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## **Thermal hydraulics behavior of a rod bundle with partially blocked area during the reflooding phase of the Loss Of Cooling Accident**

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### **ABSTRACT**

During an accident causing the loss of the coolant of the primary circuit (LOCA), partial or even complete drying of the fuel assemblies may occur. In these conditions, of the fuel temperature increase and the coolant pressure drop in the reactor core may lead to significant deformation or rupture of the fuel rod cladding. Depending on the burnup of the fuel rod, extensive fuel fragmentation may occur, leading to fuel relocation within the ballooned area and the core coolability might be impaired. “Institut de Radioprotection et de Sureté Nucléaire” has launched, with the support of EDF and more recently with the US-NRC, the COAL experiments focusing on the outstanding issue of the coolability of a partially deformed fuel assembly.

The influences due to the presence of a blockage will be evaluated through a semi-integral experiment using a 7x7 bundle geometry at the full length scale. The flow bypass of the blocked region, due to the reduction of the section between the deformed fuel rods will lead to a reduction of mass flow in the sub channels of the blockage and then the heat transfers. This paper presents the test section with the instrumentation, the thermal hydraulics parameters and pre-calculations using the DRACCAR code developed by IRSN. The results of these experiments will help to improve and validate the heat exchange models implemented in the DRACCAR code studying the 3D thermal mechanical processes coupled with a thermal hydraulics tool to deal with the complex reflooding processes.

### **KEYWORDS**

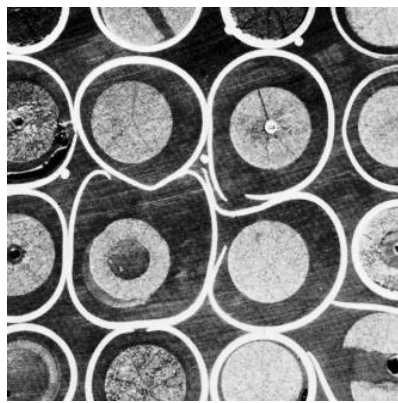
Coolability, blockage, LOCA, Fuel relocation, DRACCAR

### **1. INTRODUCTION**

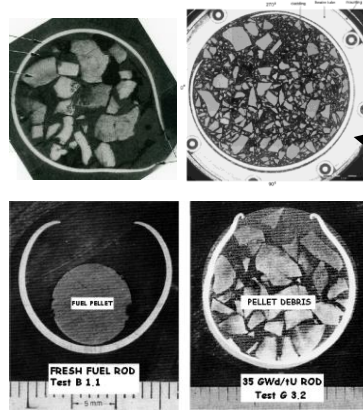
During an accident causing the loss of the primary coolant (LOCA), partial or even complete drying of the fuel assemblies may occur. In these conditions, the fuel temperature increase and the coolant pressure drop in the reactor core may lead to significant deformation and rupture of the fuel rod cladding. The results (Fig. 1), which illustrate this phenomenon, come from a LOCA experimental program performed, in the 1980's by the Institut de Protection et de Sûreté Nucléaire now IRSN [1], in 5x5 bundle including fresh fuel rods. In case of irradiated fuel rods, fuel fragmentation may occur, leading to fuel relocation within the ballooned area. Depending on the size and the distribution of the ballooned areas within the fuel bundle, the cooling flow might be impaired.

All the LOCA experiments performed with irradiated fuel rods (in particular 3 examples, at 35 GWd/t for the FR2 experiments (Germany) in 1983 (Fig. 2a) [2], in the ORNL Tests (USA) (Fig. 2b) [3] for various burnups and, more recently, in Halden (Norway) [4] at 90 GWd/t (Fig. 2c) in 2006, have shown such an accumulation of the fragmented fuel pellets in the ballooned region.

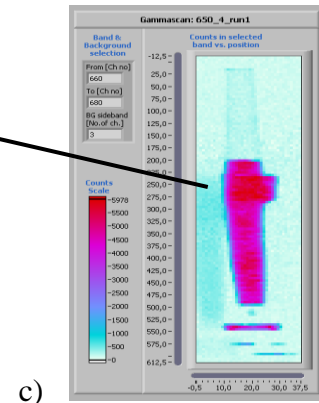
The resulting increase of the power density in the ballooned area may challenge the fuel assembly coolability and, by extension, the core coolability. Depending on the burnup of the fuel rod, extensive fragmentation may also lead to fuel particle dispersal into the coolant through the ruptured cladding.



b)



a)



c)

Fig.1. Bundle of deformed rod  
Phebus LOCA experiments (1983)

Fig. 2. Fuel relocation in the ballooned area  
a) FR2 fresh or irradi. Fuel rods. b) ORNL c) Halden test

So, the consequences of both deformations and fuel relocation on the cooling efficiency when reflooding the core by the ECCS (emergency core cooling systems) are important safety issues, and have never been experimented. The knowledge generated by these new experiments will answer long shared concerns by the international community (such as the effect of fuel relocation in blocked areas in the core), and will allow to validate the DRACCAR code [5] developed and used by IRSN since 2006 to simulate any prototypical LOCA transient. As the previous experiments (as FEBA, SEFLEX [6, 7] and others) were not representative enough (rod thermal inertia and fuel relocation was not taken into account), the need of such complementary experiments has been proposed in 2005 by IRSN [8, 9].

## 2. THE COAL EXPERIMENT

The COAL experiments, in the frame of the PERFROI project [10, 11] will concern thermal hydraulics experiments on electrically heated rods, with simulation of large blockage and fuel relocation.

### 2.1. The test section and the bundle geometry

The COAL bundle [12] will consist of rods (electrically heated), some with a pre-deformed zone with local overheating representing fuel relocation. The bundle will be made of 49 (7 x 7) rods (including 16 deformed rods and 30 non-deformed rods – Fig. 3a), similar to that of the THETIS [13, 14] tests performed in the past by AEA Winfrith UK in 1983-1984, which will also facilitate experimental comparisons. The presence of 3 guide tubes will increase the representativity of the thermal hydraulics behavior for the reactor case. The test section will also include 6 spacer grids each 500 mm apart.

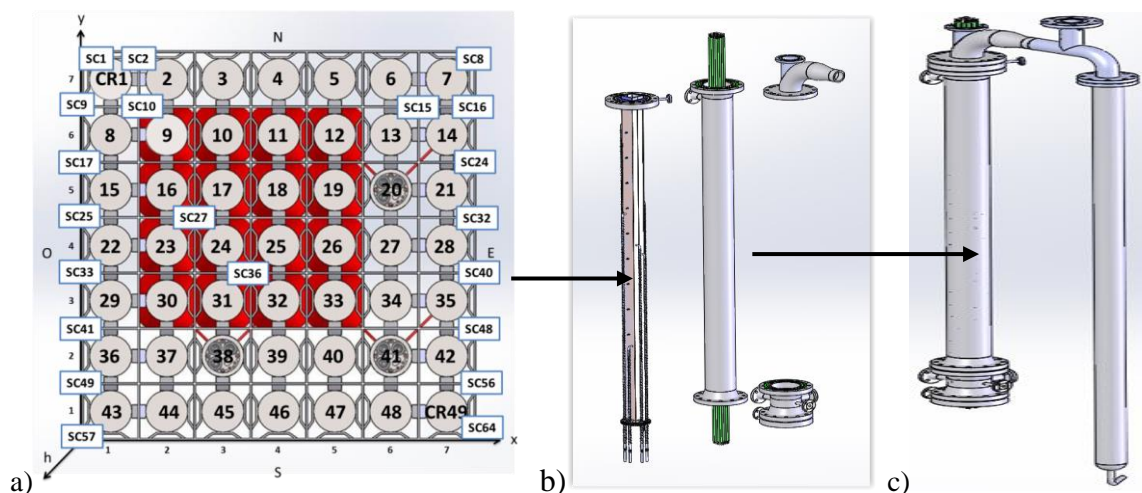


Fig. 3 Test section design.

For these experiments, the cladding of the electrical rods was proposed to be constructed with Hastalloy material to prevent oxidation. To avoid any chemical interaction, the grids should be in Inconel alloy. Inconel grids for the COAL bundle have been built with a design including mixing vanes that would have an effect of thermal hydraulic behavior. The presence of guide tubes is also necessary for instrumentation and of course mechanical reason. The heating zone is about 3 m high (close to the real PWR geometry). The bundle will be inserted in 94mm square shroud (Fig. 3b) with roughly 5 mm thickness to be representative of the surrounding fuel rods regarding their thermal inertia. The test section will be included in a pressure vessel, (220 mm diameter – Fig. 3c) with two lower and upper plenums for the electrical and instrumentation connections and the fluid supply. The COAL program will be conducted in an existing ad-hoc thermal hydraulics facility (cf section 2.2).

## 2.2. The thermal hydraulic loop

COAL experiments will be performed in the AREVA BENSON facility (Fig.4a) at Erlangen (Germany) which allows running high pressure tests to 3 MPa (30 bar). This facility has operating for roughly 40 years for different kinds of experiments in the thermal hydraulic field [15].

Figure 4b) describes the circuit of the BENSON facility able to carry out reflooding experiments without important modification, including the installed power needed for heating the electrical rods.

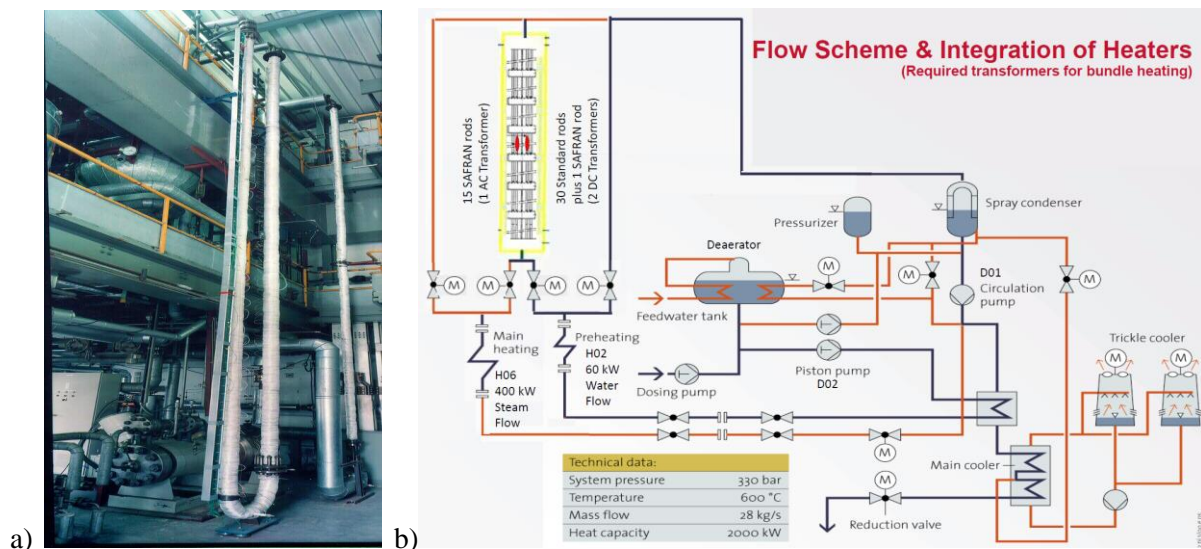


Fig. 4 The BENSON Test facility at AREVA Erlangen

The experimental work will proceed in two steps:




1. Qualification tests will be performed by the end of 2017 on a bundle with non-deformed heated rods. These tests will be used as a reference tests in order to qualify all the experimental process and to compare with already performed experiments such as PERICLES\* (cf section 3.3),
2. Then tests with heated pre-deformed simulators, including local overheating of the balloon regions, will be performed from 2018 up to 2019. Three series of tests are planned with different flow blockage ratios or ballooning lengths (cf. Table 1). In each series, the effects of thermal hydraulic parameters (cf. section 3.3) will be carefully investigated. A third campaign is optional (for 2020) and depends on the results of the previous campaigns.
3. Finally, all the tests will be analyzed and interpreted. The objective is to validate a heat transfer model adapted to bundle conditions, to be implemented in the DRACCAR code [16, 17].

The experimental parameters of the test campaigns will be defined in order to investigate the bundle geometry related phenomena (blockage ratio, balloons lengths) and the thermal hydraulic related

\* Low pressure reflooding experiment at steady flow-rate on a complete assembly of a pressurized water reactor. (Experiments carried out at the CEA Grenoble (France) between 1983 and 1986).

phenomena (local overheating of the balloon, injected water temperature, coolant flow rate and system pressure to simulate various break sizes).

**Table 1. Geometry and parameters of the blockage zone**

	B0	B1	B2
Blockage ratio and rod shape	0 % 	81% 	90% 
Corresponding cladding deformation	0%	48%	55%
Total height of the ballooning area	Intact geometry	170 mm	370 mm
Height of the maximal deformation	-	100 mm	200 mm
Maximum axial linear power (w/cm)	16 (ref.)	24 (x 1.5)	30 (x 1.9)
Singular pressure drop coefficient of the ballooned zone	0	11,58	47,24

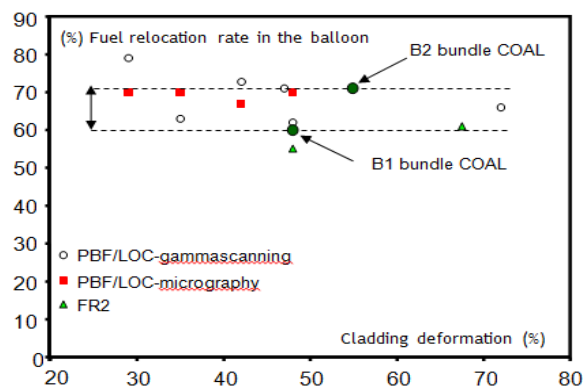


Fig. 5 : Fuel relocation rate in the balloon

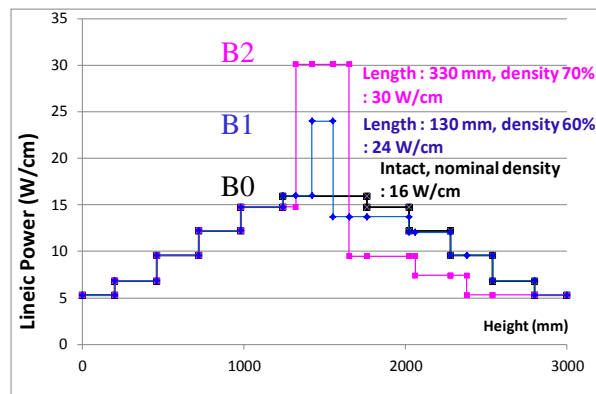


Fig. 6 : Axial power profile for inner rods

The choice of geometries and the associated axial power distributions were guided to obtain a gradual evolution of the pressure drop of the ballooned area and a gradual increase of the maximum linear power in the ballooned area of the fuel rods which constitute the different bundle (B0, B1 and B2). The axial power distributions were obtained by DRACCAR calculations which can simulate with some parameters the fuel relocation in the balloon (Fuel rating in the balloon according the cladding deformation – Fig. 5) and the corresponding power profile deformation (Fig. 6).

### 2.3. The instrumentation plan

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

- ✓ Injected water and steam mass flow rate generated during reflooding,
- ✓ Temperature of the steam at different points (type K thermocouples),
- ✓ Temperature inside the fuel rods (thermocouples at different elevations and different radial positions in the bundle) in an adequate distribution,
- ✓ Total pressure and pressure drop sensors at the periphery of the rod bundle.

Up to 184 thermocouples (4 each 46 rods) will be available every 10 cm to follow the quench front propagation. Additional thermocouples are foreseen, in some fluid channels, on the 6 grids and in the 3 guide tubes. The shroud will be also equipped with thermocouples on each faces in order to accurately set the boundary thermal conditions during the reflooding process.

The outlet mass flow rate of steam and water is foreseen to be evaluated by using a T junction as a separator (Fig. 3 c). The collected water will be measured by the increase of the differential pressure ( $\Delta P$  as function of time) inside a water collector tank while the outlet steam flow will be measured by a “venturi” technique.

A total of roughly 340 measurements is foreseen to be recorded by the data acquisition system.



### 3. PRECALCULATION USING THE DRACCAR CODE

The simulation tool DRACCAR [16, 17], developed by IRSN, with the support of EDF, is at this stage, used to define some parameters of the experiments such as the blocked bundles geometry, the deformed axial power profile, the heat-up scenario of the bundles or the test matrix. Then DRACCAR will be used to perform the pre-calculation of all the tests foreseen in the COAL program.

#### 3.1. Description of the DRACCAR code

DRACCAR is a simulation tool for fuel assembly mechanical behavior and coolability assessment during a LOCA transient. Its aim is to simulate the 3D thermomechanical deformation and reflooding of a fuel rod assembly including its coolability as well as structure embrittlement.

The DRACCAR code is based on a 3D non-structured meshing able to model a simple fuel rod, a partial or a full assembly, as well as a surrounding shroud. It is based on an axial discretization of the rod which leads to analyze quasi-independent 2D thermal mechanical problems. Important modeling such as pellet eccentricity, heat transfers (within the solid and through the fluid) or material properties evolutions (oxidation layer, phase changing,...) can thus be taken into account and the cladding integrity during a LOCA transient can be addressed even in case of contact between the structural elements. In that case, the geometry is strongly changed (flattened zone contact) as well as the loading nature (mixed stress-displacement loading) and so the rupture is more difficult to model than a threshold criteria used in most of the multi-rod codes: with DRACCAR, non-linear geometrical effects are added to non-linear behaviour laws in the modeling. Also important is the possibility to get a better knowledge on the system's capability to cool structures whatever are the evolutions of the deformation of the rods and the blockage of the sub-channels. Obviously these two critical issues which are essential to treat in modeling LOCA transient effects, can only be dealt with in a realistic manner with a multi-pin code coupled to an efficient 3D thermal hydraulics code, and that's why DRACCAR V2.3 is currently coupled to the two phase flow module CESAR of the ASTEC code [18], able to compute deformed geometry evolutions thus actualizing the coolant flow passage within the different sub-channels. In this case DRACCAR is able to calculate the heat exchange between the wall and the fluid which have been validated against PERICLES and ACHILES tests. The code has capability to deal with dispersion of flow, but droplet behavior will be developed later.

#### 3.2. DRACCAR modeling

The bundle is simulated on a height equivalent to the rods heating length, with the square housing (metallic shroud in a similar material as the cladding). One boundary condition at the inlet and one at the outlet of this portion close the system.

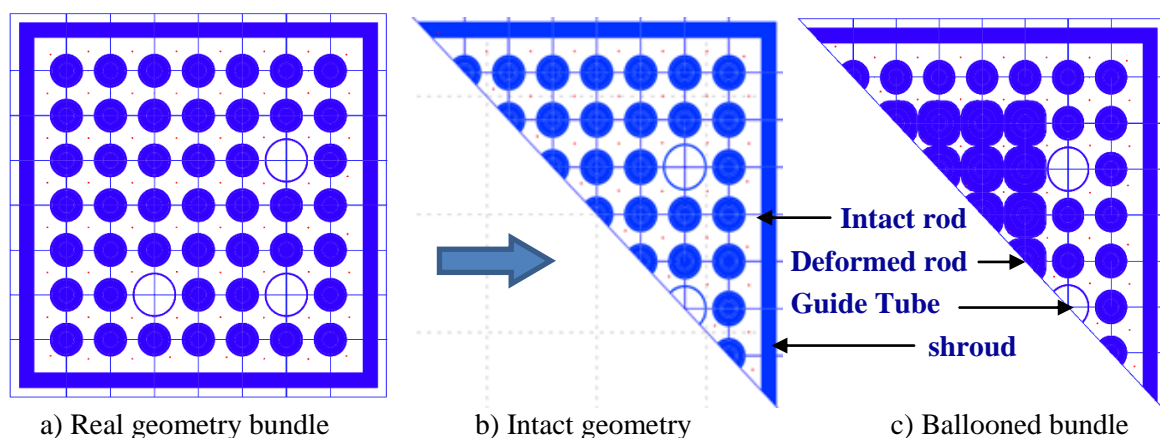


Fig. 7 : DRACCAR nodalization of the bundle

DRACCAR is able to model each 46 electrical rods of the bundle and 3 guide tubes (Fig. 7a). Taking into account the symmetry of the test section, half a bundle is modeled (Fig. 7b). The ballooned bundles included 16 rods with a local ballooning (Fig. 7c). In the balloon, the fuel fragment is simulated by a porous material which has a density and conductivity close to those of the  $\text{UO}_2$  pellet. The one presented here, for the first series of calculations, is composed of balloons that have a height of 100 mm, the same elevation at the middle of the bundle, leading to a 81 or 90% blockage of the test section. The axial power profile imposed in the intact rods has a cosine shape (Fig. 6). The relocation in the balloon has been simulated by setting a specific axial deformation profile in the ballooned rods (Fig. 6). This deformed axial power profile has been determined by a DRACCAR calculation after fuel relocation in a pre-deformed rod. The meshes height never exceeds 100mm (smaller in the ballooned area). Six grids are taken into account by setting a singular pressure loss at their positions.

### 3.3. Test scenario and preliminary test matrix

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).

The bundle will be preheated up to  $300^\circ\text{C}$  by hot steam injection (step 1). As the shroud temperature has to be as close as possible to the rods temperature at the end of the first phase in order to avoid perturbation during the reflooding, the rods and the shroud will be heated up to  $600^\circ\text{C}$  (step 2 and 3) before the water injection phase (step 4).

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

- ✓ inlet water flow velocity : 1,5 to 8 cm/s (15 to 80  $\text{kg/s/m}^2$ ),
- ✓ sub-cooling water temperature ( $-60^\circ\text{C}$  to saturation conditions),
- ✓ coolant pressure : 0.1 to 3 MPa (30 bar),
- ✓ power 3.3 kW \*, respectively 2 kW, per rod for Large Break (low pressure) scenario, respectively for Intermediate Break (high pressure) scenario.

There T/H conditions are coming from recent NPP CATHARE calculations (Table 1 of [12]) with different break sizes (1 to 40 inches) and conditions that were used for previous programs such as PERICLES experiments. The COAL test matrix referring to (Q, P) diagram where Q is the inlet water flow rate in  $\text{kg/s/m}^2$  and P, the system pressure in bar (0,1 MPa) is given in the Fig. 8 below.

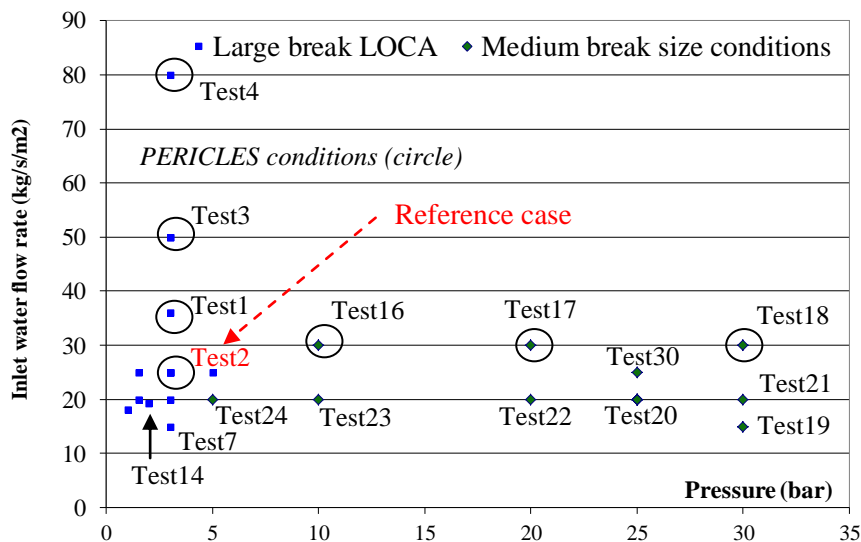


Fig. 8 : Preliminary COAL test matrix in a (Q, P) diagram.

\* in order to simplify the test procedure, the power will be keep constant during the transient, nevertheless some tests will be performed with a reduction of power representative of the decrease of the residual power such as ACHILLES Tests [19]. One of their conditions will be reproduced with COAL Test 14 (2 bar, 20  $\text{kg/s/m}^2$ ).

30 thermohydraulics conditions were proposed to develop a test matrix for the reference bundle B0 (46 intact rods + 3 guide tubes). Some thermal hydraulics conditions (circle in figure 8) are similar to those of PERICLES experiments for comparison tests for past reference cases.

About 20 experiments would be sufficient to test the effect of the pressure, the effect of coolant temperature, the injection water flow rate with the bundles including the deformed rods (B1 and B2 bundles). As the targeted number of experiments seems too ambitious, an optimization of the test matrix, in progress, is needed. The total number of tests will depend on the reliability of the rods.

### 3.4. Preliminary results of the DRACCAR simulation

The results will concern the main thermal hydraulics parameters governing the reflooding such as:

- ✓ The temperature of the rods during the transient,
- ✓ The outlet flow rate (water and steam production),
- ✓ And the quench front propagation.

#### 3.4.1. Temperature of the rods

The COAL tests matrix (§3.3) will cover the thermal-hydraulic conditions characteristics of a large break LOCA and those of an intermediate break LOCA. As far as possible, the same test conditions will be applied on the intact bundle and on the ballooned bundles, to be able to compare the impact of the blocked area with large ballooning of the fuel cladding.

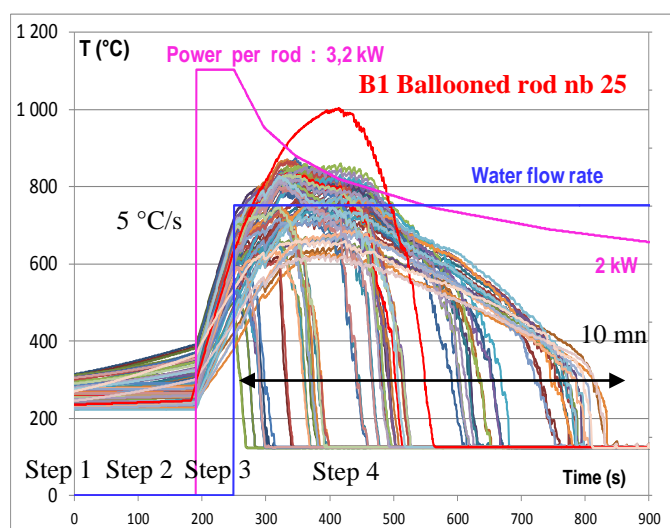


Figure 9 give typical DRACCAR results for rods temperature at different radial and axial locations in the bundle. This example corresponds to a rather representative TH conditions for a Large break scenario ( $P=2\text{bar}$ ,  $Q=20\text{kg/s/m}^2$ , water temperature  $20^\circ\text{C}$  below saturation) with power reduction during the transient. These conditions correpond to that of ACHILLES A2R038 [19]. Reflooding was launched for temperature around  $700^\circ\text{C}$  for total duration of about 10 mn leading to a complete refreezing of the rods. For this case, maximum temperature reached  $860^\circ\text{C}$  ( $1000^\circ\text{C}$  for deformed rods).

Fig. 9 : Typical DRACCAR results for intact geometry

Several reflooding pre-calculations have been performed with the DRACCAR code. The overall results regarding temperatures evolution for different water injection flow rate (from  $25$  to  $80\text{ kg/s/m}^2$ ) at low pressure ( $0.3\text{ MPa}$ ) and high pressure ( $1$  to  $3\text{ MPa}$ ) at low flow rate ( $20\text{ kg/s/m}^2$ ) are illustrated in appendix B, for the two geometries (B0 and B1 bundle with partially blocked area).

For the cases with the non-deformed bundle, all the maximum clad temperature ranged between  $650$  and  $800^\circ\text{C}$  during the transient, which lasted from  $2\text{ mm}$  to  $8\text{ mm}$ , before refreezing according to the injected water flow rate (Fig. 19a). For the lowest value of water flow rate ( $15\text{kg/s/m}^2$ ) corresponding to a flow velocity of  $1.5\text{ cm/s}$ , the maximum reached a peak temperature around  $1000^\circ\text{C}$  at level  $1.85\text{m}$  with a hottest point near  $1070^\circ\text{C}$  at the  $1.95\text{ m}$  elevation (Fig. 10): we will see later (§ 3.4.3) that this case (Test 7) was not completely coolable. The Test 19, which correspond to the same conditions except the pressure ( $30\text{ b}$  instead of  $3\text{ bar}$ ), peak temperatures were similar but the behavior of the upper part was different showing the coolability, excepted the level 2.9 (Fig 11). According to DRACCAR pre-calculations, those cases, showing too high temperatures (Figs.10-11), could be excluded from the test matrix: at least, depending on preliminary tests results, those conditions will be tested at the end of the each experimental campaigns or performed with power reduction.



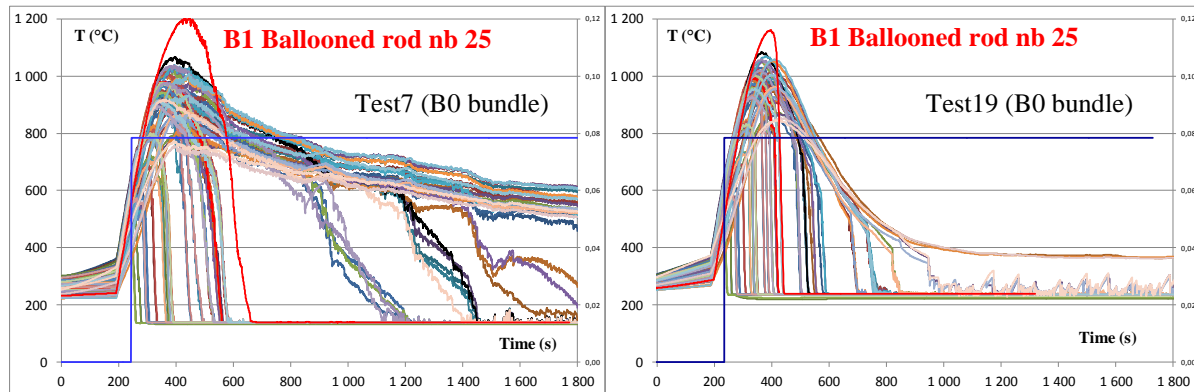


Fig. 10 : Rod temperatures (15kg/s/m<sup>2</sup> at 3 bar)

Fig. 11 : Rod temperatures (15kg/s/m<sup>2</sup> at 30 bar)

These results showed clearly the effect of the pressure on the efficiency of the reflooding.

For others tests in high pressure conditions, even at low water flow rate (20kg/s/m<sup>2</sup>), temperature never exceeded 800°C (Fig. 18a of appendix B).

For the bundle including a partially blocked area (Fig. 18b and Fig 19b), the duration of the transient was observe to be roughly similar for the same flow rate. The difference concerns the maximum temperature at the position of the blockage (Levels 1.45 to 1.55m for B0).

Figure 12 below illustrates for one thermal hydraulics condition (the reference case) the effect of the partially blocked area with simulation of fuel relocation in the balloon on the cladding temperature evolution during the transient. Both the effect of the blockage (80%) and the local power increase (x1.5) induce an over temperature of about 150°C (for the central rod – nb 25). On the contrary, the flow diversion from the blocked area to the periphery of the bundle induces a reduction of the temperature of the outer rods (example on rod nb1 which indicates a temperature 50°C lower).

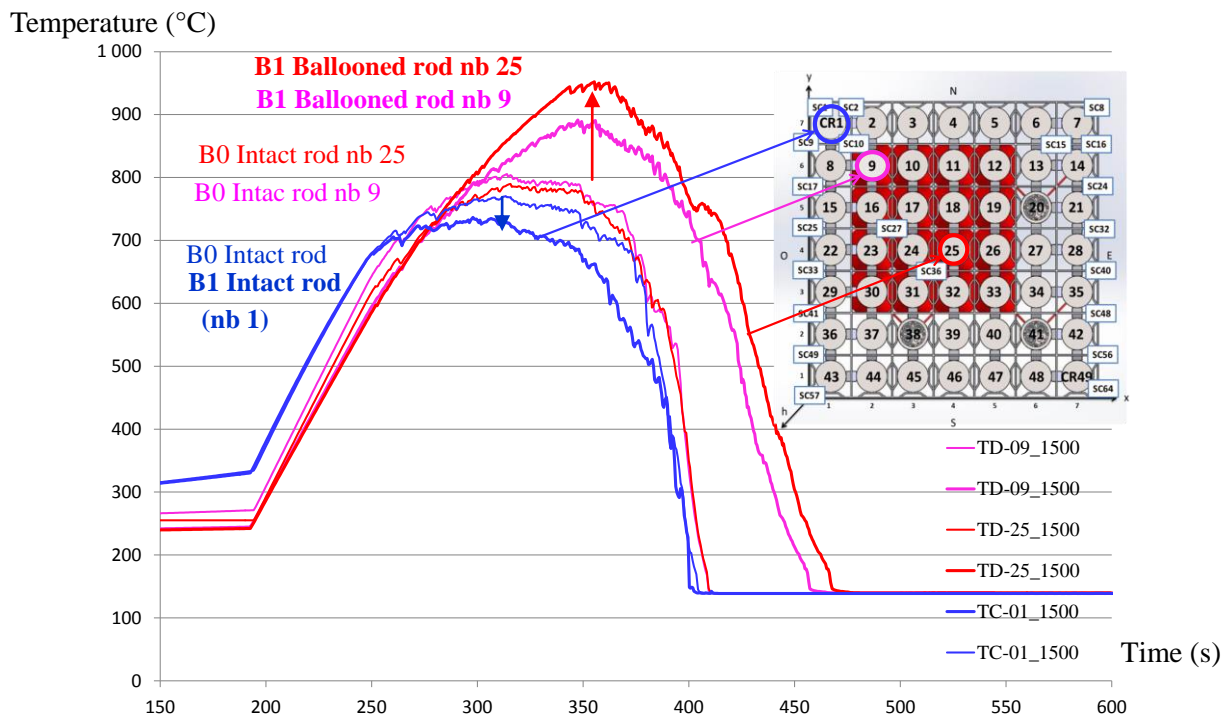


Fig. 12: Temperature evolution at the mid plan (Level 1.5 m) : Test 2

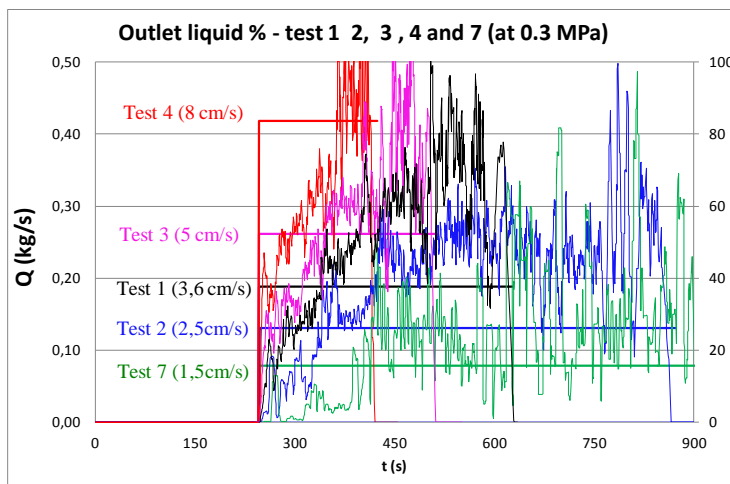
The maximum temperature (excepted some cases, low flow rate for deformed bundle, ex Fig 10) were observed to be lower than 1000°C, situation which seemed suitable according to the technological possibilities of the electrical rods. This should be taken into account for the final test matrix.

### 3.4.2. Outlet flow rate during reflooding

The results obtained by the simulation regarding the steam and the water generated at the outlet of the bundle during the reflooding of the rods are illustrated in the figures of appendix C (Fig. 20). Those results are given for extreme thermal hydraulics conditions at low (0.3 MPa) and high (3 MPa) pressure and for different inlet water flow velocity from 1,5 to 8 cm/s.

The main observations are the following:

- ✓ For low pressure conditions, large amount of droplets is remaining at the outlet of the fuel test assembly; for that pressure condition (0.3 MPa) steam is only produce when low water flow rate is injected (0.105 kg/s which correspond to the lowest velocity);
- ✓ The higher the inlet water flow is, the higher the % of water at the outlet is (Fig. 13);
- ✓ For high pressure conditions most of the injected water is vaporized due to the higher efficiency of the reflooding.



For the highest velocity, the amount of water (as droplets) represents 40 to 90% of the total injected water.

Those DRACCAR results, in a rather large range of thermal hydraulics conditions regarding the test matrix, were used for the project to the design the water/steam separator for the COAL experiments. There have confirmed the need of this kind of apparatus between the COAL test device and the BENSON loop, as large amount of water remains at the outlet of the test section, at least for low pressure tests.

Fig. 13: Pourcentage of remaining water as function of injected water .

Fig. 14 illustrates the thermal hydraulics for low and high pressure (0.3 MPa, respectively 1 MPa) and nominal flow rate (25 kg/m<sup>2</sup>/s, respectively 20 kg/m<sup>2</sup>/s) for the two configurations (intact and partially deformed bundle).

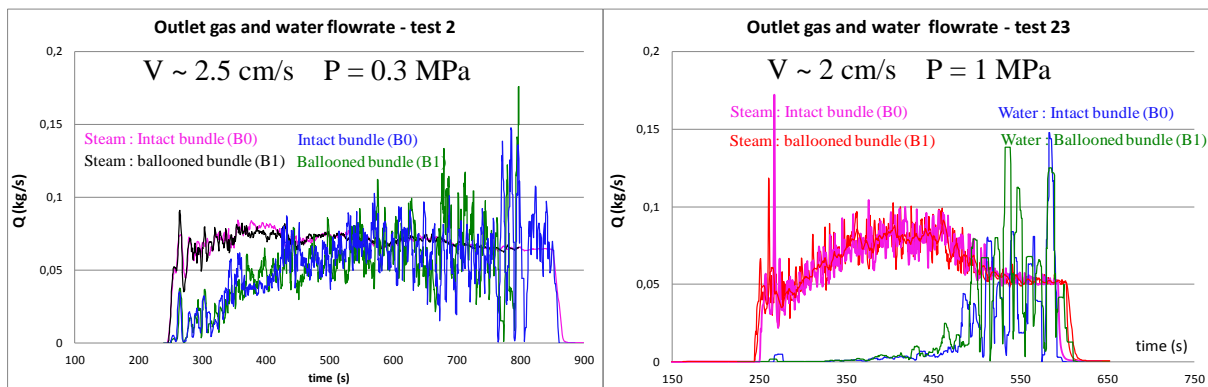
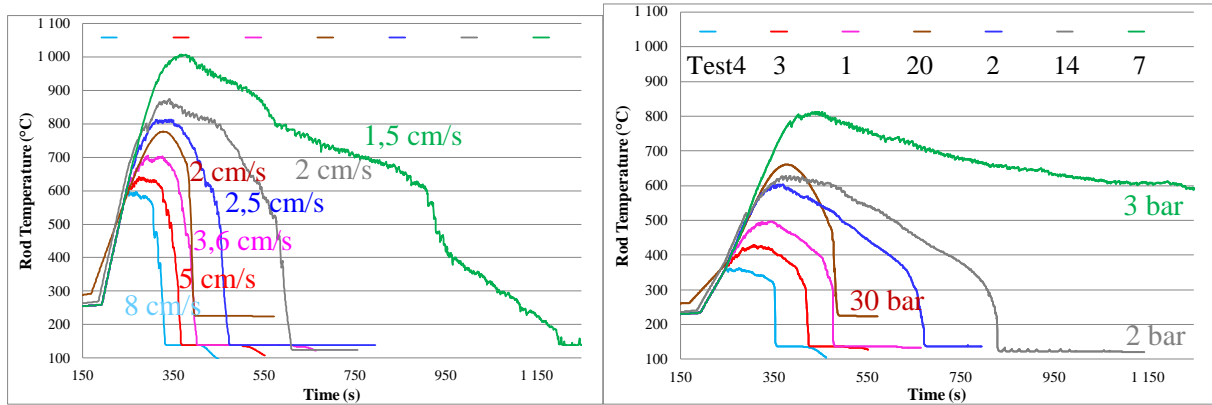


Fig. 14 : outlet steam flow rate and remaining water flow for two configurations.

The production of steam during the transient, predicted by the DRACCAR code, seems to be not very much affected by the bundle geometry, as it is a macroscopic information representing the overall behavior of the reflooding process.

### 3.4.3. Front propagation and reflooding duration

The numerous thermocouples at different axial elevations in the bundle will allow the determination of the quench front propagation. Temperature evolution, given by DRACCAR at the position of the thermocouples for different injected water flow velocities is illustrated in fig. 15 below.



a) Rod temperature Level 1.85m  
b) Rod temperature Level 2.9m  
Fig. 15 : Temperature evolution given by DRACCAR simulation (at low pressure).

For Test 7 (very low flow velocity), the upper part of the bundle was observed to be not coolable (Fig. 5b) as the quench front does not exceed the level 2.0 m over the total length of the rods (3.0 m). So, Fig. a) illustrates the quenching time as function of the water flow velocity for levels where complete reflooding was achieved (example for level 1.85 m). The results of the simulations of the two tests (Test 14 “grey curve” and test 20 “brown curve” at the same inlet flow velocity : 2 cm/s) illustrate the effect of the pressure respectively at 2 and 30 bar. At high pressure, the reflooding process is more efficiency due to the higher water density.

On the base of those calculations, Table 2 summarize the duration of the complete (and partial) reflooding for different tests as function of T/H conditions (pressure and water flow rate).

**Table 2. Time for complete reflooding of the bundle versus water flow rate and pressure**

	Test 4	Test 3	Test 1	Test 2	Test 14	Test 23	Test 20	Test 21
Pressure (bar)	3				2	10	25	30
Water flow ( kg/s/m <sup>2</sup> )	80	50	36	25	20	20	20	20
Bundle B0 (/partial)	112/77	183/109	254/138	440/189	606/249	242/131	238/130	238/130
Bundle B1 (/partial)	150	176/120	256/155	434/224	587/300	248/129	235/117	235/114

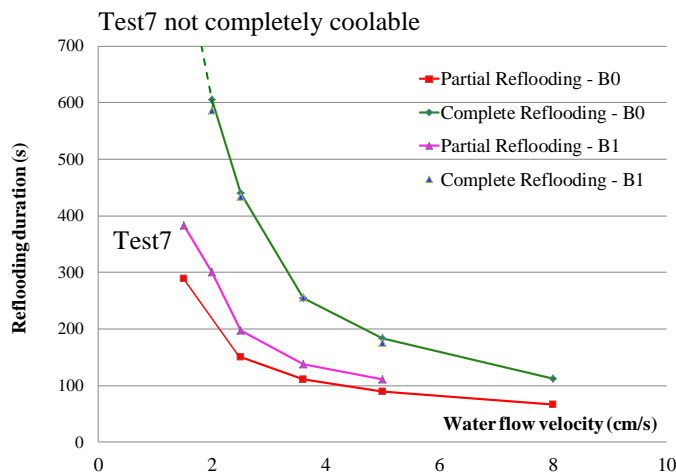


Fig. 16: Duration of reflooding as function of water flow rate

The time for a complete reflooding is decreasing as function of the increase of the inlet water flow velocity. Even for intact geometry, the configuration was not completely coolable for very low flow rate and low pressure (1,5cm/s-3bar). As the quench front propagation stopped at level 1.85m, the red curve indicates the duration of the partial reflooding (just above the blockage area) which showed a similar trend as that was observed for debris bed reflooding (Fig. 16 of [20]).

The reflooding duration is slightly increased for the bundle including a partially blocked area at least for the partial reflooding. The total reflooding is not affected by blocked area and depends only on the inlet water flow velocity. The quench propagates slowly when the water arrived in front of the blocked area due to the increase of the local power and the flow diversion, nevertheless above this region the quench front propagates faster for deformed bundle due to the reduction of the residual power in the second part of the bundle resulting to a quasi-same time for a complete reflooding for B0 and B1.

For the same flow velocity, the pressure of the system above 10 bar (Test 23, 20 and 21) seems to have weak impact on the efficiency of the reflooding. The impact occurred mainly between 3 and 10 bar.

Regarding those preliminary simulations the largest effect of the increase of the water supply occurred for flow velocities between 1 and 4 cm/s whereas the benefit of the increase of water supply seems to be weak between 4 and 8 cm/s, situation which was experimentally observed for debris bed reflooding experiment such as PRELUDE [20] or PEARL experiments.

The critical point for the coolability of the fuel assembly seems to be ranged for inlet flow velocity between 1 and 2 cm/s ( $\approx 10$  and  $20 \text{ kg/m}^2/\text{s}$ ). At the moment, the results giving by the code have shown the non-coolability of the blocked region for such low flow rate at low pressure, at least for the upper part of the bundle. The results of the COAL experiments will bring important information to confirm the amount of water supply needed for such a configuration during a LOCA transient in a Pressurized Water Reactor.

#### 4. CONCLUSION

This paper presents the new COAL experiments on the reflooding of a deformed fuel bundle with simulation of the fuel fragments relocation inside the balloons. We have described the test section, the thermal hydraulics parameters for the experiments and some pre-calculations (B0 and B1 bundle) using DRACCAR code developed by IRSN, in order to prepare the experiments planned from 2018 to 2020.

The preliminary calculations have shown the limit of the coolability of the bundle for a flow velocity ranging from 1,5 to 2 cm/s, at least for the first bundle configuration (moderate bundle deformation). The pre-calculation of the largest blocked bundle (90% and long ballooning with the B2 bundle) will be performed in the next step.

The thermal hydraulics behavior (temperature evolution, quench front propagation..) observed with the numerical simulation has to be compared with the future experimental COAL results. The results of these experiments will help to improve and validate the heat exchange models implemented in the code studying the reflooding process and the behavior of the code in such a configuration to be used to nuclear power plants for safety applications.

In addition to the COAL experiments, it is foreseen to perform specific separate-effect-tests at the sub-channel scale [21] in order to improve our understanding on different processes involved in the reflooding of a deformed fuel assembly, which is not possible, at least more difficult to get from an integral experiment.

#### NOMENCLATURE

**COAL** : COolability of a fuel Assembly during Loca

**FEBA**: Flooding Experiments with Blocked Arrays

**LOCA**: Loss Of Coolant Accident

**SEFLEX**: Simulator Effects in Flooding Experiments

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## APPENDIX A

Most of the tests for Large Break LOCA will be performed around 2 and 3 bar (fig. 17a), whereas tests for smaller break size conditions the COAL tests are planned to be performed from 5 up to 30 bar, system pressure which corresponds for a LOCA of a 5 inch break size (Fig. 17b).

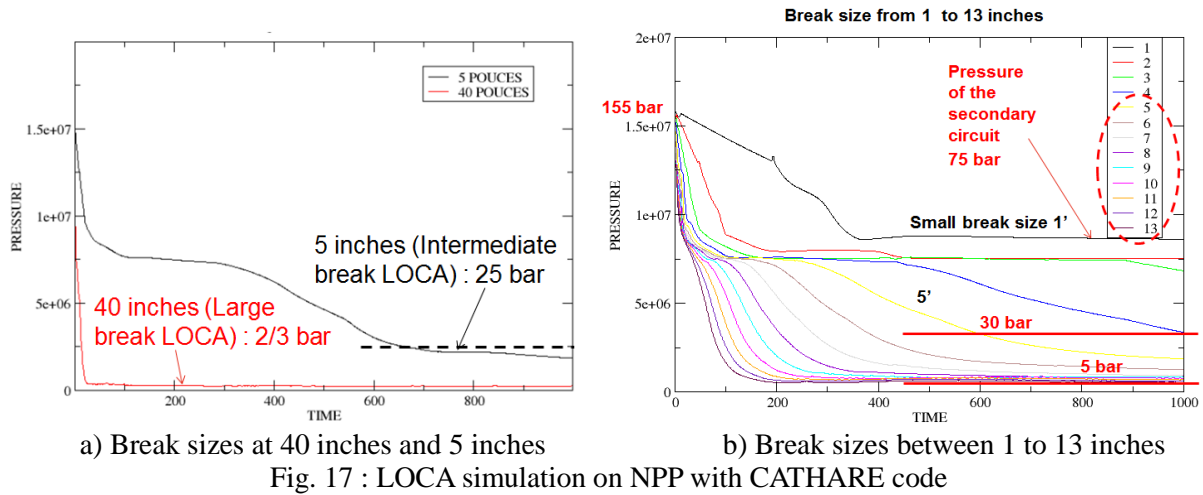


Fig. 17 : LOCA simulation on NPP with CATHARE code

Figure 17 b) gives the pressure evolution during a LOCA transient for different break sizes: with the maximum pressure (at 30 bar) foreseen for the COAL experiments, we cover most of the sequence (except for those at very small break size, lower than 5 inches).

## APPENDIX B

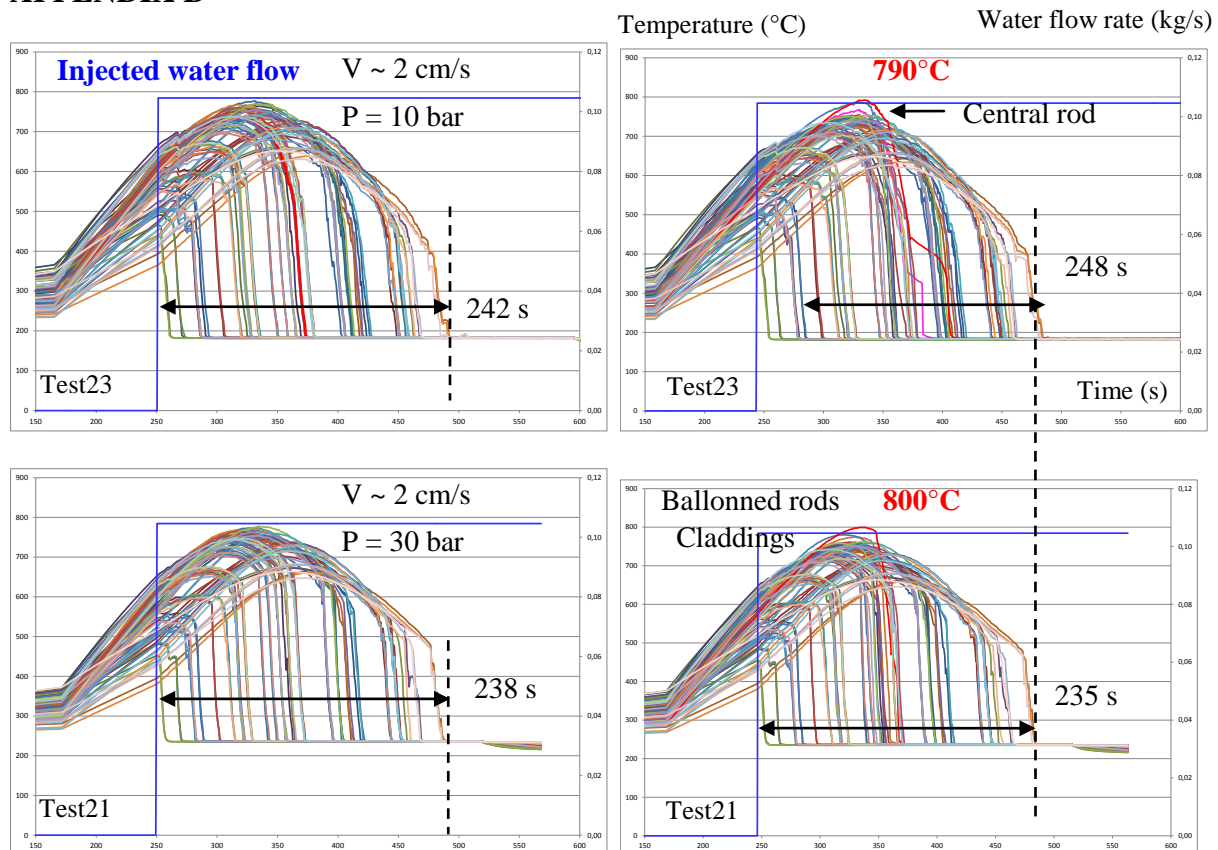


Fig. 18 : Temperature evolution given by DRACCAR simulation (at high pressure).

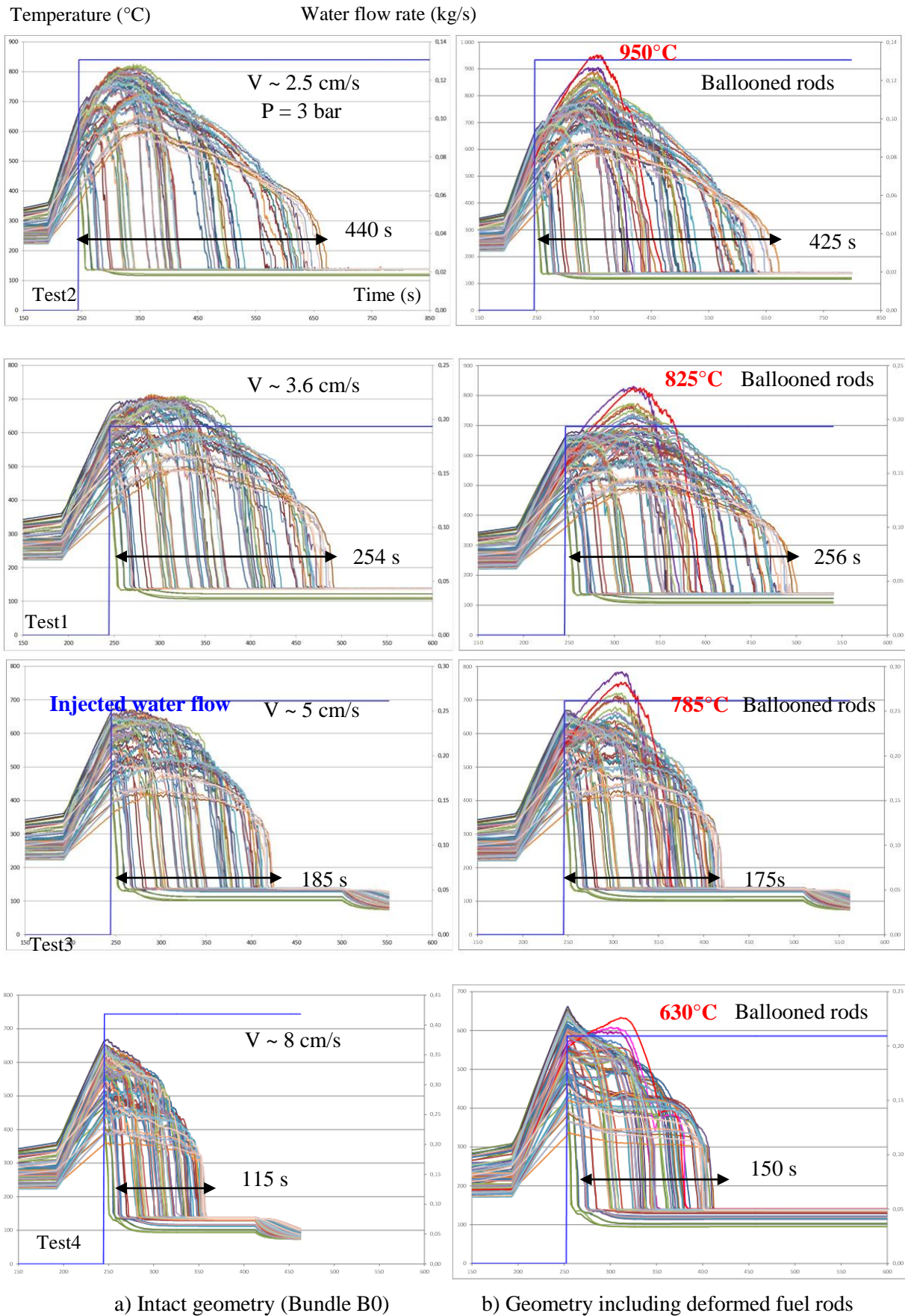


Fig. 19 : Temperature evolution given by DRACCAR simulation (at low pressure 3 bar)

## APPENDIX C

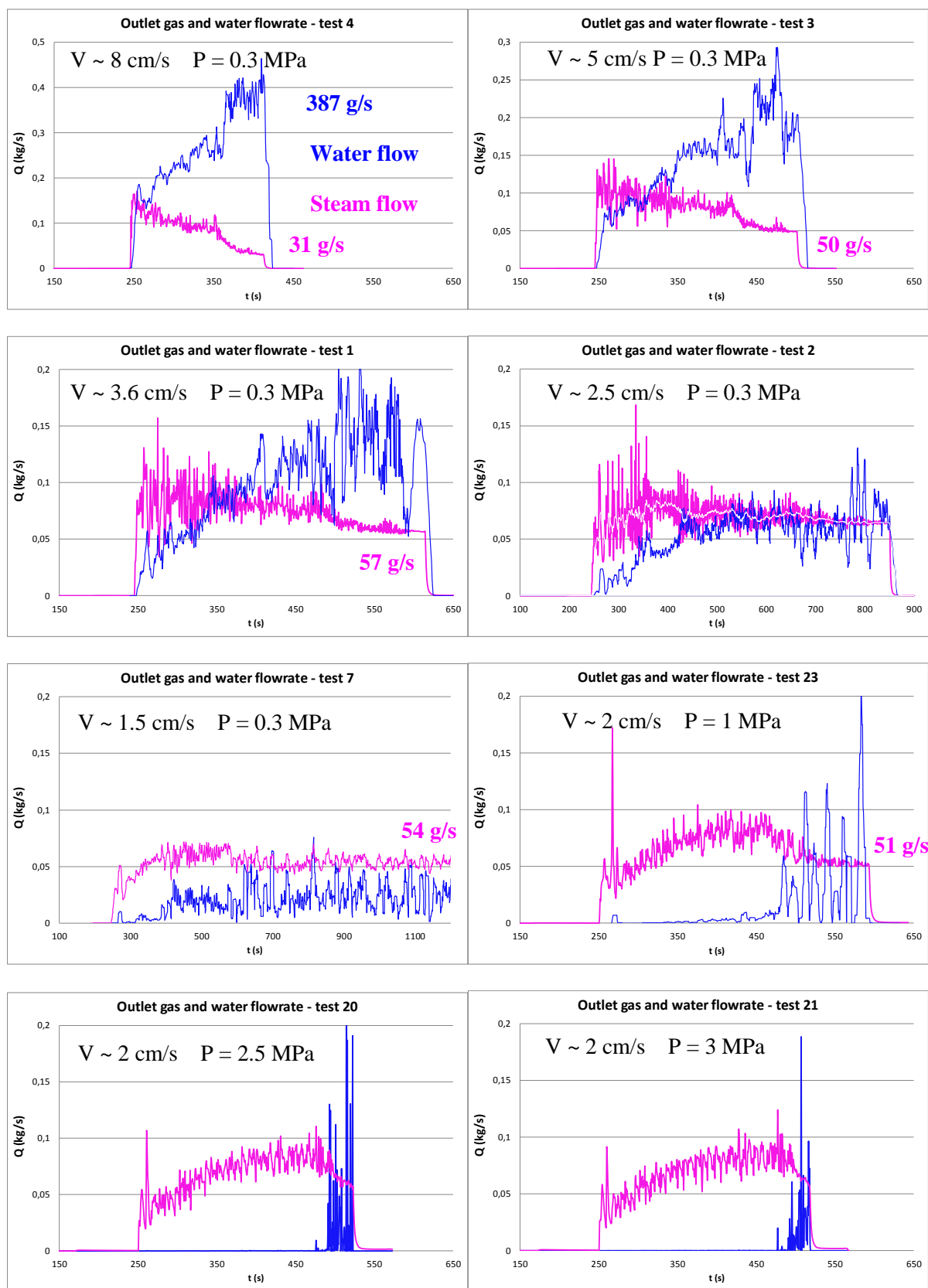


Fig. 20 : Outlet flow rate evolution (steam and water) given by DRACCAR simulation.