FUEL ROD INSTRUMENTATION TECHNIQUES IMPLEMENTED IN LECA FACILITY – DEVELOPMENT OF ADVANCED INSTRUMENTATION TECHNIQUES

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1 – General Introduction

For a better understanding and in order to improve fuel performances in terms of discharged burn-up, power up-rating and reliability without reduction of safety margins, CEA Research Laboratories are testing fuels at high burn-up in normal and off-normal operating conditions. Experiments are conducted with irradiation devices which are holding base irradiated fuel segments coming from commercial reactor.

Monitoring such experiments in **M**aterial **T**esting **R**eactors (**MTR**) requires accurate and reliable in-pile instrumentation. The quality of these experiments depending for a large part on measurements performed with these devices for parameters such as: neutron flux, temperature, sample geometry, fission gas release.

One illustration of these developments is the in-pile experiment, so-called REMORA. For this experiment, one base-irradiated fuel segment for several cycles in a French EDF commercial reactor was re-fabricated and instrumented with both a fuel centre-line thermocouple and an advanced pressure transducer.

The main goals of the REMORA experiment have been to study the thermal conductivity and its degradation as a function of Burn-Up, the fission gas release and especially its kinetics in off-normal operating conditions.

These innovative techniques especially developed for this experiment were a new concept of pressure transducer using counter-pressure principle and a specific drilling system to manufacture the central hole for the introduction of the thermocouple without cryogenic cooling. Moreover, since quick response and stability are required for the pressure transducer, methods and materials have been tested to select the most appropriate to satisfy these requirements. These significant improvements in rod instrumentation capabilities recently achieved have made possible the execution of high-performance irradiation experiments on advanced PWR fuels in the GRIFFONOS pressurized water loop of OSIRIS experimental reactor.

The investigations are focused on extracting qualified data on fuel conductivity at high burn-up. Instrumentation have been developed over the years which enable to assess in-pile fuel behaviour and properties in-pile. Additional experiments are devoted to understand the combined effects of various parameters on integral fuel rod behaviour. The key measurements include fuel centreline and outer temperature.

Two innovative technologies like fuel stack outer temperature sensor and deep hard drilling technique are in progress in LECA Facility. We will briefly present future directions of this active research field in this paper.

2- Description of the specific sensors

2.1 – Fuel thermocouple:

For the introduction of the thermocouple, the irradiated fuel segment was centre drilled through around four end pellets length using a drilling process without cryogenic cooling. This technique had been first qualified for different fuel types and burn-ups; MOX and UO_2 fuels fresh and irradiated up to 70 GWd/t_M; in order to check if any changes in fuel microstructure were induced which could result in a modification of the fuel thermal conductivity. Drilling characteristics: diameter, concentricity, length and the state of the fuel microstructure were controlled by metallographic examinations.

The end of the thermocouple was positioned in the middle of the third pellet to avoid any thermal breakdown, and checked before and after irradiation by neutronographic examinations (**Figure 1**).

The temperatures measured during the irradiation are from the centre of the 2,6 mm diameter hole drilled into the four end pellets of the rod. This hole represents a significant loss of fissile material and the radial thermal field in the hollow pellets is affected by its size. It's why, after irradiation, the value of the diameter is rechecked by metallographic examinations.

Tungsten / Rhenium alloys thermocouples are used to measure fuel centre-line temperature with a range fitted to the temperature level expected in the fuel and with accuracy fitted to short irradiation duration Under irradiation Tungsten and Rhenium are transmuted into mainly Osmium and the material composition change induce an unacceptable signal drift for long term experiments. For REMORA experiments, the maximal drift induced by thermal neutrons flux was less than 5℃ (corresponding to -1℃ by 2.10^{19}n/cm²) and the value of total accuracy is about 1,5% for temperature up to 1500℃.

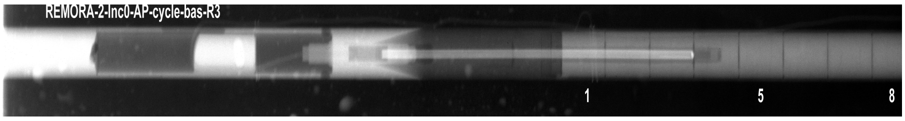


Figure 1 Neutron radiography - upper part of REMORA rod

2.2 <u>- Pressure sensor:</u>

The counter pressure sensor (**Figure 2**) is designed to be set up on a pre-irradiated fuel rod by welding process and, to avoid any thermohydraulic perturbations, the sensor diameter is close to the fuel rod diameter. This sensor operates under severe irradiation environment: high neutron flux and gamma radiations, high temperature and external pressure around 130 bars.

The counter pressure principle consists of two gas cavities, separated by a double bellow. One cavity communicates with the fuel rod plenum and the second cavity is connected to an external gas circuit acting as a "counter pressure circuit". Two electrical contacts activated by the displacement of the bellow detect the imbalance between the internal rod pressure and the counter pressure. For each measurement, the counter pressure is inflated and deflated in order to detect the two electrical contacts changes. This principle ensures a reliable driftless measurement for a large pressure range from 0 to 150 bars with accuracy of ± 0.5 bars.

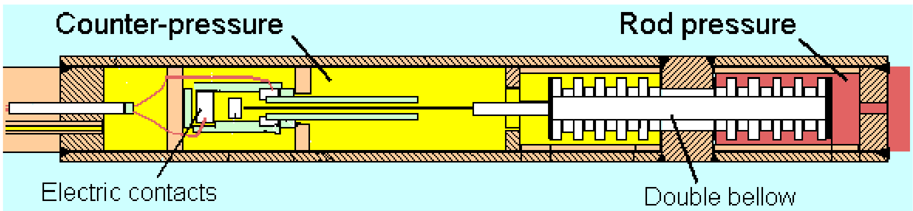


***Figure 2** : Pressure sensor*

3 –« CORALIE » A re-fabrication and instrumentation equipment (Figure 3):

The Active Fuel Examination Laboratory (**LECA**) in CEA-Cadarache developed fuel rod manufacture technologies for re-instrumentation of high burn-up nuclear fuel rod in the frame of the REMORA project. To re-fabricate fuel rods, two types of devices are needed: a drilling equipment and a YAG laser welding system integrated in the same equipment which was named "CORALIE" .

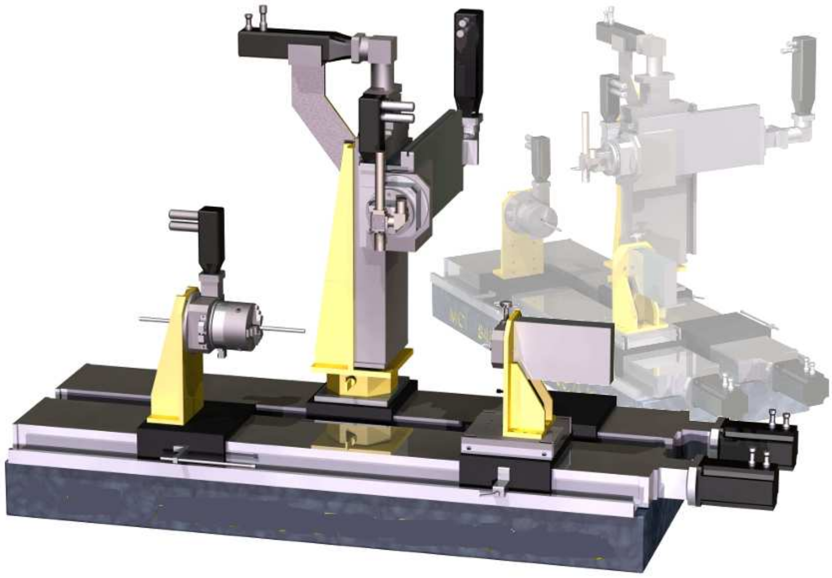


Figure 3 : Overview "CORALIE"equipment

This equipment was designed as a 4-axes (rectangular X, Y, Z axis and Z rotation axis) . Efficient laser welding and operational ability for each axis were evaluated. Before its insertion into hot cell, welding of Zircaloy cladding was carried out to verify the reliability of the process with a mock-up.

The machine allows the following tool movements in particular axes: X - 700 mm, Y - 200 mm, Z - 400 mm; It is controlled by SAFMATIC Control System, The equipment ensures the accuracy and reproducibility of machining of **0.007 mm** along each axis (**Figure 4**).

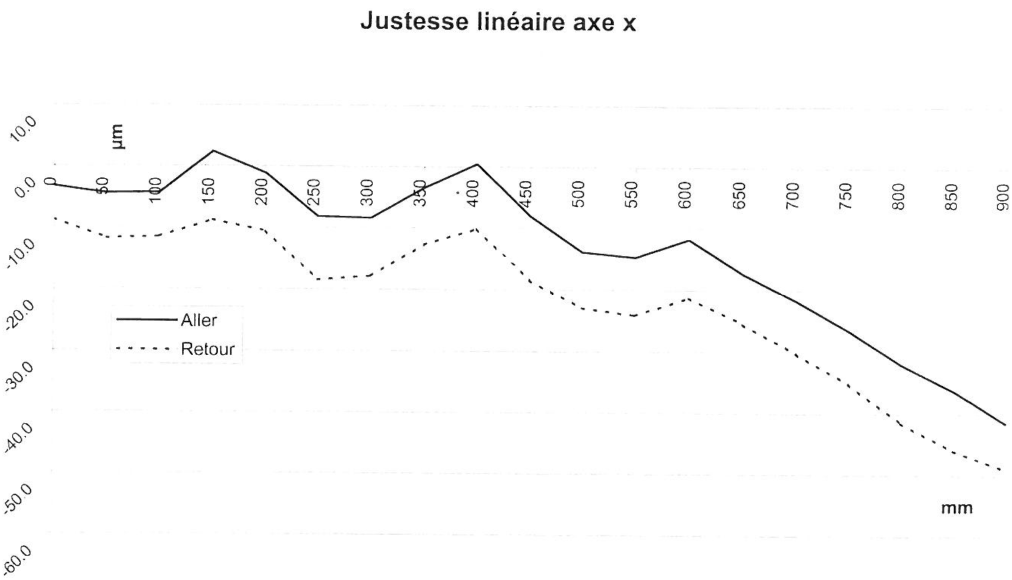


Figure 4 : Accuracy and reproducibility of machining of 0.007 mm in X -axis

Laser welding was selected because of the high energy input per unit volume in order to weld without local fusion of the considered area. In comparison with other welding process, lower global heat input is the main reason why basic material characteristics remain unaffected after welding.

In this study, for 0,6 mm thickness Zircaloy cladding optimum welding parameters are obtained using the pulsed Neodym : YAG laser (1064 nm, pulse duration 6-8 ms, power density 50 watt, frequency repetition about 10 Hz). The influences of laser welding parameters such as pulse duration, focal position, frequency, laser power, welding speed, and inert gas (Argon) pressure on penetration defining welding quality were investigated. Optimum parameters and specific qualification for this welding process have been achieved.

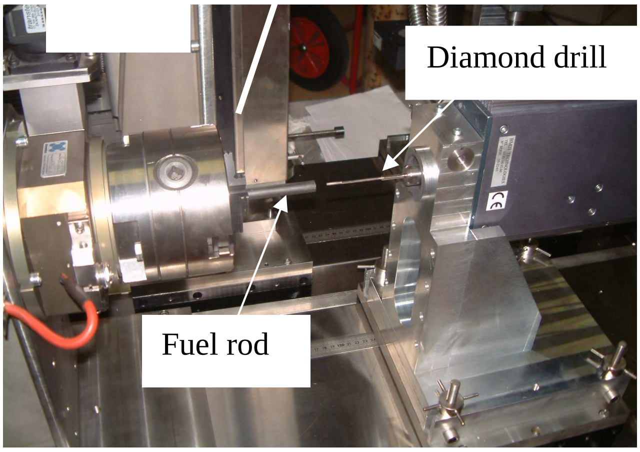
In addition, different types of Non Destructive Examinations methods are used in quality control and documenting of the work done with the fuel rod. For example digital radiography, visual inspection, dimension measurements, free volume measurements.

3-1 Hard drilling technique:

3.1.1 Process :

Two steps have been followed to carry out the development program. First a drilling technique was developed to make a centre hole in the irradiated fuel pellets stack. Different drilling tests were carried out using dummy fuel rods consisting of Zry-4 cladding and alumina pellets. Diamond drills were used to make the dry centre hole. A centre hole, 50 mm long and 2,6 mm diameter, was realized by this method. The main goal of the program was to simplify and to qualify the working process on irradiated fuel and to preserve integrity of the drilled fuel stack. One objective was also to drill the fuel stack without the need of cryogenic cooling. A laser welding machine was used to fasten an end plug on a fuel rod. Before installing the equipment in the hot cell, a try out was performed to evaluate the system. All tests were completed successfully.
The second step of this program was an in-pile demonstration test on one irradiated fuel rod instrumented with a thermocouple and a FP gas pressure gauge. The design of a dual instrumentation device has been completed.
Since 1999, LECA Cadarache Hot Lab. has developed a machine tool (**Figure 5**) able to drill fuel stack centre for thermocouple insertion.

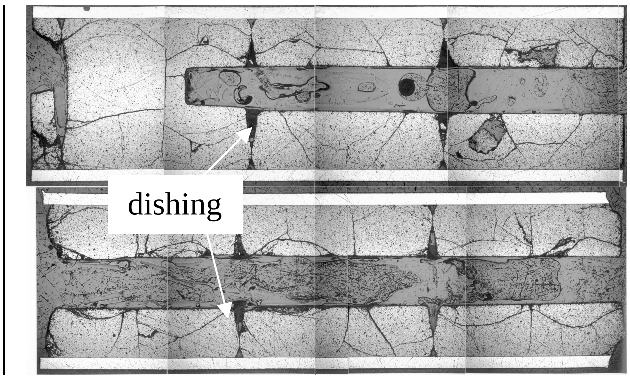
***Figure 5* : Machine tool for drilling a centre hole in fuel pellets**



Centre fuel hole is realised with diamond drill tubes of 2.3 mm diameter and 20 and 50 mm length. An important rotational speed is required and an argon flux inside the driller allows the cooling of the diamond tube and avoids its clogging. The drilling machine tool is a driller, which is commanded by remote control.
It allows to realise an unlimited number of cycles and modulated six parameters as well. Parameters are, length and speed advance, depth and speed pass, revolution speed, and number of cycles.
Strong contact between fuel stack and cladding is necessary because the drilling process could carry the pellets out of the canning. Then, application of the process is limited to two cycles irradiated fuel and beyond.
After verification of length and depth of the hole, a 2.6 mm diameter molybdenum tube is introduced as the interface between fuel and thermocouple. The 2.6 mm diameter for a 50 mm deep hole geometry is an optimum as smaller diameter is limited by drill mechanical resistance and vibrations effects.

3.1.2 Comparison with RIZO process

A well known process is cold RISÖ process. The operation consists in filling the fuel rod sample with liquid CO_2 and subsequent freezing it down with liquid Nitrogen in order to stabilise the fuel before and during the drilling operation.
Cryogenic technique is not easy to introduce in hot cells. Liquid flux in and out of cells always represents technological difficulties and safety risks. On the positive side a simplified remote control driller allows a fast operation. The drying oven use can affect the fuel microstructure and induce cracking, because of differential dilatation from thermal gradient. This cracking has been quantified, and, from what we know, has a significant effect on fuel thermal behaviour. The temperature measurement accuracy is decreased by more than 50℃ .
In the RISÖ process, the 2.5 mm molybdenum tube has to be inserted into the centreline hole immediately after the drilling operation to provide internal fuel support. Metrology of the hole is so impossible to perform.
For CEA process, the room temperature conditions allows us to realise accurate metrology measurement of the drilled hole especially depth and diameter with standard metrological tools. This new process as been qualified for different fuels and burn-ups.



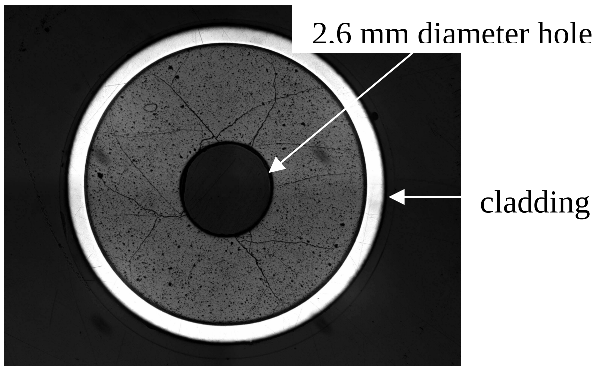


Figure 6 : drilled hole Metallographic view

Different metallographic exams confirm by comparison between drilling fuel and fuel without hole, that the fuel microstructure is not significantly affected by the drilling (**Figure 6**). Other exams give important information like concentricity and diameter of the hole. We noticed, that the hole diameter is 15 % larger than drill diameter because of drill vibrations. Dimensions knowledge is particularly necessary for fuel behaviour modelling with simulation tools.
RISÖ process is applicable for low and high burn-up, our process is applicable for two reactor cycles irradiation and higher Burn-up.

3.1.3 *Process qualification*

First tests have been realized in a glove box with unirradiated UO_2 fuel in order to validate the capability of the driller to drill fuel pellet, and also to obtain understanding and orientation on parameters. Drills have been successfully realized.
Next tests have been performed in hot cell on a vertical simple concept machine tool. The target was to know the kind of irradiated fuel we could drill, and also to know if we could drill a 50 mm deep hole. We worked on two irradiation cycle MOX fuel and high burn up UO_2 fuel. As results, we confirmed that we could drill from a two irradiations cycle MOX fuel and also with high burn up fuel, and the 50 mm depth hole has been achieved.
Two tests have been done on 70 GWd/t UO_2 fuel. It has been chosen, because it illustrates exactly the first double instrumented rod fuel. As results : concentricity of the hole has been obtained within 0.1

mm of the pellets axis, the angle is less than 1° with the rod axis, the hole diameter is 2.6 mm for a 2.3 mm drill and the hole is 50 mm long.
At the qualification issue, we have realized a hole in the instrumented rod fuel, which was perfectly conform to our specification. The molybdenum tube and the thermocouple have been successfully adjusted for measurement optimisation.

*3.2 Laser Welding (**Figure 7)** :*

3.2.1 Process:

The Zircaloy end-caps of instrumented fuel rods were welded and sealed up circumferentially using an orbital technique, connecting end-capping and fuel rod within a stream of Helium gas shielding to protect the weld pool.

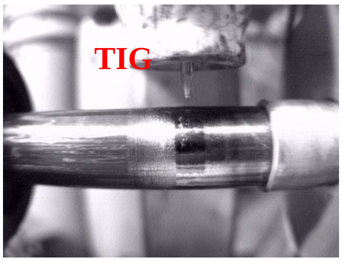


***Figure 7a** : TIG welding*

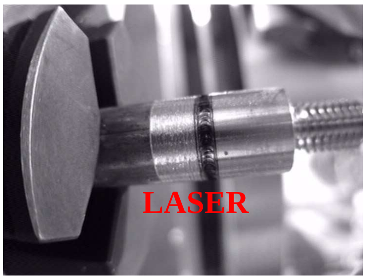


***Figure 7b**: laser welding*

It was the joint was aser welding preser e precisely due to precise focusing of the laser beam (deep weld) and a narrow heat affected zone (Figure 7b). Deep penetration and defect-free welds are achieved under an optimal combination of laser parameters including focal length of lens, pulse energy, pulse repetition rate, beam travel speed, and shielding gas arrangement.

3.2.2 Seal welding

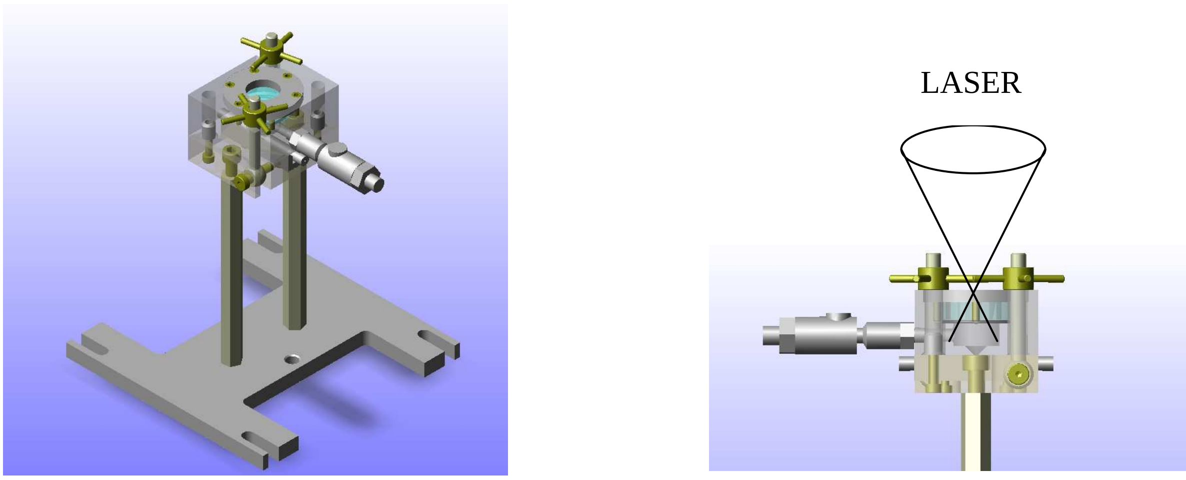


Figure 7 : Laser welding under helium gas environment for hermetic sealing of end cap to the cladding

An opening capable of inserting a cladding tube is disposed in the side wall of a welding chamber and a laser beam window is disposed in another side wall perpendicularly to said side wall. Further, a laser beam generating device is disposed outside of the welding chamber for concentrating the laser beams through a silicate window to the weld portion directly to the end plug. In order to weld the end plug the opening end of the cladding tube is inserted through the side wall opening into the chamber. Then the inside of the chamber is evacuated and replaced with Helium gas to establish a super atmospheric pressure state. A test was successfully performed using a rod internally pressurized at up to 100 bars.

The soundness of end-cap weld is very important. To evaluate the soundness of end-cap weld of fuel rods, X-ray inspection technology and Helium leak test, have been applied. The X-ray radiographic scanning machine is used in a concrete hot-cell to inspect welding bead. The smallest discernable defect is 0,2-0,3 mm in diameter.

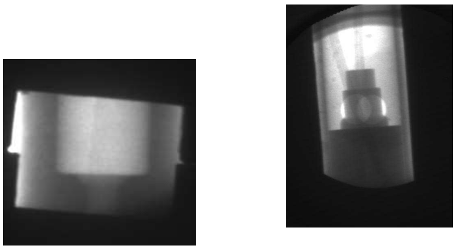


Figure 8 : Welding X-ray radiographies

Digital radiographic methods (**Figure 8**) provide more sensitive, faster and more reliable evaluation of defect images. One of the most important factors influencing the contrast and consequently the image quality is the noise on the film caused by scattered radiation. The digital image processing technique will allow to eliminate the noise and improve the image quality.

<u>3-2 Laser Head under irradiation:</u>

The interaction between process parameters, such as the exact positioning of the laser focus and the weld gap between sheets, affects the stability of the laser beam welding process and thus the quality of weld seams.
Since a number of components are not resistant to radiation, laser head can be handled allowing it to be stored in a lead shielded box when not used. Nevertheless, a try out must be performed to evaluate it before welding operation.
In this technology, **the laser beam** is used through an optical fibre which possesses marked resistance to gamma-irradiation.
A method is proposed for evaluating the gap focal spot ΔFoc by making several welding spots while a digital camera locates the position of each new focus (**Figure 9**).

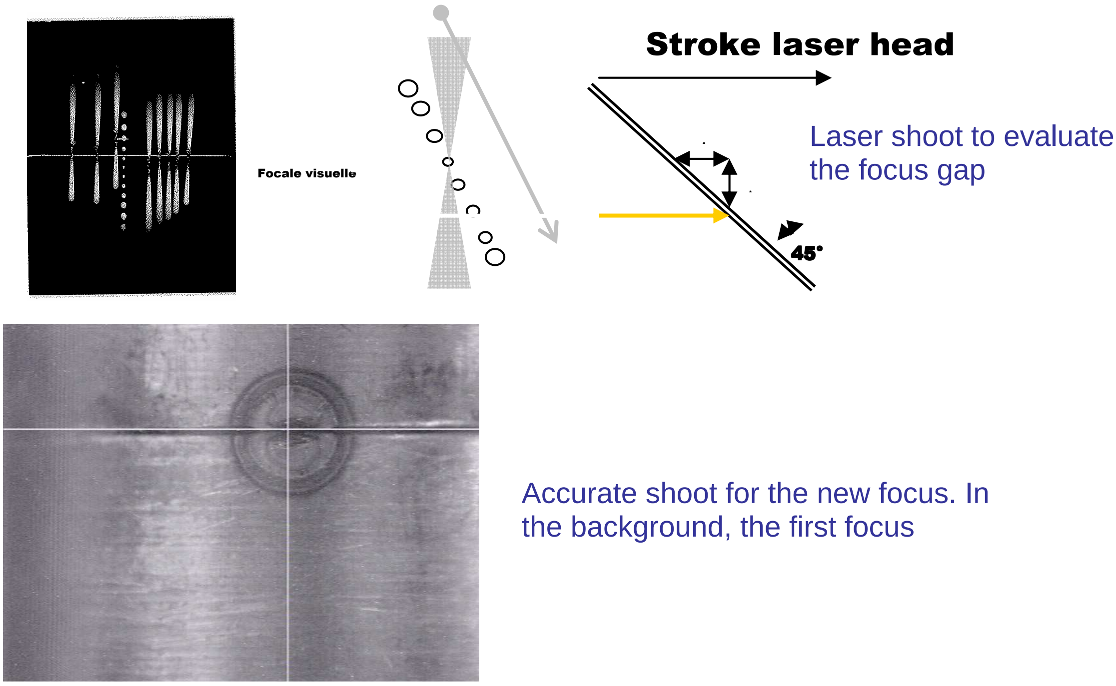


***Figure 9** : Focus evaluation method*

Beam quality must be sufficient to focus total energy on the seam. To check it, laser head shoots and moves along an anodized foil which is placed at a 45 deg. angle with respect to the beam direction plate in order to appreciate the correct size spot and the right focus. The spot size of the laser beam is monitored by a video camera.

4 In progress innovative instrumentation techniques :

Two projects are in progress to further develop innovative instrumentation techniques and these are briefly summarized. The first case concerns the location of thermocouple in the interior rod cladding surface. In the second application, a hard drilling technique to make a center 100 mm depth hole in fuel rod. The resulting designs are going to be transferred, in a later phase, to a full-scale prototype facility.

4.1 Fuel column outer temperature measurement :

In the area of instrumentation technology, the LECA facility is developing a technique enabling to measure on-line fuel stack outer temperature. Temperature evolution is measured by a Zircaloy-Rhénium thermocouple welded under the cladding surface. The zircaloy tile with thermocouple in will be introduced in the removed cladding part of the fuel rod, itself covered with a larger welded Zr clad sample (**Figure 10**).

Therefore, welding tests on instrumented cladding tile will be conducted in a mock-up to prepare the in cell operations on irradiated fuel rods. The sample have a size of 10 mm x 10 mm x 0,6 mm were cut out from Zry-4 rod, by laser head. Effect of laser beam cutting parameters such as laser power, focus position and cutting speed on quality of surface cut of 0,6 mm zircaloy cladding has been studied, Furthermore, optimizing laser cutting conditions to obtain high quality laser cutting on the basis of fine, dross-free, good surface roughness and narrow kerf width has been examined.

Many problems associated with development of welding on thin tubes were resolved. Work was initiated, in the second phase of the development task, to select a suitable technique to integrate an instrumented square clad tile under a thin welding clad. The sample clad welding test is conducting using a laser welding machine in an inert gas. For each individual task, results were optimized and process development successfully completed. Now, all the fabrication steps must be nuclearized and performed in hot cell. Appropriate weld monitoring techniques were also reviewed for their adaptation.

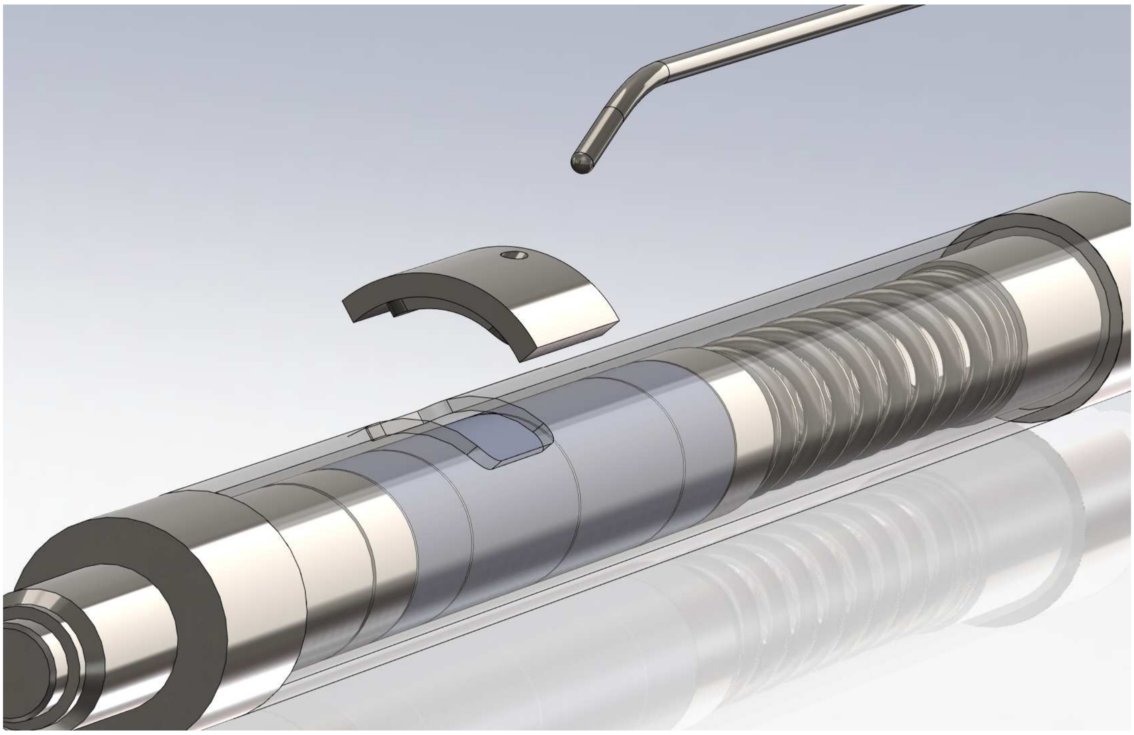


Figure 10 : fuel column outer temperature sensor

4.2 Hard drilling technique – 100 mm depth :

Now, we plan to perform some drilling tests to make a center hole of 100 mm depth and 2.5 mm diameter. We have to determine the optimum drilling condition.
We are testing a mock-up drilling machine which can drill the center on the irradiated fuel rod. Various drilling tests have already been carried out using ceramic rods. These tests were completed successfully. A center hole, 55 mm in depth and 2.5 mm in diameter, was realized by this method.
A prototype tool was fabricated for testing in a mock-up area to check drilling process and provides actual hands-on training for operators. Recent tests with an appropriate diamond tool are encouraging. The last experiment was successful, with the drill reached over 95 mm in depth of 3,1 mm diameter. The effect of processing parameters such as drill feed rate, spindle speed, and peck depth were evaluated, and the tool wear mechanism was also investigated. The results show that deep-hole mechanical drilling of alumina rod is technically feasible. Therefore, we focus to stabilize the wandering motion and achieve 2,5 mm diameter.
The boring bench is already implanted in hot cell. We developed a new tool and adapted the drilling process (diamond drills set, improved drill guide, drill material enhancement). So, this technique can be carried out normally in hot cell to instrument longer fuel rod.

Boring module

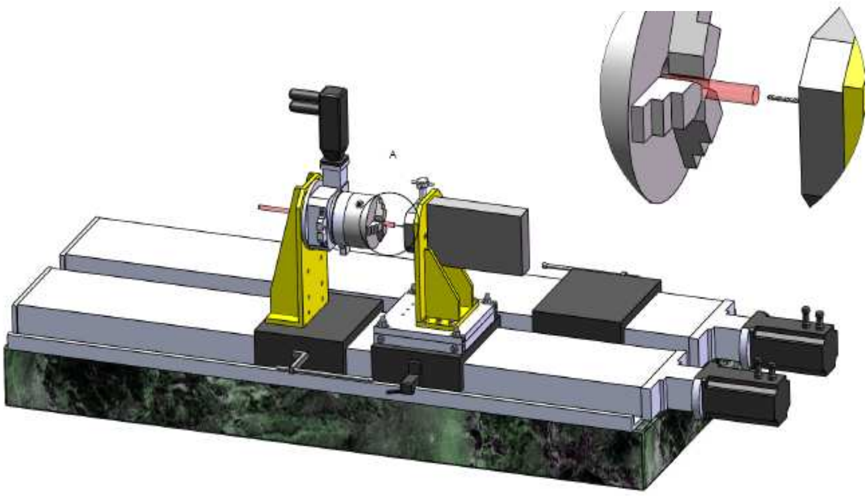


Fig. 11: Boring module in multi-axes bench Coralie

This hard drilling process offers an accurate technique for making a center hole in fuel pellets, without altering the integrity of fuel pellets. Metallographic examination will confirm the overall satisfactory performance of the hard drilling technique and the absence of significant damage. Gamma-scanning and X-ray radiography will be carried out to check the reliability of the diameter hole, as its length, the perfect parallelism between the hole and the cladding.

Drilling operation on large length are operating in a mock-up. It is difficult to drill holes over 50 mm in these materials by "conventional" tool. By improving the performances of the diamond tool, we will be able to reach 100 mm depth and less than 3 mm diameter. This technique can be easily integrated in hot cells on the bench Coralie, our multi-axes bench (**Figure 11**) devoted for instrumentation of fuel rods.

5 – REMORA

The development and qualification of a new technique called REMORA is related to a double-instrumented rod re-fabrication process developed by CEA/LECA hot laboratory facility at CADARACHE. An analytic irradiation of such a double-instrumented fuel rod was performed in OSIRIS test reactor since 2004.

The re-irradiation of the REMORA experiment consisted of a stepped power ramp in order to point out a potential degradation of the fuel thermal conductivity with increasing burn-up. During the first part of the irradiation, most of the measurements were performed at low power in order to take into account the irradiation effects on fuel thermal conductivity at high Burn-up in low range of temperature. The second part of the irradiation consisted in power cycling with one steady–state at several power levels (up to 360 W/cm) to assess both the thermal conductivity at higher temperature (until 1600℃) and the fission gas release kinetics.

Post calculations of the REMORA experiment have been carried out with the computer code which was developed by CEA for modelling the thermo-mechanical behaviour of a single rod during normal and off-normal operating conditions. The main purpose of this study was to check the thermal conductivity of high burn-up fuel, in particular the formulation associated to the thermal conductivity degradation with burn-up. Centre-line temperatures were calculated with CEA code as a function of linear heat rate at the thermocouple level (and were compared with temperature measurements. The issue from the axial power profile coming from the post irradiation gamma spectrometry with effect of the loss of fissile material in the drilled section was taken into account

The evolution of the normalized calculated temperature and the measured temperature in the hollow pellets at the thermocouple level is shown in **Figure 10**. On the whole range of investigated temperatures, we have very good agreement between the measured and calculated temperatures.

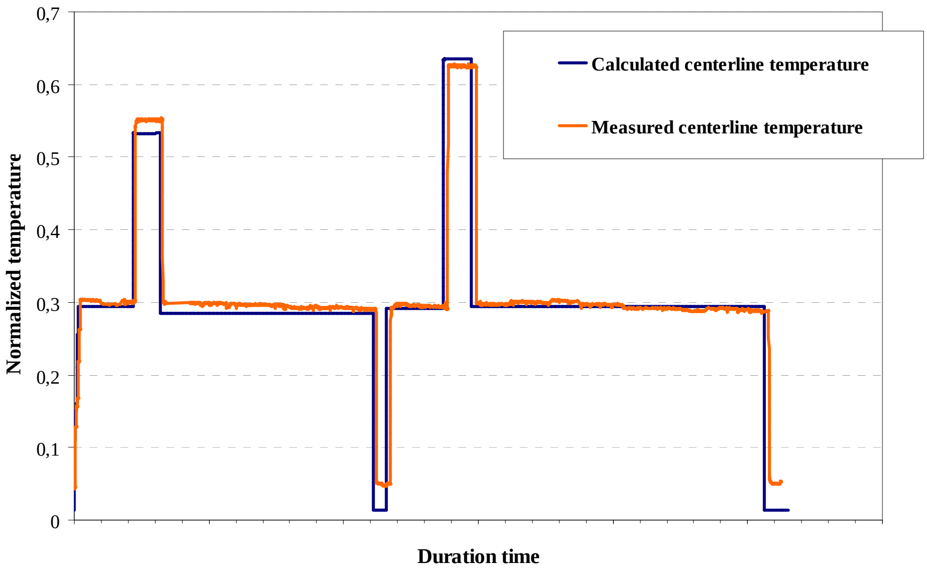


Figure 10

The evolutions of the pressure and the linear heat rate are shown in the **Figure 11**. To determine the fission gas release kinetics, different data or parameters have to be used:

- The on-line internal pressure measurement (see **Figure 11**)
- The evolution of the internal free volumes obtained by CEA code's calculation and corroborated by measurements before and after the in-pile experiment
- The internal gas average temperature obtained by a preliminary in-pile calibration phase (specifics measurements in the first part of the experiment).

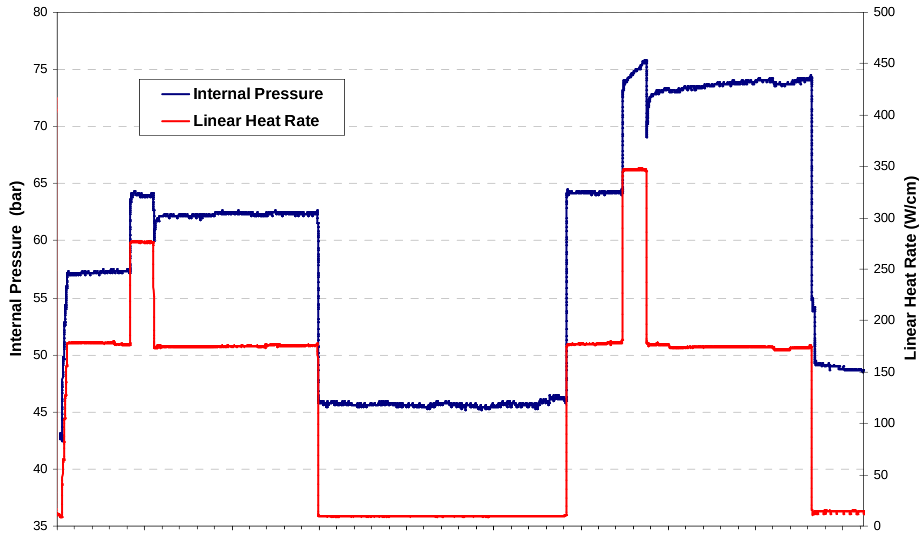


Figure11

The final rod internal pressure was also measured by post –irradiation destructive method (rod puncturing) and compared to the counter-pressure sensor signal at the end of the irradiation. The determined value is very close to the on-line measurements, corroborating the very good in-pile performances of this new kind of pressure transducer.

6 - Conclusion

The latest fuel rod instrumentation techniques implemented in CEA Hot Laboratory have been illustrated by the REMORA project experiments:

Fuel rod thermocouple for temperature measurement without cryogenic cooling drawbacks for 2 cycles irradiated fuel rods and higher Burn-up

Fuel internal pressure sensor using the technology of the counter pressure principle for accurate online pressure measurements

The CORALIE integrated equipment allows drilling of the fuel pellet stack with a maximum geometric accuracy ; welding and sealing of fuel rod end cap using laser technique for shorter intervention time, minimization of equipment contamination and reduction of fuel rod cladding heat affected zone

The improvements introduced in the processing of refabricated and instrumented irradiated fuel rod samples are expected to achieve higher accuracy of temperature and pressure measurements values and better understanding of fuel behavior to determine potential Burn-up capabilities.

Innovative instrumentation techniques are conducting in a mock-up. They are devoted to understanding the fuel rod thermal behavior.