygen diffusion in the metal leading to the formation of a significant $\alpha Zr(0)$ layer thickness.

Before test



Evolution of the $\alpha Zr(O)$ layer thickness



-The results obtained in this work are consistent with the extrapolation of the IRSN law,

-the influence of the pre-oxide on the α Zr(O) layer thickness formed during HT oxidation seems negligible.



Oxygen profiles and diffusion coefficients

Comparison between the simulated and experimental oxygen profiles in the metal



Comparison of the identified coefficients with those in the literature

	$D_{Zy-4}(cm^2/s)$		
T(°C)	This study	Literature (Ritchie,1977)	
750	5.78×10^{-11}	9.01×10^{-11}	
820	1.49×10^{-10}	3.87×10^{-10}	

The obtained O-diffusion coefficients in Zr-4 are consistent with those available in the literature.



Ballooning tests in the ELLIE device



Characteristic of the test bench:

 $-\dot{T}_{max} = 1500^{\circ}\text{C/s}$,

 $-P_i = [1 - 70]$ bar

-F = [-10, 10] kN

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- 2 environments: neutral (argon) or oxidizing (argon+O₂ mixture).



Example of a test on a 10/10 thick pre-oxidized cladding

Strain and thermal profile after 1000s of creep at T=800°C and p=30bar





The thermal and kinematic profiles are consistent, the strain is maximal at the hottest point.



Results on as fabricated cladding in neutral atmosphere and comparison with literature

Ballooning rate on as fabricated cladding under argon: $\dot{\epsilon_v}$

T~800°C	(This study) Internal pressurization	(Campello,2016) Internal pressurization	(Frechinet,2001) Uniaxial ensile test
20 bar~14.7MPa	4.9×10 ⁻⁵	5.1×10 ⁻⁵	1.7×10 ⁻⁵
30 bar~22MPa	3.1×10 ⁻⁴	1.5×10-4	3.2×10-4
50 bar~36.7MPa	2.7×10 ⁻³	1.1×10 ⁻³	4.2×10 ⁻³

The results on as fabricated Zr-4 in neutral atmosphere (argon) are consistent with the literature.



Results of tests on 10/10 thick pre-oxidized claddings at 30bar, 800°C

Normalized strain rate



 $\dot{\varepsilon}_{\rm v}$: as fabricated creep rate under argon

Zirconia reinforcement before cracking and strain localization between zirconia fragments after cracking.



Cracking of the oxide during ballooning





- cracking densification during ballooning,
- strain localization between zirconia fragments after cracking.



Conclusions and perspectives

- The growth kinetics of the oxygen enriched metal layer $\alpha(0)$ was characterized,
- identification of metal oxygen diffusion coefficient at 750°C and 820°C,
- the creep strengthening role played oxide layer was evidenced,
- Strain induced densification of oxide layer cracking evidenced during the ballooning process,
- simulation of ballooning tests on the basis of the finite element model developed in this work ("Modeling diffusive phase transformation and fracture in viscoplastic materials", In Preparation).

