THE R&D PERFROI PROJECT ON THERMAL MECHANICAL AND THERMAL HYDRAULICS BEHAVIORS OF A FUEL ROD ASSEMBLY DURING A LOSS OF COOLANT ACCIDENT

G. Repetto, C. Dominguez, B. Durville, S. Carnemolla
Institut de Radioprotection et de Sureté Nucléaire,
Cadarache, 13115 , BP3 ,Saint Paul lez Durance, France
georges.repetto@irsn.fr; cristina.dominguez@irsn.fr; benoit.durville@irsn.fr

D. Campello [1], N. Tardif [2]
1) Laboratoire de Mécanique des Contacts et des Structures- LaMCoS
2) Laboratoire de Génie Civil et Ingénierie Environnementale
Institut National des Sciences Appliqués - Lyon
27 avenue Jean Capelle F69621, Villeurbanne CEDEX , France
damien.campello@insa-lyon.fr; nicolas.tardif@insa-lyon.fr

M. Gradeck
Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, LEMTA
Université de Lorraine
2, avenue de la forêt de Haye - BP 160, 54518 Vandoeuvre les Nancy Cedex - France
michel.gradeck@univ-lorraine.fr

ABSTRACT

The safety principle in case of a LOCA is to preserve the short and long term coolability of the core. The associated safety requirements are to ensure the resistance of the fuel rods upon quench and post-quench loads and to maintain a coolable geometry in the core. An R&D program has been launched by IRSN with the support of EDF, to perform both experimental and modeling activities in the frame of the LOCA transient, on technical issues such as:

- flow blockage within a fuel rods bundle and its potential impact on coolability,
- fuel fragment relocation in the ballooned areas: its potential impact on cladding PCT (Peak Cladding Temperature) and on the maximum oxidation rate,
- potential loss of cladding integrity upon quench and post-quench loads.

The PERFROI project (2014-2019) focusing on the first above issue, is structured in two axes:

1. axis 1: thermal mechanical behavior of deformation and rupture of cladding taking into account the contact between fuel rods; specific research at LaMCoS laboratory focus on the hydrogen behavior in cladding alloys and its impact on the mechanical behavior of the rod;
2. axis 2: thermal hydraulics study of a partially blocked region of the core (ballooned area taking into account the fuel relocation with local over power), during cooling phase by water injection; More detailed activities foreseen in collaboration with LEMTA laboratory will focus on the characterization of two phase flows with heat transfer in deformed structures.

KEYWORDS
Coolability, LOCA, cladding deformation, rupture, fuel relocation.

1. INTRODUCTION AND CONTEXT OF THE PROJECT

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. Fuel fragmentation may occur, leading to fuel relocation within the ballooned area. Depending on the burnup of the fuel rod, extensive fragmentation may also lead to fuel particles dispersal into the coolant through the ruptured cladding. Depending on the size and the distribution of the ballooned areas within the fuel bundle, the cooling flow might be impaired, which may challenge the fuel assembly coolability and, by extension, the core coolability.

The results (Fig.1), which illustrate this phenomenon (deformation of a fuel rod assembly), come, in particular but not only, from an experimental LOCA program performed, in the 1980's by the Institut de Protection et de Sûreté Nucléaire former IRSN (LOCA test 215-R [1] and reported in [2]), in 5x5 bundle including fresh fuel rods. All the LOCA experiments performed with irradiated fuel rods have shown fuel relocation [3]. Figure 2 gives an example for FR2-Germany [4] at burn up about 35 GWd/t. The resulting increase of the power density in the balloonned area may also affect the core coolability.

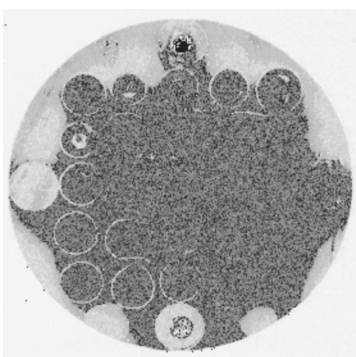


Figure 1.Bundle of deformed fuel rods
Phebus LOCA experiments (1983)

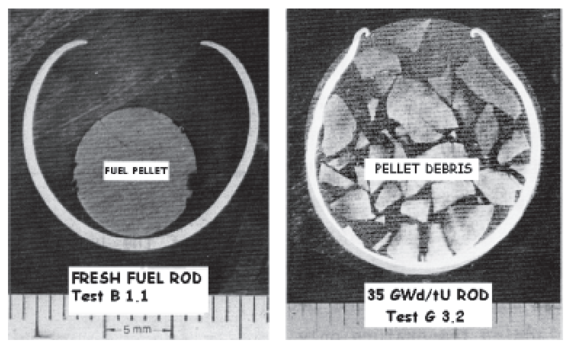


Figure 2. Fuel relocation in the ballooned area
FR2 Fuel rods fresh or irradiated (1983)

The consequences of deformations and fuel relocation on the cooling efficiency when reflooding the core by the ECCS (emergency core cooling systems) are important safety issues.
Fuel relocation, as observed in several in-pile LOCA tests with irradiated fuel and its potential impact on the local cooling of the blocked areas, have to be investigated and properly modeled.
The proposed research program is based on a state of the art review of the available experimental results.

The knowledge generated by this new project 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 to simulate any prototypical LOCA transient.

From a regulatory point of view, maintaining the short and long term core coolability is the primary requirement. More specifically, to fulfill this requirement, two criteria, which are calculable and representative of the expected physical phenomena related parameters, are usually taken into account: the Equivalent Cladding Reacted (ECR) and the maximum temperature of the cladding. The regulations often require these two values must not exceed a specific threshold during a prototypical LOCA transient. Compliance with these criteria is obtained through adapted methodologies and advanced simulation tools (carefully validated on specific experimental results).

As in other countries, LOCA rulemaking changes have been initiated in France to account for recent experimental results (impact of burn up on the LOCA limits, effect of fuel relocation on the peak cladding temperature, etc..) and to account for the fact that the current fuels are irradiated in more challenging operating conditions than in the 1970's when the former LOCA limits had been defined.
IRSN has produced a state of the art review of the R&D programs conducted during the last thirty years, especially the swelling and the rupture of the cladding [6], the impact of the fuel deformation on the cooling of fuel assemblies [7], the oxidation/hydriding and the mechanical resistance of the cladding during quench and post-quench loads [8]. This synthesis is the basis of the State Of the Art Report on LOCA [9]) showed the need of further experiments and identified three important issues (or pending questions) that must be addressed:

- What is the maximum ratio of blockage that can result from a LOCA and is the core still coolable with such a flow blockage?
- When and how the fuel fragments relocate in the ballooned areas? What is the impact of fuel relocation on the peak cladding temperature (PCT) and on the maximum oxidation rate?
- During and after the reflooding of the core, how to demonstrate long term coolability, taking into account base irradiation, transient oxidation and hydrogen pick up?

An R&D program (CYCLADES[*] [10]) was launched by IRSN with the support of EDF to provide answers to these three questions. This program includes both experimental activities and software development for simulation (DRACCAR [11 and 12]).

The PERFROI project proposes to answer the first question above. In scientific terms, the project aims firstly to quantify the thermal mechanical evolution of cladding in some specific configurations such as those involving contact between fuel rods or significant temperature gradients in the fuel rod environment, and to quantify the impact of fragmented fuel rods relocation in the balloon on cooling of the fuel assemblies during the reflooding. Specific research aims to study heat exchanges occurring between the walls of the deformed cladding and the two-phase flow in fog form (i.e. steam plus droplets); these heat exchanges conditioning temperature change in a fuel assembly. Antagonist influences due to the presence of a blockage will be evaluated. These influences result from the following physical phenomena:

- The flow bypass of the blocked region, due to the reduction of the section between the deformed fuel rods, leading to a reduction of mass flow in the sub channels of the blockage. This reduction limits the flow of the cooling capacity.
- The presence of water droplets in the steam flow may modify this trend. Their role in heat transfer is important, whether through the heat extracted at their impact on the walls or via their vaporization in the bulk flow. Due to their inertia, their paths do not necessarily follow that of the steam flow path.

2. STRUCTURE OF THE PERFROI PROJECT

As the need for further studies on two types of phenomena (mechanics and thermal hydraulics) has been shown above, the PERFROI project [13] has been structured in two axes:

Axis 1: thermal mechanical studies of the deformation and failure of fuel rods in LOCA conditions taking into account the effect of contact between rods and the effect of an azimuthal temperature gradient. The models or correlations describing the creep laws and rupture criteria from the results of these tests will be integrated in the DRACCAR software, for the assessment of the fuel assembly deformation.

[*] **C**haracterisation and **I**nvestigation for **I**mproved **C**alculation of **L**OCA **A**ddressing the **D**etermination and **E**valuation of **S**afety

The works that will be achieved in this axis are:

- Perform thermal mechanical creep and rupture tests. The main objective of these parametric tests (ELFE program - §3.1) is to assess the thermal mechanical properties of the cladding which will be used in the COCAGNE tests program (§3.2);
- Investigate the thermal mechanical swelling of cladding tubes simulating multi-rods configuration. This configuration (COCAGNE test program), never studied experimentally up to now, will provide us new insights regarding balloons formation before and after contact between adjacent rods. It will also quantify the effect of azimuthal temperature gradients;
- Define a cladding creep rupture criterion valid for multi-rods conditions, to be implemented in the DRACCAR code (Current criteria are based on single rod tests);
- Validate models against the results of these tests.

Small scale experiments at the "LaMCoS" research laboratory (INSA-Lyon) will focus on analysis of the hydrogen behavior in cladding alloys and its impact on the mechanical behavior of the fuel rod (§3.3).

Axis 2: thermal hydraulics behavior of a partially blocked core zone during the reflooding phase.

The works that will be achieved in this axis concern both semi-integral experiments and experiments at smaller sub-channel scale:

- Thermal hydraulic experiments will be performed in an out-of pile loop (COAL tests program (§4.1), including a bundle of electrical rods whose deformed areas are locally overheated to simulate the fuel fragments relocation. The results of these experiments will help to refine and validate the heat exchange models used in DRACCAR multi-physics code during the reflooding phases.

- More detailed activities on thermal hydraulic foreseen in collaboration with the LEMTA-Nancy research laboratory (University of Lorraine) will focus on the characterization of two phase flows with heat transfer in deformed structures (§4.2).

3. AXIS 1 :THERMAL MECHANICAL ACTIVITIES

3.1. ELFE experiments

The ELFE experimental results will permit to obtain the creep laws and the rupture criteria for different cladding materials useful for DRACCAR code input, but also to interpret the result of the upcoming COCAGNE experiments (§ 3.2).
ELFE experiments are performed in the FIGARO furnace (Fig. 3a) where the test section (Fig.3b) is heated at high temperature up to 1000°C. Those separate effect experiments are carried on 6 or 9 cm long samples (Fig. 3c).

Different zirconium alloys will be tested with different initial conditions:

- Alloys: Zry-4, M5™, Zirlo™
- State: as-received, hydrided, pre oxidized
- Microstructures : α, $\alpha + \beta$, β
- Temperatures : 700-1000°C
- Stresses : <100 MPa

Figure 3: a) ELFE facility b) Inside the furnace and c) Detail of the sample

During the tests, the temperature is measured by a K-type thermocouple directly welded at the centre of the inner surface of the specimen's gauge length. The strain is measured without contact by a laser extensometer that measure the position of ceramics marks sprayed on the specimen's surface (Fig 3c.). The mechanical load is monitored using a 2,5 kN load cell located inside the vacuum chamber.
Prior to the experimental program, qualification of the ELFE facility has been performed by the end of 2013.

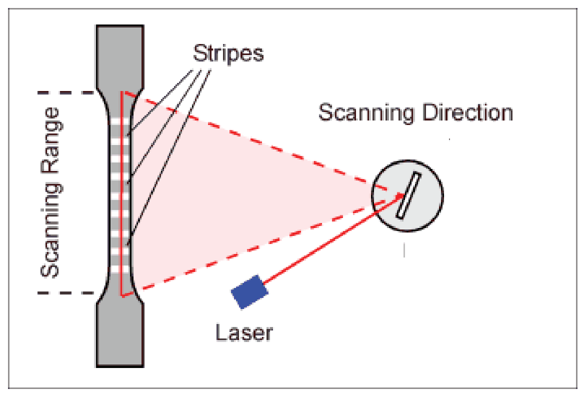


Figure 4: measurement of the deformation

Steady-state creep rates of bare zircaloy-4 fuel cladding were determined from 700 to 1000°C. At these temperatures, the Zircaloy shows three different phase ranges: α (up to temperatures close to 820°C), $\alpha + \beta$ (between 820°C and 970°C approximately) and β (from 970°C upwards). Isothermal creep tests were performed under vacuum atmosphere. Measures in the α and $\alpha + \beta$ ranges are consistent with the values given in the literature [14, 15] (Fig 5a - points in red, green, blue). The study of the tests performed in the β range is still in progress.

Figure 6 shows the evolution of Fe distribution (or distribution of the phases) with hold time at 850°C. At the beginning of the temperature plateau, both phases cannot be clearly distinguished. As the hold time increases, a small volume fraction of β phase can be observed at the α-grain boundaries.

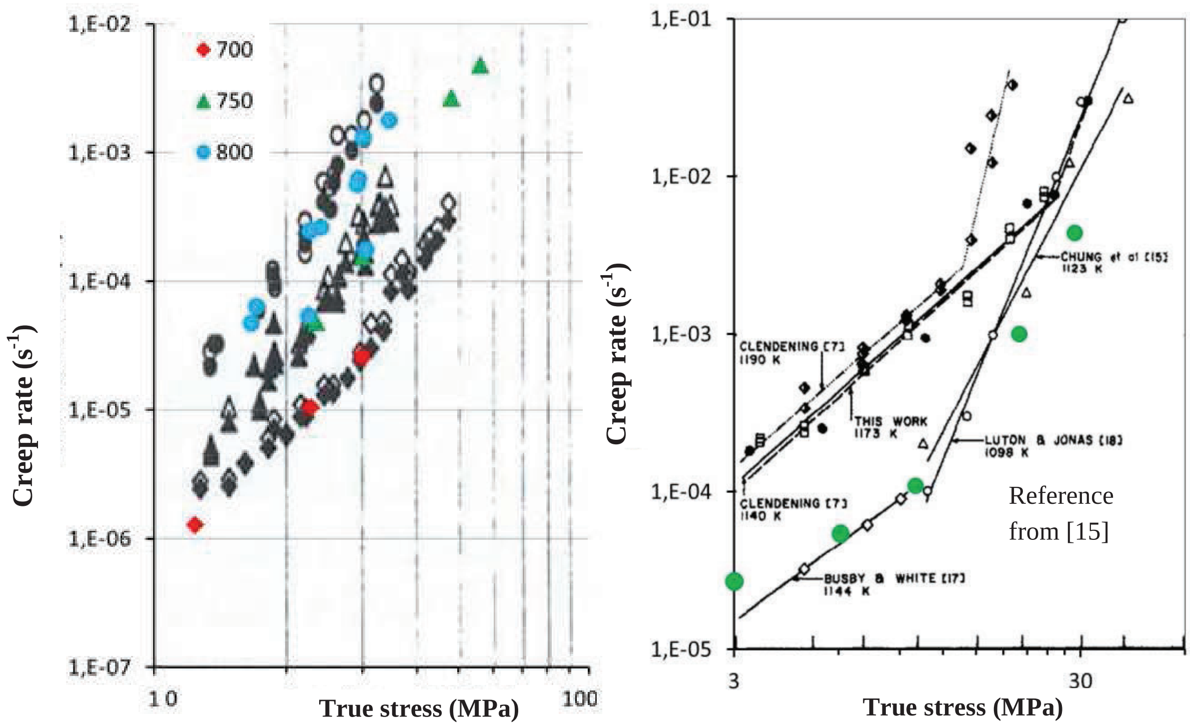


Figure 5- True strain as a function of true stress: a) Tests performed between 700 and 800°C versus Frechinet results ; b)Test performed at 850°C versus Rosinger's data collection

Longer hold times result in an increase in the thickness of the β film. Consequently, the microstructure of the cladding in the α + β phase range changes during the test as previously observed by Garde [16].

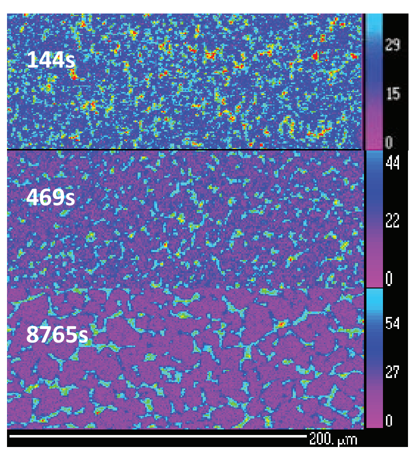


Figure 6- Phase α (purple) and phase β (light blue) distribution as a function of time exposure at 850°C.

ELFE program will continue with isothermal creep tests on pre-oxidised and pre-hydrided zircaloy-4 followed by thermal transient tests (1-5 °C/s) on bare zircaloy-4 during 2015.
Then, other cladding materials (M5^{TM} and Zirlo^{TM} if available) will be studied later 2016 and 2017.

3.2. COCAGNE experiments

The objective of these experiments (constituting the second part of the thermal mechanical axis of PERFROI) is to get precise knowledge of the three-dimensional mechanical behaviour creep of pressurized rod surrounded by structures simulating four neighbouring fuel rods to obtain a geometrical and thermal representative environment. Current criteria are based on single rod tests, and the possible effect of contacts between fuel rods (as observed in Phebus LOCA experiments Fig. 7a) will thus be taken into account resulting in new failure criteria. Experimental data will be compared with three-dimensional thermal mechanical models (Fig. 7. b), which are implemented in the DRACCAR software that computes numerical simulation of loss of coolant accident transients.

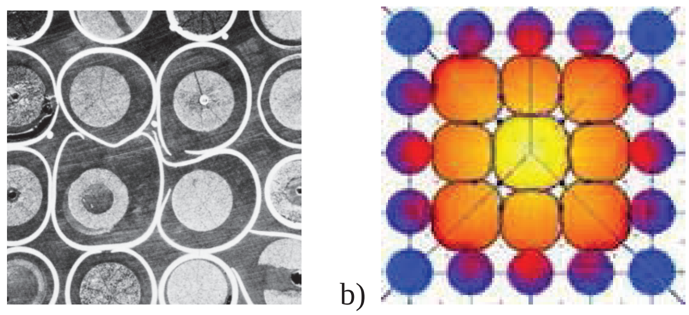
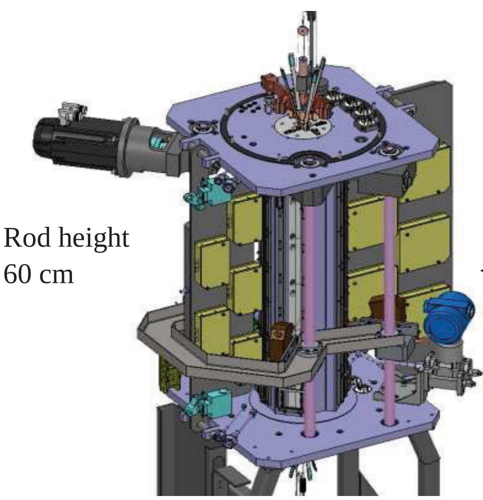
a) 

Figure .7: measurement of the deformation

Before performing the experimental program (foreseen between 2016 and 2018), it is necessary to validate the design and build a new specific test device (Fig. 8) gathering high technology solutions into a millimetric space (sub channel). The main supplies, construction and qualification tests of the COCAGNE facility are foreseen to be completed early 2016.



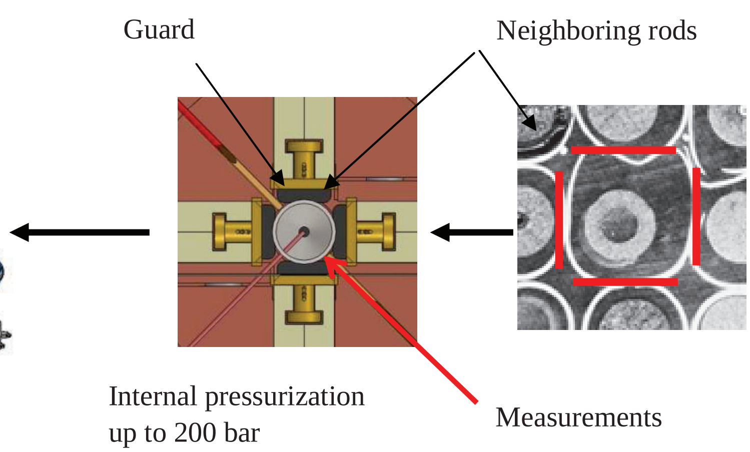


Figure 8 scheme of COCAGNE facility

Figure 9 Design of the Test section

The COCAGNE test rods will be 600 mm long to represent the interval between two grids. It will be linked to a dedicated helium skid regulating its internal pressure up to 180 bar. Its external surface will be either under vacuum or into inert gas at atmospheric pressure, to exclude zirconium oxidation, for technical and safety reasons.

The adjustable position and geometry of the peripheral rods (Fig. 9) have been chosen to simulate as accurately as possible the major types of contact related to loss of coolant conditions, such as guide tube presence for instance. The cladding tube is simultaneously pressurized and heated (direct Joule effect). Reaching the creeping field, a hot spot will initiate ballooning leading quickly to a contact with one or more adjacent heated guards (as well heated through direct Joule effect). To achieve the thermal homogeneity imposed on the sample (ΔT = 5 to 10°C), thermal leaks should be minimized.
Two main types of tests are foreseen: isothermal tests between 300 and 1100°C and linear ramp tests up to 20K/s. For the temperature increase, the Joule effect direct heating process has been chosen using 5 resistors for 1 rod and 4 guards.
Particular attention is paid to the development of the instrumentation of these tests**:**

- On-line temperature measurement along three perpendicular generating lines of the clad with an uncertainty lower than 10°C despite neighboring rods disturbance,
- On-line radial deformation along the same three generating lines,
- On-line measurement of the differential pressure applied to the cladding,
- Detection of the instant and location of each contact between the sample and its surroundings.

The technological challenge is the following: precision on the measured temperatures should be close to ± 5°C at 1000°C for ramps of about 20 K/s, on a length of 600 mm.

- Thermocouples are intrusive and just give point information. To increase the number of experimental points, IRSN developed a fast moving platform shifting UV pyrometers and laser telemetry sensors along the sample and away from the oven. Each point is scanned at high frequency, resulting in three generating lines temperature and deformation data, updated once per second.
- Standard infrared pyrometers do not meet these objectives, mainly because of the perturbing radiative fluxes: photons emitted by the guards and reflected by the sample lead to overestimate its true temperature. To address this issue, IRSN has developed with a supplier innovative UV-pyrometers (Ultra Violet), less sensible to these reflections.

<u>Temperature measurement </u>(objective of 1000± 5°C)

After the qualification tests, it appears that the use of the monochromatic pyrometry in the infrared range is not possible for the tests with guards. However, 4 monochromatic (IR) pyrometer will be used for the tests on the sample alone, because it gave a satisfying global two sigma uncertainty of ±2,8°C in these conditions..

The pyrometers in the ultraviolet range, tested early 2014, have proved encouraging results with heated guards: the errors (always positive) should be between 7°C at 700°C and 4,5°C at 1100°C, assuming a guard temperature slightly lower than that of the sample (20°C less). The design of pyrometers was improved: sensor mass and sampling time reduction for moving implementation, optic lenses and wavelength choice to fit our geometrical and emissivity conditions. Because of poor photon energy on the UV range, the weak point of this technology is to receive enough signal to start measures: 700°C would be the lower range limit.

<u>Deformation measurement </u>(objective of ±100 µm)

Regarding the measure of deformation using laser triangulation technic, the preliminary test campaign allowed to verify that the chosen sensor met the requirements of COCAGNE (accuracy of ±16 µm) even on a high temperature target (1200°C) and without disturbing the pyrometers.

<u>Measurement of the contact</u>

This original use of the ultrasonic properties into metallic components is derived from a former concept of ultrasonic thermometer already used over 2000°C. During the qualification test of this measure on a cold bench, the performances were good enough for the detection of the first contact even for a very light contact pressure and size (starting from 2600 Pascal and 3 mm²). The contact exact time can be determined by data post processing with a precision of at least 50 ms.

Four independent and synchronized systems will be implanted on the four guards. One or several guards in contact will thus be perceptible. The uncertainty of the measurement of the position of the first contact was ± 5mm. An optional post processing result of these sensors is to describe the contact evolution of the ballooned cladding developing against the guard surface. The uncertainty of this measurement is unfortunately difficult to assess in view of the systematic errors observed, influenced by the arbitrary contact pressure. As order of magnitude, on the cold bench, a balloon contact surface exceeding 20 mm can be estimated with errors ranged between 2 and 12 mm. Shorter stretch could not be differentiate from punctual contact.
Further development and qualifications are in progress on this subject before COCAGNE facility set up.

3.3. Specific research on cladding behavior

In the frame of the thermal mechanical axis 1, specific research at INSA Lyon (LaMCoS - Mechanics of Contact and Structures Laboratory) will focus on in-depth analysis of the hydrogen behavior in cladding alloys and its interaction with the fuel rod mechanical behavior through a PhD position (2014-2016).
Hydrogen, due to "hydriding", has been recognized to modify the mechanical behavior of zirconium alloys fuel cladding.

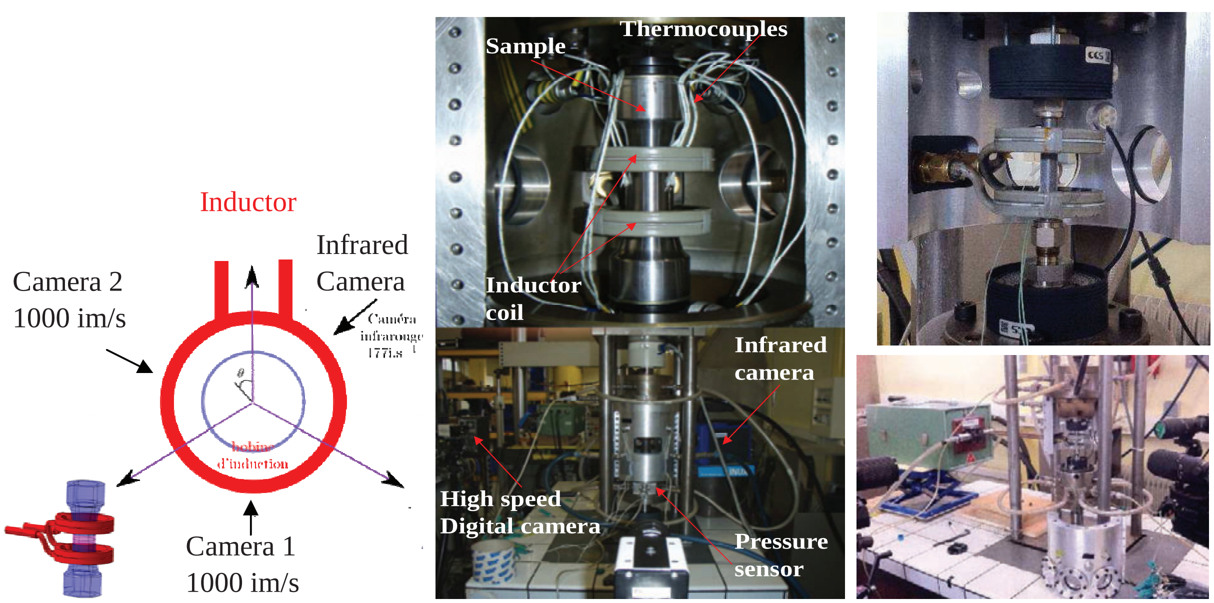
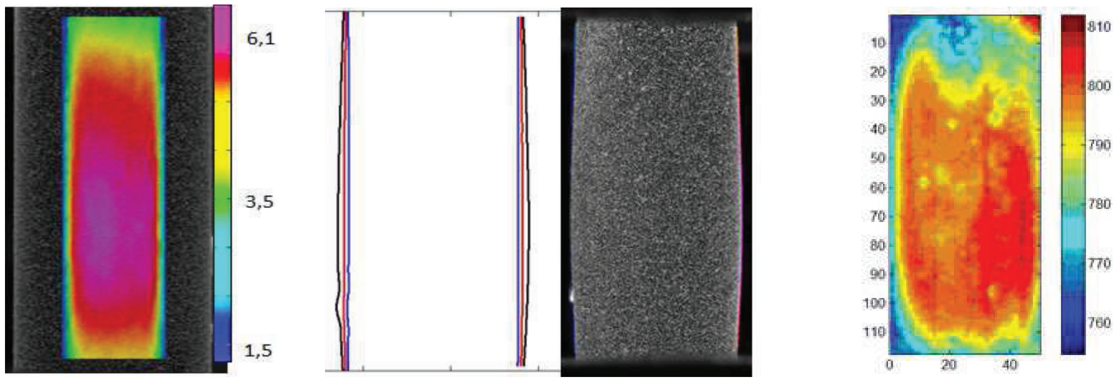


Figure 10: LaMCoS- INSA Lyon facility

This facility (Fig. 10) was developed previously, by N. Tardif & al. [18], for characterizing the fracture kinetics of a vessel bottom head during a core meltdown accident in a pressurized water reactor.
This set-up is able to perform bi-axial loading (compression and traction load) under controlled thermal uniaxial loading up to 1200 °C using pressurized tubular specimens. The experimental setup was modified (Fig.10 - right) to study the macroscopic secondary creep behaviour of as received and hydrided zircaloy-4 under a representative thermal mechanical loading of a LOCA.
The experimental matrix focuses on the following ranges, temperature between 700°C and 800°C, hoop stress in a range of 20 - 75 MPa and hydrogen content from 0 to 750 ppm.



a) Hoop strains (%) b) Outlines evolution c) Thermal field (°C) in the region of interest for a 800°C set point

Figure 11: Example of view given by digital image analysis

Specimens are cut off from an as-fabricated Zy-4 cladding by electro discharge machining. They are 90mm long, 0,57mm thick and their outer radius is 4,75 mm. The experimental setup heats-up a 20mm long length, considered as gage length, by induction heating. Internal pressure and axial force are set in order to produce a uniaxial stress state in the hoop direction. The tests are carried out under inert atmosphere (argon). In addition to the usual measurements (type K-thermocouples, force, pressure), the experimental device is upgraded in order to enable optical full field measurements (Fig.10 - left) of both displacement and temperature. The thermal field (Fig.11 c) is measured by an infrared camera. The strain state (Fig.11 a) is measured by 2D digital image correlation (FE-DIC code developed at the LaMCoS) for strain limited to some percent using high temperature paints to create a grayscale pattern. Then contour detection process [19] is used for finite strain when ballooning and speckle damaging prevent using 2D-DIC. The new setup includes 4 cameras and an infrared camera distributed over the circumference. Full field measurements enable to correlate a 20 degrees temperature evolution over the axial direction with the strain rate gradient in the region of interest (between the coils).
The secondary creep is then identified using a simple multiplicative law:

$$\varepsilon^{cr} = A \times \sigma_{VM}^{n} \times \frac{t^{m}}{m} \qquad (1)$$

Where ε^{cr} is the creep strain, σ_{VM} the Von Mises stress and t the creep time. A, m and n are the three parameters to be determined for each investigated temperature.

Additional information and more detailed results can be founded in [20].

4. AXIS 2 :THERMAL HYDRAULICS ACTIVITIES

4.1. The COAL experiments

The objective of the COAL experiments is improve the knowledge and the modeling of reflooding process of a fuel-rod assembly with large blocked area with relocated fuel simulation in the balloons:

1. The first phase was to design and to test an electrically heated rod with pre-ballooned area (SAFRAN prototype : **S**imulAted **F**uel **R**od under loc**A** conditio**N**);
2. The second phase will consist of reflooding tests with roughly full-length bundles in an out-of-pile water loop with adequate characteristics.

This program **(CO**olability of a fuel **A**ssembly during **L**oca) is detailed in [23].

4.2. Thermal hydraulics experiments performed at sub-channel scale

Within the frame of this thermal hydraulic axis, research is foreseen at the Laboratory for Energy, Theoretical and Applied Mechanics-LEMTA-University of Lorraine. It will focus on the characterization of two-phase flow with heat transfer in the deformed structures [24] (Fig. 12).

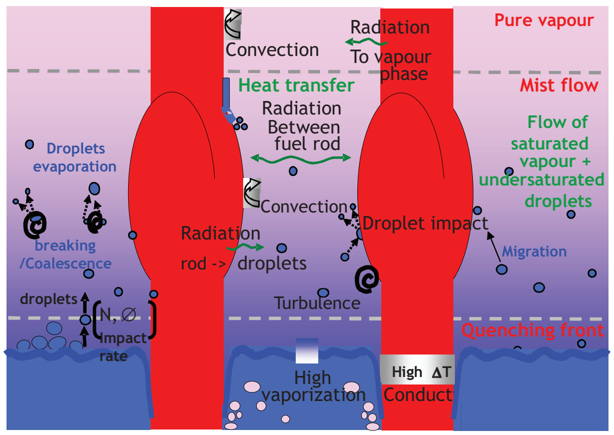


Figure.12: local phenomena involved in the process

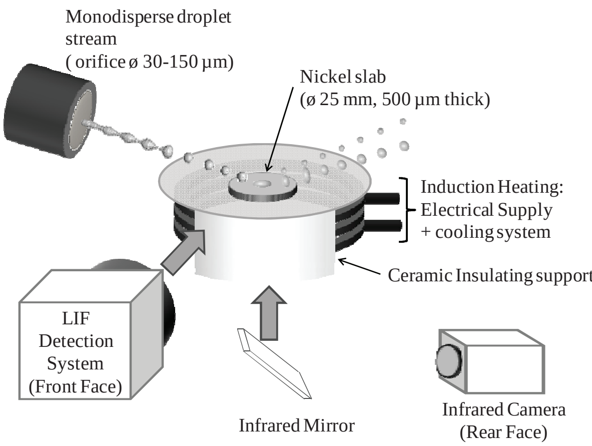


Figure. 13: Temperature measurement

This will consist in performing specific separate effect tests at the sub-channel scale (channel between fluid and rods). The proposed approach is expected to validate the models already developed on flow and heat transfer between wall and fluid [25, 26]. Realization and interpretation of these tests will be part of a PhD thesis (2015-2018).It is also planned to conduct a study of the so-called "quench front propagation" area with the aim to better model its dynamics, especially the generation of droplets and their transport by the vapour flow. This will be done as part of a post-doctoral research project.

Local phenomena involved in the process [24] are illustrated in the Fig. 12. As it can be seen on this figure, the two-phase flow occurring in the ballooned region is a mist flow (dispersed water droplet in steam). In previous works [24, 25, 26, 27], we developed a set-up to accurately measure the heat transfer between a single droplet and a hot wall for conditions close to LOCA.

As the interaction between the droplets and the wall is very short (~10^{-4}s for the droplet size of interest) and the exchanged heat fluxes very small (a few mW), we designed an experimental test device to measure the heat transfer during the resident time and also developed a specific inverse conduction measurement technique to estimate heat flux at the wall [25], from temperature measurements (Fig. 13). The hot metal target (Zircaloy or Nickel – thickness representative of that of a fuel rod cladding) are heated thanks to an electromagnetic device. The inductor is a ring so that the target can be observed on both faces: on the upper face where the droplet stream impinges, a home made Planar Laser Induced Fluorescence device allows to measure the temperature of the incoming and out coming droplets while the lower face is free to be seen by an infrared camera. These two techniques and high speed camera visualizations are combined to analyse the droplet-wall interaction. As low Weber number (defined as function of droplet diameter (D), of droplet velocity (V), of fluid density (ρ) and surface tension (σ)) are expected in LOCA conditions, the main regime which has studied is the bouncing regime (see figure 14).

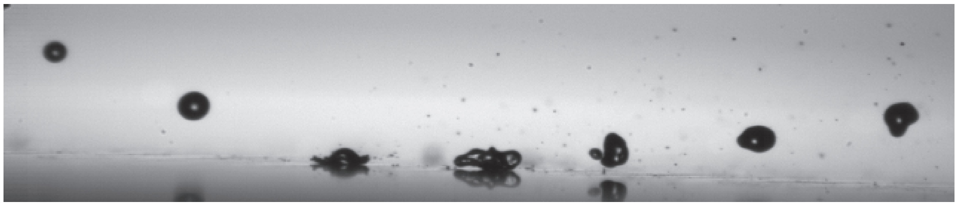


Figure 14: droplet-wall interaction in the bouncing regime (Weber < 40)

The experiments in ambient conditions were performed with very small droplets (diameter of about 50-400µm) injected at room temperature at high frequency thanks to a purpose-designed piezoelectric nozzle where the droplet frequency, velocity (V) and size ($D_{droplet}$) at injection can be adjusted. The target wall was a very thin disk (500µm thickness) pre-heated to around 600°C by an electromagnetic inductor device. At initial time, heating was shut down and the heat flux removed from the wall by the impinging droplets (front face of the disk) was calculated by post-processing the temperature field (measured in the rear face of the disk using the infrared camera) with the aid of the semi-analytical inverse heat conduction model that was developed.

The analysis of the experimental data leads to a new model for the energy released by the wall for one droplet impact [27]. This model accounts for the spreading of the droplet as a function of time and for the vapour flow beneath the droplet (the model is only valid in Leidenfrost conditions). Figure 15 shows some results of the modelling compared to experimental measurements, as function of the Weber.

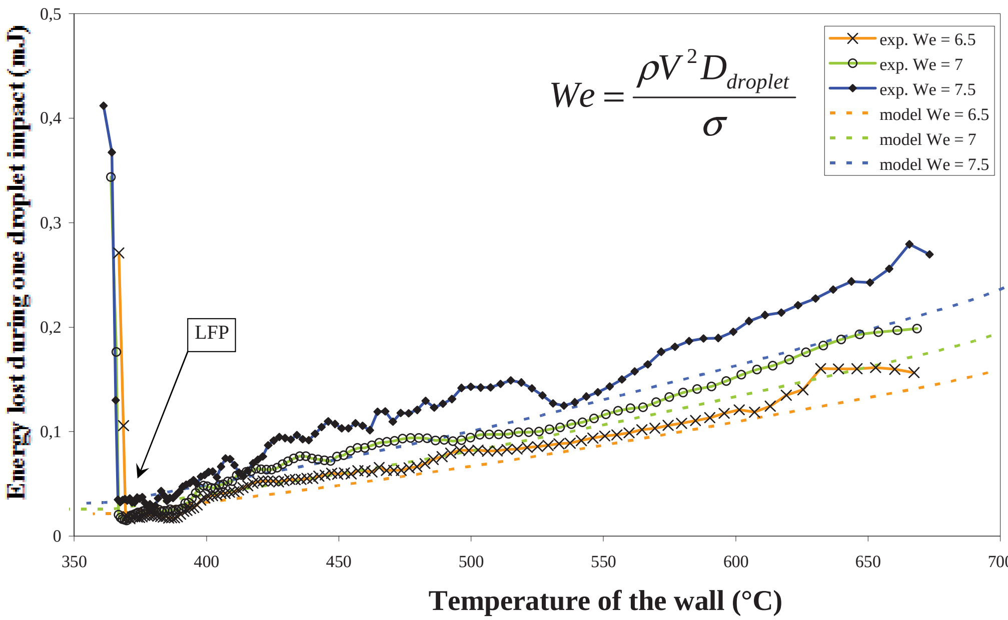


Figure 15 : Comparison between experimental data and output of the model

To study LOCA conditions closely, a new set-up will be built. The test channel will be representative of a blockage zone. A given droplet distribution will be injected in the channel; this droplet distribution will be characterized using a Phase Doppler Anemometry device and both droplet distribution at the exit of the channel and global heat transfer will be measured in order to be compared with the model previously adopted [24, 26].

5. CONCLUSION

The safety principle in case of a LOCA is to preserve the coolability of the core. The associated safety requirements are to ensure the resistance of the fuel rods upon quench and post-quench loads and to maintain a coolable geometry in the core. In the early 2000's, IRSN has conducted an extensive State-of-the-Art review relative to the fuel behaviour under LOCA conditions. The PERFROI project (2014-2019) will focus on one pending question on flow blockage within a fuel rods bundle (with mechanical aspect never addressed up to now) and its potential impact on coolability (thermal hydraulics aspect) taking into account fuel relocation with electrical rods representative as much as possible to real irradiated fuel rods regarding the thermal behaviour. For this project, IRSN and partners will use existing facilities or will develop new one with innovative solutions regarding the technical measurements in order to produce enough accurate information. The results will be used to validate code modelling and the knowledge generated by the overall PERFROI project will benefit to the international nuclear safety community.

NOMENCLATURE

COCAGNE : (in French language) « **CO**mportement d'un **C**rayon en **A**PRP soumis à un **G**radie**N**t de températur**E »** Fuel Rod Behavior under temperature gradient in LOCA conditions

DRACCAR:(in French language) **D**éformation et **R**enoyage d'un **A**ssemblage de **C**rayons **C**ombustibles pendant un **A**ccident de **R**efroidissement – simulation tool for 3D thermal mechanical behavior and Reflooding during LOCA transient.

ELFE :(in French language) « **E**tablissement des **L**ois de **F**luag**E »** (Creep Law Determination)

LOCA: Loss Of Coolant Accident

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 for his financial support.

REFERENCES

1. G. Repetto, Final Experimental Report, Phebus LOCA Test 215-R, Note IPSN Phebus 49/84, internal report (1984)
2. S. Bourdon, G. Repetto, S. Brethes, Analyses of the Phebus-LOCA tests 215-R and 2018 using FRETA-F V1.1 code, NURETH-11, 02-06 October, Avignon France, (2005).
3. NUREG-2121, Fuel fragmentation, relocation and dispersal during the loss-of coolant-accident , US-NRC , data collected by P. AC Raynaud, February 2012,
4. 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.
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, ICAPP 2009, Tokyo, Japan, May 10-14, (2009).
6. C. Grandjean, A state-of-the-art review of past programs devoted to fuel behaviour under LOCA conditions: Part One, Clad swelling and rupture – Assembly flow blockage, Internal IRSN Technical Report SEMAR 2005/313, December (2005).
7. C. Grandjean, A State-of-the-Art Review of Past Programs Devoted to Fuel Behavior under LOCA Conditions. Part Two, Impact of clad swelling upon assembly cooling, Internal IRSN Technical Report SEMCA-2006/183, June (2006).

8. C. Grandjean, G. Hache, A State-of-the-Art Review of Past Programs Devoted to Fuel Behavior under LOCA Conditions. Part three, cladding oxidation, resistance to quench and post quench loads, Internal IRSN Technical Report SEMCA-2008/093, (2008).
9. Nuclear Fuel Behavior in Loss-of-coolant Accident (LOCA) Conditions: State-of-the-art Report, ISBN 978-92-64-99091-3 © OECD 2009 - NEA No. 6846
10. F. Barré, C. Grandjean, M. Petit, JC. Micaelli - Fuel R&D Needs and Strategy towards a Revision of Acceptance Criteria, *Science and Technology of Nuclear Science*. (2010)
11. J.M. Ricaud, N. Seiler, G. Guillard, "Multi-pin Ballooning during LOCA transient: A Three Dimensional Analysis", *Nuclear Engineering and Design* (*NED),* 256 45-55, (2013).
12. S. Bascou et al., Computational Analysis of Multi-pin Ballooning during LOCA and Post LOCA Transient using the Multi-physics Code DRACCAR, *Proc. Top Fuel Congress*, Manchester, UK, September 2-6, 2012, American Nuclear Society (2012).
13. G. Repetto et. al, Core coolability in loss of coolant accident: the PERFROI project, WRFPM-*TopFuel*14, Sendai, Japan, September 14-17, (2014)
14. S. Frechinet, «Transformations et comportement du zircaloy-4 en conditions anisothermes,» Thèse Ecole Nationale Supérieure des Mines de Paris, (2001)
15. H. E. Rosinger, P.C. Bera, W.R. Clendening, «Steady-state creep of Zircaloy-4 fuel cladding from 940 to 1873K,» *J. of Nuclear Mat.,* vol. 82, pp. 286-297, (1979)
16. Garde A. M., Chung H.M, Kasnsner, T.F, «Micrograin superplasticity in zircaloy at 850°C,» *Acta Metallurgica*, vol. 26, pp. 153-166, 1978
17. V. Busser, M-C Baietto-Dubourg, J. Desquines, J-P Mardon, Mechanical response of oxidized Zircaloy-4 cladding material submitted to a ring compression test, *Journal of Nuclear Materials* 384 (2009) 87-95
18. N Tardif, M. Coret, A. Combescure, Experimental study of the fracture kinetics of a tubular 16MnNiMo5 steel specimen under biaxial loading at 900 and 1,000% Application to the rupture of a vessel bottom head during a core meltdown accident in a pressurized water reactor, *Nuclear Engineering and Design*, Vol. 241 (3), pp. 755-766 (2011).
19. J. Réthoré, and M. Francois, Curve and boundaries measurement using B-splines and virtual images.*Optics and Laser in Engineering*, 52, 145-155, (2014)
20. D. Campello, M.C. Baietto, M. Coret, N. Tardif, J. Desquines, Thermo mechanical behavior of fresh zircaloy-4 under LOCA conditions, *13th International Conf. on Creep and Fracture of Engineering Materials and structures (CREEP-15*), May 31 –June 04, Toulouse, France (2015)
21. 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, NURETH-11 (Nuclear Reactor Thermal Hydraulics) 02-06 October, Avignon France, (2005).
22. C. Grandjean, Coolability of blocked regions in a rod bundle after ballooning under LOCA conditions - Main findings from a review of past experimental programmes, *Nuclear Engineering and Design* 237, pp. 1872-1886, September (2007).
23. G. Repetto, Ch. Marquié, B. Bruyère, T. Glantz "Core coolability in Loss Of Coolant Accident: the COAL experiments," *Proceedings of the 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (Nureth16)*, Chicago, IL, USA, August 30-September 4, (2015).
24. P. Ruyer, N. Seiler, B. Biton, F. Lelong, F. Secondi, D. Baalbaki, M. Gradeck, Thermal hydraulic across a partially damaged core during the reflood phase of a LOCA, *Nuclear Engineering and Design* (NED) (2013)
25. M. Gradeck, D. Maillet, F. Lelong, N. Seiler, G. Repetto, Estimation du transfert de chaleur gouttes/paroi en situation d'APRP pour un REP, La Houille Blanche, n°4, pp. 52-57, (2009).
26. F. Lelong, M. Gradeck, N. Seiler, P. Ruyer, G. Castanet and P. Dunand, Dynamic behaviour of droplet bouncing onto hot slab, ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems, Brno, Czech Republic, September (2010).
27. M. Gradeck, N. Seiler, P. Ruyer, D. Maillet, Heat transfer for Leidenfrost drops bouncing onto a hot surface, Experimental Thermal and Fluid Science (2012).