Refabricated and Instrumented Fuel Rods

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Abstract

Nuclear Fuel for power reactors capabilities evaluation is strongly based on the intimate knowledge of its behaviour under irradiation. This knowledge can be acquired from refabricated and instrumented fuel rods irradiated at different levels in commercial reactors.

This paper presents the development and qualification of a new technique called RECTO related to a double-instrumented rod re-fabrication process developed by CEA/LECA hot laboratory facility at CADARACHE.

The technique development includes manufacturing of the properly dimensioned cavity in the fuel pellet stack to house the thermocouple and the use of a newly designed pressure transducer.

An analytic irradiation of such a double-instrumented fuel rod will be performed in OSIRIS test reactor starting October 2004

Keywords: *Experimental - Fuel - Rod - Instrumentation*

Introduction

Within two development projects in the area of fuel burn-up performance and nuclear instrumentation, CEA decided to manufacture a fuel rod instrumented with a pressure transducer and a thermocouple in order to follow its behaviour under irradiation in a test reactor. The purpose of this analytic irradiation is to quantify high burn-up fuel behaviour, through temperature and pressure on line measurement. An associated objective being also the validation of behaviour modelling, in particular conductivity degradation and fission gas release during transients. A large number of CEA expert services have contributed to reach this goal. Development of innovative processes have been necessary, in particular the new concept of a pressure transducer using counter-pressure principle, and a beyond state of the art cryogenic freezing drilling system to manufacture the centre hole for the thermocouple. All these innovative processes have been qualified on a multi-function machine tool dedicated to perform the complete fabrication of the double-instrumented fuel rod. Complementary equipment for X-Ray examination has also been developed as a free volume measurement machine.

All these innovative processes and equipment have been utilised by the CEA to realise the first new type of instrumented fuel rod. After obtaining good results in fabrication, the irradiation results in CEA OSIRIS test reactor will validate the full concept. This will allow preparing the next generation of instrumented pre-irradiated fuel rods.

Double instrumented fuel rod fabrication

Fuel rod fabrication operations have been performed in time corresponding to the planned chronology, but several inconsequent unpredictable difficulties occurred. We first chose and identified the fuel rod: a 70 GWd/t burn up UO2 fuel with M5 alloy cladding irradiated in EDF Gravelines PWR. The sequence of operations has been as follows

- Preparation of the lower end in the "FABRICE "unit used for non-instrumented experimental fuel rods fabrication including: cutting of the fuel rod in order to obtain the proper length; defuelling in order to get space for alumina pellet, un irradiated UO2 pellets, end plug; dress and remove the inner and outer oxide layer of the cladding in the welding zone.
- Drilling in the fuel centre a 50 mm long and 2.5 mm diameter hole with a diamond drill in order to position the thermocouple. This operation is described in details in the next chapter.
- Introduction of the drilled pellets of the molybdenum tube and of the lower end plug. End plug and cladding are welded by TIG welding process. This end plug is the interface for the diffused junction of the thermocouple.

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- Preparation of the upper end, introduction of the pellets, the spring and the upper end plug. This end plug is welded by TIG welding process.
- Welding of both diffused junctions with end plugs by TIG welding process. The junctions included the Molybdenum / rhenium thermocouple, and the pressure sensor. The pressure sensor specification is described in a following chapter.
- Use of an accurate free volume measurement fixture. The free volume information is very important for an accurate on line fission gas release volume determination.
- Fuel rod pressurisation at 40 bars of Helium and seal welding. The seal welded chamber volume is only a few cubic centimetres large. It does not include the complete fuel rod. This fixture allows to seal weld any fuel rod length. A helium leak test is performed afterwards.
- Testing of the pressure sensor and the thermocouple, verifying the welds by X-ray exam, decontamination of the full experimental fuel rod and transfer to OSIRIS test reactor.

Development and qualification of the fuel drilling without cryogenic cooling

Objective

Starting in 1999, LECA Cadarache hot laboratory decided to develop a machine tool able to drill a center hole in irradiated fuel pellets for thermocouple insertion. The purpose of the development program was to simplify the process and preserve integrity of the drilled fuel stack then to qualify it on irradiated fuel. The first objective was to drill the fuel without cryogenic cooling. In order to do so centre fuel hole is realised with diamond drill tubes 2.2 mm diameter and 20 and 50 mm long. The rotational speed is around 10 000 *rounds per minute and a 5 litres per minute argon flux inside the driller allows cooling of the diamond tube* and avoid its filling up from UO_2 chips The machine tool is a driller, which is commanded by remote control. It allows performing an unlimited number of cycles and modulates six parameters as well. Parameters are, length and speed advance, depth and speed pass, length and speed shrinkage, rotational speed, and number of cycles. The mechanical interaction between fuel stack and cladding induced by irradiation is absolutely needed otherwise the drill could carry the pellets out of the cladding. Thus, application of this process is devoted to a minimum of two cycles irradiated fuel rods. After verification of length and depth of the hole, a 2.5 mm diameter molybdenum tube is introduced as the interface between fuel and thermocouple. The 2.5 mm diameter is the present lower limit due to drill mechanical resistance and rotation induced vibrations.

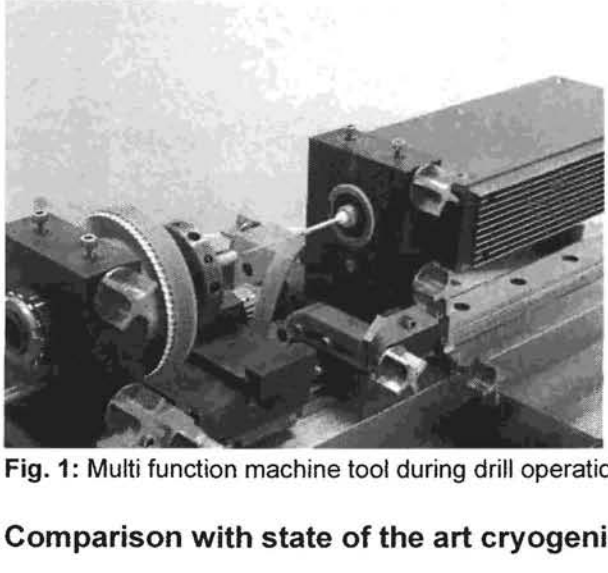

Fig. 1: Multi function machine tool during drill operation

Comparison with state of the art cryogenic freezing process

The process presently used is the cold RISÖ process developed by Halden Reactor Project. The operation consists in filling the fuel rod with liquid CO2 and subsequently freezing it down with liquid Nitrogen in order to stabilise the fuel for the purpose of drilling operation. CO2 ice material at the outside of the rod is drilled out with a standard steel drill, then diamond drill tubes are used for the centre hole drilling.

Cryogenic freezing technique is not easy to work with in hot cells facility as liquid flux in and out of cells represents technological difficulties and safety risks.
In RISÖ process, the fuel rod must be dried in a 300 °C oven, which can affect the fuel microstructure and induce cracking during the drying operation, because of differential dilatation due to thermal gradients. This effect of the fuel cracking has not yet been quantified, but may have significant effect on fuel thermal behaviour.

The room temperature process allows accurate metrology measurement for the hole, in particular depth and diameter with standard metrology devices In the RISÖ process where the molybdenum tube has to be inserted into the centreline hole directly after the drilling operation to provide mechanical support to the fuel. Thus metrology of the hole geometry is no more possible to perform.
The new process has been qualified for different fuel types and burn up. Metallographic exams confirm that the fuel microstructure is not significantly affected by the drilling operation.
Other dimensional exams provide important information such as concentricity and diameter of the hole. We have noticed, that the channel diameter is 15 % larger than drill diameter because of drilling vibrations. Accurate dimensions knowledge is particularly necessary for modelling the fuel behaviour with simulation tools.

RISÖ process is applicable for all fuel burn up values compared with the new process, which is valid for fuel rods with a minimum of two cycles irradiation. The new process needs the change of drill five times during the whole operation and a 20 mm long stiffer drill for the first phase.

Process qualification

Chronological definition of tests has been chosen according to four parameters; "complexity of making use of the job", availability of the different fuel rods, availability of the LECA hot lab cells, and fuel type choice for the first instrumented fuel rod.
First tests have been performed in a glove box with non-irradiated UO2 fuel in order to validate the capability of the driller to drill fuel pellet and also to get a first experience and provide orientation on parameters. Drills have been successfully manufactured.
The three next tests have been done in hot cell on a vertical simple concept machine tool. The target was to determine 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 UO2 fuel. As results, we confirmed that we can drill from a two irradiations cycle MOX fuel and also high burn up fuel, and the 50 mm deep hole target has been reached in both cases.
The two next tests have been performed with 70 GWd/t UO2 fuel. It has been chosen, because it is exactly representative of the first double-instrumented rod fuel. Concentricity of the hole has been obtained better than 0.1 mm with the pellet's axis, the entrance 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 end of the qualification program, we have realised 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.

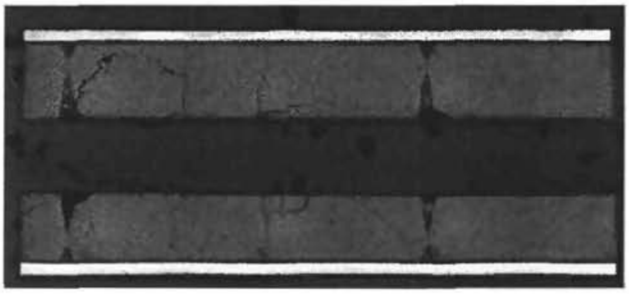

Fig. 2 Drilled pellets

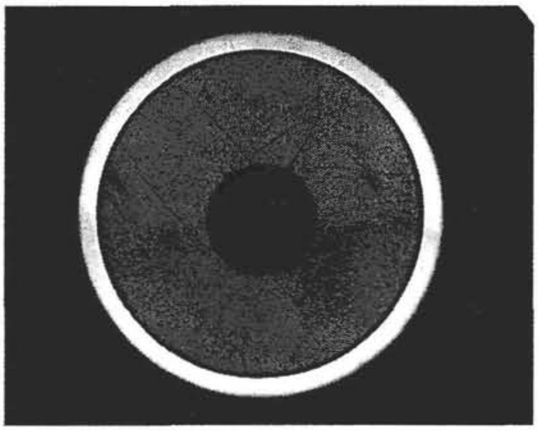

Fig 3 Centre hole pellet section

Description and qualification of the pressure sensor

The Department of Reactors and Nuclear Services of the C.E.A for online measurement of the fuel rod internal pressure have developed a specific pressure sensor during irradiation experiments. This pressure sensor is designed to be set up on a pre-irradiated PWR fuel rod, and to operate under the heavy duty from environmental conditions of Nuclear Test Reactors

Description of the pressure sensor

The sensor is designed for set up on a pre-irradiated PWR fuel rod in order to be less intrusive as possible in the experiment irradiation device. The sensor has the same diameter as the fuel rod (10 mm), and is 250 mm long. Its design allows working in severe irradiation environments, which means very high neutron flux and gamma radiation, high temperature (up to 350°C) and high pressure (up to 160 bar).

The pressure sensor design is based on the reliable drift-less counter-pressure principle. It consists of two gas cavities, separated by a double expanding wall (see Fig.4). The first cavity communicates with the internal fuel rod pressure. The second cavity is connected to an external helium circuit, which is called "counter-pressure" circuit.

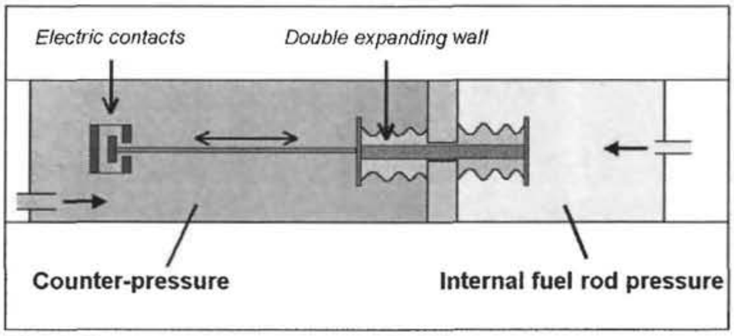

Fig. 4 Counter-pressure sensor principle

The imbalance between the internal rod pressure and the counter-pressure is accurately detected by two electric contacts, activated by the motion of the expanding wall. This imbalance can be compensated automatically by inflating or deflating the counter-pressure.
This system provides a very accurate online measurement of the internal fuel rod, through the simultaneous knowledge of the imbalance detection signals on the one hand, and the direct measurement of the counter-pressure on the other hand. The physical principle of the counter-pressure is expected to prevent any drift phenomenon induced by nuclear radiation. This pressure sensor, alike all in-

pile facilities, has to satisfy high safety criteria. As an example integrity of any of its two expanding walls is continuously checked by a specific detection system. Making transfer operations and transport easier has been a priority at each step of the design of this instrument. The lower part of the measurement system, including the two cavities and the fuel rod, is linked to the upper part of the device through a specific connector, providing both the electric and the gas transmissions. This connector is also designed for easy handling by tele-manipulators. Once it has been set up on the pre-irradiated fuel rod, the sensor can thus be linked to the upper part of the device, inserted into the experiment device, before being transferred into its irradiation station.

Qualification of the pressure sensor

These in-pile tests are performed in the GRIFFONOS pressurised water loop experiment device.
The physical parameters in this loop are specified to be very similar to those of pressurized water reactors. This experimental device is also equipped with a dedicated motion system, which makes the pressure tube translate forwards or backwards into the reactor core, in order to adjust the power released by a fuel rod during the experiment. During the first irradiation program, the thermal flux in the device was maintained mainly constant during 300 hours, at about $1.4\times10^{18}\,n.m^{-2}.s^{-1}$ (at the rod mid-plane). At the end of this phase, the integrated thermal fluence at the rod mid-plane was approximately $1.5\times10^{24} n.m^{-2}$
Further in-pile experiments have been carried out in order to run more parametric tests on the sensor performances. The sensor has operated without failure during the whole irradiation sequence, proving its complete capacity to work in the environment of severe irradiation experiments.

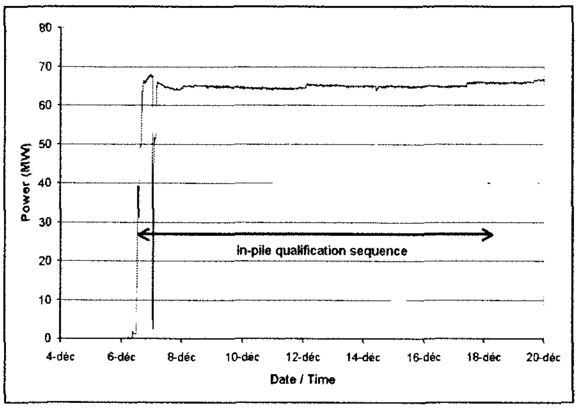

Fig. 5 Power of the OSIRIS reactor during the in-pile qualification sequence

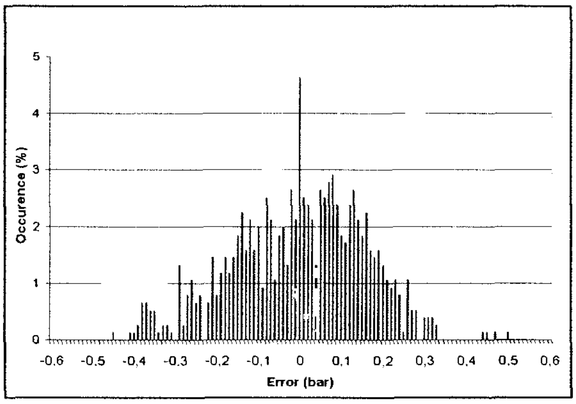

Fig. 6 Errors between the sensor measurements and the injected fuel rod pressure during the in-pile qualification

The sensor has totally reached its objectives toward performances. The accuracy of the sensor for the internal pressure measurement during the in-pile tests is ± 0.325 bar (with a confidence level of 95%), on the whole pressure range up to 120 bars.

This accuracy appears to stay at a constant level during the entire irradiation period. This observation proves that the sensor exhibits no drift due to neutron flux or gamma radiation.

Finally, the pressure sensor gave complete satisfaction during these qualification experiments, and the results validate the high performances of the device.
This new accurate tool now allows the achievement of advanced programs regarding fission gas release studies. Irradiation experiments using this sensor with pre-irradiated fuel rods are in preparation and will shortly be carried out in the OSIRIS reactor.

Conclusion

This technique of manufacturing this new type of instrumented fuel rod is expected to perturb as little as possible the original situation of the fuel when unloaded from the commercial reactor. Thus it allows to start the in pile irradiation in a Nuclear Test Reactor and the fuel behaviour follow on with maximum reliability and the best accuracy for measurement of the main governing parameters such as temperature and pressure. The mastering of the thermocouple housing geometry, the use of a no drift pressure transducer and the free volume determination are the three main features of the new instrumented fuel rod that will contribute to improved significantly the quality of the measurements and provide the proper information to be used in fuel computer simulation tools. Presently a next step and a progress in manufacturing instrumented fuel rod is under development: laser welding. It will allow higher accuracy and it will prevent thermally affected zone in the cladding. The laser welding process in hot cell is expected qualified by the middle of 2005. Furthermore the next experimental instrumented fuel rod will be manufactured using a multi function machine tool "Coralie" integrating all previous development features and that will include the laser welding technique.