Power Release Estimation inside of a Fuel Pin Neighbouring a WWER-440 Control Rod

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ABSTRACT

This work presents an estimation of the control rod (CR) influence in the WWER-440 core on the power release inside of a fuel pin neighbouring CR, that can have some consequences due to possible static and cyclic loads, for example fuel pin / fuel assembly bowing. For this purpose detailed (usual) axial power distribution measurements were performed in a WWER-440 type core on the light water, zero-power research reactor LR-0 in fuel pins near to an authentic CR model at zero boron concentration in moderator, modelling the conditions at the end of fuel cycle. To demonstrate the CR influence on power distribution inside of one fuel pin neighbouring CR, results of above measurements were used for estimation of the:

- Axial power distribution inside of the investigated fuel pin in both opposite positions on its pellets surface that are situated to- and outwards CR and corresponding gradient of the (r , z) - power distribution in above opposite positions and
- Azimuthal power distributions on pellet surface of the investigated fuel pin in horizontal planes at selected axial coordinates.

Similar information can be relevant from the viewpoint of the fuel pin failures occurrence investigation.

Keywords
Reactor physics, reactor safety, criticality

1. Introduction

It is well known that control rod (CR) used in the WWER-440 reactors was innovated to suppress neutron flash-up that can case the original CR in adjacent working fuel assembly (FA) as a consequence of the butt joint design of the absorbing adapter (part) to the CR fuel part, that is, presence of the water cavity, the beginning of which is the upper level of steel inserts in FA and the end - in FA cap. In modernized CR the plates of metallic Hafnium are arranged on the inner surface of the jacketed tube in the region of butt joint. The performed calculations showed that in this case the neutron flash-up is prevented completely [1].

According to our information, some NPPs are equipped with this “Hafnium innovation” (e.g., in the Russian Federation) others are operated with original CRs or will use modernized CRs in near future. Most of NPPs is operated with inserted CRs, but in Finnish Loviisa NPP all CRs are at their uppermost position practically during the whole cycle.

Influence of the original CR on power distribution was investigated in a series of works based on computations as well as experiments carried out on research reactors, e.g. [1] - [4]. Furthermore information about this influence provided some NPPs by means of gathered experiences from their operation, in particular concerning probability of the working FAs failure in the CR neighbourhood. For example it was stated in below cited works and comments:

- At Kozloduy NPP [5] the operational practice for the WWER-440 reactors is to keep the 6-th group position between 175 cm and 205 cm in the steady state full power conditions during the fuel cycles, after the end of the boron cycle at 6-th group position about 215 cm. It should be mentioned, the considerable local power peak in the peripheral fuel pins located next to the water cavity, exists during the entire design fuel cycle (as presented by calculations), but the single difference is, that before reaching the boron cycle end the limiting values of linear power density are not exceeded. During the last 8 cycles at Kozloduy NPP Units 3 and 4, 69 leaking assemblies are observed. Seven of them are located next to the regulating CR. This is statistically insignificant number, in order to do any general conclusions. There are two ways to avoid the local power peaking problem. Besides using innovated CR it is to keep the CR at 225 cm during the entire boron cycle. In this case, the withdrawal of the 6-th group up to 250 cm after the boron cycle end will not lead to inadmissible values of the linear power density.
- From total number of leaking assemblies 47 at Bohunice NPP, V-1 (V-230 type) Units 1 and 2 during period 1986 - 2001, in the neighbouring cells 12 FAs were loaded [6]. From this statistic results fact when in the case that assembly is loaded for at least one cycle to the 6-th group neighbouring cell, fuel leak development probability is 2,2 higher compared to rest of assemblies. This is valid also separately for Unit 1 and 2, so there is no difference between these units from this aspect. Providing one fuel rod within leaky assembly during 1986-2001, the average occurrence fuel rod failure rate of 7,98.10-5 have been achieved at V-1 Units. The occurrence frequency at V-2 Units is 3,99.10-6, which is less than PWR reactors worldwide average and this is close to 10-6, which is considered as a “zero failure goal”. Some factors were identified as possible contributors to different frequency of fuel leaks at V-1 and V-2 Units, but the parameter or group of parameters responsible for different frequency of fuel failure is not known until now. It is supposed that such parameters will stay unknown, because the failure phenomenon is caused by other factors, which are not detectable with actual level of instrumentation. Despite of unknown root causes of fuel failure, among corrective actions that were carried out to reduce the frequency of fuel failure, V-1 Units have reduced trends of power changes.

- Relative failure rate per FAs for Novovoronezh Unit 4 up to 01.01.2002 was determined by a sample of FAs surrounding regulating CRs and the rest of FAs [7]: relative failure rates are 0,67 and 0,19, respectively. Increased failure rate for FAs surrounding the regulating CRs is explained by influence of the joint piece between the absorbing part and fuel part of CR on axial power distribution in these FAs. The Technical Specification for safe operation of Novovoronezh Unit 4 that was in force up till 2001, provided the upper limit for regulating CR group movement under normal operating conditions at 200 cm above the core bottom. In this case the joint piece comes to a rather high power area and causes a local power spike in the adjacent peripheral fuel elements of the neighboring working FAs, which is an unfavorable factor for maintaining fuel integrity. In order to reduce the impact of operating factors on fuel failure the upper level for regulating group movement specified by the Technical Specification was increased to 225 cm.
- Below some comments are presented concerning a previously prepared project of the power peaking investigation on reactor LR-0 [8]. According to these comments it is true that in Loviisa NPP there is a considerable power peak in the power distribution in the vicinity of the fuel follower - absorber junction of a VVER-440 CR. In particular, the peripheral fuel rods of the neighbouring fixed FAs may see relatively high power changes when CRs are moved up or down. As a consequence one might expect an increased tendency to PCI-related fuel failures in the fuel rods next to the regulating CR group. This kind of increased failure rate of FAs next to CR has indeed been observed in Loviisa and in other VVER-440 units, too. The conclusion is, however, not straightforward. The power peaking (and resulting power change when CRs moved) is greatest in peripheral rods and dies out rather quickly when going away from the CR. Therefore one might expect that the probability of fuel failure would also be greatest in the peripheral rods. The investigations in Loviisa, however, seem to show no correlation at all between the location in the assembly of the failed rod in relation to the neighbouring CR. Another observation in Loviisa is that the CRs are at their uppermost position practically during the whole cycle. Thus, during the cycle there are no power peaks in the neighbouring fixed assemblies. In spite of this, we can see an increased failure rate in assemblies next to regulating CRs. This observation seems to indicate that CR movements during the first power increase alone are sufficient to cause incipient cracks, which later on develop into fuel failures. To eliminate the PCI failures due to CR movements one should have better knowledge of the PCI failure threshold and of the power distribution near the follower - absorber junction.
- Out of 24 (non-crud) leakers in Loviisa NPP, 10 have developed a leak to a regulating CR [9]; this is significant. In general many leakers have experienced increased power after shuffling. In 6 leakers out of the 10 the failed rods have been identified; none of them are located adjacent to the water cavity. It seems unlikely that fuel failures are caused by local power peaking phenomenon. No leakers have been observed in assemblies with new Zr spacers. Some safety implications of local power peaking in case of normal operation and transient are: (1) Movement of regulating group cause big local power ramps and (2) Lifting of a dropped CRs imposes power ramps on neighbouring FAs and (3) The lifting strategy may require re-evaluation.

More relevant information about CR influence can be found in above cited works. It can be stated, that presented experiences depend on various circumstances, for example differences between units having to do with design, operation parameters and fabrication features as well as core composition (e.g. enrichment, dummy assemblies) and position of CRs during the entire boron cycle, and so on. In connection with possible fuel failure occurrence, design criteria are defined to prevent cladding damage due to static and cyclic loads [10].

It is well known, e.g. [11], [12], that neutron flux non-uniformity, gradients of neutron current, power cycling, speed of linear power increase, time of functioning under big power can represent root causes of the fuel rod / fuel assembly growth and bowing leading to local limitation of coolant flow, reduction of heat transfer, magnifying cladding corrosion and pellet / cladding interaction (PCI). Therefore information about these values in vicinity of CR can be useful in connection with CR influence investigation.

Since detailed power distributions cannot be obtained in the NPP, some needed information are provided by means of experiments on research reactors. In case of measurements inside of fuel pins, special (e.g. track) detectors placed between fuel pellets can be used. Such works are relatively complicated and time consuming, therefore an evaluation method based on mathematical modelling and numerical approximation was proposed by means of that, using measured power release in fuel pins neighbouring CR, information about radial power release inside of one of these fuel pins, can be estimated. For this purpose an experiment on light water, zero-power reactor LR-0 was realized and axial power distribution measurements were performed in a WWER-440 type core in fuel pin positions near to an authentic CR model.

2. Aim of Work

The aim of this work is to provide some information about values and gradients of the power distribution in selected positions on pellet surface of a fuel pin neighbouring CR model in a WWER-440 type core on reactor LR-0.

3. Experimental Arrangement and Conditions

From viewpoint of boron concentration two extreme cases exist that can be investigated. The first one corresponds to the start of fuel cycle with this concentration being highest and the second case - at the end of fuel cycle with zero-boron concentration in moderator, that will be investigated because of availability of needed measured data gathered in the frame of earlier performed CR influence investigations [4].

It is to be noted that CR model on the LR-0 reactor is an “authentic” model, because it is made of original parts of a real CR, but in comparison with the original CR, the sequence of its height arrangement (the fuel, butt joint and absorbing parts) is reverse. It consists of three parts. The lower one contains 2 absorbing segments from the original WWER-440 CR: hexagonal rings with outer diameter of 136 mm, thickness - 6 mm and height - 102 mm with 6 perforations, 1 in the centre of each of their 6 sides (diameter 10 mm). These absorbing segments, made of borated steel (2.0 wt. %), are placed in a stainless steel hexagonal tube (thickness 2 mm). Inside of these 2 absorbing segments a stainless steel tube (outer diameter - 114.5 mm, thickness - 5 mm) is situated which has the following perforations: 6 apertures (60° symmetry) having diameter 10 mm being arranged in the rows with 100 mm distance between them. The upper part of the CR model is a 2.4 % enriched FA, placed in a hexagonal tube (thickness 1.5 mm) made of zirconium alloyed with niobium (2.5 wt.%). Between those two parts there is a butt joint that contains original parts of the WWER-440 CR, too. In Fig. 1 the main parts of the complicated WWER-440 CR model are demonstrated with their positions in this model (identified by corresponding numbers) [13].

A shortened WWER-440 type fuel pins were used having a 1250 mm active fuel (UO2 pellets) length with lower end situated 38 mm from the fuel pin end, excepting the 2.4% enriched fuel pins of the CR model with their active length (UO2 pellets) of 1073.6 mm and containing Zr tubes at their lower part (diameter 7.6 / 6.0 mm, length 56.7 mm, lower end 38 mm from the fuel pin end), continuing with stainless steel cylinder (diameter 7.5 mm, length - 119.7 mm) and finally continuing with active fuel pin part (UO2 pellets). The hexagonal tubes of all FAs (excepting the 2.4 enriched one of CR model mentioned above) are made of aluminium (thickness 2 mm). In all FAs the standard type stainless steel spacing grids (height 10 mm) defining the hexagonal lattice of the fuel pins in CR model and in 12 FAs (denoted by SG-CR and SG-Co in Fig. 4) were used. The vertical (axial) coordinates of the core arrangement are:

- - 38.0 mm - Lower end of the fuel pins of 12 FAs
- 0.0 mm - Lower end of the active fuel part (uranium pellets) of 12 FAs
- 5.5 mm - Bottom of absorber segments at CR model
- 209.5 mm - Top of absorber segments at CR model
- 465.0 mm - Bottom of fuel pins at CR model
- 503.0 mm - Bottom of Zr tubes at fuel pins of CR model
- 559.7 mm - Top of Zr tubes and bottom of stainless steel cylinders in CR mod. fuel pins
- 679.4 mm - Top of stainless steel cylinders and bottom of fuel active part (UO2 pellets) of CR model
- 882.9 mm - Critical height.

The core consists of the CR (model) placed in the core centre, around it - a ring of 6 FAs with fuel pins having 3.6% enrichment except their periphery rows where three pins in all 6 corners have enrichment of 3.0 % and finally next 6 periphery FAs of the same composition around those ones mentioned above. Schematic arrangement of the FAs in the LR-0 core is presented in Fig. 2. The fuel pin position numbering (the same as in [1]) and denotation of the investigated fuel pin position are presented in Fig. 3.

4. Measurement Method and Results of Estimation

The measurements of axial power distribution in fuel pins positions neighbouring CR have been performed by means of gamma activity determination (gamma scanning method) of the irradiated fuel pins detecting gamma quanta in the La peak area - 1596.5 keV of their selected parts having 20 mm length in the axial coordinates range of 50 - 950 mm with 10 mm step using a rectangular collimator (dimensions 20x10 mm). Two NaI(Tl) scintillation crystals (one as a monitor) with diameter of 40 mm were used, each of them in Pb shielding (thickness 150 mm). The measurement process was realized automatically by means of PC connected with stepping motor and CAMAC modules. The fuel pin rotated around its own axis during the gamma scanning.

Using evaluation method mentioned above and power distribution measured in fuel pin positions near to the CR, the following information concerning investigated fuel pin position No 119 (Fig. 3) were obtained:

- Axial power distribution: Values on fuel pellet surface positions to- and outwards CR and corresponding gradient (direction and relative value) of the (r , z) - power distribution on these positions at selected axial coordinates (Fig. 4) and
- Azimuthal power distribution in the above investigated fuel pin: Values on fuel pellet surface at selected axial coordinates 7, 15, …, 80 cm (Fig. 5).

The results demonstrate:

- The situation at the investigated fuel pin neighbouring CR from viewpoint of power distribution on its pellet surface positions to- and outwards CR, i.e. values and corresponding gradients of this distribution are presented and can be compared in both above surface positions

- The possibility to obtain some information concerning the static and cyclic loads and having to do with above root cases of the fuel rod / fuel assembly bowing.

Of course the obtained results have limited information relevance only, because they were determined at special conditions on reactor LR-0. Therefore they can differ from the results in real NPP cores because of their dependence, e.g., on enrichment of both the CR fuel part and neighbouring working FAs, boron concentration, positions of the CR above the core bottom - both actual as well as during the fuel cycle.

5. Conclusions

An evaluation method based on mathematical modelling and numerical approximation was applied by means of that, and using measured axial power distribution in fuel pins near to the CR, the axial power distribution in the investigated fuel pin neighbouring CR was estimated: (1) Values on its pellet surface positions to- and outwards CR and corresponding gradient (direction and relative value) of the (r , z) - power distribution on these surface positions at selected axial coordinates and (2) Azimuthal power distribution on fuel pellet surface at selected axial coordinates. For above purpose an experiment on light water, zero-power reactor LR-0 was realized with WWER-440 type core containing CR. The results demonstrate a possibility to obtain some information concerning the static and cyclic loads and having to do with root cases of the fuel rod / fuel assembly bowing.

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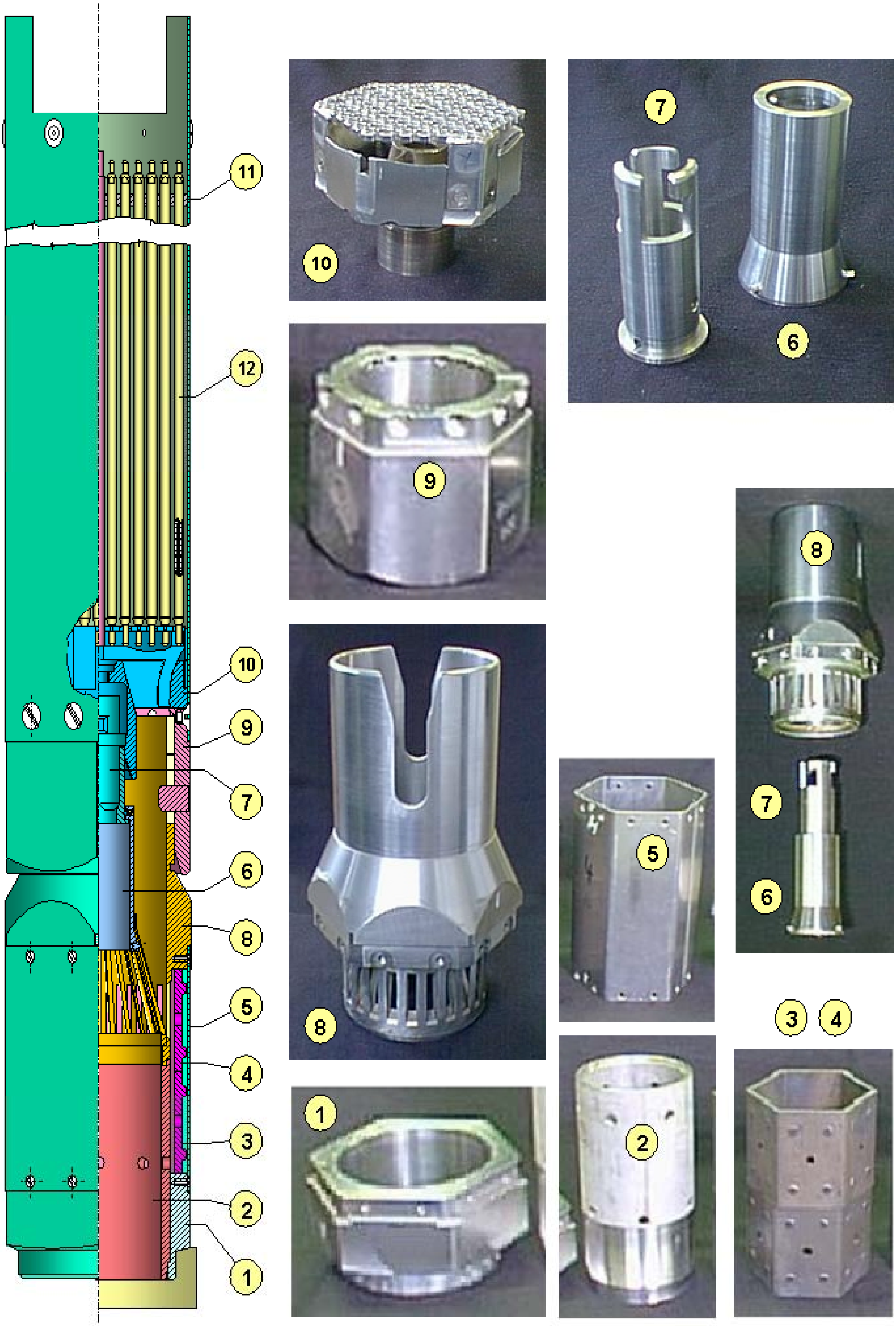

Fig. 1. Main parts of the WWER-440 CR model and their positions in this model

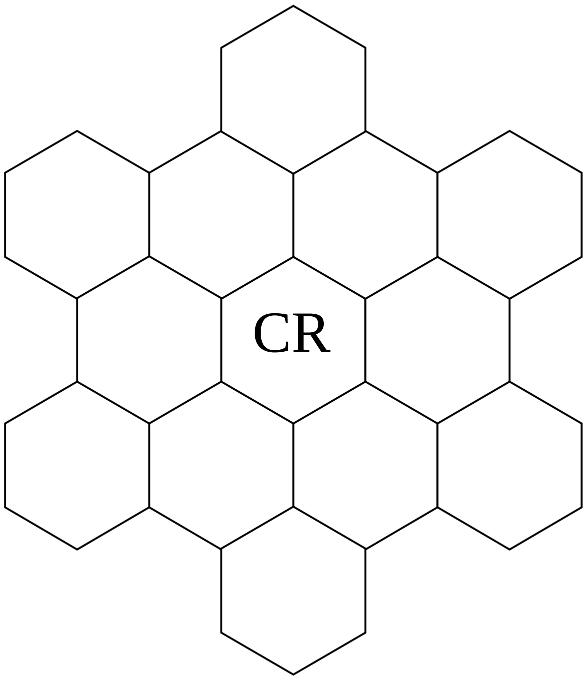

Fig. 2. Schematic arrangement of the LR-0 reactor core with CR (model) in its centre

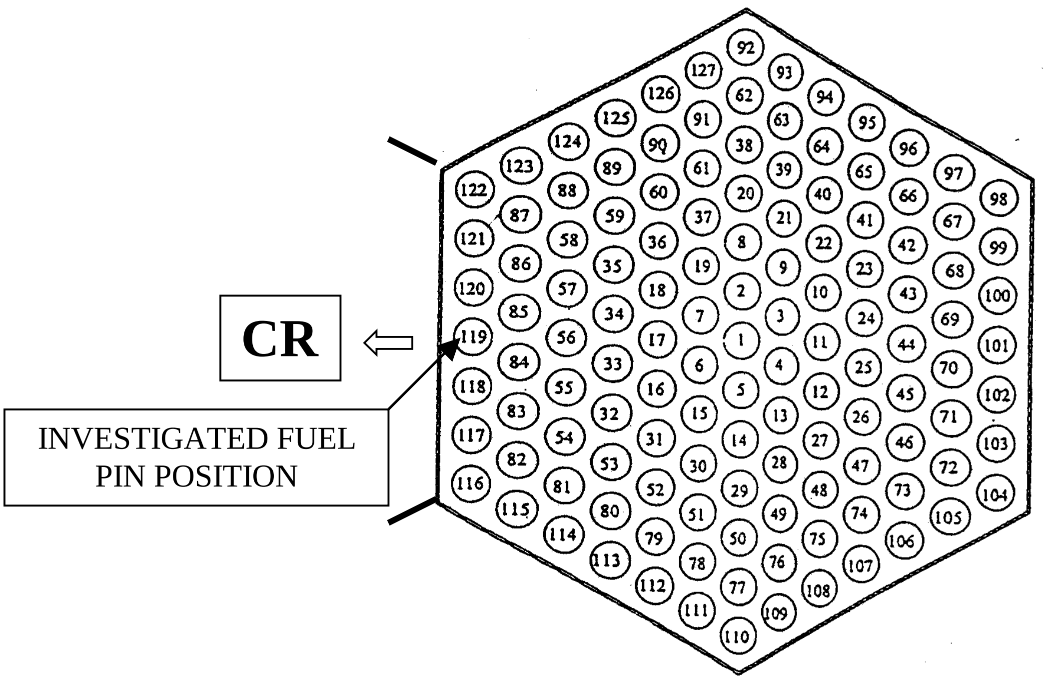

Fig. 3. Fuel pin position numbering in the working FA neighbouring CR (model) and denotation of the investigated fuel pin position

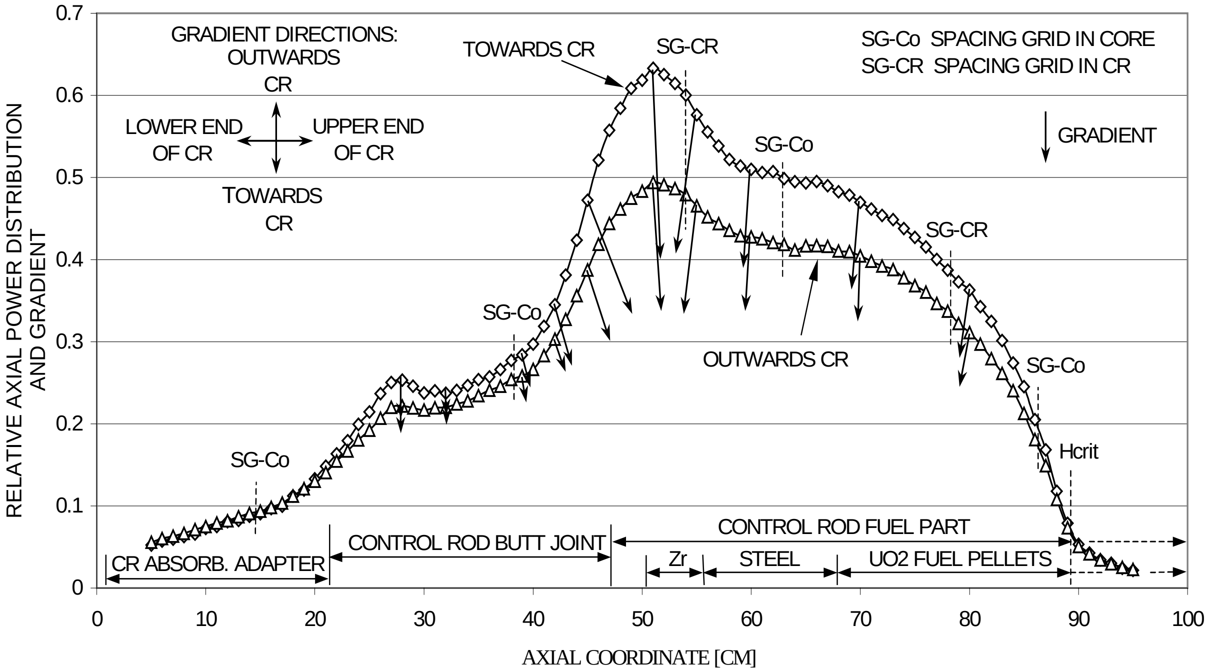

Fig. 4. Axial power distribution in investigated fuel pin position neighbouring CR: Values on the fuel pellet surface positions towards and outwards CR and corresponding gradient (direction and relative value) of the (r , z) - power distribution on above surface positions at selected axial coordinates

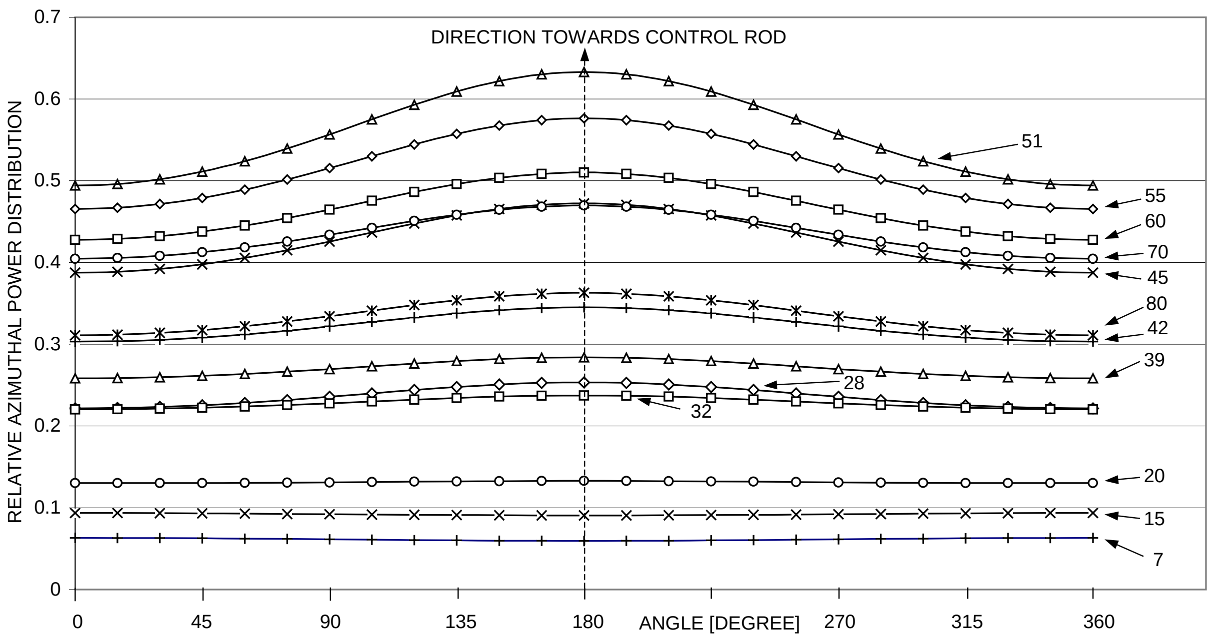

Fig. 5. Azimuthal power distribution in investigated fuel pin position neighbouring CR: Values on the fuel pellet surface at selected axial coordinates 7, 15, …, 80 cm