



ANS[®]

NURETH-20

20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics

Washington, USA, 20-25 August, 2023

**COAL experiments investigating
the reflooding of a 7 X 7 rod
bundle during a Loss Of coolant
Accident: Effect of a partially
blocked area with ballooned rods**

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R. Fortman and R. Van Lochem (STERN Lab.)

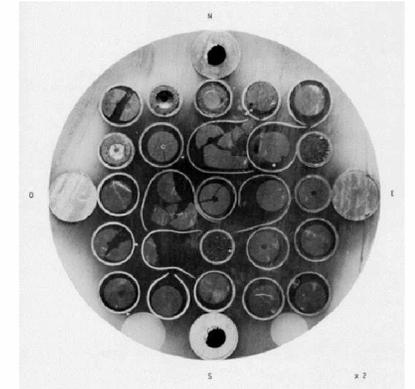
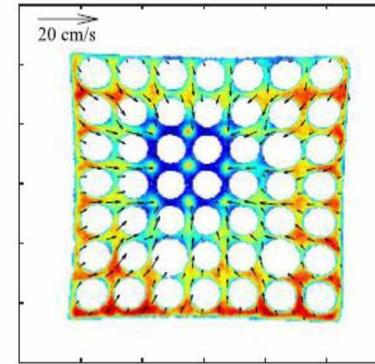
Georges REPETTO
Project Manager


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FRANÇAISE**
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Égalité
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IRSN
INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Outline of the presentation

- Context of the PERFROI project
- Objectives of the COAL experiments
- Facility/COAL tests device and Tests matrix (parameters conditions)
- Main results
- Conclusion



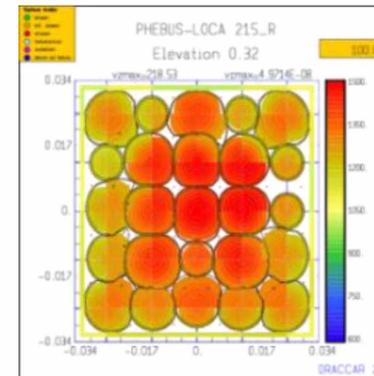
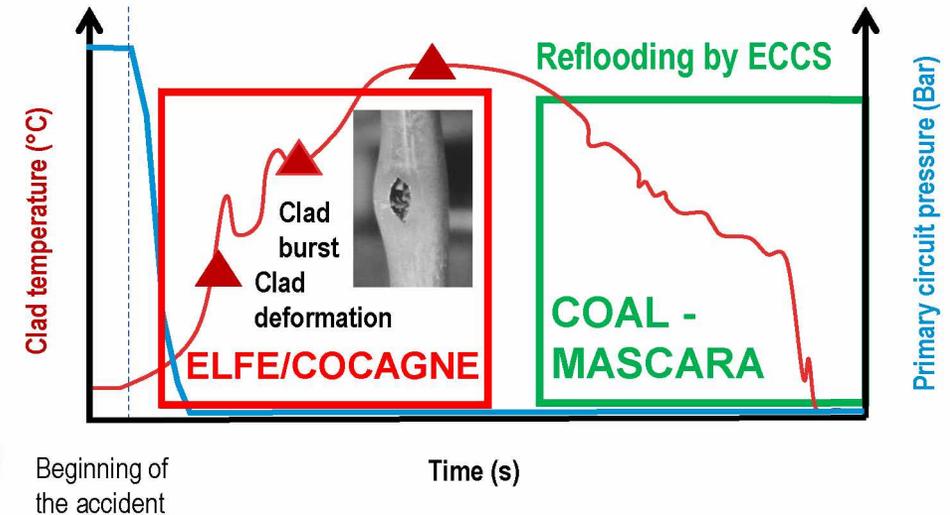
Context of the PERFROI project

In 2013, with the support of the French Research National Agency (ANR), IRSN launched the post-Fukushima PERFROI experimental program [2013-2023] dedicated to **flow blockage by ballooning rods** and **the core coolability**

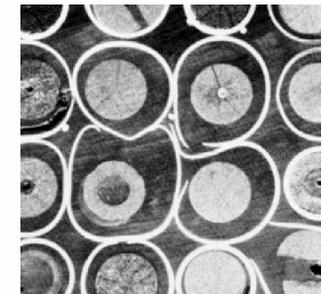
- **Axis 1** dedicated to the thermal-mechanical behavior of cladding during LOCA transients (creep laws, cladding deformation with contact between fuel rods)
- **Axis 2** dedicated to the reflooding processes and coolability issues of deformed fuel assembly geometries

The PERFROI project is in strong interaction with the development and the validation of the IRSN DRACCAR code

→ The paper is focussed on the **COAL** experiments



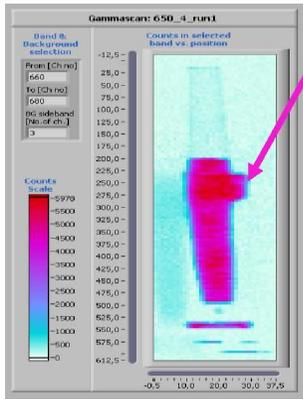
DRACCAR simulation



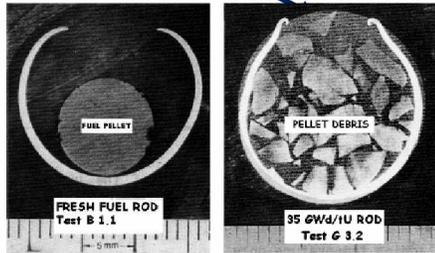
Phebus test (1983)

Objectives of the COAL experiments

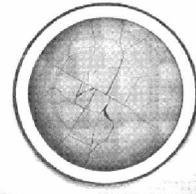
To improve knowledge / modeling of reflooding process of a fuel-rod assembly with **a partially blocked area** and **relocated fuel** simulation (taking into account the local power increase in the balloons)



Halden test
(90 GWd/t)
(2006)



FR2 tests
(35 GWd/t)
(1983)

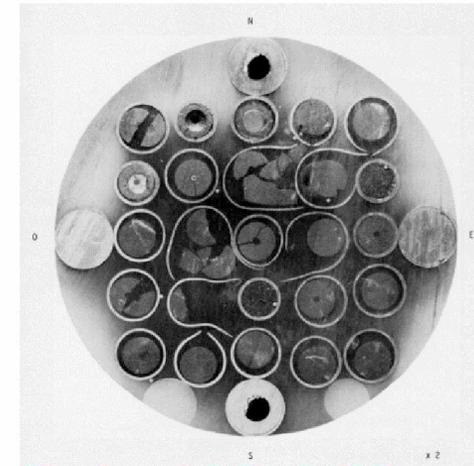


As-received Specimen:
180 mm away from the LOCA sample

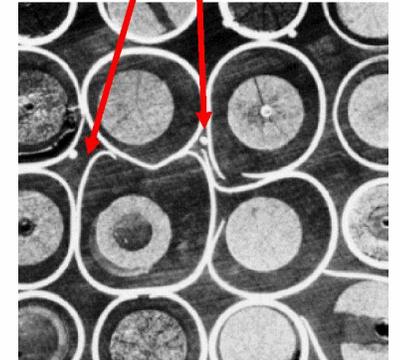


Post-test Specimen B:
+12 mm above the burst mid-plane
Strain: 15% - 25%

ANL tests
(55 GWd/t)
(1983)



Phebus LOCA 215R test
(1983)

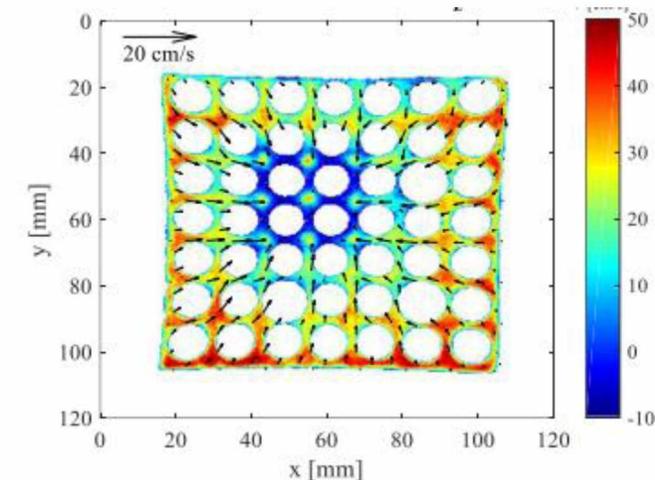


Phebus LOCA

Opposing influences due to the presence of a blockage will be evaluated through an integral experiment in a bundle geometry at the full length scale.

→ On one hand, the reduction of the section between the deformed fuel rods will **increase the flow velocity** and the potential increase of heat transfers.

→ On the other hand, the flow bypass from the blocked area to the intact rods (**cross-flow phenomena**) will lead to a **reduction of mass flow** in the sub channels of the blockage and therefore the **decrease of the heat transfers**.



COAL COolability of a fuel Assembly under LOCA

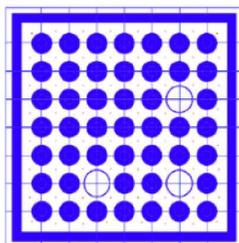
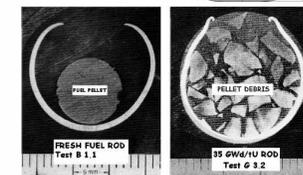
Reflooding experiments performed on a 7x7 full length (3 m) electrically heated fuel-rod assembly with 4x4 deformed fuel rods with simulation of fuel relocation (local overpower)

THERMOCOAX

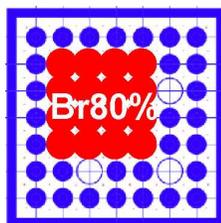
Heater

Simulation of relocated fuel (thermal contact and representative thermal inertia)

Hastalloy C22



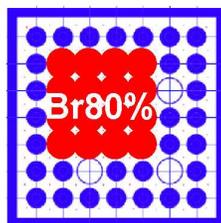
B0 (2020) (~28 tests)



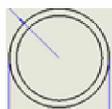
B1 (2021) (~26 tests)



B2 (2022) (~28 tests)



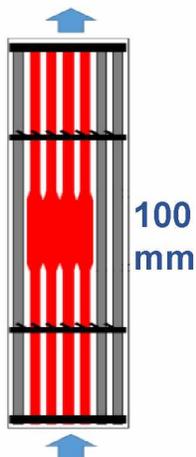
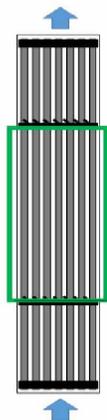
B3 (scheduled 2023/24) (~26 test)



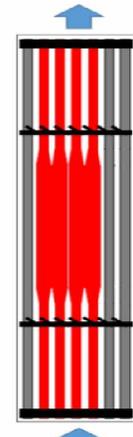
Reference case



Non coplanar balloons



100 mm



300 mm

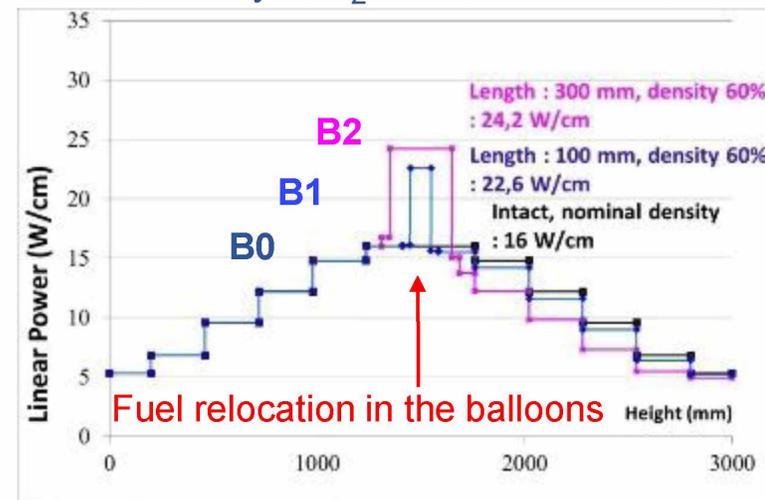


100 mm
100 mm

→ In total : 82 tests

Rod diffusivity coefficient : 0.22 kJ/m/K

Close to Zry+UO₂ : 0.26 kJ/m/K at 600°C

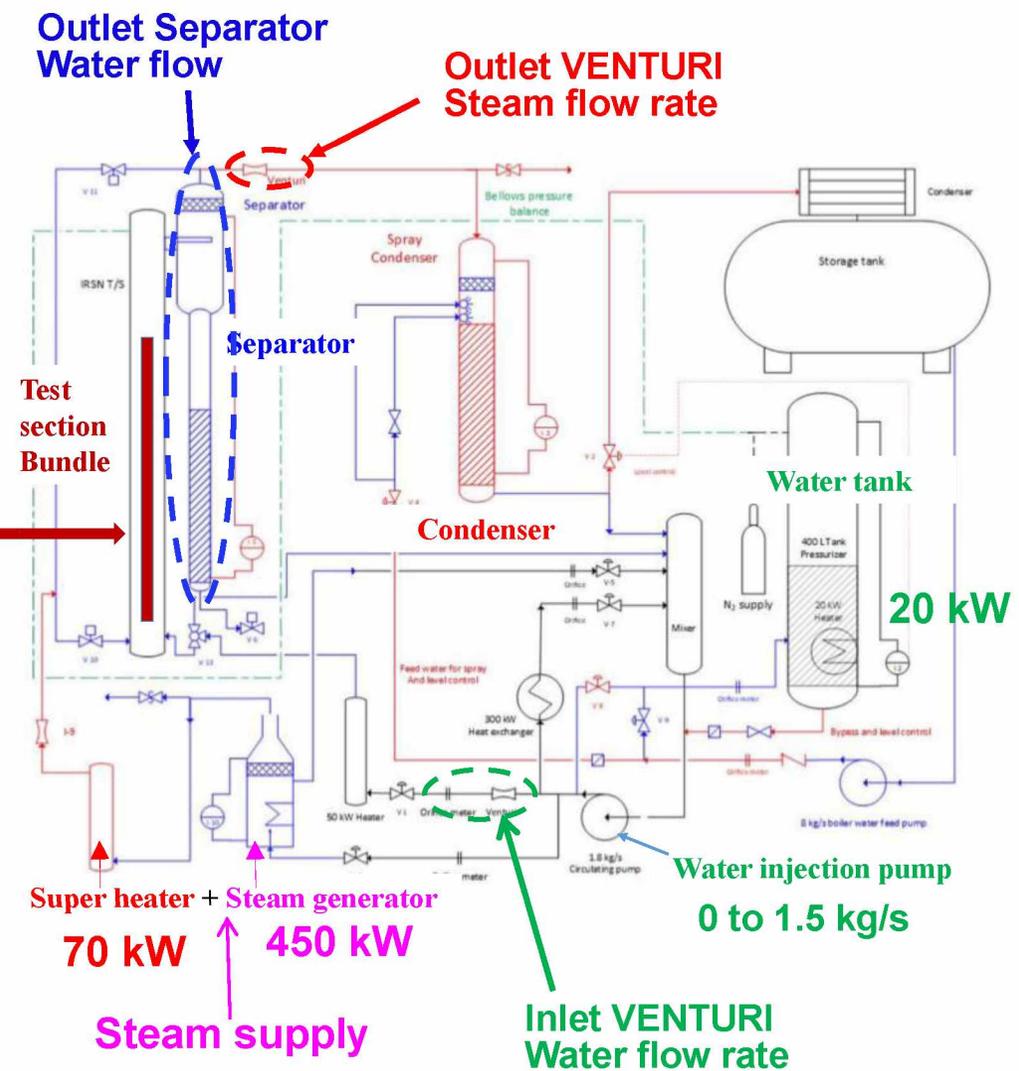
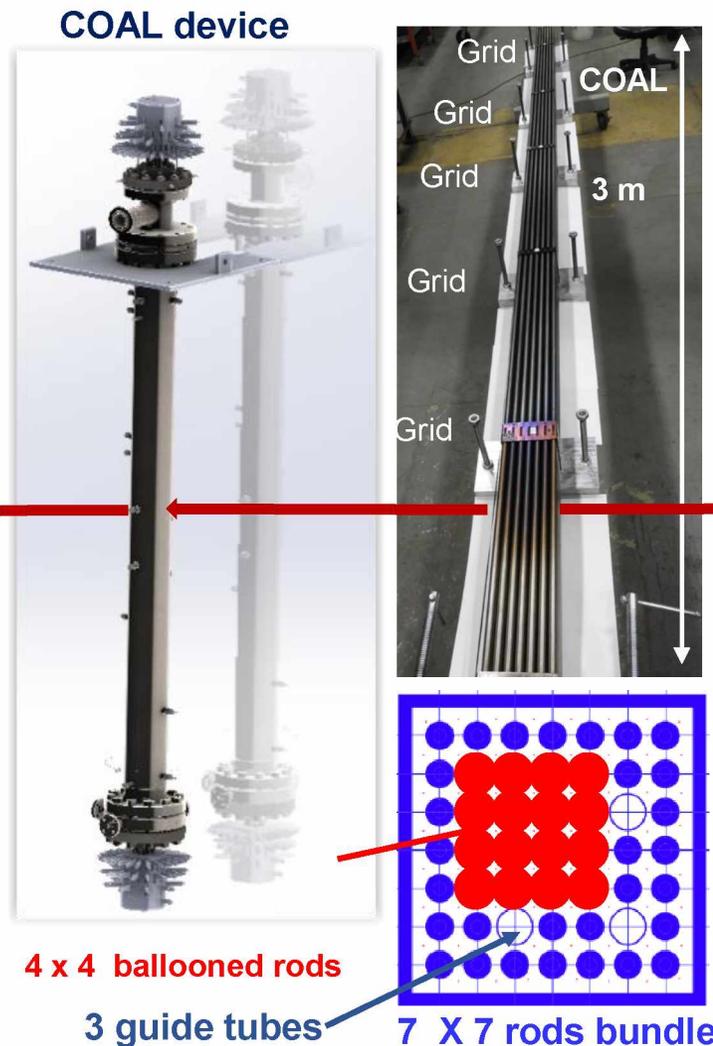


Fixed parameters

- a) Axial power profile
- b) Blockage Ratio (BR : 80 and 90%)
- c) Length of the ballooning (100/300mm)

Reflooding facility and COAL tests device

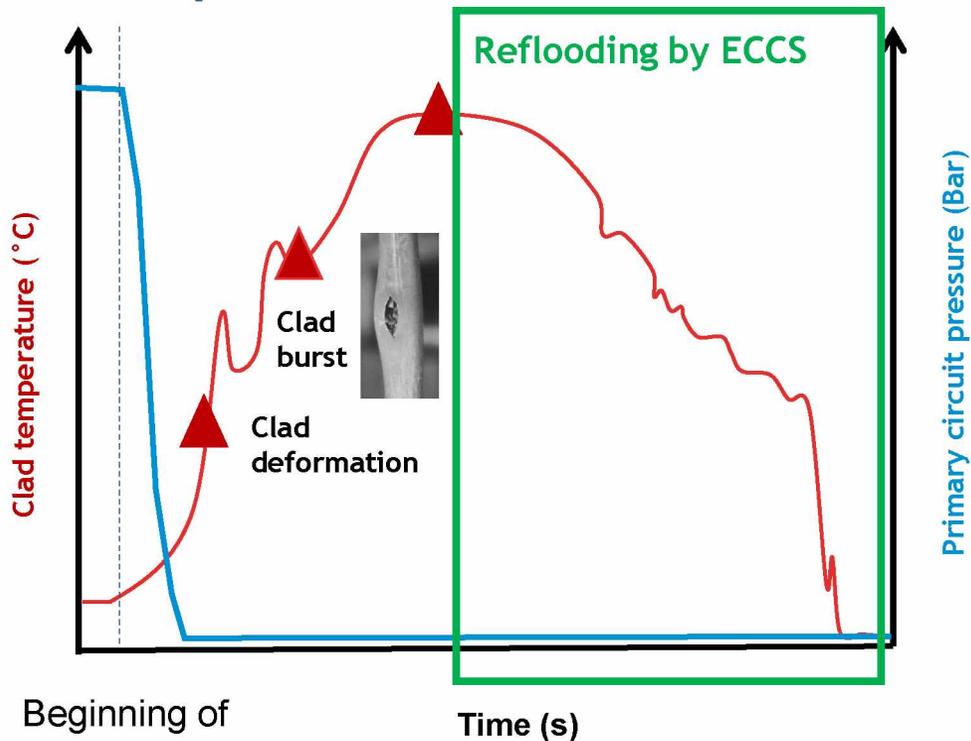
STERN Lab. in Hamilton (Canada)
LABORATORIES INC.



→ In order to analyse the reflooding, specific efforts were done on the instrumentation (roughly 400 Tc's) and in particular with the inlet / outlet water flow measurements

COAL test procedure and parameters

Starting from the
“Representative” LOCA transient



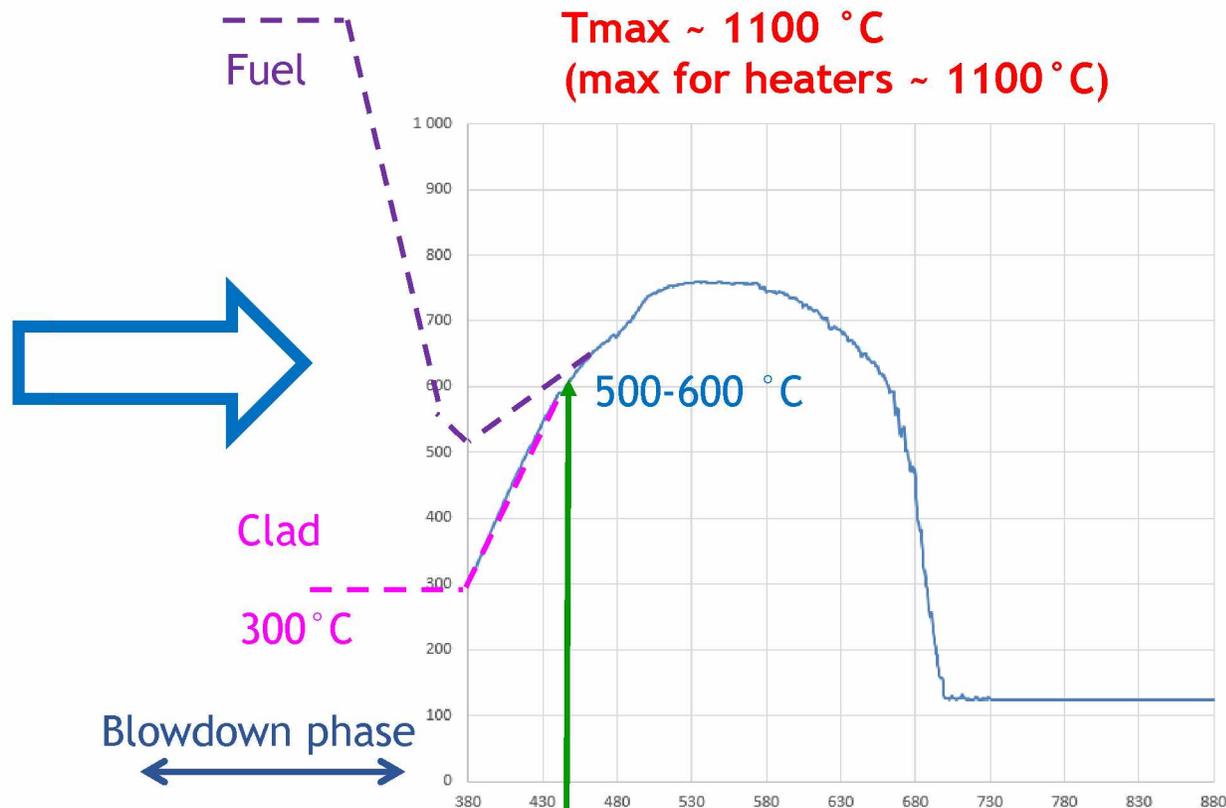
Beginning of the accident

Thermal hydraulic parameters

- System pressure (2 b up to 30 bar)
- Water Flow velocity (1.5 to 8 cm/s)
- Water inlet temperature
- Power per rod (2, 2.4, 3.3 kW/rod)

COAL experimental procedure

1. Heat up phase in dry steam atmosphere
2. Reflooding by water injection



Tmax ~ 1100 °C
(max for heaters ~ 1100°C)

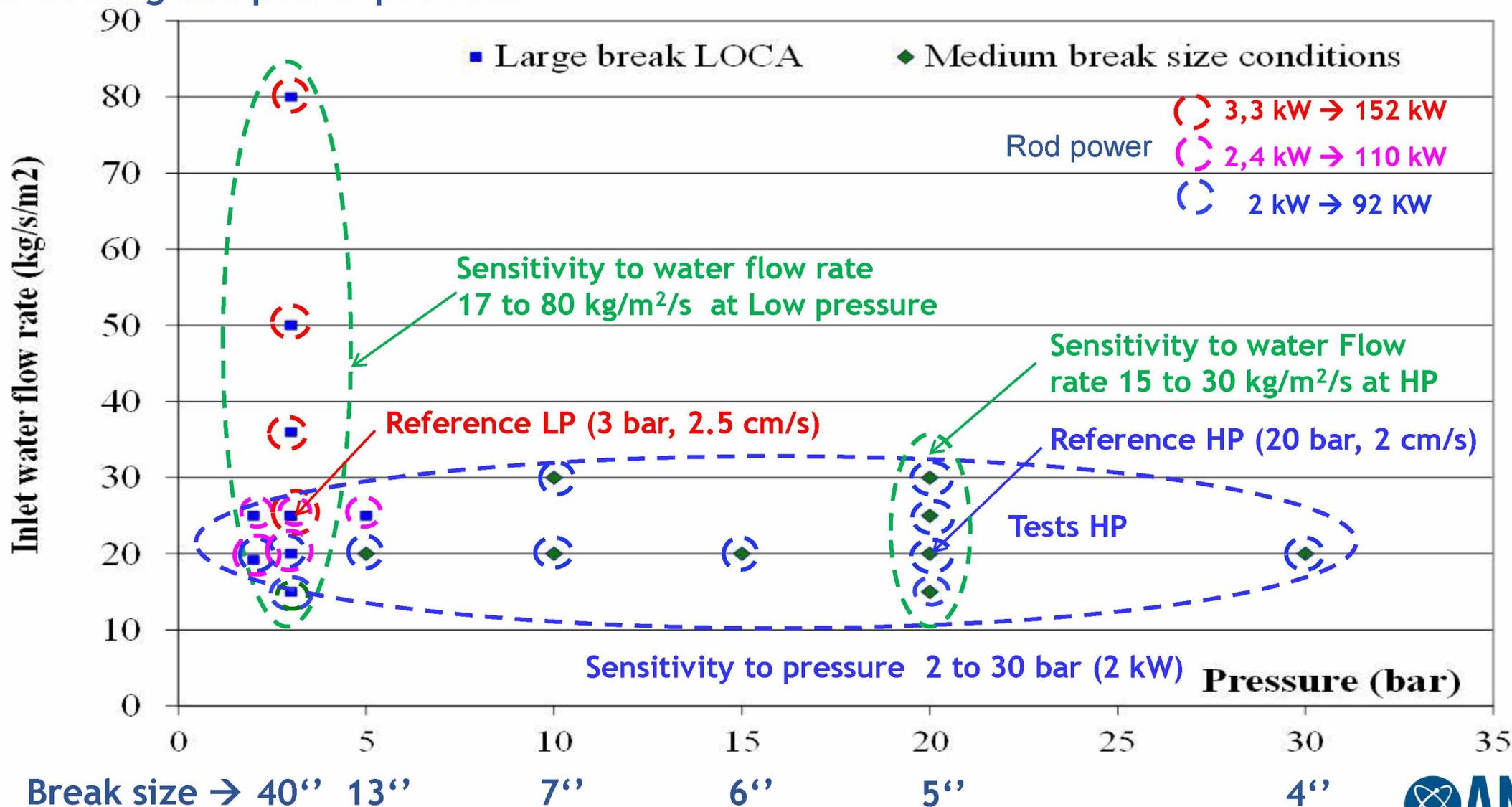
Blowdown phase

LB or MB LOCA transient
Not reproduced

Water Injection according to different T/H conditions

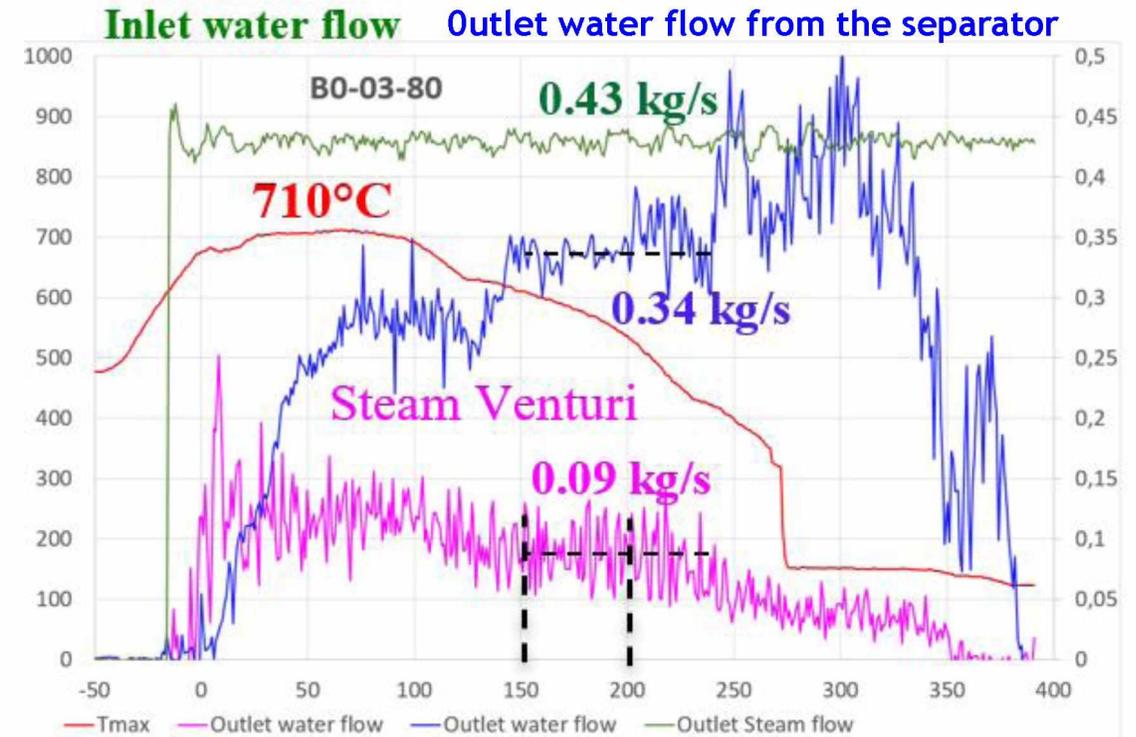
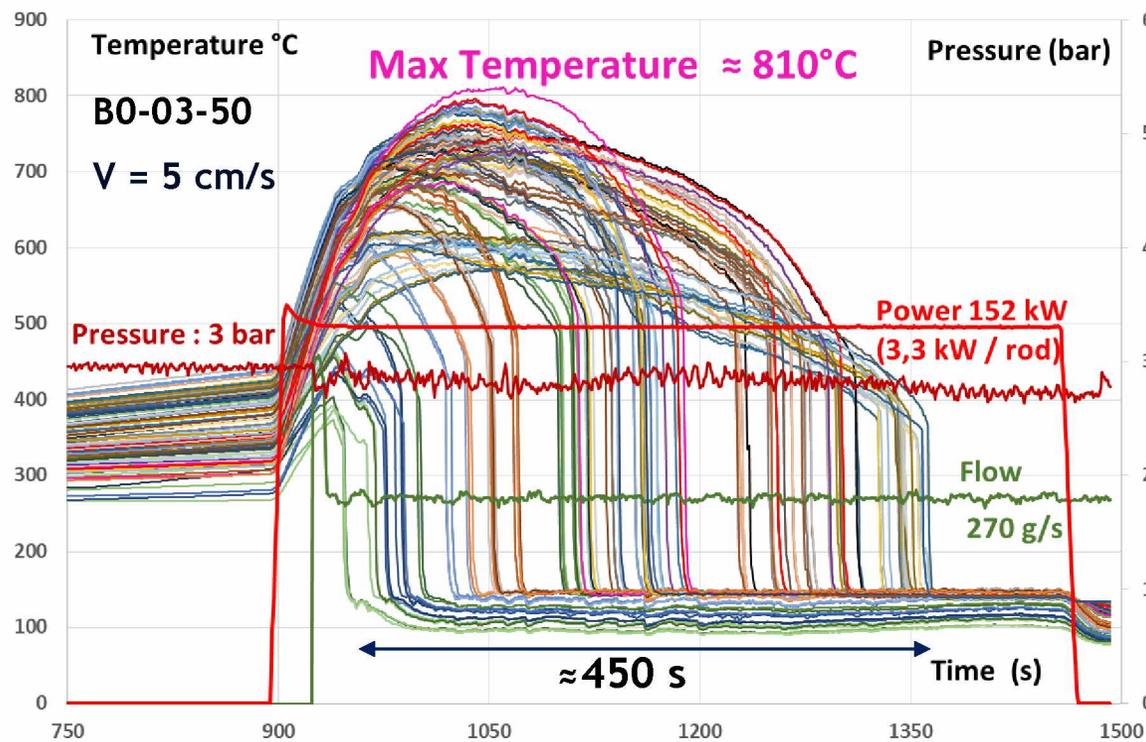
COAL test matrix (as Q, P diagram)

Roughly 25 tests for each campaign enough to investigate the effect of pressure, water flow rate, water sub-cooling and power per rods



Typical COAL results for low pressure test (Large break LOCA conditions)

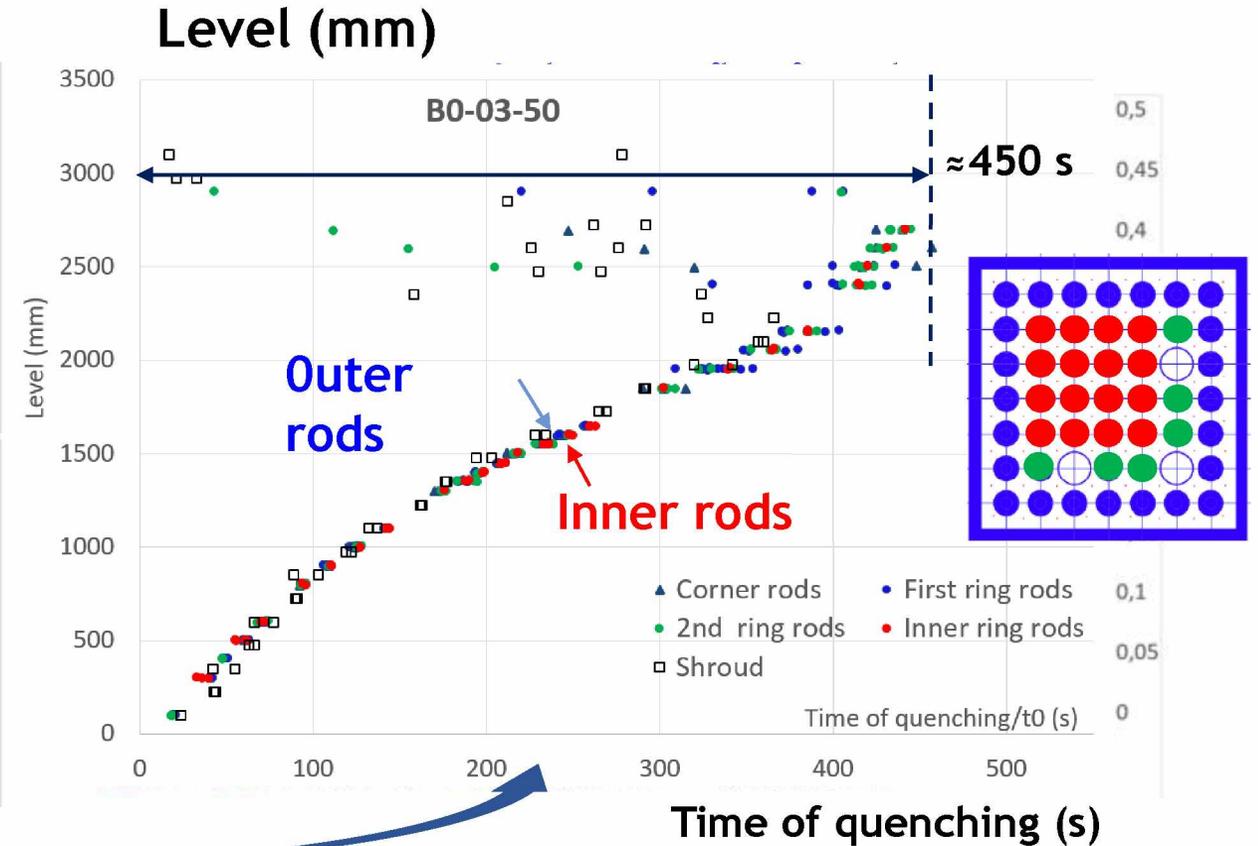
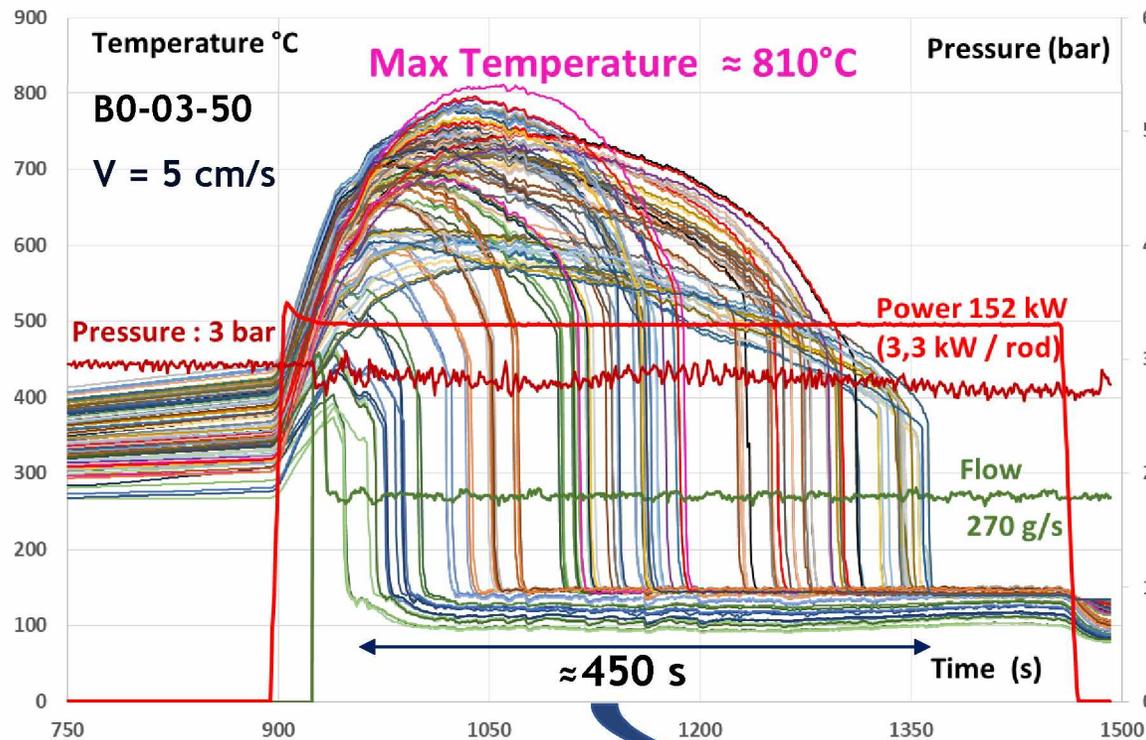
For rather high water flow rate, the maximum temperature was recorded around 810°C on the inner rods just above the middle plan



→ For all the tests, we got the temperatures evolution every where in the bundle, the pressure, the inlet water flow rate and the outlet flow rate (steam release and water as droplets)

Typical COAL results for low pressure test (Large break LOCA conditions)

For rather high water flow rate, the maximum temperature was recorded around 810°C on the inner rods just above the middle plan



→ The numerous rod thermocouples (≈300) allow the determination of the quench front propagation

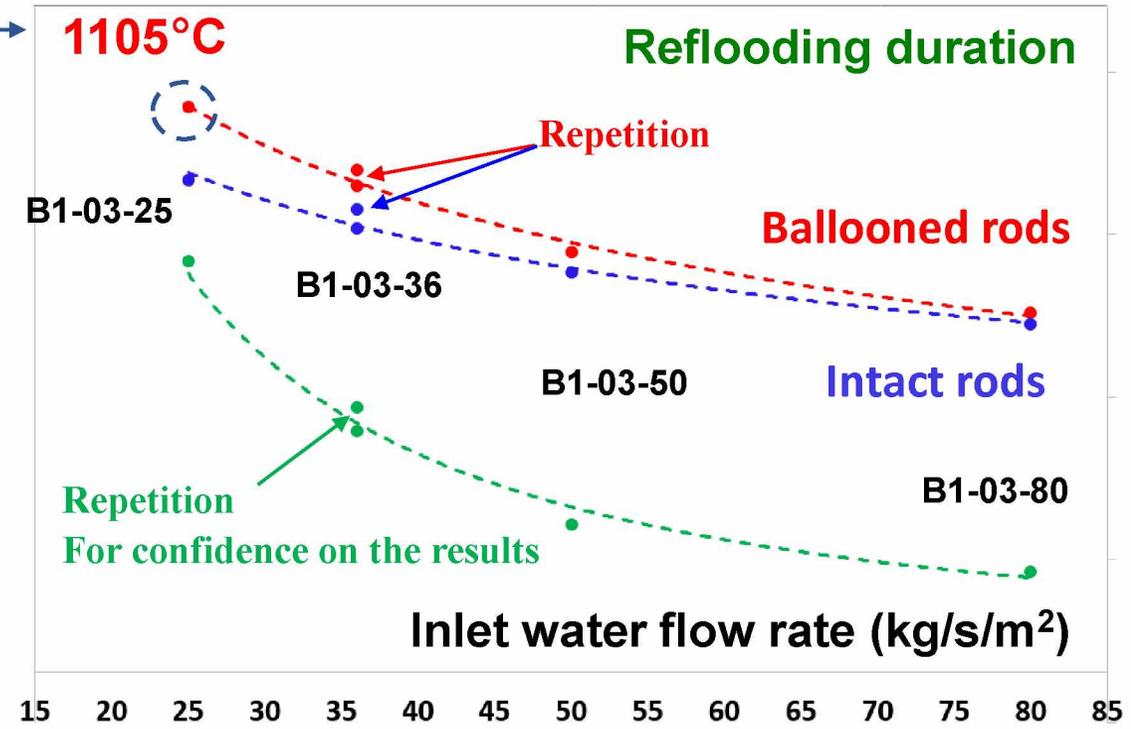
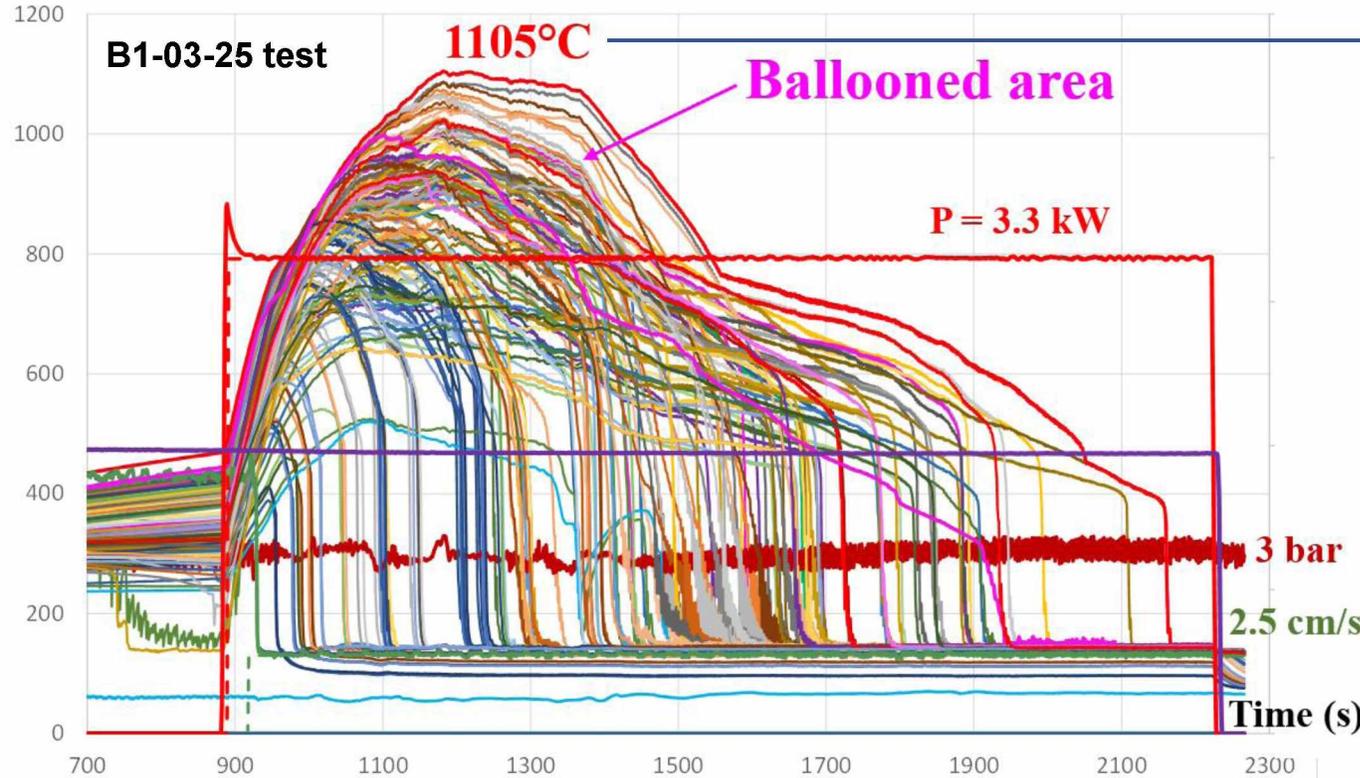
→ For intact geometry, the quench front propagations (QFP) look rather similar for all rods rings

B1 (80% blockage, short balloons) - Large Break size LOCA conditions

Typical COAL results

Maximum rods temperature (°C)

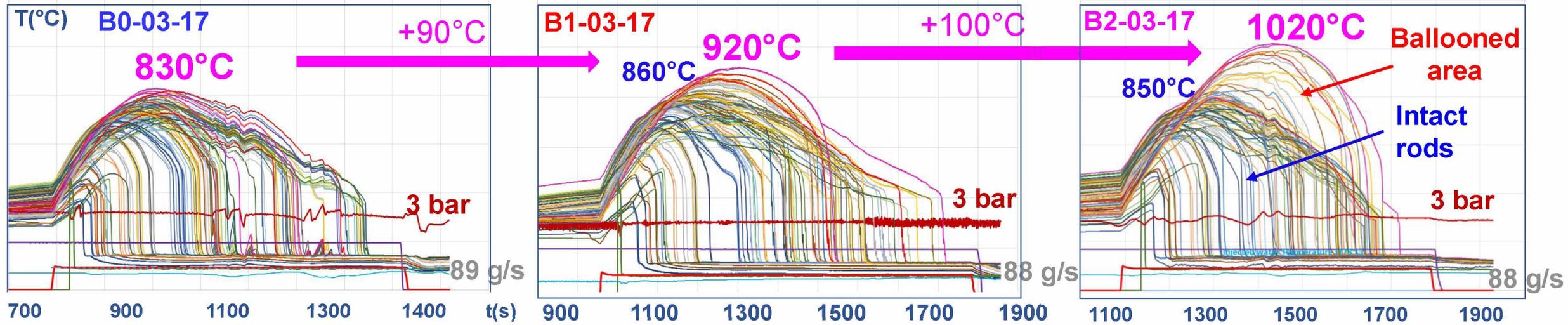
Effect of the inlet water flow rate on the maximum temperature and the time for reflooding



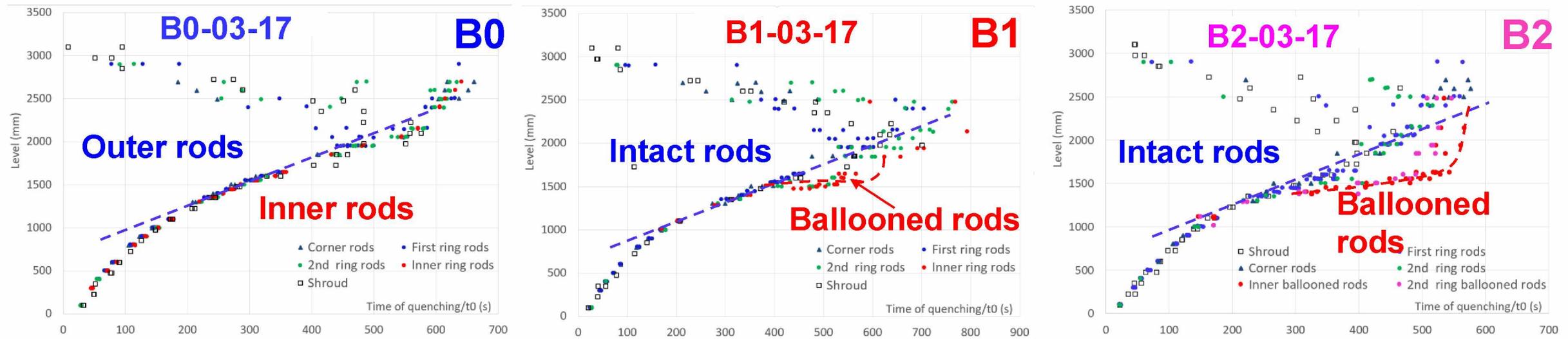
→ The increase of the flow rate lead to a decrease of the max T°C and the duration of the reflooding

We succeed in the objective with 8 experiments above 1000°C (among the 82 tests) without any damage on the rods and few losses of thermocouples (less than 5%): quite a good performance to underline

B0 (intact) B1 (80% blockage, short balloon) B2 (90% blockage, long balloon) – LB conditions

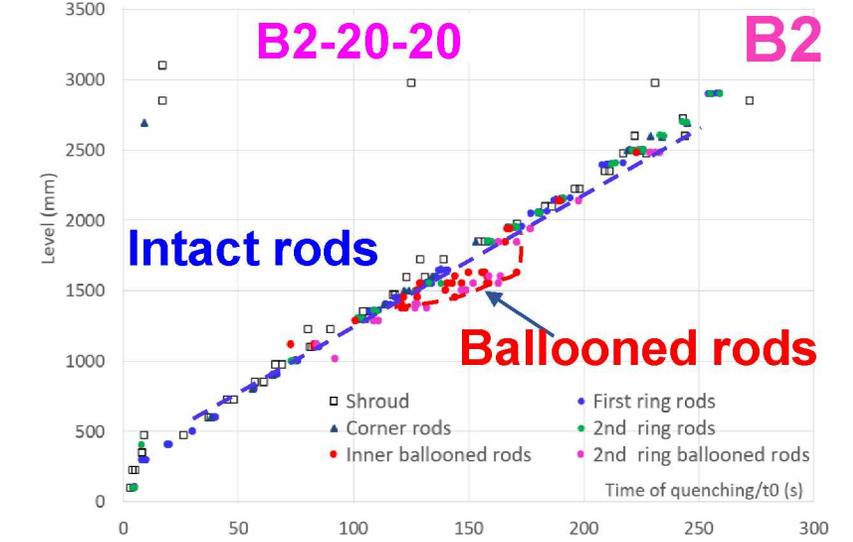
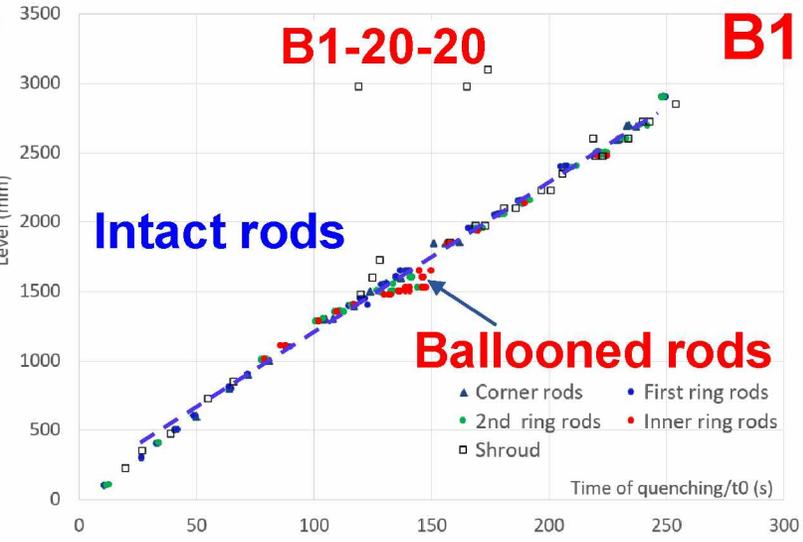
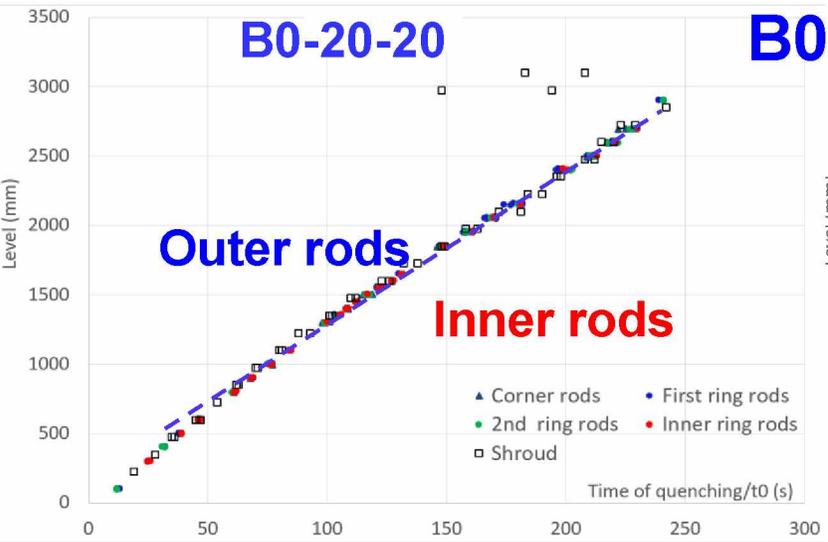
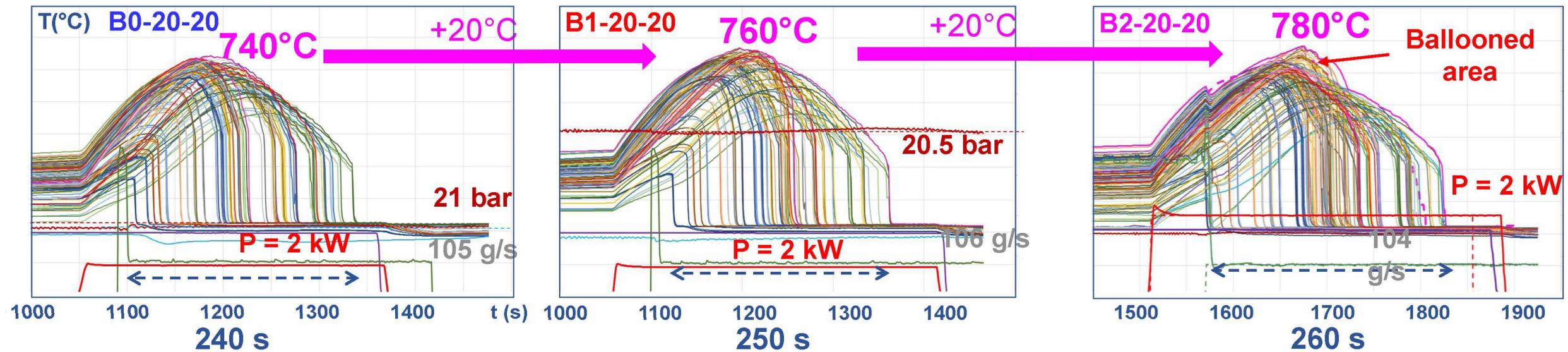


→ Significant effect on the max $T^{\circ}\text{C}$ increasing with the size of the balloons



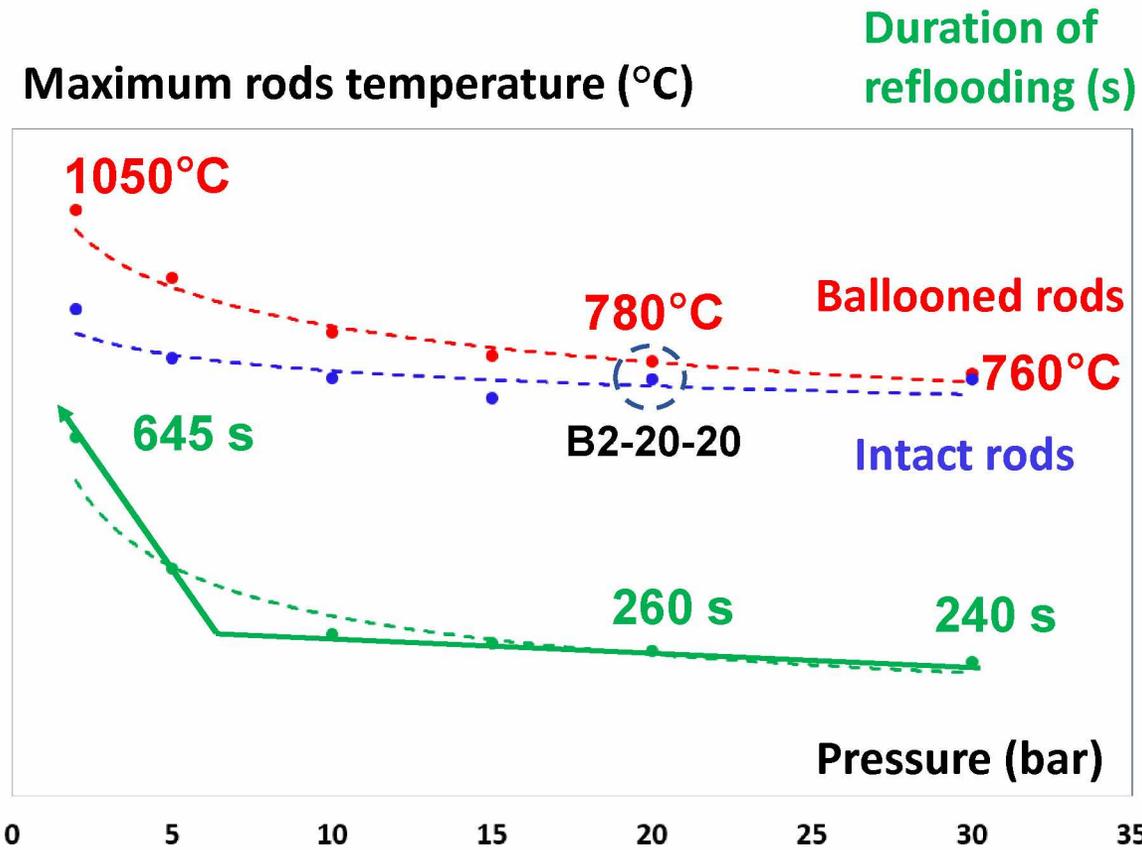
→ Significant effect on QFP increasing with the size of the balloons

B0 (intact) B1 (80% blockage, short balloon) B2 (90% blockage, long balloon) – MB conditions

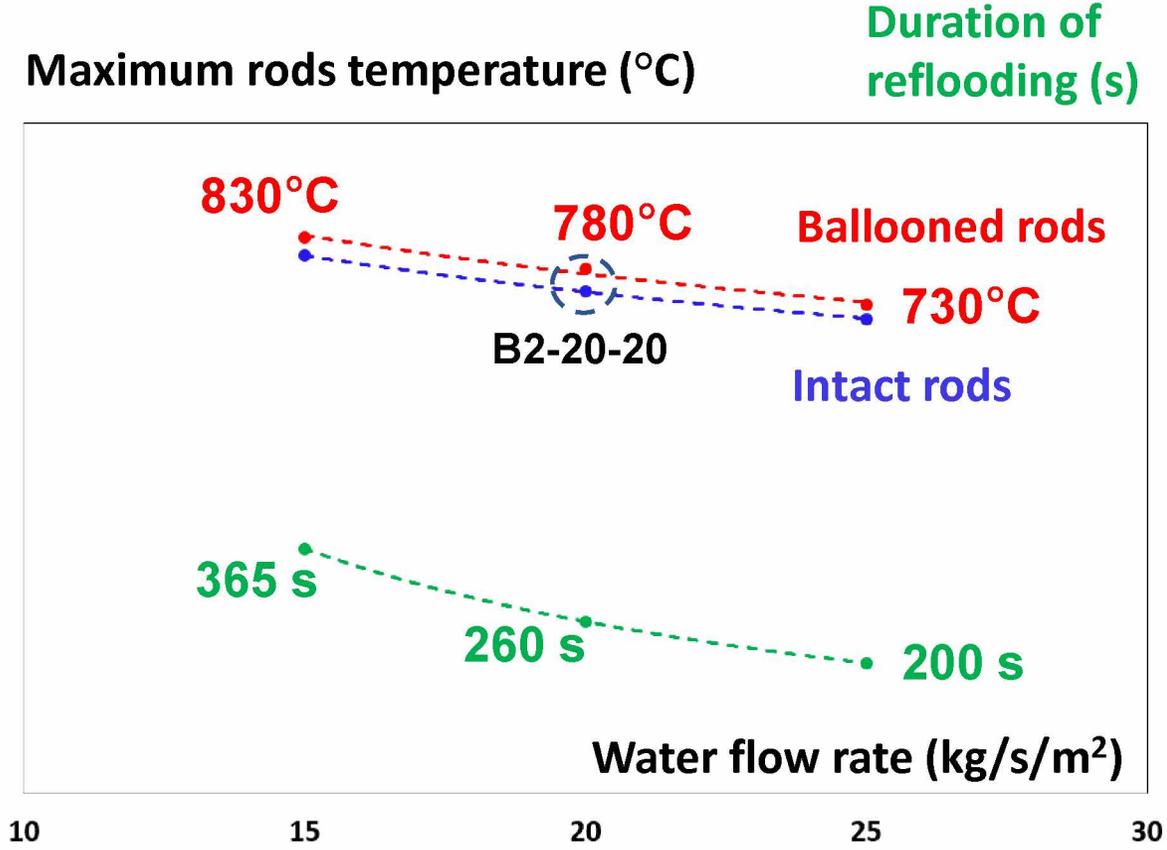


→ Less effect of the balloons at high pressure (20 bar) for both the maximum rods temperature and the QFP

COAL experimental results : effect of pressure (2→30 b) and flow rate at 20 bar



Effect of the pressure (2 → 30 b)



Effect of the water flow (1.5 → 2.5 cm/s)

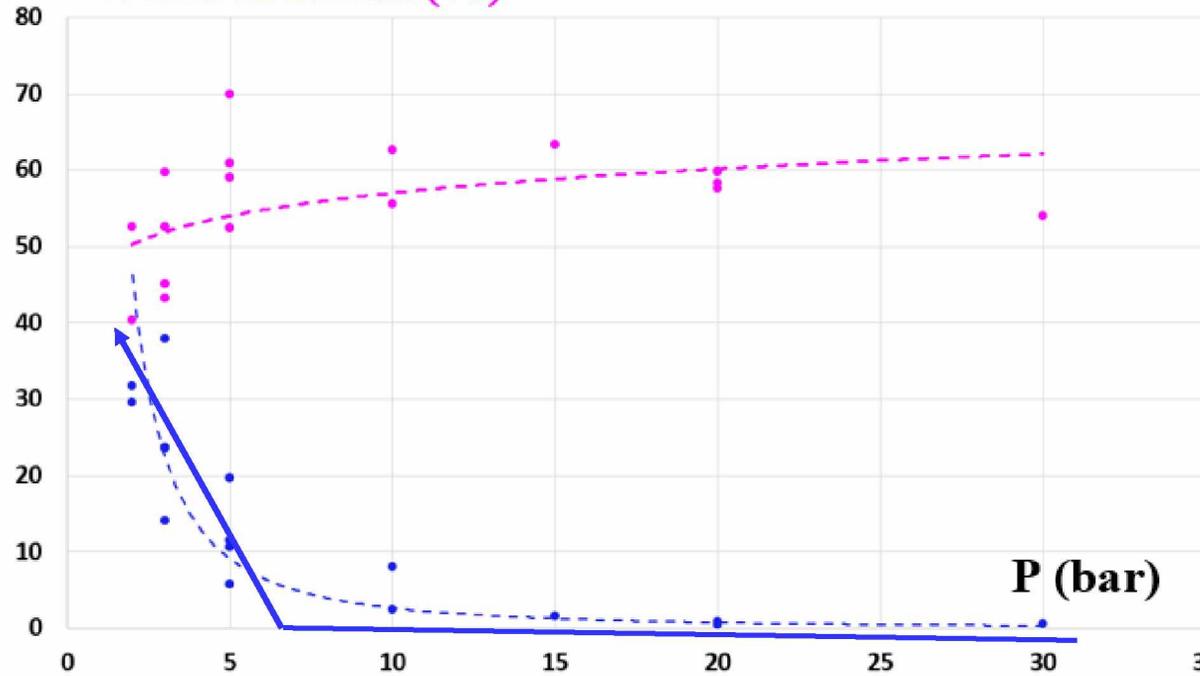
→ Less efficiency of the reflooding process below 10 bar clearly identified on both the PCT and on the duration of the complete reflooding

Conversion factor water to steam according to the pressure and the water flow

Effect of the pressure (2 → 30 b)

Ratio: outlet water to inlet water (%)

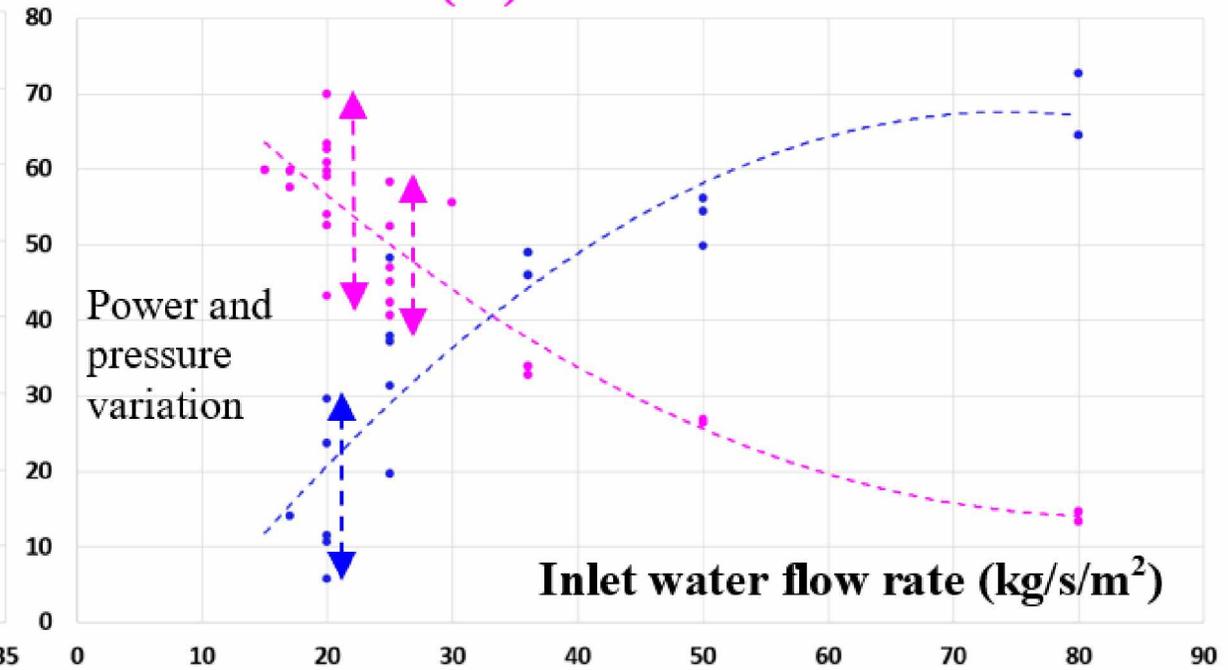
Water to steam (%)



Effect of the water flow velocity (1.5 → 8 cm/s)

Ratio: outlet water to inlet water (%)

Water to steam (%)



→ The numerous information regarding the thermal hydraulics results allowed to obtain clear results on the effect of the inlet water flow and the pressure on the conversion factor during the reflooding processes

→ Less efficiency of the reflooding process below 10 bar is confirmed on the water remaining at the outlet of the test section : above 5 bar all the injected water is converted into steam

Some conclusions

IRSN COAL experiments to address the issue of the coolability of ballooned fuel rod with relocated fuel fragments (i.e. irradiated fuel) have been performed in the past three years (within the PERFROI project)

COAL : reflooding tests with 4 ≠ bundle with blockage ratio (0, 80%, 90%, 80% non coplanar)

B0 * B1 B2
(2020) (2021) (2022)

- Investigation of the effect of pressure, water flow rate and power per rod
- More than 80 tests have been performed. More to come in 2023/2024 (B3 non coplanar ballooned rods)
- Significant effect of the ballooned region at low pressure (3 bar)
- Several tests reached 1105°C (close to the LOCA criteria) for low pressure and low flow rate conditions
- Less at higher pressure as the reflooding processes appear to be more efficient above 10 bar

These experiments provide thermal hydraulic information needed to improve the codes modelling during the reflooding under LOCA sequence, with the thermal behavior of the rods in a well define boundary conditions (heated shroud at well controlled temperature) and all the hydraulic parameters such as the water (as droplets) and the steam flow at the outlet of the test section)

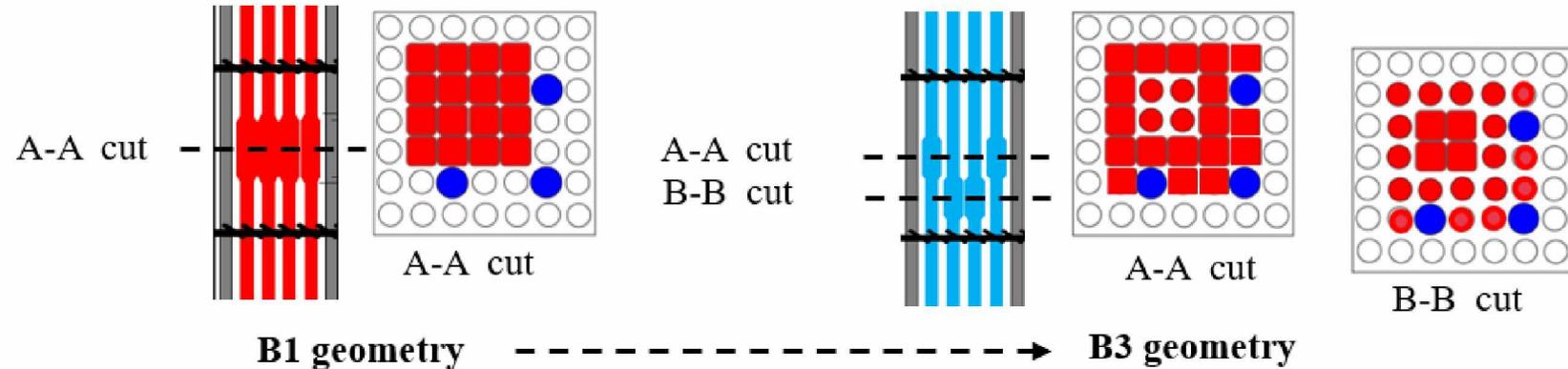
Once the simulation tools validated in such complex configuration, their may be used for safety study in real nuclear reactor conditions

Some COAL experiments are proposed for an OECD - ISP in 2024

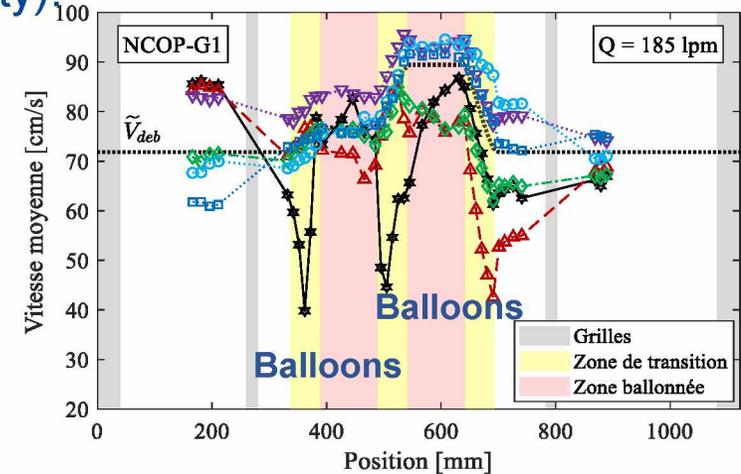
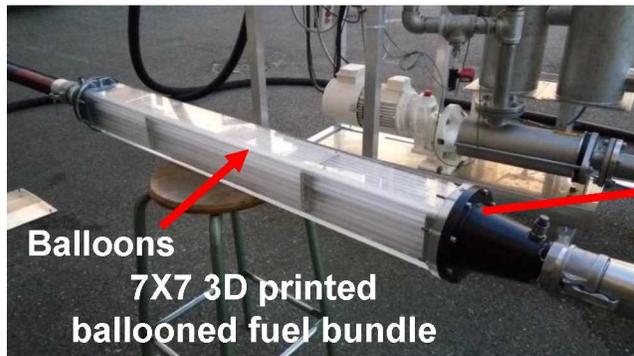
* G. Repetto et al, "COAL experiments investigating the reflooding of a 7 x 7 rod bundle during the a loos of cooling accident – thermal hydraulics results," *Proceedings of 2019 International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, Brussels, Belgium, March 6–11 (2022).

Perspectives for 2023/24

The next experimental campaign will be performed in 2023/2024 with a bundle including a partially blocked area by ballooned rods at a blockage ratio of 80% (length of the maximum deformation 100 mm) with non coplanar positions of the balloons.



Close configuration was tested in MASCARA facility (within the PERFROI project) and highlighted more complex flows at the level of the flow redistributions (several zones of less velocity).



MRI scanner to measure 3D flow velocity fields *

* A.V.S. Oliveira, D. Stemmelen, S. Leclerc, T. Glantz, A. Labergue, G. Repetto, and M. Gradeck, "Velocity field and flow redistribution in a ballooned 7x7 fuel bundle measured by magnetic resonance velocimetry", Nuclear Engineering and Design., vol. 369, p. 110828 (2020)

Thank you for your attention

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