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I. Guenot-Delahaie, Jérôme Sercombe, Antoine Bouloré, Eric Federici, Rodrigue Largenton, et al..
Simulation of RIA transients on MOX fuel rods with ALCYONE fuel performance code. TopFuel2018
- Light Water Reactor (LWR) Fuel Performance Meeting, Sep 2018, Prague, Czech Republic. cea-
02338540

HAL Id: cea-02338540

<https://cea.hal.science/cea-02338540v1>

Submitted on 24 Feb 2020

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FROM RESEARCH TO INDUSTRY



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SIMULATION OF **RIA** TRANSIENTS
ON **MOX** FUEL RODS
WITH **ALCYONE**
FUEL PERFORMANCE CODE

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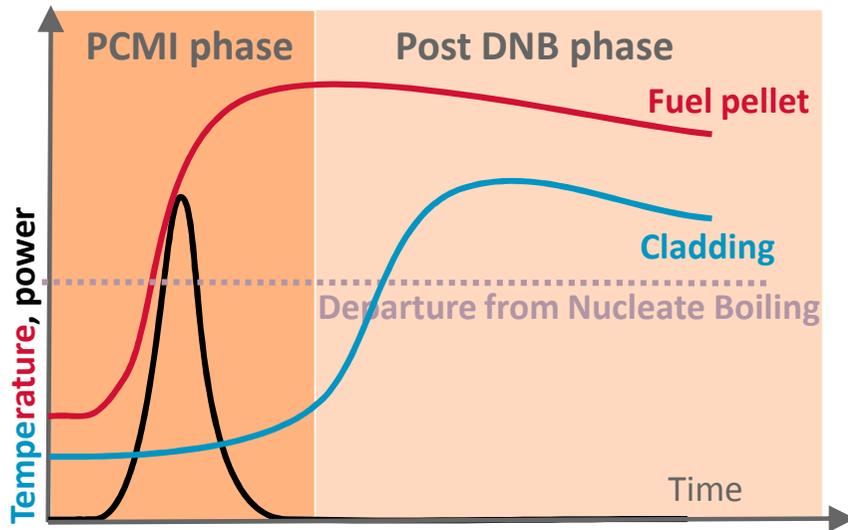
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TOPFUEL 2018 | SEPTEMBER 30 – OCTOBER 4, 2018 | PRAGUE (CZECH REPUBLIC)

- ALCYONE V1.4 RIA-related features: from UO₂ fuel to MOX fuel
 - ▶ Main modelling assumptions and capabilities
 - ▶ Recent developments
- Simulations of (sodium-loop) CABRI integral tests on MOX fuel rodlets
 - ▶ Tests main characteristics and posttest results
 - ▶ Some simulation results and discussion vs measurements/examinations
- Conclusion and prospects

Reactivity-Initiated Accident phenomenology



Need for a better understanding of the mechanisms to avoid the consequences (at first, clad rupture)

COLLABORATION

MULTI-PHYSICS FUEL PERFORMANCE SIMULATION PLATFORM

MULTI-DIMENSIONAL FUEL PERFORMANCE CODE
to study PWR FUEL ROD BEHAVIOUR
(steady state & transients)

➔ **ALCYONE... - RIA**



- Continuous and automatic calculation sequencing between base and pulse-irradiation periods

- Non steady heat and mass transport

- Irradiated cladding material constitutive laws suitable for RIA loading conditions

- ▶ High strain rates and temperatures

- CARACAS fission gas model (creation and evolution at the grain scale)

- ▶ Relevant for fuels with complex microstructures (cf. Bouloré et al., *Proc. of WRFPM 2017*, paper 157)

- MOX MIMAS AUC or ADU (wet route); MOX MIMAS dry route

- ▶ 3-phase description of MOX MIMAS AUC microstructure (UO₂ matrix and two Pu-cluster phases) for use with MOX fuels tested so far in CABRI

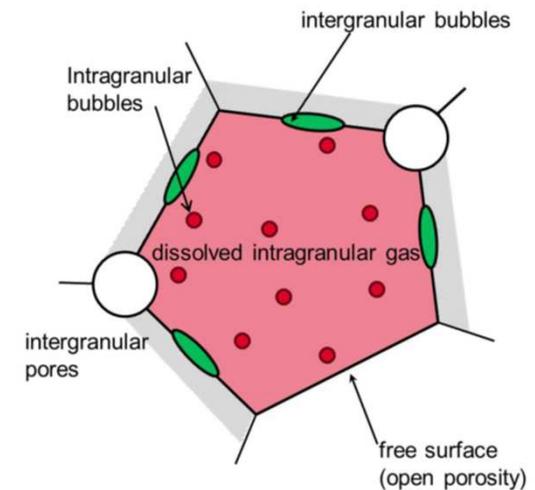
- ▶ *Access to gas creation, gas release and development of High Burnup Structure during base-irradiation period*

- ▶ *Access to intra- and intergranular gas inventory and location (dissolved, in bubbles, in porosity) before pulse*

- ▶ *Gas populations evaluated at each time step and for each modelled MOX phase*

- ▶ *Continuous sequencing between base and pulse-irradiation periods*

- ▶ *So far, CARACAS parameters calibrated on base irradiation and power ramps only*



M. SALVO et al., *J. Nucl. Mater.*, 456, 54 (2015)
M. SALVO et al., *J. Nucl. Mater.*, 460, 184 (2015)

■ UO₂ fuel constitutive law suitable for RIA loading conditions

- ▶ Model proposed by **SALVO** based on compression tests performed on fresh UO₂ fuel :
 - high temperatures [1100°C-1700°C] | high strain rates [$10^{-4} \text{ s}^{-1} - 10^{-1} \text{ s}^{-1}$]
 - tensile stress state (**PELLET CRACKING**) + **CREEP**
 - **GRAIN BOUNDARY CRACKING** (plastic flow) generated by excessive (biaxial) compressive stresses | related induced pore volume increase (**PLASTIC POROSITY**)

■ GB cracking used by CARACAS as the main criterion for intergranular **FGR** + additional temperature criterion for intergranular and intragranular **FGR** from any HBS zone

- ▶ cf. I. Guénot-Delahaie et al., *Nucl. Eng. Technol.*, 50, 268 (2018) for ALCYONE V1.4 RIA 1.5D scheme validation on UO₂ fuels

■ Extension to MOX fuel – Modelling first approach

- ▶ Same constitutive law as for UO₂ fuel, with modified parameters for creep
- ▶ Mechanical homogeneous framework
 - No distinction in the model between the UO₂ matrix phase and the Pu-cluster phases in the calculation of the stresses and thus of the GB cracking
- ▶ Same FGR approach however with a restriction to the sole UO₂ matrix phase
- ▶ Use of a similar behaviour law for UO₂ and MOX fuels justified by post pulse test observations:
 - MOX pellets creep at least of the same order than UO₂ pellets one
 - MOX pellets radial macroscopic cracking similar to UO₂ pellets one
 - UO₂ phase grain boundary cracking leads to FGR that contributes in a major way to the total FGR

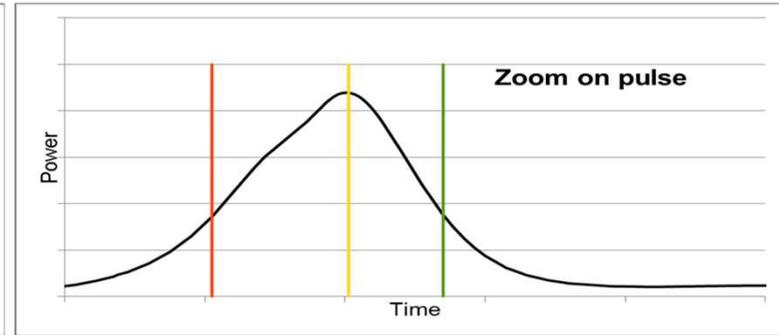
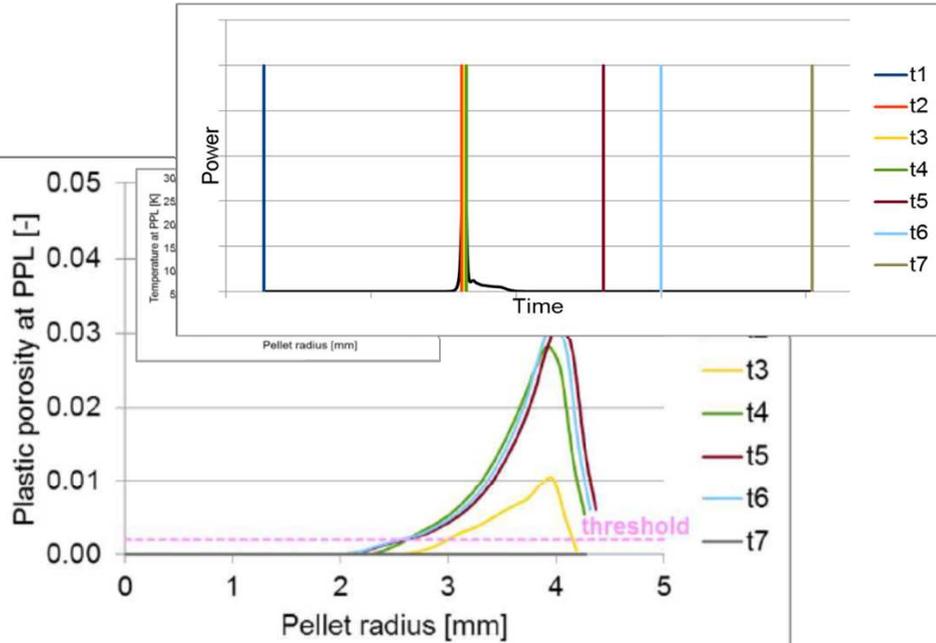


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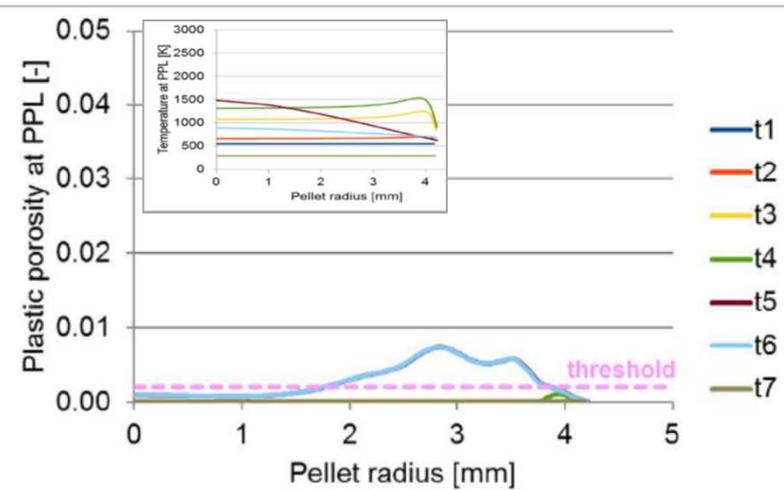
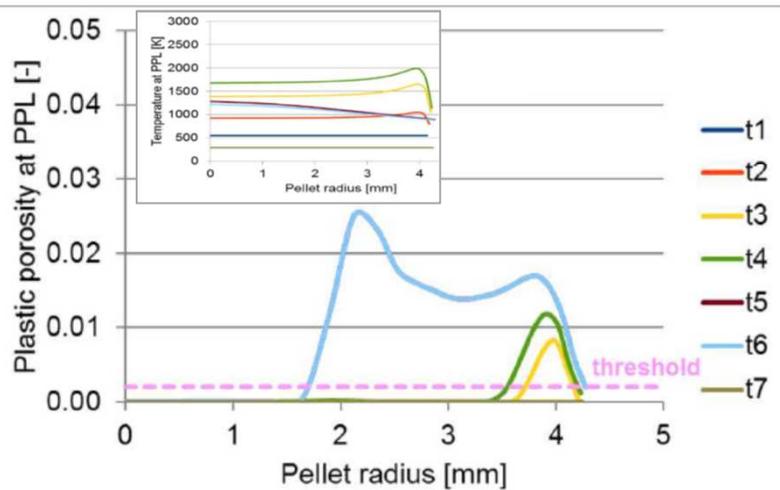
Test ID.	REPNa-9	REPNa-6	REPNa-12
Performed in	CABRI reactor equipped with former sodium-loop flowing Na 280°C 0.1 to 0.3 MPa		
Mother rod: Cladding alloy Pellet Initial enrichment Pu/(U+Pu), wt% Corrosion thickness, µm	Zy4 MOX MIMAS AUC		
	6.559 10 (max)	5.925 35 (max)	5.89 59-72 (max)
RIA test on rodlet:			
Local burnup, GWd/tM MEDIUM to VERY HIGH	28	47	65
Pellet stack length, mm	561.2	553.5	559.6
Rod filling gas pressure, MPa	0.3	0.3	0.3
Pulse width, ms	33	32	62.5
Energy injected** , cal/g MEDIUM to VERY HIGH	233	156	106
Peak fuel enthalpy, cal/g	197*	133*	103*
Failure diagnosis	NO	NO	NO
Max. clad residual hoop strain, %	7.2	2.6	1.1
	-	Oxide transient spalling	Oxide transient spalling
Fission Gas Release FGR, %	33.4	21.6	20.5
Posttest measurements	<ul style="list-style-type: none"> ▶ No fuel melting sign ▶ Grain boundary decohesion detected in all cases ▶ GB decohesion from the very external pellet rim to an inward extension of 82% (REPNa-6) and 75% (REPNa-9, 12) ▶ GB decohesion also present (less important; none REPNa-12) towards the internal part of the pellet 		
Posttest examinations			

* SCANAIR calculation; ** at 1.2 s after TOP, at PPL

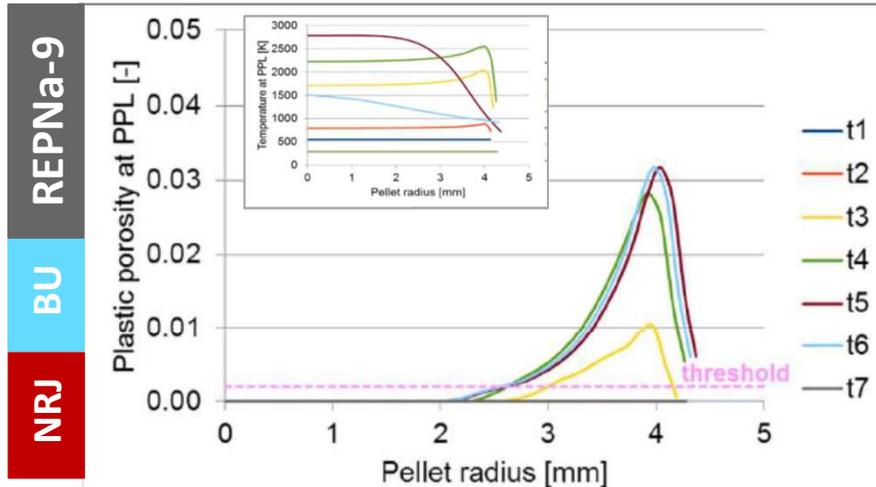
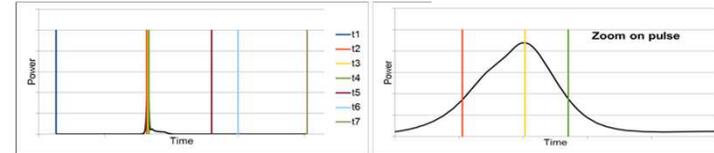
REPNa-9
BU
NRJ



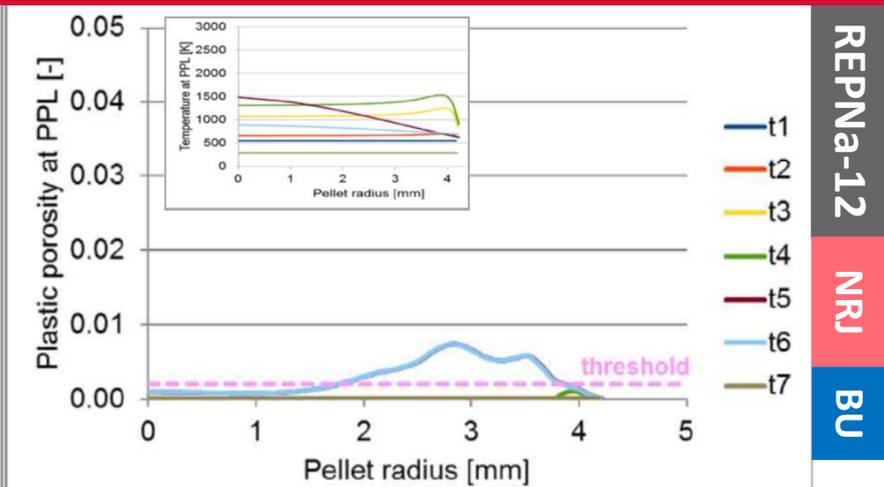
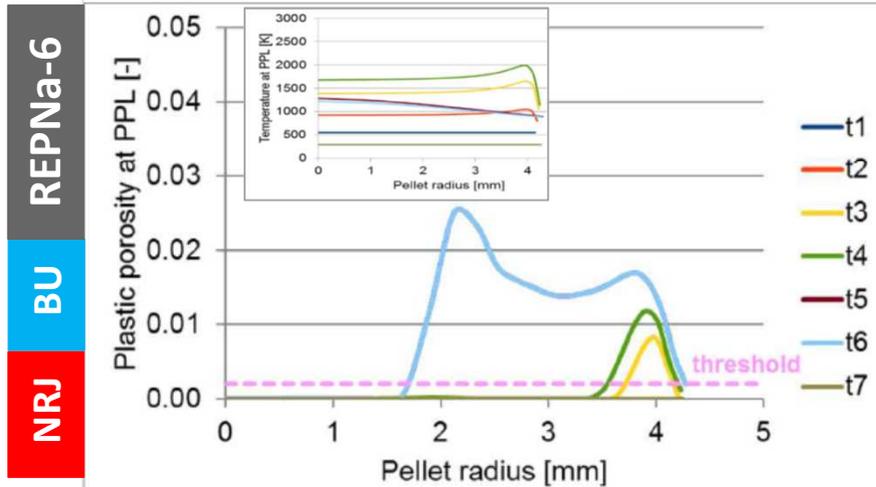
REPNa-6
BU
NRJ

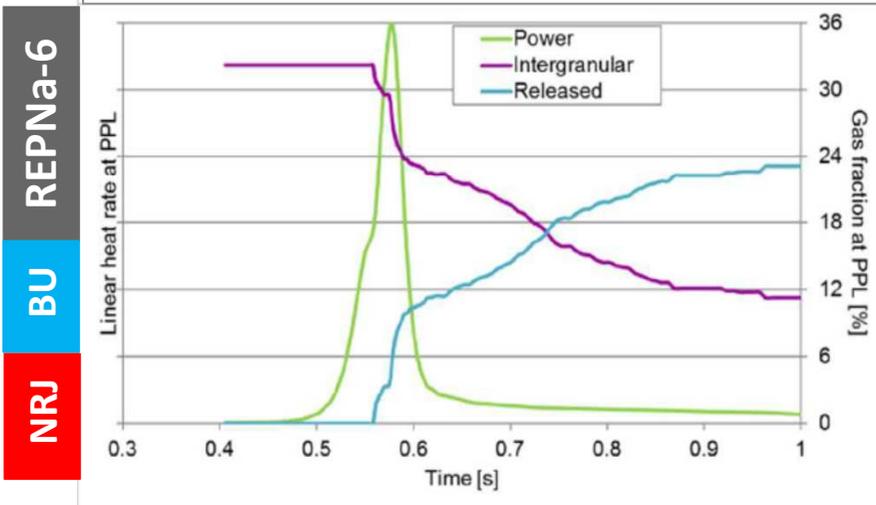
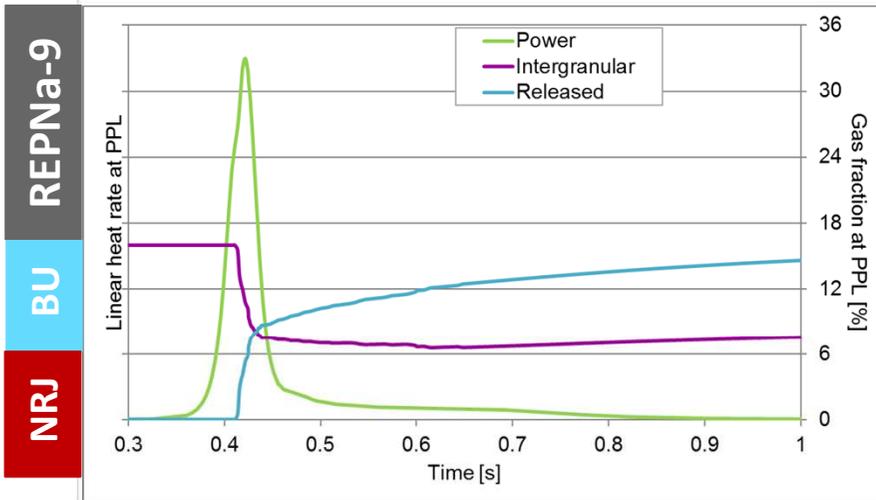


REPNa-12
NRJ
BU

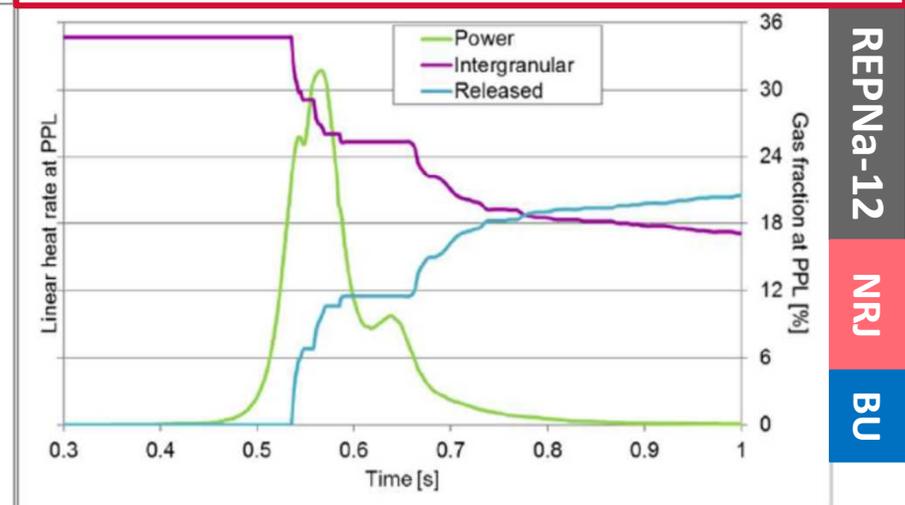


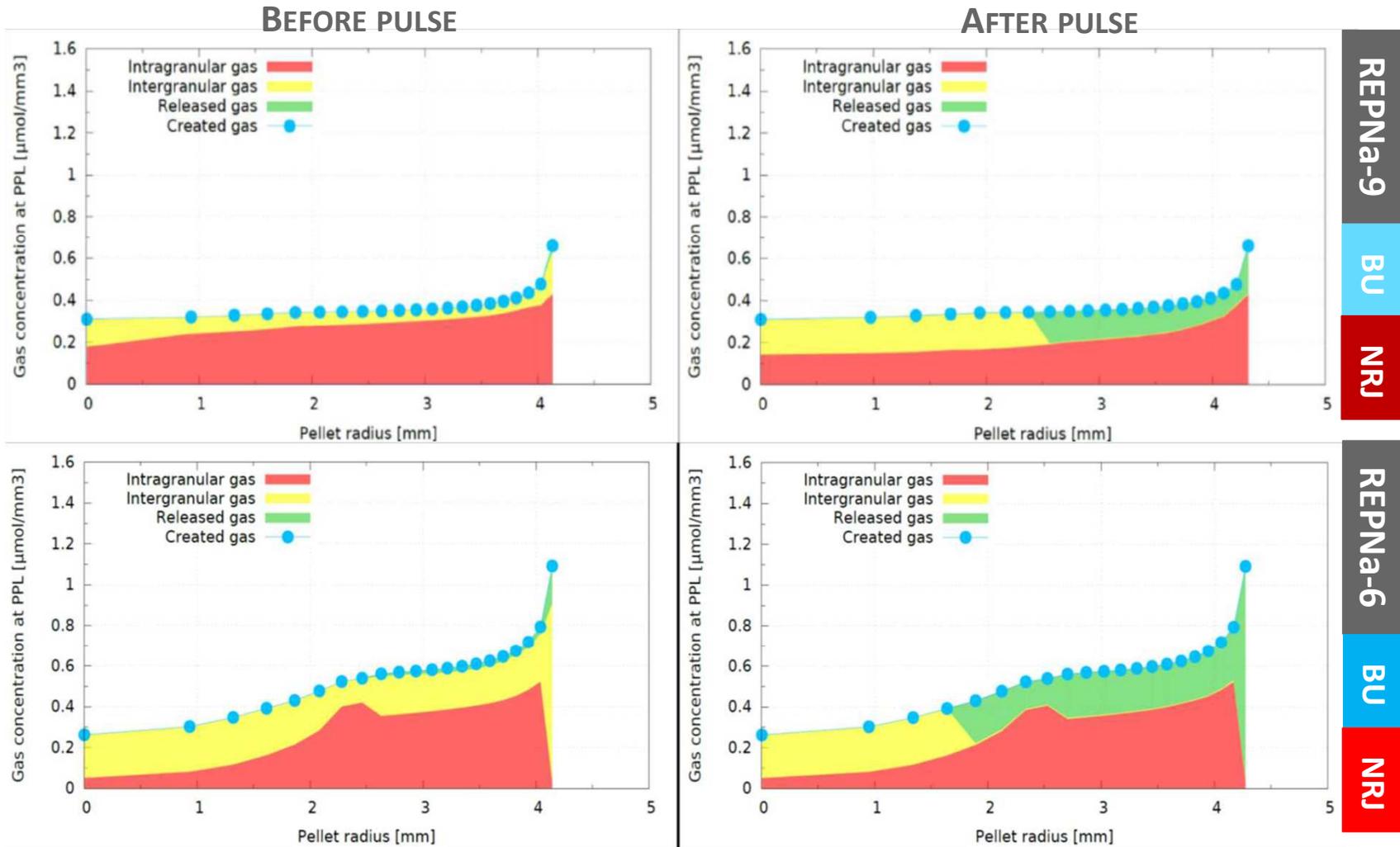
- ▶ Maximum fuel temperature 2790 K consistent with the absence of fuel melting sign
- ▶ GB cracking predicted in all cases (plastic porosity above threshold) → GB cracking not solely depending on BU and consequently before-pulse GB gas content
- ▶ High plastic porosity localisation globally matching the experimental area where GB decohesion was detected



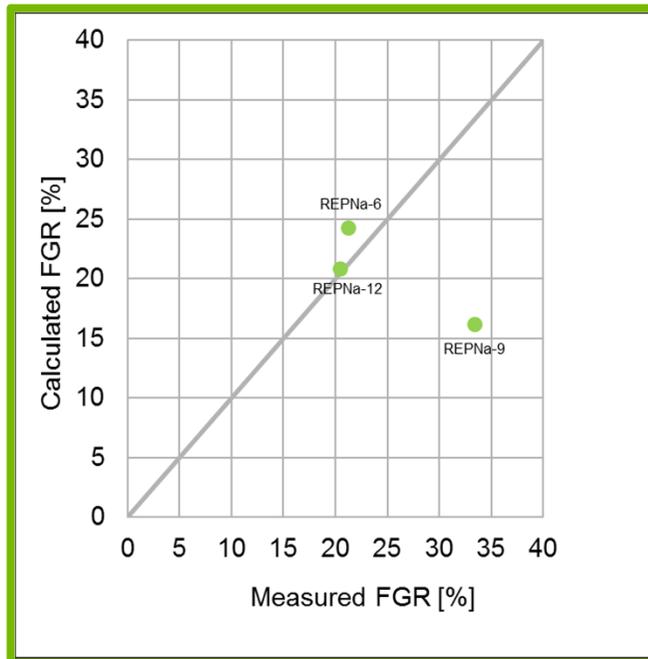


- ▶ FGR starting before the pulse power peak and not finished at the end of pulse transient
- ▶ REPNa-6, 12 (high BUs):
 - FGR by steps, progressive GB cracking, mainly INTER gas
 - High FGR because high INTER inventory
- ▶ REPNa-9 (high NRJ):
 - FGR smoother
 - Related not only to GB cracking but also to INTRA gas diffusion mechanism (cf. high T°)
 - Additional FGR vs initial INTER gas inventory



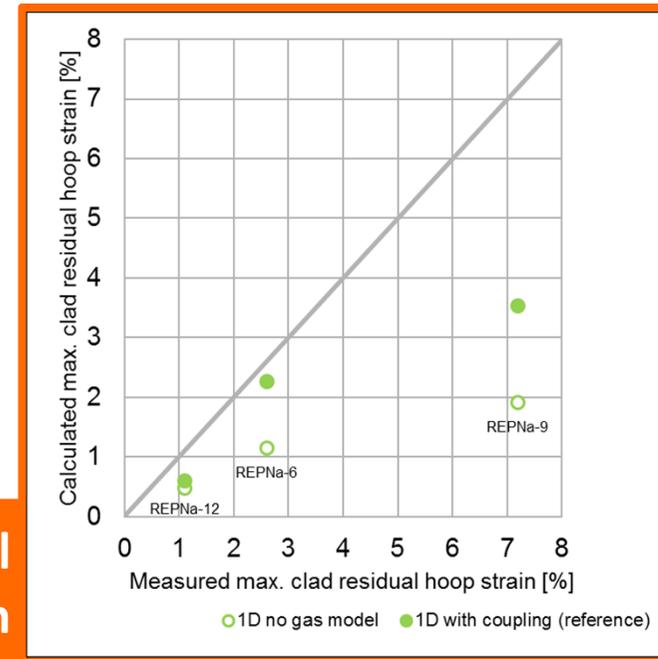


► Another illustration of INTRA gas diffusion mechanism contribution in REPNa-9 case and not in REPNa-6 case



FGR

Clad residual hoop strain



With our simple approach:

- ▶ Reasonable agreement with experimental results
- ▶ Better prediction of the clad residual hoop strain when taking account of the fission gas swelling
- ▶ REPNa-9: noticeable underestimation of FGR and clad residual hoop strain

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■ 1.5D ALCYONE simulations:

- ▶ of RIA transients performed on MOX fuel rods in flowing sodium coolant conditions
- ▶ compared to the relevant experimental results gained from REPNa-6, REPNa-9 and REPNa-12 (CABRI)

■ Modelling:

- ▶ Use of CARACAS fission gas model (3-phase description of MOX microstructure) not yet suitable for RIA (CARACAS parameters calibrated on base irradiation and power ramps only)
- ▶ (similar to UO₂ fuel) Extension to RIA via implementation of a grain boundary cracking criterion and an additional temperature criterion for HBS zones
- ▶ Mechanical homogeneous framework

■ Despite this **simple approach**, the discrepancies among the CABRI pulses (various BUs, various injected energies) are **satisfactorily reproduced in terms of Na temperatures, FGR and clad hoop strains**.

■ Non-negligible underestimation of clad strains and FGR in case of high-energy tests on medium burnup fuel rods

- ▶ Temperatures reached far above those considered in the calibration of CARACAS
- ▶ Potential other explanations under investigation

- **Some further work to complement and/or improve the results:**
 - ▶ Development of more advanced behaviour laws (stress states calculated per phase and not on average)
 - ▶ Experimental work/data as regards grain boundary cracking during RIA (MOX phase-dependent)
 - ▶ Modelling of helium release during RIA.

- **More local description/heterogeneous modelling useful to understand, via numerical simulations, what happens at meso- and microscopic scales during RIAs**





Thank you for your attention



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