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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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ABSTRACT

During a loss of the coolant of the primary circuit (LOCA) in a pressurized water reactor, the drying of the fuel assemblies may lead to the fuel temperature increase and deformation of the fuel rod claddings. In addition to the restriction of the flow area, the fragmented irradiated fuel relocation within the ballooned zone leads to an increase of the local residual power.

The COAL experiments will focus on the coolability issue of a partially deformed fuel assembly during water injection with the safety systems using a 7x7 bundle of electrically heated rods. These experiments are part of the PERFROI project launched by IRSN with the support of the french “Agence Nationale pour la Recherche” (ANR), EDF and the US-NRC.

The effect of the flow blockage {intact geometry up to long ballooning (100 to 300 mm) with different blockage ratios (80 to 90%)} will be evaluated for various power, mass flow rates and different pressures representative to Large (LBLOCA at 0.3 MPa) and Medium break size (MBLOCA : 0.5 to 3 MPa) configuration. Relocation of fragmented fuel in the balloons are taken into account by a local increase of the power by a factor of 1.5.

This paper presents the thermal hydraulics parameters and the main results of the experiments performed in a facility of the STERN Laboratories (Canada). The presence of the balloons increases significantly the Peak Cladding Temperature. These results will be used to improve and validate the heat exchange models of thermal hydraulics codes dealing with the complex reflooding processes in such configuration.

KEYWORDS

Coolability, blockage, LOCA, COAL, PERFROI

1. INTRODUCTION

During an accident causing a loss of the coolant of the primary circuit (LOCA) in a pressurized water reactor, the drying of the fuel assemblies may lead to the fuel temperature increase and significant deformation of the fuel rod claddings. In addition to the restriction of the flow area, the fragmented irradiated fuel relocation within the ballooned zone leads to an increase of the local residual power.

The COAL experiments are part of the PERFROI project [1] launched by “Institut de Radioprotection et de Sureté Nucléaire” with the support of the french “Agence Nationale pour la Recherche” (ANR), EDF and the US-NRC. In this framework, IRSN has designed and developed these specific experiments focusing on the coolability issue of a partially deformed fuel assembly during the cooling phase by water injection with the safety systems using a 7x7 bundle of electrically heated rods.

Competing influences of two phenomena, due to the blockage (Fig. 1 a), (1) increase of the velocity in the deformed fuel rods region and (2) the bypass of the blockage (reduction of mass flow in the sub channels), is evaluated through integral experiments. The effect of the flow blockage (intact geometry up to long ballooning with different blockage ratios 80 to 90%) will be evaluated for various flow rates and different pressures representative to Large (LB LOCA) and Medium Break LOCA (MB LOCA) size configuration. Numerous reflooding (mainly “out-of-pile”) experiments were already performed in the past, mainly in the 80’s, with different bundle geometries:

- Some square bundle scaled size: 4 X 4 (ROSCO in France), 5 x 5 rods (FEBA, SEFLEX in Germany, PHEBUS in pile-experiments in France - Fig. 1a), 7 x 7 (RBHT in USA and THETIS in Great Britain);
- Some with scaled cylindrical geometry: 44 rods (CEGB) and 69 rods (ACHILLES) in Great Britain;
- Some at Fuel assembly (F.A) scale: PERICLES (in CEA – France) and FLECHT-SEASET in USA.

Reference of these experimental programs are provided in [2-3]. Nevertheless, IRSN considered that the configuration of the simulating rods, used in out of pile experiments, were not representative enough because they did not take into account the fuel relocation and the right thermal inertia of the deformed fuel rods (bad contact between the heaters and the cladding). Past experiments were performed with rods for which the balloon was represent by ballooned cladding (SEFLEX) fare for the heat source (heater) or by metallic sleeves FEBA (Fig. 1). One of the challenges of the COAL program was to perform tests with electrical rods (Fig. 1b) simulating a correct inertia of the deformed rods, representative enough as compared to real deformed nuclear fuel rod (see Fig. 1.c). The global thermal inertia of our rod (C22 Cladding + ceramic) is 0.216 kJ/m/K compared to that of real fuel rod (Zry+UO₂: 0.261 kJ/m/K at 600°C). The fuel relocation is simulated by a local increase of the electrical power in the balloons (see - Fig. 7). The rods were designed for a maximum power of 3.5 kW but used materials may allow power up to 5 kW.

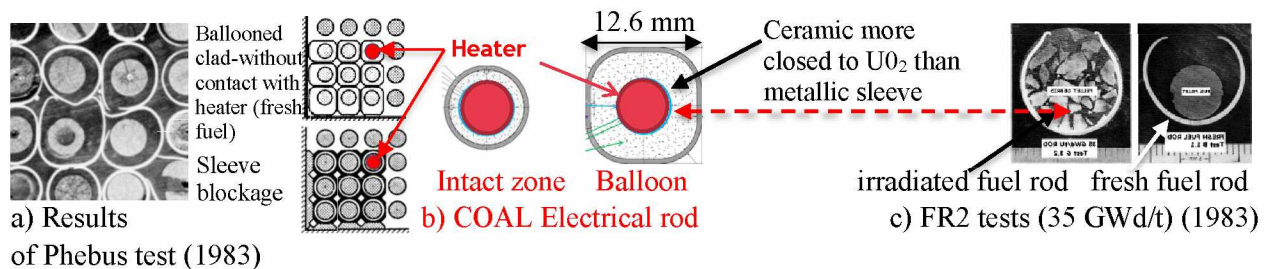


Figure 1. Deformed rods with balloon

2. THE COAL EXPERIMENTS

The objective of the COAL experiments, within the PERFROI Project [4], is to improve the knowledge and the modeling of reflooding process of a fuel-rod assembly with partially large blocked area with relocated fuel in the balloons simulated by a local power increase. The results of these “reflooding” experiments will be used to develop, to validate, to improve or the thermal hydraulic models of the DRACCAR code [6-7]. Numerous pre-calculations were performed with the code [8-9] in order to prepare these experiments.

The specific objectives of the COAL experiments are double:

- To study the “reflooding” at rather low flow rate (**Obj 1**): it has been already demonstrated that for high water velocity, the core coolability may not be impaired in a Large Break LOCA conditions (2 to 3 bar);
- To study the coolability for Medium Break LOCA conditions for pressure 5 to 30 bar (**Obj 2**).

Several experimental campaigns are foreseen with different geometries of the bundle. The main objective of the B0 tests campaign was to have a “Reference state” with intact rods. The main objective of B1 and B2 campaigns is to investigate the effect of the presence of ballooned rods in the inner part of the bundle for the geometries described in the following section §2.1. This paper concerns the results of the preliminary synthesis of these campaigns performed successively in 2020 for B0, 2021 for B1 and 2022 and B2.

2.1. The test section design and the bundle geometry

The COAL bundle [5] will consist of rods (electrically heated) some with a pre-deformed zone (Fig. 2a) with local overheating representing fuel relocation. The bundle will be made of 49 (7 x 7) rods, including in the center for B1 and B2, 16 deformed rods, 30 non-deformed rods and 3 guide tubes (Fig. 2b).

B1 and B2 bundles include a partially blocked area by ballooned rods at a blockage ratio respectively 80% and 90% (length of the maximum deformation respectively 100 mm and 300 mm),

The presence of 3 guide tubes (external Φ : 12.4 mm) will increase the representativeness of the thermal hydraulics behavior for the reactor case (Fig. 3 of [4]) part of the PWR 17x17 fuel assembly. The test section will also include 6 spacer grids (4 mixing vanes grids plus 2 holding grids at the bottom and at the top of the bundle) with a distance of 522 mm between two grids as for the reactor case.

For these experiments, the cladding (external Φ : 9.5 mm for the intact zone) of the electrical rods used is Hastelloy Haynes C22 material to prevent oxidation. To avoid any chemical interaction, the grids are in Inconel 718 alloy and include mixing vanes that would have an effect of thermal hydraulic behavior.

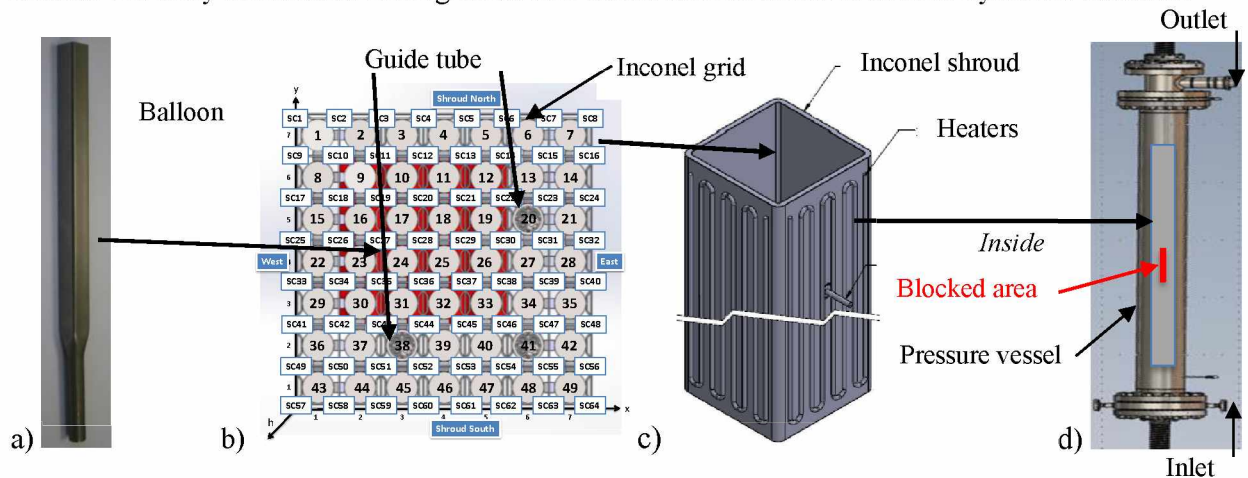


Figure 2. Experimental device (deformed rod, bundle, shroud, test section)

The presence of guide tubes (GT) is also necessary for instrumentation (see § 2.3) and for mechanical reasons. The heated zone is about 3m high (close to the real french 900 MWe PWR geometry: 3.7 m up to \approx 4 m for 1300/1450 Mwe PWR). The bundle will be inserted in 94 mm square electrically heated shroud (Fig. 2c) with roughly 4-5 mm thickness to be representative of the surrounding fuel rods regarding their thermal inertia. The test section is included in a pressure vessel, (4/5 m high, 220 mm diameter – Fig. 2d) with two lower and upper plenums for the electrical and instrumentation connections and the fluid supply.

2.2. The test facility

For this project, we used the STERN Lab. facility in Hamilton (Canada) based on the 20MPa Single Element test Loop, where additional components were constructed in order to perform reflooding tests.

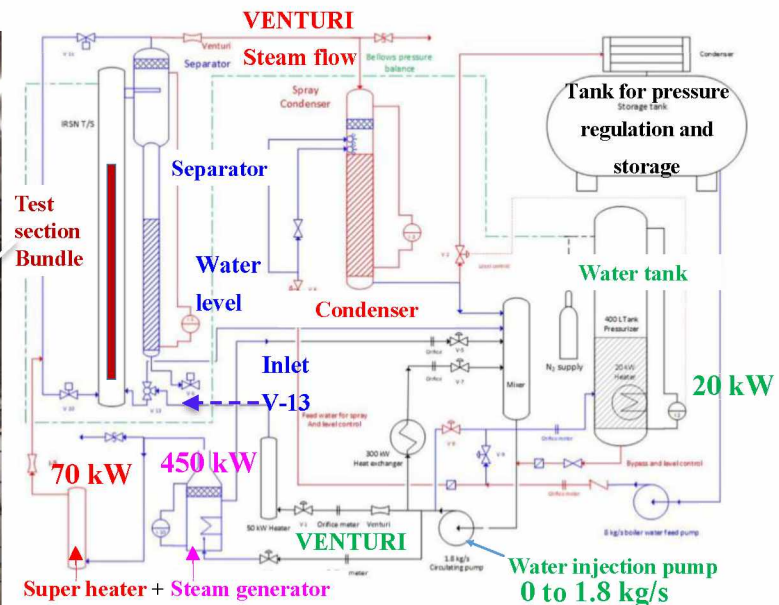
The loop (Fig. 3) is composed of different components in order to perform the COAL experiments:

- A water tank with heaters in order to pre-set the water temperature;
- A pump for water injection at different flow rate (0.05 to 0.5 kg/s); The combined capacity of the main circulation pump is 1.8 kg/s, which was largely enough for the maximum inlet water flow rate, foreseen in the test matrix (80 kg/m²/s which corresponds to 0.42 kg/s);
- A 20 kW heater in order to set the inlet water temperature at the specified value;
- An inlet valve V-13 to open at the desired time to start the reflooding;

- A 450 kW steam generator in order to fill the loop with steam for the initial conditions after a LOCA scenario (see § 2.4);
- A 70 kW super heater in order to provide high temperature steam at 300°C as required by the test protocol;
- The COAL test section which includes the rods bundle (described in the previous section § 2.1);
- A bypass line provide steam in the test section for the initial conditions: during the reflooding, the steam is injected in the bypass line and join the outlet line;
- A water/steam separator in order to obtain results on the outlet water flow rate;
- A steam condenser and a pressurizer system including a storage tank used also for pressure regulation.



a) General overview



b) The thermal hydraulic loop

Figure 3. The STERN Laboratory test facility in Hamilton (Canada)

2.3. The test instrumentation plan

For these kinds of experiments, the major physical variables for model validation are as follows:

- Inlet and outlet water and steam mass flow rates (flow diversion inside the bundle are investigated in small scale experiments within the PERFROI project);
- Temperature of the fluid at different points (type K thermocouples: ± 2.2 °C);
- Temperature inside the fuel rods (thermocouples at different elevations and different radial positions in the bundle) in an adequate distribution, temperature of the shroud, grids and guide tubes;
- Total pressure and pressure drop sensors at the periphery of the rod bundle.

The test device is equipped with different types of instrumentation (up to 400 Tc's):

- Thermocouples in the electrical rods (6 Tc's per rod) positioned every 10 cm (for different types of rods - Fig. 9 of [9]) to follow the quench front propagation (QFP);
- Thermocouples in the guides tubes (21 Tc's each GT) in order to have measurements on the guide surface, the fluid channel and the grids (6 Tc's);
- Thermocouples on the outer surface of the shroud (54 Tc's); the shroud is also equipped with thermocouples on each face in order to accurately set the boundary thermal conditions during the reflooding process.

The outlet mass flow rates of steam and water are foreseen to be evaluated by the separator and the outlet steam flow by mean of a “Venturi type” device (Fig. 4). The sensors (with accuracy) are given here after:

- FLMO flow orifice ($\pm 3.1\%$) and FLMV flow VENTURI ($\pm 0.42\%$) for the inlet flow rate;
- FLSV flow VENTURI ($\pm 0.55\%$) for the bypass steam outlet flow rate;
- FLCV combined flow VENTURI ($\pm 0.55\%$) for the total steam outlet flow rate;
- LV3 level of the separator (for the amount of water at the outlet of the test section as droplets).

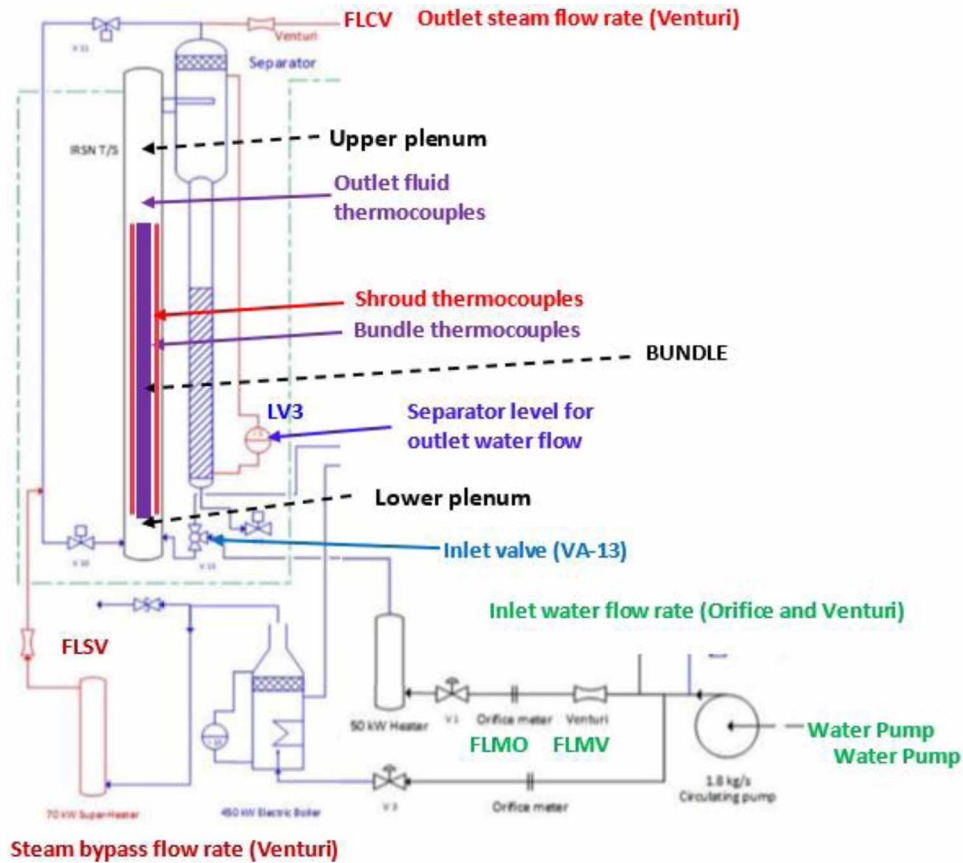


Figure 4. The thermal hydraulics measurements for the COAL experiments

The outlet steam flow rate from the bundle is evaluated using the difference between “FLCV” and “FLSV” venturi measurements (Fig. 5).

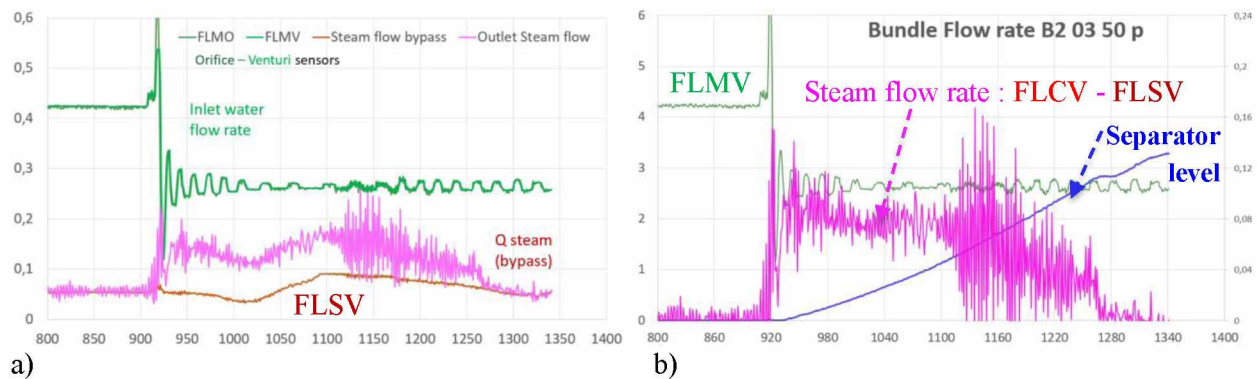


Figure 5. Example of the thermal hydraulics results

2.4. The test scenario and the thermal hydraulics parameters

The scenario is divided in two phases as for classical “Reflooding experiments” performed in the 80’s [3]:

1. Heat up phase in dry steam atmosphere (the depressurization is not simulated),
2. Reflooding by water injection with different thermal hydraulic conditions (see test matrix § 2.5).

The so-called test protocol (Fig. 6) will contain several steps as below:

- Step 1: the bundle will be preheated up to 300°C by hot steam injection (initial conditions after LOCA);
- Step 2: the shroud is heated by mean of heaters (20 kW: 5 kW each faces) up to 500°C;
- Step 3: when the shroud temperatures reach the “500°C”, the rods power started at the level needed for the test;
- Step 4: the rods will be heated up to 520-550°C before the water injection phase (“reflooding” period); the maximum water flow rate (80 kg/s/m²) is injected at the beginning in order to fill the lower plenum;
- Step 5: power and water flow will be successively stopped after the complete quenching of the bundle.

The main thermal hydraulics parameters foreseen are in the range below:

- coolant pressure: 0.2 to 3 MPa (2 to 30 bar);
- power per rod: 3.3 Kw or 2.4 kW or 2 kW for Large Break size LOCA scenario (low pressure - LP) and 2 kW for Medium Break size scenario (high pressure - HP) with a typical cosine profile;
- inlet water flow velocity: 1,7 to 8 cm/s (17 to 80 kg/s/m²);
- sub-cooling water temperature: -60°C (for LP tests) /-20°C (for HP tests) to saturation conditions.

The axial power profile is recalled by the figure 7 (Fig. 2 of [9]). A local power increase in the balloons (factor 1.5) is provided to simulate the fragmented irradiated fuel relocation in the balloons (see Fig. 1.c). Specific power has been reduced above the balloons in order to take into account the fuel relocation.

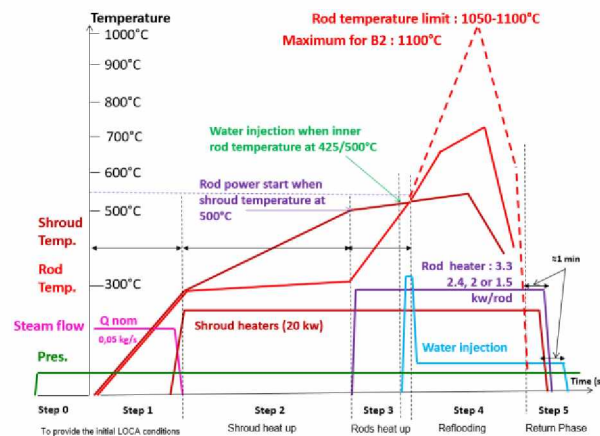


Figure 6. Test protocol for conducting COAL tests

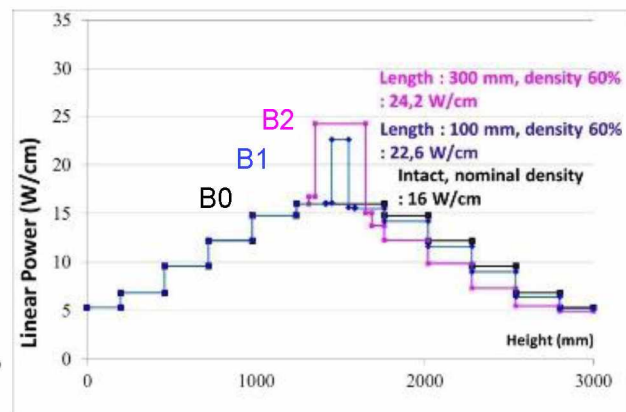


Figure 7. Axial power profile of rods

2.5. The COAL test matrix

The general COAL test matrix referring to (Q, P) diagram where Q is the inlet water flow rate in kg/s/m² and P, the system pressure in bar, is given in Fig. 8 below. The pressure conditions come from NPP CATHARE calculations (Table 1 of [5]) with different break sizes (4 to 40 inches).

Roughly 25/30 experiments were enough in order to investigate the different physical main inlet parameters (power, pressure, water flow velocity and water sub cooling). 2/3 tests were repeated in order to investigate the reproducibility of the results. 82 experiments were performed (respectively 28 in 2020 for B0, 26 in 2021 for B1 and 28 in 2022 for B2 campaign) to investigate the different physical main inlet parameters.

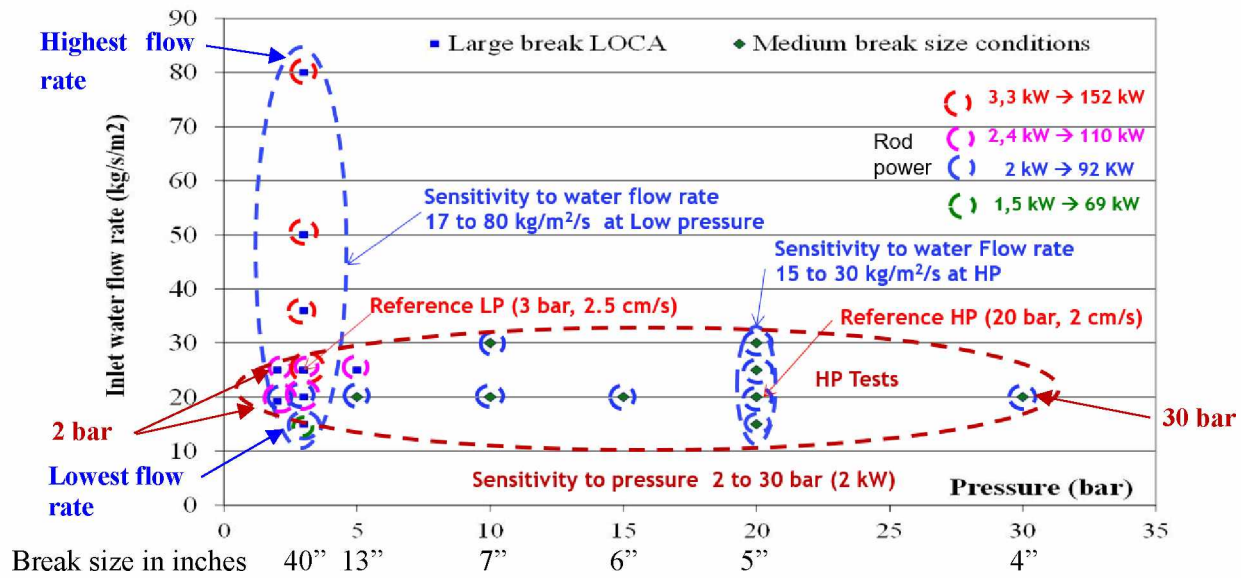


Figure 8. COAL test matrix in a (Q, P) diagram.

Note: Each test is reported in the paper as the following label: BX-YY (water flow specific velocity given in kg/s/m^2) ZZ (pressure in bar). So, B0-20-20 corresponds to experiment with B0 bundle (intact rods) at 2MPa (20 bar) and 20 kg/s/m^2 .

3. THE MAIN EXPERIMENTAL RESULTS

This section gives the main results of some typical experiments in order to investigate both the effect of the inlet flow rate (at 3.3/2.4/2 kW per rod and 3 bar – LB LOCA conditions) and the effect of the pressure (at 2 kW per rod and 20 kg/s/m^2 – MB LOCA conditions).

3.1. The thermal results

3.1.1. Effect of the inlet water flow velocity (flow rate)

Four (4) tests were performed at a rather high power generated in each rod (3.3 kW), so for a total bundle power of 152 kW and similar pressure for the system (3 bar). For these tests, we varied the inlet water flow rate (from 25 to $80 \text{ kg/m}^2/\text{s}$). The results for the intact geometry, were already described in a previous paper (Fig. 6 of [10]).

Fig. 9 provides, as an example, the main results of the B1-03-25 for these conditions: 3 bar and inlet water flow velocity of $25 \text{ kg/m}^2/\text{s}$ (i.e 132 g/s). During these tests with the B1 configuration, the maximum temperatures were recorded around 1105°C on the inner rods: these conditions were not tested in the B2 configuration due to the higher blockage area, and the risk that the maximum rods temperature would overpass the designed temperature of the electrical rods. The maximum temperature reached during the last B2 campaign was observed for the 5 bar test at 2.4 kW/rod and a rather low water flow velocity ($20 \text{ kg/m}^2/\text{s}$).

Running tests at high temperatures was one of the challenges of the COAL experiments. For that, specific rods design was proposed for this project with original deformed rods described in section § 2.1.

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

Fig. 10 illustrates the evolutions of the maximum rods temperatures and the duration of the reflooding as function of the inlet water flow rate. The maximum temperatures range from 700 to 1105°C.

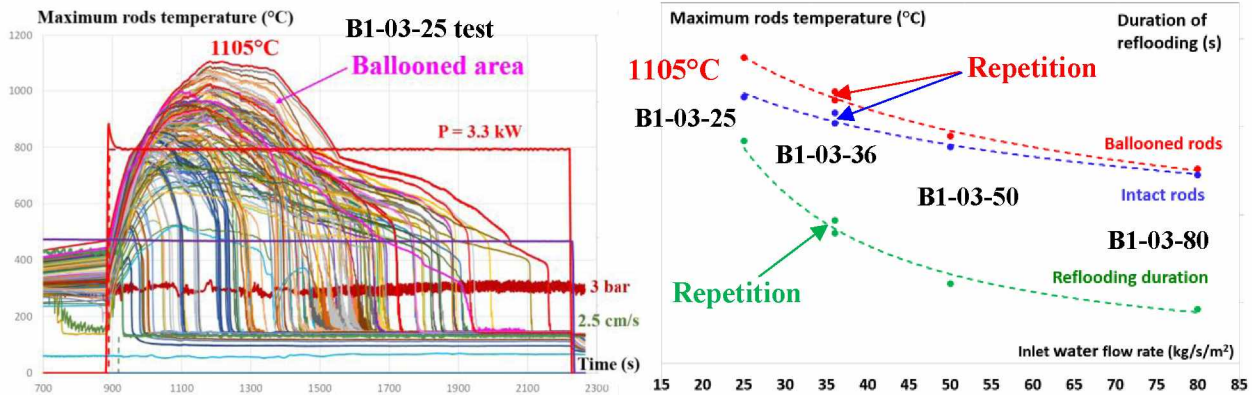


Figure 9. Temperatures for LP tests.

Figure 10. T max and duration versus water velocity

The very smooth tendency of the results (maximum temperatures and time for a complete quenching according to the water flow rate) underlines the very good consistency of these experiments as well as the reproducibility of the results of B1-03-36 as an example.

Analyses of the Fig. 6 of [10] show that results of maximum cladding temperatures are far below the Peak Cladding Temperature (1204°C) for intact geometry: in that case, “ductile coolability” is insure, even for very low inlet water flow rate such as 15 kg/s/m². The margin will be probably reduced (Fig. 10) by taking into account such partially blocked area and the fuel relocation in the balloons (B1): less margin is also expected with the so-called “long ballooning” at 90% blockage ratio (B2).

As the first objective of the COAL experiments (see § 2) is to study the “coolability” at rather low flow rate, tests were performed at 17 kg/s/m² (roughly 20% of the maximum flow rate available at low pressure with safety pumps – see Fig. 8).

Fig. 11 gives the evolution the thermal results of the Bx-03-17 serie of tests, in such situations, as the partially blocked area is increasing by ballooned rods : we clearly see the effect of the ballooned area mainly due to flow diversion from the inner to peripheral ring of rods.

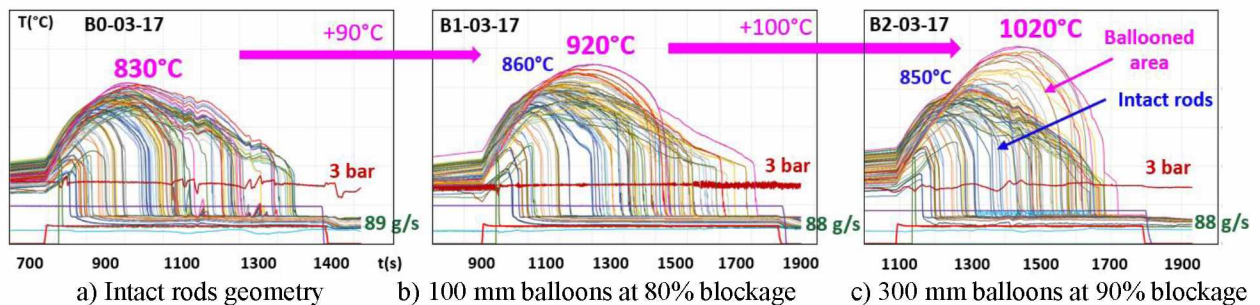


Figure 11. Temperatures for LP tests (3 bar) at low flow rate (17 kg/s/m²)

As the second objective of the COAL experiments (see § 2) is to study the “coolability” for Medium Break size LOCA conditions, experiments were performed at higher pressure (from 5 bar representative of a 13 inches break size scenario up to 30 bar representative of a 4 inches break size). These results are described in the following section (§ 3.1.2).

Nota: below 4 inches (SB LOCA), the configuration corresponds to severe accident conditions.

3.1.2. Effect of the system pressure

Several tests were performed at different pressure 2, 3, 5, 10, 15, 20 and 30 bar with similar inlet water flow rate (20 kg/m²/s, i.e 0.105 kg/s) and power 2 kW/rod for a total bundle power of 92 kW.

Fig. 12 provides the main results of the Bx-20-20 serie, the reference HP test for these conditions: 20 bar and inlet water flow velocity of 20 kg/m²/s for the 3 geometries of the blockage area. Maximum temperatures were recorded around 740°C up to 780°C on the inner rod.

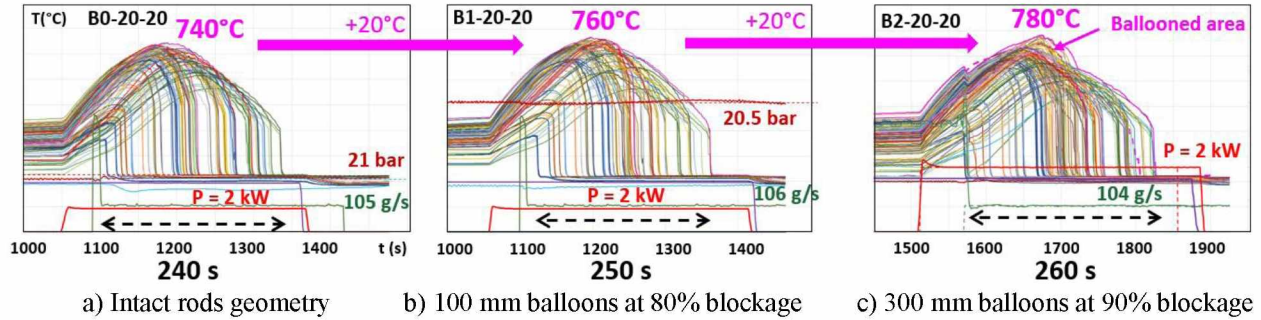


Figure 12. Temperatures for HP tests (20 bar)

The increase of the duration of the reflooding is not significant for these conditions (high pressure).

Fig. 13a) gives the evolution of the maximum rod temperatures and the duration of the reflooding according to the pressure for the B2 configuration as an example. The maximum ballooned rods temperatures increase from 760 to 1050 °C with the decrease of the pressure.

As observed for the intact geometry (Fig. 8 of [10]), above 10 bar up to 30 bar, we do not observe any variation of the duration of the reflooding, whereas the reduction of the pressure below 10 bar lead to a strong increase of the duration with a less efficiency of the reflooding process in particular below 5 bar.

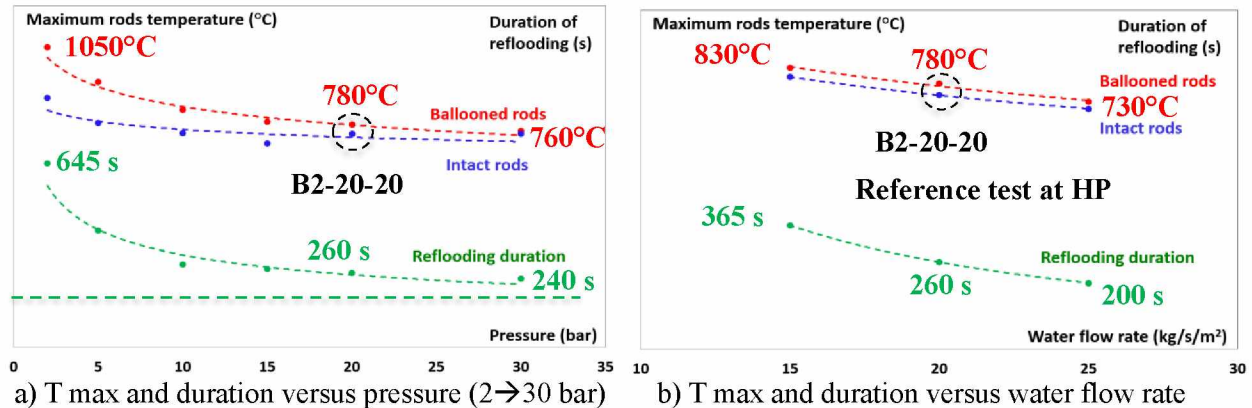


Figure 13. Maximum temperature and duration versus pressure and flow rate at 20 bar

Note: the choice to limit the high pressures tests and the test device design to 30 bar was reasonable.

Fig. 13b) gives the evolution of the maximum rod temperatures and the duration of the reflooding according to the pressure. The rods temperatures increase from 730 to 850 °C with the decrease of the flow.

These behaviours (according to the pressure at a constant flow rate and according to the flow rate at constant pressure) are in quite good agreement with our DRACCAR pre simulations (Table 2 of [8]) above 10/15 bar, nevertheless with some underestimation of the duration of the reflooding, increasing with the decrease of the pressure at below 5 bar.

3.2. The hydraulic results

This section concerns the results of the injected water inside the bundle and the corresponding outlet results of steam production and the remaining water as droplets at the outlet of the bundle.

We provide here after these results (Fig. 14) for test which leads to the highest value of outlet water flow rate as droplets, stored in the water/steam separator. This experiment corresponds to test with the highest inlet water flow rate (Flow VENTURI – see § 2.3) foreseen in the tests matrix (B0-03-80).

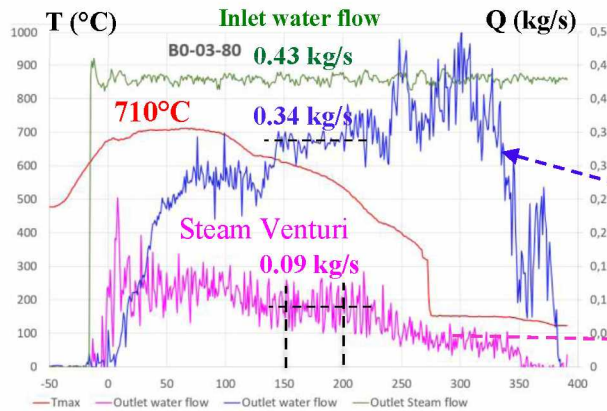


Figure 14. Water/ steam flow rate for LP tests

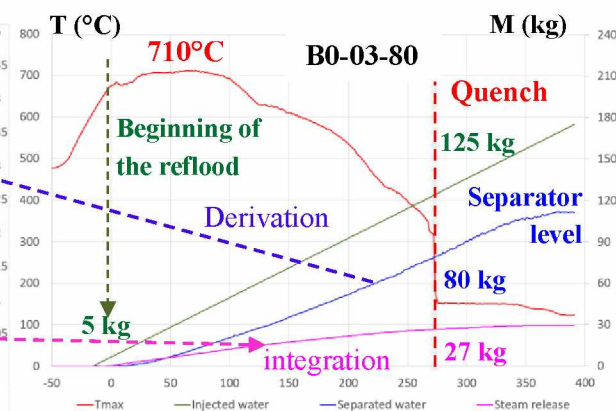


Figure 15. T max and water balance

The total amount of steam produced during the reflooding is obtained by the integration during the transient of the instantaneous steam flow rate (using sensors measuring steam from the bundle, § 2.3) whereas the instantaneous water flow rate at the outlet of the bundle is obtained by the derivation of the cumulative value of water collected in the water/steam separator (Fig.15). The analyses of these values (0.43 kg/s of injected water \approx 0.09 kg/s of steam + 0.34 kg/s of water, from $t=150$ to 200 s) outline rather well consistent results of B0-03-80, with the same observation for others experiments.

The balance of water at the end of the transient (complete quenching of the rods) provides also satisfactory results: at the beginning of the reflooding, \approx 4/5 kg of water is needed to fill the lower plenum.

We provide also these results (Fig. 16 and 17) for test performed in the B2 campaign (including ballooned rods). This experiment (B2-02-25p) corresponds to the test with the lowest pressure (2 bar – cf Fig. 8) and the medium inlet water flow rate. The balance of water at the end of the complete quenching of the rods, provides also satisfactory results. The remaining water in the test section (11.5 kg after the quenching and 16 kg after the power switch off) are in agreement with the free volume of the rod bundle (15.7 dm³). After the quench, the power is maintained in the bundle, so, the two-phase (water/steam) is present in the bundle which explain these differences. These informations provide rather high confidence for all the hydraulic flow measurements obtained during these COAL experiments.

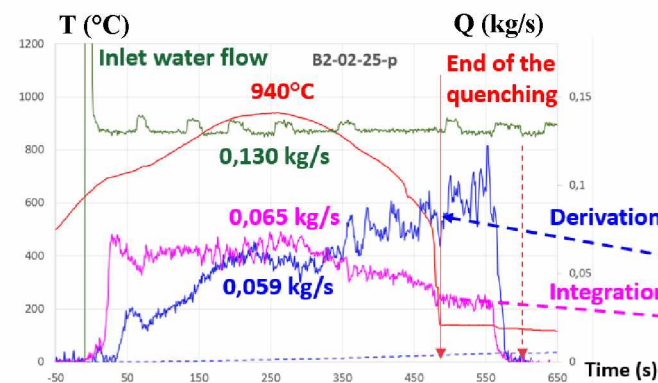


Figure 16. Water/ steam flow rate for LP tests

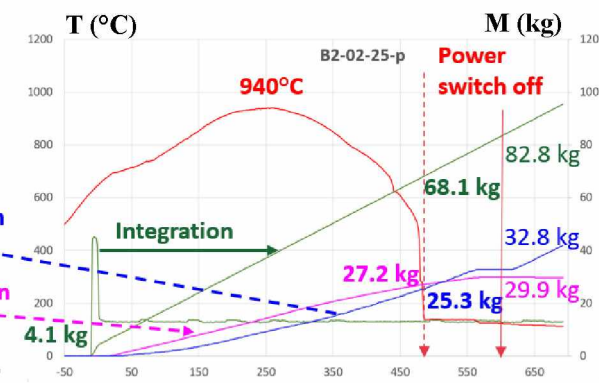


Figure 17. T max and water balance

Table II gives the steam production versus flow rate and pressure for some tests typical of the 3 campaigns.

For a constant pressure (3 bar), the production of steam (in % of the injected water in the bundle) is increasing while the flow velocity is reduced.

As the pressure is increased, the efficiency of the reflooding process is increased, leading to a complete vaporization of the injected water (if we take into account the water stored in the bundle): less amount is needed to a complete refreezing of the bundle.

This trend confirms the physical consistency of these hydraulic results and confidence for using these data for code validation.

Table II. Steam production versus flow rate and pressure

Test	B0-03-50	B0-03-36	B0-20-20	B0-30-20
Pressure	3 bar		20 bar	30 bar
Velocity	5 cm/s	3.6 cm/s	2 cm/s	
% of SP *	35%	49%	64%	71%
Test	B1-03-50	B1-03-36	B1-20-20	B1-30-20
Pressure	3 bar		20 bar	30 bar
Velocity	5 cm/s	3.6 cm/s	2 cm/s	
% of SP *	30%	45%	67%	62%
Test	B2-03-50p	B2-03-36p	B2-20-20	B2-30-20
Pressure	3 bar		20 bar	30 bar
Velocity	5 cm/s	3.6 cm/s	2 cm/s	
% of SP *	26%	33%	60%	54%

* SP : steam production ratio as function of the injected water flow rate

The tendency (experimental observation) is to decrease the amount of steam production as we increase the blocked area from intact geometry (B0) to further B1 and B2 geometries including ballooned rods with increasing the size of the balloon (length 100 → 300 mm and blockage ratio 80 → 90%). These observations may be due to flow diversion: less flow rate in the blocked area leading to less steam production. This is observed for most of the cases, of course taking into account the uncertainties of such measurements.

To conclude this section, Fig. 18 below shows the conversion factor (water to steam) and the ratio outlet water to inlet water according to the pressure (left figure) and to the inlet water flow rate (right figure) for the B2 campaign. Here also, the tendencies look pretty good, which illustrate the quality of the thermal hydraulic results of these COAL semi large scale experiments (small assembly scale at 3 meters high rods).

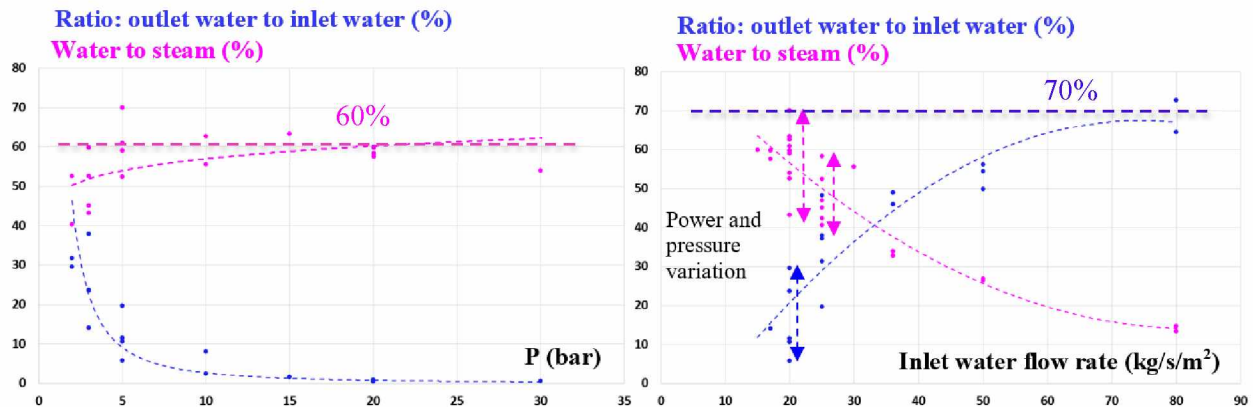


Figure 18. Conversion factor water/steam according to the pressure and the water flow rate

The conclusions are clear. The water remaining at the outlet of the bundle (as droplets) is decreasing with the pressure (in particular above 5/10 bar): as the pressure is increasing, most of the injected water (60%) is vaporized due to the higher efficiency of the reflooding process at high pressure. Part of the injected water is stored in the bundle to complete the quenching of the rods. In the contrary, the remaining water (non-vaporised at the outlet) is increasing as the inlet injected water is increasing with a saturation to 70%.

3.3. Quench front propagation

Fig. 19 and Fig. 20 give examples of the measured quench front propagation from the bottom to the top (time for quenching versus elevation) for two tests representatives series of LB LOCA (BX-03-25p) at 3 bar and MB LOCA (BX-30-20) at 30 bar (the highest pressure proposed in the COAL experiments).

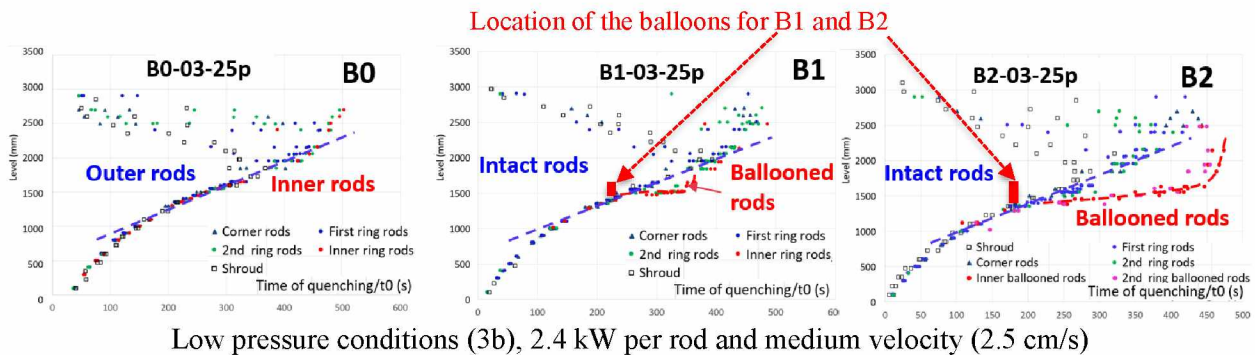


Figure 19. Example of QFP for LP test (3 bar)

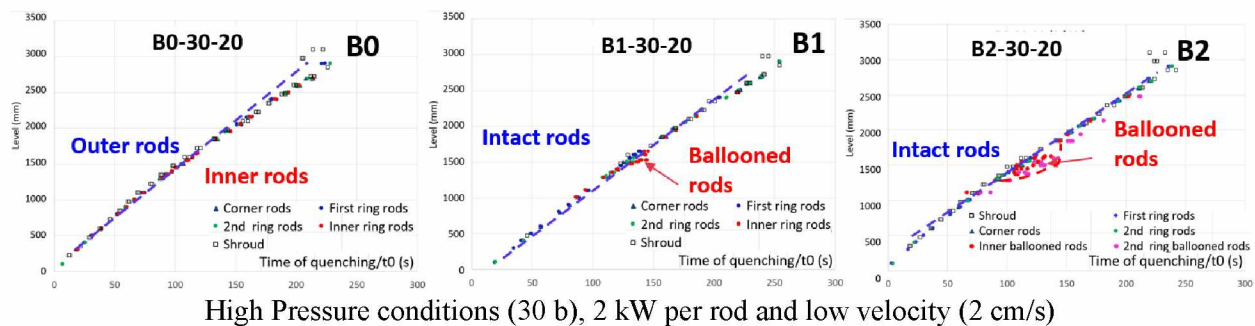


Figure 20. Example of QFP for HP test (20 bar)

The different points (given by T_c 's located on the different rings of rods) clearly indicate a rather uniform quench front propagation for the intact geometry: some early quenching of thermocouples located mainly on the shroud, only at the top of the bundle (above 2.2 m) are due to falling of water droplets, in particular for low pressure tests: it was not the case for all the high pressures tests. In any cases, the coming back droplets in the bundle appear limited and not impacting the middle plane of the bundle where partially blocked area with ballooned rods are located. This information is rather important in order to properly analyzing the effect of the flow diversion due to the balloons on the reflooding processes (main objectives of the COAL experimental campaigns). We clearly see on the graphs, that the ballooned rods impact the quench front propagation for B1 and B2 tests with an increasing delay of the quenching as the size of the balloons is increasing, in particular for low pressure tests. At high pressure (30 bar), we observed the effect of the balloons but with smaller impact, as the efficiency of the reflooding is higher according to the pressure.

4. CONCLUSIONS

This paper presents some thermal hydraulic results of the recent COAL experiments performed by IRSN. 82 experiments were performed (28 tests for B0 reference campaign in 2020, 26 tests for B1 campaign in 2021 and 28 tests for B2 campaign in 2022) to investigate the different physical main inlet parameters such as the power (1.5, 2, 2.4 and 3.3 kW per rod), the pressure (ranging from 0.2 to 3 MPa) and the water flow velocity (ranging from 15 to 80 kg/s/m²). B1 and B2 campaigns were performed with bundles including a partially blocked by ballooned rods at a blockage ratio respectively 80% and 90% (length of the maximum deformation respectively 100 mm and 300 mm), including a local power in the balloons of factor 1.5 with respect to the normal cosine profile in order to take into account the fuel relocation in the balloons, more representative to irradiated fuel rods with fragmented pellets.

The maximum temperature (1105°C) was obtained during the test performed at low pressure (0.3 MPa) with the maximum power per rod (3.3 kW) and a medium water flow rate (25 kg/m²/s) for the B1 configuration, conditions not tested in the B2 configuration due to the higher blockage area.

We succeeded to perform high pressure tests from 1 up to 3 MPa which was one of the major objectives of the COAL experiments in order to investigate the coolability for Medium Break size LOCA conditions.

These COAL experiments outlined very important results regarding the duration of the reflooding and the impact on the PCT (increase of peak cladding temperature) due to the presence of a blockage inside the fuel assembly. These experiments will 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, they may be used for safety study in real nuclear reactor conditions.

The next experimental campaign will be performed in 2023 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.

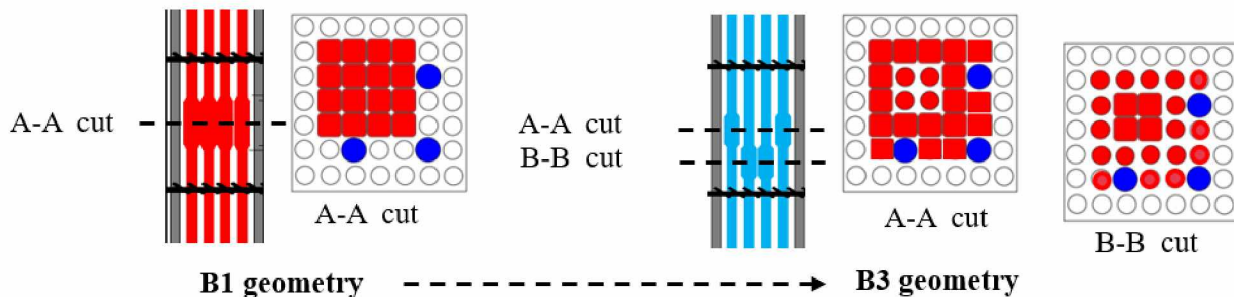


Figure 21. Geometry of the next B3 COAL campaign

Close configuration was tested in MASCARA facility [11] (within the PERFROI project) and highlighted more complex flows, in particular, at the level of the flow redistributions (several zones of less velocity) with a geometry of non-coplanar balloons. Such geometry needs to be investigated with thermal experiments for code modelling.

NOMENCLATURE

COAL: COolability of a fuel Assembly during Loca

LB, MB and SB LOCA: Large or Medium or Small Break size Loss Of Coolant Accident

LP: Low Pressure test - **HP:** High Pressure test

PCT: Peak Cladding Temperature

QFP: Quench Front Propagation

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This work is completed within the framework of Reactor Safety Nuclear Research Project from a French State aid managed by the National Agency of Research under the program of Investments for the Future carrying the reference n ANR-11-RSNR-0017. Particular acknowledgments are also given to EDF and to US-NRC for their financial supports.

REFERENCES

1. G. Repetto et. al, "Core coolability in loss of coolant accident: the PERFROI project", WRFPM conference - *Top Fuel14*, Sendai, Japan, September 14-17 (2014)
2. C. Grandjean, G. Repetto, F. Barré, "Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions, Main findings from a review of the past experimental programmes", *Proceedings of Nureth11*, Avignon France, 02-06 October (2005).
3. C. Grandjean, "Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions Main findings from a review of past experimental programs", *Nuclear Engineering and Design* 237, pp. 1872-1886, September (2007).
4. G. Repetto et. al, "The R&D PERFROI project on Thermal mechanical and thermal hydraulics behaviors of a fuel rod assembly during a Loss Of Coolant Accident", *Proceedings of Nureth16*, Chicago, USA, August 30-September 4 (2015)
5. G. Repetto, Ch. Marquié, B. Bruyère, T. Glantz, "The core coolability in a Loss Of Coolant Accident: the COAL experiments", *Proceedings of Nureth16*, Chicago, USA, August 30-September 4 (2015)
6. T. Glantz, T. Taurines, O. De Luze, S. Belon, G. Guillard, and F. Jacq. DRACCAR: A multi-physics code for computational analysis of multi-rod ballooning, coolability and fuel relocation during LOCA transients. Part one: General modeling description. *Nuclear Engineering and Design*, 339:269 – 285, (2018).
7. T. Glantz, T. Taurines, S. Belon, O. De Luze, G. Guillard, and F. Jacq. DRACCAR: A multi-physics code for computational analysis of multi-rod ballooning, coolability and fuel relocation during LOCA transients. Part Two: Overview of modeling capabilities for LOCA. *Nuclear Engineering and Design*, 339:202 – 214 (2018).
8. G. Repetto, B. Bruyère, S. Eymery, T. Glantz, "Thermal hydraulics behavior of a rod bundle with partially blocked area during the reflooding phase of the Loss Of Cooling accident", *11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety*, Gyeongju, Korea, October 9-13 (2016)
9. G. Repetto, et all "Core coolability in loss of coolant accident: the COAL experiments investigating the thermal hydraulics of a rod bundle with blocked area during the reflooding," *Proceedings of 2017 International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17)*, Xi'an, China, September 3–8 (2017).
10. G. Repetto et all, "COAL experiments investigating the reflooding of a 7 x 7 rod bundle during the a loss 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).
11. 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)