Power Distribution Gradients and Fuel Pin Failure Root Causes in WWER-1000 Cores

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ABSTRACT

The purpose of this work consists in the influence investigation of some heterogeneities and construction materials on space power distribution in WWER-1000 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. Since detailed power distribution cannot be obtained in nuclear power plants, needed information is provided by means of experiments on research reactors – in this case on LR-0. Two cases were investigated concerning the:

1. Power distribution inside of FPs neighbouring a FP containing gadolinium (Gd₂O₃) burnable absorber integrated into fuel. For this purpose an evaluation method based on mathematical modelling and numerical approximation was proposed by means of that, and using measured (integral) power release in selected fuel pins, some information about power release inside of needed (investigated) fuel pin can be obtained. Application of this method is demonstrated on investigated FPs neighbouring a FP with gadolinium by means of the relative azimuthal power distribution estimation on their pellet surface in horizontal plane and

2. Power distribution in FAs situated on the periphery of the WWER-1000 type cores, neighbouring the baffle (thermal shielding).

Similar information can be used for code validation and FP failure occurrence investigation.

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 UO₂ or MOX fuel. The exploitation of this facility is determined by the maximum power of 5 kW and maximum thermal neutron flux density of 10¹³ 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 UO₂ 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 ²³⁵U. 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 to 12 g/l) and control clusters (B₄C 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 on the LR-0 reactor, 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 Gd (Gd FPs) integrated into fuel (e.g. [1], [2]). 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. [3], [4]). 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 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. [5], [6]), 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 and inside of FPs in vicinity of the 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 the power release inside of FPs. For this purpose an evaluation method based on mathematical modelling and numerical approximation [7] was proposed by means of that, and using above (integral) power release in selected FPs, some information about power release on pellet surface of the investigated FP can be obtained.

As for the fuel performance reliability and fuel failure rates and root causes concerning WWER fuel, it was stated [8]:

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 [8]:

- 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 [9]: 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 above heterogeneities and construction materials influence on power distribution in WWER-1000 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 a WWER-1000 type core and
- Influence of the baffle on power distribution in neighbouring FA by means of values in selected FP positions in two WWER-1000 type cores.

3 GD FP INFLUENCE ON POWER DISTRIBUTION IN WWER-1000 TYPE CORE

3.1 Experimental Arrangement and Conditions

The materials published in [1] and [2] 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. 1 - left), 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$_2$O$_3$ (Gd FP pellets with O.D. 7.50 mm, int. central 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. 1 - right. More information concerning experimental arrangement and conditions can be find in [1] and [2]. 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$_2$O$_3$ contents.

Figure 1: Schematic arrangement of the LR-0 reactor core containing 7 WWER-1000 type FAs with central FA (CFA) for Gd FP influence investigation (left) and the 30-degree symmetry sector of the CFA with 10 investigated FPs in positions neighbouring 3 Gd FPs (right)
3.2 Results

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

- Estimation of the relative power distribution values on fuel pellet surface in 12 positions with step of 30° (Figs. 2a-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.

Figure 2a: Relative azimuthal power distribution values in 12 positions on pellet surface of four (Fig. 2a) and three (Figs. 2b, c) investigated FPs neighbouring three Gd FPs (see Fig. 1) - 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 2b: See text concerning Fig. 2a above

Figure 2c: See text concerning Fig. 2a above
4 INFLUENCE OF THE BAFFLE IN WWER-1000 TYPE CORE ON POWER DISTRIBUTION IN NEIGHBOURING FA

4.1 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. 3, 4).

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 [3]). The materials published in [3] and [4] were used for this work preparation.

Figure 3: The section of the mock-up by the XY plane
4.2 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 [3]. Obtained results are illustrated by means of values in selected FP positions in FA No. 4 (Fig. 5).

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 [4] were performed at 4.6 g/l boron acid concentration and in a different core composition as mentioned in point 4.1 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 with 2.0% enrichment (more information in [4]). Power distribution measurements carried out in FA No. 4 were not so systematic and detailed as in [3] - they are presented in Fig. 6 - left. These experimental results were completed by calculation carried out in all 312 FA positions ([4]). They are illustrated by values in selected FP positions in Fig. 6 - right (for easy comparison with experimental results presented in Fig. 5, the same FP positions were selected). Obtained experimental and calculation results enable following conclusion: the depression, i.e., the above ratio of about 19% can be expected in this case of baffle influence.

5 DISCUSSION

As for gadolinium influence, the obtained power release on opposite pellet surface positions to- and outwards Gd FP differs about 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. Presented result has
limited information relevance, because the experiment was realized in 1990 at special conditions as mentioned above and therefore it can differ from the results determined by means of the data from real NPP cores because of dependence, e.g., on enrichment and dimensions of the (Gd) FPs, Gd₂O₃ contents, FP pitch and Gd FPs positions in FA, boron acid concentration, temperature, pressure, etc.

As for the baffle influence it can be expected less influence in a core with real WWER-1000 dimension because of less dimension of LR-0 core used for investigation and periphery position of FA No. 4.

![Diagram](image)

**Figure 6:** Experimental (left) and calculation (right) power distribution values in selected FP positions in FA No. 4 ([4])

6 CONCLUSIONS

Using measured (integral) power release in selected FPs in WWER-1000 type core 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% Gd₂O₃. In investigated WWER-1000 type core with 4.4% enrichment the power release on opposite pellet surface positions to- and outwards Gd FP differs about 2 times, with maximum obtained power distribution depression of 46.8%.

In two WWER-1000 type cores on reactor LR-0 the influence of the baffle on power distribution in neighbouring FA was investigated. The power release depression of 32.0% and about 19% was estimated, given by the ratio of the power distribution (mean) values in 2 opposite FP rows to- and outwards the baffle.

The above results can be used for code validation and obtaining some information concerning temperature gradients and resulting loads estimation in FPs neighbouring Gd FP and in FAs neighbouring the baffle to consider possible contributions of these loads to the FP failure root causes.
REFERENCES


