MELODIE, an advanced device for study of the irradiation creep of LWR cladding with online biaxial control of stress and strain

Ph. Guimbal[1], M. Auclair[2], S. Carassou[3], P. Moilanen[4], S. Tähtinen[4], J.-F. Villard[1]

[1] CEA, DEN, DER, F-13108 St-Paul-lez-Durance, France
[2] CEA, DEN, DRSN/SIREN, F-91191 Gif-sur-Yvette, France
[3] CEA, DEN, DMN/SEMI, F-91191 Gif-sur-Yvette, France
[4] VTT Technical Research Centre of Finland, Materials performance division, Espoo, FI-02044 VTT, Finland
Corresponding author : philippe.guimbal@cea.fr

Abstract — **MELODIE is an innovative sample holder, designed for creep experiments on LWR cladding sample in the OSIRIS reactor. Its main feature will be its ability to perform an online-controlled biaxial loading of the sample and an online biaxial measurement of its deformation. Start of irradiation is planned in 2011. An improved version of MELODIE should be in a second step designed for the wardrobe of the Jules Horowitz reactor.**

Index Terms — **OSIRIS, JHR, Zircaloy, biaxial, irradiation creep, online measurements**

A SCIENTIFIC CASE FOR THE MELODIE EXPERIMENT

During normal and incidental operation of LWRs, Fission Gas release and Pellet-Cladding Interaction combine to impose to the fuel cladding a non-monotonic multiaxial thermo-mechanical loading sequence. The continuous push for better agility and for higher burn-up operation without reduction of safety margins drives the research for higher performance clad materials and hence the need of reliable experimental data on their behaviour under irradiation, when submitted to a multiaxial stress. Indeed, the modeling of LWR fuel performance is complicated by the fact that zirconium alloys of industrial interest are strongly anisotropic, not only due to their hexagonal crystal structure but also to the texture induced by the manufacturing process.

This need for reliable biaxial data was addressed at the conceptual design level by the work package WP1.1 of the European MTR+I3 program [1]. The MELODIE proof-of-principle experiment is a follow-on of this program. Its unprecedented level of online control and command is a technological challenge and marks a strong departure from the cook-and-look paradigm. Its design is a joint effort of several departments of the CEA and of VTT, the Technical Research center of Finland, in the framework of the Jules Horowitz reactor project.

MELODIE, an acronym which stands for MEchanical LOading Device for Irradiation Experiments, is planned as a 2-year in-core irradiation in the OSIRIS research reactor, aiming to assess the capabilities of an innovative sample holder for the study of the creep behaviour of advanced PWR fuel cladding. In a second step, MELODIE should evolve in an improved version to be later implemented in the Jules Horowitz Reactor (JHR).

MELODIE GENERAL DESCRIPTION

Functional specification for MELODIE is simpler to summarize than to achieve: the ability to apply a precise online-controlled biaxial stress to a fuel-cladding tubular sample, maintained at a well defined temperature under a high fast neutron flux, and to perform, also in real time, a biaxial measurement of its strain. Highly desirable also is the implementation of a strain-controlled mode, in order to perform relaxation tests

Tough issues in the MELODIE design arise from the fact that these specifications hide contradictory constraints that are to be resolved by some kind of trade-off : usually, higher neutron flux not only means higher nuclear heating and hence, poorer temperature homogeneity, but also smaller diameter irradiation positions, which translates to lower limits for the loading frame.

Hosting device for the MELODIE sample holder is a CHOUCA, a standard device for incore irradiation of materials in OSIRIS reactor [2]. Its effective diameter is 24 mm. Target temperature is 350°C. Requested temperature homogeneity is 10 K. Static coolant medium is NaK-56.

MELODIE is to be placed either in location 44 or 64 of OSIRIS core. Nuclear characteristics of these locations are :

	44	64
Neutron fast flux (above 1 MeV)	1.9e18 $n/m^2/s$	2.3e18 $n/m^2/s$
Neutron fast flux (above 0.1 MeV)	4e18 $n/m^2/s$	4.5e18 $n/m^2/s$
Specific nuclear heating (z=0, Z=6)	9.5 W/g	12.5 W/g
dpa (Zr) /yr (1 yr=216 EFPD)	5.6	6.7

Besides the scientific interest of a fast neutron flux as high as possible, the choice of the "hottest" locations in OSIRIS core is also dictated by the fact that MELODIE is intended as being used in JHR reactor, whose specific nuclear heating is still higher in the central locations.

BIAXIAL LOADING

By biaxial stress control on a tubular cladding sample, one means the ability to apply on this sample in an independent way, an axial stress σ_z and a circumferential ("hoop") stress σ_θ.

Biaxiality ratio will be defined as :

$$\alpha = \frac{\sigma_z}{\sigma_\theta}$$

It is well known that, by plain pressurization of a long, thin-walled cylinder, the stress field in the mid-region corresponds to :

$$\alpha=0.5$$

For a real world PWR cladding, correction for wall thickness *e* implies a slight departure from this asymptotic value. First order formulas, taking into account not only internal pressure *p*, but also an axial force *F* may be written as :

$$\sigma_\theta = \frac{r_i}{e} p$$

$$\sigma_z = \frac{\sigma_\theta}{2} \frac{r_i}{\bar{r}} \left(1 + \frac{F}{\pi r_i^2 p}\right)$$

hence :

$$\alpha = 0.5\left(1 - \frac{e}{2r_i}\right)\left(1 + \frac{F}{\pi r_i^2 p}\right)$$

where r_i is the internal radius and $\bar{r}$ the mean radius.

For a standard 8.36x9.50 french PWR cladding,

r_i=4.18 mm, $\bar{r}$ =4.465 mm, *e*=0.57 mm and $\pi r_i^2 = 5.49$ N/bar.

Full-control of stress and biaxiality is performed in the MELODIE sample holder, by three independent high-pressure helium circuits (see figure 2) :

- one to pressurize the sample : the nominal design pressure of 160 bar translates, for a standard PWR fuel clad, to a maximum hoop stress of about 117 MPa and about half this value for the axial stress (55 MPa)
- two to pressurize the bellows of a push-pull system (see figure 1) able to generate a positive or negative axial stress for the sample. Baseline spec for this system is the ability to cover a biaxiality ratio α between 0 and 1, which translates to a swing between a 880 N push (biaxiality ratio of 0) and a 1000 N pull (biaxiality ratio of 1). Designing in the small available space, a loading frame able to withstand such a force while permitting micrometer-class elongation measurements is one of the challenges for MELODIE.

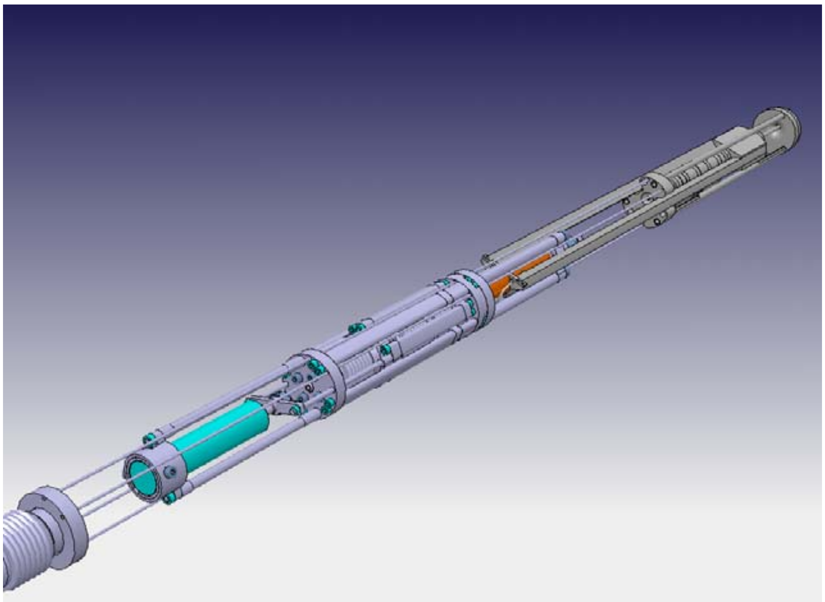

Fig. 1. Preliminary CATIA drawing of the MELODIE sample holder. From left to right: the LVDT body (in cyan), the push-pull bellows creating a bipolar axial stress, the pressurized Zry-4 sample (in brown) and the moving diameter gauge (in grey). Inner diameter of the irradiation capsule housing this sample holder is 24.1 mm.

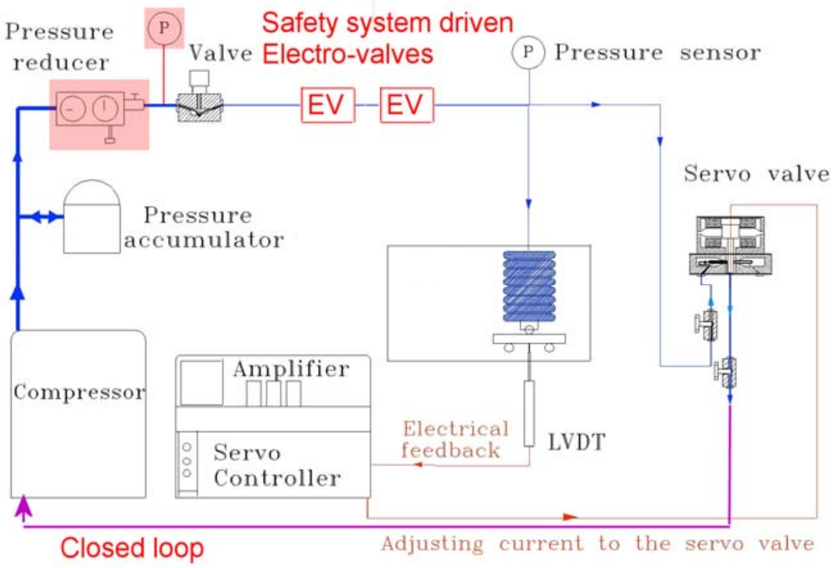

Fig. 2. Schematic of the pressure adjusting loop, designed to perform either stress- or strain-controlled irradiations.

BIAXIAL ONLINE MEASUREMENT

Two measurement systems, tailored by the Institutt for Energitekniik (IFE) Halden to our specific flux and dimensional requirements, will be used in order to obtain a biaxial strain information :

- The elongation of the 90 mm-long clad sample will be measured with a self-compensating LVDT, an enhanced version of the IFE standard product, ruggedized for operation under OSIRIS maximum nuclear heating conditions. Expected performance is about 2 µm, but needs to be confirmed.
- A radial information at mid-height of the sample will be measured by an electromagnetic Diameter Gauge, highly modified from the IFE standard product [3] to be compatible with our small 24-mm in diameter acceptance and, which is equally important, with our measurement needs. To avoid unwanted thermal or mechanical interaction between the feelers (2 reference feelers and one movable) and the sample, the system will be parked at the bottom of the sample, where a self-calibrating zone, "read" at the beginning of each scan, will allow to get rid of the unavoidable drifts of the system.

In the past decades, two experiments performing online diameter measurements of fuel rods or claddings, were successfully conducted in the CEA Material Testing Reactors :

- DECOR (1990-1996), in the SILOE reactor, whose goal was the in-pile measurement of the entire radial profile of a 360 mm fuel rod, under normal or transient off-normal condition, up to 500 W/cm linear power [4],
- ZIRCIMOG 2 (1999-2002), in the OSIRIS reactor, which measured the creep behaviour of Zry-4 [5] and M5 90 mm-long fuel clad samples, under very high levels of stress (up to 350 MPa), but without any control of biaxiality ratio, the stress being created only by internal pressure, and without an elongation measurement.

Both experiments showed that pressure of the feelers had to be carefully chosen to ensure a good contact without wearing the surface of the zircaloy. Oxide layer reinforcement appeared as a key parameter to increase the reliability of the measurement.
Both experiments used strain gauges to perform the diametral measurement and both experiments exhibited a micrometer-level resolution, roughly equivalent to the expected performance of IFE Halden technology. The decision to use electromagnetic gauges for MELODIE was therefore not determined by absolute performance, but because of the better linearity and ageing, greater range and because the optimum MELODIE design exposes the diameter measurement system to the full flux of the OSIRIS reactor. This last constraint is definitely incompatible with available strain gauges.

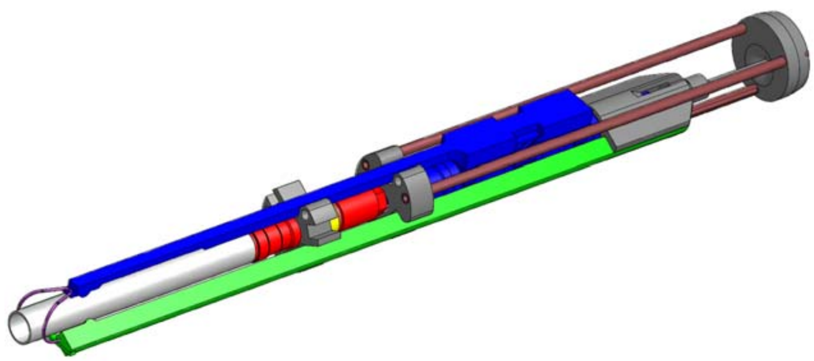

Fig. 3. Preliminary drawing of the lower part of the MELODIE sample holder : on the left, the Zry tubular sample with the 3 feelers and the self-calibrating zone (in red). On the right, the electromagnetic Diameter Gauge (IFE Halden and CEA design).

THERMAL DESIGN

Despite the high level of nuclear heating (more than 10W/g in OSIRIS) unavoidable when requiring high fast neutron flux and fluences, temperature homogeneity is expected to be acceptable, thanks to the high thermal conductivity of the NaK coolant. This temperature control is essential for an optimum interpretation of the experimental results, vs predictions of fuel evolution codes. Low temperature gradients in the loading frame are also required in order to ensure a proper reference for the elongation measurements. Therefore, thermo-mechanical design is expected to be a crucial issue for the MELODIE experiment, which is strongly constrained by the available space. For comparison with two experiments cited above, DECOR was done in a 45 mm inner diameter device (GRIFFON), ZIRCIMOG in a 30 mm section (CHOUCA NLa-type), whereas MELODIE, which packs more functions, must fit in a 24 mm circular section (CHOUCA OLa-type).

CONCLUSION

MELODIE should be put in pile in 2011 with a Zy-4 SR sample, a well-known alloy, for a one-year benchmark irradiation in OSIRIS. Meanwhile, numerous design issues must be solved and extensive tests on a mockup be done.

REFERENCES

[1] J. Dekeyser, D. Iracane and the participants to the MTR+I3 project, "Integrated Infrastructure Initiatives for Material Testing Reactors", in Proc. FISA'09 conference, Praha, 22-24 may 2009.

[2] M. Auclair, L. Gosmain, P. Guimbal, D. Moulin, P. Roux, C. Sauder and JF. Villard, "CEDRIC experiment", elsewhere in these proceedings.

[3] S. Solstad and R. Van Nieuwenhowe, "Instrument capabilities and developments at the Halden Reactor Project", in Proc. 6th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies NPIC&HMIT, Knoxville, 2009

[4] L. Caillot, C. Lemaignan, J. Joseph, "In-situ measurements of cladding strain during power transients using the DÉCOR device", in Proc. ANS international Topical Meeting on LWR fuel performances, West Palm Beach, 18-21 april 1994.

[5] A. Soniak, N. L'Hullier, J-P. Mardon, V. Rebeyrolle, P. Bouffioux and C. Bernaudat, "Irradiation creep behavior of Zr-base alloys", in Zirconium in the Nuclear Industry : Thirteenth International Symposium, G. D. Moan and P. Rudling, Eds., ASTM STP 1423, West Conshohocken, PA, 2002, pp 837-862.