ГЛОБАЛЬНАЯ ЯДЕРНАЯ БЕЗОПАСНОСТЬ, 2022 № 4(45), С. 69–78
GLOBAL NUCLEAR SAFETY

ЭКСПЛУАТАЦИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ
OPERATION OF FACILITIES NUCLEAR INDUSTRY

УДК 621.039.5.0 : 621.039.519
DOI 10.26583/gns-2022-04-07
EDN HFCGGJ

ВЛИЯНИЕ ЗАВИСИМОСТИ РАСПРЕДЕЛЕНИЯ ТЕМПЕРАТУРЫ ТОПЛИВА НА НЕЙТРОННО-ФИЗИЧЕСКИЕ ХАРАКТЕРИСТИКИ АКТИВНОЙ ЗОНЫ С ВВЭР-1000 (1200)

© 2022 Малкави Ращдан Талал Аль[1], Заидан Лаит Джамиль[2]

[1]Иорданский исследовательский и учебный реактор (JRTR), Ирбид, Иордания
[2]Техасский университет A&M,Колледж Стейшн, Техас
[1]rashdanmalkawi@gmail.com, https://orcid.ord/0000-0003-4458-7264
[2]L.zaidan@tamu.edu, https://orcid.ord/0000-0001-8355-7207

Аннотация. В работе представлены результаты исследований физических явлений, определяющих параметры ксеноновых колебаний. В том числе уточнена зависимость нейтрон-но-физических характеристик активной зоны ВВЭР-1000 (1200) от температурного распределения в топливе и его влияния на параметры ксеноновых процессов в зоне. Разработан усовершенствованный метод расчета резонансного поглощения в ^{238}UO2 (эффект доплеровской реактивности) с неоднородным температурным профилем. Результаты расчета параметров ксеноновых колебаний были рассчитаны с помощью комплексной программы PROSTOR. Валидность усовершенствованного метода была проверена путем сравнения рассчитанных параметров ксенона с результатами измерений, полученными при пусконаладочных испытаниях энергоблоков реактора ВВЭР-1000. Результаты показали более точный расчет резонансного поглощения в ^{238}UO2, они значительно уменьшают стабилизацию уширения эффекта Доплера, следовательно, эти факты имеют жизненно важное значение в случае работы реактора в маневренных режимах, сопровождающегося ксеноновыми процессами в активной зоне. Усовершенствованный способ внедрен в компьютерное программное обеспечение Полномасштабного тренажера 3-го энергоблока Ростовской АЭС и полномасштабного тренажера 4-го энергоблока Калининской АЭС. Метод был опробован в ходе приемо-сдаточных испытаний этих полномасштабных тренажеров.

Ключевые слова: ВВЭР-1000, ксеноновые колебания, реактивность, эффект Доплера, распределение температуры топлива.

Для цитирования: Аль Малкави Р.Т., Заидан Л.Д. Влияние зависимости распределения температуры топлива на нейтронно-физические характеристики активной зоны с ВВЭР-1000 (1200) // Глобальная ядерная безопасность. – 2022. – № 4(45). – С. 69-78. http://dx.doi.org/10.26583/gns-2022-04-07.

Поступила в редакцию 20.07.2022
После доработки 03.10.2022
Принята к печати 12.10.2022

Introduction

This study, as well as other similar studies, relates to the problems of determining the so-called «small effects» in reactor physics. In most cases, small effects are usually limited to reactor operations and manual troubleshooting, or minor design changes of certain units of nuclear power plant. However, the appearance of small effects is not only a result of manufacturing tolerances and structural failures but also physical phenomena, which are unaccounted in the computational justification of the NPP project, and important for some operational modes. These phenomena are clearly seen when the reactor operates in load following modes [1, 2], which induce axial Xenon oscillations. Nowadays one of the main requirements for current NPP designs is to operate on load-following mode, in order to be able to adapt daily, and seasonal electricity supply, or any other variations in power demand.

Many studies have investigated the influence of fuel temperature distribution on resonance capture by U-238 [3-6]. The steady state radial temperature distribution across the fuel pellet forms a parabolic curve, in which the center of the fuel pellet acquires the highest temperature, which decreases down to its minimum value at the pellet surface.

In order to study temperature profile across the pellet, 1D cylindrical heat conduction equation with a heat source (q) is utilized with a zero-gradient temperature at the center $\frac{dT}{dx} = 0$, and a defined heat transfer coefficient at the surface (h) – equation (1). The presence of forced convection at the surface justifies the temperature drop across the pellet. Thermal conductivity (λ) is assumed to be constant.

$$T\ (r) = \frac{T_0 + q/4r^2}{\lambda(1-(r/r_0)^2)} \tag{1}$$

where r_0 – the outer radius of the fuel element, T_0 – the surface temperature of the fuel element.

Fuel temperature distribution can be constant along to the radius only in the absence of heat release in the fuel pellet or in a very rapid growth of heat release (acceleration at prompt neutrons) from the cold state of the reactor without power from fractions of a second.

Complex program PROSTOR was adopted in modeling. The main goal of the program PROSTOR, is the implementation of coordinated both neutronics and thermal hydraulics calculations of stationery and transient processes in primary system equipment to integrate modeling of protection and control system work at NPP with WWER-1000 [7, 8].

Methodology

Stationary and dynamic processes occurring in the reactor require thermal hydraulic calculations to find temperature and power distributions in the core. Accordingly, these calculations will be used to find all constants the averaged fuel temperature as shown in equation (2).

$$\bar{T} = \frac{\int T(r)\,r\,dr}{\int \mathrm{rdr}}, \tag{2}$$

equation 2 shows that temperature distribution T(r) can differ depending on the power density of the fuel pellet and/or the heat transfer coefficient at the pellet surface, and this change in the temperature across the pellet might neutron capture cross section in the fuel. In other words, the lower the temperature near the pellet surface, the lower the probability for resonance capture. However, external fuel layers shield the central regions of the fuel; thus, the effect of resonance broadening is lower in the central regions.

In WWER-1000 [9], reactivity feedback due to fuel temperature is mainly caused by resonance capture of neutrons and a first approximation of the resonance absorption integral is shown in equation (3), where T_0 is assumed to be 293 K.

$$\mathrm{I}(T) = I(T_0)(1 + \beta\left(\sqrt{T} - \sqrt{T_0}\right), \tag{3}$$

where, I(T), $I(T_0)$ are the temperature dependent resonance absorption integrals;

β is an experimentally measured constant factor.

This expression implies that the whole region is occupied by a fuel of the same temperature.

Temperature distribution and resonance absorption

Temperature profile along the fuel pellet radius is calculated, which is necessary to correctly calculate heat flows into the coolant and to determine the maximum fuel temperature. This is solved numerically for more accurate calculations in the case of non-stationary heat transfer equation, at least for one-dimension.

During preparation of neutron cross section libraries, a series of fuel cell calculations is conducted with different values of the fuel temperatures, which is held for the whole fuel volume. Therefore, neutron cross sections used in the neutron-physical calculations, which correspond to the fuel cell, are related to the same temperature in the whole fuel cell volume.

Calculating the temperature profile for neutron cross sections preparation stage is unreal; because it could be the most diverse profile depending on the local power varying in the core, see figure 1. Therefore, another way is suggested to calculate the real temperature profile, which will be used to calculate the neutron cross-sections in the resonance energy region.

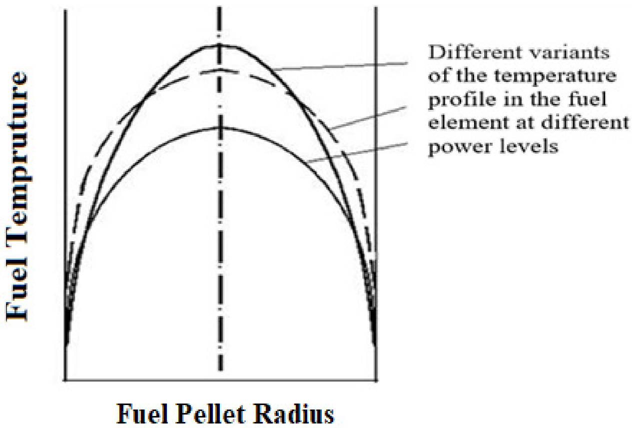

Figure 1 – Variants of the temperature profile in the fuel

There are a couple of factors to determine the temperature distribution in the fuel cell. Starting from the second equation, the neutron resonance capture is proportional to the value $\sqrt{T(r)}$ in the case of homogeneous distribution of a neutron collision density in the resonance region. This leads to a decrease of the resonance capture probability compared to the resonance capture calculated over an average temperature.

Self-shielding effect should be put into considerations as a factor. Self-shielding plays an important role, where it reduces neutron capture near the center of the fuel pellet compared to the surface. This in turn leads to a decrease in the total resonance calculated depending on the average temperature.

Based on this, the effective fuel temperature should be evaluated, which is homogeneous over the fuel volume, where the value of resonance capture is the same as in the real radial profile.

Accordingly, it could be possible to use the effective fuel temperature for the interpolation of neutron cross sections in the complex codes, which are prepared using spectral program, regardless of the Doppler Effect value distortion.

Reference [3] proposes that the infinite multiplication factor K_∞, which is calculated in a regular fuel cell has the same value in both cases, either K_∞ regarding the effective average temperature, or in the case of actual parabolic temperature profile along the radius of the fuel.

It was also concluded that there is a more accurate approach for temperature averaging than the illustrated above in equation 2, because equation 2 doesn't consider the weighting factor as in equation 3. The effective fuel temperature was estimated as follows:

$$T_{эфф} = \frac{\int T(r)\,\varphi(r) r dr}{\int \varphi(r) r dr}, \quad (4)$$

where the weighting factor formula: $\varphi(\mathrm{r}) = 1/\sqrt{\mathrm{T(r)}}$.

This is considered as the currently accepted method. However, Thisapproach does not the effect of self-shielding in the fuel. This concerns the effect of scattered neutrons in the water, which have reached the surface of fuel pellet, falling into the resonance.

Accurate calculation of the fuel temperature profile along the fuel radius requires a more detailed partitioning of the fuel radially than what was done in [3], division of the fuel pellet into 8 layers leaves each layer optically "gray" for resonance neutrons.

A simplified model was developed to calculate the resonance neutron absorption of the resolved-resonance region in the fuel pellet.

Parameters of WWER-1000 type fuel cell (fig. 2), and eight resolved resonances of ^{238}U from 6 ev to 200 ev were taken into consideration.

Neutrons will be divided in two categories depending on whether they scattered in moderator or in the fuel, where they will fall in eight resolved resonances of ^{238}U.

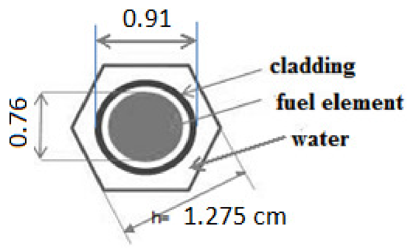

Figure 2 – WWER-1000 fuel cell

Now, the effective fuel temperature can be estimated with a non-uniform temperature profile. The total number of neutrons that absorbed by the energy region of 8 resolved resonances is:

$$F(T_0, T_1, \dots, T_N) = \sqrt{\frac{T_N}{300}} \left((1-\alpha) \sum_{j=1}^{8} \frac{h_j}{E_j} I_{Sj}(T_0, T_1, \dots, T_N) + \alpha \sum_{j=1}^{8} \frac{h_j}{E_j} I_{Mj}(T_0, T_1, \dots, T_N) \right), \quad (5)$$

where: h_j The width of the j-th resonance;

E_j j-th resonance peak energy;

T_0 The value of temperature at the surface of the fuel pellet;

T_N The maximum temperature in the fuel pellet (k);

$\sqrt{T_N/300}$ broadening of the resonance with increasing temperature.

The parameter α is defined as follows:

$$\alpha = \frac{S_{UO_2}\Sigma_{sUO_2}}{P_U S_{H_2O}\Sigma_{sH_2O} + S_{UO_2}\Sigma_{sUO_2}}$$

S_{H_2O} – The area occupied by water in a regular fuel cell;

$\Sigma_{sH_2O} = \Sigma_{sH_2} + \Sigma_{sO}$ – Macroscopic scattering cross section of neutrons in the water;

S_{UO_2} − The area occupied by the fuel in a regular fuel cell;

$\Sigma_{sUO_2} = \Sigma_{sU} + \Sigma_{sO_2}$ − Macroscopic scattering cross section of neutrons in the fuel;

$$P_U \approx \frac{\pi d_U}{\pi d_U + 2\sqrt{3}h} \frac{1}{\Sigma_{sh_2o}\ell_i + \frac{\pi d_U}{\pi d_U + 2\sqrt{3}h}}$$

$$\ell_i = \frac{2\sqrt{3}h^2 - \pi d_T^2}{2\sqrt{3}h + \pi d_T}$$

d_U − Fuel pellet diameter, d_T − Cladding outside diameter;

$$I_{Sj} = \sqrt{T_0/T_N}\, W_{j0}(R_0, T_N) + \sum_{i=1}^{N} (\sqrt{T_i/T_N} - \sqrt{T_{i-1}/T_N}) W_{ji}(R_i, T_i) \prod_1^i P_{jk}$$

$$\prod_1^i P_{jk} \approx \prod_1^i R_k/R_{k-1} = R_i/R_0$$

$$I_{Mj} = \left(\sum_{i=1}^{N} \frac{R_i}{R_0^2} \Delta R_i \left(\sqrt{\frac{T_i}{T_N}} W_{ji}(R_i, T_i) + \sum_{k=i+1}^{N} \left(\sqrt{\frac{T_k}{T_N}} - \sqrt{\frac{T_{k-1}}{T_N}} \right) W_{jk}(R_k, T_i) \frac{R_k}{R_i} \right) \right.$$

$$\left. + \sqrt{\frac{T_0}{T_N}} W_{ji}(R_0 - R_i, T_0) + \sum_{k=1}^{i-1} \left(\sqrt{\frac{T_k}{T_N}} - \sqrt{\frac{T_{k-1}}{T_N}} \right) W_{jk}(R_k - R_i, T_i)) \right) / \sum_{i=1}^{N} \frac{2R_i}{R_0^2} \Delta R_i$$

The value I_{Mj} is the absorption probability of neutrons that scattered in the fuel in one of the 8 resonances with a non-uniform temperature profile along the radius, and the value I_{sj} is the absorption probability of neutrons that scattered in the water in one of the 8 resonance with a non-uniform temperature profile along the radius. Then the absorption probability in each fuel layer:

$$W_{ji}(R_i, T_i) \approx \frac{\sigma_r(300)\sqrt{300/T_i}\,\ell_i}{1 + \sigma_r(300)\sqrt{300/T_i}\,\ell_i}, \ell_i = 2R_i,$$

where T_i − The value of temperature in i-th layer of the fuel pellet;
$\sigma_r(300)$ − A resonant absorption cross section at T=300 K.

$$W_{jk}(R_k - R_i, T_0) \approx \frac{\sigma_r(300)\sqrt{300/T_0}\,\ell_i}{1 + \sigma_r(300)\sqrt{300/T_0}\,\ell_i}, \ell_i = 2(R_k - R_i),$$

where R_i − The radius of fuel pellet in i-th layer.

The effective temperature value is substituted in equation (5), and then another equation that has the same parameters as equation 5 except one parameter (T_{eff}) was obtained to determine its value:

$$F(T_{eff}) = \sqrt{\frac{T_{eff}}{300}} \left((1-\alpha) \sum_{j=1}^{8} \frac{h_j}{E_j} I_{Sj}(T_{eff}) + \alpha \sum_{j=1}^{8} \frac{h_j}{E_j} I_{\text{M}j}(T_{eff}) \right)$$

$$I_{Sj}(T_{eff}) = W_{j0}(R_0, T_{eff})$$

$$I_{\text{M}j}(T_{eff}) = (\sum_{i=1}^{N} \frac{R_i}{R_0^2} \Delta R_i (W_{ji}(R_i, T_{eff}) + W_{ji}(R_0 - R_i, T_{eff}))/ \sum_{i=1}^{N} \frac{2R_i}{R_0^2} \Delta R_i$$

$$F_0(T_{eff}) = (1-\alpha) \sum_{j=1}^{8} \frac{h_j}{E_j} I_{Sj}(T_{eff}) + \alpha \sum_{j=1}^{8} \frac{h_j}{E_j} I_{\text{M}j}(T_{eff})$$

$$F(T_0, T_1, \ldots, T_N) = \sqrt{\frac{T_{eff}}{300}} F_0(T_{eff}) \quad (6)$$

Xenon oscillation

Xenon oscillation can be represented as a convergent or divergent harmonic oscillation in the following form:

$$A(t) = A(t_0)\exp\big(\alpha(t - t_0)\big)\cos\big(\omega(t - t_0)\big) \quad (7)$$

where $A(t) = Ao(t) - Ao*$;

$Ao(t)$ – The absolute value of the offset at the time t;

$Ao*$ –The equilibrium offset;

t_0 – The moment of reaching first absolute;

$\omega = 2\pi/T_{Xe}; T_{Xe}$ – *the* period of xenon oscillations;

α – stability index, α = T–1×ln(A2/A1), A1 is the amplitude of the first maximum, A2 is the amplitude of the second maximum. α defines the type of harmonic oscillation, if $\alpha > 0$ oscillation diverges, and if $\alpha < 0$ oscillation converges.

Xenon oscillations were excited by the immersion of the control rods (CR) for 20 % of the reactor height. Due to this the configuration of the axial power distribution was changed, and then control rods were maintained for 3 hours. The reactor power was set to be 75% by changing the critical concentration of boric acid.

Axial oscillations are described by axial offset-AO (the percentage of the power difference between the upper and lower halves of the core to the total power) [10-13].

Results

The results for Xenon oscillations were obtained during the commissioning tests for the first cycle of Rostov's NPP 3rd unit and 9th cycle for 3rd unit of Kalinin NPP. The calculations were done using three methods; the effective fuel temperature, the currently accepted method, and by the proposed method in this paper (equation 5). The calculations were performed using "PROSTOR".

Figure 3 shows the axial offset as a function of time for Xenon oscillations of the initial core for 3rd unit of Rostov NPP at 75% of nominal power. It can be noticed that there is a significant difference in Xenon oscillations among the three methods. Furthermore, the improved method indicates the importance of considering the dependence effective temperature value on the coolant density to obtain more accurate results for the neutron flux distribution.

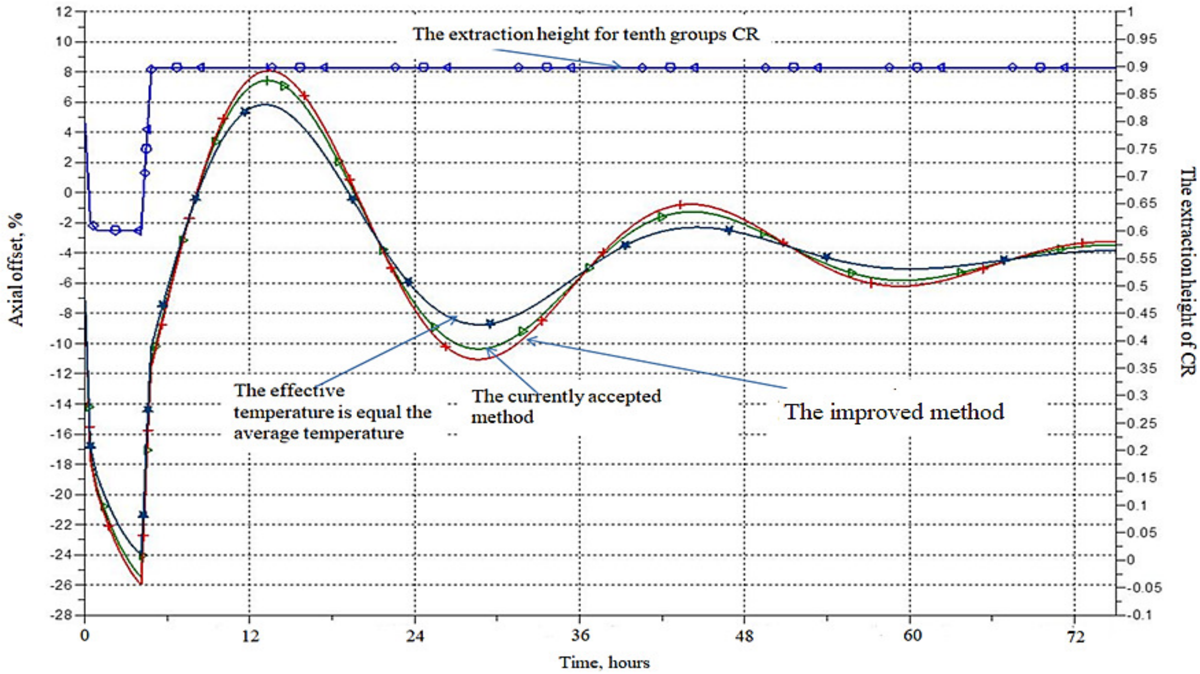

Figure 3 – Axial offset as a function of time of the initial core for 3rd unit of Rostov NPP at 75% of nominal power

Figure 4 shows the axial offset as a function of time for Xenon oscillations at the end of 9th fuel cycle for 3rd unit of Kalinin NPP at 100% of nominal power.

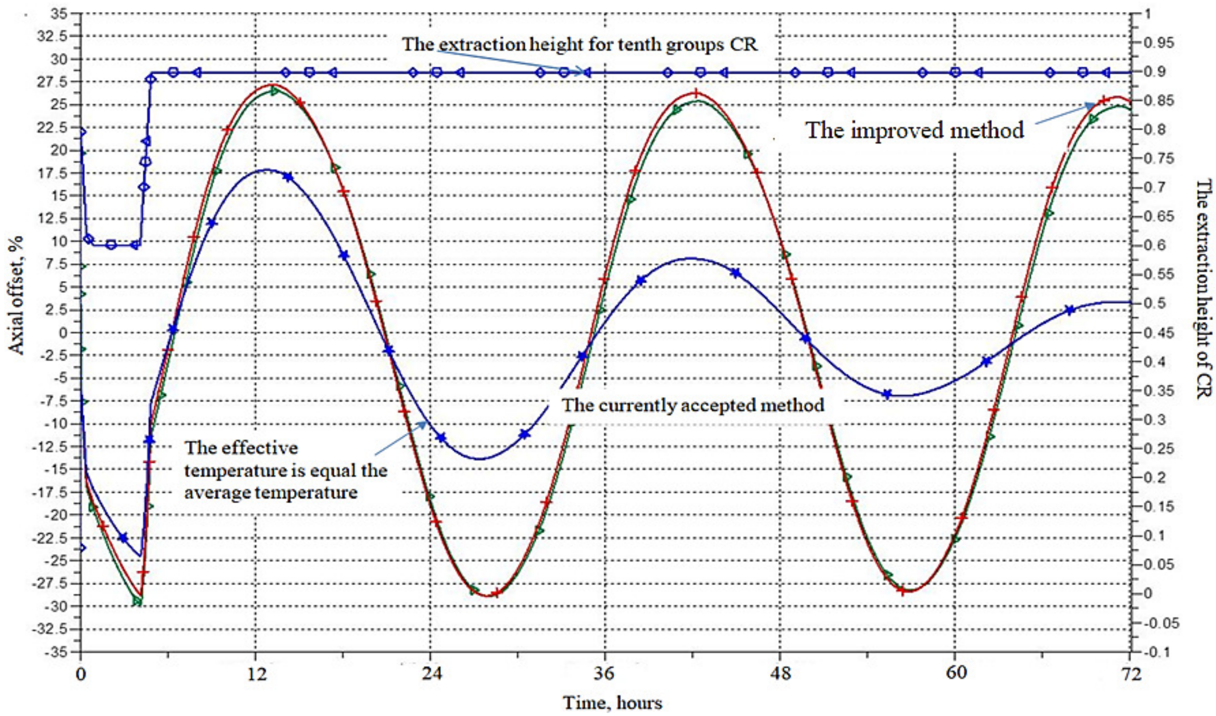

Figure 4 – Axial offset as a function of time at the end of 9th fuel cycle for 3rd unit of Kalinin NPP at 100% power

Table 1 shows the main parameters of xenon oscillations at 75 % of nominal power during commissioning tests for the 3rd unit of Rostov NPP.

Table 1 – the parameters of xenon oscillations at 75% of nominal power at the beginning of the initial core for 3rd unit of Rostov NPP

Oscillation Parameters	Calculation method				
	The effective temperature is equal the average temperature	The currently accepted method	The improved method	Experiment	Program (IR)
The period of Oscillations [hr]	31.08	30.61	30.34±Δ1	30.2	30.50
Stability Index [1/hr]	-0.052	-0.044	-0.0401±Δ2	-0.040	-0.030
Equilibrium offset [percent]	-4.20	-4.25	-3.98	-4.81	-5.60

Program (IR) – staff program of support for NPP operation with WWER-1000(1200).

Where, Δ1=0.21 hr, Δ2=0.0012 1 / hr- standard deviation from verification data of software complex PROSTOR. The stability index is the main indicator of the reactor stability with respect to Xenon oscillations.

Three methods of Doppler Effect modeling were considered to obtain different values of stability index: I1, I2, I3. The improved method gives the value of I3. Standard deviation Δ2 calculated from the experimental data, is established from verification data of software complex PROSTOR. If the difference between the values obtained of the three methods is significantly greater than the value of 3Δ2, it can be argued about the advantage of the chosen method of calculation:

If |I3-I2|>>3Δ2, |I3-I1|>> 3Δ2, then I 3 is preferable.

Table 2 shows the difference between the values of K_{eff} for the end of 9th fuel cycle for 3rd unit of Kalinin NPP at 100% nominal power by using different methods for calculating the effective temperature. The same table shows the critical concentration of boric acid that was obtained for the same state of the reactor core by using different methods for calculating the effective fuel temperature.

Table 2 – Kalinin NPP core parameters at the end of 9th fuel cycle for 3rd unit of Kalinin NPP at 100% of nominal power

Parameters of the reactor core	Calculation method		
	The effective temperature is equal the average temperature	The currently accepted method	The improved method
ΔKeff, %	0	0.16	0.23
The critical concentration of boric acid, g / Kg	7.98	8.12	8.19
The average effective fuel temperature, c^0	790	745	720

Conclusions

The most important result of the research is that method of accounting the influence of the temperature distribution in the fuel WWER reactors on the resonance capture of neutrons was constructed, which is different from the currently accepted methods in that it takes into account the fuel lattice parameters and the distribution of thermal parameters along the volume of the reactor core. This method does not require special configuration of the model when switching from one type of fuel element to the other and it takes into account effect of Doppler broadening on reactivity coefficients in the presence of fuel temperature profile in the emergency situations related to dehydration of the reactor core.

These results showed that a more accurate temperature distribution calculated in fuel significantly reduces the stabilization of Doppler Effect. This fact becomes particularly important in the implementation of the daily power control during load following modes. This is implemented in new NPPs generation.

The improved method for calculating ^{238}UO2 resonance absorption with a Nonuniform temperature profile is implemented into the computer-software of the full-scale simulator of Rostov NPP 3rd Power unit and the full-scale simulator of the 4th Power unit of the Kalinin NPP. The method was tested during acceptance tests of these full-scale simulators.

СПИСОК ИСТОЧНИКОВ

1. *Выговский, С.Б.* Оптимизация алгоритмов управления ЯЭУ с ВВЭР-1200 для минимизации водообмена в 1-ом контуре при реализации суточных маневренных режимов АЭС / С.Б. Выговский, Р.Т. Аль Малкави, А.Г. Хачатрян, Ш.А. Абраамян. – Глобальная ядерная безопасность. – 2018. – № 3(28). – С. 43-57.
2. *Выговский, С.Б.* Исследование алгоритмов управления ЯЭУ с ВВЭР-1200 для реализации суточных маневренных режимов на АЭС / С.Б. Выговский, Р.Т. Аль Малкави, А.Г. Хачатрян // Известия вузов. Сер.: Ядерная энергетика. – 2019. – № 2. – С. 67-79.
3. *Вейнберг, А.* Физическая теория ядерных реакторов / А. Вайнберг, Е. Вигнер. – Москва : Издательство иностранной литературы, 1961. – 724 с.
4. *Артемов, В.Г.* Исследование влияния выгорания топлива на теплофизические свойства твэла в совместных нейтронно-физически теплогидравлических моделях / В.Г. Артемов, Л.М. Артемова, Ю.П. Шемаев. – Сосновый Бор : ФГУП НИТИ им. А.П. Александрова, 2007. – 10 с.
5. *Бать, Г.А.* Основы теории и методы расчета ядерных энергетических реакторов / Г.А. Бать. – Москва : Энергоатомиздат, 1982. – 510 с.
6. *Kudrov A., Kuzmin Y., Rakov Y.* Effective fuel temperature of WWER-1000. MATEC Web of Conferences, Tomsk, 2017. 4 p.
7. *Семенов, А.А.* Опыт использования программного комплекса «ПРОСТОР» и перспективы его дальнейшего применения / А.А. Семенов, С.Б. Выговский, В.А. Чернаков, Н.В. Щукин // Материалы научной сессии НИЯУ МИФИ – 2004. – Москва, 2004. – С. 79-80.
8. *Выговский, С.Б.* Приложение к аттестационному паспорту № 182 от 28.10.2004 г. Программный комплекс ПРОСТОР (версия 1) / С.Б. Выговский, В.Г. Зимин, Е.В. Чернов. – Москва : НИЯУ МИФИ, 2004. – 8 с.
9. *Дреснер, Л.* Резонансное поглощение в ядерных реакторах / Л. Дреснер. – Москва : Госатомиздат, 1962. – 136 с.
10. *Rashdan Talal Al Malkawi, Sergey B. Vygovsky, Osama Wasef Batayneh.* Investigation of the impact of steady-state WWER-1000 (1200) core characteristics on the reactor stability with respect to xenon oscillations. Nuclear Energy and Technology, no. 4, 2020, p. 289.
11. *Аверьянова, С.П.* Ксеноновая устойчивость ВВЭР-1200 / С.П. Аверьянова, П.Е. Филимонов // Атомная энергия. – 2009. – Т. 107, № 6. – С. 348-351.
12. *Аверьянова, С.П.* Исследование ксеноновых переходных процессов в ВВЭР-1000 на Тяньваньской АЭС (Китай) / С.П. Аверьянова, К.Б. Косоуров, Ю.М. Семченков // Атомная энергия. – 2008. – Т. 105, № 4. – С. 183-190.
13. *Хитчкок, А.* Устойчивость ядерных реакторов / А. Хитчкок ; пер. с англ. – Москва : Госатомиздат, 1963. – 68 с.

REFERENCES

[1] Vygovsky S.B., Al Malkawi R.T., Khachatryan A. G., Abrahamyan S. A. Optimizaciya algo-ritmov upravleniya YAEU s WWER-1200 dlya minimizacii vodoobmena v 1-om konture pri realizacii sutochnyh manevrennyh rezhimov [Optimization of Control Algorithms of Nuclear Power Plants with WWER-1200 to Minimize Water Exchange in the 1st Circuit during the Implementation of Daily Maneuvering Modes], Global'naya yadernaya bezopasnost' [Global Nuclear Safety], 2018, no. 3(28), pp. 43-57 (in Russian).

[2] Vygovskiy S.B., Al Malkawi R.T., Khachatryan A.G. Issledovanie algoritmov upravleniya YAEU s WWER-1200 dlya realizacii sutochnyh manevrennyh rezhimov na AES [Research of WWER-1200 Reactor Core Control Algorithms for Implementation of Flexible (Load Tracing) Operating Modes]. Izvestiya vuzov. Yaderna Energitka [News of Higher Education Institutions. Series: Nuclear Power Engineering], 2019, № 2, pp. 67-79 (in Russian).

[3] A. Weinberg, J. Wegner, Fizicheskaya teoriya yadernyh reaktorov [Physical Theory of Nuclear Reactors]. Moscow: Publishing House of Foreign Literature, 1961, 724 p. (in Russian).

[4] Artemov V.G., Artemova L.M., SHemaev Yu.P. Issledovanie vliyaniya vygoraniya topliva na teplofizicheskie svojstva tvela v sovmestnyh nejtronno-fizicheski teplogidravlicheskih modelyah [The Influence of Dependence of Burn-Up for Thermophysical Properties of a Fuel Element in Thermal-hydraulic and Neutron-Physical Models]. Sosnovy Bor: FGUP NITI im. A.P. Aleksandrova [Sosnovy Bor: A.P. Alexandrov NITI Federal State Unitary Enterprise], 2007, 10 p. (in Russian).

[5] Bat G.A. Osnovy teorii i metody rascheta yadernyh energeticheskih reaktorov [Fundamentals of Theory and Calculation Methods in Nuclear Power Reactors]. Moscow: Energoatomisdat Publ.,1982, 510 p. (in Russian).
[6] Kudrov A., Kuzmin Y., Rakov Y. Effective Fuel Temperature of WWER-1000. MATEC Web of Conferences, Tomsk, 2017, 4 p. (in English).
[7] Semenov A.A., Vygovsky S.B., Chernakov V.A., Shchukin N.V. Opyt ispol'zovaniya programmnogo kompleksa «PROSTOR» i perspektivy ego dal'nejshego primeneniya [Experience in Using the Software Complex «PROSTOR» and the Prospects of its Further Application], Materialy nauchnoj sessii NIYAU MIFI [Proceedings of MEPhI scientific session]. Moscow, 2004, pp. 7980 (in Russian).
[8] Vygovsky S.B., Zimin V.G., Chernov Ye.V., Korikovsky K.P., Krayushkin Yu.A., Mischerin S.A., Osadchy M.A., Semyonov A.A., Strashnykh V.P., Chernov E.V., Chernakov V.A. Prilozhenie k attestacionnomu pasportu № 182 ot 28.10.2004 g. Programmnyj kompleks PROSTOR (versiya 1) [PROSTOR Software Complex (Ver. 1). The Appendix to the Certification Passport No. 182], October 28, 2004, 8 p. (in Russian).
[9] Dresner L. Rezonansnoe pogloshchenie v yadernyh reaktorah [Resonance Absorption in Nuclear Reactors]. Moscow: Gosatomizdat, 1962, pp. 136 (in Russian).
[10] Rashdan Talal Al Malkawi, Sergey B. Vygovsky, Osama Wasef Batayneh. Investigation of the Impact of Steady-State WWER-1000 (1200) Core Characteristics on the Reactor Stability with Respect to Xenon Oscillations. Nuclear Energy and Technology, no. 4, 2020, p. 289 (in English).
[11] Averyanova S.P., Filimonov P.E. Ksenonovaya ustojchivost' WWER-1200 [Xenon Stability of WWER-1200], Atomnaya Energiya [Atomic Energy], 2009, vol. 107, no. 6, pp. 348-351 (in Russian).
[12] Averyanova S.P., Kosourov K.B., Semchenkov Yu.M. () Issledovanie ksenonovyh perekhodnyh processov v WWER-1000 na Tyan'van'skoj AES (Kitaj) [Study of Xenon Transients in WWER-1000 at Tianwan NPP (China)], Atomnaya Energiya [Atomic Energy], 2008, vol. 105, no. 4, pp. 183-190 (in Russian).
[13] Hitchcock A. Ustojchivost' yadernyh reaktorov [Stability of Nuclear Reactors]. Moscow: Gosatomizdat Publ., 1963, 68 p. (in Russian).

Influence of Fuel Temperature Distribution Dependence on Neutron-Physical Characteristics of Nuclear Core with WWER-1000 (1200)

Rashdan T. Al Malkawi[1], Laith J. Zaidan[2]

[1]Jordan Research and Training Reactor (JRTR), Irbid, Jordan
[2] Texas A&M University Техасский университет A&M, College Station, Texas
[1]rashdanmalkawi@gmail.com; ORCID iD: 0000-0003-4458-7264; WosResearher ID: P-5338-2018
[2]L.zaidan@tamu.edu; ORCID iD0000-0001-8355-7207; WosResearher ID: HCH-0363-2022

Received by the editorial office on 07/20/2022
After revision on 10/03/2022
Accepted for publication on 10/12/2022

Abstract. This paper presents the results of the influence of reactivity on fuel temperature distribution for the neutron-physical characteristics of WWER 1000-1200 cores, which in turn affects the parameters of Xenon oscillation. The improved method for calculating Resonance Absorption in a $^{238}UO_2$ (Doppler reactivity effect) with a Nonuniform Temperature Profile are developed. The parameters calculation results for Xenon oscillations have been calculated using complex program PROSTOR. The validation of the improved method was examined by comparing the calculated xenon parameters to measurement results obtained during commissioning tests of WWER-1000 reactor power units. Results showed a more accurate calculation for the Resonance Absorption in a $^{238}UO2$, they significantly reduce the stabilization of Doppler Effect broadening, hence these facts, are vital importance in the case of load following mode accompanied by Xenon processes in the core. The improved method is implemented into the computer-software of the Full-Scale Simulator of the 3rd Power Unit of the Rostov NPP and the Full-Scale Simulator of the 4th Power Unit of the Kalinin NPP. The method was tested during acceptance tests of these Full-Scale Simulators.

Keywords: WWER-1000, Xenon oscillations, reactivity, Doppler Effect, fuel temperature distribution.

For citation: Al Malkawi R.T., Zadan L.J. Influence of Fuel Temperature Distribution Dependence on Neutron-Physical Characteristics of Nuclear Core with WWER-1000 (1200) // Global Nuclear Safety. – 2022. – № 4(45). – P. 69-78. http://dx.doi.org/10.26583/gns-2022-04-07