Long term under internal pressure creep test device in K6 LECI hot cell

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Abstract

This paper describes a new facility implemented in K6 hot cell of LECI in CEA Saclay, to perform creep tests in internal pressure on irradiated defuelled cladding tubes. This new device has been specially designed in the framework of the French studies on the long term behaviour of spent fuel under interim storage. Functions that can be allocated to the cladding during interim storage depend upon the evolution of cladding properties with time. Creep of the cladding under internal pressure is considered as the major limiting mechanism, which might lead to rupture, for dry storage of spent fuel sub-assemblies. A predictive creep model of the irradiated cladding has to be obtained and qualified, through experimental data.

CEA, EDF and FRAMATOME-ANP have developed a stepwise approach in which the representative interim storage conditions are progressively approached from more reactive conditions during thermal creep tests on irradiated material. The first step consists of a first set of short term creep tests under internal pressure on irradiated CWSR (Cold Worked Stress Relieved) Zircaloy-4 cladding, performed in a short creep test device. A first creep model was established within the temperature range of 380-420°C and the hoop stress range from 150 to 250 MPa, and for durations up to 67 days [1]. Several creep tests were extended up to 120 and 210 days. To propose a new formulation of the creep model to extrapolate to real storage durations, it was necessary to perform long term creep tests of about one year in more interim storage representative conditions (lower temperatures and stress levels). The creep device, used since 1996 for surveillance programs, consists of 6 furnaces, one sample by furnace. Because of their duration, we cannot wait for the result of 6 long-term creep tests before to perform the following. We need to test simultaneously a larger number of samples in various conditions. The realization of a new complementary creep test device appeared necessary for the long-term studies.

Presently devoted to specific applications to dry storage, it consists of a pressurization device and 5 independent furnaces located in the same K6 hot cell. Several samples can be put in a basket in each furnace. The samples are defuelled cladding tubes of various geometries and operating conditions, with welded end caps and strengthening sleeves located in front of the heat-affected zone. Before the tests, the irradiated samples are pressurized with argon to obtain the stress according to the test specification and closed by the new pressurization disposal, and then introduced in the furnaces and vacuum-heated. The maximum pressure is 200 bar NTP. The temperature range can be large, between 300 to 700°C. Each furnace comprises 6 independent heating zones, in order to assure a small axial thermal gradient on a sample length of about 100 mm. However, the ranges of interest for the interim storage studies are typically between 40 to 80 bar NTP and 320 to 420°C.The samples have to be regularly got out be measured by laser and weighted outside of the furnaces.

A qualification program has been realized on unirradiated Zircaloy tubes in order to qualify the temperature and the thermal axial gradient in the furnaces, and the pressurization device. The end cap TIG welding device has been optimised and qualified on irradiated Zircaloy tubes.

The safety authority authorization for testing irradiated material in this new facility has been obtained during this summer. A test campaign on irradiated Zircaloy-4 AFA 2G cladding is planed from the end of 2003 and for several years.

1 Context

This paper describes a new facility implemented in K6 hot cell of the LECI, to perform creep tests in internal pressure on irradiated defuelled cladding tubes. The LECI and the PELECI are the laboratories of CEA Saclay Centre devoted to the micro structural and mechanical characterization of non-fissile irradiated materials.

This new device has been specially designed in the framework of the French studies on the long-term behaviour of spent fuel under interim storage (PRECCI program). Functions that can be allocated to the cladding during interim storage depend on the evolution of cladding properties with time. Creep of the cladding under internal pressure is considered as the major limiting mechanism, which might lead to cladding rupture, for dry storage of spent fuel sub-assemblies. A predictive creep model of the irradiated cladding has to be obtained and qualified, through experimental data.

CEA, EDF and FRAMATOME-ANP have developed a stepwise approach in which the representative interim storage conditions are progressively approached from more reactive conditions during thermal creep tests on irradiated material. The first step consists of a first set of short term creep tests under internal pressure on irradiated CWSR (Cold Worked Stress Relieved) Zircaloy-4 cladding, performed in a short creep test device. A first creep model has been established within the temperature range of 380-420°C and the hoop stress range from 150 to 250 MPa, and for durations up to 67 days [1]. Several creep tests were extended up to 120 and 210 days.

To propose a new formulation of the creep model to extrapolate to real storage durations, it is necessary to perform long term creep tests in more interim storage representative conditions (lower temperatures and stress levels, longer durations). The realization of a new complementary creep test device appeared necessary for the long-term studies. Moreover a technique of irradiated samples fabrication tested for the FABRICE rods realisation has been chosen and adapted to dry interim storage conditions.

This paper describes the experimental device, gives indications on the sample preparation, the test operations and the data processing and summarizes the qualification program realized on unirradiated Zircaloy tubes.

2 Description

2.1 Device

To perform a long-term creep test under internal pressure on a defuelled cladding tube, the chosen technique, already tested on unirradiated material, consists in heating a previously pressurized sample in a furnace. The objective is to determine the sample geometry evolution, in particular the diametric elongation.

The main elements of the facility are the following:

- The pressurisation/seal welding device whose functions are first to create vacuum in the sample, then to pressurize it with argon to obtain the stress according to the test specification, and last to seal it,
- Five furnaces,
- The sample characterisation device, comprising a measurement and a weighting device.

2.2 Pressurisation device

A pressurisation/seal device used for the FABRICE rods realisation has existed for 30 years in K line of the LECI. However its maximum pressure is 40 bar NTP, which is not high enough for PRECCI needs. So a new device has been specially designed for maximum pressure of 200 bar NTP.

Two identical pressurisation/seal equipments have been realized, one of them located in the hot cell, the second outside. They share the same control unit. The “cold” device is used for seal adjusting and qualifying (figure 1).

Each equipment consists in a pressure vessel, with a movable hemispherical top cap, an immovable base and a nut (figure 2). The cap opening and closing are motorized. There are a sample clip, a welding electrode and the power supply in each vessel. The seal/electrode distance is optically adjusted with a camera. The sample is located in a metallic tube in the base. Only one sample can be pressurized at the same time.

The control unit consists notably in an overpressure device and a TIG welding control system.

The pressurisation device characteristics are summarized in table 1.

Table 1: pressurisation device characteristics

Features	Pressurization device
Maximum samples length (mm)	700
Overall dimension - Length (mm) - Diameter (mm)	 750 380
Maximum pressure (bar NTP)	200
Pressurization gas	Argon or Helium

2.3 Creep test furnaces

Five electrical horizontal tubular furnaces have been identically designed and realized in order to operate in hot cell (figure 3). Each furnace has got six independent heating zones. In order to guaranty a homogeneous internal furnace temperature, the temperature controller of the central heating zone, which allows the temperature regulation with a precision of ± 0.1°C, plays the role of the master and gives the target-temperature value to the other zone controllers (slaves).

Each furnace contains a stainless steel tight jacket of internal diameter 55 mm, in which is located a samples carrier. The number of samples by furnace depends on the samples geometry; eight REP cladding tubes of 120 mm can be contained in a samples carrier. The creep tests are performed in primary vacuum obtained by a vacuum pump, to avoid additional oxidation of the samples during the tests.

The temperature range is between 300 to 700°C. The furnaces are independent and can heat simultaneously. Each furnace has been calibrated for one temperature (420, 400, 380, 350, 320°C). Three K thermocouples are fixed all along the sample carrier in order to control the internal temperature and the axial temperature gradient (figure 4). During the test, a PC computer records all the in-furnace temperature informations. All the thermocouples are periodically verified by a standard thermocouple.

The furnaces characteristics are summarized in table 2.

Table 2: furnaces characteristics

Features	Long term creep test
Number of furnaces	5
Temperature range (°C)	300-700
Internal jacket diameter (mm)	50
Maximum samples length (mm)	120
Overall dimension - Length (mm)	 450

- Diameter (mm)	220
Power/furnace (W)	1500
Recording of parameters	Furnace temperature
Samples geometry measurement	Periodic measurement outside of the furnace
Test duration	≈ 1 year

2.4 K6 hot cell

The pressurization/seal welding device and the furnaces are located in the K6 hot cell, which is a concrete cell of 3.6 m^2 included in LECI K line. Figure 5 shows the furnaces and the pressurization/seal welding device in the hot cell through the shielding window. Because of the remaining dose rate after cleaning, experimental devices have been realized to avoid direct human action in the cell for all the operations (equipment installation, tests, maintenance and dismantling). The cell is mainly equipped with two telemanipulators in its front area, a removable roof for equipment entrance and exit, a lifting machine and a horizontal service deck that supports the furnaces and the pressure vessel. An electromechanical conveyor can move in a tunnel, located under the service deck, up to the other cells of the K line.

2.5 End plugs welding device

PRECCI samples are cladding tubes, previously chemically defuelled, at the both side of which two end plugs are circularly welded before pressurization. For FABRICE rods refabrication, TIG welding is usually performed with an existing device in K9 hot cell (figures 6 and 7). This technique has been tested on a 4 cycles Zircaloy-4 cladding tube closed at one end by a TIG welded plug, during an internal pressure creep test performed 20 days at 350°C under 250 MPa in the short term creep device (High Activity Laboratory). A much more important hoop strain is measured in the weld and heat-affected zones of about 10 mm long, than in the current part of the tube (figure 8). The smaller creep resistance of the weld and heat-affected zones can be attributed to microstructure changes, in particular the annealing of irradiation defects due to the important temperature during welding. In the case of FABRICE rods, the inside pressure and ramp tests conditions are less severe at the end parts of the rods, and no problem of over deformation has ever appeared.

Such an important heat-affected zone length, where could appear a potential early rupture during an internal pressure creep test because of its important strain, is the major inconvenient of the TIG device.

Until the laser-welding device, which is going to be adapted to nuclear environment in LECI, could replace the TIG process, it was imperative to reduce the TIG heat-affected zone length by optimising the welding parameters without reducing the penetration depth or the welding quality. The different sensitive welding parameters which could be optimized are the following:

- Welding generator intensity
- Welding duration
- Sample rotation rate
- Inert gas flow
- Sample/electrode length
- Energy removal

The welding parameters have been first optimised on unirradiated material. After plug welding, the tubes were longitudinally cut and polished (figure 9). The penetration depth was determined by optical microscopy and the heat-affected zone length was estimated by Vickers micro hardness measurements. On the figure 10 is reported an example of axial evolution of Vickers micro hardness as a function of the distance from the end part of the plug. Its shows how the heat-affected zone is clearly softened compared to the current part of the tube. The optimisation allows reducing the heat-affected zone to 4 mm.

But X-ray controls reveal gas bubbles in the heat-affected zone of irradiated tubes welded with these parameters, probably of hydrogen present in the irradiated material. This gas has to be degassed to obtain a healthy weld bead, requiring longer welding duration, then inducing a longer heat-welded zone than on unirradiated material. The optimisation on irradiated material leads to a minimal heat-affected zone of about 6 mm. The improvement due to the optimisation is unfortunately not sufficient to avoid the risk of cladding rupture in the heat-affected zone during creep test.

Thus Zircaloy strengthening sleeves are located around the heat-affected zones of the tube and fixed by a small screw (figure 11), which complicates the irradiated sample preparation and reduces from eight to five the maximum number of PWR cladding tube samples in the carrier.

3 Test operation mode and data processing

3.1 Test operation mode

After sample cutting according to the length specification (typically 90 mm long) and alcohol cleaning, the zirconia layer is removed by mechanical abrasion by diamond grinding at the both ends of the tube. After this preparation, the diameter and thickness of the sample are accurately measured (± 0.002 mm for the diameter measurement) to allow the best possible strain and stress calculations. Diameter value comes from the mean value of 8 measurements performed at 45° each on the middle tube section and on two sections located at 20 mm right and left from this section. The thickness value comes from the mean value of 8 measurements performed at 45° at 10 mm of the two ends of the tube.

Then the plugs are TIG welded at the both side of the tube. One of them has a drilled hole, in order to allow sample argon filling. Another alcohol cleaning is planned after caps welding. A mark is engraved on the plugs.

The sample is put in the tight chamber of the pressure vessel, first in a primary vacuum before argon pressurization. Then the end plug is sealed by TIG flash welding without using filler material. Another weighting allows controlling the pressure level in the sample. The sleeves are then fixed on the both side of the tube, which is once again weighted.

Then the sample is introduced in a furnace, which is closed. The vacuum is created and the regulation temperature is set to the required value. The test begins after thermal stabilisation at ±1°C. The samples are periodically got out for diameter measurement by laser and weighting outside of the furnaces. The creep test is stopped when weighting indicates a leak of the sample.

3.2 Data processing

For the test, two parameters, the mean hoop stress and the mean hoop strain are deducted from the diameter and thickness measurement as:

$$(s_{qq} - s_{rr}) \approx (P_i - P_e) \times \frac{D_m}{2e} \approx P_{i0} \times \frac{D_{mo}}{2e_0}$$

$$e_{qq} = \frac{\Delta D_m}{D_{m0}} \approx \frac{\Delta D_e}{D_{m0}}$$

With

- P_i: sample internal pressure (MPa)
- P_{i0}: initial sample internal pressure (MPa)
- P_e: in-furnace pressure (MPa) (P_e negligible because vacuum in furnace)
- D_m: mean diameter of the tube (m)
- e: tube thickness (m)
- e_0: initial tube thickness (m)
- D_{mo}: mean diameter of the tube before test (m)
- D_e: external diameter at the middle of the tube (m)
- e_{qq}: mean hoop strain

In fact, the hoop stress remains constant throughout the entire test in such closed pressurized sample [2].

4 Qualification program

In order to qualify the temperature and the thermal axial gradient in the furnaces and the pressurization device, a program of pressurization and creep tests has been performed on unirradiated SRA Zircaloy-4 cladding tubes. Fives couples of temperature/stress level have been chosen in order to obtain significant hoop strain after one month of test: (420°C, 100MPa), (400°C, 150MPa), (380°C, 150MPa), (350°C, 200MPa), (320°C, 250MPa).

A similar pressurisation/seal device and similar furnaces implanted in a “cold” laboratory (SRMA) have been considered as the reference. The creep hoop strains deduced from measurements after test in the two installations remain very similar during the whole test duration (figure 12).

Moreover the model gives an estimation of the thermal axial gradients in the central 40 mm of the sample of between 2 and 3 degrees depending on the furnace. By turning over the sample each time it is put in the furnace after measurement and weighting, this value is reduced to 0.5°C. This is illustrated by the figure 13 for a sample tested at 380°C.

5 Conclusion

LECI has been just equipped with a new pressurization device allowing high internal pressure (200NTP) and 5 independent furnaces located in K6 hot cell. This device allows performing creep tests under internal pressure on irradiated tubular samples for long durations (typically one year). Several samples can be put in a basket in each furnace. The samples are defuelled cladding tubes of various geometries and operating conditions, with welded end caps. The TIG welding device usually used for FABRICE fuel rods refabrication has been optimised to reduce the heat-affected zone length and then the risk of failure during creep test in this zone. Moreover, additional strengthening sleeves are located in front of the heat-affected zone to limit its hoop strain. Before the tests, the samples are pressurized with argon to obtain the stress according to the test specification and sealed by the new pressurization disposal, and then introduced in the furnaces and vacuum-heated. The samples have to be regularly got out to be measured by laser and weighted outside of the furnaces. The qualification of the machines using a similar equipment implemented in a “cold” laboratory insures the quality of the results. A laser end caps welding device installation in hand will be an important improvement for the irradiated samples fabrication and sleeves will be no more essential.

The safety authority authorization for testing irradiated material in this new facility has just been obtained. An experimental program is planned on 4 cycles Zircaloy-4 AFA-G cladding tubes to specific applications to dry storage from the end of 2003 for several years.

6 References

[1] - R. Limon, C. Cappelaere, T Bredel, P Bouffioux: “ A formulation of the spent fuel cladding behavior for long term storage” - ANS International Topical Meeting on Light water Reactor Fuel Performance, Park City, Utah, April 10-13, 2000.

[2] – H. Spilker, M. Peehs, H-P. Dyck, G. Kaspar, K. Nissen: “Spent LWR fuel dry storage in large transport and storage casks after extended burnup” – Journal of Nuclear Materials 250 (1997) 63-74

Figure 1 : « cold » pressurisation/seal device

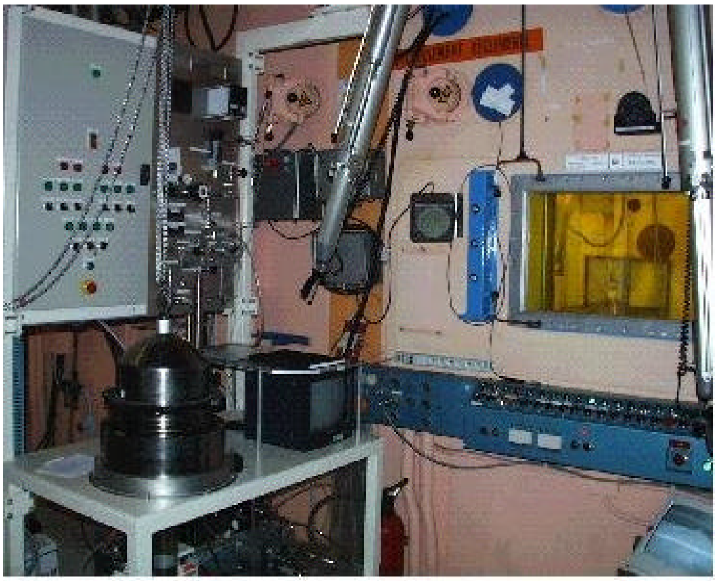

Figure 2: pressure vessel, with a movable hemispherical top cap, an immovable base and a nut

Figure 3 : the furnaces before their introduction in the hot cell

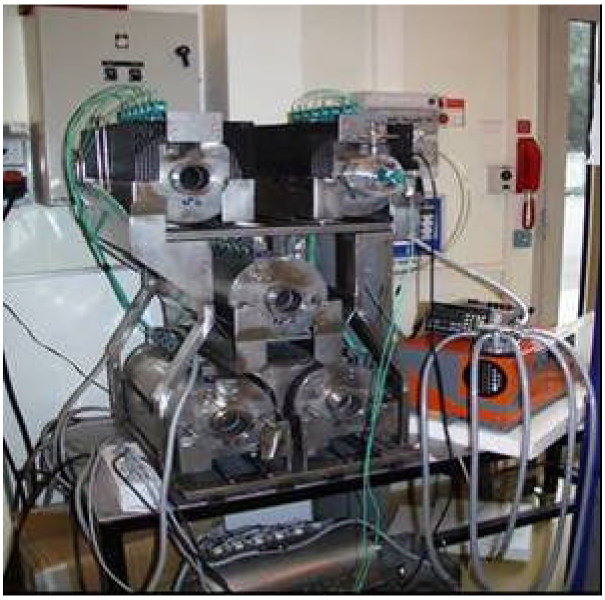

Figure 4 : furnace section

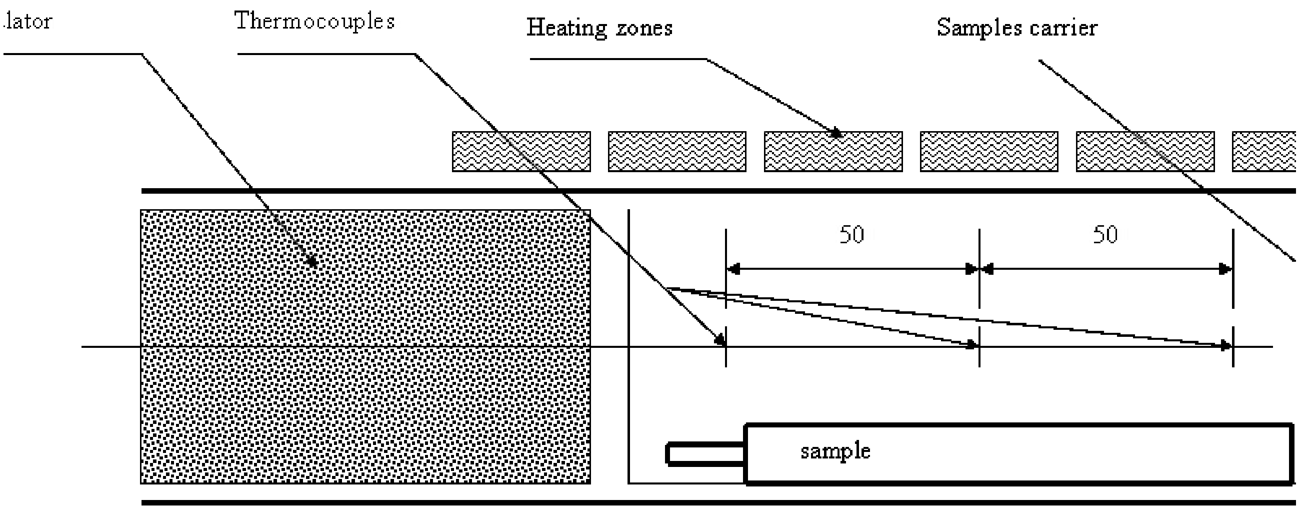

Figure 5 : the furnaces and the pressurization/seal welding device in K6 hot cell through the shielding window

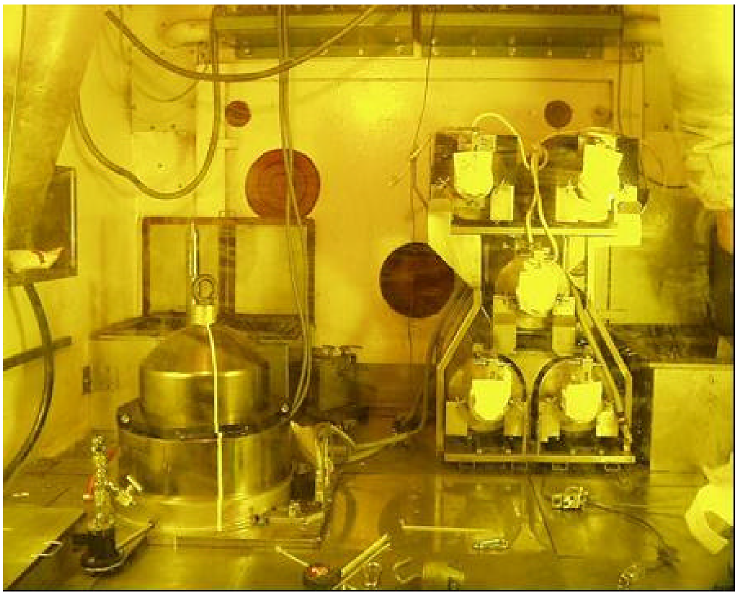

Figure 6: TIG welding device in K9 hot cell

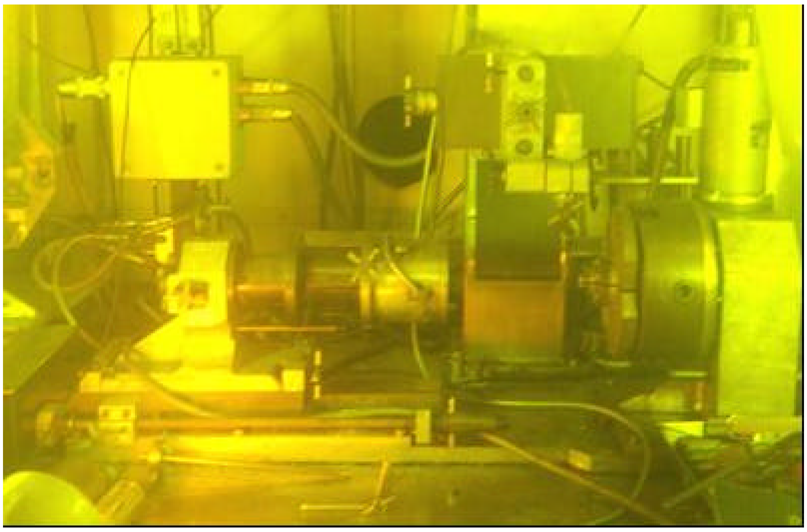

Figure 7: Irradiated sample TIG welding

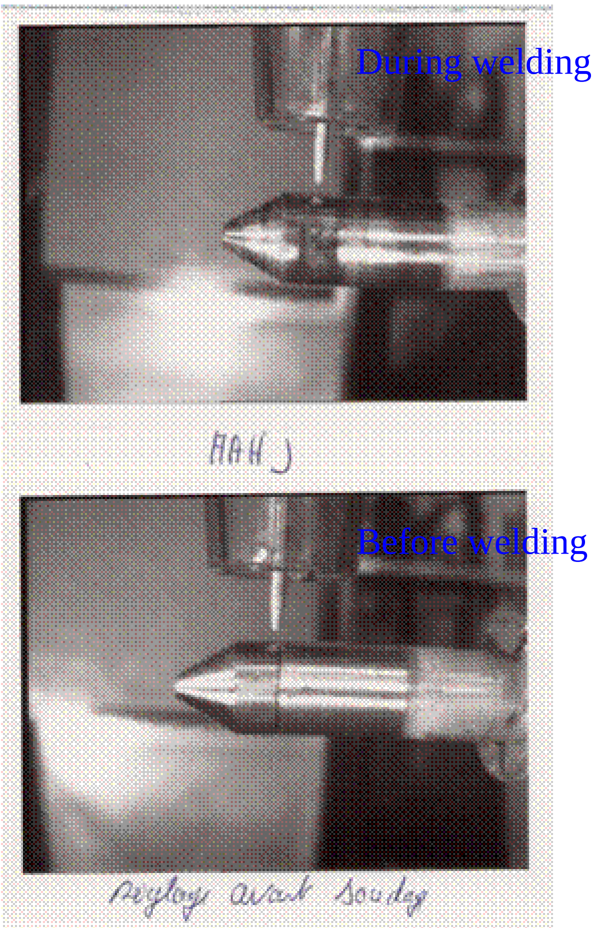

Figure 8: Creep hoop strain after 20 days at 350°C and 250 MPa of a 4 cycles tube with a TIG welded cap according to the FABRICE rods welding parameters

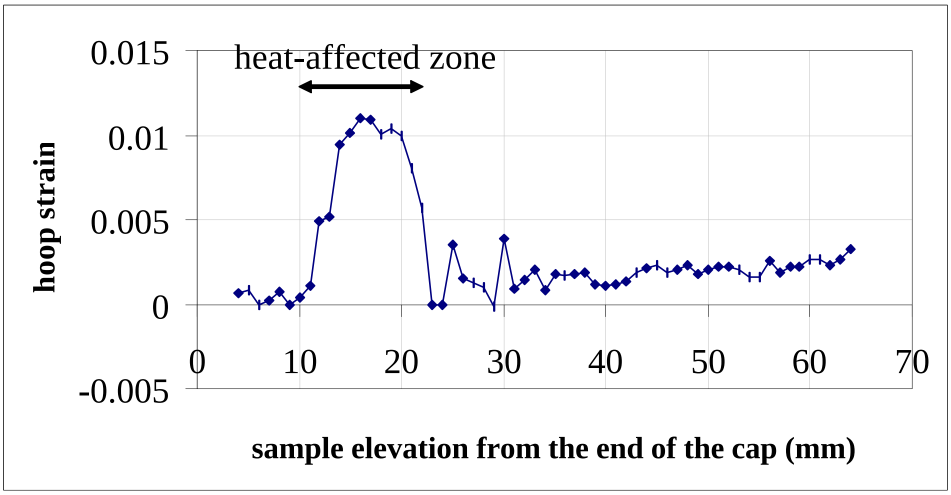

Figure 9 : tubes preparation after welding and before optical microscopy observation and hardness measurement

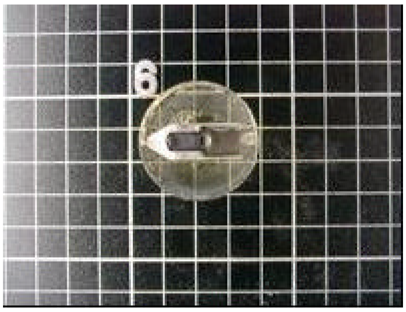

Figure 10 : Microhardness evolution as a function of the distance from the end of the cap on unirradiated Zircaloy-4 tubes

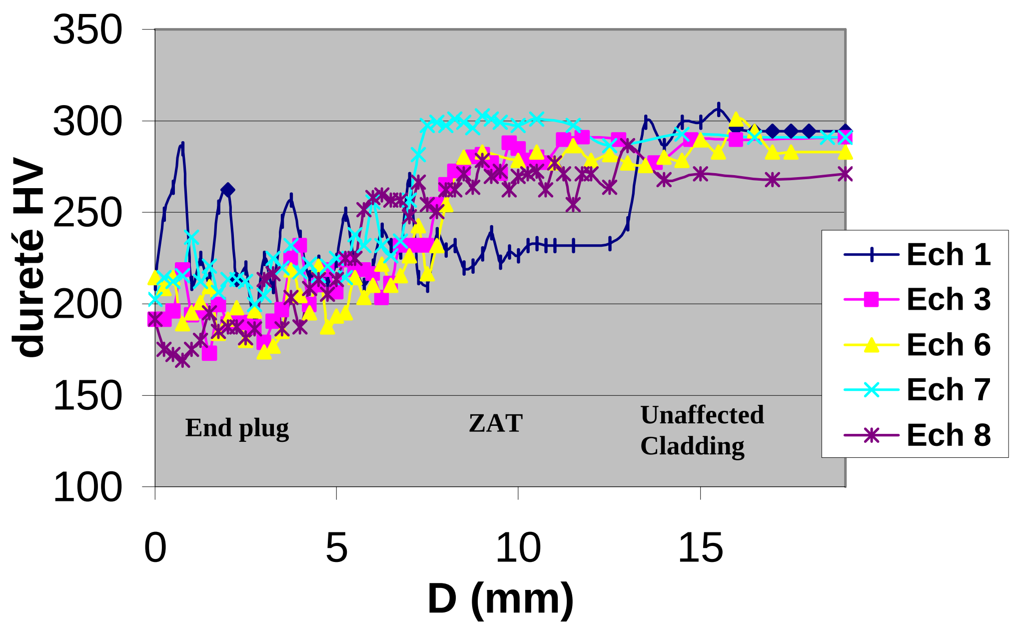

Figure 11: strengthening Zircaloy sleeves

Figure 12: Comparison between hoop strains after tests performed on unirradiated Zircaloy-4 in the « cold » SRMA device and the « hot » K6 device

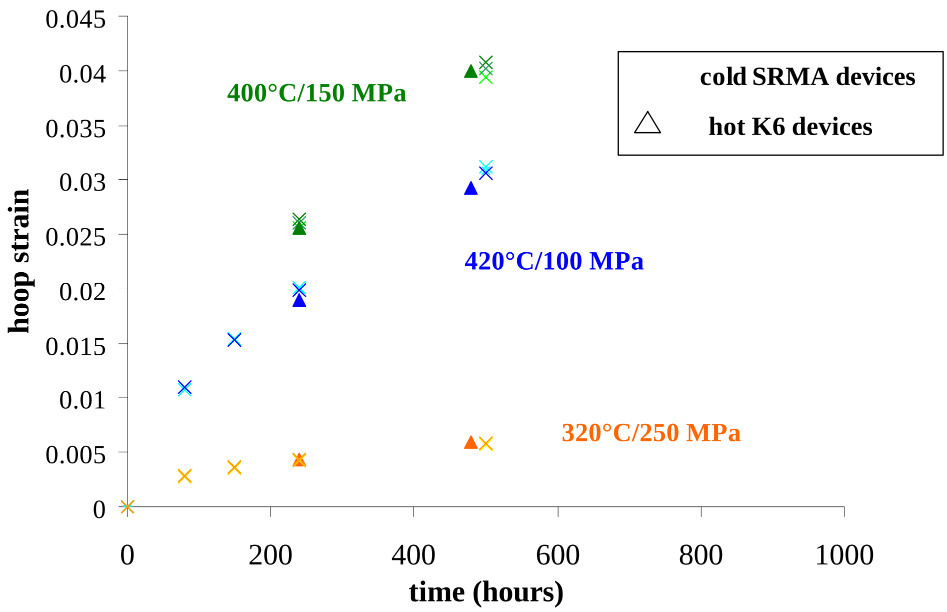

Figure 13: estimation by the model of the thermal axial gradient in the central 40 mm of a sample tested at 380°C