Studies on the Sintering Behaviour of UO_2-Gd_2O_3 Fuel Pellets

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Abstract. Atucha-1 NPP is a Siemens-KWU designed PHWR which started its operation in June 1974 and has accumulated up to December 2010 around 26 fpy, that mean a load factor of above 72%. It began its operation with natural uranium fuel and since 1995 the core has been converted to SEU (0.85% enriched). Moreover, in the recent years CNEA Fuel Engineering Branch has developed a program to increase the U mass, involving a new structural design of the fuel element (FE), in order to achieve a higher burn-up and to reduce the frequency of daily on-line refueling.On the other hand, this type of reactor design involves the use of coolant channels (CC) which interact strongly with the FEs. The original CCs had to be replaced when signs of degradation were noticed at about 10.4 fpy. The new CCs have an improved design and are made of Zircaloy-4 with enhanced oxidation and mechanical properties. According to these needs a number of activities were planned for the follow-up and periodic control of the FEs and CCs in service. This presentation describes the poolside facilities used to perform visual inspection and dimensional measurements as well as the contribution of these results to both programs.

1. INTRODUCTION

NA-SA and CNEA have performed different activities regarding the follow-up and periodic control of the behavior of the FE and their interaction with the coolant channels (CCs) under operational conditions. The CCs are structural components which are characteristic of these type of reactors moderated and cooled by heavy water.

Being originally a natural uranium prototype reactor, Atucha-1 has undergone constant improvements in order to get a better efficiency in the utilization of the FEs, as well as concerning safety in operation. Improved fuel management implies that the FEs are now working at a lower linear power and reach a higher burn-up.

In the recent years, our Fuel Engineering Branch has implemented a program to increase U mass in the FE. Also, NA-SA has replaced all original CCs by ones with an improved new design. The effects of these modifications were monitored through visual inspection and PIE activities.

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2. ATUCHA-1 REACTOR, MAIN CHARACTERISTICS

Atucha-1 is Argentina's first NPP and began its commercial operation in 1974. It is a PHWR designed by Siemens, with a gross electrical power of 360 MWe. The reactor core has 250 vertical coolant channels which contain the FE and separate the coolant from the moderator. Refueling is made periodically during operation.

Power regulation is made through three absorber rods made of stainless steel for coarse control, three rods made of Hf for fine control, and additional rods of both types for shut down. All rods are inserted at different angles, thus allowing online fuel shuffling by the refueling machine. Up to date the plant has operated with a 72% load factor (26 fpy).

Fig. 2.1 shows a schematic view of the pressure vessel which contains the moderator tank and structural components defined as reactor internals, such as: guide tubes for detector probes, control rod guide tubes, and coolant channels inside which the FE dwell.

All internals are fixed to the reactor lid and slide into the moderator tank bottom to allow for axial displacements due to different temperatures and materials. Also dimensional changes such as irradiation growth have to be considered and continuously monitored.

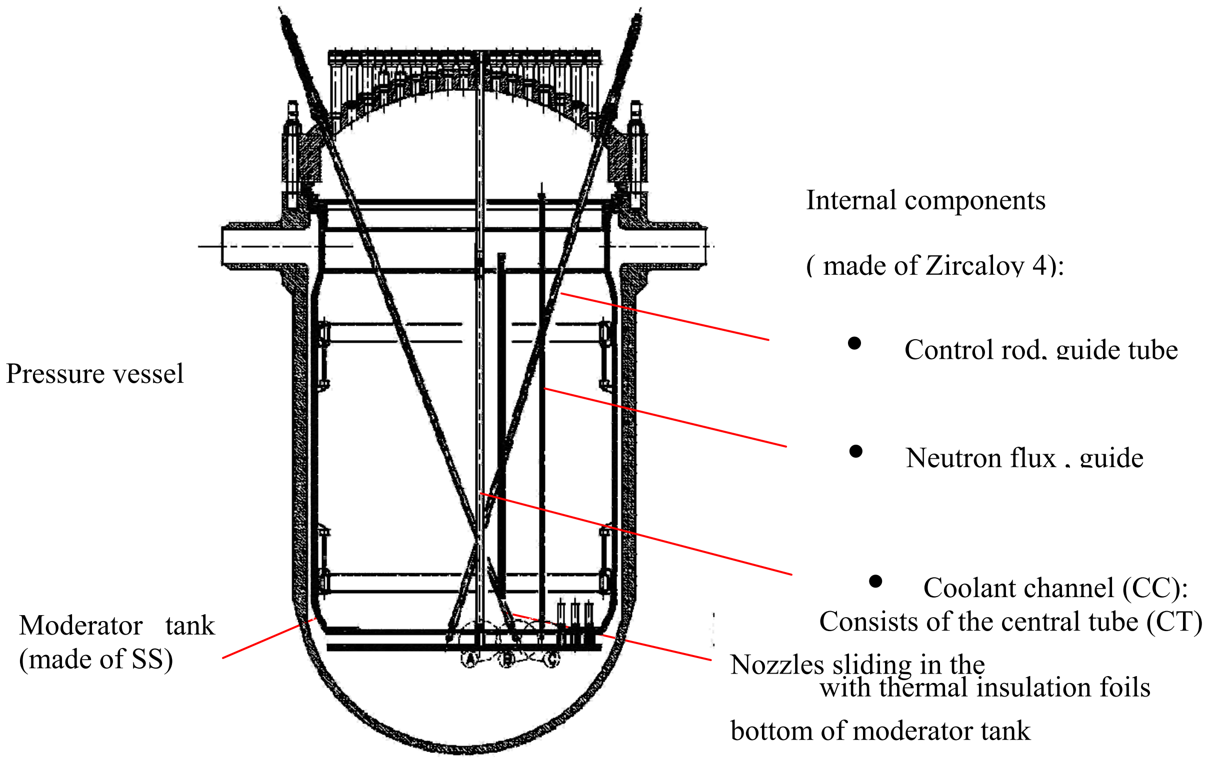

FIG. 2.1. Simplified cut view of Atucha-1 reactor.

The central tube (CT) of CC (also called shroud tube of FE) is made of Zircaloy 4 of 1.73 mm thick; it bears major temperature gradients and undergoes mechanical interactions with the FE. Operating conditions involve:

- Temperatures above 300°C on its inner surface. The outer surface is in contact with the moderator water at about 180°C, and an insulation foil is used to minimize heat flux through the CT wall.
- Fast neutron flux ($f \approx 10+^{13} n/cm^2/seg$; E> 1 Mev).
- D_2O with controlled chemistry.

Microstructural changes undergone by CT during service bring about macroscopic effects such us:

- Axial elongation.
- Diameter expansion or shrinking.
- Growth of zirconium oxide layer.
- Increase of hydrogen/deuterium concentration.
- Degradation of mechanical properties (mainly a decrease in ductility).

In fact, in 1988 (at about 10.4 fpy of reactor operation), signs of degradation were observed on those CC with the highest fluences [1]. The main features were an excessive axial growth of CT (exceeding in some cases the design limit), and a high degree of oxidation and embrittlement of the insulation foils which led to their breaking into pieces. Both phenomena (high axial growth and the presence of debris) resulted in the restriction of sliding of CC guidance nozzle at the bottom of the moderator tank; some of them got stuck and underwent bending [1].

Original CCs and guide tubes were then gradually replaced by ones of a new design. The main modifications introduced in the improved new CC design were:

- The gap of the CC nozzle at the bottom of the moderator tank was increased and a special piece was added to avoid dirt accumulation above the nozzle.
- The original two-foil insulation was replaced by only one foil of 0.4 mm thick.
- The manufacturing process of CT and insulation foil was improved. A modified Zircaloy-4 (PCA-S) with a different texture and lower tin content was used to obtain better properties regarding dimensional changes and oxidation resistance.

All CCs were replaced by those with the new design between 1996 and 2005. The operator of the plant (NA-SA) developed consequently a strict surveillance plan of continuous monitoring of reactor internal components as part of an “Early Alert Program” (early warning failure detection).

3. CONTROL METHODOLOGY OF THE CC

The surveillance plan consists of the following actions, which are being taken during planned outage:

- Remote visual inspection (RVI), inner and outer surfaces;
- Dimensional control of the CT , internal diameter and length;
- Metallurgical evaluation by destructive testing in hot cell.

3.1. Remote visual inspection inside the reactor

During each planned outage about 5% of resident CCs are inspected in situ with an underwater radiation resistant TV camera mounted on a column with a LED lighting system.

In the first place, the inner surface is scanned in its entire length with an axial lens; any signs of fretting, wearing or scratches are then further inspected using a radial lens. Documentation is recorded by image digitalization. A screen editor is used to annotate the position of the feature and other useful information. Special care is taken in the observation of marks left by interaction of the FE and the oxidation layer appearance of the surface (see Fig. 3.1).

3.2. Metrology and Inspection in the SFP

During each planned outage about 4 resident CCs are taken out form the reactor and sent to the SFP for a complete inspection (inner and outer surfaces) and the measurement of the internal diameter (ID) and length of the CT.

The criteria to choose the CCs for inspection and metrology in the SFP are:

1. To get data from CC with different fluence.
2. To allow a remote visual inspection of different internal zones of the moderator tank with a TV camera inserted through the opening left when the CC is taken out.
3. To follow the evolution of the macroscopic changes, the same CCs are inspected every four planned outages (approx. 6 years).

Up to date the CC of the following positions are being measured:

- 8 CC of central zone (without water flow throttle).
- 2 CC of maximum dose (throttle #7).
- 1 CC of medium dose (throttle #6).
- 1 CC of peripheral zone (throttle #1).

Fig. 3.2 shows the plan view of reactor lattice, the position pointed in black are the CC under follow-up. For the inspection, the CC is hung vertically from a shelf at the water level of the pool. Figure 3.3 shows the inspection bay. The remote visual inspection procedure is the same than that used inside the reactor, but also the outer surface of CC is inspected to check the state of the thermal insulating foil.

Axial length Measurement of the CT is obtained by direct comparison with a calibrated ruler made of a Zircaloy cladding FE skeleton (a column so-called squirrel cage) which have three millimeter rulers at a 120° angular distance in both ends. The observation of the end position of the CT respect to the ruler is done by the same TV column used in the inspection. As the ruler column has the same thermal dilatation coefficient than the CT, the measurement can be done at any temperature condition (including thermal gradients) and also on a CC inside the reactor.

Fig. 3.3 shows the ruler during its introduction into the CC and Fig. 3.4 shows an image captured from the TV screen showing the upper end position of the CT relative to the ruler.

Internal diameter (ID) measurement is performed using an ad-hoc gauging head consisting of an underwater LVDT sensor which self centers on the CT through a roller pad guide. Calibration of the head is done with a centesimal micrometer and verified using a reference calibrated tube. Fig. 3.5 shows the gauging head during calibration. Axial scans are performed and the maximum and minimum ID at each 50 cm of length are recorded; in this way the ID profile along the CT is obtained. Fig. 3.6 shows the comparison of measured ID growth with the theoretical profile predicted by code calculation.

3.3. Metallurgical evaluation by destructive testing in hot cells

In order to perform metallurgical analysis, it was necessary to extract samples from different zones of the CT and insulation foil. A practical method was designed and implemented in the SFP to obtain the desired pieces of both materials by mechanical cutting, without affecting the integrity of the CC needed for its handling during storage maneuvers.

The device for the extraction of samples consists of a Grey H-column supported by underwater shelves, where the CC is positioned horizontally.(see Fig. 3.7). A pneumatic low speed motor driven by a trolley and sliding over the Grey performs the cutting and extraction of the sample of CT and insulation foil at any desired axial position (see Fig. 3.8). The cutting tool is a diamond disk which performs a clean cut leaving a “window” of approx. 10 x 30 cm on the CT wall and insulation foil.

The samples are sent to the hot cells facility at Ezeiza Atomic Center (CELCA) [2]. The following tests are performed sequentially:

- Visual inspection, characterization and measurement of oxide layer by an eddy current technique on both inner and outer sides.
- Machining of the normalized tensile specimen with a numeric control mill assisted by computer (CAD-CNC) (see Fig. 3.9).
- Tensile testing is performed with a universal testing machine (see Fig. 3.10).
- The remaining parts of the sample are cut in an appropriate size to perform destructive analysis, metallographic studies (by optical microscope and SEM) and the measurement of Hydrogen and Deuterium content by hot vacuum extraction (LECO equipment).

4. INSPECTION AND METROLOGY OF THE FUEL ELEMENT

Atucha-1, initially designed for natural uranium fuel, has gradually performed improvements in fuel discharge BU and consequently in the fuel economy. The first action taken was to increase the enrichment to 0.85 wt% U235, this program was began during 1993 and concluded when the core was fully converted to SEU in 2000 [3]. At the same time, a second program to increase U mass was implemented through a modification in the design of pellet geometry and a reduction in the inner free volume of the rod. The result of this program was an increase of 2.5 wt% in U mass.

The last action in the U mass increase program is the replacement of the structural rod by an active one which adds up to 5.3 wt% of U mass to the original design. This modification involved the redesign of the elastic pad which adjusts the FE to the CC; this pad was originally fixed to the structural tube and now it is fixed to the spacer grid. Then, this new FE design consists of a circumferential array of 37 rods with an active length of 530 cm, assembled by fifteen rigid spacers. The rod adjusts to each spacer through three rigid pads welded to the rod at specific axial positions. Fig. 3.11 shows the main features and obtained Bu of the new design FE in comparison with the original one.

For the follow up of the behavior of this modification, visual inspection and metrology control of the rods was implemented at the SFP. Visual inspection is done by viewing directly through a diagonal mirror inverted periscope installed at a bay of the reception pool [4]. This equipment has been working since the beginning of the operation of the plant and its upgraded version now gives an excellent image quality. A digital camera can be attached to the telescope for displaying images on the TV screen and taking pictures. Visual inspection is normally used to check the surface condition of the rod (oxide layer appearance and crud deposits), and to identify defects or secondary degradation signs.

Regarding the new 37 active rod FE design the main interest is to evaluate the wear condition of the structural part, the interaction of the elastic pad and rigid pad that are fixed in each spacer with the CC and any fretting mark induced by vibration. The evaluation of the loosening or relaxation of the elastic pad fixed to the spacer is done by comparison of its curvature with a reference image taken during pre-irradiation inspection. Fig. 3.12 shows a side view of the elastic pad fixed in the spacer.

The measurement of total and partial elongation along the rod is of interest to assess the possible effects of U mass increase. Elongation data give information about differential growth caused by any hard pellet-cladding interaction at sections of the rod with different linear power. Partial elongation is obtained measuring the change in length (pre and post irradiation) in four sections of one outer rod.

Each section is defined between the sharp edges of the rigid pads of the rod corresponding to spacers 1–4, 4–7, 7–10 and 10–15. Total length is considered between the rigid pads of the rod corresponding to the spacers 1–15. Length measurements are performed observing the displacement of the mast of the crane bridge, when the FE is lifted in front of the periscope. A laser distance meter (precision 0.1 mm) attached to the mast measures the displacement while the pad edge level is observed on the TV screen from the periscope view. Fig. 3.13 shows edge levels corresponding to spacers 1 and 15, between which Δ length is measured.

5. FINAL REMARKS

Underwater inspection and metrology techniques are being applied for the monitoring of cooling channels and fuel elements behavior, as useful tools to assure the safety in operation of Atucha-1 NPP.

Regarding cooling channels, the inspection methodology provides enough data about the state of irradiation-induced degradation and consequently preventive actions can be taken in advance of any incident. The length and internal diameter measurements on the central tube allow the assessment of the dimensional stability of the CC of new design. The tools and instruments used in the measurements show a good precision and are easy to operate. Also a novel underwater technique was developed for the extraction of samples of the central tube, minimizing the costs and risks of material handling. The samples were then sent to the hot cells for metallurgical analysis.

Concerning fuel element, visual inspection and metrology controls assured the progressive implementation of the U mass increase program. As a result of this, nowadays a fuel discharge burn-up of about twice the original value has been achieved and the refueling frequency has been reduced to one half of the previous one, which means a huge improvement in fuel economy.

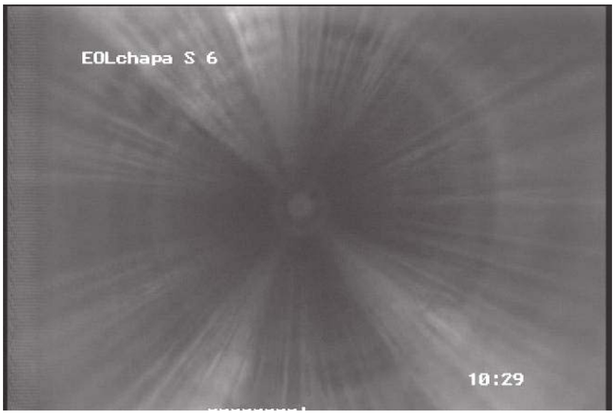

FIG 3.1. CC internal visual inspection. Contact marks left by interaction of the FE shoes.

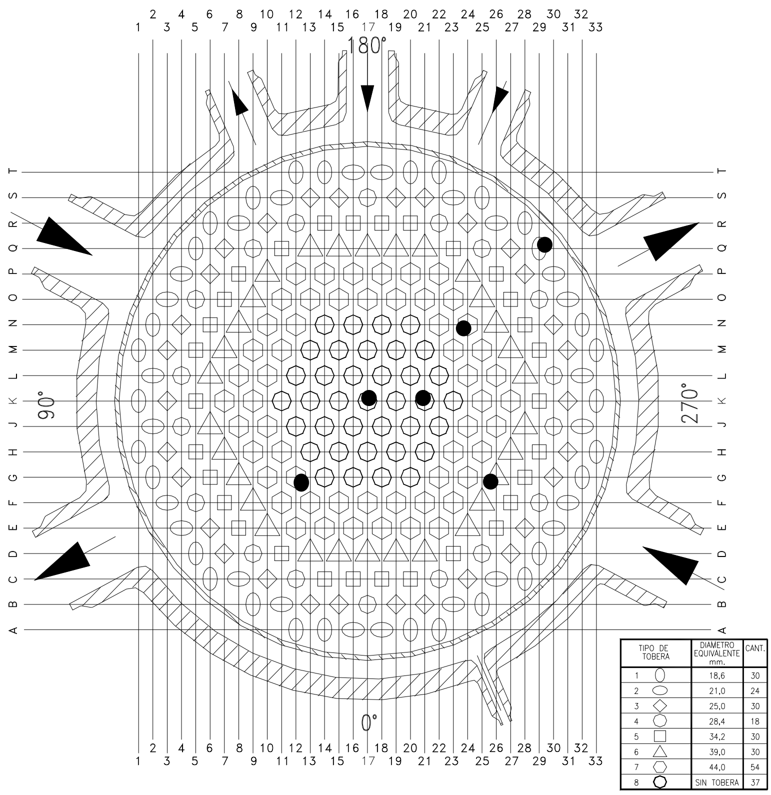

FIG. 3.2. Plan view of reactor lattice, the position pointed in black are the CC under follow-up.

FIG. 3.3. Shows the inspection bay for the CC in the SFP.

FIG. 3.4. Shows the ruler during the introduction in the CC for the length measurement.

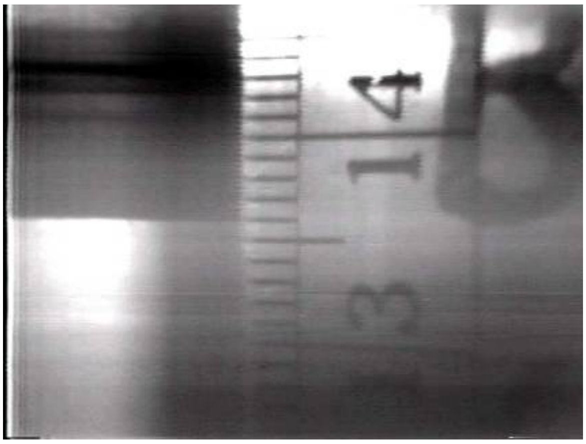

FIG. 3.5. Image captured from the TV screen showing upper end position of the CT respect to the ruler (resolution 0.5 mm).

FIG. 3.6. Self centered ID gauging head, during calibration.

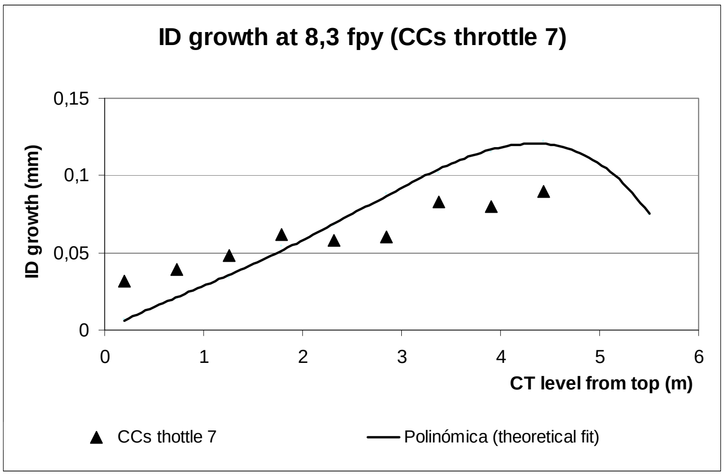

FIG. 3.7. Comparison of measured ID growth with the theoretical profile predicted by code calculation. (Values are the average of two CCs with throttle 7, maximum dose).

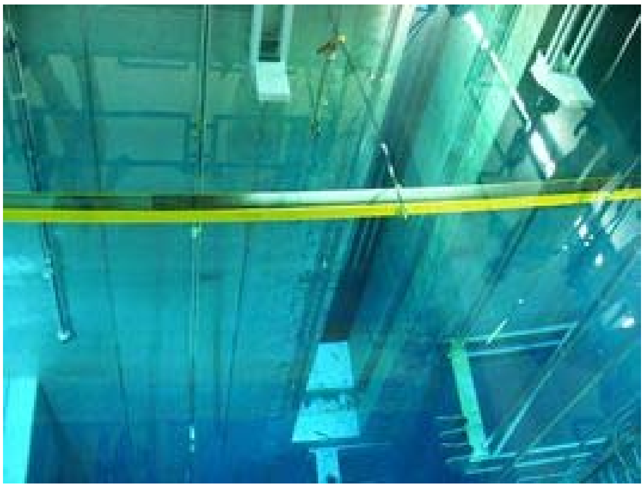

FIG. 3.8. Allocation of the CC in the grey H beam supported on underwater shelves.

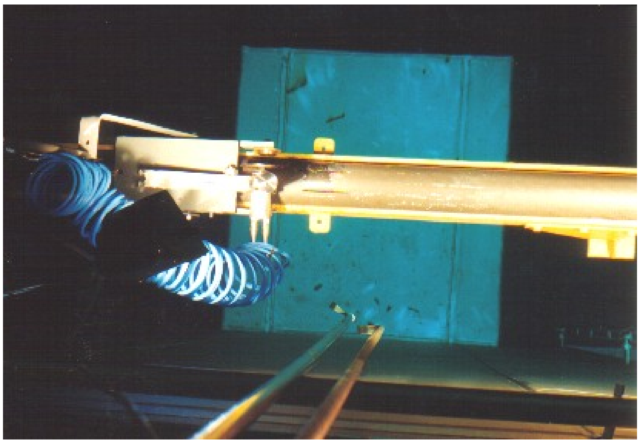

FIG. 3.9. A pneumatic motor driven by a trolley and sliding over the grey is cutting and extracting the sample of CT and insulation foil.

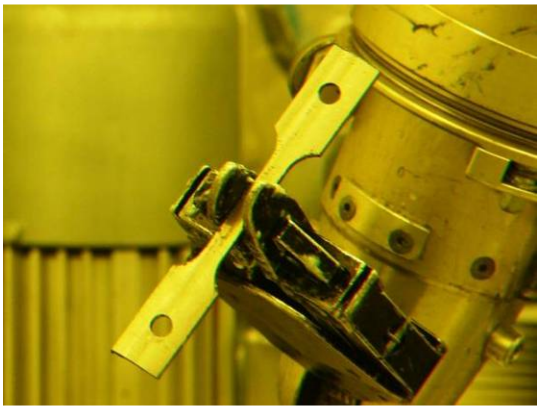

FIG. 3.10. Tensile specimen is obtained by machining in CAD-CNC mill.

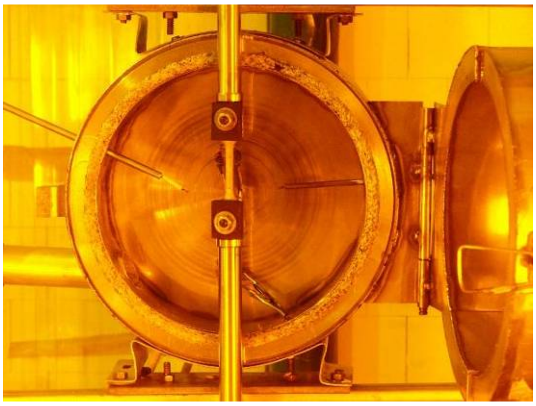

FIG. 3.11. Tensile testing in an environmental furnace at room temperature and 250°C

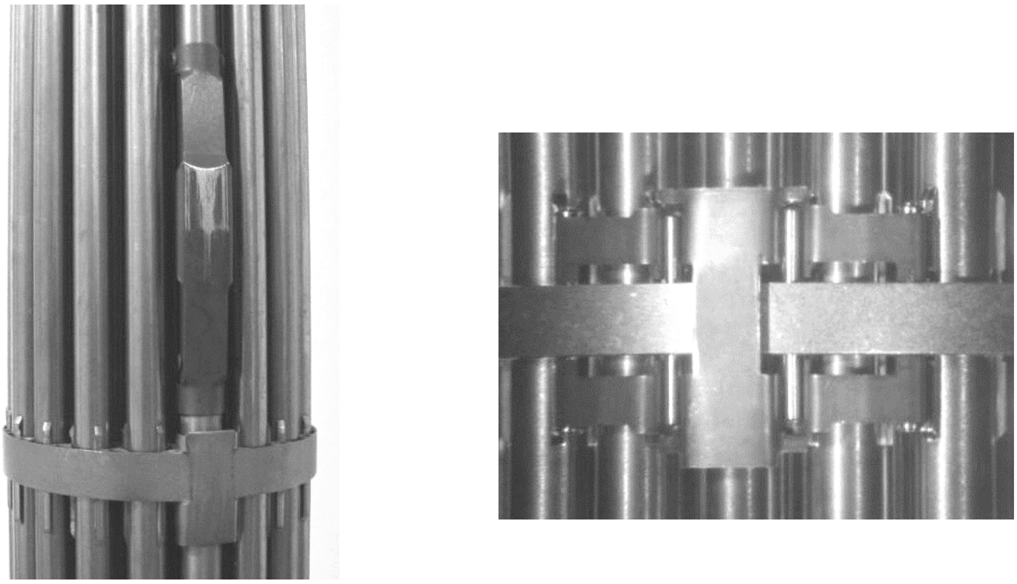

FIG. 3.12. Main characteristic of the Atucha 1 FE.

TABLE 3.1. CHANGES INTRODUCED IN FUEL ELEMENTS

	Changes introduced in fuel elements		
	Original design		New design
Assembly geometry	Circular array		
Fuel rods	36		37
Structural rod	1		none
Enrichment	natural		0.85% (SEU)
Uranium mass [kg·FE^{-1}]	152.5		160.5
Tie plate	1		
Rigid spacer grids	15		
Active length [mm]	5300		
Cladding material	Zircaloy-4		
Outside diameter [mm]	10.90 mm		
Cladding wall thickness [mm]	0.55 mm		
UO_2 pellet density [g·cm^{-3}]	10.60		
Elastic pad for adjusting to the CC	In structural rod		In spacer
Discharge burn-up [MW·d·kg^{-1} U]	5.8		11.1
Refueling frequency [FE·fpd^{-1}]	1.4		0.7

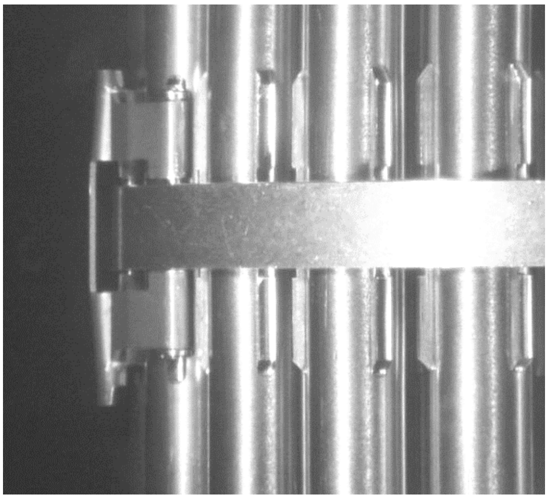

FIG. 3.13. Evaluation of relaxation and wearing *from the visual inspection of the side view of elastic shoes.*

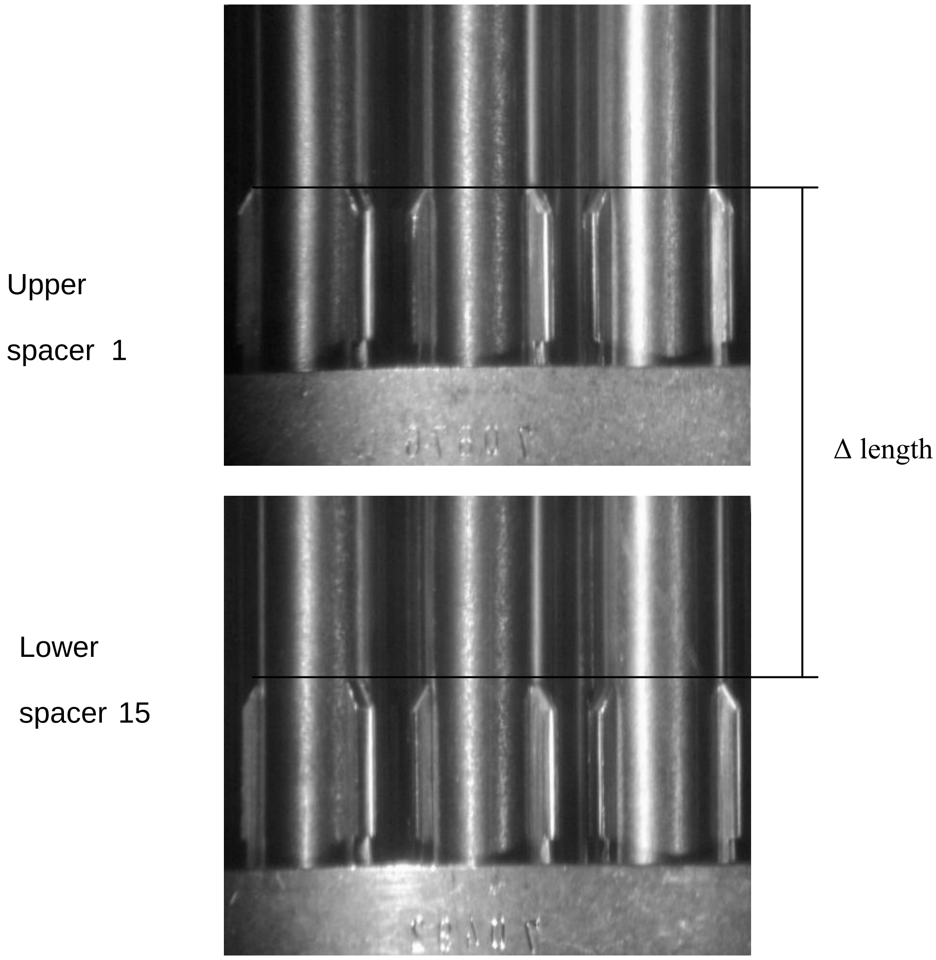

FIG. 3.1.4. Reference level taken at the rigid pads (central rod) from an image of the periscope to measure the rod length. Resolution 0.5 mm.

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