



## Simulation of RIA transients on MOX fuel rods with ALCYONE fuel performance code

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

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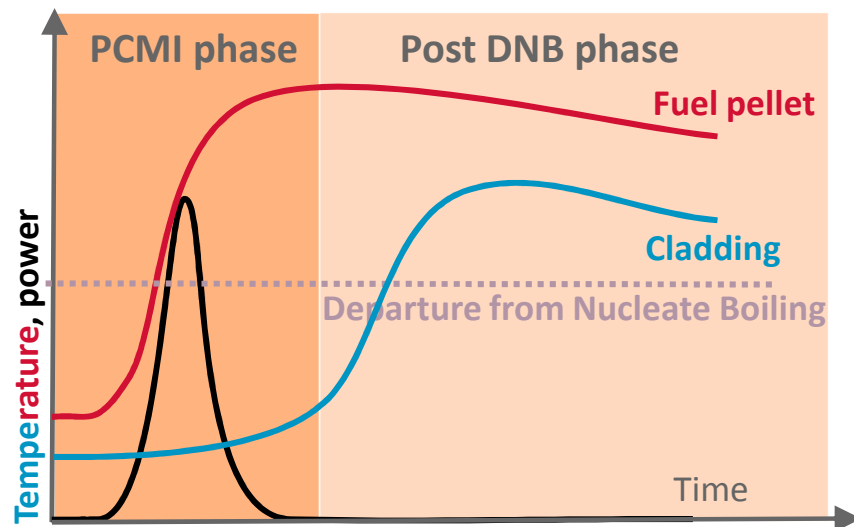
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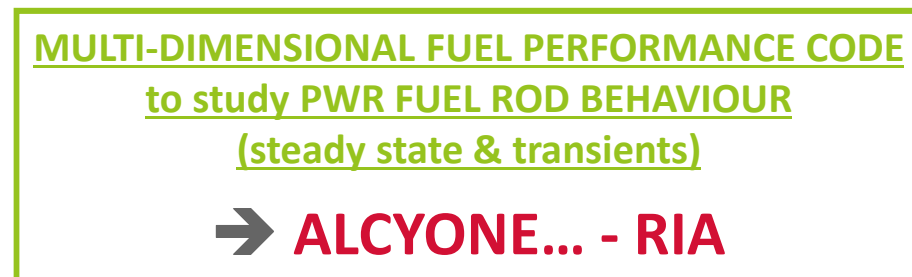
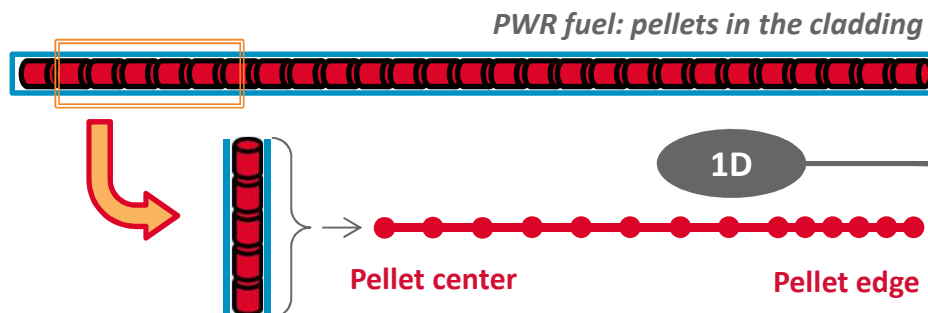
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- ALCYONE V1.4 RIA-related features: from  $\text{UO}_2$  fuel to MOX fuel
  - ▶ Main modelling assumptions and capabilities
  - ▶ Recent developments
- Simulations of (sodium-loop) CABRI integral tests on MOX fuel rodlets
  - ▶ Tests main characteristics and posttest results
  - ▶ Some simulation results and discussion vs measurements/examinations
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## Reactivity-Initiated Accident phenomenology



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



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

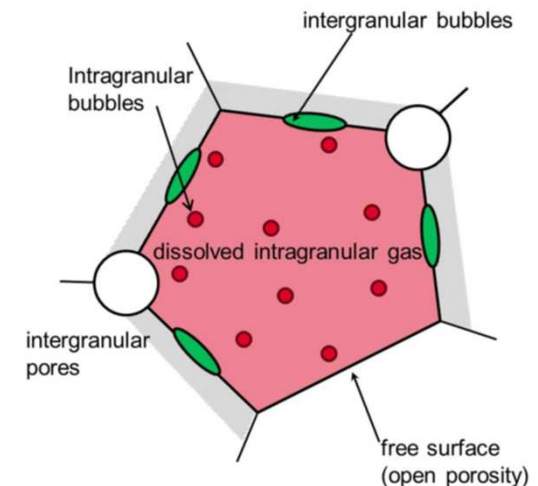
- Non steady heat and mass transport

- 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 ( $\text{UO}_2$  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)

### ■ UO<sub>2</sub> fuel constitutive law suitable for RIA loading conditions

- ▶ Model proposed by **SALVO** based on compression tests performed on fresh UO<sub>2</sub> 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 UO<sub>2</sub> fuels

### ■ Extension to MOX fuel – Modelling first approach

- ▶ Same constitutive law as for UO<sub>2</sub> fuel, with modified parameters for creep
- ▶ Mechanical homogeneous framework
  - No distinction in the model between the UO<sub>2</sub> 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 UO<sub>2</sub> matrix phase
- ▶ Use of a similar behaviour law for UO<sub>2</sub> and MOX fuels justified by post pulse test observations:
  - MOX pellets creep at least of the same order than UO<sub>2</sub> pellets one
  - MOX pellets radial macroscopic cracking similar to UO<sub>2</sub> pellets one
  - UO<sub>2</sub> phase grain boundary cracking leads to FGR that contributes in a major way to the total FGR



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# SIMULATIONS OF CABRI INTEGRAL TESTS ON MOX FUEL RODLETS

## TESTS MAIN CHARACTERISTICS AND POSTTEST RESULTS

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		
<b>Mother rod:</b> 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)
<b>RIA test on rodlet:</b>			
<b>Local burnup</b> , GWd/tM <b>MEDIUM to VERY HIGH</b>	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
<b>Energy injected**</b> , cal/g <b>MEDIUM to VERY HIGH</b>	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
<b>Posttest measurements</b>	<ul style="list-style-type: none"> <li>▶ No fuel melting sign</li> <li>▶ Grain boundary decohesion detected in all cases</li> <li>▶ GB decohesion from the very external pellet rim to an inward extension of 82% (REPNa-6) and 75% (REPNa-9, 12)</li> <li>▶ GB decohesion also present (less important; none REPNa-12) towards the internal part of the pellet</li> </ul>		
<b>Posttest examinations</b>			

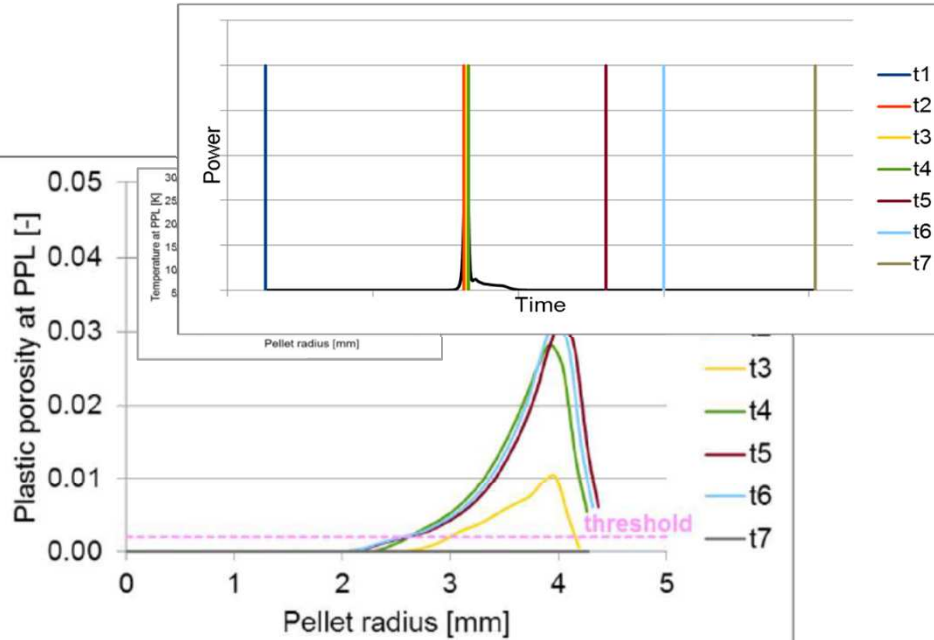
\* SCANAIR calculation; \*\* at 1.2 s after TOP, at PPL



REPNa-9

BU

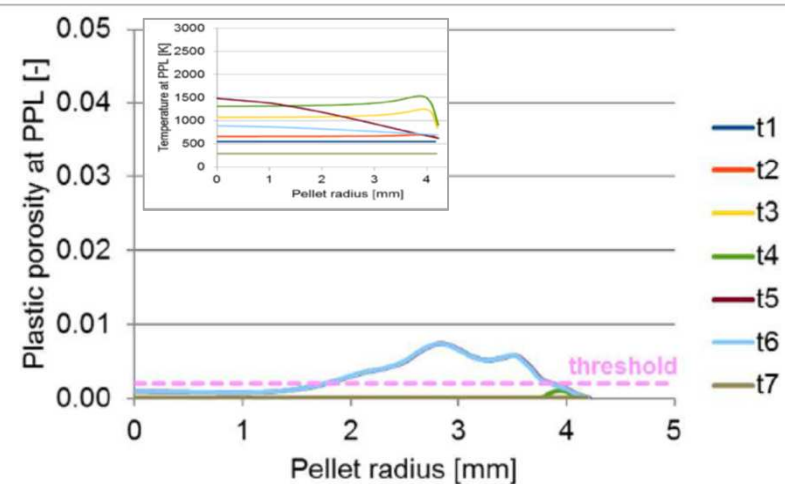
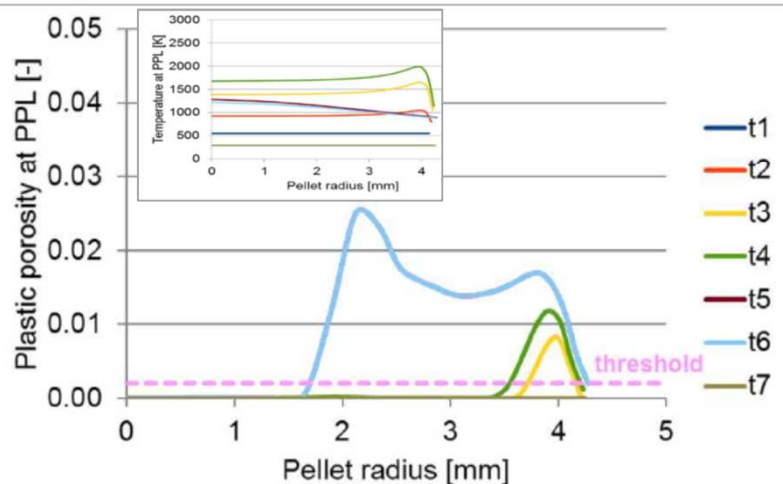
NRJ



REPNa-6

BU

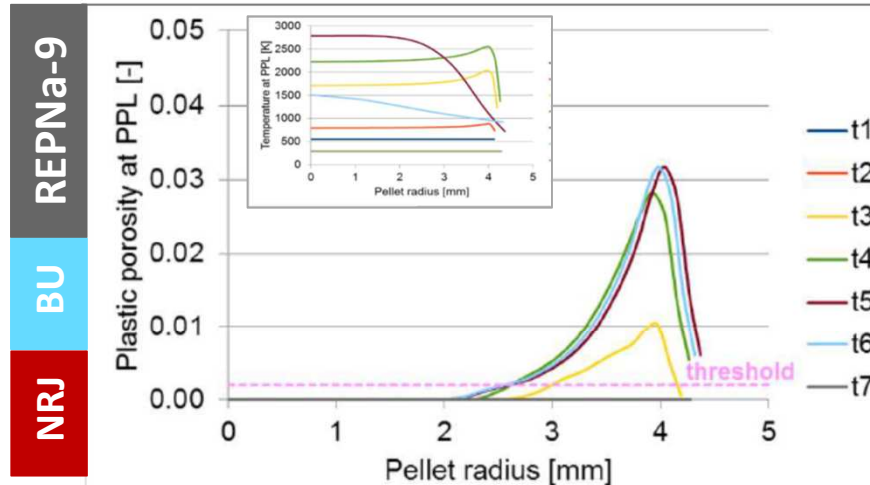
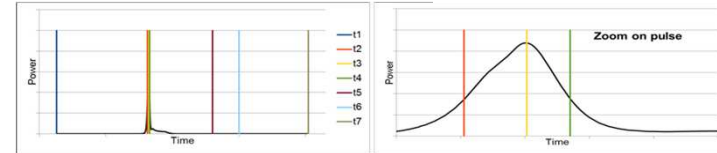
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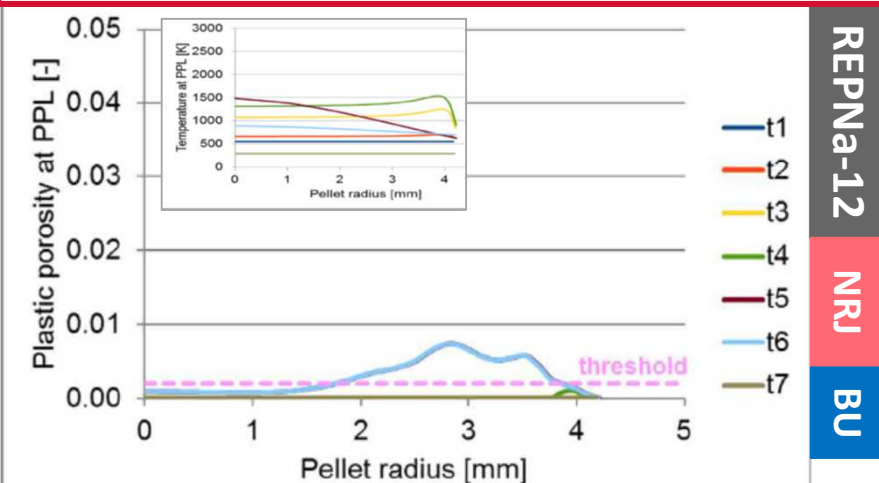
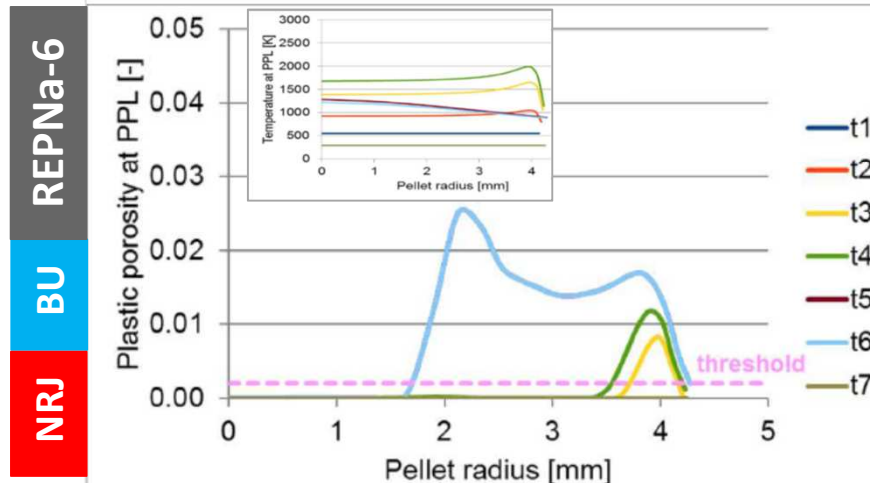
REPNa-12

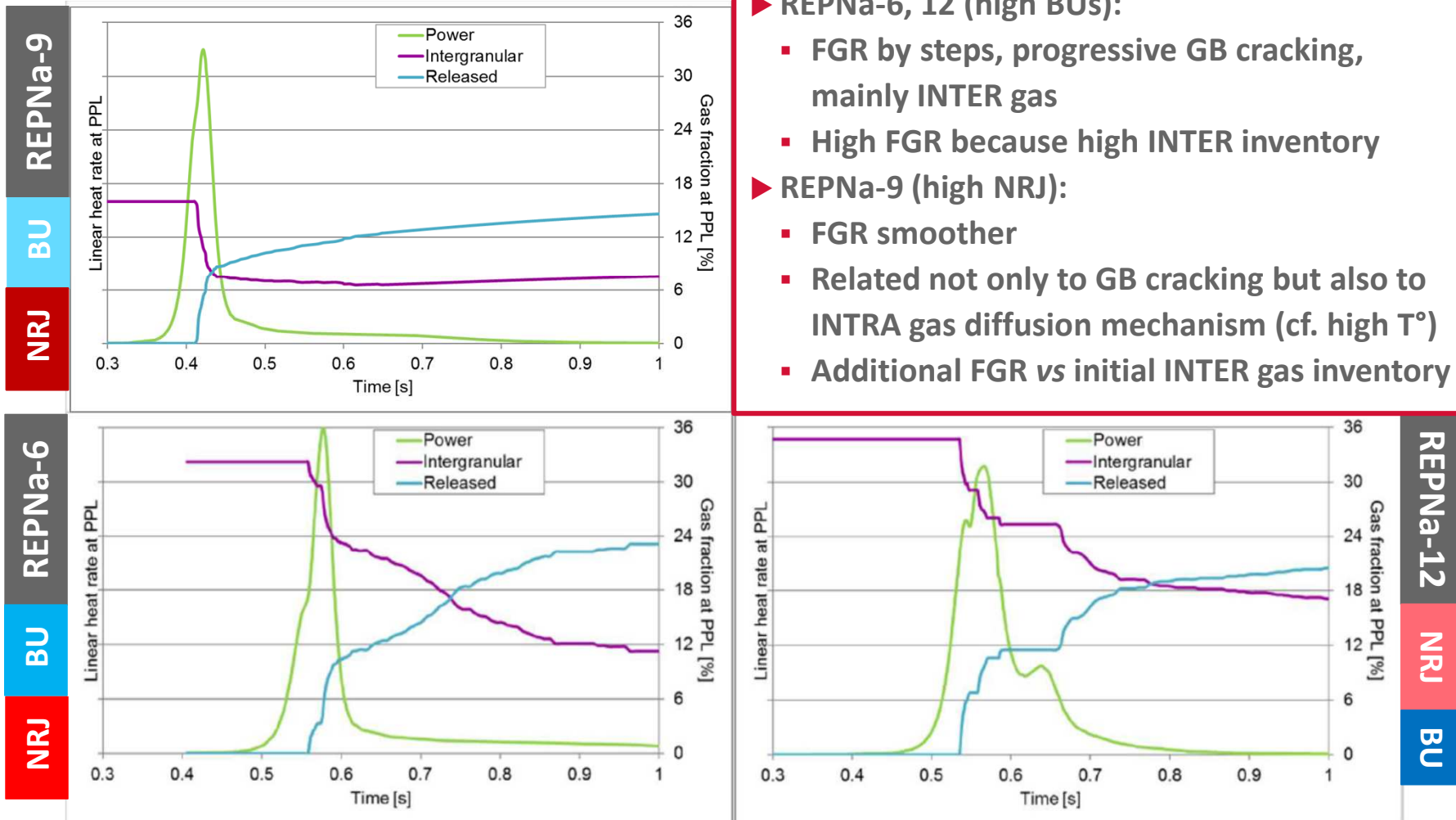
NRJ

BU

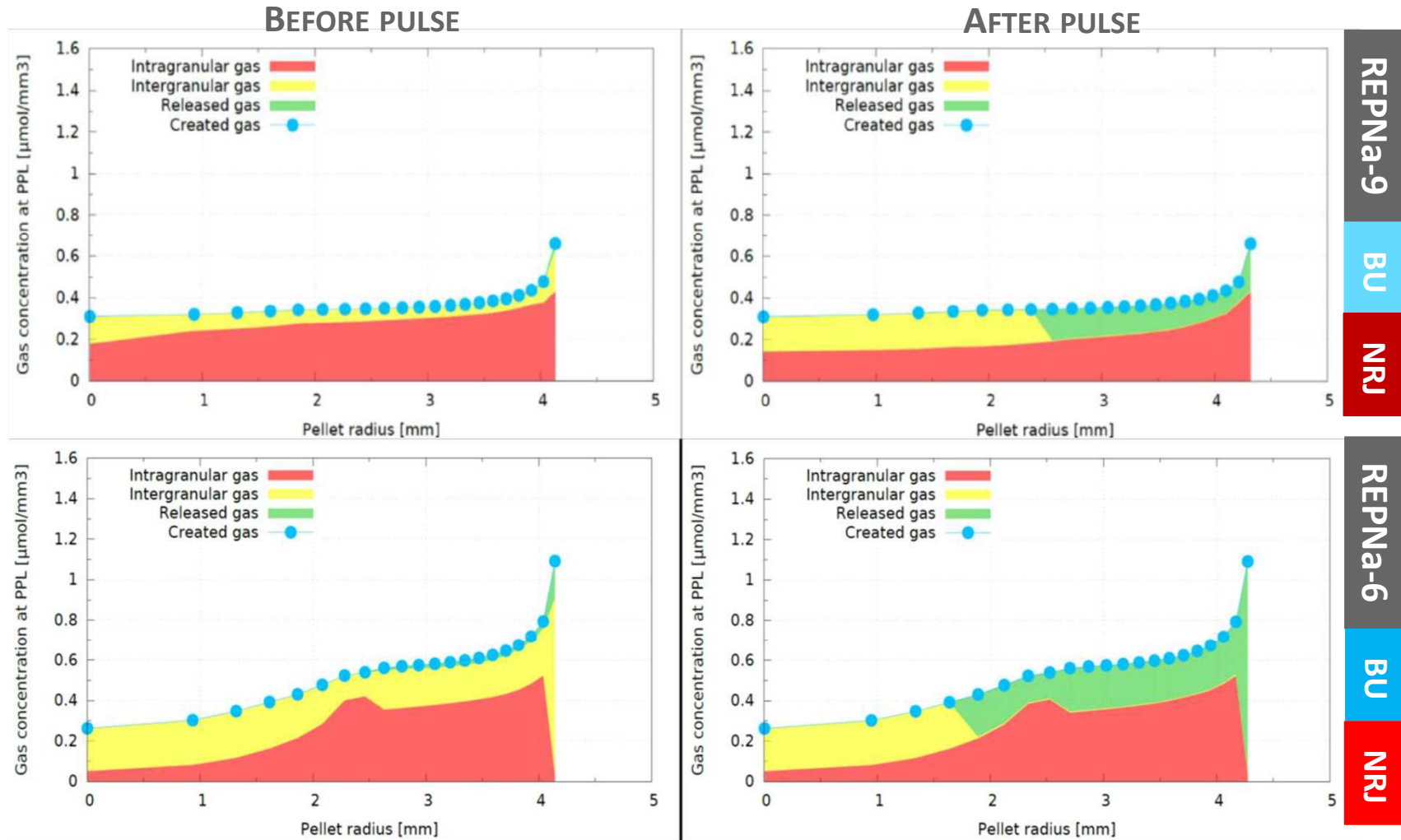


- ▶ Maximum fuel temperature 2790 K consistent with the absence of fuel melting sign
- ▶ GB cracking predicted in all cases (plastic porosity above threshold) → GB cracking not solely depending on BU and consequently before-pulse GB gas content
- ▶ High plastic porosity localisation globally matching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

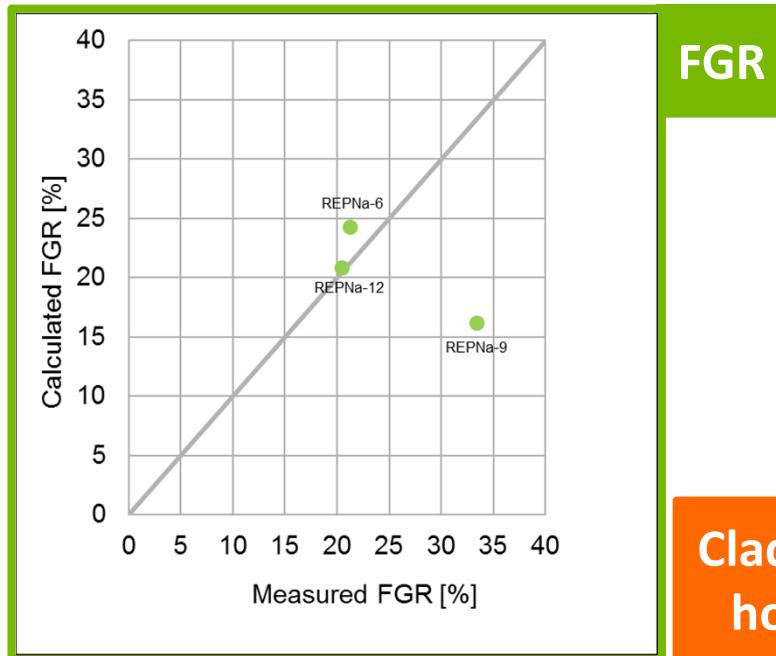




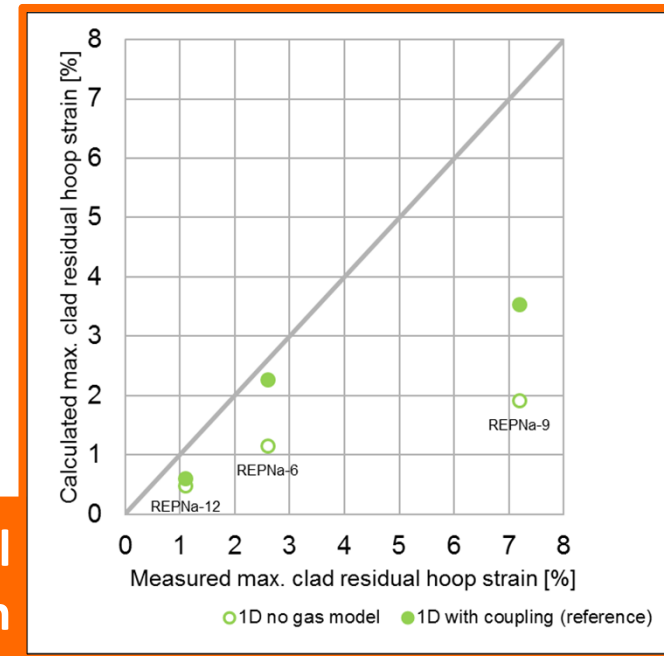
- ▶ FGR starting before the pulse power peak and not finished at the end of pulse transient
- ▶ REPNa-6, 12 (high BUs):
  - FGR by steps, progressive GB cracking, mainly INTER gas
  - High FGR because high INTER inventory
- ▶ REPNa-9 (high NRJ):
  - FGR smoother
  - Related not only to GB cracking but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



**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 UO<sub>2</sub> 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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