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COAL EXPERIMENTS INVESTIGATING THE REFLOODING OF A 7 X 7 RODS BUNDLE DURING A LOSS OF COOLANT ACCIDENT THERMALHYDRAULICS RESULTS

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ABSTRACT

During an accident causing loss of the coolant of the primary circuit (LOCA) in a pressurized water reactor, partial or complete 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 launched by “Institut de Radioprotection et de Sureté Nucléaire” with the support of the French National Agency of Research (ANR), EDF and the US-NRC. In this framework, IRSN has designed and developed those 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 effect of the flow blockage (intact geometry up to long ballooning with different blockage ratios 80 to 90%) will be evaluated for various mass flow rates and different pressures representative to Large (LBLOCA) and Medium break size (MBLOCA) configuration.

This paper presents the thermal hydraulics parameters and the preliminary results of the experiments.

KEYWORDS

Coolability, blockage, LOCA, COAL, DRACCAR

1. INTRODUCTION

During an accident causing loss of the coolant of the primary circuit (LOCA) in a pressurized water reactor, partial or complete 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 National Agency of Research (ANR), EDF and the US-NRC. In this framework, IRSN has designed and developed those 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 presence of a blockage (Fig. 1 a), **(1)** increase of the flow velocity in the deformed fuel rods region and **(2)** the flow bypass of the blocked region (reduction of mass flow in the sub channels of the blockage), will be 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 mass 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 - see 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 those 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 enough representative 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). One of the challenges of the COAL campaign is 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 fuel relocation is simulated by a local increase of the electrical power in the balloons.

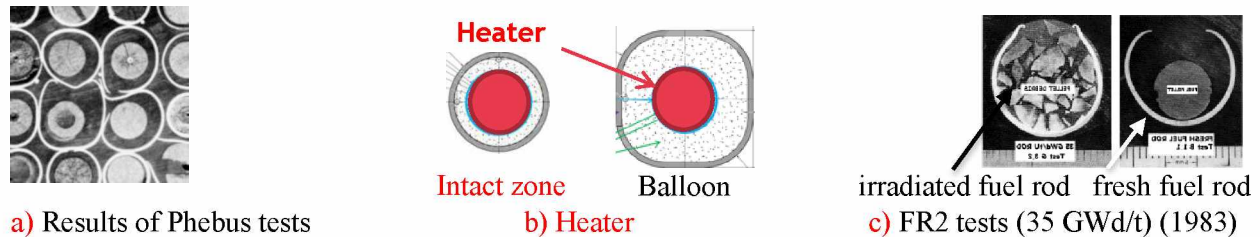


Figure 1. Deformed rods with balloon

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 validate, to improve or to develop the thermal hydraulic models of the DRACCAR code [6-7].

The specific objectives of the COAL experiments are double:

- To study the “reflooding” at rather low flow rate (**Obj 1**): it has been already demonstrate 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 (intact rods) was to have a “Reference state”. The main objective of B1/B2 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 recent B0 campaign performed in last October 2020.

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/B2, 16 deformed rods, 30 non-deformed rods and 3 guide tubes (Fig. 2b).

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) of the electrical rods used is Hasteloy 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.

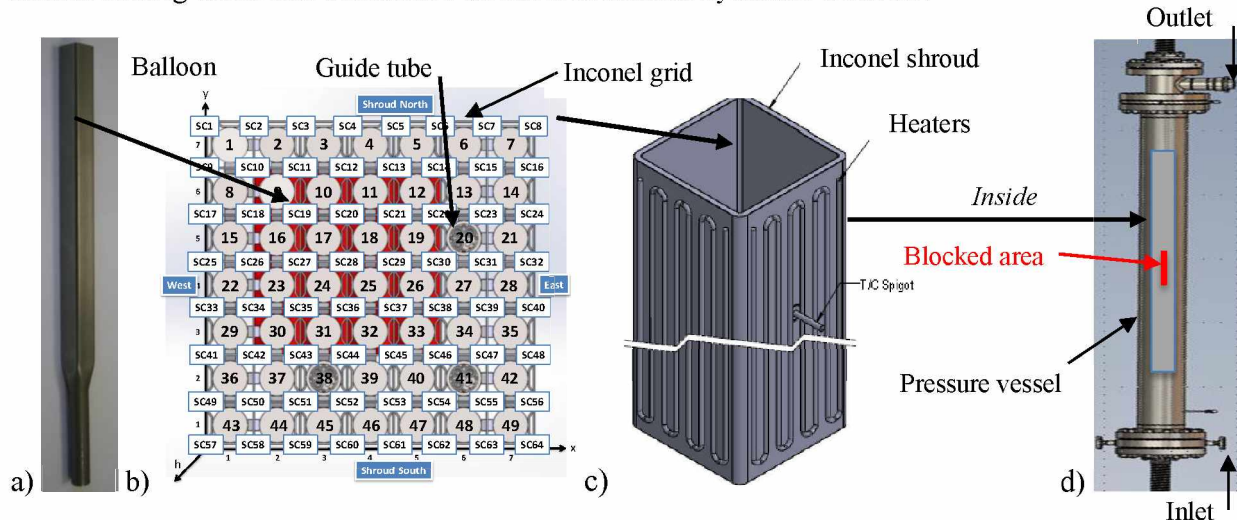


Figure 2. Experimental device (deformed rod, bundle, shroud, test section)

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). 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, (4m 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 (already existing component);
- 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 (existing components);
- A inlet valve V-13 to open at the desired time to start the reflooding;
- A 450 kW steam generator (added component) in order to fill the loop with steam for the initial conditions after a LOCA scenario (see § 2.4);
- A 70 kW super heater (added component) 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 was added, in parallel of the device, to 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 (added component);
- A steam condenser and a pressurizer system including a storage tank (already existing components).

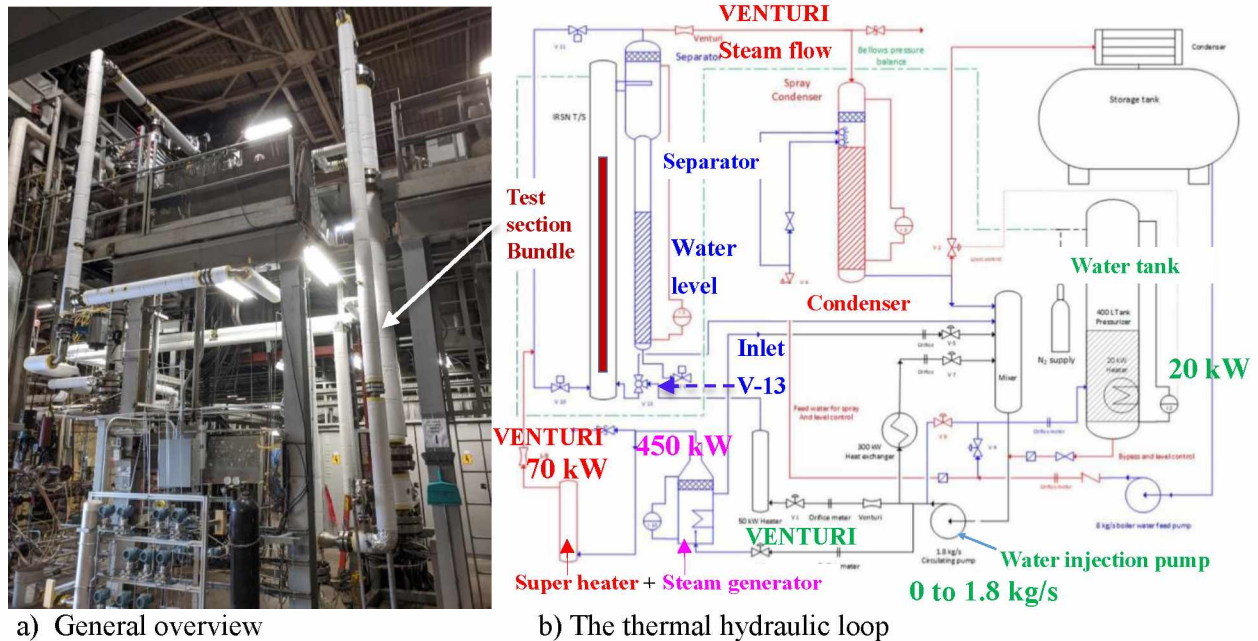


Figure 3. The STERN Laboratory test facility in Hamilton (Canada)

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 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. The list of sensors (with accuracy) is given here after:

- Flow orifice ($\pm 3.1\%$) and Flow VENTURI ($\pm 0.42\%$) for the inlet flow rate;
- Flow VENTURI ($\pm 0.55\%$) for the bypass steam outlet flow rate;
- Combined flow VENTURI ($\pm 0.55\%$) for the total steam outlet flow rate;
- Level of the separator (for the integral amount of water at the outlet of the test section).

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:

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 will contains several steps as below:

- Step 1: the bundle will be preheated up to 300°C by hot steam injection;
- 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 (1.5, 2, 2.4 or 3.3 kW);
- Step 4: the rods will be heated up to 550°C before the water injection phase (“reflooding” period);
- Step 5: power and water flow will be 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;
- power per rod : 3.3 kW/2.4 kW respectively 2 kW for Large Break (low pressure - LP) scenario, respectively for Medium Break (high pressure - HP) scenario 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 T/H conditions come from recent NPP CATHARE calculations (Table 1 of [5]) with different break sizes (1 to 40 inches) and conditions that were used for past programs such as PERICLES experiments. The axial power profile (Fig. 6 of [8]) is well described in the previous Nuthos/Nureth publications [8-9] (presentation of COAL experiments and simulations using DRACCAR) and not reported in this paper.

2.5. The COAL test matrix

The 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. 4 below.

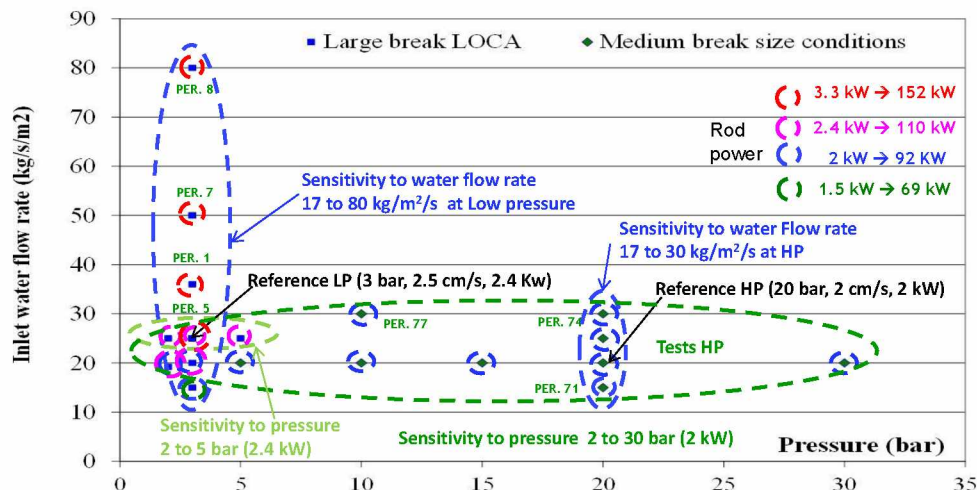


Figure 4. COAL test matrix in a (Q, P) diagram.

Roughly 25 experiments was enough in order to investigate the different physical main inlet parameters (power, pressure, water flow velocity and water sub cooling). Some thermal hydraulics conditions (PER xx in Fig. 4) are similar to those of PERICLES experiments for comparison tests with past reference cases.

3 tests were repeated in order to investigate the reproducibility of the results. As peripheral rods will be used for two experimental campaigns, these intact rods need to resist to roughly 50 (25+25) refloodings. So, the prototype of electrical rod has been tested successfully 55 times for various initial temperatures (from 600 to 1000°C) at different flow rates without any damage. The behavior of the electrical rods during the first campaign confirms the resistance with only 1 Tc's failure over 276 thermocouples in the rod bundle.

Note: Each tests are reported in the paper as the following label: B0-XX (water flow specific velocity given in kg/s/m²) YY (pressure in bar). So, B0-03-25 corresponds to experiment with B0 bundle (intact rods) at 0.3 MPa (3 bar) and 25 kg/s/m². Low pressure tests are performed at 3.3 or 2.4 kW or 2 kW per rods whereas HP tests (above 5 bar) are performed at 2 kW/rod.

3. THE MAIN EXPERIMENTAL RESULTS

28 “Reflooding” experiments were successfully performed in October 2020, for 25 different thermal hydraulic (T/H) conditions plus 3 repetitions.

Table I provides a summary of the main results of some typical experiments in order to investigate 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/m² – MB LOCA conditions), as well as the impact of the rod power (3.3/2.4 kW).

Table I. summary of the main thermal hydraulic results

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

More details and analyses are provided in the following section.

3.1. The thermal results

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

Five (5) tests were performed at a rather high power generated in each rods (3.3 kW), so for a total bundle power of 152 kW and similar pressure for the system (3 bar). For those tests, we varied the inlet water flow rate (from 25 to 80 kg/m²/s).

Fig. 5 provides the main results of the B0-03-50 for those conditions: 3 bar and inlet water flow velocity of 50 kg/m²/s (i.e 270 g/s). Maximum temperatures were recorded around 810°C on the inner rod at level 1650 mm, just above the middle plan, with a rather satisfactory quench front propagation (see § 3.3) in agreement with our physical understanding and a quite well controlled pressure.

Fig. 6 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 710 to 925°C. After running the first 3 tests, the maximum temperature estimated for B0-03-25 was roughly 1000°C, closed to the electrical rods limit of about 1050°C due to the design. So, this test was postponed to the end of the campaign with lower initial temperature ($\approx 500^\circ\text{C}$) when water is injected. So, the maximum temperature was around 925°C, with enough marge to the design and for running further test with the balloons for the next B1 campaign, as we may expected higher temperatures for the same T/H conditions.

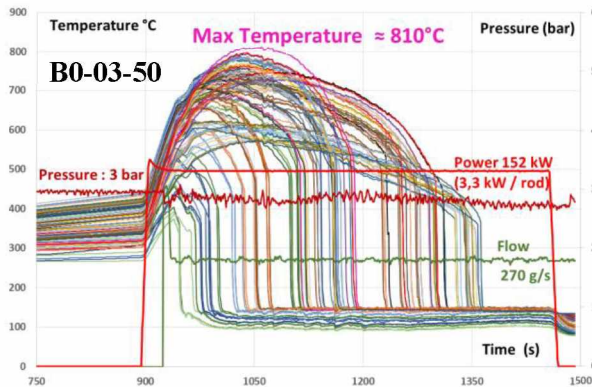


Figure 5. Temperatures for LP tests.

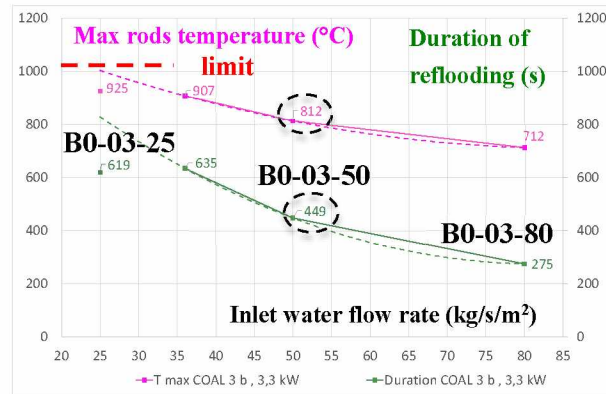


Figure 6. T max and duration versus water velocity

Analyses of the Figure 6 show that results of maximum cladding temperatures are fare 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/m^2 . The margin will be probably reduced by taking into account the partially blocked area and the fuel relocation in the balloons.

3.1.2. Effect of the system pressure

Eight (8) tests were performed at different pressure 2, 3, 5, 10, 15, 20 and 30 bar with similar inlet water flow rate ($20 \text{ kg/m}^2/\text{s}$, i.e 0.105 kg/s) and power 2 kW/rod for a total bundle power of 92 kW .

Fig. 7 provides the main results of the B0-20-20, the reference HP test for those conditions: 20 bar and inlet water flow velocity of $20 \text{ kg/m}^2/\text{s}$. Maximum temperatures were recorded around 745°C on the inner rod at level 1650 mm just above the middle plane.

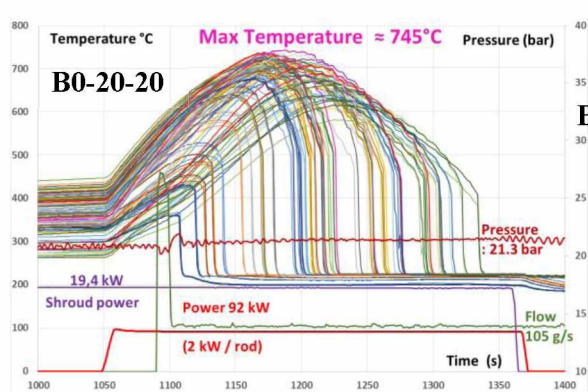


Figure 7. Temperatures for HP tests.

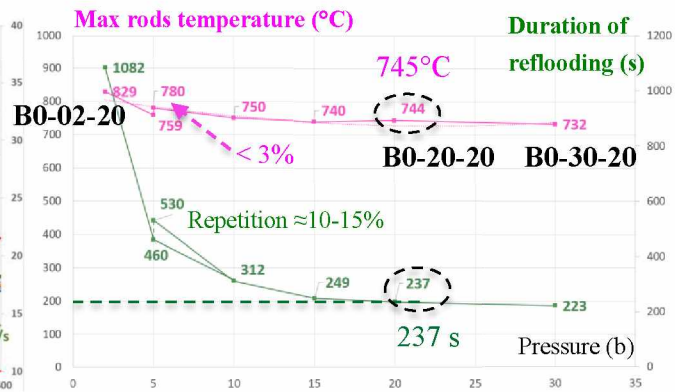


Figure 8. T max and duration versus pressure

Fig. 8 gives the evolution of the maximum rods temperatures and the duration of the reflooding according the pressure. The rods temperatures increase from 730 to 830°C with the decrease of the pressure.

Above 15 bar 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 lead to a strong increase of the duration with a less efficiency of the reflooding process in particular below 5 bar. This behaviour is 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.

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

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 those results (Fig. 9) 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).

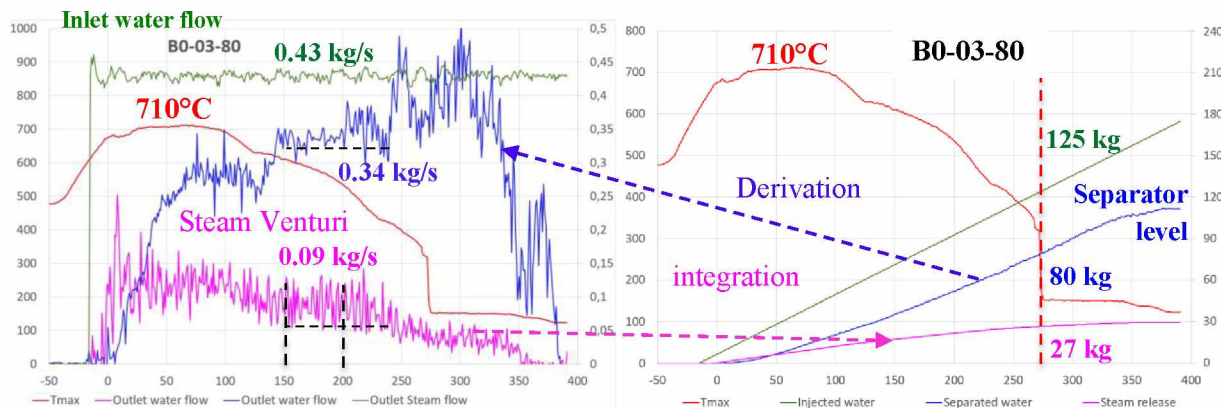


Figure 9. Water/ steam flow rate for LP tests

Figure 10. 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.10). The preliminary analyses of those 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 constant results of B0-03-80 and 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 5 kg of water is needed to fill the lower plenum. The remaining water in the test section (13 kg) is in agreement with the free volume of the rod bundle (15.7 dm³). These information gives rather high confidence for all the hydraulic flow measurements obtained during those COAL experiments.

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 II). 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 those hydraulic results: confidence for using those data for code validation.

Table II. Steam production versus flow rate and pressure

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 function of the injected water flow rate

3.3. Quench front propagation

Fig. 11 and Fig. 12 give 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) at 30 bar.

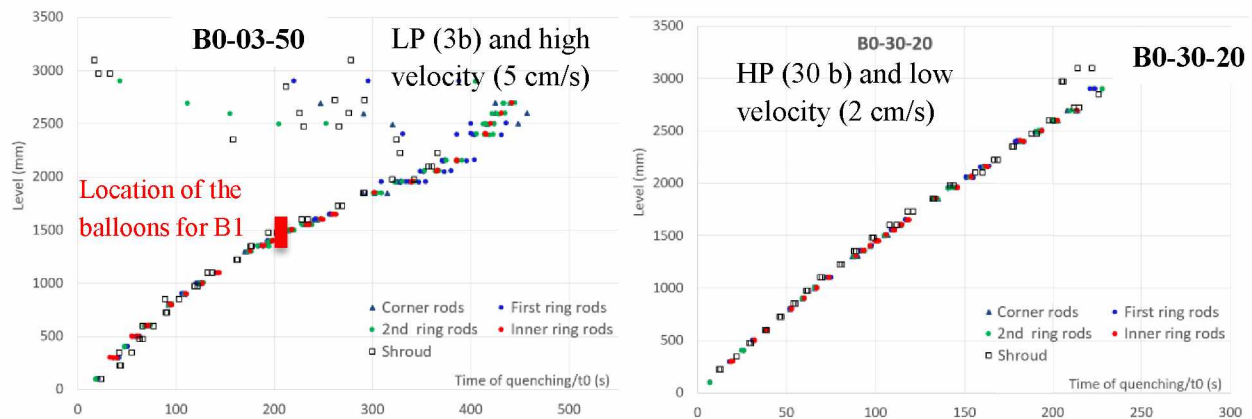


Figure 11. Example of QFP for LP test (3 bar) Figure 12. Example of QFP for HP test (30 bar)

The different points (given by T_c 's located on the different rings of rods) clearly indicate an uniform quench front propagation: some early quenching of thermocouples located on the shroud, only at the top of the bundle (above 2.2 m) are due to falling of water droplets, mainly for low pressure tests: it was not the case for all the high pressure tests. In any cases, the coming back droplets in the bundle appears limited and not impacting the middle plane of the bundle where partially blocked area with ballooned rods are foreseen to be located. This information is rather important in order to properly analyzing the effect of the flow diversion due the balloons on the reflooding processes (main objectives of the further COAL experimental campaigns).

4. CONCLUSIONS

This paper presents the preliminary results of the COAL experiments.

25 experiments was performed to investigate the different physical main inlet parameters such as the power per rod (1.5, 2, 2.4 and 3.3 KW), the pressure (ranging from 0.2 to 3 MPa) and the inlet water flow velocity (ranging from 17 to 80 kg/s/m²).

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 succeed to perform high pressure experiments from 1 up to 3 MPa which was one of the major objective of the COAL experiments in order to investigate the coolability for Medium Break LOCA condition.

The results of those 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 and the steam at the outlet of the test section.

Now as the installation is fully operational, further experiments (B1 and B2 campaigns) will be performed with bundles including a partially blocked by ballooned rods at a blockage ratio respectively 80% and 90% (length of the maximum deformation 100 mm “respectively 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.

NOMENCLATURE

COAL: COolability of a fuel Assembly during Loca
LB and MB LOCA: Large or Medium Break Loss Of Coolant Accident
LP: Low Pressure test - **HP:** High Pressure test
PCT: Peak Cladding Temperature
QFP: Quench Front Propagation

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