



**HAL**  
open science

**CORE COOLABILITY IN LOSS OF COOLANT  
ACCIDENT: THE COAL EXPERIMENTS  
INVESTIGATING THE THERMAL HYDRAULICS  
OF A ROD BUNDLE WITH BLOCKED AREA  
DURING THE REFLOODING**

Georges Repetto, Tony Glantz, Gaétan Guillard, Benoit Bruyère, Quentin  
Grando

► **To cite this version:**

Georges Repetto, Tony Glantz, Gaétan Guillard, Benoit Bruyère, Quentin Grando. CORE COOLABILITY IN LOSS OF COOLANT ACCIDENT: THE COAL EXPERIMENTS INVESTIGATING THE THERMAL HYDRAULICS OF A ROD BUNDLE WITH BLOCKED AREA DURING THE REFLOODING. 2017 International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), American Nuclear Society, Sep 2017, Xi'an, China. irsn-04474794

**HAL Id: irsn-04474794**

**<https://irsn.hal.science/irsn-04474794v1>**

Submitted on 23 Feb 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

# **CORE COOLABILITY IN LOSS OF COOLANT ACCIDENT: THE COAL EXPERIMENTS INVESTIGATING THE THERMAL HYDRAULICS OF A ROD BUNDLE WITH BLOCKED AREA DURING THE REFLOODING**

**G. Repetto \*, T. Glantz, G. Guillard, B. Bruyère and Q. Grando**

Institut de Radioprotection et de Sûreté Nucléaire  
Cadarache, BP3, 13115 Saint Paul lez Durance, France

\* Corresponding author: [georges.repetto@irsn.fr](mailto:georges.repetto@irsn.fr)

## **ABSTRACT**

During an accident causing loss of the coolant of the primary circuit (LOCA) in a pressurized water reactor, partial or even complete drying of the fuel assemblies may lead to the fuel temperature increase, significant deformation and, consequently the rupture of the fuel rod claddings. In addition to the restriction of the flow area, the fragmented fuel relocation within the ballooned zone leads to an increase of the local residual power. The COAL experiments will focus on the outstanding issue of the coolability of a partially deformed fuel assembly, in particular the study of the thermo hydraulic behavior during the cooling phase by water injection with the safety systems.

Competing influences due to the presence of a blockage will be evaluated through integral experiments using a 7x7 bundle of electrically heated rods. In one hand, the reduction of the cross-section between the deformed fuel rods will increase the flow velocity and consequently the heat transfer. On the other hand, the flow bypass of the blocked region, towards the periphery of the fuel assembly will lead to a reduction of mass flow in the sub channels of the blockage and therefore the cooling capacity.

This paper presents the scenario and the pre-calculations of the COAL experiments using the 3D DRACCAR code coupled to the CESAR thermal hydraulics module developed by IRSN. 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.

## **KEYWORDS**

Coolability, blockage, LOCA, Fuel relocation, DRACCAR

## **1. INTRODUCTION**

During an accident causing loss of the primary coolant (LOCA) in a pressurized water reactor, partial or even complete dryout 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, 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 [2], in the ORNL Tests (USA) [3] for various burnups and, more recently, in Halden (Norway) [4] at 90 GWd/t 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 whole core coolability. 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 with representative rods ballooning with irradiated fuels (simulated by electrical rods). 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 [6], SEFLEX [7], THETIS [8,9] and ACHILLES [10]) were not representative enough (rod thermal inertia and fuel relocation was not taken into account), the need of such complementary experiments have been proposed in 2005 by IRSN [11,12]. DRACCAR [13, 14], developed by IRSN with the support of EDF, 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 surrounding shrouds. It is based on an axial discretization of the rod which leads to analyze quasi-independent 2D thermal mechanical problems.

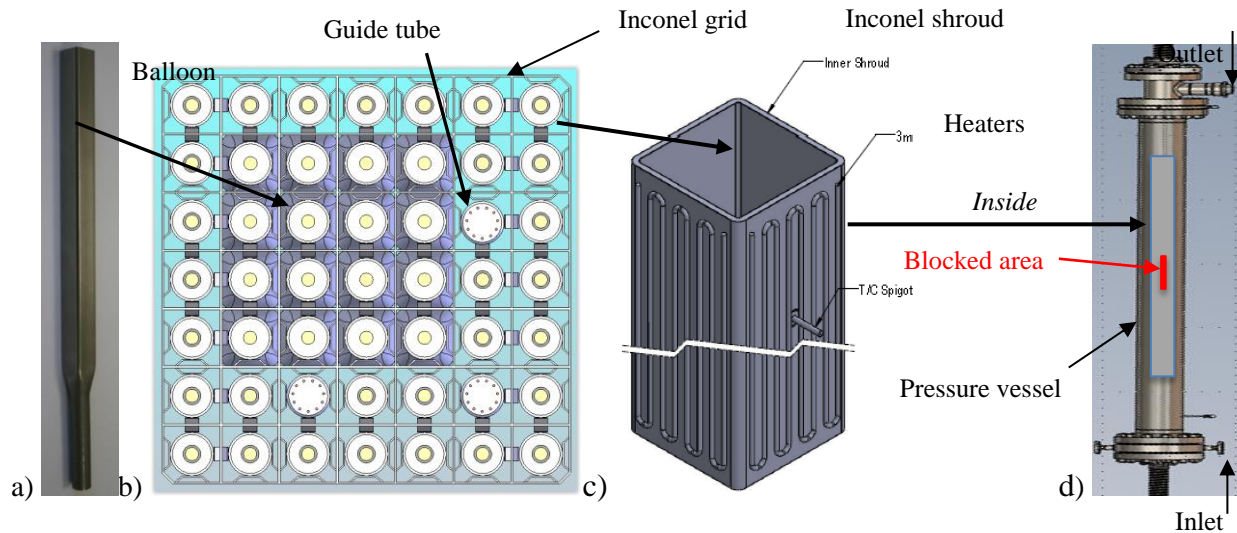
Important features such as pellet eccentricity, heat transfers (within the solid and through the fluid) or material properties evolution (oxidation layer, phase changing,...) can be taken into account and the cladding integrity during a LOCA transient can be addressed even in case of contact between 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 [15], 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 exchanges between the wall and the fluid which have been validated against PERICLES and ACHILLES tests.

## **2. THE COAL EXPERIMENTS**

The COAL experiments, in the frame of the PERFROI project [16-17] will concern thermal hydraulics experiments on electrically heated rods, with simulation of large blockage and fuel relocation.

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

The COAL bundle [18] will consist of rods (electrically heated), some with a pre-deformed zone (Fig. 1a) with local overheating representing fuel relocation. The bundle will be made of 49 (7 x 7) rods (including in the center 16 deformed rods, 30 non-deformed rods and 3 guide tubes (Fig. 1b)). The presence of 3 guide tubes will increase the representativity of the thermal hydraulics behavior for the reactor case (Fig.3 of [17]) 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) each 500 mm apart. 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 and including mixing vanes that would have an effect of thermal hydraulic behavior.



**Figure 1. Experimental device (deformed rod, bundle, shroud, test section)**




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 and including mixing vanes that would have an effect of thermal hydraulic behavior. The presence of guide tubes is also necessary for instrumentation and for mechanical reasons. The heated zone is about 3m high (close to the real PWR geometry). The bundle will be inserted in 94mm square electrically heated shroud (Fig. 1c) with roughly 4-5 mm thickness to be representative of the surrounding fuel rods regarding their thermal inertia. The test section will be included in a pressure vessel, (4m high, 220 mm diameter – Fig. 1d) with two lower and upper plenums for the electrical and instrumentation connections and the fluid supply. The COAL experiments will be performed in the AREVA BENSON facility at Erlangen (Germany) which allows running high system pressure tests to 3 MPa [18].

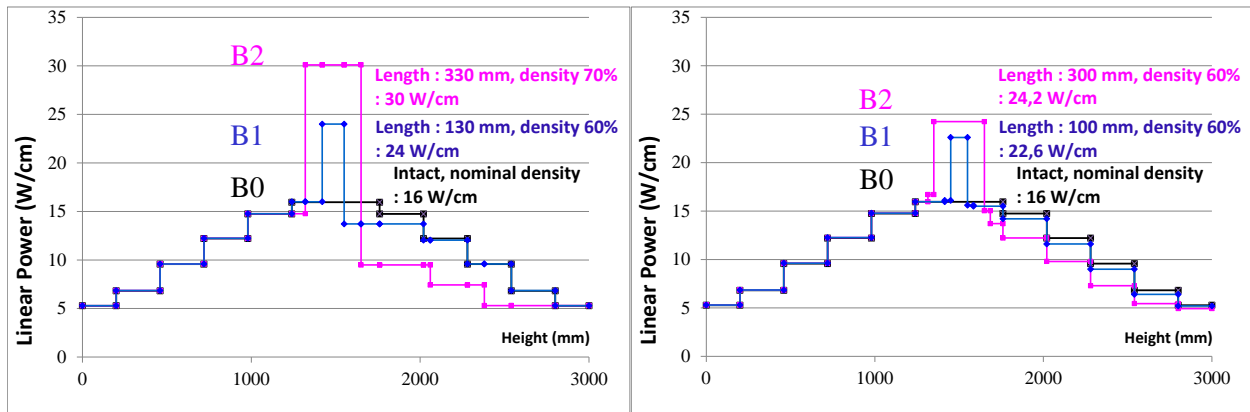
## 2.2. The geometry of the blockage and the axial power distribution

The experimental parameters of the test campaigns will be defined in order to investigate the bundle geometry related phenomena (blockage ratio, balloon length) and the thermal hydraulic related phenomena (local overheating of the balloon, injected water temperature, coolant flow rate and system pressure to simulate various break sizes). The geometrical parameters are reported in Table I below. The choice of geometries and the associated axial power distributions were designed to obtain a gradual evolution of the pressure drop in the ballooned zone and a gradual increase of the maximum linear power in the ballooned area of the fuel rods which constitute the different bundles (B0, B1 and B2). So, the configuration for the B2 bundle would be the worst conditions for the coolability concern. The axial power distributions were obtained by DRACCAR calculations which can simulate with some parameters the fuel relocation in the balloon (fuel filling ratio in the balloon) according the cladding deformation (Fig. 5 of [19]) and the corresponding power profile deformation (Fig. 2a).

Some modifications were done on the axial power profile, in particular for the bundle B2, as with the previous axial power profile, temperature in the balloons were too high compared to the technical limits of the electrical rods (roughly 1000°C) (cf § 3.3.1). For both the cases (B1 and B2), the powers in the connection from the non-deformed part to the part of the maximum deformation were reduced to take into account the real fuel inventory. In the balloon of the rods for the B2 bundle, the axial peaking factor was significantly reduced by assuming a density of 60% for the fuel relocation instead of 70% (both values were observed for irradiated fuels (Fig. 5 of [19])). The new proposition is illustrated by the Fig. 2b. Thus, we will change only one parameter between B1 and B2 bundles.

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

	Bundle B0	Bundle B1	Bundle B2
<b>Blockage ratio and rod shape</b>	0 % 	81% 	90% 
<b>Corresponding cladding deformation</b>	0%	48%	55%
<b>Total height of the ballooning zone</b>	Intact geometry	170 mm	370 mm
<b>Height of the maximal deformation</b>	-	100 mm	300 mm
<b>Maximum axial linear power (w/cm) First Proposal (fig. 2a)</b>	16 (cosine ref.)	24 (x 1.5)	30 (~x 1.9)
<b>Maximum axial linear power (w/cm) Second Proposal (Fig 2 b)</b>	16 (cosine ref.)	22,6 (~x 1.4)	24,2 (~x 1.5)
<b>Singular pressure drop coefficient of the ballooned zone</b>	0	11,58	47,24



a) First proposition

b) Second proposition

**Figure 2. Axial power profile for inner rods (cosine profile for outer rods)**

### 2.3. The test instrumentation plan

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

- Inlet and outlet water and steam mass flow rates (other two phase flow measurements such as void fraction, droplet size will be not available),
- Temperature of the fluid 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, temperature of the shroud, grids and guide tubes,
- Total pressure and pressure drop sensors at the periphery of the rod bundle.

Up to 184 thermocouples (4 each 46 rods) will be positioned every 10 cm to follow the quench front propagation (QFP). 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 face 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 a specific techniques developed by AREVA (vaporization of the droplets and measurement of the outlet steam flow by mean of a “venturi type” device. A thermal balance will allow the evaluation of water remaining at the outlet of the 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).

The bundle will be preheated up to 300°C by hot steam injection (step 1). As the shroud temperature has to be as close as possible to the rod temperatures 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°C (step 2 and 3) before the water injection phase (step 4). Rod power and water flow will be stopped for Step 5.

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

- ✓ inlet water flow velocity: 1,5 to 8 cm/s (15 to 80 kg/s/m<sup>2</sup>),
- ✓ sub-cooling water temperature: -60°C/0 to saturation conditions,
- ✓ coolant pressure: 0.2 to 3 MPa,
- ✓ power 3.3 kW \*, respectively 2 kW, per rod for Large Break (low pressure) scenario, respectively for Intermediate Break (high pressure) scenario.

The T/H conditions come from recent NPP CATHARE calculations (Table 1 of [18]) with different break sizes (1 to 40 inches) and conditions that were used for past programs such as PERICLES experiments.

## 2.5. The test matrix

The COAL test matrix referring to (Q, P) diagram where Q is the inlet water flow rate in kg/s/m<sup>2</sup> and P, the system pressure in bar is given in Fig. 3 below.

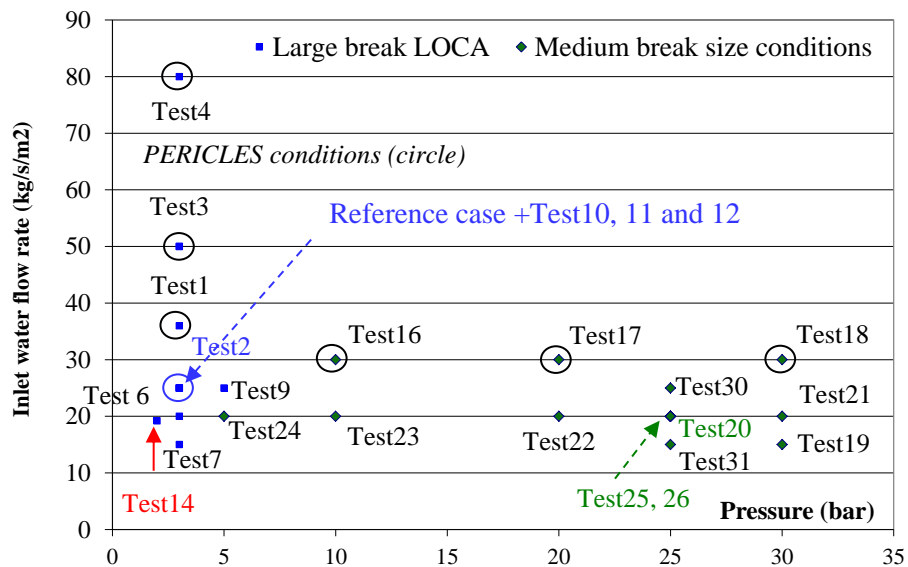


Figure 3. COAL test matrix in a (Q, P) diagram.

As the targeted number of experiments was initially too ambitious, optimization of the test matrix was necessary. 24 thermal hydraulics conditions were proposed to develop a test matrix for the reference bundle B0 (46 intact rods + 3 guide tubes “GT”). Some thermal hydraulics conditions (circle in Fig. 3) are similar to those of PERICLES experiments for comparison tests for past reference cases. Tests 10 to 12,

\* in order to simplify the test procedure, the power will be kept constant during the transient, nevertheless some tests could be performed with a reduction of power representative of the decrease of the residual power such as ACHILLES Tests [10]. One of their conditions will be reproduced with COAL Test 14 (0.2 MPa, 20 kg/s/m<sup>2</sup>).



Tests 25 and 26 will be focused to explore different thermal hydraulics boundary conditions, such as sub-cooling of the coolant (at low and high pressures), shroud temperature and initial temperature of the rods. Six tests (25%) will be repeated in order to investigate the reproducibility of the results.

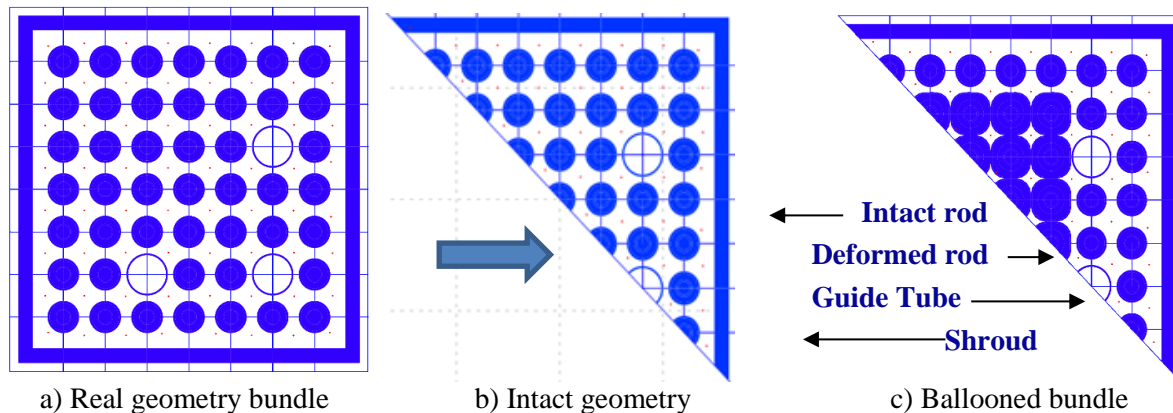
About 16 experiments (+4 repetitions) would be sufficient to test the effect of the pressure and the injection water flow rate with the bundles including the deformed rods (B1 and B2). The total number of tests will depend on the reliability of the rods and the thermocouples. As peripheral rods will be used for two experimental campaigns, these intact rods need to resist to roughly 50 (30+20) refloodings. So, the prototype of electrical rod, fabricated by the Stern Lab. Company (from Canada) has been tested successfully 55 times for various initial temperatures (from 600 to 900°C) at different flow rates.

### 3. PRECALCULATION USING THE DRACCAR CODE

The simulation tool DRACCAR, was used, at this stage, to define the parameters of the experiments such as the blocked bundle geometry, the deformed axial power profile and the heat-up scenario. Most of the tests of the test matrix have been simulated with DRACCAR code in order to prepare technical aspects for the COAL experiments (adaptation of the BENSON facility, to support the design of some equipment GT/rods and the test section design). All the physical models, used in these calculations, are described in detail in [20]. Thermal mechanical models are not activated, as the geometry is fixed (Table I).

#### 3.1. DRACCAR code modeling

The bundle is simulated on a height equivalent to the rod heated length, with a 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 the system.



**Figure 4. DRACCAR nodalization of the bundle**

DRACCAR is able to model each 46 electrical rods of the bundle and 3 guide tubes (Fig. 4a). Taking into account the symmetry of the test section, half a bundle is modeled (Fig. 4b). The ballooned bundle includes 16 rods with a local ballooning (Fig. 4c). In the balloon, the fuel fragments are simulated by a porous material which has a density, a heat capacity and a conductivity leading to properties (thermal inertia and conductivity) close to those of the UO<sub>2</sub> fragments. The calculation presented here, is composed of balloons that have a height of 100 (B1) and 300 mm (B2), at the middle of the bundle, combined to 80 (B1) and 90% (B2) blockage of the test section. The axial power profile imposed in the intact rods has a cosine shape (Fig. 3). The relocation in the balloon has been simulated by setting a specific axial deformation profile in the ballooned rods (Fig. 3). These 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 to simulate the two cones up and downstream the balloon: 35 mm each: two “50 mm” meshes for the 100 mm balloon and eight “37,5 mm” meshes for the 300 mm long balloon. Six grids are taken into account by setting a singular pressure loss at their positions.

### 3.2. Results of the DRACCAR simulation

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

- the temperature of the rods during the transient,
- the quench front propagation,
- and the duration of the cooling of the fuel rods.

#### 3.2.1. Temperature of the rods

The temperature evolution for B0 (intact geometry) and B1 bundles (moderate partially blockage area) were largely detailed in [19]. The results for reference cases (Test1 at low pressure: 0,3 MPa, 36 kg/m<sup>2</sup>/s and Test 21 at high pressure: 3 MPa, 20 kg/m<sup>2</sup>/s) are illustrated by the Figs. 12 a), b), c) and d) reported in the appendix A. Rod temperatures were roughly limited to 800°C during the whole transient, for which the residual power was maintain constant, in order to simplify the test procedure (3.3 kW for LBLOCA and 2 kW for IBLOCA conditions).

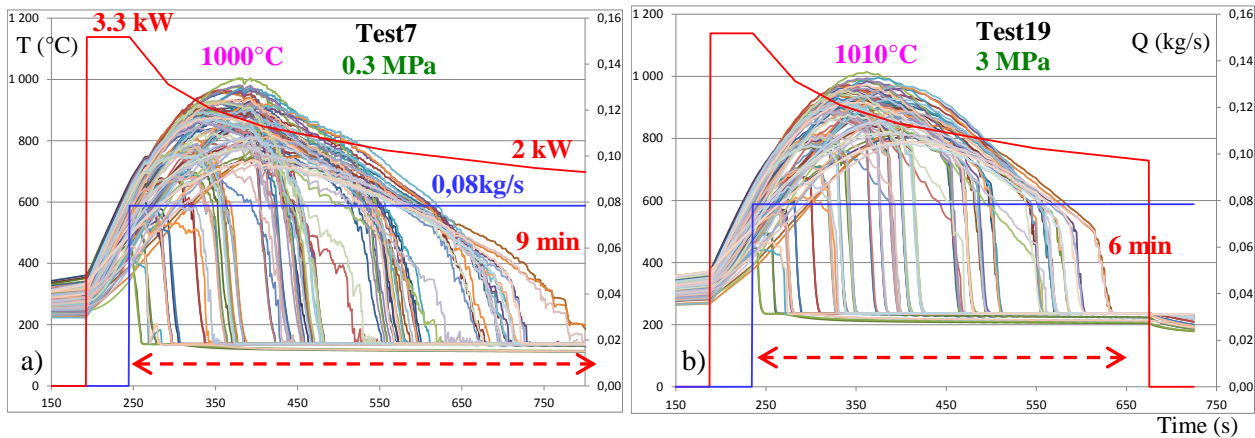


Figure 5. DRACCAR simulation for a low flow rate situation (low and high pressure)

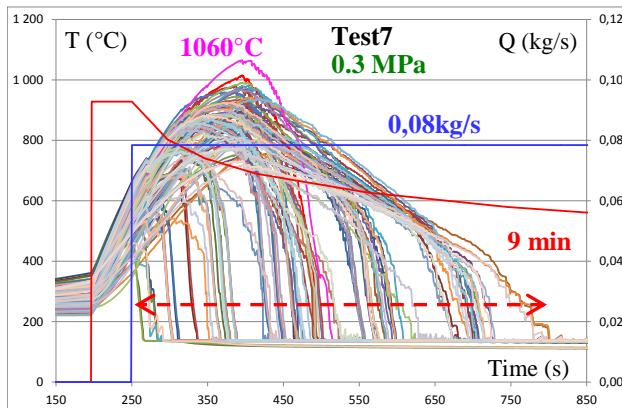


Figure 6. DRACCAR simulation at a low flow rate

The Test7 at low flow velocity (1,5 cm/s) and low pressure (0.3 MPa) for which the reflooding would be the less efficient has been simulated for the partially blocked (80%) bundle B1 (short balloon with moderate power increase).

Temperature in the balloon was increased by about 60°C (Fig. 6). This test that reached the technology limit of the electrical rod (1050°C) will be surely performed at the end of the experimental campaign.



Fig. 5, gives the results of the simulation for the two tests (Test 7 and Test 19) that will be performed at the lowest water flow rate (i.e. velocity at 1,5 cm/s). In these calculations, the real decrease of residual power is simulated and the maximum rod temperatures never exceed the limit of 1000°C. These two simulations performed at the same T/H conditions except the pressure show the effect of this parameter (0.3 and 3 MPa) on the efficiency of the reflooding process, by decreasing the time for a complete cooling of the fuel bundle by roughly 30% (9 minutes down to 6 minutes).

Some preliminary simulations were performed with the B2 bundle configuration representing the worst conditions for the coolability concern: the so-called long-ballooning (370mm), the largest blocked area (90% restriction of the fluid channel) and factor roughly 2 for the local power increase to simulate the fuel relocation in the balloon, with the largest rate of fragmented pellets observed for irradiated fuel rods. The results for reference cases (Test 1 at low pressure: 0,3 MPa, 36 kg/m<sup>2</sup>/s and Test 21 at the maximum pressure: 3 MPa, 20 kg/m<sup>2</sup>/s) are illustrated by the Figs. 12 g) and h) reported in the appendix A. The maximum temperature of the rods reached 900°C for the high pressure test whereas for the low pressure test the maximum temperature at the level of the balloons over past the limit of 1000°C for the electrical rods, even for moderate flow velocity ( $v = 3,6$  cm/s): it means that for all the cases at lower flow rate, internal rods will also over past this limit (Test 1, Test 2, Test 6, Test 7 and Test 19). In the particular test for very low flow rate 15 kg/m<sup>2</sup>/s (i.e.  $V = 1,5$  cm/s), with the nominal protocol, the maximum rods temperature exceeds the LOCA criteria (Table II). So, it was decided to decrease the specific power in the blocked area for the bundle G2 and to change the increase of the power from factor of 2 down to factor of 1,5 (cf § 2.2).

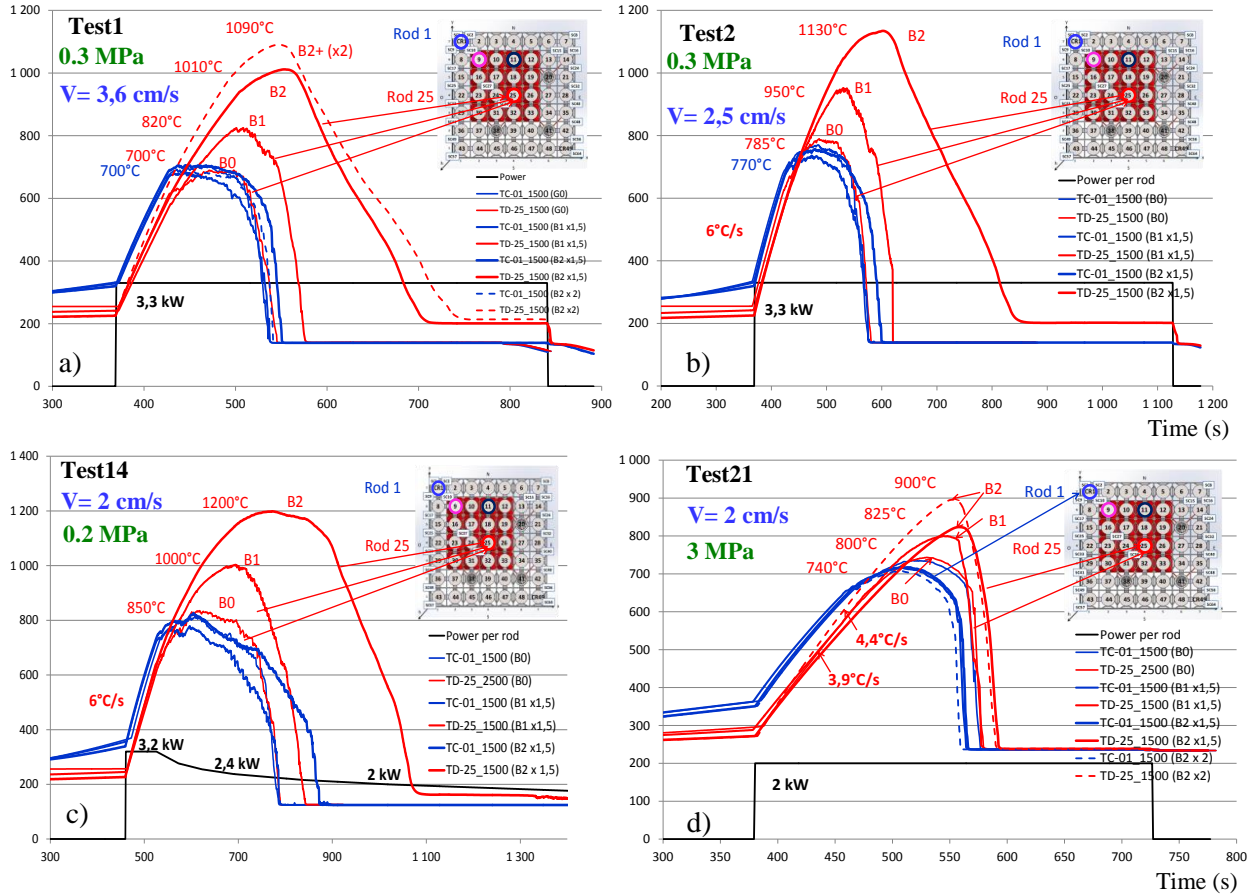
**Table II. Maximum clad temperature as a function of the blockage ratio and local power peak**

	<b>B0 (16 w/cm)</b>	<b>B1 (24 w/cm)</b>	<b>B2 (24 w/cm)</b>	<b>B2 (30 w/cm)</b>
<b>Test 7</b> (1,5 cm/s - 3 b)	1000°C	1060°C	1080°C	1240°C
<b>Test 14</b> (2 cm/s - 2 b)	860°C	1000°C	1200°C	
<b>Test 2</b> (2,5 cm/s - 3 b)	825°C	950°C	1130°C	
<b>Test 1</b> (3,6 cm/s - 3 b)	710°C	830°C	1010°C	1090°C
<b>Test 3</b> (5 cm/s - 3 b)	680°C	785°C		
<b>Test 19</b> (1,5 cm/s - 30 b)	1010°C	1060°C	1130°C	
<b>Test 21</b> (2 cm/s - 30 b)	780°C	800°C	825°C	900°C

The results (Test 1-0,3 MPa and Test 21-3MPa) for the new configuration for B2 bundle, are given by the Fig. 12 e) and f) reported in the appendix A. The decrease of the power in the balloon leads to lower temperature of about 80°C, nevertheless, maximum temperatures remain over 1000°C for all the cases at rather low flow rate (table II – column 4) for which we have to test the coolability of the partially blocked area. As, the so-called Test Protocol provides the power shutdown during the transient when the rod temperatures exceed 1000°C (to protect the electrical wires), those results need to change some parameters of the transient. One possibility could be to inject the water for lower initial temperature (500°C instead of 600°C). Another solution could be to modify the initial power.

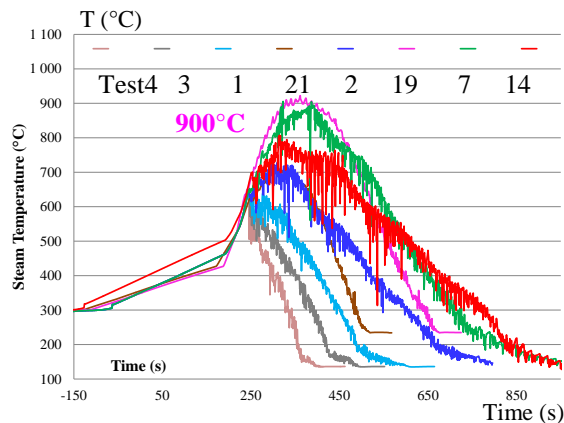
Fig. 7 summarizes temperatures at the middle elevation of the ballooned area for representative tests of the test matrix, as function of the geometry of the partially blocked area (B0, B1, B2 and B2+).

The red curves indicate temperature for internal rod (i.e n°25) in the ballooned zone, whereas the blue curves the corresponding temperature for external intact rod (i.e n° 1). The temperatures of the inner rod are increasing with the increase of the local power and the blockage, whereas the temperature at the periphery remain at rather lower temperature for both the cases (around 700 to 800°C) due to the bypass of the flow.



**Figure 7. DRACCAR temperature for different flow blockage (low and high pressures)**

For low pressure and velocity above 2 cm/s (respectively high pressure tests) the power is kept constant at 3,3 kW/rod i.e. 1 kW/m average (respectively 2 kW/rod) in order to simplify the test scenario (§2.4). The decrease of the power (representative of the residual power) is necessary for low flow rate (1,5 and 2 cm/s) at low pressure. In that case, when the water front reaches the blocked area, the power is roughly 2,4 kW. To reduce maximum temperatures and for simplification, this power transient could be simulated by a constant power fixed at 2,4 kW. So, to simplify the test procedure, it is proposed to perform all the tests for the LBLOCA conditions ( $P < 0,5$  MPa) at 2,4 kW and IBLOCA conditions (at 2 kW).

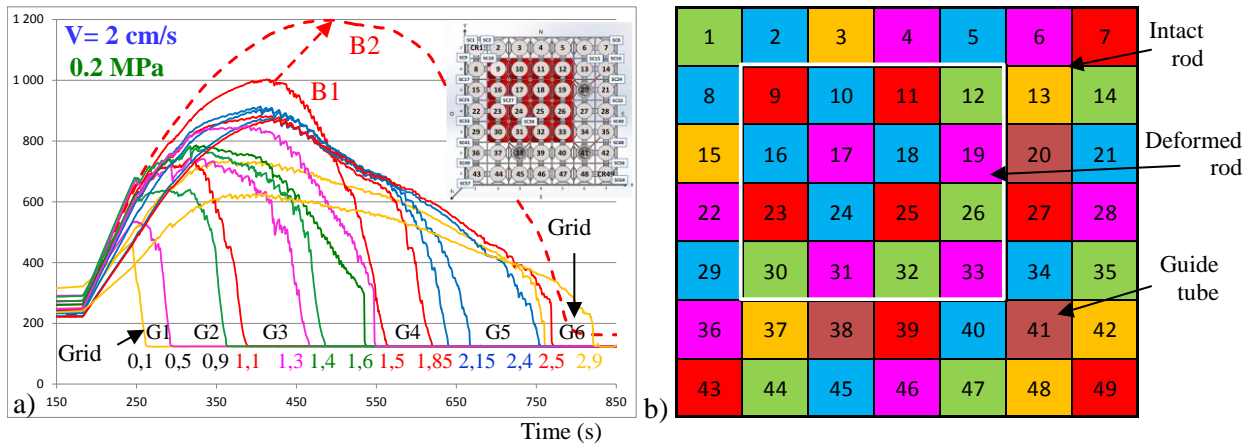


**Figure 8. Maximum steam temperature calculated by the DRACCAR code**

DRACCAR was also used for the design of the equipment of the test section. As an example, Fig. 8 illustrates the maximum temperature evolution of the fluid for different T/H conditions and shows that very high temperature (from 600 up to 900°C) are obtained during the reflooding phase, in particular for low water flow velocity ( $v = 1,5$  cm/s). This means that noble materials such as Inconel were chosen for the structure of the test section in order to have a corrosion resistance for running numerous experiments and for several test campaigns.

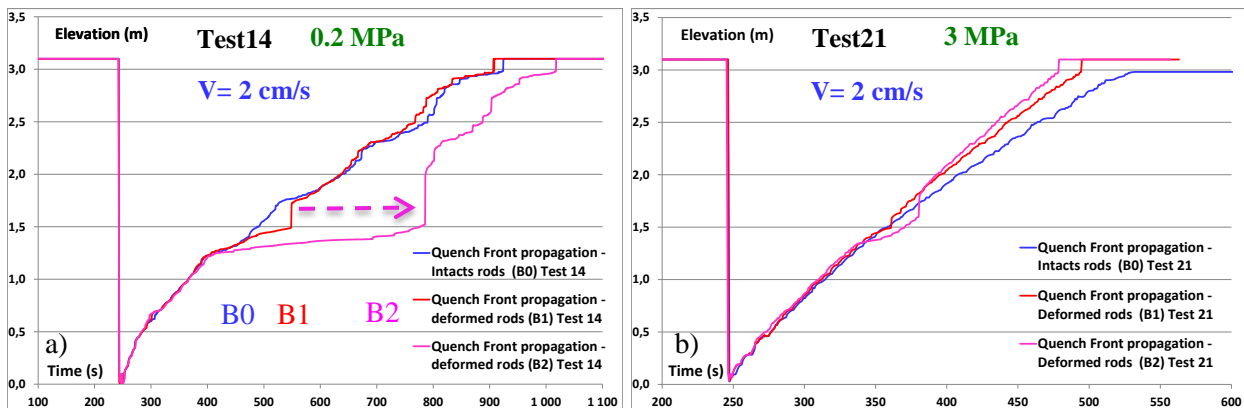
### 3.2.4. The quench front propagation and duration of the reflooding

Four types of series of internal rods with different positions (elevations) of thermocouples are foreseen in order to follow the quench front propagation (QFP) and to get from the experiment an overall thermal behavior of the temperatures. One additional type is foreseen for intact rods. Each series have the same instrumentation (4 Tc's at 4 elevations). Provisional distribution of the rods is illustrated by Fig. 9 b). Temperature evolutions, given by DRACCAR at the position of the thermocouples for different elevations (0.1 to 2.9 m) are illustrated in fig. 9a for Test14. Gx indicates the location of the six grids.



**Figure 9. DRACCAR simulation – quench front propagation (Example of Test14 for B1)**

Fig. 10 gives examples of the continuous quench front propagation from the bottom to the top (time for quenching versus elevation) for two tests representatives of LBLOCA (Test14) and IBLOCA (Test21).



**Figure 10. DRACCAR simulation – quench front propagation (low and high pressure)**

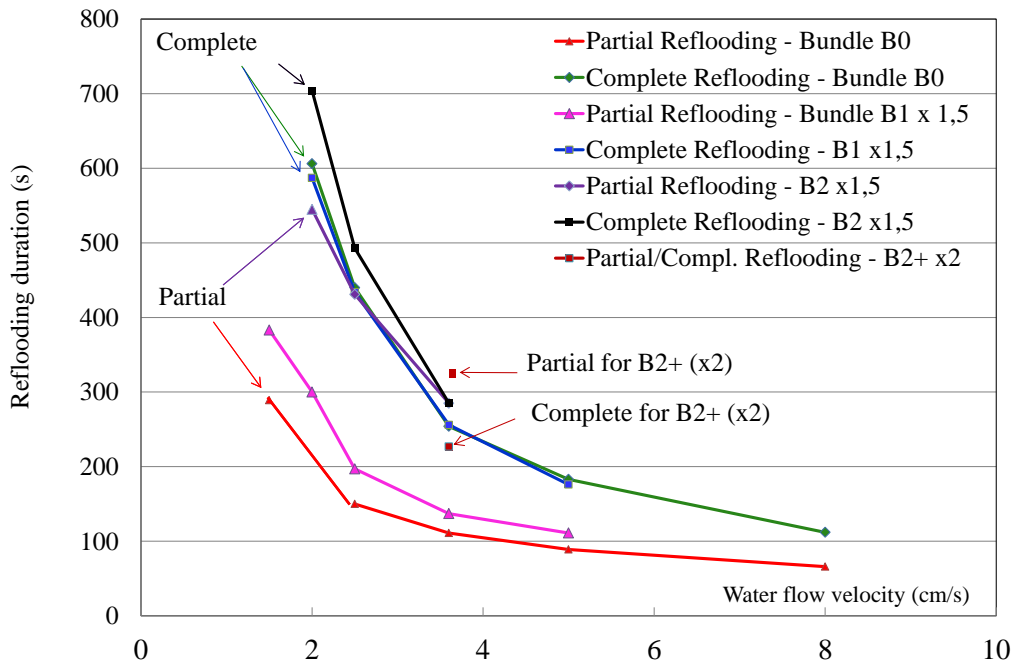
For the highest pressure (3 MPa), we observe a slight delay for the cooling of the blocked zone, but the complete reflooding is obtained earlier (Fig. 10 b) due to the acceleration of the QFP after the balloons (lowest power in the upper part of the bundle due to fuel motion in the fissile column). Whereas, for low pressure (0.2 MPa), due to the reduced efficiency of the heat exchanges, the reflooding of the partially blocked area is largely delayed (Fig. 10a) in particular for the so-called long ballooning (bundle B2) with the largest blocked area (90%). The reflooding of the blocked area (located in the middle part) takes roughly 300 s more. In that case, the maximum temperature reached 1200°C (Fig. 9 a) with 200°C more compared to the smallest balloon situation (bundle B1). This configuration seems to be the limit for the

coolability concern to respect the LOCA criteria for the maximum cladding temperature (i.e. 1204°C: 2200°F). On the basis of the numerous DRACCAR calculations, Table III summarizes the duration of the complete (and partial) reflooding for different tests as function of T/H conditions (pressure and water flow rate) and different bundles geometries (B0, B1, B2 and B2+ (maximum power in the balloons).

**Table III. Time for complete/partial 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
<b>Pressure (MPa)</b>	0,3 (3 bar)				0.2	1	2.5	3
<b>Water flow (kg/s/m<sup>2</sup>)</b>	80	50	36	25	20	20	20	20
Bundle B0 (comp/part.)	112/77	183/109	254/138	440/189	606/249	242/131	238/130	238/130
Bundle B1 (comp/part.)	150	176/120	256/155	434/224	587/300	248/129	235/117	235/114
Bundle B2 (comp/part.)			350/285	484/437	704/545		226/142	225/139
Bundle B2+(comp/part.)			227/329					227/143

The time for a complete reflooding is decreasing as a function of the increase of the inlet water flow velocity. The red curve indicates the duration of the partial reflooding when the quench front propagation reached the level 1.65 m (just above the blockage area). The duration of the reflooding of the blocked area is significantly increased in particular for the largest blockage (Bundle B2) for which the partial and the complete reflooding are roughly similar (Fig. 12 g in appendix A).



**Figure 11. DRACCAR simulation - duration of reflooding**

The partial reflooding occurs later than the complete reflooding for the so-called B2+ bundle (Test1 : Q = 36 kg/m<sup>2</sup>/s); it means that the quench front arrives at the top of the bundle whereas the partially blocked area remains not completely quenched due to the flow diversion and the high value of the local power simulating the fuel relocation.

The reflooding appears to be more efficient at high pressure. The pressure effect is mainly observed between 0.3 and 1 MPa (Table III). Above this pressure limit (1 MPa), as well as for the increase of the water flow rate (Fig. 11), the gain seems to be negligible.

## 4. CONCLUSION

This paper presents the new COAL experiments on the reflooding of a deformed fuel bundle with simulation of the fuel fragment relocation inside the balloons. We have described the test section, the thermal hydraulic parameters for the experiments and pre-calculations (B0, B1 and B2 bundles) using the 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 second bundle configuration (moderate power increase in the balloons which simulates the fuel relocation). The pre-calculation of the largest blocked bundle (90% and long ballooning with the B2 bundle) shows that in some cases, in particular for low water flow rates, the maximum clad temperature is close or even greater than the LOCA criteria. The reflooding appears to be more efficient at high pressure above a certain limit: this “finding” has to be compared to experimental results. The thermal hydraulics behavior (temperature evolution, quench front propagation...) observed with the numerical simulation has to be compared with the future experimental COAL results in order to bring more comprehensive understanding of these phenomena: those data 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.

Specific separate-effect-tests at the sub-channel scale are in progress in order to improve our understanding on different processes involved in the reflooding of a deformed fuel assembly, in particular the evaluation of the heat transfers taking into account steam charged with droplets [21, 22].

In addition to the COAL experiments, experiments at atmospheric pressure and in air conditions including droplet fields are foreseen to be performed in order to get information of the flow map around the partially blocked area, in particular the flow diversion, data which are not possible, at least more difficult, to get from an integral experiment.

## NOMENCLATURE

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

**LB and MB LOCA:** Large or Medium Break Loss Of Coolant Accident

**QFP:** Quench Front Propagation

## ACKNOWLEDGMENTS

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

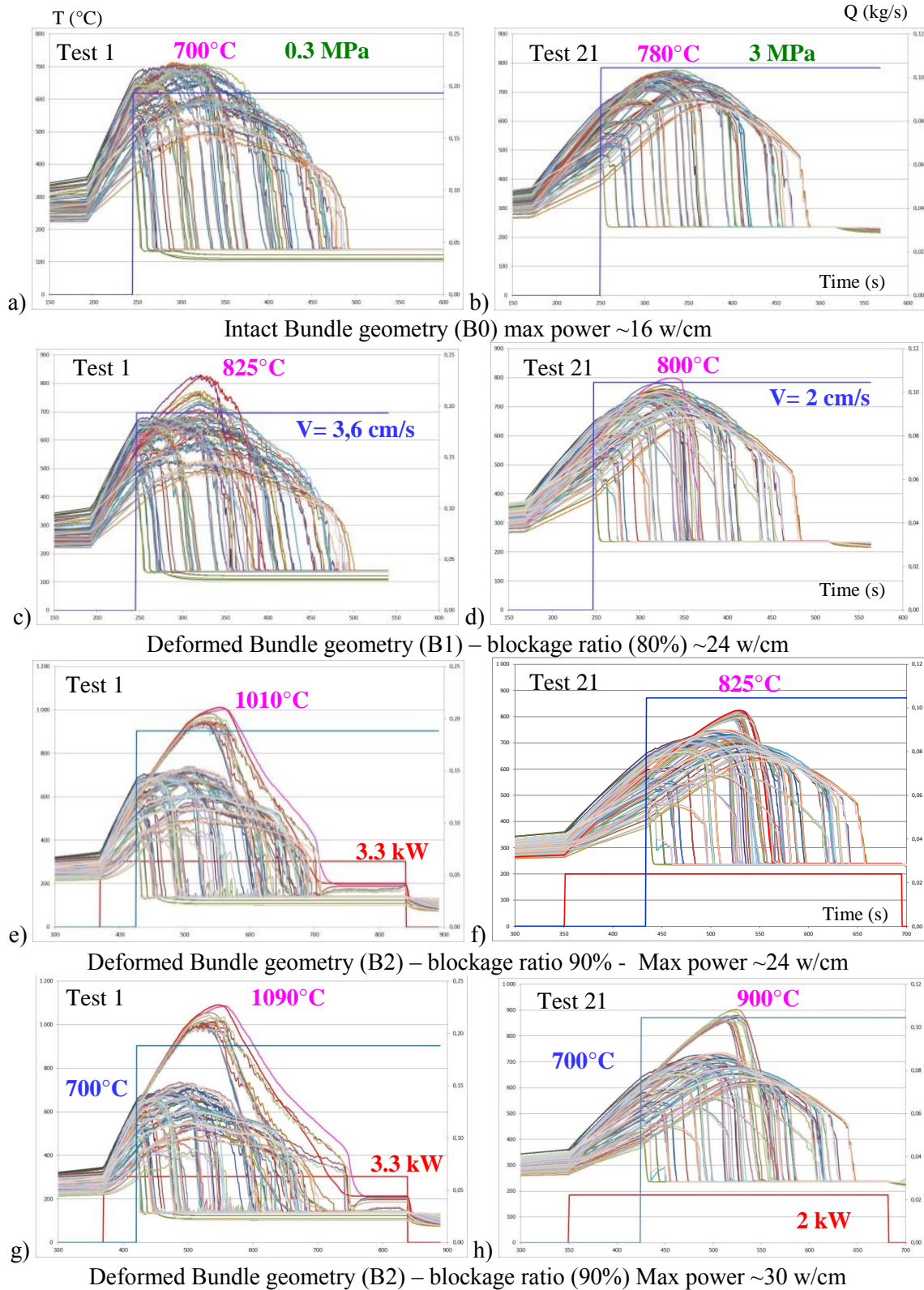
## REFERENCES

1. S. Bourdon, G. Repetto, S. Brethes, “Analyses of the Phebus-LOCA tests 215-R and 2018 using FRETA-F V1.1 code”, *Proceedings of Nureth11*, 02-06 October, Avignon France (2005).
2. E.H. Karb *et al.*, “LWR fuel rod behaviour in the FR2 in-pile tests simulating the heat up phase of a LOCA”, KfK 3346, March 1983
3. NUREG-2121, “Fuel fragmentation, relocation and dispersal during the loss-of coolant-accident”, US-NRC, data collected by P. Raynaud (2012)
4. L Kekkonen, “LOCA testing at Halden, the fourth experiment IFA-650.4”, OECD Halden Reactor Project, HWR-838 (2007)

5. G. Repetto, F. Jacq, F. Barré, F. Lamare, J.M. Ricaud, "DRACCAR: a new 3D-thermal mechanical computer code to simulate LOCA transient on Nuclear Power Plants - Status of the development and the validation", *Proceedings of ICAPP 2009*, Tokyo, Japan, May 10-14 (2009)
6. P. Ihle, K. Rust, FEBA "Flooding Experiments with Blocked Arrays. Evaluation Report KfK 3657, March (1984)
7. P. Ihle, K. Rust, SEFLEX - Fuel Rod Simulator Effects in Flooding Experiments. Part 1: Evaluation Report, KfK 4024, March (1986)
8. K.G. Pearson, C.A. Cooper, D. Jowitt, J.H. Kinneir, "Reflooding Experiments on a 49-Rod Cluster Containing a Long 90% Blockage, AEEW – R 1591, January (1983)
9. C.A. Cooper, K.G. Pearson, D. Jowitt - "The THETIS 80% Blocked Cluster Experiment. Forced Reflood Experiments - Part 3: AEEW – R 1765, September 1984 and "Gravity Reflood Experiments – Part 4: AEEW – R 1766, September (1984)
10. M.K. Denham, D. Jowitt, K.G. Pearson, "ACHILLES Un-ballooned Cluster Experiments – Part 1 : Description of the ACHILLES Rig, Test section and Experimental Procedures", AEEW-R2336, November (1989)
11. C. Grandjean, G. Repetto, F. Barré, "Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions, Main findings from a review of the past experimental programmes", *Proceedings of Nureth11*, Avignon France, 02-06 October (2005)
12. C. Grandjean, "Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions Main findings from a review of past experimental programs", *Nucl. Eng. Des.*, 237, pp. 1872-1886, September (2007)
13. S. Bascou et al., "Computational Analysis of Multi-pin Ballooning during LOCA and Post LOCA Transient using the Multi-physics Code DRACCAR", *Proceedings of Top Fuel Congress*, Manchester, United Kingdom, September 2-6, 2012, American Nuclear Society (2012)
14. J.M. Ricaud, N. Seiler, G. Guillard, "Multi-pin Ballooning during LOCA transient: A Three Dimensional Analysis", *Nucl. Eng. Des.*, 256 45-55 (2013)
15. N. Trégoures et al., "Reactor Cooling Systems Assessment of the ASTEC V1.3 code in Support to the French IRSN PSA-2 on the 1300 MWe PWR", *Nucl. Eng. Des.*, 240 p1468-1486
16. G. Repetto et. al, "Core coolability in loss of coolant accident: the PERFROI project", *WRFPM-TopFuel14*, Sendai, Japan, September 14-17 (2014)
17. G. Repetto et. al, "The R&D PERFROI project on Thermal mechanical and thermal hydraulics behaviors of a fuel rod assembly during a Loss Of Coolant Accident", *Proceedings of Nureth16*, Chicago, USA, August 30-September 4 (2015)
18. G. Repetto, Ch. Marquié, B. Bruyère, T. Glantz, "The core coolability in a Loss Of Coolant Accident: the COAL experiments", *Proceedings of Nureth16*, Chicago, USA, August 30-September 4 (2015)
19. G. Repetto, B. Bruyère, S. Eymery, T. Glantz, "Thermal hydraulics behavior of a rod bundle with partially blocked area during the reflooding phase of the Loss Of Cooling accident", *11<sup>th</sup> International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety*, Gyeongju, Korea, October 9-13 (2016)
20. T. Glantz, T. Taurines, G. Guillard, O. De Luze, S. Belon, F. Jacq, DRACCAR: a multi-physics code for computational analysis of multi-rod ballooning and fuel relocation during LOCA transient. Part one: General modeling description, *Nucl. Eng. Des. (to be published)*
21. J.D. Pena Carrillo, T. Glantz, G. Repetto, M. Gradeck, A. Labergue, "Experimental study on heat transfer inside a blocked region of a rod bundle during LOCA", *11<sup>th</sup> International Topical Meeting on Nuclear Reactor Thermal Hydraulics Operation and Safety*, Gyeongju, Korea, October 9-13 (2016)
22. J.D. Pena Carrillo, T. Glantz, G. Repetto, M. Gradeck, A. Labergue, "Study on heat transfer inside a blocked region of a rod bundle during LOCA - Model and experimental approach", *11<sup>th</sup> International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, Xi'an, China, September 3-8 (2017)



**APPENDIX A: DRACCAR simulations for different bundle configurations**



**Figure 12. Synthesis of DRACCAR simulations - rod temperatures for low and high pressures tests**