Fuel Pin Failure Root Causes and Power Distribution Gradients in WWER Cores

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ABSTRACT

The purpose of this work consists in investigation of some core heterogeneities and reactor construction materials influence on space power distribution in WWER type cores, especially from viewpoint of the values and gradient occurrence that could result in static loads with some consequences, e.g., fuel pin (FP) or fuel assembly (FA) bowing and possible contribution to the FP failure root causes. Presented information were obtained by means of experiments on research reactor LR-0 concerning the:

- Power distribution estimation on pellet surface of the FPs neighbouring a FP containing gadolinium (Gd_2O_3) burnable absorber integrated into fuel in WWER-440 and -1000 type cores,
- Power distribution measurement in periphery FAs neighbouring the baffle in WWER-1000 type cores and
- Power distribution in FAs neighbouring the control rod absorbing part in a WWER-440 type core.

Keywords
Reactor physics, reactor safety, criticality

1. Introduction

The LR-0 reactor in the Nuclear Research Institute Rez plc is an experimental facility for the determination of the neutron - physical characteristics of the WWER and PWR type lattices and shielding with UO_2 or MOX fuel. The exploitation of this reactor is determined by the maximum power of 5 kW and maximum thermal flux of 10^{13} $n.m^{-2}.s^{-1}$, atmospheric pressure and room temperature (or heating up to 70°C). The fuel consists of the shortened WWER-1000 and WWER-440 type fuel assemblies (FAs) containing the fuel pins (FPs) with UO_2 pellets (O.D. 7.53 mm, internal central hole 1.4 mm) having a Zr+1%Nb cladding (O.D. 9.15×0.72 mm) with the active length of 1250 mm and enrichment of 1.6 - 4.4 wt.% in ^{235}U. The FAs can be arranged in a reactor vessel of aluminium (diameter 3.5 m, height 6.5 m); the criticality is controlled by moderator level (boron acid with concentration up to12 g/l) and control clusters (B_4C pellets).

The most important applications on LR-0 reactor concern the nuclear safety and economy of the WWER type NPPs operation. In the frame of their modernization, a set of experiments has been performed, e.g., with new type FAs with various burnable absorbers arranged in appropriate configurations and cores of the both WWER-440 and WWER-1000 types including a number of experiments with FAs containing FPs with gadolinium (Gd_2O_3) (Gd FPs) burnable absorber integrated into fuel (e.g. [1] - [3]). Next experiments were devoted to the measurements concerning determination of the power distribution in periphery FAs neighbouring the baffle in WWER-1000 type cores (e.g. [4], [5]) and power distribution in FAs neighbouring the control rod (CR) in WWER-440 type cores [6]. It is well known that presence of Gd FPs in reactor core results in a depression of thermal neutrons in Gd FPs and corresponding gradients in neighbouring FPs. As for the CR absorbing part and baffle influence, thermal neutron gradients can be expected in neighbouring FAs, too. Similar situation can also be stated as for the power release and corresponding temperature.

It is also well known (e.g. [7], [8]), that neutron flux non-uniformity, gradients of the temperature and neutron current can represent root causes of the FP / FA growth and bowing leading to local limitation of coolant flow, reduction of heat transfer, magnifying cladding corrosion and pellet / cladding interaction (PCI). Therefore detailed information about power distribution in periphery FAs neighbouring the baffle in WWER-1000 type cores, in FAs neighbouring CR in WWER-440 type cores and inside of FPs in vicinity of a Gd FP can be useful for above phenomenon investigation. Since such data cannot be obtained in the NPPs, some experiments on research reactors are provided. As for Gd FP influence, measurements inside of neighbouring FPs can be realized by means of special (e.g. track) detectors placed between fuel pellets, but such measurements are relatively complicated and time consuming. On other hand results of usual (integral pin by pin) power distribution measurements can be utilized to determine some information about power release inside of investigated FPs neighbouring a Gd FP. For this purpose an evaluation method based on mathematical modelling and numerical approximation [9] was proposed by means of that, and using above (integral) power release in selected FPs, power release on fuel pellet surface of the investigated FPs can be estimated.

As regards possible fuel failure occurrence, design criteria are defined to prevent cladding damage due to static and cyclic loads in [10]. As for the fuel performance reliability and fuel failure rates and root causes concerning WWER fuel, it was stated in [11]:

An overview on WWER fuel failure root causes identified during 1992 - 2002 shows, that:

- Most frequent cause is damage by debris
- Different from Western PWR fuel experience, fuel-rod-to-spacer-fretting does not play a significant role

- On the other hand there is a very high number of defected fuel where no failure cause is known

In case of the PWR fuel the EPRI evaluation of 2004 on US PWR fuel failure rates shows ([11]):

- After a continuous decrease from 1980 to 2001 there is some increase observed in 2002 and 2003
- The major contributor to fuel failure rates in PWRs remains grid-to-rod fretting
- There is also an increase of fuel failures with unknown root causes that primarily affects optimised fuel designs with a thinner rod diameter.

The above information is in accordance with results concerning examination of 5 WWER-440 and 7 WWER-1000 FAs presented in [12]: causes of failure are debris fretting (54%), local overheating (15%), grid-rod fretting (8%) and “the cause is not determined” (23%).

2. Aim of Work

The aim of this work is providing some information concerning following heterogeneities and reactor construction materials influence on power distribution in WWER type cores, namely the:

- Gd FPs influence on neutron flux non-uniformity in their vicinity by means of the relative azimuthal power distribution estimation on pellet surface of the neighbouring FPs in WWER-440 and -1000 type cores,
- Influence of the baffle on power distribution in neighbouring FAs by means of values in selected FP positions in WWER-1000 type cores and
- Influence of the CR absorbing part on power distribution in neighbouring FAs by means of values in selected FP positions in a WWER-440 type core.

3. Gd FP Influence on Power Distribution in WWER-440 Type Core

3.1. Experimental Arrangement and Conditions

The materials published in [2] were used for this work preparation. Experiment was realized on reactor LR-0 in WWER-440 type core with 19 FAs at zero boron acid concentration, atmospheric pressure and room temperature (Fig. 1).

Power distribution values measured in selected FPs in central FA (CFA) were used in the frame of proposed evaluation method. The CFA contained 120 FPs having enrichment of 3.6% and 6 ones with 3.6 % enrichment and 2% Gd_2O_3 (pellets with O.D. 7.50 mm, internal central hole 1.5 mm), arranged with FP pitch of 12.2 mm. The Gd FPs were arranged in symmetric (equivalent) positions; the 30-degree symmetry sector of CFA is shown in Fig. 2. More information concerning experimental arrangement and conditions are published in [2].

In this connection it should be mentioned, the experiment was realized in 1988 and therefore some technical parameters and the arrangement are different as used at present time. For example as can be seen in Fig. 2 the Gd FPs are situated in 6 equivalent corner positions of the fourth FP row and these positions differ of those ones used in present FAs that are in the corners of the second FP row. Further the above Gd FPs having enrichment of 3.6% ^{235}U / 2% Gd_2O_3 contents also differ of Gd FPs used in NPPs at present time, e.g., in the Czech NPP Dukovany the Gd FPs have enrichment of 4.0% or 4.6% ^{235}U / 3.35% Gd_2O_3 contents [13].

3.2. Results

Using proposed evaluation method mentioned above and power distribution measured in selected FPs in the CFA the following information concerning 4 investigated FPs (Fig. 2) were obtained:

- Estimation of the relative power distribution values on fuel pellet surface in 12 positions with step of 30° (Fig. 3)
- Influence of the Gd FP on power release on pellet surface of neighbouring FPs, in particular, the depression corresponding the ratio of the values to- and outwards Gd FP. The maximum depression, i.e., minimum above ratio of 48.7% was stated in Pos. 4.

4. Influence of the CR Absorbing Part on Power Distribution in Neighbouring FAs in WWER-440 Type Core

4.1. Experimental Arrangement and Conditions

Experiment was realized on reactor LR-0 in WWER-440 type core containing 19 FAs at 4.83 g/l boron acid concentration, atmospheric pressure and room temperature with CR situated in position of the central FA (CFA) and following enrichment of the FAs: A - 2.0%, B - 4.4% and remaining 16 FAs - 3.6% (Figs. 1, 4). The materials published in [6] were used for this work preparation.

4.2. Results

Influence of the CR absorbing part on power distribution is illustrated by means of the values in selected positions in two FAs neighbouring CR, and situated between CR and FAs A and B (Fig. 5). The presented results demonstrate the depression given by the ratio of the power release values corresponding opposite FPs in both FAs to- and outwards the CR. The depression, i.e., the above ratio of 67.0% and 67.6% can be stated in FAs between CR and FA A and B, respectively.

5. Gd FP Influence on Power Distribution in WWER-1000 Type Core

5.1. Experimental Arrangement and Conditions

The materials published in [1] and [3] were used for this work preparation. Experiment was realized on reactor LR-0 at zero boron acid concentration, atmospheric pressure and room temperature in a WWER-1000 type core consisting 7 FAs (Fig. 6), each containing 312 FPs with 4.4% enrichment, whereas 18 FPs in central FA (CFA) were replaced by FPs with 3.6% enrichment containing 2% Gd_2O_3 (Gd FP pellets with O.D. 7.50 mm, int. centr. hole 1.5 mm), arranged with FP pitch of 12.75 mm. Power distribution values measured in selected FPs in central FA were used in the frame of proposed evaluation method. The 30-degree symmetry sector of CFA containing 10 investigated FPs neighbouring 3 Gd FPs is shown in Fig. 7. More information concerning experimental arrangement and conditions is in [1] and [3]. In this connection it should be mentioned, the experiment was realized in 1990 and therefore some technical parameters and the CFA arrangement are different as used at present time, especially higher both the FPs enrichment and Gd_2O_3 contents.

5.2. Results

Using proposed evaluation method mentioned above and power distribution measured in selected FPs in the CFA the following information concerning 10 investigated FPs (Fig. 7) were obtained:

- Estimation of the relative power distribution values on fuel pellet surface in 12 positions with step of 30° (Figs. 8a-c)
- Influence of the Gd FP on power release on pellet surface of neighbouring FPs, in particular, the depression corresponding the ratio of the values to- and outwards Gd FP. The maximum depression, i.e., minimum above ratio of 46.8% was stated in Pos. 4.

6. Influence of the Baffle in WWER-1000 Type Cores on Power Distribution in Neighbouring FAs

6.1. Experimental Arrangement and Conditions

A 60-degree symmetry sector of WWER-1000 mock-up in radial direction was realized in the LR-0 reactor at 6.37 g/l boron acid concentration, atmospheric pressure and room temperature (Figs. 9, 10). This mock-up represents the core periphery and radial shielding heterogeneities of the WWER-1000. The core loading was chosen to imitate neutron source in R - θ geometry with following FAs No. / enrichment: 7 FAs No. 2, 3, 4, 5, 6, 7, 13 / 4.4%, 8 FAs No. 1, 8, 9, 11, 15, 17, 27, 31 / 3.6%, 6 FAs No. 10, 16, 25, 29, 30, 32 / 3.0%, 2 FAs No. 12, 14 / 3.3% and 9 FAs No. 18, 19, 20, 21, 22, 23, 24 26, 28 / 2.0% (more in [4]). The materials published in [4] and [5] were used for this work preparation.

6.2. Results

Influence of the baffle was investigated by means of power distribution measurements carried out in neighbouring FAs No. 2 and 3 in 84 FP positions and in FAs No. 4 and 13 in all 312 positions. Obtained results are illustrated by means of values in selected FP positions in FA No. 4 (Fig. 11). The presented results demonstrate the depression given by the ratio of the power distribution mean values corresponding 2 opposite FP rows in FA No. 4 to- and outwards the baffle. The depression, i.e., the above ratio of 32.0% can be stated.

It can be mentioned next measurements described in [5] were performed at 4.6 g/l boron acid concentration and in a different core composition as mentioned in point 6.1 above, i.e., with following FAs No. / enrichment: 2 FAs No. 9, 17 / 3.3%, 6 FAs No. 18, 24, 25, 29, 30, 32 / 3.0% and remaining 24 FAs (including FA No. 4) with 2.0% enrichment (more information in [5]). Power distribution measurements carried out in FA No. 4 [5] were not so detailed as in [4], but obtained results (and taking into account detailed calculations in [5]) enable following conclusion: depression, i.e., the above ratio of about 19% can be expected in this case of baffle influence.

7. Discussion

The obtained Gd FP influence is practically the same in both investigated WWER-440 and -1000 type cores: the power release on opposite pellet surface positions to- and outwards Gd FP differs more than 2 times. On other hand this result should be compared with measurements and / or calculations based on more sophisticated methods, because above obtained power release difference seems to be too high. Of course, presented results have limited information relevance only, because they were determined on the basis of experiments realized on reactor LR-0 in 1988 - 90 at special conditions as mentioned above. Therefore they can differ from the results determined by means of the data from real NPP cores because of their dependence, e.g., on enrichment and dimensions of the (Gd) FPs, Gd_2O_3 contents, FP pitch and Gd FPs positions in FA, boron acid concentration, temperature, pressure, etc. Especially it is to be noted, higher depressions on pellet surface can be expected in FAs used at present time because of higher Gd_2O_3 contents in Gd FPs.

As for the baffle influence the situation concerned relevance of the presented results is similar as in case of Gd FPs. On other hand it can be expected less baffle influence in case of a core with real WWER-1000 dimension because of less dimension of LR-0 core used for WWER-1000 mock-up investigation and periphery position of FA No. 4.

Finally similar relevance of obtained information as above can be stated for CR absorbing part influence, too. Because of less dimension of LR-0 core as in real WWER-440 and due to central position of CR in this relative small core, the influence in a core with real WWER-440 dimension can be expected to be higher.

8. Conclusions

Using measured (integral) power release in selected FPs in WWER-440 and -1000 type cores on reactor LR-0, an evaluation method based on mathematical modelling and numerical approximation was applied for gadolinium influence investigation, i.e., for estimation of the relative azimuthal power distribution on pellet surface of the FPs neighbouring a FP with 3.6% enrichment containing 2% Gd_2O_3. In both investigated WWER-440 and -1000 type cores (enrichment of 3.6% and 4.4%, respectively) the power release on opposite pellet surface positions to- and outwards Gd FP differs more than 2 times, with maximum obtained power distribution depression of 48.7% and 46.8%, respectively.

In WWER-1000 type core on reactor LR-0 the influence of the baffle on power distribution in neighbouring FA was investigated. The power release depression of 32.0% was estimated, given by the ratio of the power distribution mean values in 2 opposite FP rows to- and outwards baffle. Measurements in a next WWER-1000 type core show, that depression of about 19% can be expected.

In WWER-440 type core on reactor LR-0 the influence of the CR absorbing part on power distribution in 2 neighbouring FAs was investigated. The depressions of 67.0% and 67.6% were estimated, given by the ratio of the power release values corresponding opposite FPs in above FAs to- and outwards the CR.

The results demonstrate a possibility obtaining some information for the temperature gradients and resulting loads estimation in FPs neighbouring Gd FPs and in FAs neighbouring the baffle and CR absorbing part to consider possible contributions of these loads to the FP failure root causes.

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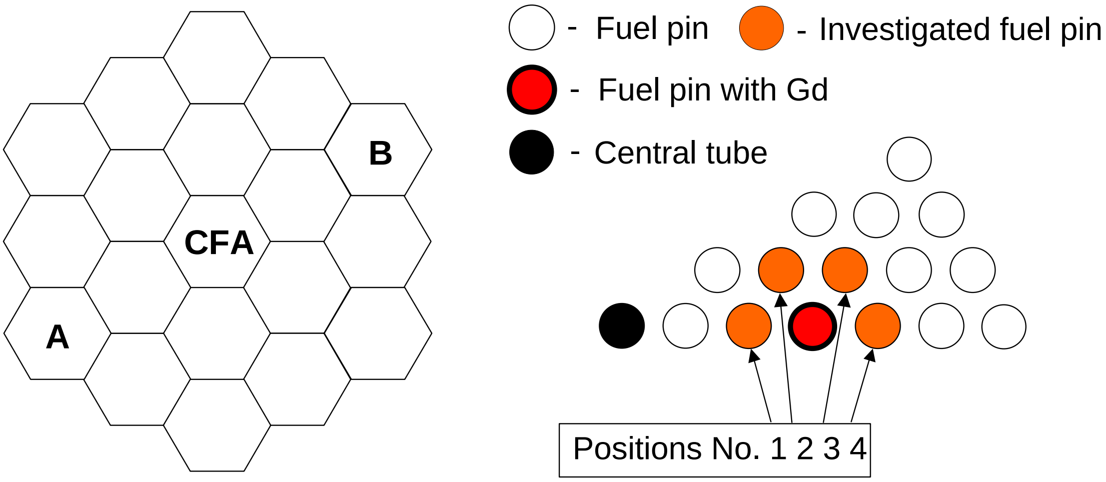

Figure 1 and 2. Schematic arrangement of the LR-0 reactor core containing 19 WWER-440 type FAs (3.6% enrichment) with central FA (CFA) for Gd FP influence investigation (Fig. 1 - left) (FAs A and B - see the CR influence below) and the 30-degree symmetry sector of CFA with 4 investigated FPs neighbouring Gd FP (Fig. 2 - right)

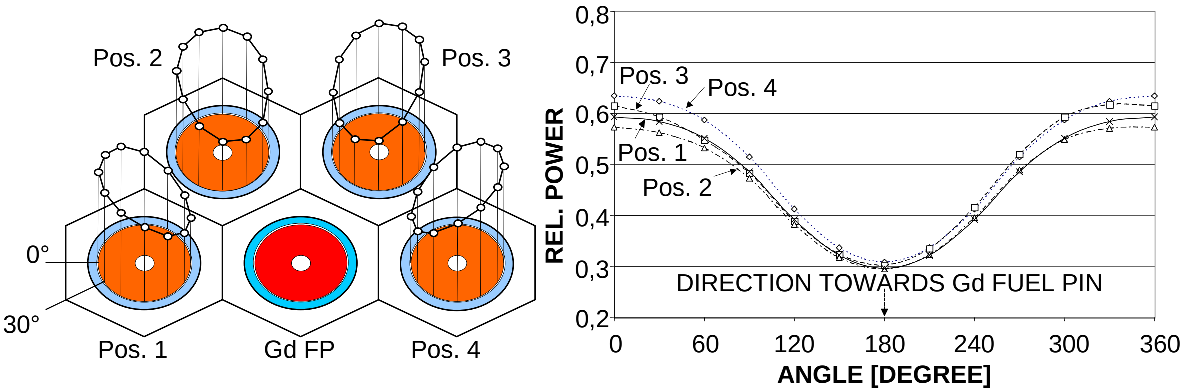

Figure 3. Relative azimuthal power distribution values in 12 positions on pellet surface of 4 investigated FPs neighbouring Gd FPs (see Fig. 2) - the first value outwards Gd FP and next 11 ones with step of 30° in positive direction (see FP Pos. 1). Joining lines serve only as eye guides.

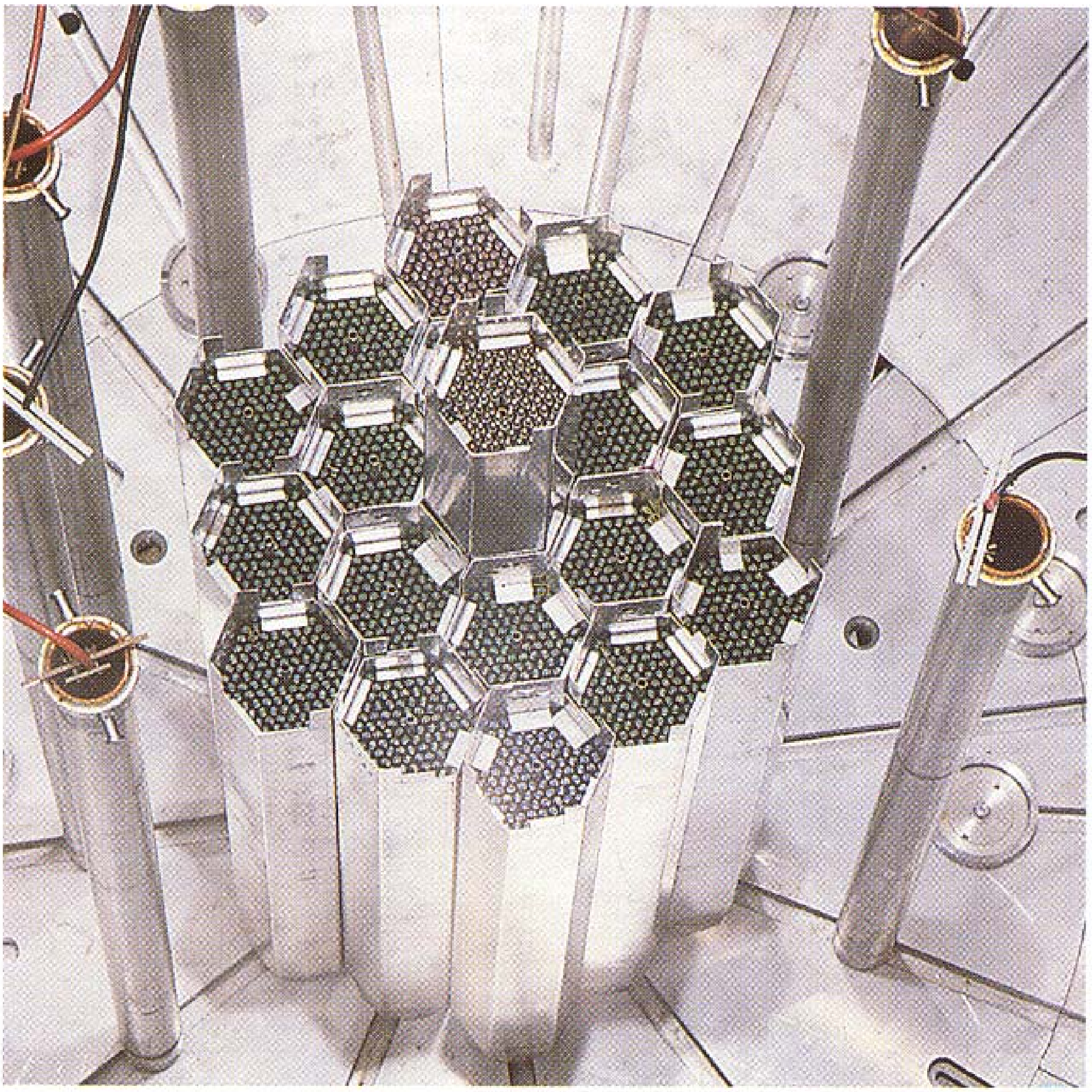

Figure 4. Core arrangement with CR on reactor LR-0

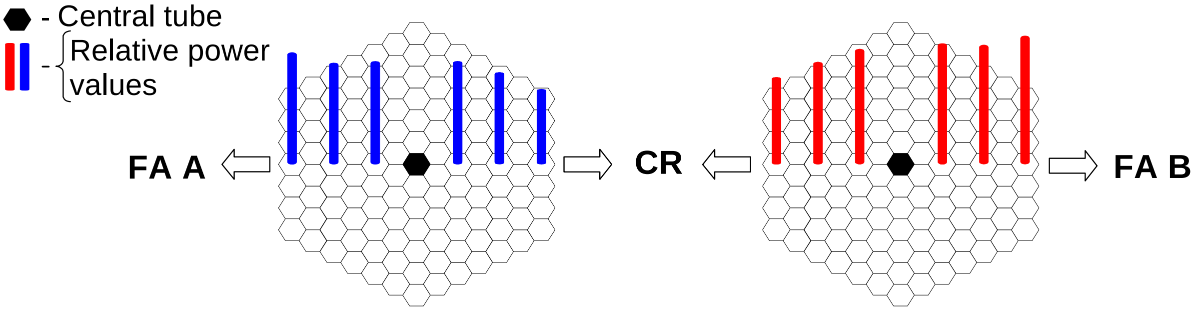

Figure 5. Power distribution values in selected FP positions in two FAs neighbouring CR

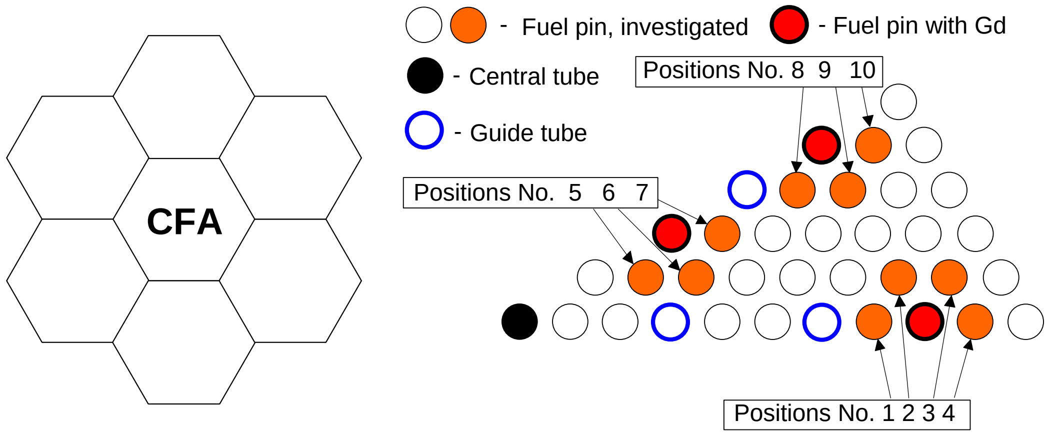

Figure 6 and 7. Schematic arrangement of the LR-0 reactor core containing 7 WWER-1000 type FAs with central FA (CFA) for Gd FP influence investigation (Fig. 6 - left) and the 30-degree symmetry sector of the CFA with 10 investigated FPs neighbouring 3 Gd FPs (Fig. 7 - right)

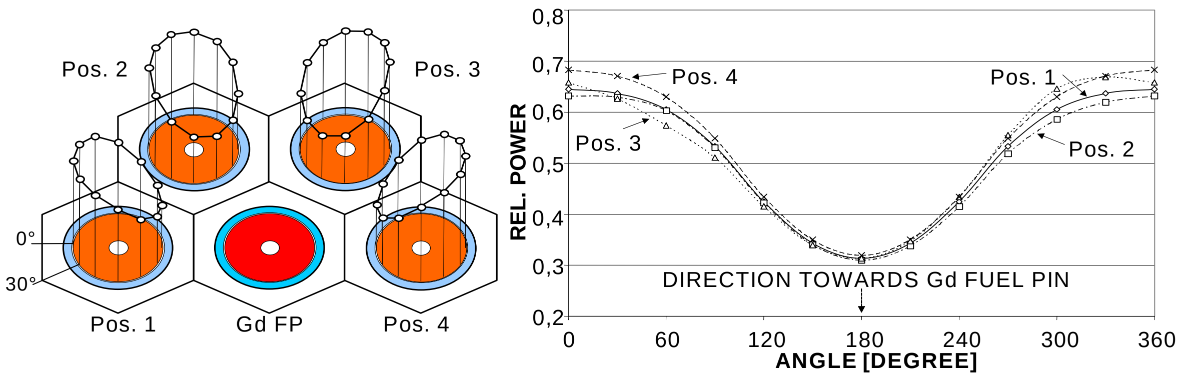

Figure 8a. Relative azimuthal power distribution values in 12 positions on pellet surface of 4 (Fig. 8a) and 3 (Figs. 8b, c) investigated FPs neighbouring 3 Gd FPs (see Fig. 7) - the first value outwards Gd FP and next 11 ones with step of 30° in positive direction (see FP Pos. 1). Joining lines serve only as eye guides.

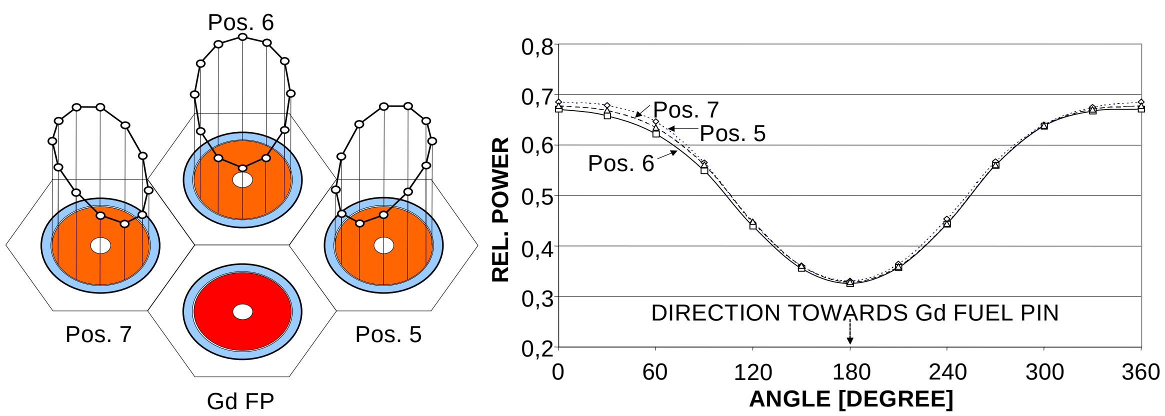

Figure 8b. See text concerning Fig. 8a above

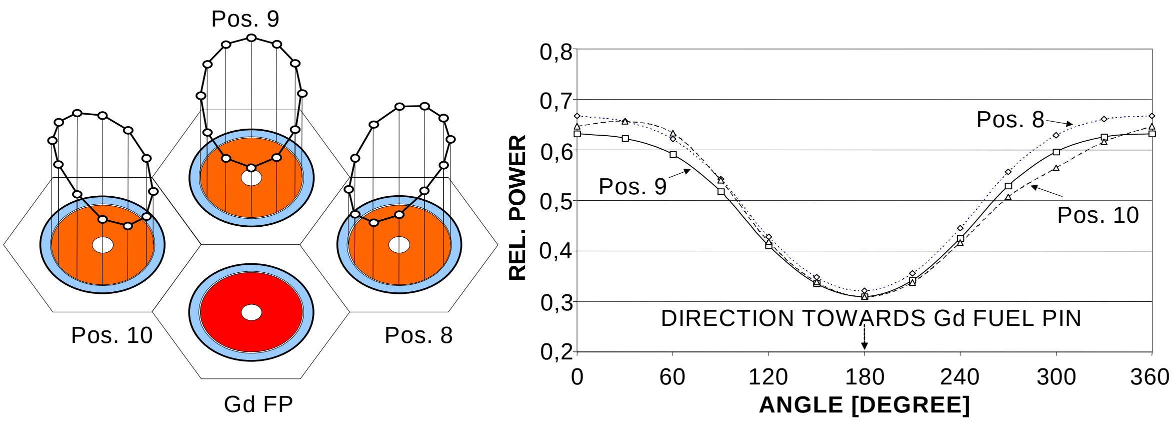

Figure 8c. See text concerning Fig. 8a above

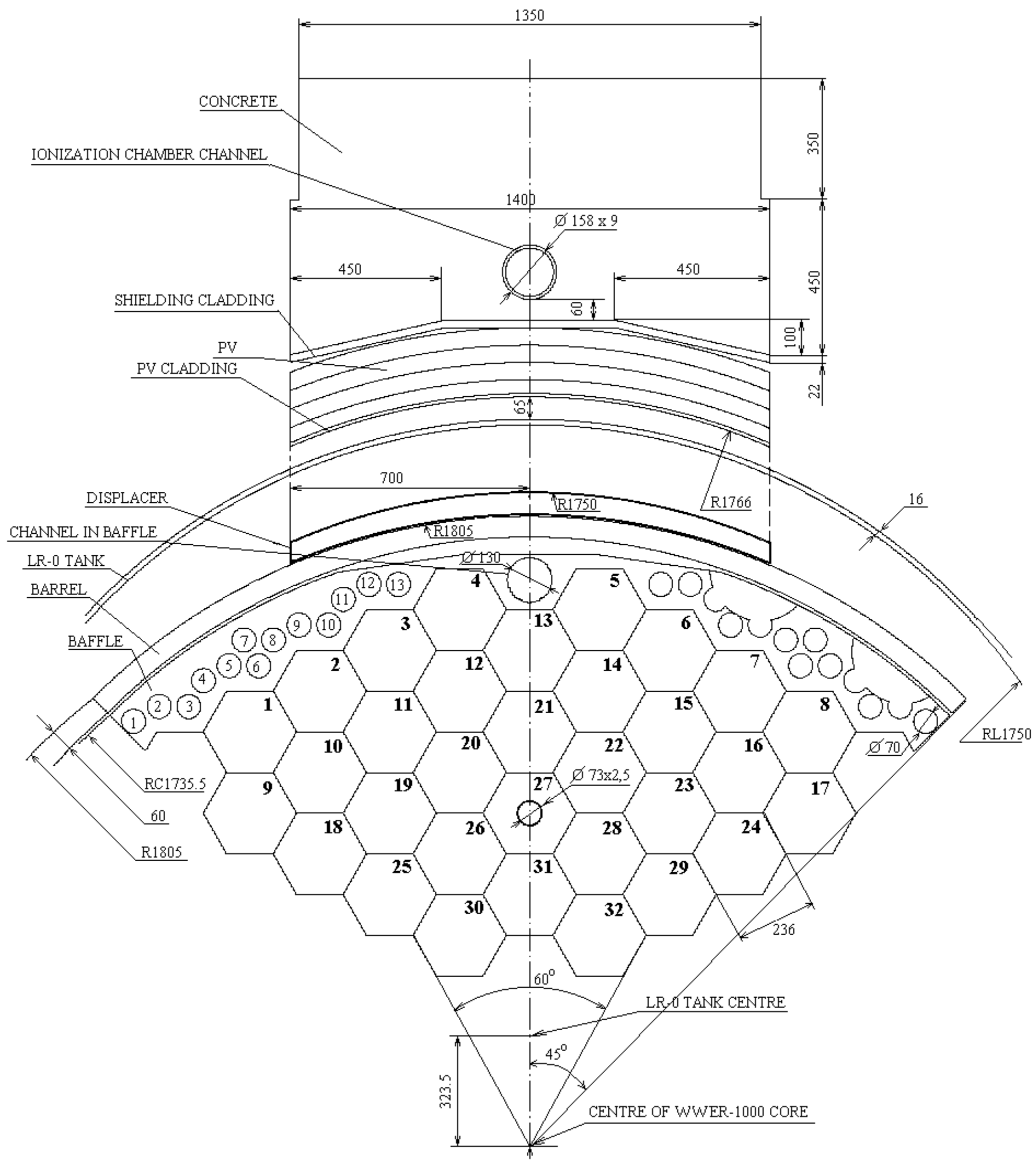

Figure 9. The section of the mock-up by the XY plane

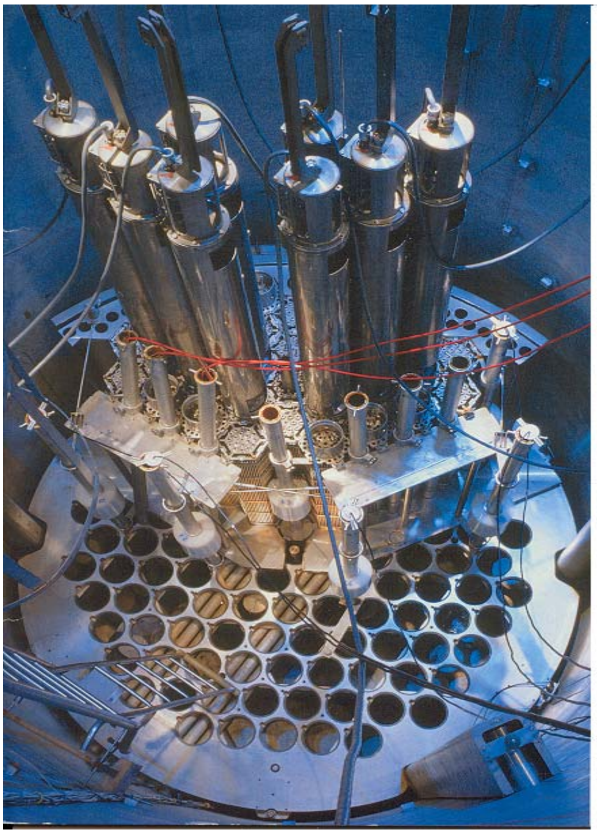

Figure 10. WWER-1000 mock-up general view on reactor LR-0

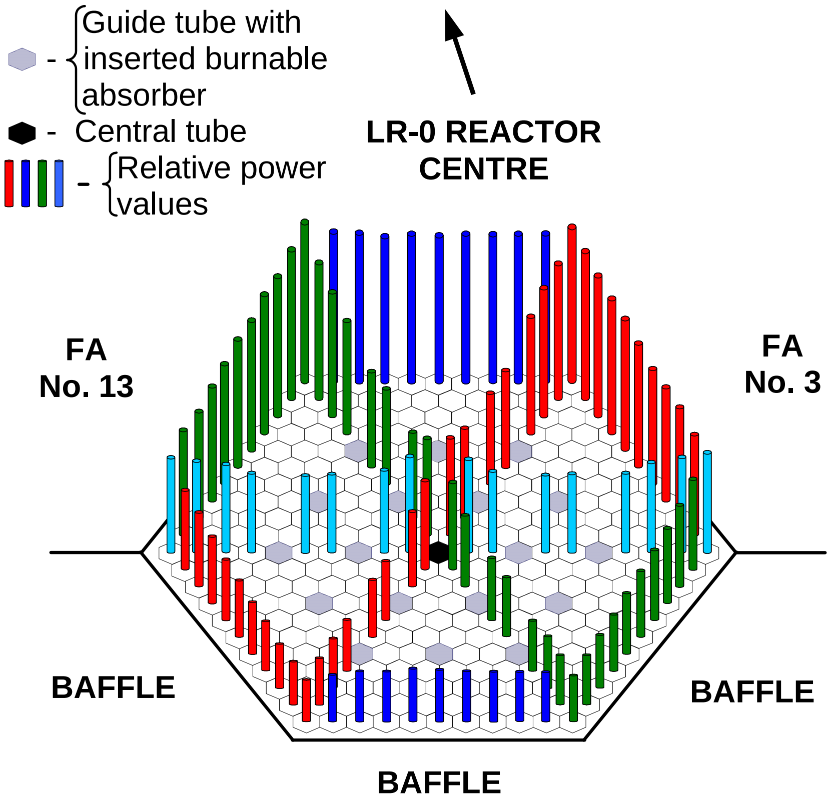

Figure 11. Power distribution values in selected FP positions in FA No. 4