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Computer Analysis of Elongation of the WWER Fuel Rod Claddings

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Key words: WWER fuel rod, computer analysis, changes of the fuel rod length, pellet – cladding mechanical interaction (PCMI), high burnup of fuel.

Presented is the description of mechanisms influencing changes of the WWER fuel cladding length. Axial forces influencing fuel and cladding are described in the presentation. It is shown that shortening of the fuel claddings in case of high burnup can be explained by the change of the fuel and cladding reference state caused by reduction of the fuel rod power level – during reactor outages. It is noted that the presented calculated data are to be reviewed and interpreted as the preliminary results; further work is needed for their confirmation.

This report presents new data on the mechanism causing, in particular, changes of the cladding length of the WWER fuel rods with high burnup. Significance of the fuel rod elongation in the cause of operation is due to the fact that one of the deformation acceptance criterion, used for justification of the fuel rod work ability, is non-exceeding of a certain length value (there is to be a gap between the fuel rod plug and the upper head of the fuel assembly). Correct analysis of the fuel rod elongation also indicates correct consideration of the phenomena taking place in it during operation and improves validity of the predictive calculations and performance of fuel rods.

Let's review change of the fuel rod length in the process of operation and the mechanisms influencing it. Fuel rod #7 of the fuel assembly #222 will be reviewed as an example. This fuel rod operated successfully as part of the core of the Kola 3 reactor unit up to the burnup level of 49.33 MWt×day/kgU [1]. History of this fuel rod was changed for clearness by increase of the operation time by 9%. Burnup of this fuel rod was accordingly increased to 60 MWt×day/kgU.

Subject of Review

Let's review changes of the length caused only by fixing of the fuel rod and start of its operation in the reactor core as part of the fuel assembly. This can be – tension under the influence of spring (if any) holding the pellet column fixed, changes of length under the influence pressure of the coolant and gas inside the cladding (4 components), thermal expansion and elastic tension when interacting with fuel pellets according to the so-called ratcheting mechanism (for example, [2]).

Subject of the further review will be the **irreversible** change of the fuel rod length caused by its stay in the core. Simply speaking by the irreversible change of the fuel rod length we will mean elongation of its cladding after being discharged from the core, i.e. without consideration of thermal expansion and elastic deformations. For the computer analysis it is necessary to assume that in the process of operation fuel swells isotropically proportionally to burnup, thus increasing its diameter and height.

Factors Causing Irreversible Change of the Fuel Rod Length

These are two anisotropic factors:

- Radiation growth. Its influence becomes apparent in elongation of the fuel rod under irradiation of the cladding by the fast neutron flux. Central tube of the fuel assembly grows also. Approximately 30% of the changes of the fuel rod length are caused by this mechanism.
- Creeping of the cladding material.

Change of the length due to creeping takes place within time. Based on its influence this change can be divided into 2 mechanisms. According to the first mechanism it takes place as a result of imposing **axial forces**. These are:

1. tension under the influence of the axial ratchet. It is assumed that it is effective in the initial period of the fuel rod operation, only.
2. compaction due to mutual action of pressure of the coolant and gas inside the cladding.
3. tension due to the fixing spring (if any). These three components are insignificant under high burnup; we shall not take them into consideration for the further review.
4. tension caused by the influence of the fuel column that swells in the process of burnup. This tension starts after coming to the rigid pellet-cladding mechanical interaction (PCMI).

Resultant axial force can be obtained by summing-up these four components. As a result of its action change of the fuel rod length takes place **due to creeping caused by axial forces**.

The second mechanism of the length change due to creeping is determined by the cladding **diameter change**. Irreversible cladding diameter reduction due to creeping under the influence of the coolant pressure takes place before beginning of PCMI. Change of the axial (length) and radial (thickness) deformations takes place due to redistribution of the amount of the cladding material along with the diameter decrease (hoop strains). This is due to the condition of conservation of the amount of material in case of creeping. The cladding properties are such that it gets longer, **when the diameter decreases**. That means that the length of the fuel rod becomes larger.

After beginning of PCMI in the fuel rod section, and after the pellet-cladding contact pressure reaches some “certain” value, change of the length of this section according to the reviewed mechanism becomes different. By “certain” we mean the value at which change of the diameter determined by creeping becomes positive due to mutual action of the contact pressure and coolant pressure. In this case the mechanism described above becomes active, but with the inverse sign. That means that the fuel cladding **irreversibly increases its diameter** and **reduces its length**.

Changes of the Fuel Rod Length

Let’s review changes of the fuel rod length prior to PCMI. Fuel rod gets longer due to radiation growth and creeping of the cladding material, including reduction of the cladding diameter. Detailed situation is presented in the documents of RIAR [3].

PCMI for higher elevations of the fuel rod sections starts at the burnup of 40-45 MWt×day/kgU. After this upon reaching of a certain contact pressure:

- radiation growth continues to increase the length;
- creeping of the cladding material due to the **increase of diameter** (caused by interaction with the fuel that increases its diameter) leads to shortening of the length;
- after stoppage of sliding (due to friction forces between fuel and cladding) fuel contacts the cladding, and while expanding it pulls the cladding in the axial direction, thus increasing the length.

Combination of these three mechanisms determines changes of the length of the fuel rod section.

It is important to note that we stated the possibility of shortening of the length of the WWER fuel rods after beginning of PCMI in our presentation for Albena-2003 [4]. No data of the post-test investigation of fuel rods with the burnup higher than 55 MWt×day/kgU were available then. Then we assumed that the rate of elongation of fuel rods after beginning of PCMI did not get slower, but got faster. That is why in our presentation of the year 2003 we did not directly speak about shortening, we spoke about “slowing down of the elongation rate”.

The first data of the post-test investigation of fuel rods with the burnup of ~ 57 MWt×day/kgU became available in 2004. Burnup level of some fuel rods was as high 65.3 MWt×day/kgU. It is important to note that operational data for 12 fuel assemblies (including the reviewed one) were presented in the Albena-2003 report [4]. In the RIAR presentations for Albena-2005 [5] the data on post-test investigations of fuel rods of this fuel assembly indicate that fuel rods start getting shorter after the burnup gets as high as 50 MWt×day/kgU. Data presented in [5] are presented in fig. 1.

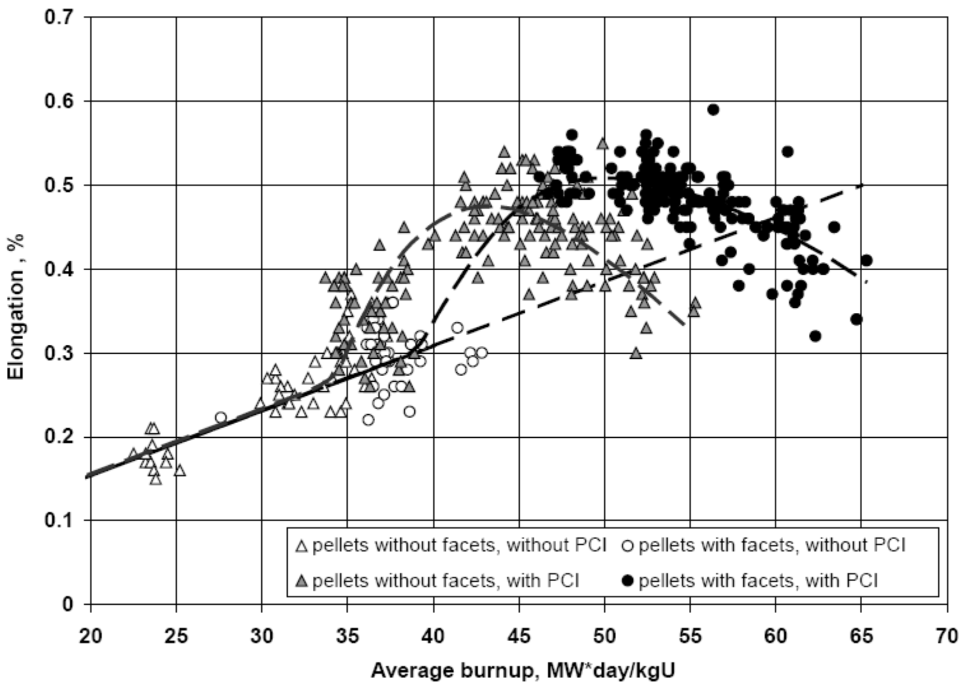

Fig. 1. Change of the Fuel Rod Length as the Function of Average Burnup [5].

Arguments against the Possibility of Shortening of Fuel Rods

Under small contact pressure fuel pellets slip against the cladding. Effective is the growing axial force caused by the friction forces of immobility and sliding. Still, in this case cladding diameter is still decreasing due to the influence of the coolant pressure, and therefore fuel rod gets longer in accordance with the mechanism determined by the diameter reduction. Sliding stops as the contact pressure gets higher. This can be proved by the profilograms presented in the RIAR report [6]. One can see local maximums close to facets, and minimums close to the gap between pellets. Local diameter changes (the so-called "ridges"), the pitch of which is divisible by the length the fuel pellet length (in average – 11-12 mm), appear on the cladding under high burnup. Local decreases of diameter correspond to the joints of fuel pellets; some decrease of the cladding diameter is also seen in the pellet middle part. That means that the fuel is rigidly coupled with the cladding, and no sliding can take place.

Fig. 2. Changes of the Cladding Diameter along the Height [6].

Coupling of the fuel and cladding result in appearing of the axial force that compacts the fuel and expands the cladding. The magnitude, for which the fuel tends to get elongated, is compensated for as the result of action of these elastic forces. Value of the axial force gets larger along with the further swelling of fuel. Increase of the fuel rod length determined by this force due to cladding creep is to prevail over reduction of the fuel rod length due to the increase of the cladding diameter. Fuel is more rigid than the cladding from the standpoint of elastic properties and creeping.

TOPRA-2 code [7] accounts for all the above processes. Axial force model of the TOPRA-2 code is built based on the analysis of the published data of the similar model, developed by K. Lassmann [8].

Let's review calculated results of the changes of the fuel rod length during operation. Fig. 3 presents changes of the fuel rod length versus burnup calculated by TOPRA-2. Elongation for ~4 mm takes place while getting to power first of all due to thermal expansion of the cladding. Later fuel rod elongates irreversibly due to radiation growth creeping of the cladding. Changes of the coolant temperature and linear heat rate contribute to elongation due to thermal expansion.

Contribution of the axial force elastically elongating the cladding, and in case of the long-term action – contribution due to creeping has a stronger influence than the contribution of the diameter increase onto shortening of the cladding.

During discharge of a fuel rod shortening of the elongation takes place due to thermal expansion, as well as elimination of the elastic action of the axial force. Later during release of the coolant pressure some minor elongation takes place. Resultant elongation of the fuel rod is 16.455 mm, i.e. it does not coincide with the expected (according to the data of the post-test investigations) elongation of the fuel rods of such burnup – 9.5 – 12.5 mm.

"New" Mechanism Influencing the Fuel Rod Length

Let's review the influence of the fuel rod operational mode onto the effective axial force. Power histories of fuel rods built with the data of neutronic calculations are usually used in the computer analyses. According to these data fuel rods operate continuously from the very beginning of operation till discharge from the reactor. That means that periods of the reactor operation at lower power levels, as well as reactor outages for reloading and maintenance are not taken into account. Use of such "uninterruptible" power histories leads to discrepancy between the values of the calculated and real axial forces. Loss of rigid contact and sliding of the fuel against the cladding takes place when the linear heat rate falls to the zero level in the axial zones of the fuel rod. In case of a real operational mode of the fuel rod, when its power level gets down (after reloadings, or when the reactor power level is decreased) change of the so-called reference state (state of elevations of the fuel and cladding zones, when rigid contact becomes the reality with no possibility of sliding) can take place. During the next increase of the power level fuel gets into rigid contact with the cladding again, but the zone boundaries in the fuel and cladding will be different.

During operation of the reviewed fuel rod (with consideration of reloadings) more than 15 reductions of the power level (three for the fuel cycle – on the average) took place within the five years of operation. The number of times of the power level change for the fuel rods of Zaporozhskaya NPP with WWER-1000 reactor was even larger. Calculation results for these fuel rods were presented here in 2005 [7,9].

Let's review calculated results for the fuel rod with consideration of the power level reduction. It is assumed that at some certain time moments power level was reduced to the zero value, then the power was raised to the initial level. Temperature of cooling was 20 ^{o}C. Power level was reduced at the time moments when the fuel was in the rigid contact with the cladding. The results indicate that after power reduction and the following increase of it changes occur in the axial force. This is due to the fact that after reduction of the power level fuel "got out" of the contact, and during the following increase of the power it got into the contact again, but with the changed reference state. As a result the axial force (that elongates the cladding and compacts the fuel) gets weaker, and the rate for the cladding elongation slows down. Fig. 3 presents change of the fuel rod length as the function of the average burnup for two calculations – without and with consideration of the power level reduction. It is shown that consideration of the power level reduction leads to less elongation of the fuel rod – from 16.455 mm to 12.675 mm.

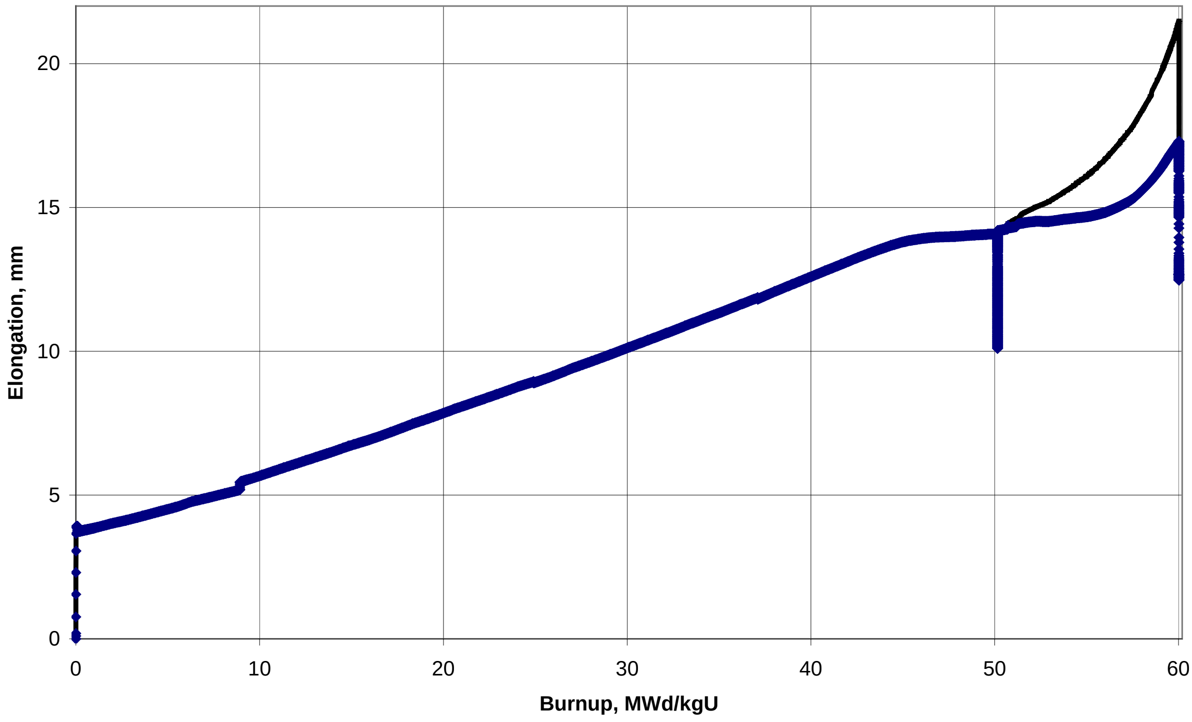

Fig. 3. Change of the Fuel Rod Length versus Burnup.

The option of “complete” force was used in the subroutine of axial forse.

At the same time it is important to account for closing of the gaps between pellets in the fuel column during reduction of the power level. Closing of gaps can also lead to redistribution of the reference states.

Conclusions.

Presented is the description of mechanisms influencing changes of the WWER fuel cladding length. Axial forces influencing fuel (compaction) and cladding (elongation) are described in the presentation. It is shown that shortening of the fuel claddings in case of high burnup can be explained by the change of the fuel and cladding reference state caused by reduction of the fuel rod power level – during reactor outages.

It is to be specially noted that the presented calculated data are to be reviewed and interpreted as the preliminary results; further work is needed for their confirmation. This confirmation is needed from the standpoint of theory (computer analyses and potential corrections of the model accounting for the axial force). Specific analysis of the data of post-test investigations (including the values of elongations of fuel columns in the fuel rods with high burnup) will help improving the results.

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