ADVANCEMENT OF HOTLAB/RESEARCH REACTOR TECHNIQUES WITH PARTICULAR REFERENCE TO THE REACTOR PRESSURE VESSEL MATERIALS EXAMINATION

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ABSTRACT

Paper reviews the advancement of the Russian Research Centre «Kurchatov Institute» Hotlab/Research Reactor techniques with particular reference to the reactor pressure vessel (RPV) materials examination. As a main barrier against radioactivity outlet RPV is a key component in terms of PWR safety. In Russia along with routine investigations, systematic research on actual radiation damage of the in-service and decommissioned RPVs has been carried out. Unique origin and value of these probe materials forced undertaking considerable efforts for hotlab techniques advancement. Sum of the measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the hotlab segment concerned with RPV materials study.

Particular and significant advancement have been made for the RPV steels behavior examination by means of the progressive methodology development for the primary irradiation, annealing and re-irradiation conducting. Transference of the centre of gravity to before- and after-irradiation stages leads to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall including ecological aftereffect.

1. Introduction

As a main barrier against radioactivity outlet reactor pressure vessel (RPV) is a key component in terms of PWR safety. RPVs are subject to multi-factor influence. It is practically impossible to reproduce some of this factors («long-time bias», e.g.) in the framework of experimental investigations including RPV surveillance specimens tests. At the same time, detailed information that can be obtained by means of taking of the through vessel wall probes (trepans) immediate from the ex-service (decommissioned) NPP RPVs is more representative than received by any another ways and therefore has the highest value.

2. Decommissioned RPV material actual properties study. HotLab specialization and modernization

Along with routine investigations in Russia systematic research on actual radiation embrittlement of the decommissioned PWR pressure vessel via trepans has been carried out. The earliest commercial PWR prototype unit Novovoronezh-1 (210 MWe) RPV after 20 years (1964-1984) of operation was trepanned in 1987. Then Novovoronezh-2 (365 MWe, 1969-1990), the oldest PWR type experimental reactor-prototype ERP (1956-1986) and, finely, nuclear icebreaker «Lenin» RPVs after shutdown were trepanned. List of these decommissioned units is present in table1.

Unit name	Output (MW)	Start of operation	Shut down	Operating temperature,^{o}C	Max. neutron fluence,cm^{-2}
Novovoronezh Unit 1 (NV1)	210e	1964	1984	250	$2{,}5\times10^{19}$
Novovoronezh Unit 2(NV2)	365e	1969	1990	250	9×10^{19}
Experimental Prototype (ERP)	<100t	1956	1986	275	7×10^{19}
Nuclear icebreacer “Lenin”	159t	1970	1989	290	$1{,}7\times10^{20}$

Table 1: List of the decommissioned units

Through-thickness RPV wall samples had been cut out remotely using trepanning tools such as boring machine with annular drill, anodic-mechanical and electric resistance cut machines. Typical dimensions of these probes were 120-140 mm in diameter, 120-140 mm lengthwise and up to 17 kg by mass. Schemes of the RPVs trepanning are presented in fig.1.

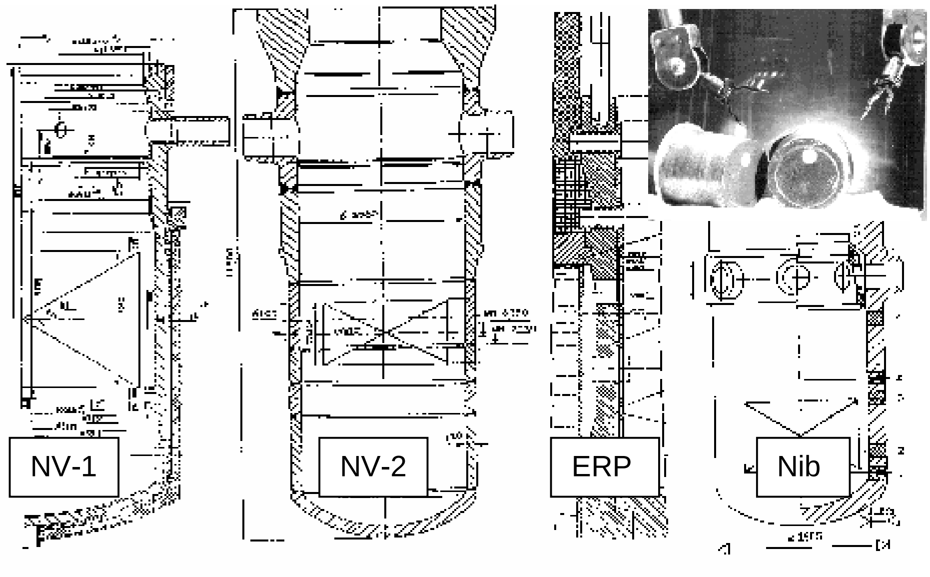

Fig.1. Schemes of the RPVs trepanning (NV-1, 2: Novovoronezh-1 and 2 units; EPR – experimental prototype reactor; Nib– nuclear icebreaker)

Through-thickness RPV wall samples had been cut out using trepanning tools such as boring machine with annular drill, anodic-mechanical and electric resistance cut machines.

Mechanical technique is the most advanced one, but the use requires periodic presence of a man in the reactor for inspections and adjustments. Thus, the use of a heavy protection cabin is necessary.
Anodic-mechanical cutting and contact arc cutting are fully remote technologies. However, each of them has a set of disadvantages, which eliminate this convenience.
Anodic-mechanical cutting requires liquid glass as a technological substance with following utilization of this radioactive waste.
Electric resistance cutting use water as a technological substance but is a very rough cutting method. The main disadvantage is a significant size of the heat-affected zone, therefore trepan material cannot be completely used. The emission of hydrogen is a potentially dangerous factor.
Typical dimensions of trepans were 120-140 mm in diameter and 120 mm lengthwise (fig.2).

Fig.2. Novovoronezh-2 NPP RPV Trepan

Unique origin and value of these materials forced undertaking considerable efforts for hotlab techniques advancement:

1. introduction of the electro discharge machines (EDM) as tools for trepans and their fragments processing to diminish volume of wastes sharply;
2. EDM equipment application for precise manufacturing of the test specimens with low tailings;

Test pieces and specimens have been manufactured from trepans by means of wire cutting EDM (figs.3).

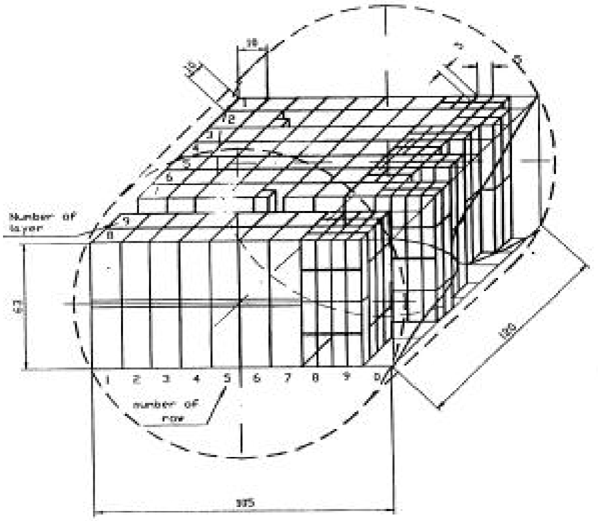

Fig.3. Typical scheme of the trepan cutting by EDM machine – up to 10 standard Charpy specimens have been manufactured from the disk 120 mm in diameter

EDM techniques came to change such routine methods of metalworking as milling and lathe approximately as it shown in fig.4 [1].

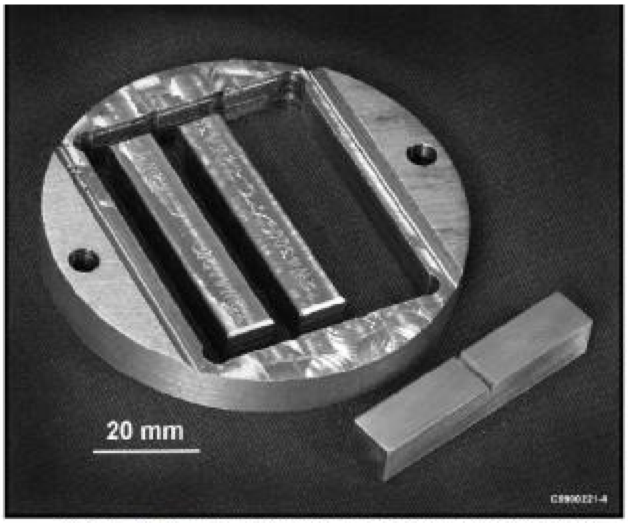

Fig. C.4. The three Charpy specimen blanks have been milled to final thickness and parted from the disk.

Fig.4. The three standard Charpy specimens have been milled and parted from the disk 87 mm in diameter (ORNL) [1]

3. using a fully automatic optical emission spectrometer to provide fast and exact simultaneous elemental analysis for both alloying and trace elements with minimum material losses (fig.5).

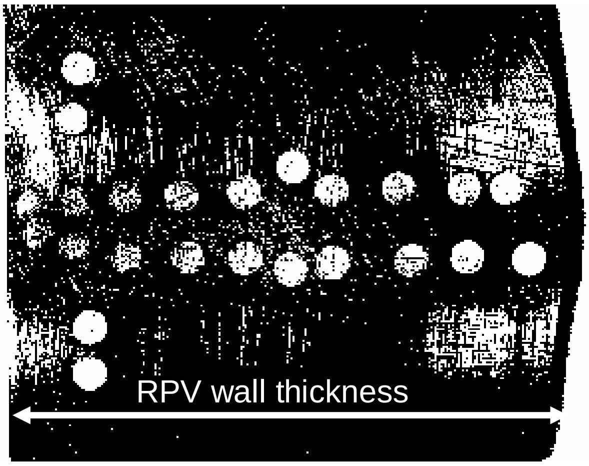

Fig.5. Using of the optical emission spectrometer for elemental analysis of both alloying and trace elements and their bulk distribution (white spots – places of analysis)

4. application of the reconstitution technique achievements (arc stud and laser welding) to use the RPV materials as efficiently as possible («materials recycling») (fig.6).

Fig.6. Examples of the reconstitution technique application (arc stud welding) for materials recycling. Left: standard Charpy 10×10mm^2; .right: subsize Charpies 5×5mm^2 and 3×4mm^2.

Sum of these measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the hotlab segment concerned with RPV materials study.

In particular, following results were obtained:

- controlling radiation embrittlement by means of RPVs thermal annealing was substantiated providing vessels «recycling»;
- annealing conditions for the first generation of Russian NPP with PWRs were optimized;
- taking templetes and using for in-service escort of WWER-440/230 units instead cancelled surveillance programmes was grounded, also absence of hydrogen-assisted degradation for uncladed RPVs was confirmed;
- as applied to WWER-1000 surveillance specimen program deep modernization was carried out: additional standard Charpy-V specimens were reconstituted from a broken specimens halves and, as a result, extended experimental data availability allowed to satisfy and conform the Guide requirements concerning the test specimens quantity and quality;

– data on actual radiation stability and through the RPVs thickness embrittlement change taking into account chemical factor and neutron flux level were obtained.

Thus, examination of the specimens manufactured from templetes and trepans presented a unique opportunity for qualifying the effects of long-term irradiation and multi-factor influence on actual RPV properties.

3. Novel methodology for the primary irradiation, annealing and re-irradiation development

Particular and significant advancement have been made for the RPV steels radiation stability examination by means of the progressive methodology development for the primary irradiation and re-irradiation conducting.

The main idea consists in utilization of the Unified Radiation-ReIrradiation Specimen (URRIS) for experimentation. URRIS represents metal block of the simplest form e.g. cylinder or parallelepiped. It undergoes irradiation, annealing and reirradiation as a hole, and test specimens are manufactured later to satisfy the present-day requirements непосредственно *immediately* before testing and examination. Inasmuch as metal under irradiation-annealing-reirradiation treats as monolithic piece the gradients of neutron flux and/or temperatures during irradiation and/or annealing are as small as possible. Moreover, simple form of the blocks give a chance to simplify rigging strongly.

Reconstitution application is the midpoint of the technology proposed. Damage zone (plastic deformation zone) at mechanical tests occupy no more then 25-30% of the specimen volume. Therefore, according to routine technology basic part of the specimen is irradiated uselessly. According to new technology, only useful volume of the metal are under irradiation and ballast parts of the specimen have to be welded to the irradiated one later, before tests. At the same time, small target dimensions lead to high uniformity of the temperature field during irradiation. So, as a result target material, reactor space, neutrons and nuclear fuel use more effectively. In addition, the quantity of the wastes decreases radically.

Transference of the centre of gravity to before- and after-irradiation stages leads toward to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall.

Prototype version of the abovementioned technology successfully was tested in the commercial and research reactors during composite multi-aspect reactor experimentation:

– cylinder-type fragments of the nuclear icebreaker «Lenin» RPV trepans were extra irradiated in the WWER-440/213 immediately in contact with coolant (fig.7) to provide data for functioning nuclear-driven icebreakers RPVs lifetime prolongation.

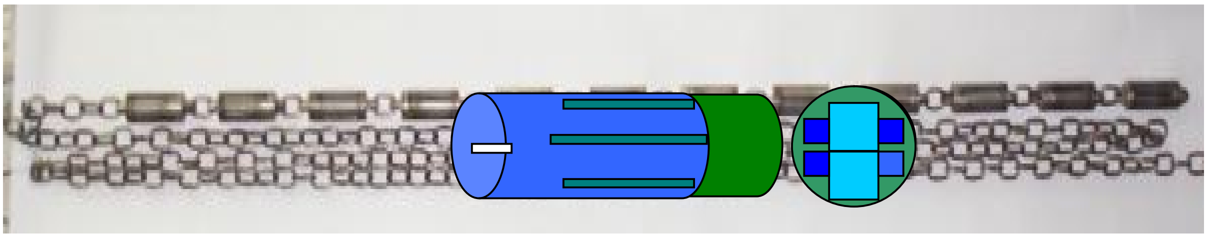

Fig.7. Set of the perforated capsules with cylindrical billets inside before reirradiation and sketch of the specimens by EDM manufacturing after reirradiation

As an example of the URRIS techniques potentiality, experiment on so-called «wet» annealing effectiveness of the reactor vessel was conducted. Pre-irradiated in WWER-440/213 SS channels immediately in running water up to 9×10^{19}sm^{-2} at 270°C base metal billets of the cylindrical shape were additionally irradiated in test reactor IR-8 at 330°C and neutron flux level of $3\times10^{11}sm^{-2}s^{-1}$ during 87 hours. Fig.8 shows the experimental device. One can see and understand that simple forms of the billets and device components allows providing the possibility of operative and inexpensive irradiation process.

Fig.8. Experimental device for RPV steel billets irradiation.
(1 and 2 – RPV metal billets, 3 - capsule for neutron monitors, 4 – heater)

As it follows from fig.9, where experimental results are demonstrated, 17°C recovery of the transition temperature shift (TTS) take place. This value is equivalent to 1,5 - fold neutron fluence reduction and therefore «wet» annealing technology has evident practical benefit.

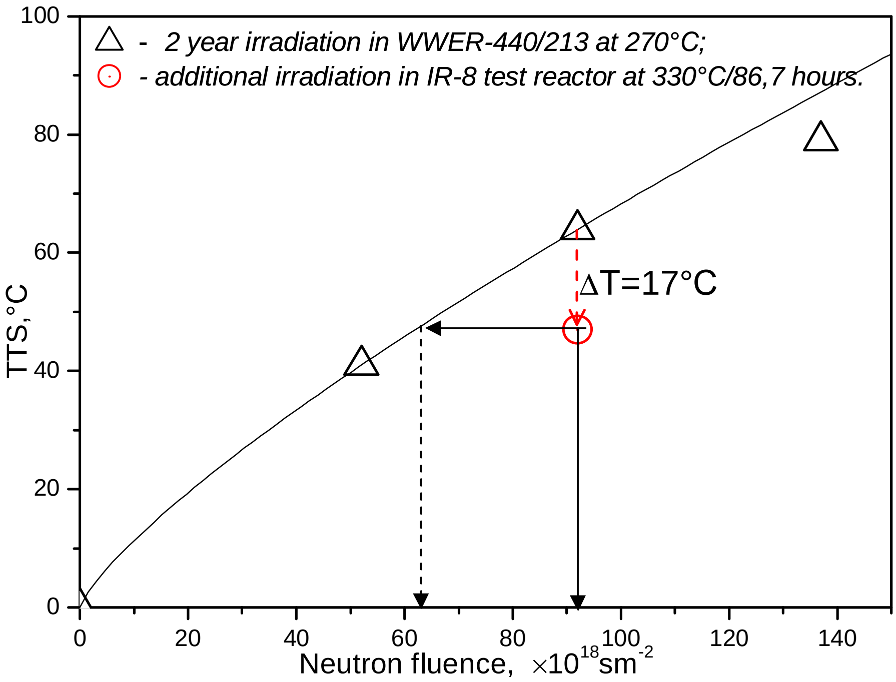

Fig.9. Results of the experiment on potential effectiveness of the RPV «wet» annealing study.

4. Advancements of hotlab techniques as prerequisites for going to manageable RPV surveillance programmes

Routine RPV surveillance programmes (SP) are characterized by high laboriousness (fig.8[2]) because call for precious rigging, containers pressurizing and tightening, necessity of the surveillance specimens (SS) temperature control, in case of depressurizing or temperature exceeding the SSs may be lost.

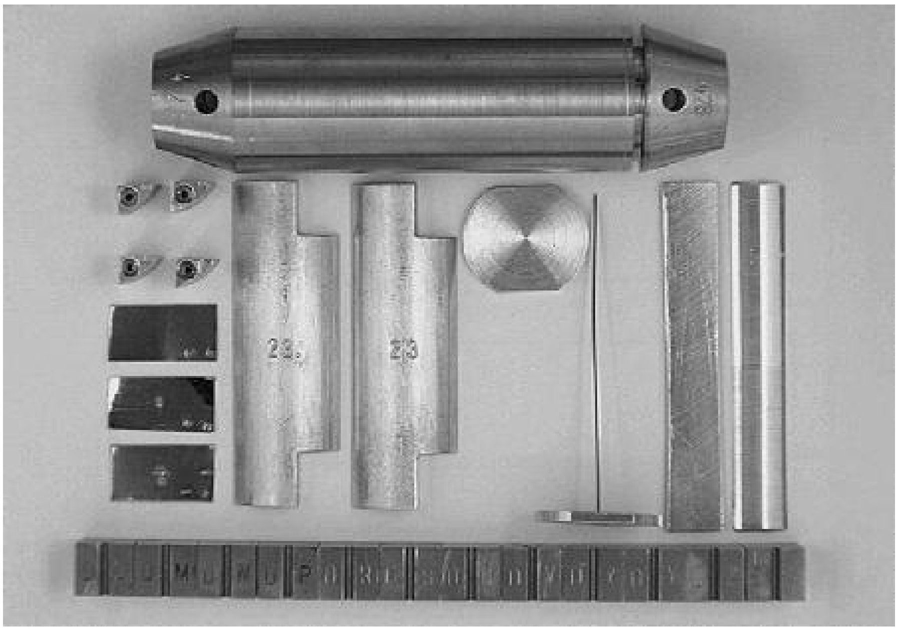

Fig.10. Set of modern SS capsule internals [2]

Using the above mention results and cumulative experience with particular reference to the reactor pressure vessel materials examination we have proposed [3] going from routine «hard» SPs to adaptable, «open» SPs that in potentiality allow the actualization and specialization of SPs and SSs types. These manageable SP (MSP) will be based on sets of archive material billets placed inside the RPV closely to wall and will cooled directly by primary circuit water.

It clears the way to a perspective in case of need put into practice an innovative MSP of anyone content and complexity, taking into account state-of-the-art of the safety standards, technical progress, level of science and technology.

Certainly MSPs development and application have to be based on disposable similar experience understanding and utilization. Let remember it.

It is known [4,5] that for the first generation of the Russian PWRs (WWERs) instead of the cancelled SPs just RPV (100% surveillance material) for a long time serve as billet for thin plates cutting and test specimens manufacturing as needed. As a matter, this practice is the first prerequisite of the proposed SP technology.

The second prerequisite is a worldwide experience on the through wall probes (trepans) of the ex-service RPVs using for actual metal properties examination [6-14].

The third prerequisite is our own long-term practice in SSs testing and long-term experience in decommissioned LWR pressure vessel material properties study [15]. Recently for the first time in the history of the RPV materials study set of the 1T-CT type specimens for fracture mechanics tests was produced from 140 mm in diameter ERP RPV trepan.

Fig.11 shows the steps of the 1T-CT type specimens manufacturing and testing. Encouraging results are obtained and analyzed now.

In a certain sense, proposed MSP procedure (technology) is the closest analogy to trepans investigation with the exception surveillance billets (SB) in advance should be placed inside RPV and ready for examination in case of need without extra complex RPV cutting. SBs placement inside the RPV as close as possible to RPV wall should be the best decision in SP performance from all points of view.

In the upshot, one can say that the scientific and technological prerequisites to LWRs surveillance programme improvement by means of going to manageable SPs (MSP) exist.

Fig.11. Steps of 1T-CT type specimens from 140 mm in diameter EPR RPV trepan manufacturing (left side) and testing.

5. Conclusion

Sum of the measures especially taking into consideration their synergistic effects allows modernizing up to high scientific, technological and ecological level the HotLab segment concerned with RPV materials study.

Examination of the probe materials from ex-service RPVs presented a unique opportunity for qualifying the effects of long-term irradiation and multi-factor influence on actual RPV properties.

Particular and significant advancement have been made for the RPV steels behavior examination by means of the progressive methodology development for the primary irradiation, annealing and re-irradiation conducting. Transference of the centre of gravity to before- and after-irradiation stages leads to irradiation procedure simplifying and reduction of prices under the improvement of the experiment quality overall including ecological after-effect.

Prototype version of the abovementioned technologies was tested in the hotlab/research reactor/commercial reactor successfully.

Eventually, highly productive and the cost effective hotlab/research reactor/commercial reactor techniques for RPV materials examination is created and operated.

Advancement of hotlab/research reactor techniques with particular reference to the reactor pressure vessel materials examination allows proposing the new SP conception based on substitution of the surveillance speci/commercial reactor mens irradiation in sealed capsules by the surveillance billets irradiation in perforated containers with following test specimens manufacturing that can provide:

- strengthening the contribution of surveillance investigations to improve the safety and performance of PWRs;
- increasing the level of PWR type safety on account of more adequate conditions of the surveillance metal irradiation;
- improving the informativeness owing to carrying over the specimens of actual nomenclature manufacturing process immediately to moment of testing from initial stage of RPV producing;
- decreasing the laboriousness and specific quantity of rigging metal for surveillance metal irradiation and to reduce the quantity of radioactive wastes ;
- releasing funds and resources, to reduce the cost of the joint RPV metal surveillance programme execution;
- making better PWR’s competitiveness.

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Determination of dimensional evolutions for irradiated material with a large panel of experimental means

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Abstract

The CEA LECI hotlab facility [1-5] is devoted to the study the mechanical behaviour and microstructure of materials after irradiation. Some of the phenomena are studied through dimensional measurements, such as in-pile creep, growth, or swelling.

This is the purpose of the M02 hotcell of the LECI, which offers a wide array of experimental equipments to characterize the dimensional evolution of specimens. Creep or growth is mostly studied on pressurized tubes made of cladding material, on which the diameter and length profiles are measured between each irradiation period, through shadow measurements and mechanical sensors. Moreover, the LECI facilities allow the fabrication of pressurized specimens from pre-irradiated cladding sections. The dimensional measurements made after each irradiation period then lead to establish constitutive laws. Through finite element calculation, it is thereafter possible to compare measurements with numerical experience simulation.

This presentation highlights the different steps from the initial development of an experiment, the fabrication and successive measurements of the specimens, to the final determination of a constitutive law for the material studied. An example of a typical creep and growth study is given.

Special attention is brought on the advantages of having the exact same experimental means outside and inside hotcells (assessing precisely the feasibility of new experiments, determining measurement accuracy, performing initial measurements). Other types of specimens can also be used to study growth or swelling, thanks to the adaptability of the different experimental setups.

Keywords

Dimensional measurements ; irradiation creep ; growth ; pressurized samples

1 Introduction

The M line of the LECI facilities, composed of 19 lead shielded hotcells, is devoted to the study the mechanical behaviour and microstructure of irradiated materials (without any fuel). In particular, some of the phenomena occurring under irradiation such as irradiation creep, growth on Zirconium alloys, or swelling on stainless steels, are studied through dimensional measurements.

Such measurements are carried out in the M02 hotcell of the LECI, which is devoted to this type of activities.

2 Equipment of the M02 hotcell

The M02 hotcell is devoted to dimensional measurements. These include measurements on creep and growth samples between irradiation phases, measurements on samples after mechanical tests, as a mean to check or supplement online strain measurements, and also measurements on samples machined inside hotcells in order to check dimensions and validate the geometry.

The equipment includes two optical scanning benches, a mechanical sensors bench, and a macroscope equipped with micrometric tables.

2.1 Infrared light scanning device

This device (see fig. 1) allows diameter measurements on samples with a precision of 1 µm (including repeatability studies), and also length measurements on the vertical axis, with a precision of a few microns (proportional to sample length). The sample is positioned vertically, between an infrared light source on one

side and a CCD Sensor on the other side. It is held in position between two precision live centers, the lower one of which can be replaced by a mandrel. Rotation of the sample is ensured through a step-by-step motor (with an encoder measuring the angular position).
The profile of the sample is scanned over the specified height, and the projected profile is measured. The sample can then be turned around in order to measure the profile at a different angular position. Furthermore, an angular reference (such as a notch) can be measured on the specimen, thereby ensuring a reproducible angular position from each measure, which is crucial when it comes to measuring evolutions of a few tens of microns.

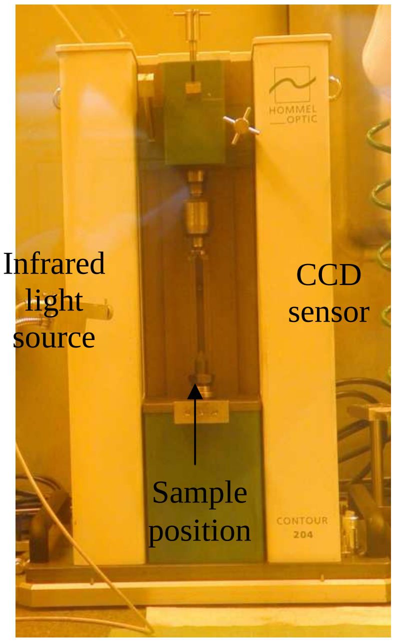

Fig. 1 view of the infrared scanning device

Tubular but also complex shapes can be scanned with this device, and distances on any feature of a sample can be measured. Geometries of samples measured with this device include tubular samples, flat tensile test specimens (on a dedicated setup), and small plates. This equipment presents the advantage to propose a large adaptability to the sample geometries, through specific setups designs.

2.2 Laser scanning device

Another device is a laser light scanning device (see fig. 2), equipped with a laser lightsource, and a precision linear scale on which a rotating mandrel is mounted for the positioning of the samples. The sample is set in the mandrel, and the scale is moved in order to scan the sample.

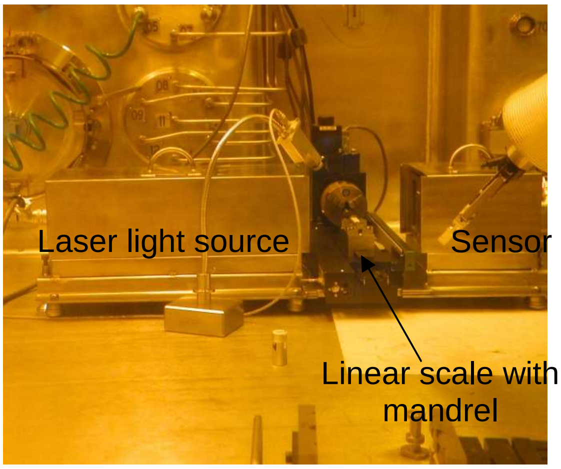

Fig. 2 view of the laser scanning device

As for the infrared scanning device, different geometries of samples can be measured on this bench by mounting a dedicated setup directly on the linear scale

2.3 LVDT Bench

As growth mainly takes place in the axial direction for cladding material, it is also important to measure precisely the lengths of tubular samples used for such studies.

The M02 hotcell is equipped with a bench using Linear Variable Differential Transformer (LVDT) sensors set into contact with both ends of the sample.

The setup allows a precise and reproducible positioning of the sample, and the length is measured at eight different angular positions, with a precision of less than 5 µm.

On the same bench (fig 3), three different lines have been mounted to measure several types of samples. These lines can be dismounted from the basis and replaced in case new geometries should be tested.

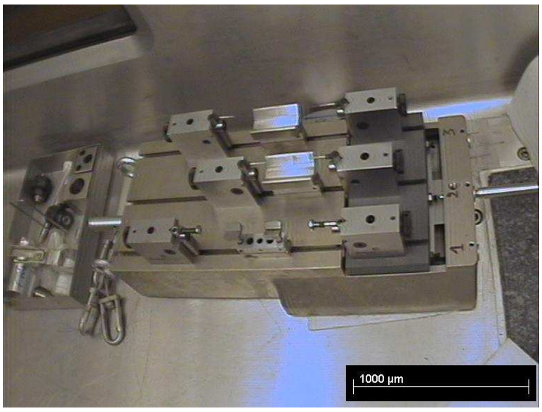

Fig. 3 view of the length measurement bench

2.4 Macroscope

Some measurements cannot be done easily with scanning devices or through contact sensors, either because of the geometry of the sample or because it may be too brittle.

For these cases, a macroscope (fig 4) equipped with two cross-linked micrometric tables and a goniometric sample-holder is used.

The macroscope can be used in two modes:

- To measure distances through the displacement of the tables, usually with a precision of 10 µm (depending on the geometry and surface roughness).
- To measure distances and areas on an image by converting pixels into distances. This mode in particular is used for the measures of necking surfaces on tensile test specimens.

As for the two preceding devices, special setups can be designed and mounted on the macroscope to ensure a precise and reproducible positioning of the sample.

For the measurements of the necking surface, the motorized Z-axis of the macroscope can be used to assemble views at different altitudes to reconstitute a clear image of an inclined fracture surface.

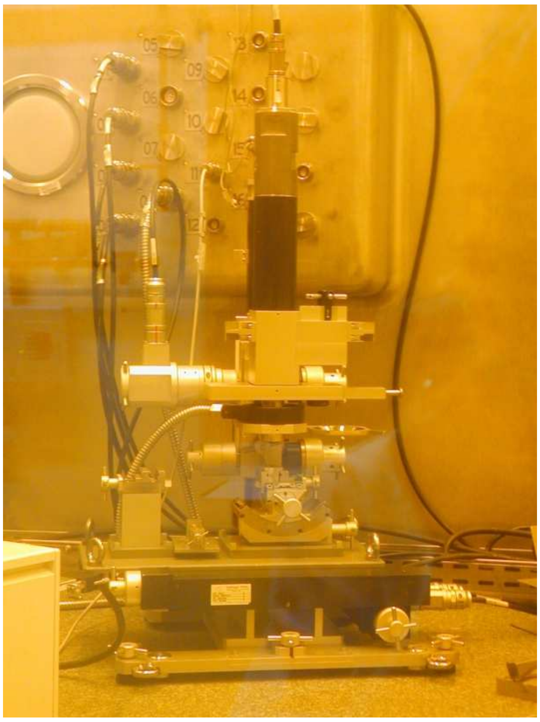

Fig 4. View of the macroscope

3 Irradiation creep studies on pressurized samples

3.1 Context

The release of fission gasses during irradiation and the Pellet-Cladding Interaction impose stresses on the cladding of PWR. Among other things, these phenomena result in irradiation activated creep, which must be well characterized as it plays an important part for the study of the maximum service life of cladding material. This creates the need for creep and growth experimental studies, on material representative of end of life cladding sections.

3.2 Sample fabrication

To meet this need, pressurized samples made of irradiated defueled cladding sections are fabricated in the hotcells of the LECI facilities: the cladding section is first machined to the desired length, then measured to determine fabrication parameters (cap dimensions and gas pressure) and then two tailor made caps (one of which has a hole) are laser welded onto the cladding. The sample is then pressurized with Argon or Helium at room temperature in order to obtain the prescribed stress level at irradiation temperature, and the hole is sealed. One such sample is pictured on figure 5.

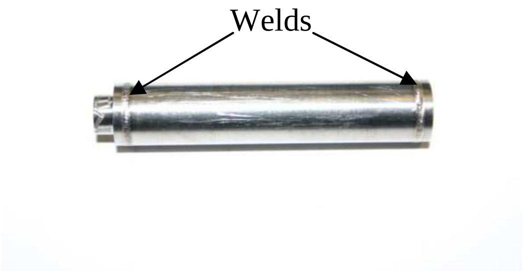

Fig. 5 typical pressurized sample

After the sample has been assembled and pressurized, pressure is controlled via the weight intake on a precision scales, and an X-ray scan is made to ensure that the sealing has been properly made. Currently, samples with gas pressures up to 150 bars have been fabricated in the LECI hotcells.

3.3 Measurements and irradiation

The initial measurements are conducted on the infrared scanning device in the M02 hotcell. One of the caps welded on the cladding section is notched to provide an angular reference for the measurements.
Diameter measurements are usually made every millimeter over the length of the sample, at different angles (every 45°). It is thus possible to reconstitute the diameter profile of the sample. Features such as primary folds due to the pellet-cladding interaction can be measured (see fig. 6).

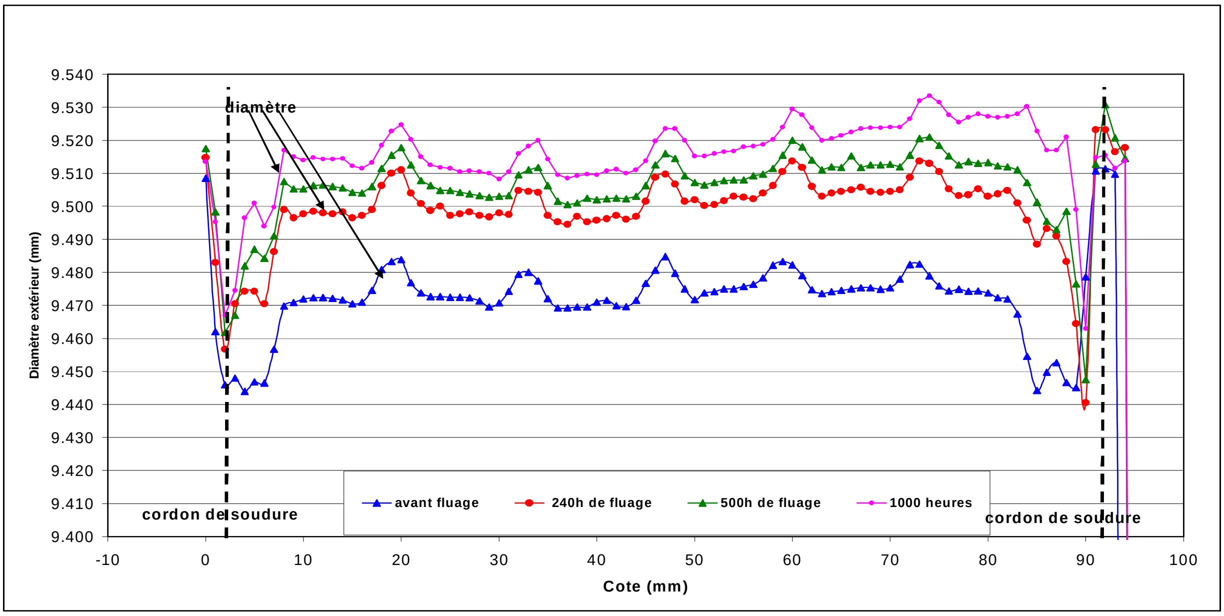

Fig. 6 typical diameter profile of a cladding section

Beside diameters, length is measured every 45° on the LVDT bench. After each irradiation phase in the research reactor (or heating phase in case of thermal ageing on irradiated materials), the samples are sent back to the M02 hotcell, and the measurements are repeated using the same machine, setup and protocol. The strain due to irradiation creep and growth can then be measured, and it is furthermore possible to check is the folds are still present, or if the deformation is homogeneous or not.

3.4 Modeling

After the irradiations phases are completed and the measures have been made, resulting data is used to adjust models for the behavior of the material, taking into account the effect of stress, temperature, and neutron flux. A typical example of the results obtained is given on figure 7 [6]. The creep rate increases with increasing stress (from 0 to 120 MPa on figure 7), and the effect of flux can also be seen. Unpressurized samples do not exhibit changes in diameters.

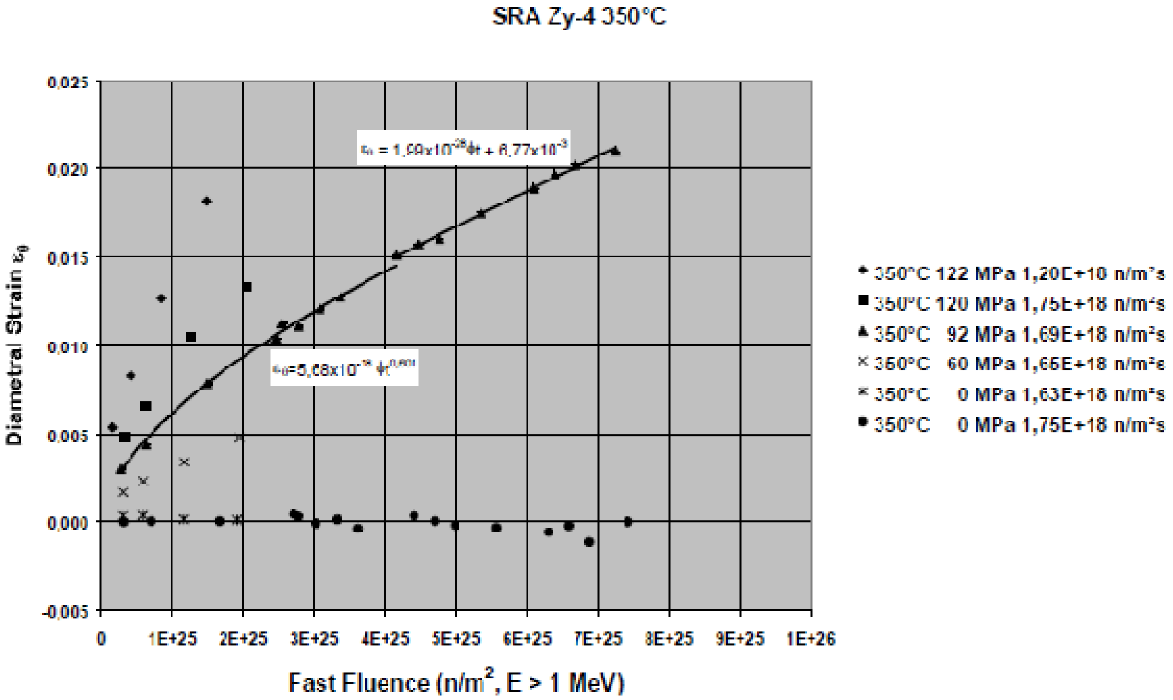

Fig. 7 results obtained after a creep experiment using pressurized samples [6]

It is thereafter possible to use the measured complete profile of the samples on a Finite Element model to see if the modeled deformation is in good agreement with the measured one.

4 Development of new irradiations

The example given above is typical for the study of the creep behavior of cladding material under irradiation, but other experiments using different geometries are also possible with the equipment present in the M02 hotcell.

4.1 Development process

The first step of the development process for a new experiment involving dimensional measurements is to decide of the sample geometry. Factors taken into account include the material original shape (plate, tube,,…), the phenomenon to be investigated, the sample machinability, the parameters to be measured (length, diameter, at different axial or angular position) and also the measurement device to be used.

For this last point, it is very important to assess beforehand the precision which can be obtained using the foreseen geometry and experimental setup. For this purpose, the LECI is equipped with the exact replica of the experimental devices of the M02 hotcell, in a separate lab (cf. fig. 8). This includes the cable length and connectors used for the hotcell devices.

New geometries can then be tested, the precision can be assessed, and optimization can take place without disturbing the activities of the hotcells, and, most importantly, without all the constraints associated to the work in a hotcell environment.

This equipment can also be used for the initial measurements of experiments involving unirradiated samples at the start (which is often the case for new materials).

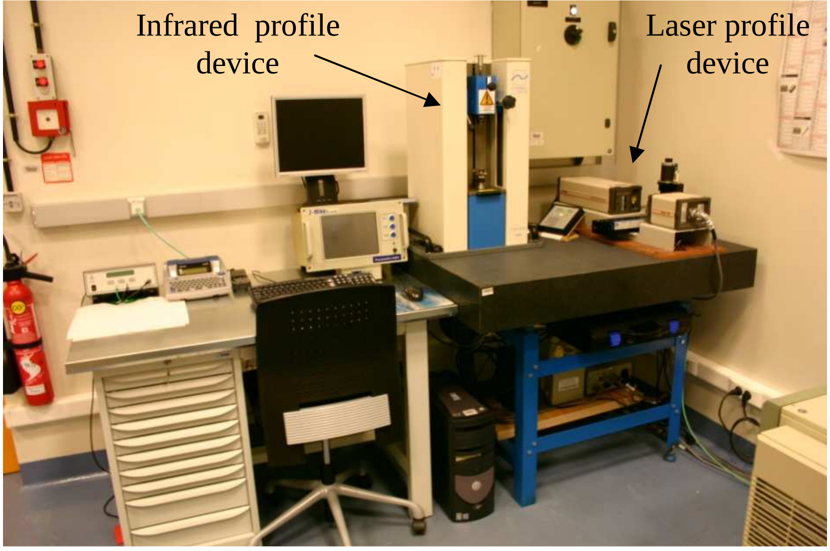

Fig. 8 view of the experimental devices outside hotcells

4.2 REFLET: an example of a relaxation study

One example of experiment is the study of the relaxation behavior occurring under irradiation for grid material [2, 7]: an experiment was designed using blades set in three points bending under irradiation. The blades are removed from the setup after each irradiation phase and their profile is measured. The evolution of this profile corresponds to the relaxation of the sample (see fig. 9 for a brief overview of the experiment).

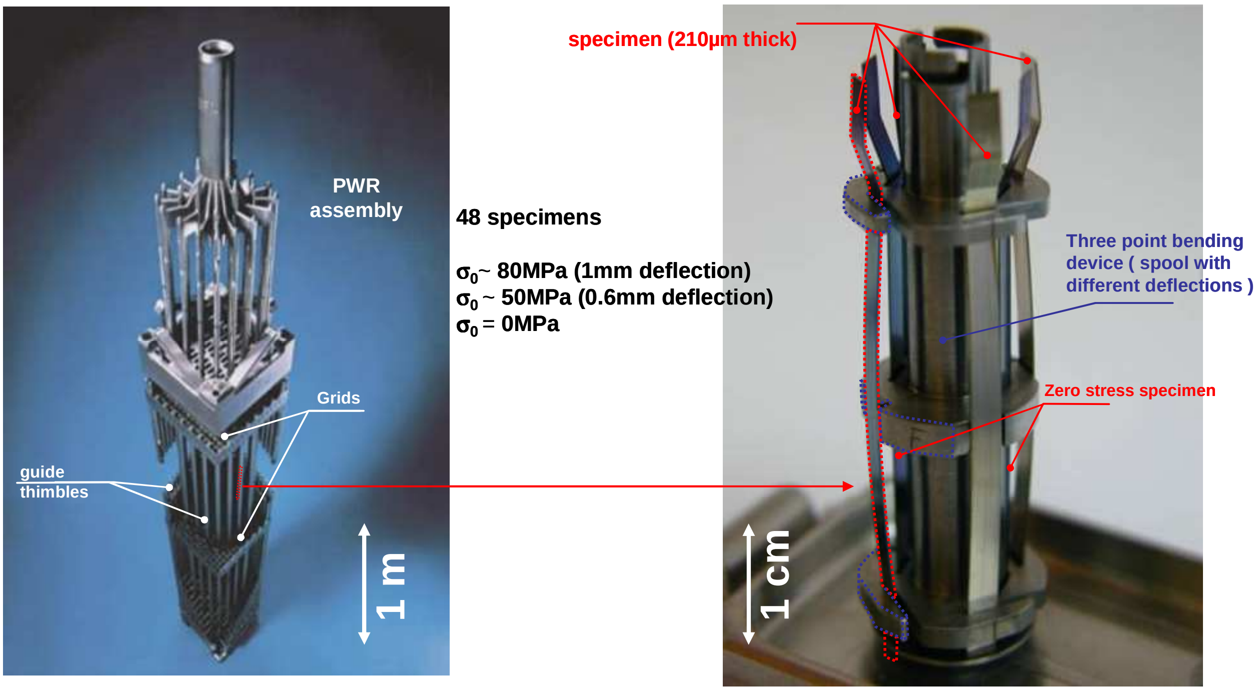

Fig. 9 Overview of the REFLET relaxation experiment

The profile of the blades was measured with the laser profile device, on a dedicated setup (see fig. 10). The setup ensures a reproducible positioning of the blade in front of the laser beam. Under the blade is a cylindrical gage block which acts as a reference level for the profil measurement.

The blade is scanned over its whole length, and the profile of the lower and upper edges are recorded each millimeter (it is thus possible to track any change in the blade thickness, which could be the sign of a faulty positioning). On the figure 10, typical results obtained after six irradiation phases are shown.

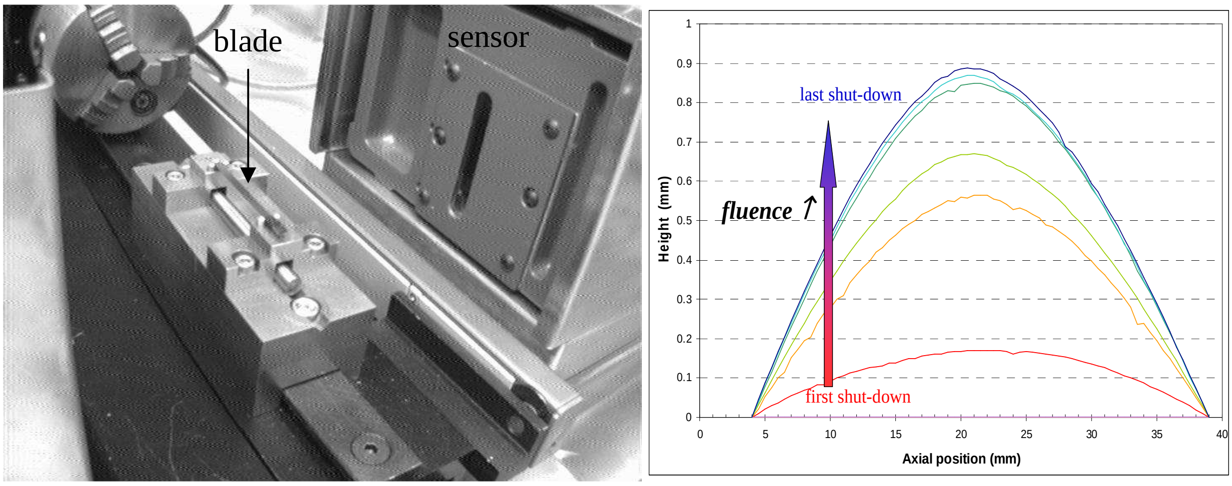

Fig. 10 Experimental setup for REFLET and results obtained [7]

The results are then processed in order to identify the parameters of the behavior law of the material, as is shown on figure 11.

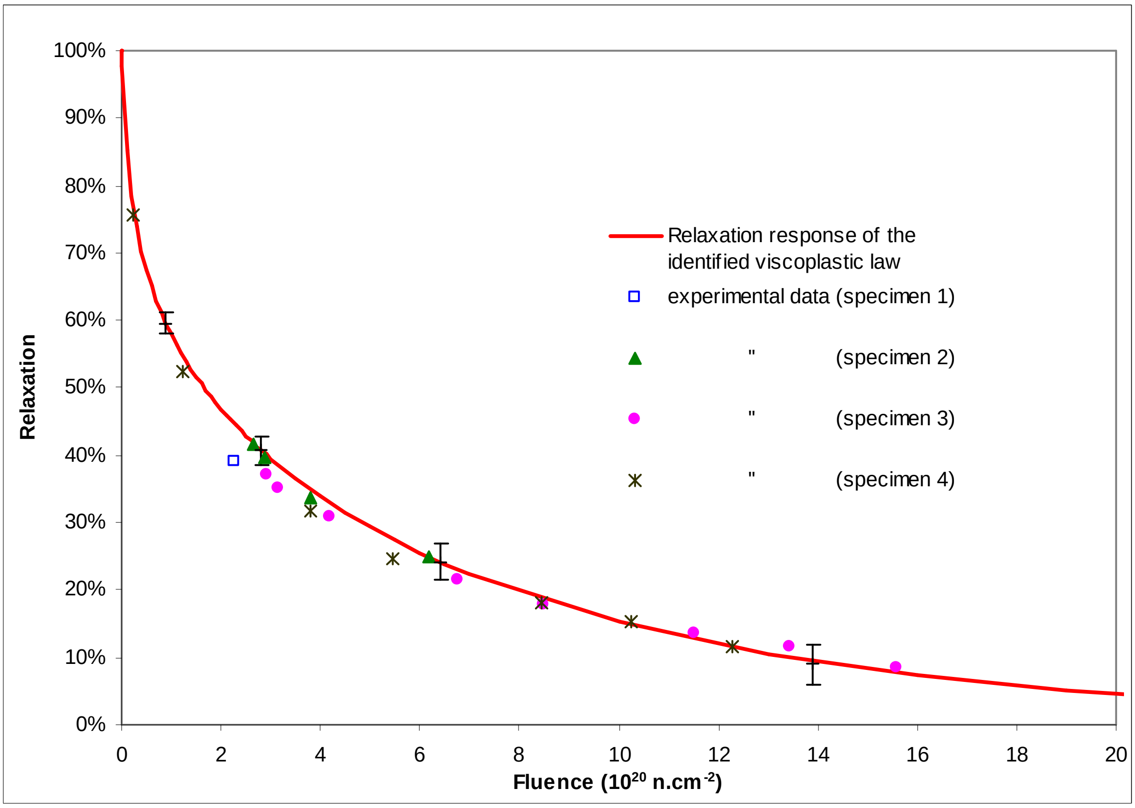

Fig. 11 *Identification of the behaviour law on the global response [7]*

5 Conclusion

The experimental devices available for the study of the dimensional evolutions of irradiated samples at the LECI have been reviewed, and some examples of experiments using these devices have been given.
It should be stressed that having a dedicated hotcell for dimensional measurements, with different means for characterization, makes it possible to develop a wide array of experiments using different kinds of sample geometries.
Also, the devices available outside the hotcell allow the development and validation process much more efficient and accurate, without interfering with the activities of the hotcell.

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