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Fuel Cladding Deformation During LOCA: Comparison Between Single-rod and Multi-rod tests

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ABSTRACT

The purpose of the COCAGNE experiments, performed in the framework of the PERFROI program, is to study the deformation and burst of fuel cladding under Loss-Of-Coolant-Accident (LOCA) conditions in “multi-rod” configuration. This configuration enables to study cladding ballooning in situations of contact/blockage between peripheral rods, burst conditions after contact, and azimuthal temperature gradient influence on cladding deformation.

Six ramp tests have been performed in single-rod configuration and seventeen in “multi-rod” configuration. The tests were performed on pre-oxidized Zy-4 claddings at three heating rates (1, 5 and 10 °C/s) and at pressures from 2 to 10 MPa.

The performed tests revealed that the presence of the peripheral rods can affect not only the size and the shape of the balloon but also the size of the burst opening.

1 INTRODUCTION

The aim of the PERFROI project [1-2] is to study the cooling of a nuclear reactor core during a Loss-Of-Coolant-Accident (LOCA), considering both the thermo-mechanical and thermo-hydraulic phenomena within the fuel assemblies. During this accident, the fuel assemblies of a nuclear reactor core can be partially or completely dried out. Consequently, the fuel rods heat up while the reactor coolant pressure drops below the fuel rod internal pressure. These conditions can lead to significant cladding ballooning and even to burst. The consequences of these geometrical modifications on the core cooling efficiency during the injection of water by the safety systems are an important safety issue.

Different phenomena are involved in the different phases of a LOCA transient as ballooning, burst, oxidation, hydriding, fuel relocation and possible fracture during quench. These phenomena are complex due to the changes of the cladding alloy properties which take place during the transient. A myriad of tests under LOCA conditions have been performed since the 1970s: from separate effect tests performed on small samples for the study of one phenomenon, to semi-integral tests on single fuel rod or fuel bundles [3-4]. The considerable experimental work performed has led to a broader and deeper understanding of LOCA-related phenomena. Even if many studies have been devoted to cladding ballooning, that occurs during the first stage of a LOCA transient, they were mainly focused on the behaviour of a single rod and they cannot be taken as representative of those occurring in an assembly, since the effect of neighbouring rods is not present.

The first axis of the PERFROI project concerns the thermo-mechanical study of the deformation and fracture of fuel rods under LOCA conditions. It includes thermo-mechanical creep and sample rupture tests (ELFE tests) [5-6] and tests with ballooning and burst of cladding tube sections in “multi-rod” configurations (COCAGNE tests). The objective of COCAGNE experiments is to get precise knowledge of the three-dimensional mechanical behaviour of pressurized rods surrounded by structures simulating four neighbouring fuel rods, under a geometrical and thermal representative environment. Current burst criteria are mainly based on single rod tests, and the possible effect of contacts between fuel rods will thus be considered resulting in new burst criteria. Experimental data will be compared with three-dimensional thermo-mechanical models, which are implemented in the FUEL+/DRACCAR software (developed by IRSN for the simulation of LOCA type accidents, [7-8]) that can simulate rod and multi-rods behaviour during a loss of coolant accident transients.

This paper is focused on main results obtained during the three tests campaigns performed with Zy-4 claddings. Detailed information about the facility, instrumentation, test samples and test conduct can be found in a previous paper [9].

2 EXPERIMENTAL PROCEDURE

The COCAGNE facility has been designed to study fuel rods ballooning under LOCA conditions in an environment representative of a fuel assembly. The facility can heat a rod cladding up to 1200 °C under an internal pressure up to 10 MPa. The rod can be surrounded by four “guards” that simulate peripheral deformed rods. The temperatures of the neighbouring structures are controlled independently, thus it is possible to induce an azimuthal temperature gradient around the tested rod.

The tests were performed with pre-oxidized claddings (590 mm long) both single-sided (10 µm of external pre-oxide) or double-sided (10 µm of external and internal pre-oxides, configuration used exclusively in the first two tests). To simulate the thermal behaviour of the fuel pellets, alumina pellets are located inside the cladding.

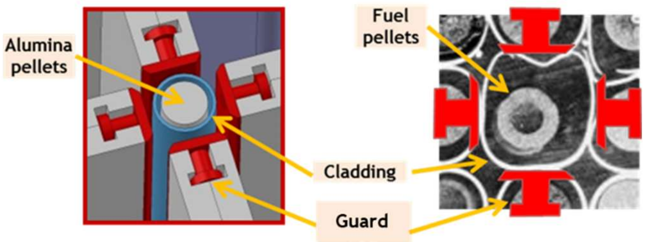

Figure 1: Layout of test rod and peripheral rods (guards) in COCAGNE facility

The cladding tube is simultaneously pressurized and heated. Reaching the creeping field, a hot spot will initiate ballooning of the cladding, leading quickly to a contact with one or more peripheral guards (Figure 1). The cladding tube and the guards are all heated electrically by direct current. Tests are performed under vacuum atmosphere. The temperature and the radial deformation of the test rod external surface are measured on-line along three parallel generating lines of the cladding.

The test matrix (Table 1) is composed of six single-rod tests (without the guards simulating the neighbouring rods) and 17 “multi-rod” tests (with the guards). The tests were performed at constant heating rate (H_{rate} in Table 1) and internal pressure (P) with different temperature gaps between the test rod and the guards ($\Delta T_{r\text{-}g}$, measured at burst). ΔT_{az} in the table is the azimuthal temperature gradient measured on the ballooned region just before burst.

Table 1: Test matrix

Test	H_{rate} (°C/s)	P (MPa)	ΔT_{r-g} (°C)	ΔT_{az} (°C)	Test	H_{rate} (°C/s)	P (MPa)	ΔT_{r-g} (°C)	ΔT_{az} (°C)
Single-rod					**Multi-rod**				
COC-1*	5	5,00	-	16	COC-15	1	10,00	38	15
COC-2*	5	2,19	-	14	COC-16	1	4,96	28	7
COC-4	5	5,24	-	12	COC-17	5	5,00	52	12
COC-5	5	10,01	-	6	COC-18	5	5,01	498	7
COC-6	10	5,00	-	11	COC-20	1	5,01	302	10
COC-7	5	2,00	-	18	COC-21	1	5,00	94	6
Multi-rod					COC-22	1	5,27	0	12
COC-10	5	4,99	62	3	COC-23	1	5,18	-46	26
COC-11	5	10,71	77	14	COC-24	1	4,99	10	49
COC-12	5	4,99	24	15	COC-25	5	5,00	162	15
COC-13	5	2,00	102	17	COC-26	5	4,99	291	2
COC-14	1	5,01	27	24	COC-27	5	5,18	83	30

*Double-sided pre-oxidized cladding

3 RESULTS AND DISCUSSION

Burst temperature (mean temperature measured on the ballooned region just before burst) of all the test performed is presented in left graph of Figure 2 as a function of internal pressure and heating rate. It can be observed that, as pointed out before by different authors [10-11], burst temperature decreases when internal pressure increases and heating rate decreases. The comparison of the values obtained at 5 °C/s without (single-rod tests, green triangles) and with the guards (multi-rod tests, red triangles), reveals that, at this heating rate, burst temperature is not significantly affected by the presence of the guards. This fact is confirmed in the right graph of Figure 2: burst temperature is not affected by guards temperature in the tests performed at 5 °C/s. At 1 °C/s, on the contrary, burst temperature slowly decreases when guard temperatures diminish. In the latter case, the lower heating rate promotes slower and higher deformations. Consequently, contact surface between the rod cladding and the guards is more extended, allowing a better and longer heat transfer through this surface.

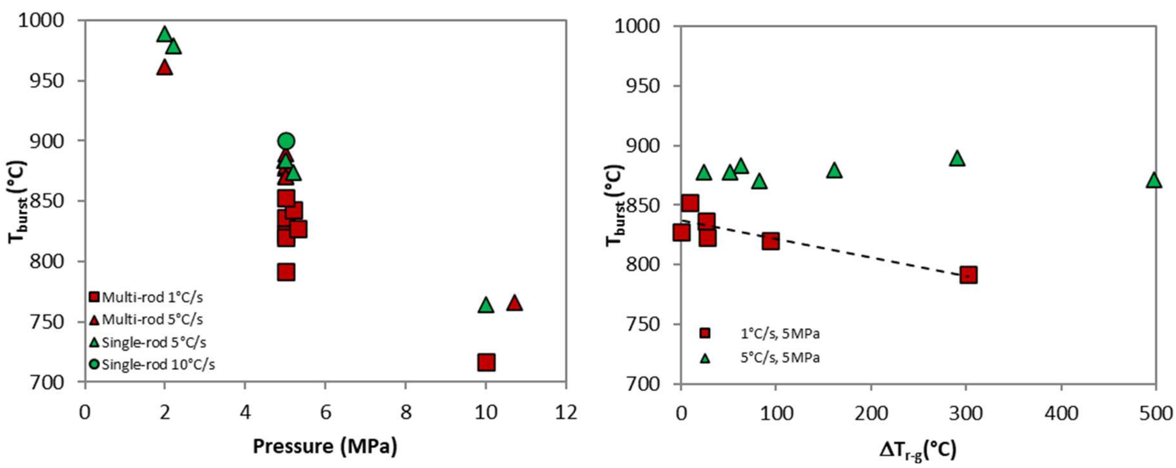

Figure 2: Burst temperature as a function of internal pressure (left, all tests) and of the temperature difference between the test rod and the guards (right, multi-rod tests at 5 MPa)

Cladding strain is characterized by 3D scanning which allows to measure burst strain at burst elevation and axial extension of the contact between the rod and the guards. Both parameters are presented in Figure 3 versus burst temperature. Burst strain is the maximum circumferential strain measured after the test. The axial extension of strain is quantified by the length of the cladding zone where the strain exceeds 32.6 % (strain at which neighbouring rods that balloon symmetrically and simultaneously will come into contact between themselves in a PWR reactor).

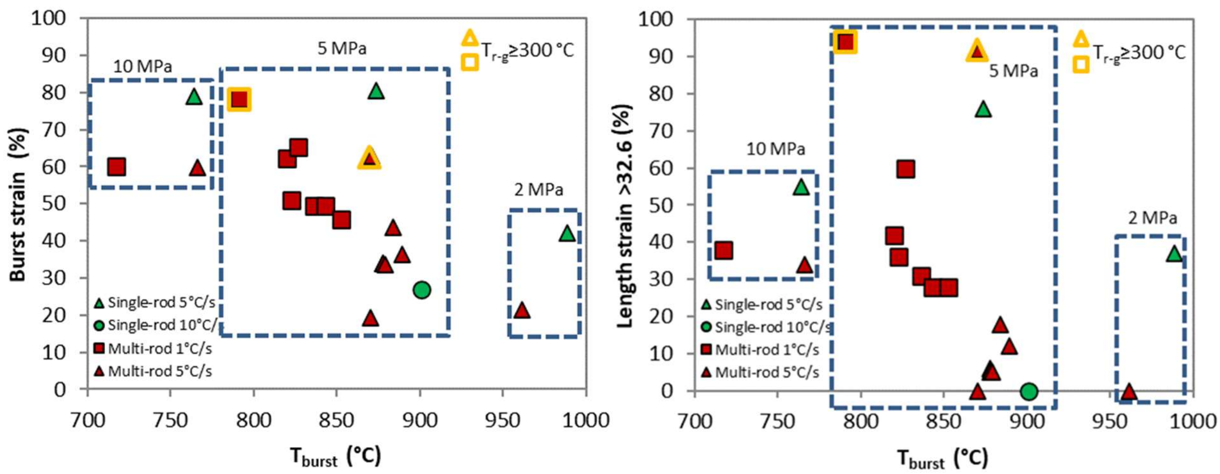

Figure 3 : Burst strain (left) and axial extension of strain (right) as a function of burst temperature

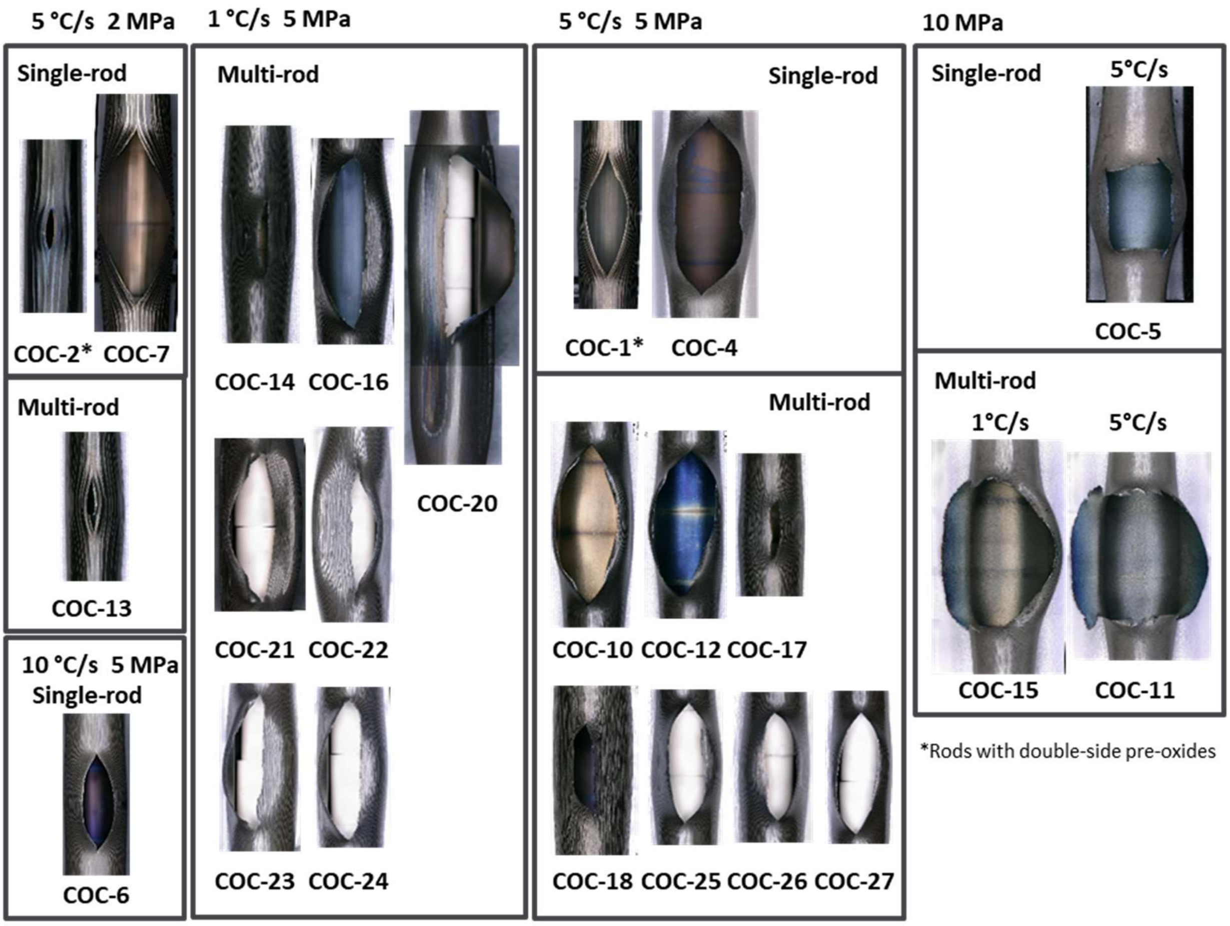

Figure 4: Comparison of burst openings

As previously observed [10], when burst temperature remains below ~900 °C, larger strains are reached in the tests performed at slow heating rates (compare red squares and triangles at 5 MPa). If tests performed at the same heating rates are compared (green and red triangles in the figure), it can be noticed that burst strains are lower in “multi-rod” tests than in single-rod tests. It must be noticed that the azimuthal deformation of the cladding is limited in “multi-rod” tests by the presence of peripheral rods, explaining lower burst strains.

Right graph of Figure 3 shows that the axial extension of strain is lower in the “multi-rod” tests, except when the temperature difference between the rod and the guards is greater than 300 °C (yellow surrounded points). It should be noted that colder guards induce lower axial temperature gradients in the test rod. Another effect of cold guards is that, when the temperature of the guards is cold enough, the temperature of the test rod locally decreases during contact development. In this case, burst is delayed, and the cladding has more time to deform. Consequently, in multi-rod tests, the strain axial extension increases with the temperature difference between the test rod and the guards.

The dispersion observed in burst strain and axial extension of strain is mainly caused by differences in the temperature gradients (azimuthal and axial) in the cladding, especially in “multi-rod” tests (cladding thermal profiles are relatively flat in the test performed in single-rod configuration but they become uneven in the presence of guards).

Figure 4 compares the opening formed on burst balloons. The effect of an internal pre-oxide on burst strain can be observed in the figure (compare COC-2 and COC-7 performed at 2 MPa and 5 °C/s and COC-1 and COC-4 performed at 5 MPa and 5 °C/s). It can be noticed that the size of the balloons is sensibly smaller in the tests performed with double-sided pre-oxidised claddings, that is, claddings with an internal pre-oxide layer. Consequently, burst strain is significantly reduced in the presence of an internal pre-oxidize layer. Nevertheless, an internal pre-oxidize layer seems to have no effect on burst temperature (864 and 871 °C in COC-1 and COC-4 tests respectively; 985 and 977 °C in COC-2 and COC-7 tests).

The shape of the balloon is conditioned by the shape and the position of the guards. Figure 5 illustrates how the balloon adapts to the free space available. In the azimuthal direction, the deformation of the balloon is limited by the guards. On the contrary, under certain boundary conditions, deformation in the axial direction can extend leading to long balloons. It must be noticed that, at high temperatures, the guards are more rigid than a zircaloy cladding. In a real bundle, the deformation and shape of a balloon will depend not only on those of the surrounding rods, but also on their location. Location that will depend on the deformation and position of the surrounding rods.

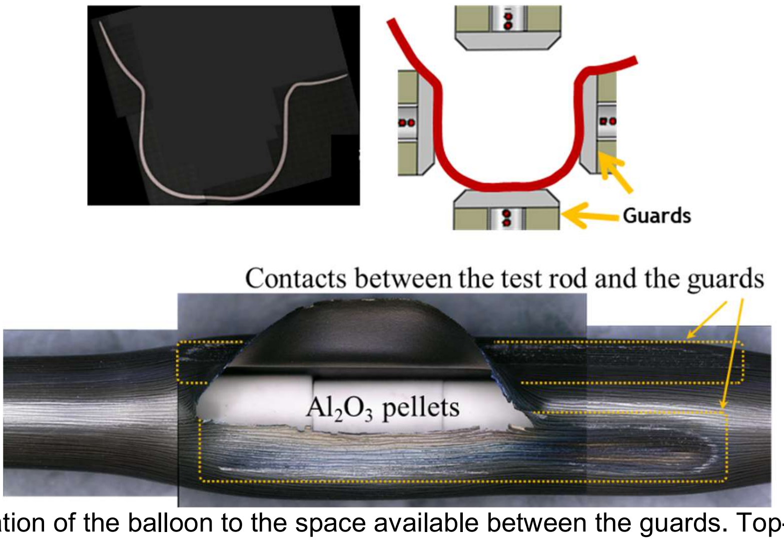

Figure 5: Adaptation of the balloon to the space available between the guards. Top- In the azimuthal direction (COC-11 test); Bottom- In the axial direction (COC20 test)

Opening dimensions formed on burst balloons are presented in Figure 6 as a function of internal pressure. It can be observed that the openings of the three tests performed with an internal pressure of 10 MPa are wider than the others. The shape of the openings formed in these tests is rectangular, they look like an open casement window. At this pressure, bigger openings are obtained in the multi-rod tests.

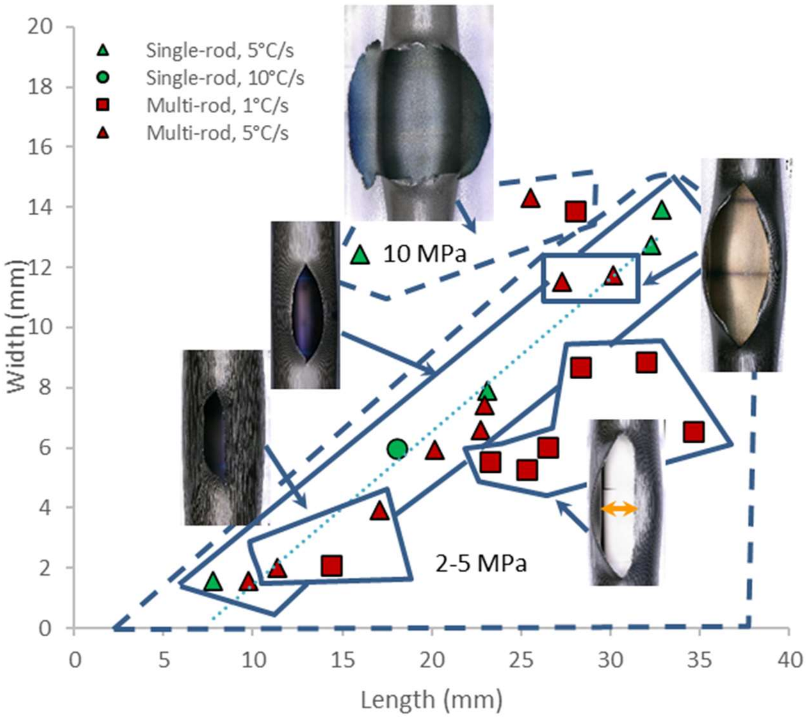

Figure 6: Burst opening width versus burst opening length.

In the tests performed at 2 and 5 MPa, the opening has an elongated shape (looks like a fish-mouth). They are narrower than those obtained at higher pressure. It should be noted that burst temperature took place in the α-phase region in tests performed at 10 MPa and in the $\alpha+\beta$ region in test performed at 2 and 5 MPa. Consequently, even if the rectangular opening is probably caused by the violence of burst at 10 MPa, the possible influence of the formation of β-phase in the opening shape cannot be eliminated.

Burst strain is sensibly higher in tests performed at 1 °C/s than in those carried out at higher heating rates. In the case of high strains, there is limited space between the cladding and the guards at burst, and hence burst opening is constrained by the presence of the guards (see orange arrow in Figure 6). For this reason, the width openings are lower at 1 °C/s than at higher heating rates and the corresponding points of the figure (red squares) are clearly placed below those at higher heating rates.

4 CONCLUSIONS AND PERSPECTIVES

Six ramp tests have been performed in single-rod configuration and seventeen in “multi-rod” configuration (with peripheral rods) at COCAGNE facility. The tests were performed on single-sided or double-sided pre-oxidised claddings (pre-oxides ~10 μm thick) at three heating rates (1, 5 and 10 °C/s) and at pressures from 2 to 10 MPa.

It has been observed that the presence of an internal pre-oxidize layer does not affect burst temperature but significantly reduces burst strain.

The temperature measured on the main balloon at burst is not affected by guards temperature in the tests performed at 5 °C/s. At 1 °C/s, on the contrary, balloons can be cooled by colder guards leading to lower burst temperatures.

It must be noticed that the cladding temperature during the tests is axially and azimuthally heterogeneous and that strain diminish as temperature gradients increase. Main balloon forms where the temperature is higher. At high temperatures, few degrees can have a strong influence on creep rate. Thus, strain develops mainly in hottest area, leading quickly to burst. In the neighbouring and lightly cooler regions, creep rate is smaller, and the cladding has not enough time to deform. Consequently, to promote high deformations and axial propagation of ballooning, the temperature of the ballooned area (hotter part of the rod) must be homogeneous. It must be pointed out that the pressure difference between the inside and the outside of the cladding varies during a LOCA accident while COCAGNE tests are performed at constant pressure. With a fixed gas quantity, the decreasing pressure during ballooning will delay the formation of the plastic instability that leads to burst and promotes bigger balloons.

The presence of the four guards affects the size and the shape of the formed balloon. In “multi-rod” tests, azimuthal deformation is limited by the guards leading to lower maximal strains compared to single-rod tests. Nevertheless, under certain boundary conditions, the ballooning can develop in the axial direction. The round balloon formed in single-rod tests, adapts to the available space between the guards in multi-rod tests becoming squarer.

COCAGNE experiments have allowed to accurately measure the three-dimensional mechanical behaviour of pressurized rods surrounded by structures simulating four neighbouring fuel rods, under a geometrical and thermal representative environment.

Experimental data are currently used to validate three-dimensional thermo-mechanical models implemented in the FUEL+/DRACCAR software (developed by IRSN for the simulation of LOCA type accidents) that can simulate rod and multi-rods behaviour during LOCA transients.

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