MEXIICO a new equipment to study the pressure impact on the irradiated fuel behavior

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Abstract. The new MEXIICO experimental loop has recently been started in the LECA-STAR hot-cell facility of the CEA Cadarache. It is dedicated to the understanding of the basic mechanisms occurring in nuclear fuels during nuclear reactor power transients and accidental situations. Under such conditions the nuclear fuels are submitted to thermo-mechanical stresses. These stresses play a major role on fission product release and fuel fragmentation. Evaluating such fuel behavior represents a key issue for reactor safety analyses.

In the first part of the paper, we describe the complete MEXIICO device, which main component is a hot isostatic press allowing to perform analytical experiments in the [20 °C -1600 °C / 10 MPa - 160 MPa] region. As shown by simulations (ALCYONE fuel performance code), the upper value of the pressure (160 MPa) is consistent with the one experienced by fuels under nuclear power transients. We also present the experimental loop starting from the argon pressurized feed-line, the furnace and its associated instrumentation and the exhaust line equipped with specific valves and flowmeters controlling the pressure and flowrate. We then focus on the gamma spectrometry measurement which allows recording the fission gas release kinetics.

In the second part of the paper, we detail the capability of the MEXIICO device to provide new experimental data regarding the influence of pressure on the fission gas release and fuel fragmentation, and to determine a pressure threshold above which fission gas release and fuel fragmentation may be inhibited. This device also allows investigating the impact of pressure on the microstructure evolution, coupling it with post-test microanalysis examinations: this procedure will allow characterizing the effect of temperature and pressure on the bubble evolution and interconnection. Evolutions of the fuel modeling, needed to simulate correctly these new experimental data, will be also presented.

In the last section of the paper, we present the commissioning tests of the MEXIICO device showing the good reproducibility of the tests performed first in conventional laboratory and then in hot-cell laboratory.

Keywords: Experimental device, nuclear fuel, pressure, loss of coolant accident, nuclear power ramp, fission gas release, fuel fragmentation, modeling.

INTRODUCTION

The MEXIICO experimental loop, recently implemented in the LECA-STAR facility in the CEA Cadarache center has been designed to measure fission gas release (FGR) from a nuclear irradiated fuel sample submitted to temperature and pressure transients. It will thus allow performing analytical separate effect tests, which will help better understanding the fuel behavior under different kind of nuclear reactor accidents. Indeed, depending on the choice of the temperature (up to 1600°C), pressure (up to 160 MPa) and pressure drop (standard or fast) histories it will be possible to reproduce conditions representative of certain aspects of Loss Of Coolant Accident (LOCA) or

Power Transients. Furthermore, it will provide useful data regarding the impact of pressure and pressure drop on FGR and fuel fragmentation mechanisms for different kind of fuels, UO_2 or MOX fuel at various burn-up, i.e. for different kind of fuel microstructure with or without High Burn-Up structures.

The present paper is divided into three main parts. First, the MEXIICO experimental loop is detailed with particular emphasis on the furnace, the FGR measurement and the fast pressure drop device. The second part is devoted to the R&D programs that will be carried out with this new equipment. Finally commissioning tests are presented illustrating thus the MEXIICO capabilities for the current R&D programs.

EXPERIMENTAL LOOP DESCRIPTION

In this section we will describe the new MEXIICO experimental loop, focusing first on its main part which is the furnace and moving then to the global loop with its two important circuits: the standard configuration with on-line measurement of the fission gas release kinetics and the fast pressure drop configuration for fuel fragmentation evaluation.

The MEXIICO furnace

In order to apply appropriate temperature and pressure transients, the key component of the MEXIICO experimental loop is the Hot Isostatic Press (HIP) which is depicted in Figure 1. As for other HIPs used in ceramic industry, temperature is confined in the center of the pressure vessel thanks to a large insulator covering both sample and heating element. Such design allows using a thick metallic core to sustain pressure at a rather low temperature inhibiting core creep.

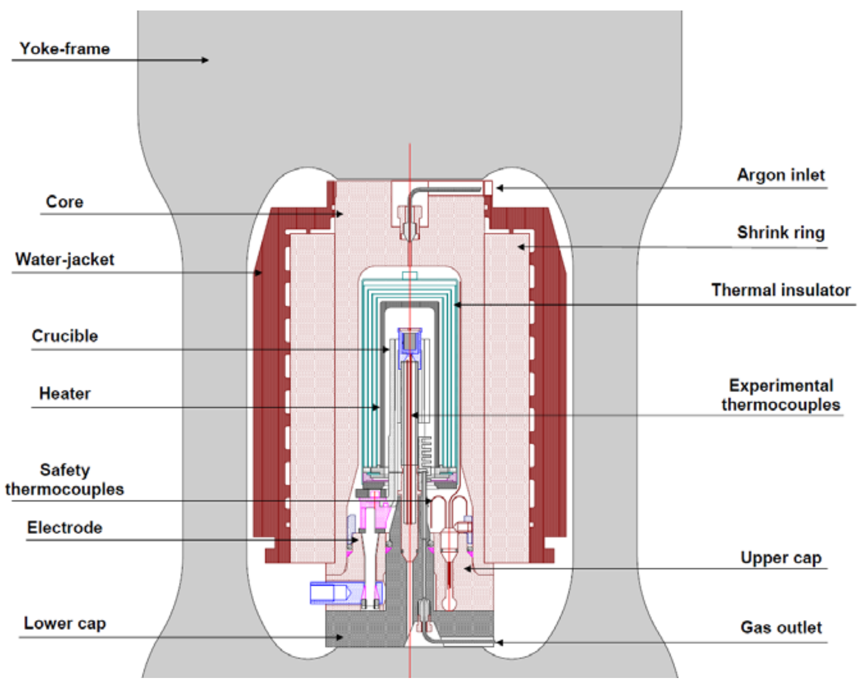


FIGURE 1: Main components of the MEXIICO furnace.

The internal parts of the furnace are:

- A graphite electric resistance, with a current supply provided by copper electrodes
- A graphite crucible in which the sample will be located
- A multi-layer graphite socket acting as insulator
- A stainless steel core, cooled by a water jacket, which useful volume is about 1 liter

It is worth mentioning at this stage, that the crucible has been designed so that the sample can be an entire fuel pellet.

Temperature is measured and controlled in different ways. Core temperature, which is limited to 150°C, is measured at three locations with safety thermocouples (TC), one in the upper part of the core chamber and two in the bottom part of the chamber. Sample temperature is monitored up to 1600°C, thanks to two TC located right beneath the crucible. Pressure is applied to the core chamber through the argon gas inlet located in the upper part of the core chamber. Pressure is monitored up to 160 MPa and measured upstream from the chamber on the feed-line connected to compressors.

In order to limit the consequences of an accidental explosion during operation in a nuclear facility, the MEXIICO furnace meets not only the traditional requirements encountered in conventional laboratory, but its design also allows coping with additional independent countermeasures:

- Regarding conventional risk assessment, the core which represents the pressure vessel and the shrink ring embedding the core, have been both designed to sustain maximum energy dispersal during the bounding accidental scenario. In addition the yoke frame, which function is to maintain the core lower and upper caps has also been designed to face independently such accidental conditions.
- In addition to this traditional approach, the MEXIICO furnace has been upgraded in two ways to comply with more demanding requirements associated to its operation in the French nuclear LECA-STAR facility. The water jacket, which role is to cool down the core in order to avoid its creep, has been reinforced to also cope with the maximum energy failure induced by an explosion, in case of a hypothetical simultaneous rupture of both core and shrink ring. Finally, an additional and independent yoke frame has been placed around the original one in case of failure.

With such redundant mechanical barriers, the MEXIICO furnace has been favorably evaluated by regulatory authorities.

The MEXIICO experimental loop

In order to perform analytical tests, the furnace is part of a more complete experimental loop, described in Figure 2, which can be split into two main sections: the high pressure feed line and the low pressure exhaust line containing the released fission gases emitted from the nuclear fuel sample during the temperature and pressure transient.

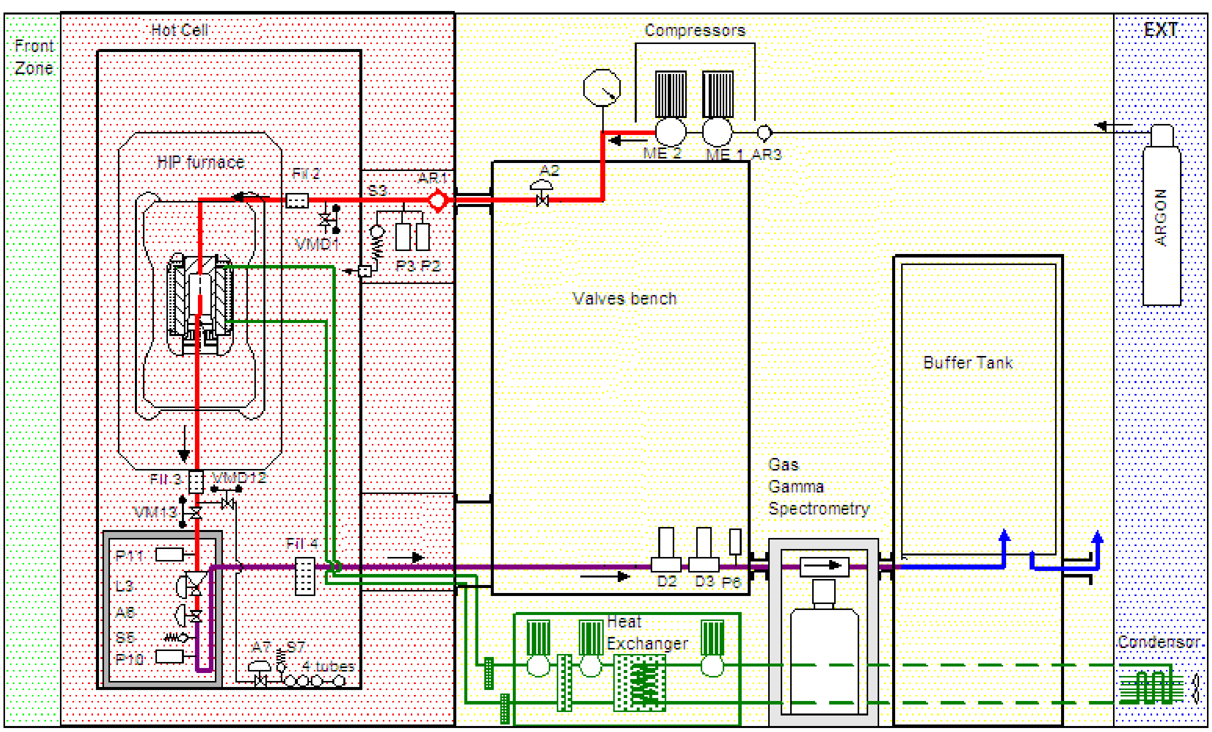


FIGURE 2: Global view of the MEXIICO experimental loop with its main components inside the hot cell, its full instrumentation in the rear zone and the control – command unit in the front cell.

The loop main components are:

- Starting outside the laboratory, the argon pressure tank delivering gas up to 20 MPa,
- Two compressors, located in the rear zone, which enable increasing pressure up to 160 MPa into the high pressure circuit, identified as a red line,
- The afore described furnace in the hot cell
- A throttle valve, located downstream the furnace in a shielded casemate inside the hot cell, which allows expanding instantaneously the high pressure argon gas carrying also the released fission gases. After the associated pressure drop down to roughly atmospheric pressure, the low pressure circuit, depicted as a purple line, allows transporting the fission gases to the rear zone
- The gases are then moved in front of a gamma spectrometer, placed itself in a shielded casemate in the rear zone of the hot cell. This equipment, presented in the following sub-section, gives access to the fission gas release kinetics
- All the gases are then stored temporarily in a buffer tank before being released out of the facility.

In addition to this so-called standard loop configuration, another device has been implemented to study the influence of fast pressure drops on fuel fragmentation. As depicted in Figure 2, the device consists in expanding the argon gas directly in the hot cell thanks to four tubes located under the furnace, on the hot cell floor.

The fission gas release measurement

In this standard configuration of the MEXIICO loop, the throttle valve combined to flow regulators induce a rather slow gas flowrate in the low pressure circuit. Thanks to this hydraulics management, it is possible to record the ^{85}Kr fission gas release kinetics on a hyper-pure germanium detector. This detector is the same as the one used in the MERARG loop, dedicated to thermal transients at atmospheric pressure. However flowrates associated to both types of thermal transients are very different with typical flowrate about 100 times higher for a MEXIICO test than for a MERARG test. To get the most accurate FGR kinetics curve, it is therefore necessary to improve the detector sensitivity. This has been achieved with a specific capacity, implemented in front of the detector, located in a shielded casemate, which volume has been maximized in order to increase the counting rate statistics: see Figure 3.

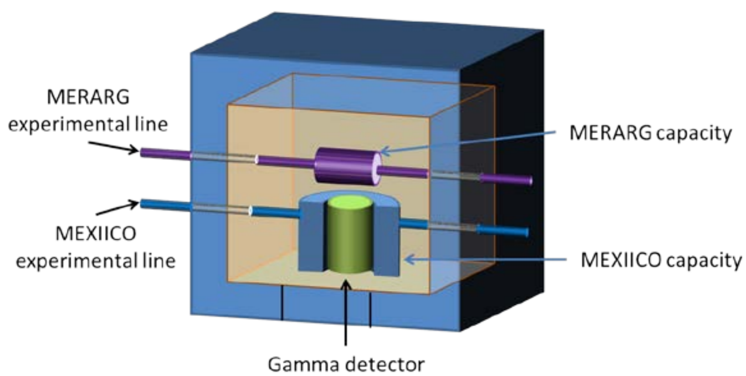


FIGURE 3: The chamber in front of the gamma detector to measure fission gas transport in the exhaust line

With such a procedure a 1,5 L capacity has been designed for the MEXIICO circuit, which is more than six times the MERARG capacity volume. After a quantitative calibration with a reference sample, the release rate detection limit of MEXIICO loop has been established, for a 120 s acquisition period, at about $4.3\text{x}10^{11}$ at.s^{-1} compared to $1.5\text{x}10^{10}$ at.s^{-1} for MERARG loop. Such low detection level allows an accurate detection of FGR bursts. Regarding the overall FGR, it will be measured in two different ways: by integrating the on-line kinetics measurements and by measuring off-line an aliquot representative of the total gas which is collected in the buffer tank. Uncertainties can be calculated for both routes and, typically, the uncertainty for the off-line measurement is about 7 % of the measured FGR within two standard deviations.

Note that, for the fast pressure drop configuration, FGR kinetics measurement is not available since exhaust gases are directed towards the tubes in the cell and not towards the gamma detector in the rear zone. In this case, only the overall release is obtained, at the end of the test.

Since the gamma detector is located in the rear zone of the hot cell, several meters downstream the sample, it is necessary to take into account the residence time of the gas in the circuit to accurately correlate fission gas release events to the local temperature and pressure conditions when the release occurred from the sample. This evaluation was performed by a dual approach:

- Experimentally, gas injections in the furnace exhaust line during temperature and pressure transients,
- By modelling, combining analytical equations and computational fluids dynamics calculations.

The results of this work, exhibiting a nice comparison between experiments and modelling, are fully described in [1].

MEXIICO ON-GOING RESEARCH PROGRAMS

After having presented the MEXIICO experimental set-up, we detail in this section the first research programs using the MEXIICO capacities. They are focused on two major concerns, Pellet-Cladding Mechanical Interaction and cladding Stress Corrosion Cracking (PCMI-SCC) during power transients, and fuel behavior in case of LOCA.

Supporting the PCMI-SCC modeling

In the power transient situations, the release of the fission gases and of the corrosive fission product compounds is highly influenced by the grain boundary behavior in the central part of the pellets. PIE of fuel submitted to high temperatures during ramp tests or during out of pile annealing tests show that there is an influence of hydrostatic restraint on the formation and interlinkage of intergranular bubbles with consequential effect on fission product release (Figure 4). Theoretical and experimental work in this domain started long ago [2-4], yet, precise experimental data are still needed for the validation of the modeling and even of the scenarios [5]. Indeed, as shown by detailed modeling of ramp tests, such as that in [6] (Figure 5) the hydrostatic stress history during such a test is complicated and highly influenced by fuel creep and cladding behavior in addition to thermal expansion and fuel swelling. Dedicated experiments in the MEXIICO device, with high temperature ramps, under selected high hydrostatic steady pressures, followed by detailed post-test SEM characterizations as well as EPMA and SIMS microanalyses and intergranular gas measurements [7-8], will facilitate the validation process of the fission gas models as well as of the whole fuel behavior codes for this type of situations.

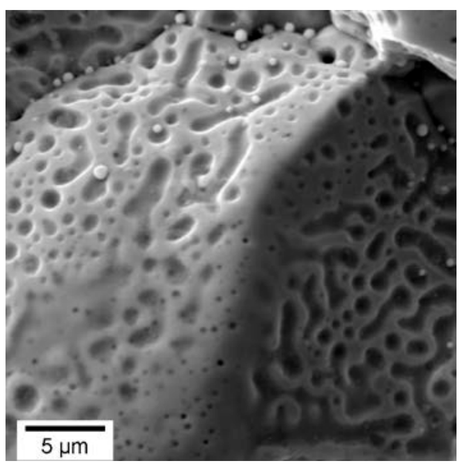


FIGURE 4 : Scanning Electron Micrograph (SEM) of the grain surface of a 38.8 GWd/t_U UO_2 fuel in the central area, after a ramp test with a maximum power of 520 $W.cm^{-1}$, held during 90 s [9].

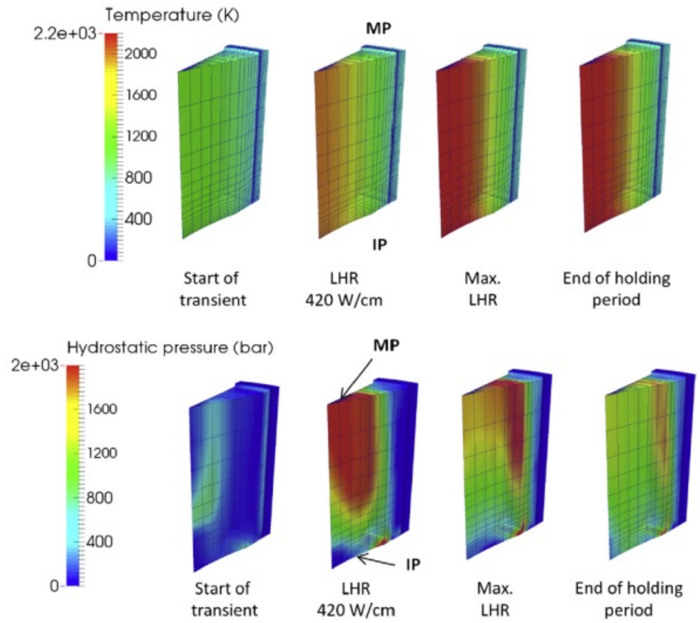


FIGURE 5 : Calculated evolution of temperature and hydrostatic pressure in a fuel fragment during a power ramp [6].

Establishing fuel fragmentation limits and fission gas release in LOCA situations

In the understanding of the phenomena involved in fission gas release and in the fragmentation and pulverization of high burn-up fuels in LOCA situations, in addition to the so called integral tests, highly controlled tests on smaller samples are necessary. Their role is to evaluate the mechanisms responsible for the observed phenomena but also to establish limits and to explore the impact of various parameters, of the fuel state or of fuel variants. In this field, the MERARG device allows measurements at 0.1 MPa [9-10]. However, it has been shown that the restraint of the fuel has an impact on FGR and on fragmentation [4, 11-12]. For instance, a critical pressure leading to an onset of burst release has been clearly evidenced (see Figure 6) for annealing tests performed at 1500 °C on very small samples (10-15 mg) of UO_2 fuel at 37 GWd/t: when the external pressure falls from 60 to 40 MPa, a simultaneous strong burst release is monitored.

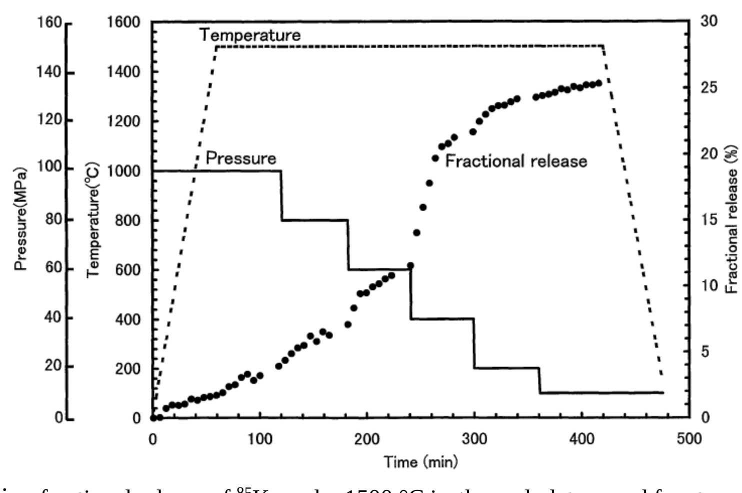


FIGURE 6 : Cumulative fractional release of ^{85}Kr under 1500 °C isothermal plateau and for stepwise decreasing restraint pressure from 100 to 10 MPa [4]

With the MEXIICO device, specific work will be carried out on entire fuel pellets with cladding, large fragments representative of the whole pellet, selected areas sampled in LWR irradiated fuels and also almost isothermally irradiated discs of various fuel types, as within the NFIR EPRI international program [13-14], see Figure 7. The capacity of the MEXIICO device to work with large samples and smaller ones is important to evaluate, for each fuel, the fragmentation limits of the various areas in the pellets [15]. It is all the more important that it has been shown that the size of the sample has an impact of its fragmentation behavior [16].

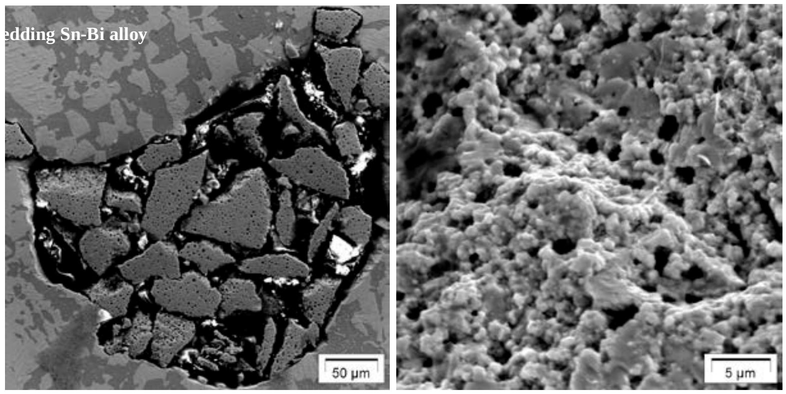


FIGURE 7 : SEM images of 103.5 GWd/t_U UO_2 NFIR disc fragments after a 1200°C annealing test at 0.1 MPa in the MERARG device [14].

Moreover, two hypotheses have been proposed to explain the lower fragmentation of the high burn-up fuels above or below highly fragmented areas around the burst balloon of some integral LOCA tests [17]. When compared to the situation at the burst and balloon location, it may come from slightly lower temperatures during the test [18], or it may come from a slower pressure drop when the balloon bursts. In order to evaluate this possible effect, fast pressure drops will be applied to fuel fragments, in the range of temperatures where clad balloons burst occurs in the LOCA integral tests. These tests will be compared to equivalent tests around 0.1 MPa in the MERARG device.

COMMISSIONING TESTS

In this section, we present the commissioning tests of the MEXIICO loop that were performed first in a conventional laboratory and then in a hot cell of the LECA-STAR facility. At first, we focus on the thermal qualification of the furnace and then, for illustration purpose, we detail two types of tests that can be conducted in the MEXIICO loop. In the last sub-section we cover the fast pressure drop tests that were carried out in conventional laboratory before introducing all the equipment into the hot cell.

Furnace thermal characterization is a key point since we intend to perform transient tests on rather large samples, typically one LWR pellet with its cladding, it is thus necessary to place the sample in a homogeneous environment. To address this issue, a specific set-up has been operated during which a thermocouple has been placed at the sample location inside the crucible. The results, shown in Figure 8, highlight a flat profile in the region of interest, which fulfills the requirements.

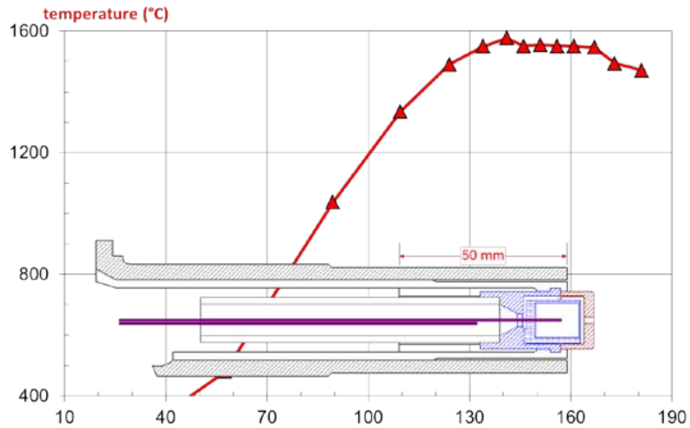
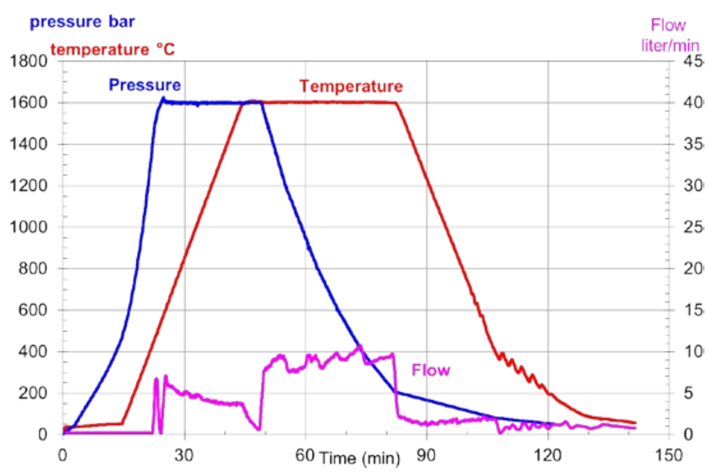


FIGURE 8 : Thermal profile with temperature in °C on y-coordinate. Sample will be placed in the blue crucible

Regarding experimental temperature and pressure transients, lots of tests were carried out in a conventional laboratory to fully investigate the MEXIICO capabilities, in terms of maximum temperature and pressure, but also in terms of pressure drops at selected temperatures consistent with the 150 °C core temperature limit. After having established this operating range, it was decided to transfer the equipment in hot cell. The additional tests, performed in the LECA-STAR facility, confirmed those performed in a conventional laboratory. In Figure 9 two types of tests are presented. The first one consists in a pressure drop screening at a selected temperature of 1600 °C which will allow identifying the first FGR burst. The second one, which can be used in comparison to MERARG tests performed at atmospheric pressure, is dedicated to evaluate the influence of pressure on a thermal transient. For this latter test, a specific procedure has been applied during the temperature and pressure plateau. Indeed, during the 1200 °C and 18 MPa plateau, a thermal-hydraulic equilibrium is reached in the furnace with no gas flow. Since FG may release, it would not be detected by the gamma detector. To compensate for this bias, a special use of the compressors has been developed so that a flow continuously passes through the furnace allowing FGR detection (see input and output flows in Figure 9).



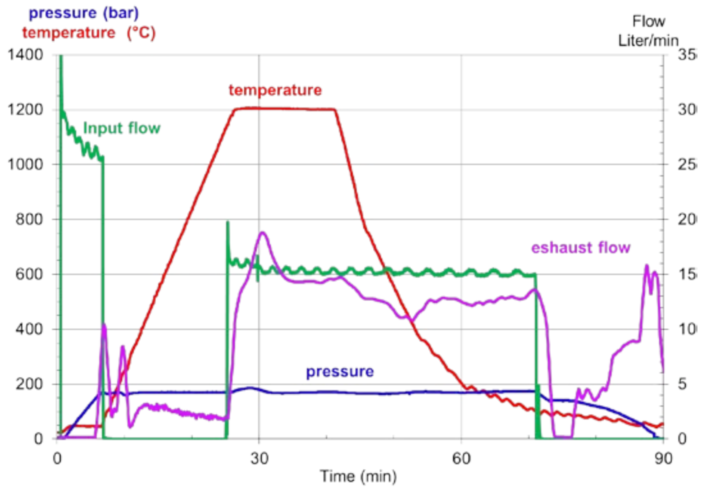


FIGURE 9 : Typical temperature and pressure transients in the MEXIICO furnace.

Regarding fast pressure drop tests, they will be first devoted to evaluate fuel behavior, particularly in term of fragmentation during a LOCA balloon burst. Figure 10 shows a typical test sequence at 800°C and 160 MPa. The test procedure will be performed in three steps. First, the compressors induce a pressure increase, heating is then turned on in order to reach smoothly the pressure plateau and finally the temperature plateau. Secondly, the valve on the furnace exhaust line is opened, so that the gases are directed towards the tubes inducing a fast pressure drop, heating is stopped at the same time. Finally, after some time, when pressure and temperature reach predetermined values, the throttle valve opens and the gases are transferred in the rear zone. Gas sampling from the buffer tank will allow evaluating the global FG released fraction.

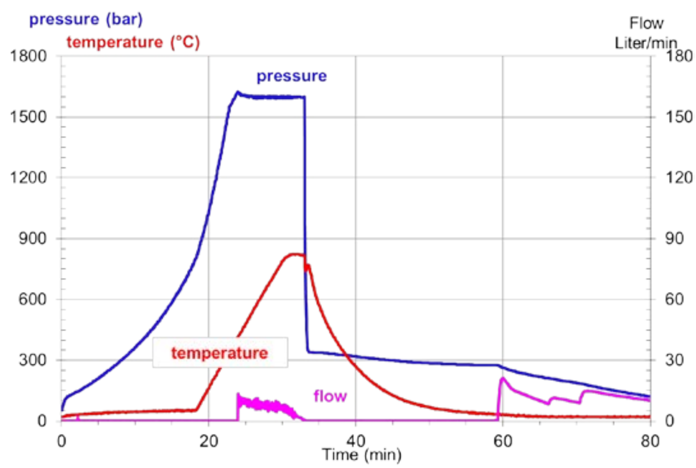


FIGURE 10 : Typical temperature and pressure transients with the fast pressure drop MEXIICO configuration

CONCLUSION

In this paper we have first described the new MEXIICO experimental loop which has been started in 2015 in the LECA-STAR facility of the CEA Cadarache. Thanks to its key component, a hot isostatic press, we are now able to perform analytical experiments in the [20 °C -1600 °C / 10 MPa - 160 MPa] region. By implementing a gamma detector on the gas exhaust line, we also have access to on-line ^{85}Kr measurement and thus to the fission gas release kinetics during the analytical experiments. We also have developed an additional specific device enabling fast pressure drop experiments.

We have presented the commissioning tests for the different MEXIICO set-ups which confirm and illustrate the different capabilities of this new experimental device. In a dedicated part, we have identified the research axes that will be first addressed with the MEXIICO loop: fission gas release under LOCA or power ramp conditions and fuel fragmentation-pulverization under fast pressure drop experiments. By investing the samples, either fuel pellet or specific region of such element, through complementary post MEXIICO test microanalyses, focused on microstructure and gas distribution evolution, we expect to collect precious data to characterize FGR and fuel fragmentation mechanisms. The future MEXIICO results will therefore contribute to improve fuel modeling and fuel safety analysis.

ACKNOWLEDGMENTS

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