EFFECT OF BURNUP HISTORY BY MODERATOR DENSITY ON NEUTRON-PHYSICAL CHARACTERISTICS OF WWER-1000 CORE

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ABSTRACT

Results of assessment of burnup history effect by moderator density on neutron physical characteristics of WWER-1000 core are presented on example of stationary fuel loading with Russian design FA TWSA and AER benchmark for Khmelnitsky NPP that was proposed by TUV and SSTC NRC at 19th symposium. Assessment was performed by DYN3D code and cross section library sets generated by HELIOS code.

Burnup history was taken into account by preparing of numerous cross section sets with different isotopic composition each of which was obtained by burning under different moderator density. For analysis of history effect 20 cross section sets were prepared for each FA corresponded to each of 20 axial layers of reactor core model for DYN3D code. Four fuel cycles were modeled both for stationary fuel loading with TWSA and AER benchmark for Khmelnitsky NPP to obtain steady value of error due to neglect of burnup history effect.

Main attention of study was paid to effect of burnup history by moderator density to axial power distribution. Results of study for AER benchmark were compared with experimental values of axial power distribution for FAs of 1st, 2nd, 3rd and 4th year operation.

The work was performed in framework of orders BMU SR 2511 and BMU R0801504 (SR2611). The report describes the opinion and view of the contractor – SSTC N&RS - and does not necessarily represent the opinion of the ordering party - BMU-BfS/GRS and TÜV SÜD.

INTRODUCTION

Moderator density in axial direction of core is changed due to coolant heating. Change of moderator density has valuable effect on neutron spectrum and, accordingly, on nuclide concentration during fuel burning. Therefore cross section will be differed and this difference will be increase with growing of fuel burnup. Neglect of this effect during preparation of cross section library and macro calculation of reactor core leads to additional component of error of neutron-physical characteristics of core, first at all such parameter as linear power distribution in axial direction.

Main goal of this work – assessment of effect of burnup history by moderator density on neutron physical characteristics of WWER-1000 core on example of stationary fuel loading with Russian design FA TWSA and AER benchmark for Khmelnitsky NPP, that was proposed by TUV and SSTC NRC at 19th symposium [2].

REALIZATION

Change of moderator density has valuable effect on neutron spectrum and, accordingly, on change of nuclide concentration during fuel burnup and multiplying properties of fuel cell. Change of ^{239}Pu concentration makes a most valuable impact on multiplying properties in presented case. The change of ^{239}Pu concentration can exceed 10% at burnup 50-60MW*d/kgHM for FA 398GO (Fig. 1) and difference in multiplication factor is achieved up to ΔKinf=0.026 (Fig. 2) under calculation of fuel burnup with moderator density from 0.68 up to 0.76g/cm^3. Such range of moderator density is typical for WWER-1000 at rated level of power from bottom to upper part of core. Fig. 2 follows that increase of multiplying properties in upper part of reactor core is to be expect with taking into account effect of burnup history by moderator density.

Analyzing an obtained set of libraries, a close to linear dependence of 2 group cross section on moderator density under which fuel was burned should be noted. This factor can be used for more comfortable and rational accounting of historical effect of moderator density for cross section library preparation, namely by introducing of some linear coefficient in parameterization dependence of cross section.

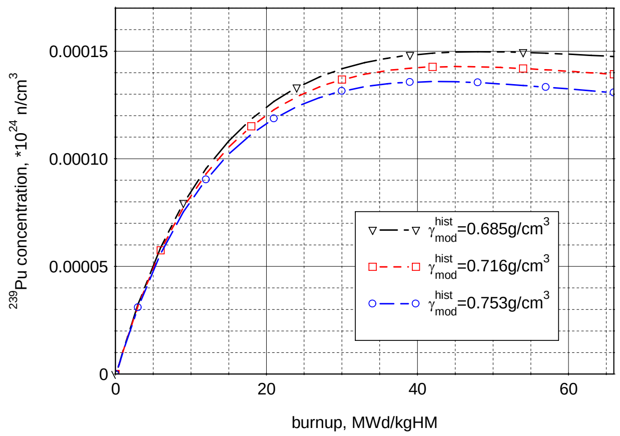

Fig. 1 – ^{239}Pu concentration under different moderator density burnup history for FA 398GO

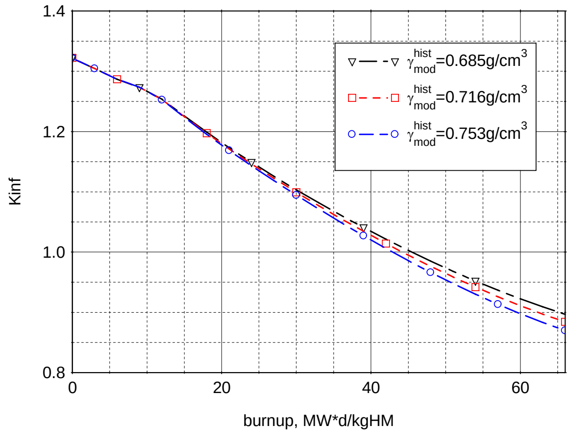

Fig. 2 – Multiplication factor for FA 398GO under different moderator density burnup history

It should be noted that cross section dependence on ^{239}Pu concentration also is close to linear in a range of change burnup history of moderator density from 0.68 up to 0.76g/cm^3. So introducing of some additional coefficients in parameterization dependence vs ^{239}Pu concentration is also acceptable and moreover reasonable due to possibility of accounting rest of reactor core parameter under which isotope concentration were calculated during preparing of cross section library (first at all – fuel temperature and also boron acid concentration and moderator temperature) [4].

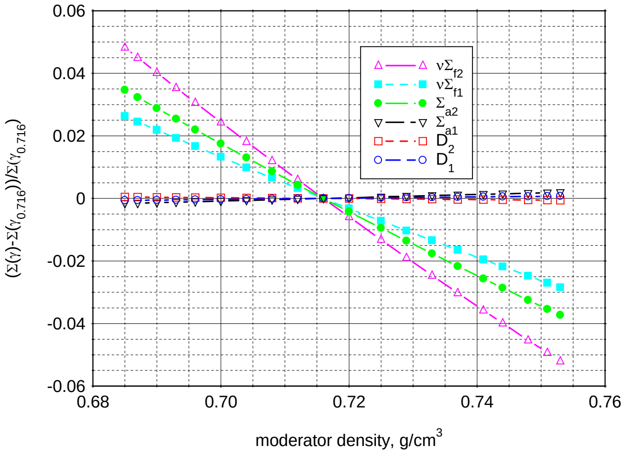

Fig. 3 – Cross sections for FA 398GO under different moderator density burnup history (B=60MWd/kgHM)

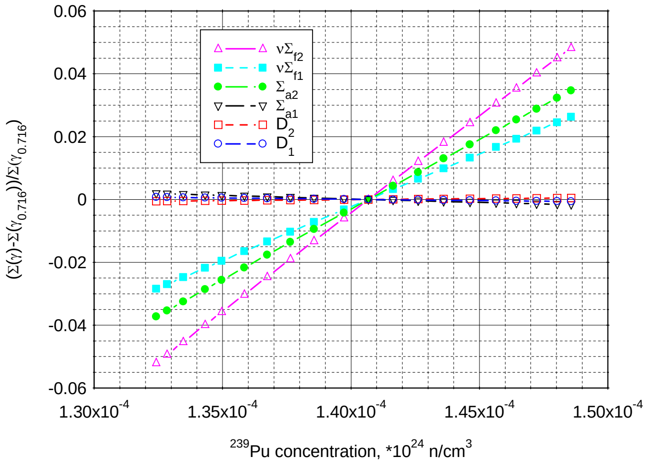

Fig. 4 – Cross sections for FA 398GO vs ^{239}Pu concentration under different moderator density burnup history (B=60MWd/kgHM)

Study of effect of burnup history was performed with use of DYN3D code [1]. Presently used by SSTC NRS cross section library was prepared by HELIOS code [3] for one burnup path with average value of moderator density in WWER-1000 (0.716 g/cm^3). Traditionally used scheme of cross section preparing is next. For averaged value of moderator density a nuclide concentration is calculated for whole range of burnup. Then with obtained nuclide concentration a set of branches for different core parameters (moderator temperature and density, boron acid concentration, fuel temperature) are calculating. Based on calculated in these branches cross sections a reference cross sections and parameterization coefficients are calculated.

Accounting of historical effect in frame of the given work was realized in the given way. Model of WWER-1000 core is divided on 20 axial layers. For averaged loaded FA the moderator density is changed from 0.68 up to 0.76g/cm^3 from bottom to top of core. For each axial layer the cross section library for corresponded moderator density was prepared by HELIOS – so, each FA has 20 sets of cross section data.

It's obviously that first transition fuel loadings don’t give an accurate account of the studied effect. In report meaning “transition fuel loadings” used regard to taking into account of historical effect. It connected with effect of compensation – the caused by historic effect fuel with greater values of burnup will be characterized by smaller power. So, it's necessary to study minimum 3-4 fuel loading to make steady assessment of effect of burnup history by moderator density on neutron physical characteristics of WWER-1000 core.

Such assessment was performed for stationary fuel loading with Russian design FA TWSA (from 8th up to 11th fuel loadings) and AER benchmark for Khmelnitsky NPP that was proposed by TUV and SSTC NRC at 19th symposium (from 1st up to 4th fuel loadings).

RESULTS OF CALCULATION STUDIES FOR STATIONARY FUEL LOADING

For stationary fuel loading the four loadings were calculated from 8th up to 11th. Calculation of four fuel cycles is necessary to obtain steady value of historical effect. Thus the taking into account of historical effect at 1st transient fuel loading gives valuable influence on axial profile of power distribution. The difference between core overall relative axial power distribution with accounting of historical effect and without one achieves 10% for beginning of 1st transition fuel loading (Fig. 5). It should be noted that the difference in axial power profile is lesser for FA of first year operation and greater for deep burned FA (third and fourth year operation). Up to end of fuel loading operation this difference is essentially decreased up to value of ≈2% due to compensation of power by value of fuel burnup.

For steady fuel loading difference between core overall relative axial power distribution with accounting of historical effect and without one amounts both up to 2% at beginning and end of fuel loading operation.

Regarding to axial power profile in FA as it was above mentioned biggest value of difference amount 2.2% for FA of 4th year operation – maximal values are achieved at height ≈50cm from top and bottom of core. Decrease of power difference near to the edge of core is caused by lesser values of neutron flux and fuel burnup at the top and bottom of reactor core.

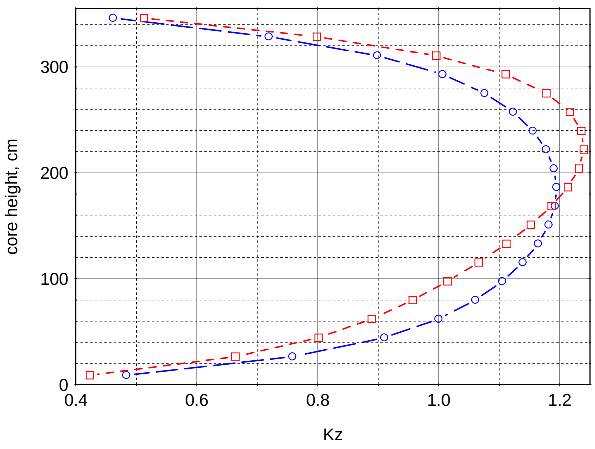

Fig. 5 – Core axial power profile at the beginning of 1st transition fuel loading

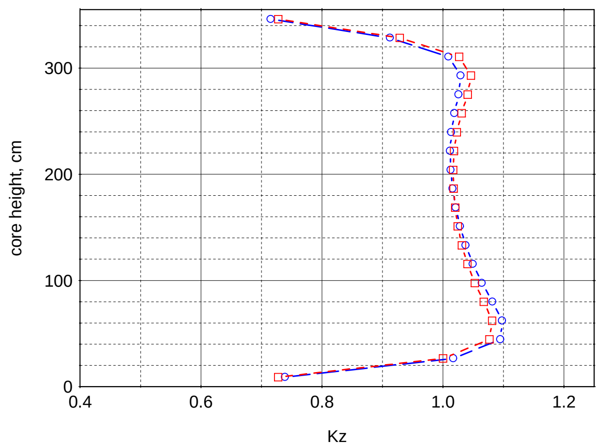

Fig. 6 – Core axial power profile at the end of 1st transition fuel loading

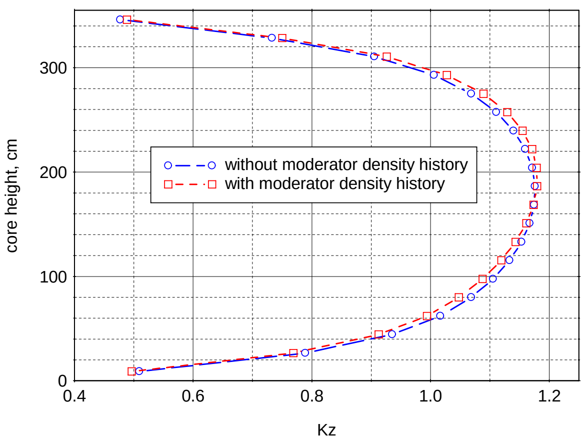

Fig. 7 – Core axial power profile at the beginning of steady fuel loading

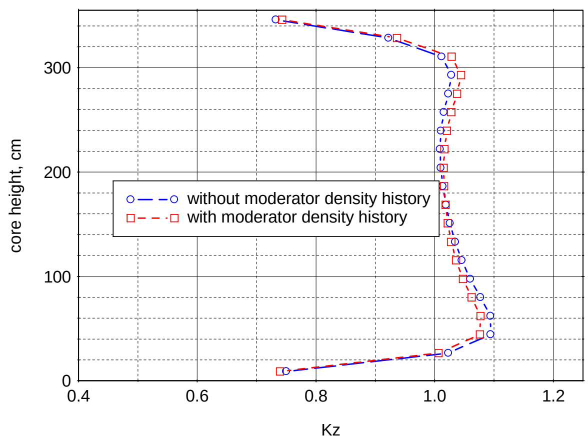

Fig. 8– Core axial power profile at the end of steady fuel loading

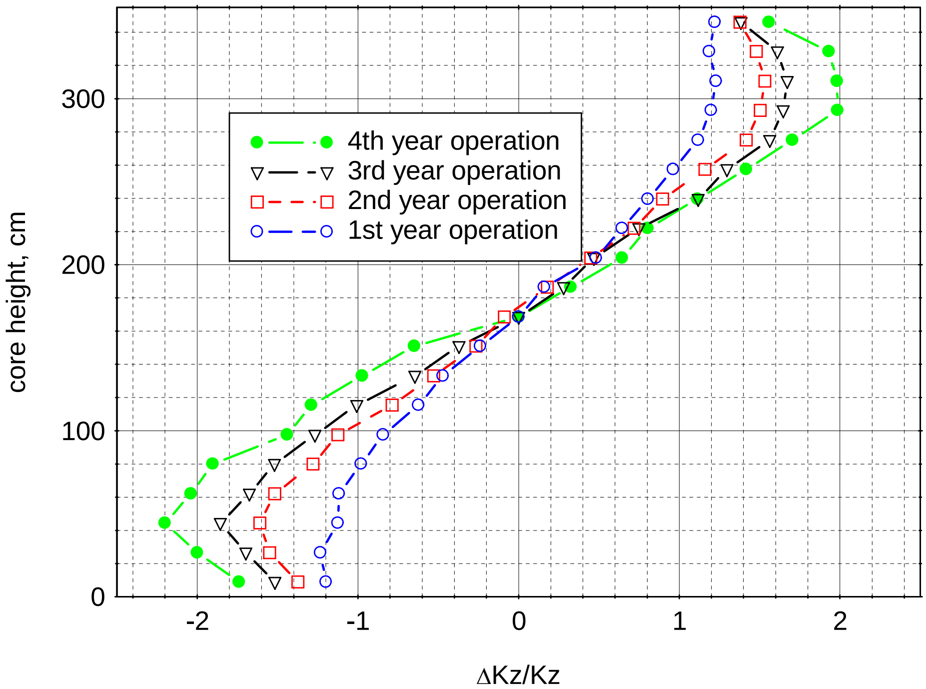

Fig. 9 – Effect of burnup history for FA of different year of operation

As was expected influence of accounting of historical effect on macro-characteristic of reactor core is minimal. Thus change of boron acid concentration during burning-out due to accounting of historical effect doesn't exceed 0.01g/kg. Also difference in calculated values of reactivity coefficients, worth of control rods and radial power distribution are insignificant.

RESULTS OF CALCULATION STUDIES FOR AER BENCHMARK

Four fuel loadings – from 1st up to 4th were calculated in frame of proposed by TUV and SSTC NRC at 19th symposium AER benchmark for Khmelnitsky NPP.

It should be noted that accounting of historical effect is good appreciable already at the end of first fuel campaign. Thus historical effect amounts 2.5% for FA with initial ^{235}U enrichment 1.3% (middle burnup 9.52MWd/kgHM) and 1.4% for FA with initial ^{235}U enrichment 3.90% (middle burnup 10.9MWd/kgHM) correspondingly.

For 4th fuel campaign historical effect amounts up to 2.5% for FA mostly of 3rd and 4th year operation. It should be note that value of effect depends not only operation year (and correspondingly fuel burnup) but also on FA situation in the reactor core due to influence of surrounded assemblies.

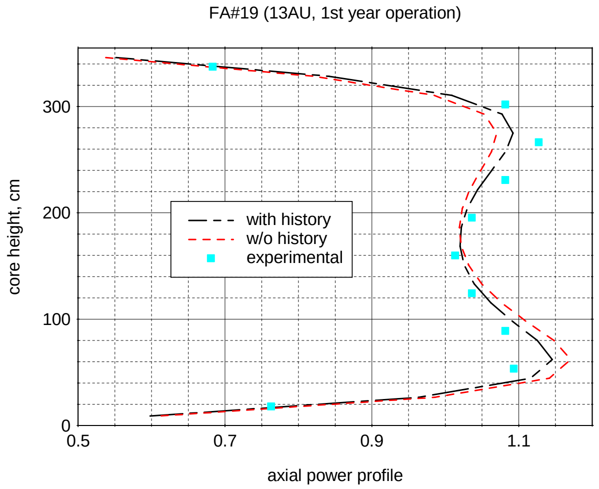

Fig. 10 – Axial power distribution for FA with 1.3% ^{235}U enrichment (1th loading)

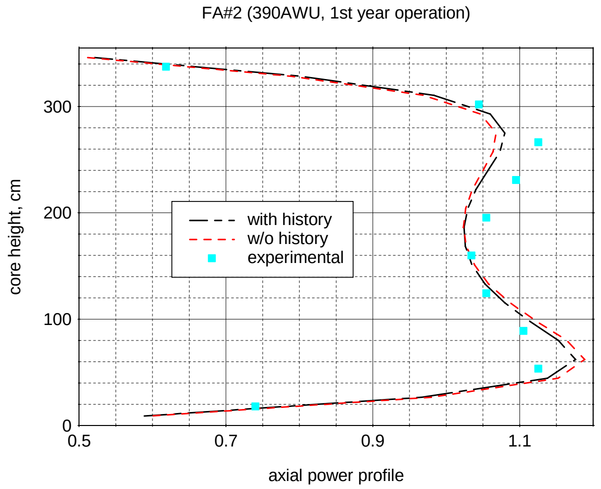

Fig. 11– Axial power distribution for FA with 3.9% ^{235}U enrichment (1th loading)

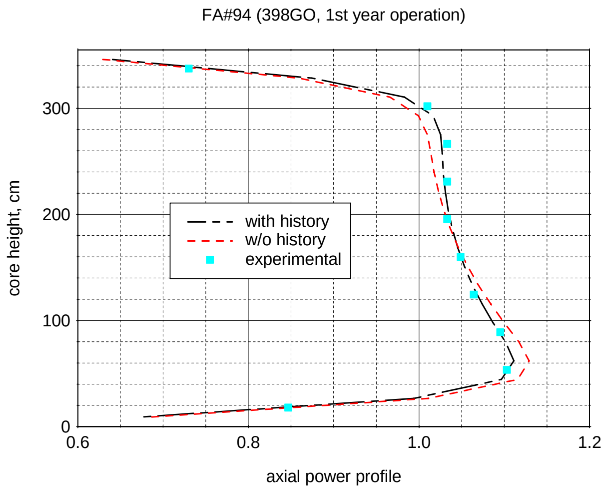

Fig. 12 – Axial power distribution for FA of 1st year operation (4th loading)

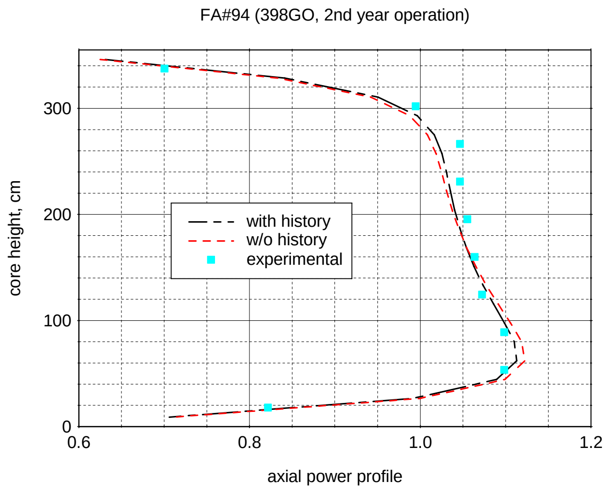

Fig. 13– Axial power distribution for FA of 2nd year operation (4th loading)

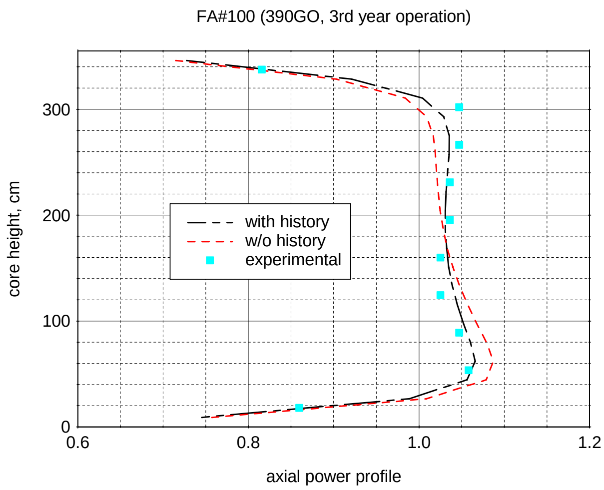

Fig. 14 – Axial power distribution for FA of 3rd year operation (4th loading)

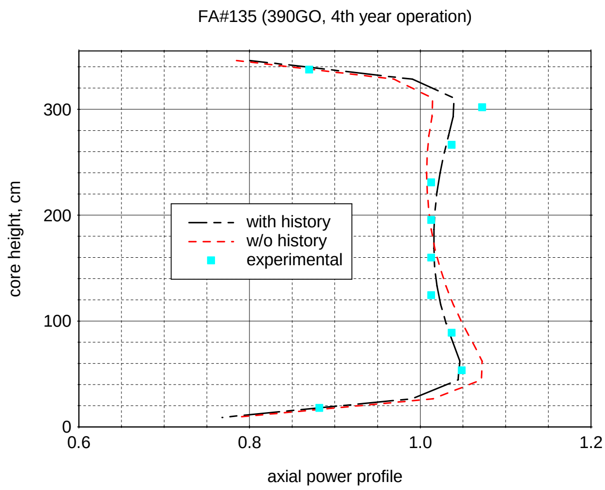

Fig. 15 – Axial power distribution for FA of 4th year operation (4th loading)

CONCLUSIONS

1. Neglect of historical effect by moderator density causes to calculation error of ^{239}Pu concentration up to ±6% for WWER-1000 burned FA during preparing of cross section library.

2. Dependence of 2 group cross section on moderator density under which fuel was burned is close to linear. Accounting of historical effect by moderator density can be realized by introducing of some linear coefficient in parameterization dependence of cross section.

3. Accounting of historical effect by moderator density increases accuracy of calculation of axial power distribution for burned FAs up to 2.5%.

LIST OF NOMENCLATURE

CR - control rod;
FA - fuel assembly;
NPP - nuclear power plant;

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