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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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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

During a loss of coolant accident (LOCA) in a pressurized water reactor, the drying of the fuel assemblies leads to an increase in the fuel temperature and deformation of the fuel rod claddings. In addition to the restriction of the flow area, the relocation of the fragmented irradiated fuel within the ballooned area leads to an increase of the local residual power. The COAL experiments (**CO**olability of a fuel **A**ssembly during **L**oca) 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 (FRENCH acronym : **PER**te de **reFROI**dissement) 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%)} were evaluated for various powers, inlet water mass flow rates and different pressures representative to Large (LBLOCA at 0.3 MPa) and Medium break size (MBLOCA from 0.5 to 3 MPa) configurations. 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). We studied the effect of the inlet water flow rate which is the consequence of the amount of water entering the reactor core after the break of the primary circuit and the effect of the pressure. The presence of the balloons increases significantly the Peak Cladding Temperature according to the flow rate, the pressure and the power. These results are used to improve and validate the heat exchange models of thermal hydraulics codes dealing with the complex reflooding processes in such a configuration.

Keywords: Coolability, blockage, LOCA, COAL, PERFROI

I. INTRODUCTION

During an accident causing a loss of coolant of the primary circuit (LOCA) in a pressurized water reactor, the drying of the fuel assemblies can lead to an increase in the fuel temperature and a

significant deformation of the fuel rod claddings. In addition to the restriction of the flow area, the relocation of fragmented irradiated fuel within the ballooned area leads to an increase of the local residual power.

The COAL experiments (**CO**olability of a fuel **A**ssembly during **L**oca) are part of the PERFROI project project (FRENCH acronym : **PER**te de **reFROI**dissement – Loss of cooling) (Ref. 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.

The competing influence of two phenomena, because of the blockage [Figure 1(a)], **(1)** increase in velocity in the region of deformed fuel rods and **(2)** bypass of blockage (reduction of mass flow in constricted subchannels), is evaluated through integral experiments. The effect of the flow blockage (intact geometry up to long ballooning with different blockage ratios from 80 to 90%) are evaluated for various flow rates and different pressures representative to Large Break (LB LOCA) and Medium Break (MB LOCA) LOCA size configurations.

Numerous reflooding (mainly “out of-pile”) experiments were already performed in the past, mainly in the 80’s, with different bundle geometries:

- Some on a reduced scale of a fuel assembly using square geometries: 5 x 5 PHEBUS in pile-experiments in France (Ref. 2) [Figure 1(a)], 7 x 7 RBHT in USA and THETIS in Great Britain, 4 x 4 ROSCO in France, 5 x 5 FEBA and SEFLEX in Germany [Figure 1(b)];
- Some on a reduced scale of a fuel assembly using cylindrical geometries: 44 rods (CEGB) and 69 rods (ACHILLES) in Great Britain;
- Some at the Fuel Assembly scale: PERICLES in France and FLECHT-SEASET in USA.

Reference of these experimental programs are provided in (Ref. 3), (Ref. 4). Nevertheless, IRSN considered that the configuration of the simulating rods, used in out of pile experiments, were not representative enough (Ref. 3) because they did not take into account the fuel fragments relocation and the right thermal inertia of the deformed fuel rods (bad contact between the heated materials and the cladding). Past experiments were performed with rods for which the balloon was represented by ballooned cladding (SEFLEX) far from the heat source (heater) or by metallic sleeves FEBA (Figure 1).

Several programs were done more recently on reflooding but concern only intact rods geometries and also low pressure tests. The specifications of the COAL experiments are the geometry with bundle including partially blockage with ballooned rods with local power increase and the level of pressure up to 30 bar.

One of the challenges of the COAL program was to carried out tests with electrical rods [Figure 1(b)] simulating a correct inertia of the deformed rods, representative enough as compared to real deformed nuclear fuel rods [Figure 1(c)]. The global thermal inertia of a COAL rod (C22 Cladding + boron nitride 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 – later Figure 8). The rods were designed for a maximum power of 3.5 kW but used materials may allow power up to 5 kW.

II. THE COAL EXPERIMENTS

Within the PERFROI Project (Ref. 5), the objective of the COAL experiments (Ref. 6), is to improve the knowledge and modeling of the reflooding process of a fuel rod assembly with a large partially blocked area accounting for relocated fuel fragments in the balloons and simulated by a local increase in power. The results of these “reflooding” experiments will be used to improve and to validate the thermal hydraulic models of the DRACCAR code developed by IRSN (Ref. 7). Numerous pre-calculations were carried out with this code (Ref. 8), (Ref. 9) in order to prepare these COAL experiments.

The specific objectives of the COAL experiments are twofold:

- Study of reflooding at rather low flow rates (**Obj 1**): it has already been demonstrated that for high water velocities, the core coolability cannot be impaired under Large Break LOCA conditions (2 to 3 bar);
- Study of coolability for Medium Break LOCA conditions for pressures from 5 to 30 bar (**Obj 2**). Several experimental campaigns are foreseen with different bundle geometries. 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 study the effect of the presence of ballooned rods in the inner part of the bundle for the geometries described in the following section section II.A. This paper concerns the results of the preliminary synthesis of these campaigns performed successively in 2020 for B0, 2021 for B1 and 2022 for B2.

II.A. The test section design and the bundle geometry

The COAL bundle consists of 46 rods (electrically heated) some with a pre-deformed zone [Figure 2(a)] with local overheating representing the relocation of fuel fragments. The bundle will be made of 49 rods (7 x 7), including in the center for B1 and B2, 16 deformed rods, 30 non-deformed (intact) rods and 3 guide tubes [Figure 2(b)]. B1 and B2 bundles (Table I) include an area partially blocked by ballooned rods with a blockage ratio of 80% and 90% respectively (the maximum deformation length is 100 mm and 300 mm respectively).

The presence of the 3 guide tubes (external diameter: 12.4 mm) in the scaled 7 x 7 bundle increases the representativeness of the thermal hydraulics behavior for the reactor case (Figure 3 of Ref. 6) as a part of the FRENCH PWR 17x17 fuel assembly (scale 1/4).

The test section will also include 6 spacer grids (4 mixing vane 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 diameter: 9.5 mm for the intact zone) of the electrical rods used is Hastelloy Haynes C22 material to prevent cladding oxidation. The zircaloy cladding (exothermic reaction) occurring during LOCA transient which is of course not considered in the COAL experiments using Hastalloy cladding. To avoid any chemical interaction, the grids are made of Inconel 718 alloy and include mixing vane that have an effect on the thermal hydraulic behavior.

The presence of guide tubes (GT) was also necessary for instrumentation (see section II.C) and for mechanical reasons. The heated zone is about 3 m high (close to scale 1 referring to the real FRENCH 900 MWe PWR geometry: 3.7 m up to \approx 5 m for 1300/1450 MWe PWR).

The bundle is inserted into an electrically heated 94 mm square shroud [Figure 2(c)] 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 [\approx 5 m high, 220 mm diameter – Figure 2(d)] with two lower and upper plenums for the electrical and instrumentation connections, the fluid supply and the outlet.

II.B. 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 to perform reflooding tests.

The loop (Figure 3) is composed of different components to perform the COAL experiments:

- A water tank with heaters to pre-set the water temperature;
- A pump for water injection at different flow rates (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 the depressurization phase of a LOCA scenario (see section II.D);
- A 70 kW super heater in order to provide high temperature steam at 300°C as required by the test protocol, to provide the initial LOCA conditions of the cladding;
- The COAL test section which includes the rod bundle (described in the section II.A);
- A bypass line provides steam in the test section for the initial conditions: during the reflooding, the steam is injected in the bypass line and joins the outlet line to maintain the pressure constant;
- A water/steam separator to obtain information on the outlet water flow rate;
- A steam condenser (to collect) and a pressurizer system including a storage tank used also for pressure regulation.

II.C. The instrumentation of the test device

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 studied separately in small scale MASCARA experiments (Ref. 10) within the PERFROI project);
- Temperature of the fluid at different points (type K thermocouples with uncertainty of : ± 2.2 °C);
- Temperature inside the fuel rods (thermocouples at different elevations and different radial positions in the bundle with uncertainty of : ± 2.2 °C) in an adequate distribution (see below);
- Temperature of the shroud, grids and guide tubes (with uncertainty of : ± 2.2 °C);
- Total pressure (with uncertainty of : $\pm 0.5\%$ of the reading) and pressure drop sensors at the periphery of the rod bundle;
- Bundle power .

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

- Numerous thermocouples in the electrical rods (6 Tc's per intact rod and 4 Tc's per ballooned rod) positioned every 10 cm (for different types of rods - Figure 4) to obtain a complete (x, y, z) temperature profile and to follow the quench front propagation (QFP);
- 63 thermocouples in the guides tubes (21 Tc's per GT) in order to have measurements on the guide tube surface (18 Tc's) and the fluid sub-channels;
- Thermocouples (Tc) on the outer surface of the shroud (54 Tc's); the shroud is also equipped with thermocouples on each internal face in order to accurately set the boundary thermal conditions during the reflooding process.

Each type of rods has a similar instrumentation.

So, we have 276 thermocouples in the B0 bundle and 244 thermocouples in the B1 and B2 bundles to get a well distributed x, y and z rods temperature.

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 (Figure 5).

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 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).

The outlet steam flow rate from the bundle is evaluated using the difference between "FLCV" and "FLSV" venturi measurements (Figure 6).

II.D. The test scenario and the thermal hydraulics parameters

The scenario is divided in 2 phases as for "Reflooding tests" carried out in the 80's (Ref. 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).

The so-called test protocol (Figure 7) contains several steps as below:

- Step 1: the bundle is preheated up to 300°C by hot steam injection in order to provide the initial conditions after the depressurization phase of a LOCA;
- Step 2: the shroud is heated by mean of heaters (20 kW: 5 kW each face) up to 500°C;

- Step 3: when the shroud temperature reaches the “500°C” threshold, rod power starts at the level needed for the test. The duration of the rod heat-up lasts about 1 mn;
- Step 4: the rods are heated up to 520-550°C before the water injection phase (“reflooding” period); the maximum water flow (80 kg/s/m²) is injected at the beginning in order to fill as fast as possible the lower plenum then set at the level needed for the test;
- Step 5: power and water flow are 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, 2.4, 2 or 1.5 kW for Large Break size LOCA (low pressure - LP) and 2 kW for Medium Break size LOCA 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 of the water temperature: -60°C (for LP tests) and -20°C (for HP tests) referring to saturation conditions.

The axial power profile is recalled by the figure 8. A local power increase in the balloons (factor ≈1.5) is provided to simulate the relocation of fragmented irradiated fuel in the balloons [Figure 1(c)]. Specific power is reduced above the balloons in order to take into account the fuel relocation. The axial power distributions were defined using DRACCAR calculations which can simulate with some parameters the fuel relocation in the balloon (filling ratio in the balloon according to the cladding deformation). The density of the relocated pellets may range between 60 and 70 % (results from tests with irradiated fuel recalled in the left part of the figure 8). To limit, the temperature on the electrical rods, we have chosen the lowest value. Density of 70 % would increase the local power up to 30 W/cm (+25%) and lead to excessive temperatures (Ref. 9).

II.E. The COAL test matrix

The general COAL test matrix referring to (Q, P) diagram where Q is the inlet water flow in kg/s/m² and P, the system pressure in bar, is given in Figure 9 below. The pressure conditions come from NPP CATHARE calculations (Table 1 of Ref. 6) with different break sizes (4 to 40 inches).

Roughly 25/30 experiments were enough to study the different physical main parameters (power, pressure, water flow velocity and water sub cooling). 2 or 3 tests were repeated to study 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 study the impact of the different physical main parameters.

Note: Each test is reported in the paper with 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 20 bar and 20 kg/s/m^2 .

III. THE MAIN THERMAL RESULTS

This section gives the main results of some typical experiments to study 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).

III.A. The thermal results

Table II provides a summary of the main results of some typical experiments (for the intact geometry from Ref. 11) in order to study both the effect of the inlet flow rate (at 3.3 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), as well as the impact of the rod power (3.3, 2.4 and 2 kW).

More details are provided in the following section with the analysis of the inlet water flow rate and the pressure effect.

III.A.1. Effect of the inlet water flow velocity (flow rate)

Four (4) tests were carried out at a rather high power generated in each rod (3.3 kW), i.e. for a total bundle power of 152 kW and a similar pressure for the system (3 bar). For these tests, we varied the inlet water flow rate (from 25 to 80 $\text{kg/m}^2/\text{s}$).

Figure 10(a) provides the main results of the B0-03-50 for these conditions: 3 bar and inlet water flow velocity of 50 $\text{kg/m}^2/\text{s}$ (i.e 270 g/s).

For this test, the maximum temperatures were recorded around 810°C on the inner rod at level 1650 mm, just above the middle plane, with a rather satisfactory quench front propagation (see section III.C) in agreement with our physical understanding and a quite well controlled pressure. Figure 10(b) illustrates the evolutions of the maximum rod temperatures and the reflooding duration as a function of the inlet water flow rate. The maximum temperatures range from 710 to 925°C.

After running the first 3 tests, the maximum temperature estimated for B0-03-25 was roughly 1000°C, close to the electrical rods design limit of approximately 1050°C. So, this test was postponed to the end of the campaign with a lower initial temperature ($\approx 500^\circ\text{C}$) when water is injected. So, the maximum temperature was around 925°C, with sufficient margin from the design and for running further tests with the balloons for the next B1 campaign, as higher temperatures can be expected for the same T/H conditions.

Analysis of the results for intact geometry [Figure 10(b)] shows that results of maximum cladding temperatures are far below the Peak Cladding Temperature LOCA criteria (1204°C): in that case, “ductile coolability” is ensured, even for very low inlet water flow rate such as 10 to 15 kg/s/m². The margin is expected to be reduced by taking into account the partially blocked area and the fuel relocation in the balloons. The margin will be also surely reduced by taking into account the additional increase of rods power because of the oxidation process on the zircaloy cladding (exothermic reaction) occurring during LOCA transient which is of course not considered in the COAL experiments using Hastalloy cladding.

Figure 11(a) provides, as an example, the main results of the B1-03-25 test carried out at 3 bar and with an inlet water flow velocity of 25 kg/m²/s (i.e. 132 g/s).

During this test with the B1 configuration (Ref. 12), the maximum temperatures were recorded around 1105°C on the inner rods: these conditions were not tested in the B2 configuration because of the higher blockage area, and the risk that the maximum rods temperature would overpass the design 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 inlet water flow velocity (20 kg/m²/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 II.A. We succeeded 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.

Figure 11(b) illustrates the evolutions of the maximum rod temperatures and the duration of the reflooding as a function of the inlet water flow rate. The maximum temperatures range from 700 to 1105°C (roughly at the design limit of the electrical rods).

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.

Analysis of the results for B1 [Figure 11(b)] allows the estimation of the limit of the flow rate by extrapolation (below 25 kg/s/m²) in the order of ≈ 20 kg/s/m² for which the coolability may be impaired at the maximum rod power: 3.3 kW. This power level is the decay heat 1mn after the scram in the LOCA scenario when the reflooding started: one can note that this limit would be below that estimated for an intact geometry [about ≈ 10 kg/s/m² – Figure 10(b)], of course without taking into account the additional power of the exothermic zircalloy – steam reaction.

The effect of the inlet water flow rate is illustrated by the Figure 12 for the B1 bundle.

These conditions were also tested in the B2 configuration but at lower power (2.4 kW) because of the higher blockage area, and the risk that the maximum rod temperatures would overpass the design temperature of the electrical rods. In that cases (Figure 13), maximum rod temperatures range between 725°C to 1000°C without taking into account the zircalloy/steam reaction as we have used Hastalloy claddings.

As the first objective of the COAL experiments (see section II) 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 test matrix - Figure 9). Figure 14 gives the evolution the thermal results of the Bx-03-17 series of tests , in such a situation, but at a lower power 2 kW. As the partially blocked area is increasing by ballooned rods, we clearly see the increasing effect of the ballooned area, mainly because of the flow diversion from the inner ring to the peripheral ring of rods.

As the second objective of the COAL experiments (see section II) 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 (section II.A.2).

III.A.2. Effect of the system pressure

Seven (7) tests were performed at different pressures 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, i.e. a total power of 92 kW), in the intact geometry. Figure 15(a) provides the main results of the B0-20-20, the reference

HP test for these conditions: 20 bar and inlet water flow velocity of 20 kg/m²/s. Maximum temperatures were recorded around 745°C on the inner rod at level 1650 mm just above the middle plane.

Figure 15(b) 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 830 °C with the decrease of the pressure. Above 15 bar and up to 30 bar, we do not observe any variation of the duration of the reflooding, whereas the reduction of the pressure below 15 bar leads to a strong increase in duration with lower efficiency of the reflooding process, in particularly below 5 bar.

Figure 16 provides the main results of the Bx-20-20 series, the reference HP test for these conditions: 20 bar and 20 kg/m²/s for the 3 geometries. Maximum temperatures were recorded around 745°C up to 780°C on the inner rod.

Figure 17(a) 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 rod temperatures increase from 760 to 1050°C with the decrease of the pressure.

The difference between ballooned and intact rods is increasing as the pressure is decreasing much more with the B2 geometry than that observed with the B0 intact geometry [Figure 15(a)].

As observed for the intact geometry [Figure 15(b)], above 10 bar up to 30 bar, we do not observe any variation of the duration of the reflooding, with a bundle including blockage area (long balloon - 300 mm and blockage ratio – 90%), whereas the reduction of the pressure below 10 bar leads to a strong increase in the duration with lower efficiency of the reflooding process, particularly below 5 bar.

We clearly see the evolution of the efficiency of the reflooding process as the pressure is increasing on the duration of the complete quenching of the rods. The presence of the balloons does not change the previous conclusion with the intact geometry [Figure 15(b)], with a strong variation between 2 and 3 bar for both the B0 and the B2 geometry.

Figure 17(b) gives the evolution of the maximum rod temperatures and the duration of the reflooding according to the inlet water flow rate. The rod temperatures increase from 730 to 850°C with the decrease of the flow velocity. 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 Ref. 8) above 10/15 bar, nevertheless with some

underestimation of the duration of the reflooding, increasing with the decrease of the pressure below 5 bar. Improvement of the models are in progress.

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

III.B. The hydraulic results

This section concerns the water balance with 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, as an example, these results (Figure 18 – left graph) 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 section II.C) foreseen in the tests matrix (B0-03-80).

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, section II.C) 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 (Figure 19 – right graph). Analysis 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) outlines rather fairly 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. The remaining water in the test section in double phase mixture (13 kg after the quenching) is in agreement with the free volume of the rod bundle (15.7 dm^3) taking into account that the power is maintained during a saturation plateau.

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

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 for a complete refreezing of the bundle. This trend confirms the physical consistency of these hydraulic results and the confidence in the use of these data for code validation.

We provide also these results (Figure 19) for test performed in the B2 campaign (including ballooned rods). This experiment (B2-02-25p) corresponds to the test carried out with the lowest pressure (2 bar – cf Figure 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 – Figure 19 – left graph) are in agreement with the free volume of the rod bundle (15.7 dm^3). After the quench, the power is maintained in the bundle; so, the two-phase (water/steam) is present in the bundle which explains this difference, already observed for the previous case. Of course, the quality of the mixture after the quenching may depend on the bundle power, the pressure and the water mass flow rate.

These informations provide rather high confidence for all the hydraulic flow measurements obtained during these COAL experiments.

Table IV gives the steam production versus flow rate and pressure for some typical tests 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 large amount of vaporization of the injected water (if we take into account the water stored in the bundle) for all the bundle geometry: less amount of water is needed to a complete refreezing of the rods.

This trend confirms the physical consistency of these hydraulic results even for bundle with partially blocked area and the confidence for using these data for code validation, not only for the thermal information but also for the water balance.

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 increase in ballon size (length $100 \rightarrow 300 \text{ mm}$ and blockage ratio $80 \rightarrow 90\%$). These observations may be because of the 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 these kind of measurements.

To conclude this section regarding the hydraulic results, Figure 20 below shows the conversion factor (water to steam) and the ratio outlet water to inlet water according to the pressure (left graph) and to the inlet water flow rate (right graph) for the B2 campaign. Here also, the tendencies seem

rather good, which illustrates the quality of the thermal hydraulic results of these COAL semi large scale experiments (small assembly scale 7 x 7, at 3 meters height rods).

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 because of the higher efficiency of the reflooding process at high pressure [Figure 21(a)]. 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%, outlined in the Figure 20(b).

III.C. The quench front propagation

Figure 21 gives examples of the quench front propagation from the bottom to the top (time for quenching versus elevation) for two tests representatives of LB LOCA (B0-03-50) at 3 bar and MB LOCA (B0-30-20) carried out at 30 bar (the highest pressure considered in the COAL program).

The different points (given by Tc's located on the different rings of rods) clearly indicate a uniform quench front propagation. Some early quenching of thermocouples (Tc) located on the shroud, only at the top of the bundle (above 2.2 m) are because of the fallout of water droplets, mainly for low pressure tests; it was not the case for all the high-pressure tests [Figure 21(b)]. In any case, the droplet fallout in the bundle appears 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 analyze the effect of the flow diversion because of balloons on the reflooding processes (one of the objectives of the COAL B1 and B2 experimental campaigns).

Figure 22 and Figure 23 give two examples of the measured quench front propagation from the bottom to the top (time for quenching versus elevation) for three tests representatives of LB LOCA (BX-03-25p) series at 3 bar and MB LOCA (BX-30-20) series at 30 bar (the highest pressure proposed in the COAL experiments) according to the bundle geometry.

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 observe the effect of balloons but with less impact, as the efficiency of the reflooding is higher.

IV. CONCLUSIONS

This paper presents 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 study 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) according to the bundle geometry.

For the intact geometry, the maximum temperature (925°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). We succeeded to perform high pressure experiments from 1 up to 3 MPa (30 bar) which was one of the major objectives of the COAL experiments in order to study the coolability for Medium Break LOCA conditions.

B1 and B2 campaigns were performed with bundles including a zone partially blocked by ballooned rods with a blockage ratio of 80% and 90% respectively (length of the maximum deformation 100 mm and 300 mm respectively). They include a local power in the balloons by a factor of 1.5 compared 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 that may move during the burst of the rod cladding (observed during experiments with real fuel - Figure 1.c).

The maximum rod temperature (1105°C) was obtained during the test carried out 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 because of the higher blockage area: these conditions would lead to exceeding 1200°C, well above the design temperature of electrical rods.

Running tests at high temperatures and high pressure was one of the challenges of the COAL experiments. For that, a specific design of rods by the FRENCH THERMOCOAX company according to the IRSN specifications was proposed for this project with original deformed rods described in section section II.A.

We achieved this objective with 8 experiments (*among the 82 carried out up to now*) above 1000°C without any damage on the rods and little loss of thermocouples (less than 5%), which is a fairly good performance to underline.

These COAL experiments outlined very important results regarding the duration of the reflooding and the impact on the PCT (increase of peak cladding temperature) because of the presence of a blockage inside the fuel assembly. These experiments provide thermal hydraulic information needed to improve the codes modelling during LOCA transient reflooding, with the thermal behavior of the rods under well-defined boundary conditions (heated shroud at 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 simulation tools, such as DRACCAR developed by IRSN, have been validated in such a complex configuration, they can be used for safety studies in real nuclear reactor conditions, particularly for coolability aspect.

The next experimental campaign will be performed in 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 (Figure 24).

Close configuration was tested in MASCARA facility (Ref. 10) 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 a geometry needs to be studied with thermal experiments for code modelling.

NOMENCLATURE

COAL: COolability of a fuel Assembly during Loca

HP: High Pressure test

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

LP: Low Pressure test

NPP: Nuclear Power Plant

PCT: Peak Cladding Temperature

PERFROI (FRENCH acronym : **PER**te de **reFROI**dissement – Loss of coolant)

PWR: Pressurized Water Reactor

QFP: Quench Front Propagation

ACKNOWLEDGMENTS

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Table I. Geometry and parameters of the partially blocked area compared to intact geometry

| | B0 | B1 | B2 |
|--|---|--|--|
| Blockage ratio and shape of the rods * | 0 %  | 81 %  | 90 %  |
| Corresponding cladding deformation | 0 % | 41 % | 50 % |
| Total height of the ballooning area | Intact geometry | 170 mm | 370 mm |
| Height of the maximal deformation | - | 100 mm | 300 mm |
| Maximum axial linear power (w/cm) | 16 (ref. cosine) | 22.6 (x 1.4) | 24.2 (x 1.5) |
| Singular pressure drops coefficient of the ballooned zone (arbitrary unit) | 0 | 11,58 | 47,24 |

* These shapes were already observed in the in-pile Phebus experiments [Figure 1(a) - Ref. 2]

Table II. Summary of the main thermal results for the intact bundle geometry

| Test | Power | Pressure | Flowrate | Max temperature | Duration of reflooding | Injected water Steam release |
|------------------|--------|----------|------------|-----------------|------------------------|------------------------------|
| B0-03-80 | 3.3 kW | 2.8 bar | 0.429 kg/s | 712°C | 275 s | 124.7/26.8 kg |
| B0-03-50 | 3.3 kW | 2.8 bar | 0.270 kg/s | 812°C | 449 s | 126.9/42.9 kg |
| B0-03-36 | 3.3 kW | 2.9 bar | 0.189 kg/s | 907°C | 637 s | 124.9/58.3 kg |
| B0-03-25 | 3.3 kW | 3.0 bar | 0.132 kg/s | 927°C | 619 s | 86.1/42.7 kg |
| B0-03-25p | 2.4 kW | 3.0 bar | 0.132 kg/s | 800 (850°C) | 480 (510 s) | 68.1/31.2 kg |
| B0-02-20 | 2.0 kW | 1.9 bar | 0.105 kg/s | 829°C | 1082 s | 118.7/72.6 kg |
| B0-05-20 | 2.0 kW | 5.3 bar | 0.105 kg/s | 759 (780°C) | 460 (530 s) | 52.9/26.4 kg |
| B0-10-20 | 2.0 kW | 10.2 bar | 0.105 kg/s | 750°C | 312 s | 37.3/19.9 kg |
| B0-15-20 | 2.0 kW | 15.0 bar | 0.105 kg/s | 740°C | 249 s | 30.7/16.8 kg |
| B0-20-20 | 2.0 kW | 21.3 bar | 0.105 kg/s | 744°C | 237 s | 29.3/15.6 kg |
| B0-30-20 | 2.0 kW | 29.8 bar | 0.105 kg/s | 732 °C | 223 s | 27.3/15.9 kg |

Table III. Steam production according to the water flow rate and pressure (B0 bundle geometry)

| Test | B0-03-80 | B0-03-50 | B0-03-36 | B0-03-25 | B0-05-20 | B0-10-20 | B0-20-20 | B0-30-20 |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Pressure | 3 bar | | | | 5 bar | 10 bar | 20 bar | 30 bar |
| Velocity | 5 cm/s | 3.6 cm/s | 2.5 cm/s | 5 cm/s | 2 cm/s | | | |
| % of SP * | 22% | 35% | 48% | 53% | 55% | 62% | 64% | 71% |

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

Table IV. Steam production according to the water flow rate and pressure (B0/B1/B2 geometry)

| 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 a function of the injected water flow rate

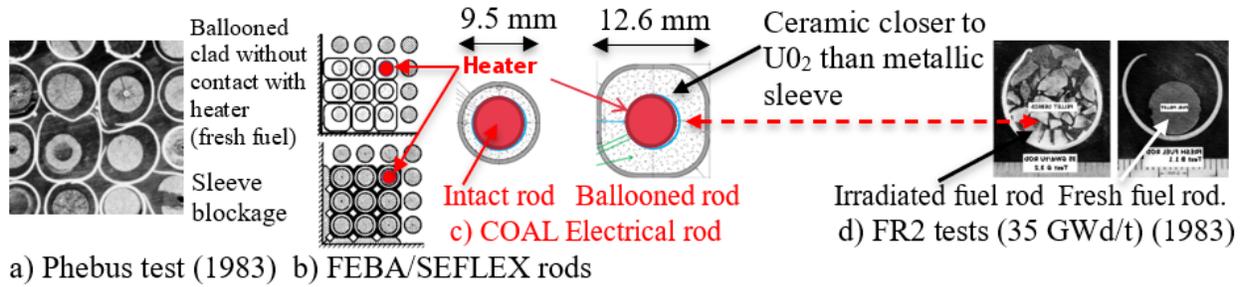


Figure 1. Deformed rods with balloon for fresh and irradiated fuel rods

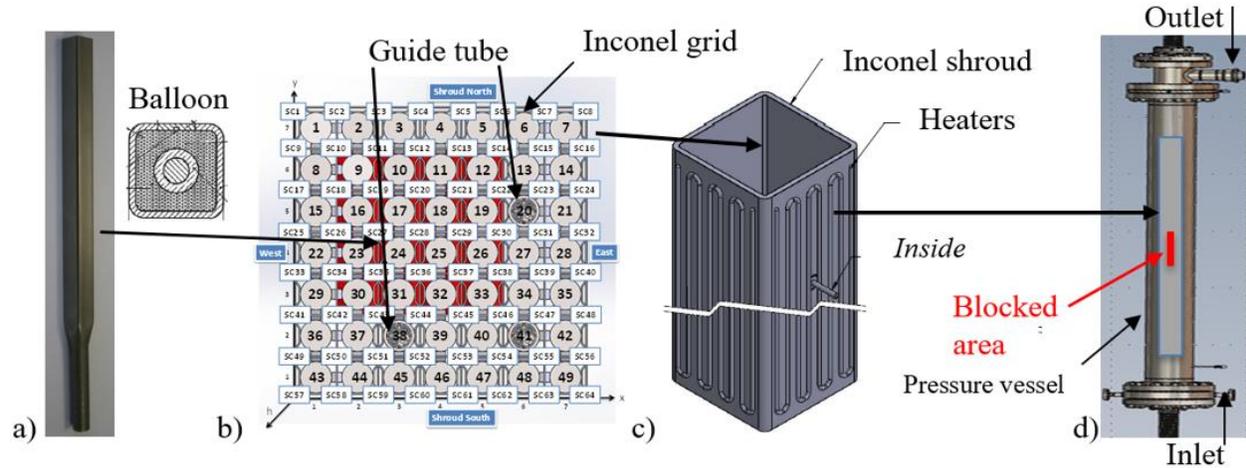


Figure 2. Experimental device (deformed rod, bundle, shroud, test section)

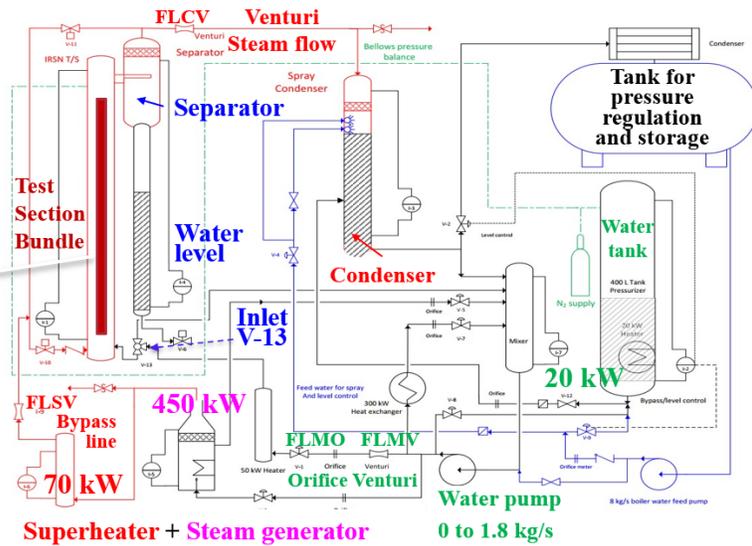


Figure 3. The STERN Laboratory test facility in Hamilton (Canada)

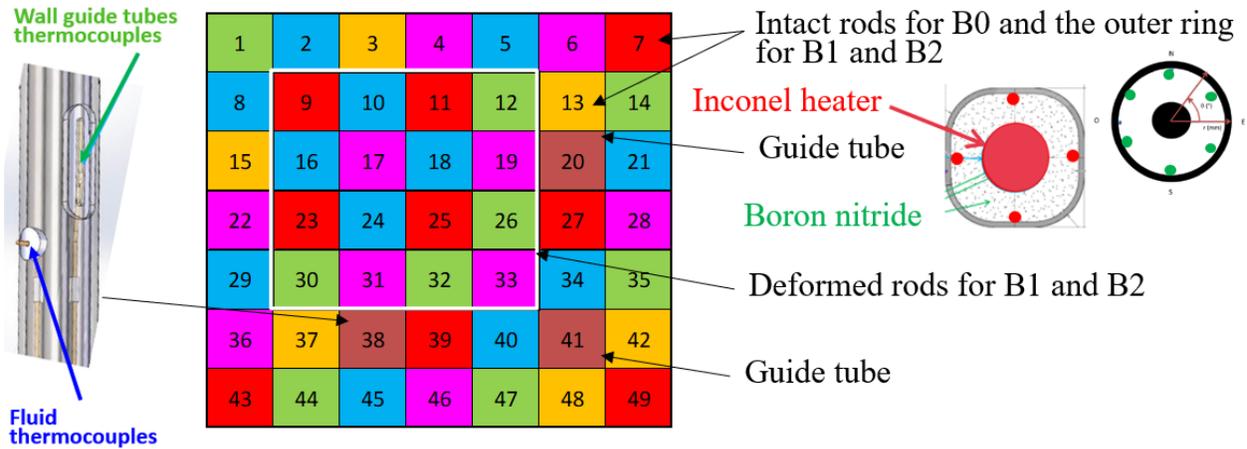


Figure 4. Types of rods with various thermocouples positions

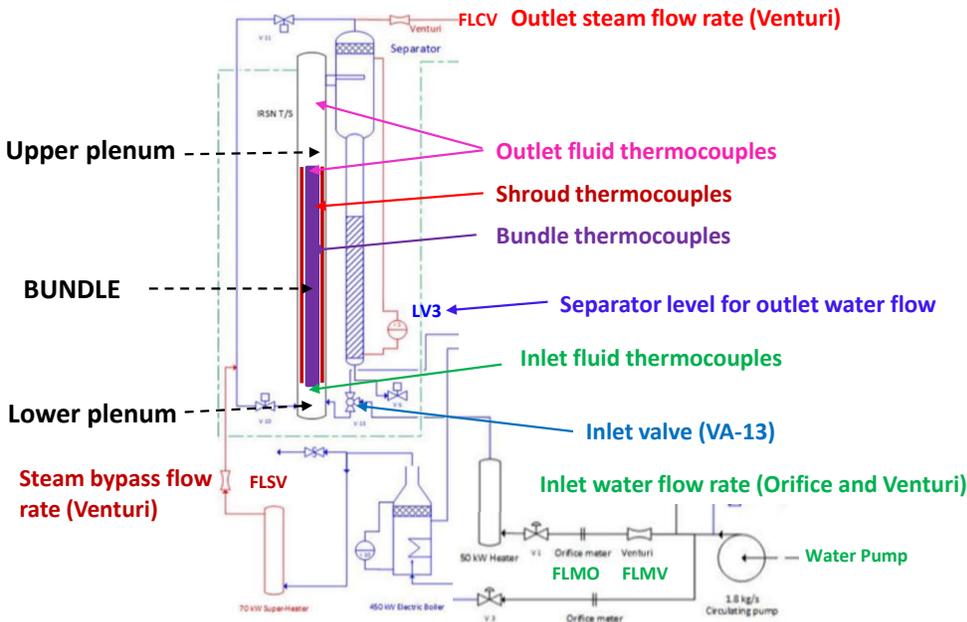


Figure 5. The thermal hydraulics measurement for the COAL experiments

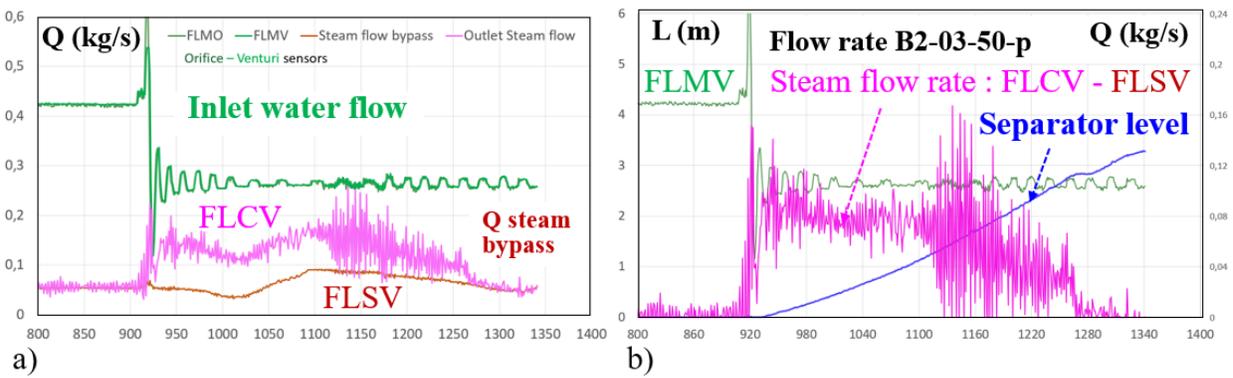


Figure 6. Example of the thermal hydraulics results

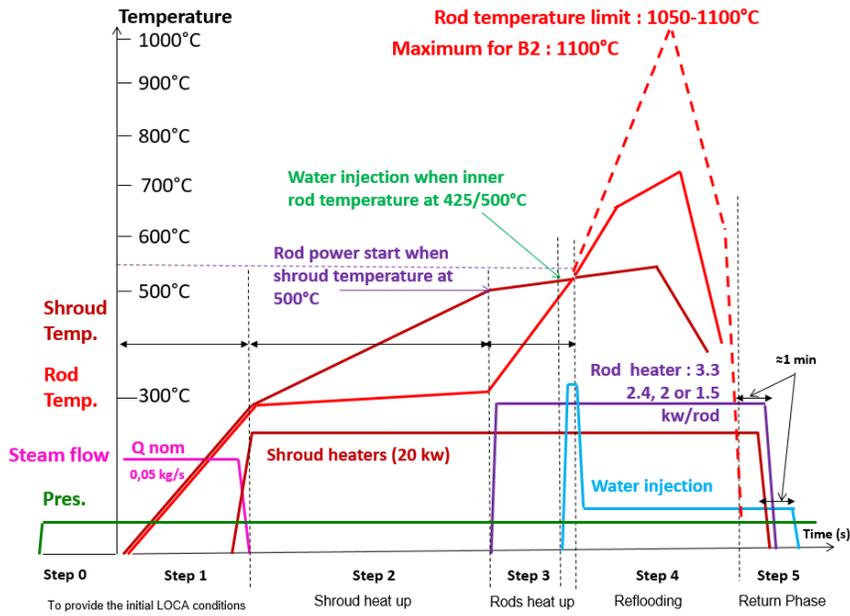


Figure 7. Test protocol followed for conducting the COAL “Reflooding” experiments

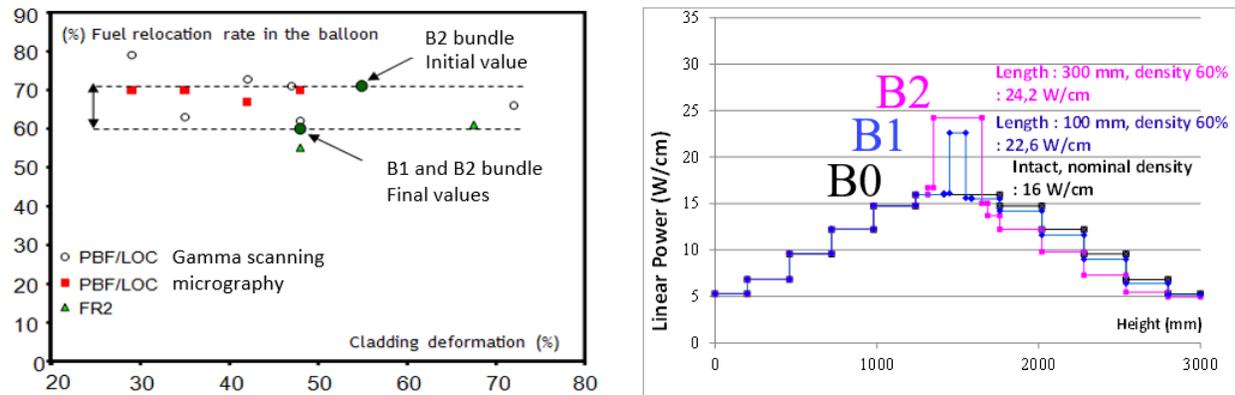


Figure 8. The fuel relocation rate and the axial power profile of the rods

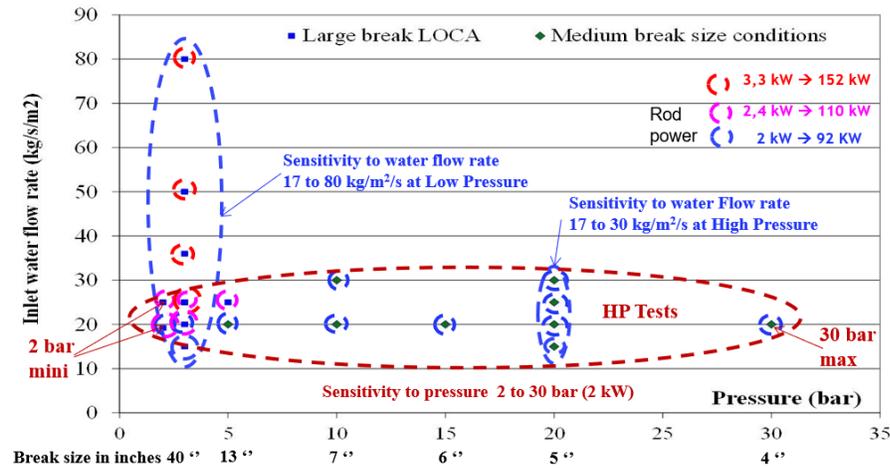
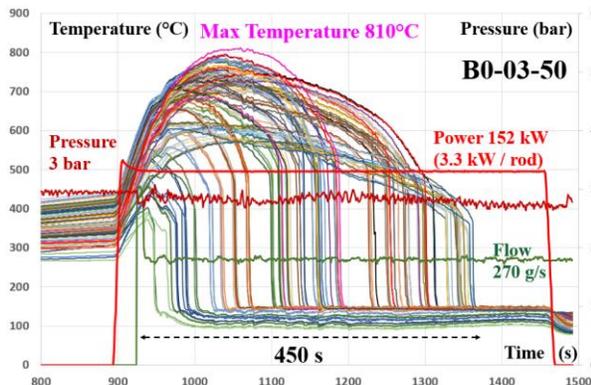
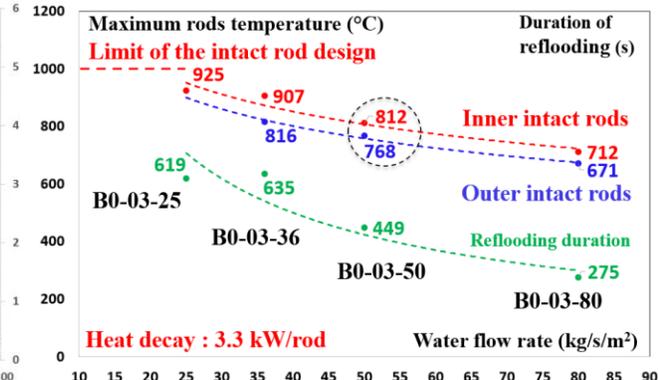


Figure 9. COAL test matrix in a (Q, P) diagram

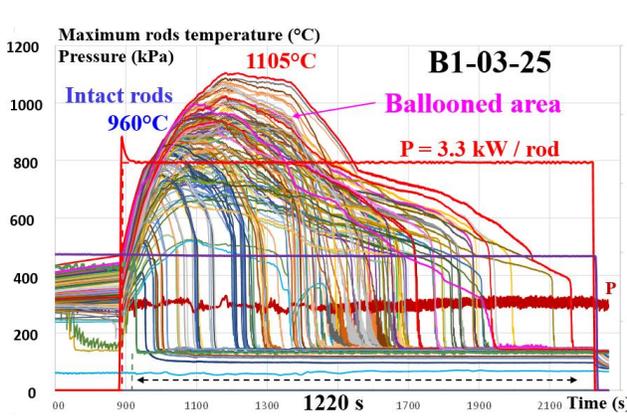


a) Typical COAL LP (3 bar) test results

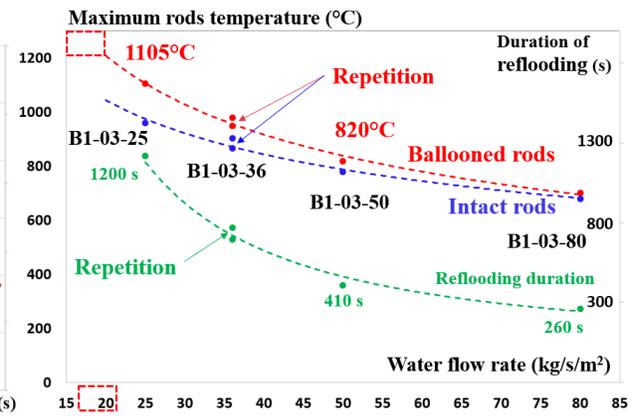


b) Maximum temperature and refueling duration versus water flow rate

Figure 10. Results of tests for B0 (intact bundle) at low pressure

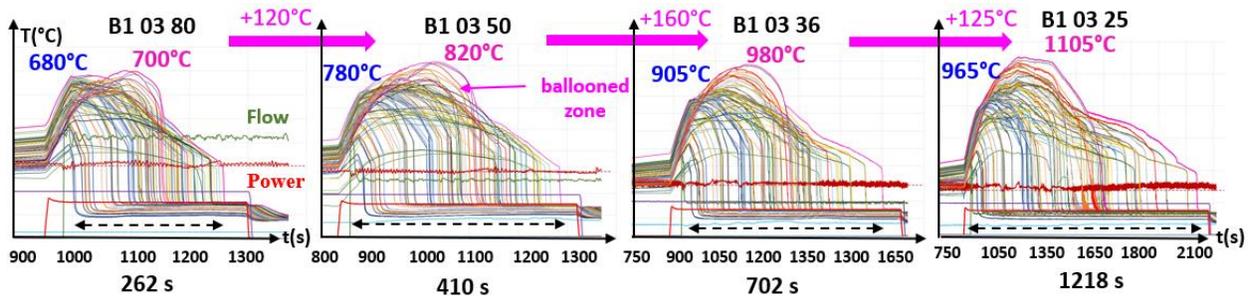


a) Typical COAL LP (3 bar) test results



b) Maximum temperature and refueling duration versus water flow rate at 3 kW/rod

Figure 11. Results of tests for B1 (bundle including moderate partially blockage) at low pressure



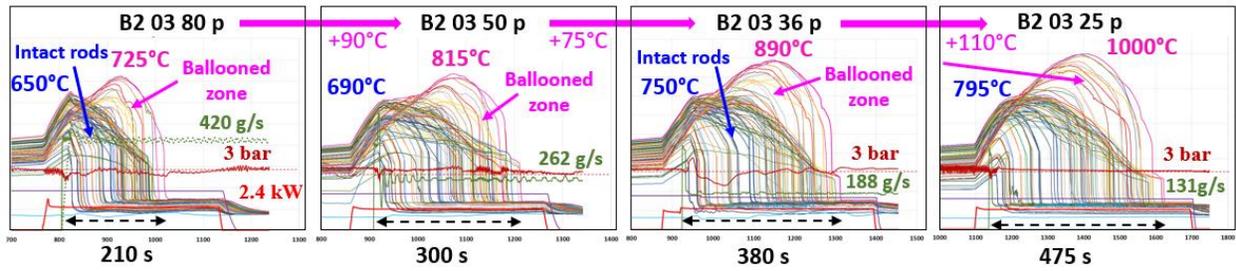
a) Flow velocity: 8 cm/s

b) Flow velocity: 5 cm/s

c) Flow velocity: 3.6 cm/s

d) Flow velocity: 2.5 cm/s

Figure 12. Temperatures for various flow velocities at 3 bar 3.3 kW/rod (for B1 geometry)



a) Flow velocity: 8 cm/s b) Flow velocity: 5 cm/s c) Flow velocity: 3.6 cm/s d) Flow velocity: 2.5 cm/s

Figure 13. Temperatures for various flow velocities at 2.4 kW/rod and 3 bar (for B2 geometry)

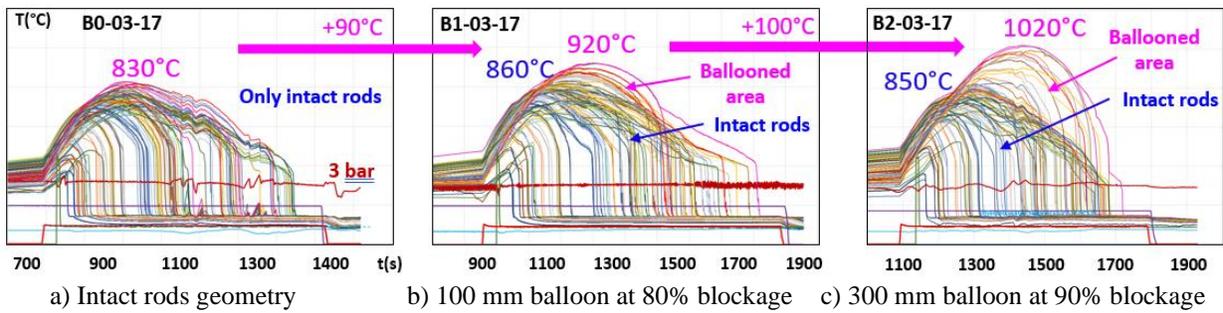


Figure 14. Temperatures for LP tests (3 bar) at low flow rate (17 kg/s/m^2) at 3 bar and 2 kW/rod

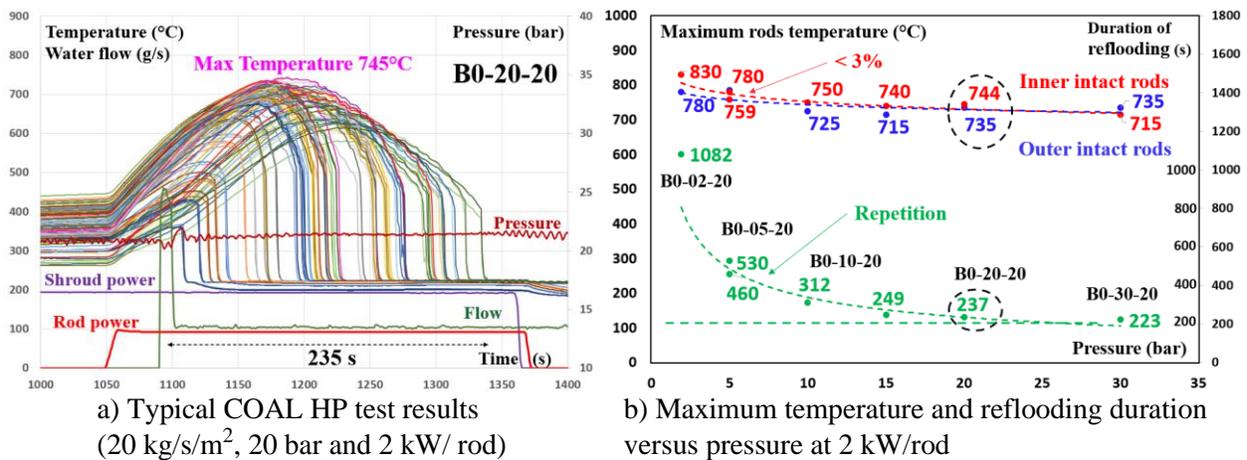


Figure 15. Results of tests for B0 intact bundle at High Pressure (2 → 30 bar)

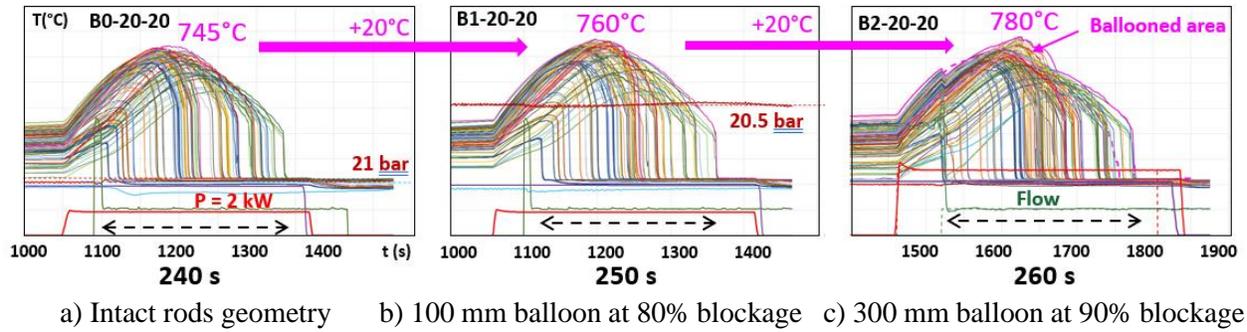


Figure 16. Temperatures for HP tests (20 bar) for various bundle geometry

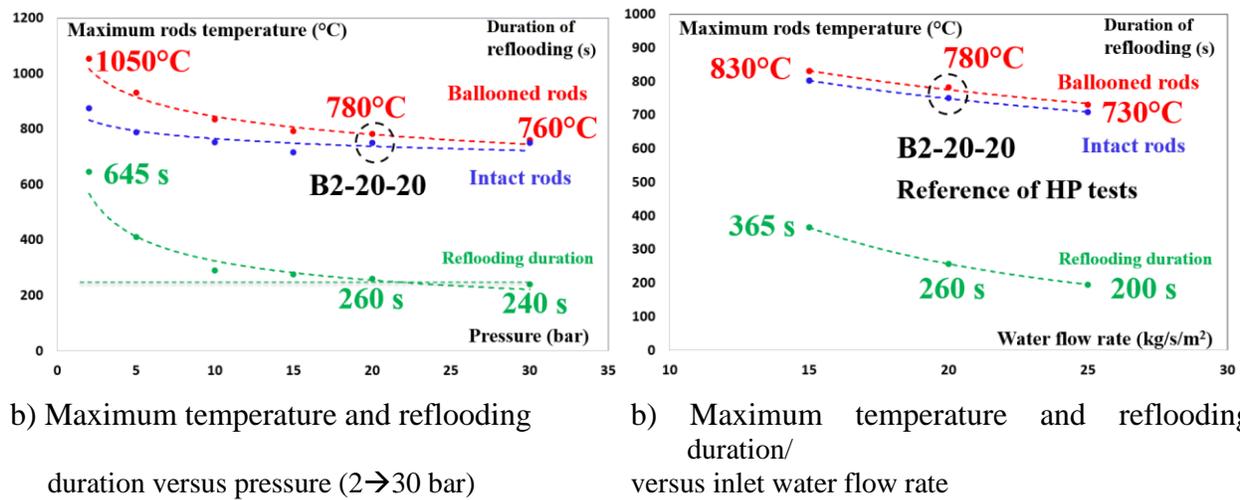


Figure 17. Temperatures and reflooding duration versus pressure and flow rate with B2 geometry

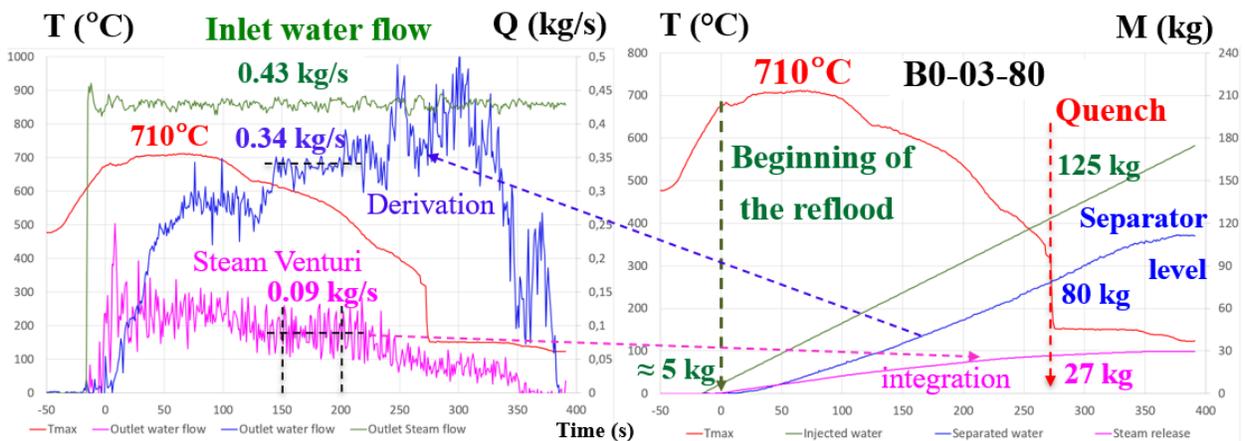


Figure 18. Water/steam flow rate for B0 LP test – maximum temperature and water balance

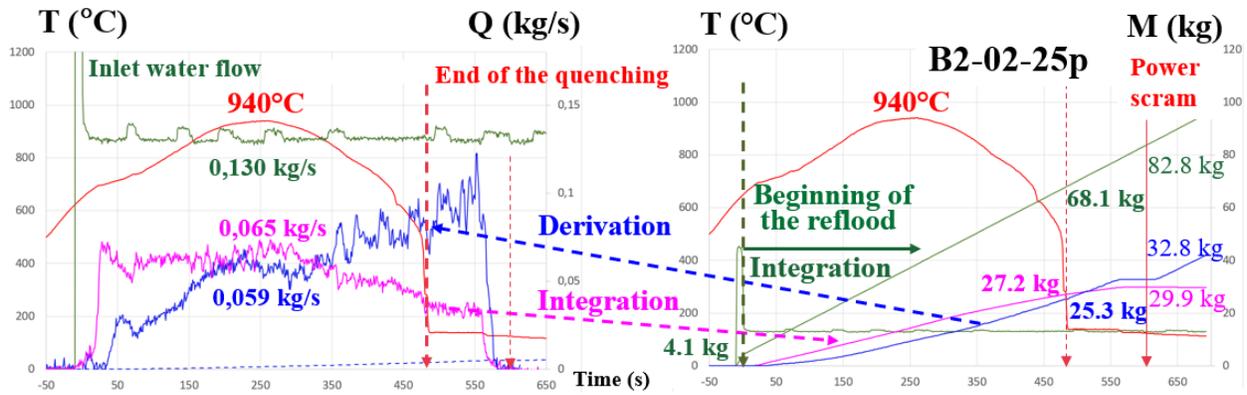


Figure 19. Water/steam flow rate for B2 LP test – maximum temperature and water balance

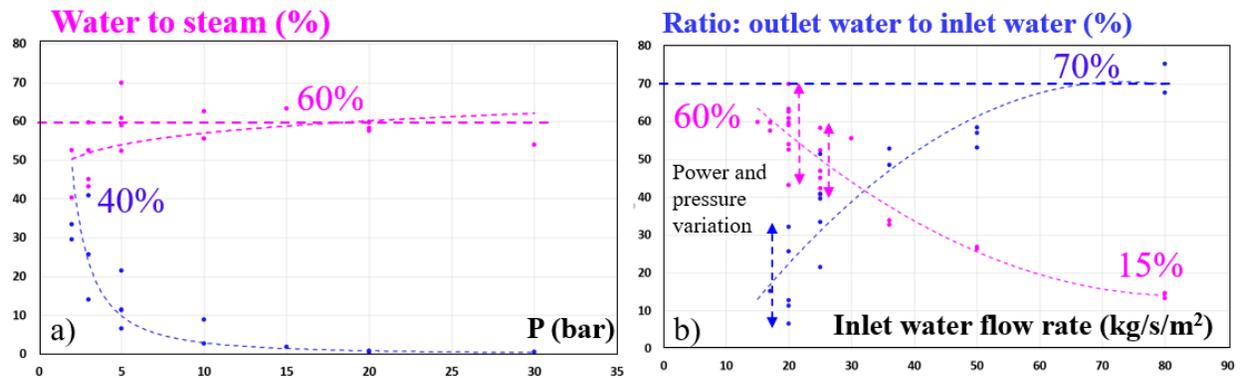
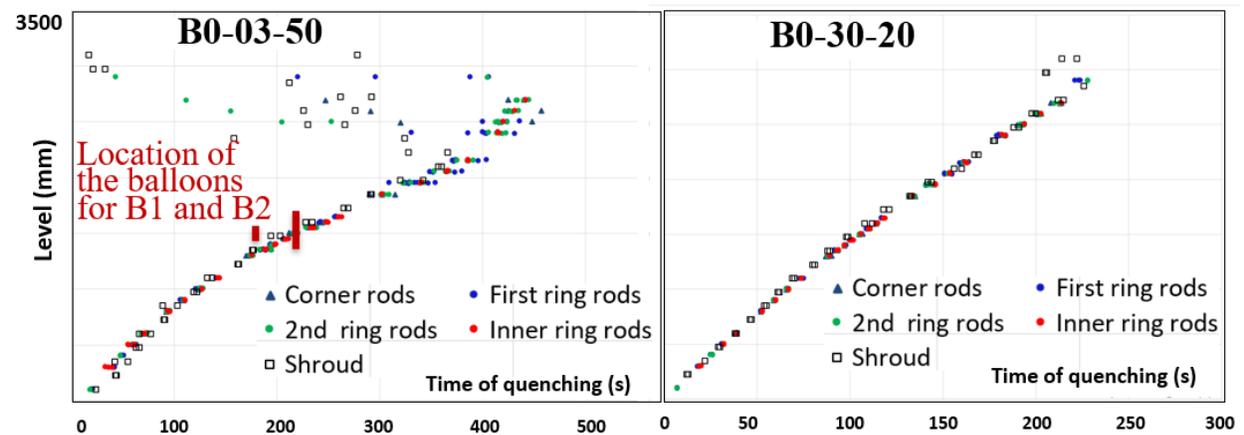


Figure 20. Conversion factor water/steam according to the pressure and the water flow rate



a) 3.3 kW, LP and high velocity 5 cm/s

b) 2 kW, HP (30 b) and high velocity 2 cm/s

Figure 21. Examples of the QFP for LP test (3 bar) and for HP test (30 bar)

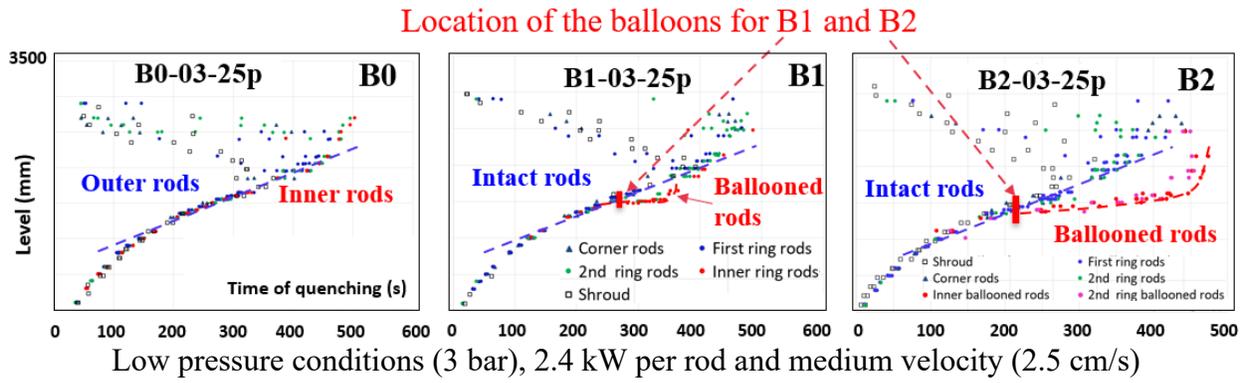


Figure 22. Examples of the QFP for LP test (3 bar) according to the bundle geometry

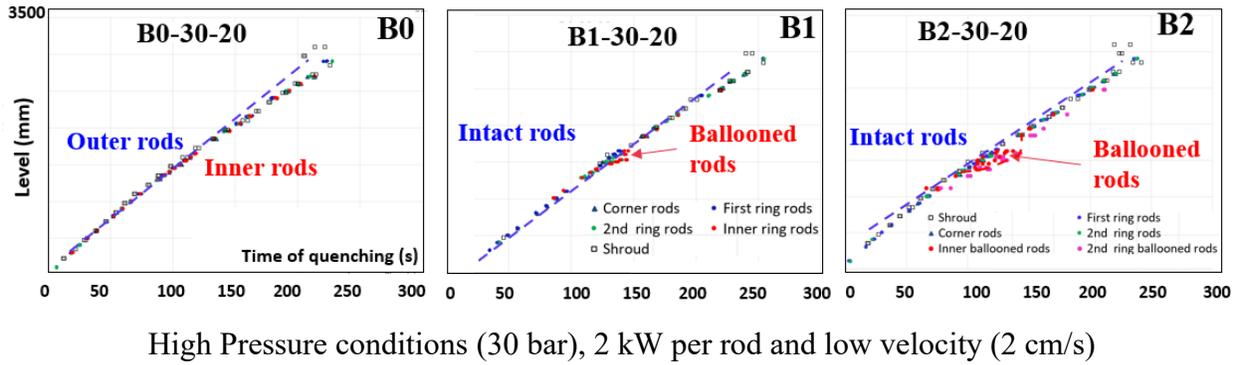


Figure 23. Examples of the QFP for HP test (30 bar) according to the bundle geometry

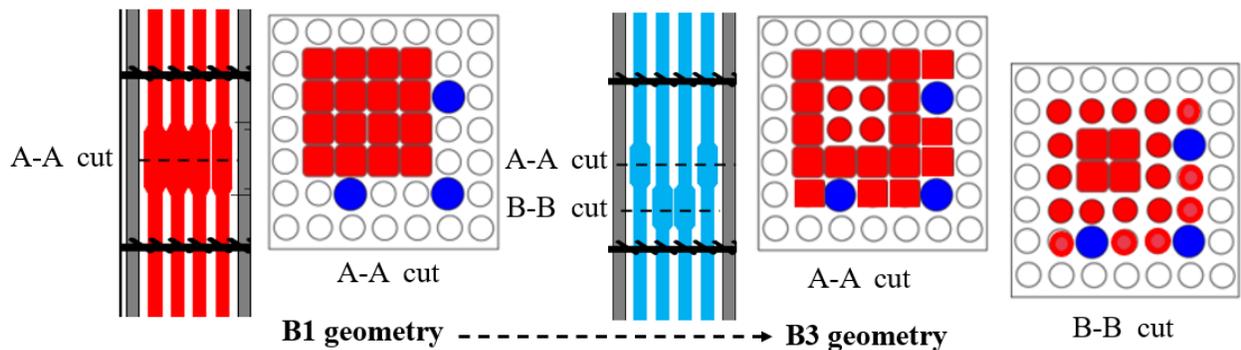


Figure 24. Geometry of the B3 COAL campaign with non coplanar balloons