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Research Article

A study into the dependence of the cladding-fuel pellet gap conductance on burn-up and the effects on the reactor core neutronic performance*

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Abstract

This paper presents the results of the research to study the dependence of the VVER-1000 (1200) cores neutronic characteristics on the cladding – fuel pellet gap conductance coefficient in the process of the fuel burn-up. The purpose of the study was to determine more accurately the dependence of the cladding – fuel pellet gap conductance coefficient on the fuel burn-up as shown in the Final Safety Report for the Bushehr NPP and to determine the extent of the effects this dependence had on the spatial distribution of the neutron field, on the xenon accumulation rate, and on the kinetic and dynamic behavior of the reactor facility. The paper presents the results of calculating the parameters using which the heat engineering safety of the reactor core is monitored in the process of the fuel burn- up (for a generalized fuel load of a VVER-1000) during the transition to an 18-month nuclear fuel cycle. This paper also includes the results of a numerical research to determine the cladding – fuel gap conductance coefficient depending on the fuel burn-up. These results have shown that, in reality, the gap conductance coefficient dependence on the burn-up does not affect greatly the steady-state characteristics. At the same time, it affects to rather a great extent the xenon accumulation rate, specifically in the event of an extended fuel life. In conditions of maneuvering (load following) modes accompanied by the xenon processes in the reactor core. These facts should be into consideration in design of engineering codes, that used to support the operation of the VVER-1000 (1200) and full-scale simulators.

Keywords

VVER-1000, gap conductance coefficient, burn-up, xenon oscillations, reactivity, Doppler effect

Status of research

The paper presents the results of the studies into the conductance of the gas gap between the cladding and the fuel pellet (the *gap* hereinafter for brevity) in the VVER fuel as a function of fuel burn-up and the effects this dependence has on the neutronic performance of the reactor core. The timeliness of the studies is explained by the need for the gap conductance parameters and their influence on the magnitude of the power reactivity effect to be taken into account with greater accuracy in full-scale codes. This is especially important for the more accurate simulation of

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in-core xenon transients during the reactor plant modes with transition from one power value to another. Such modes involve in-core xenon transients leading potentially to local power fluctuations across the reactor core.

The purpose of the study was to investigate the dependence of the VVER-1000 (1200) cores neutronic performance on the gap conductance behavior in a fuel element in the process of burn-up. The study deals with a problem of determining the extent of influence the so-called small effects in reactor physics have on the neutronic performance of thermal neutron reactors. A small effect has nothing to do with manufacturing tolerances or design errors. It is the authors' opinion that the effect in question is the result of the failure to take into account the thermal resistance of the gap between the fuel cladding and the fuel matrix (Thermal Contact Resistance or the TCR hereinafter) in the VVER-1000 as a function of fuel burn-up in standard codes for the computational support of the NPP operation which is of a vital importance for some of the operating modes. These phenomena manifest themselves largely in maneuvering modes taking place during the reactor plant transition from one power to another and involving in-core xenon processes, as well as in fuel burn-up modes in conditions of extended fuel cycles (up to 18 months). While, earlier, the VVER-1000 maneuvering modes were one-off in the event of primary and secondary frequency regulation in the energy system, VVER-1200 NPPs nowadays have scheduled testing of daily modes with power maneuvers in a broad range of their values at an arbitrary reactor life point (ATOMEXPO-2010). In daily modes with a change of power, Doppler reactivity effect, which accounts for the most part of the power effect, is the key stabilization factor for the xenon local power oscillations across the core. As the gap conductance affects considerably the temperature distribution in the fuel and, hence, the magnitude of the power reactivity effect, greater emphasis needs to be placed on a more accurate calculation of this reactivity effect in integrated models used in engineering codes, that used to support the operation of the VVER-1000 (1200) and full-scale simulators.

Physical model

With only the dependence of the gap conductance relied on for fresh fuel with no burn-up effects taken into account, the magnitude of the temperature reactivity effect at different moments of the fuel cycle can be misjudged severely. The physics of the phenomena taking place in fuel during burn-up is as follows (Artemov et al. 2007, Ainscough 1982, Dean 1962, Ainscough and Hobbs 1979).

The fuel matrix swells and the fuel cracks in the radial direction at the initial burn-up point as gaseous fission products are formed. This leads to a reduction of the fuel element gap between the fuel and the cladding and to an increase in the gap conductance.

The intensity of these processes depends to a large extent on the fuel pellet diameter, the availability of a central hole, and the specific heat load. The larger the diameter of the pellet and the smaller the pellet's central hole are, and the greater the fuel's specific heat load is, the more pronounced the process described is. For example, there is a more marked TCR increase of a stable and steady-state nature observed at high burn-up values for the KONVOI-design fuel matrix used in the fuel elements of the reactor core at the Gösgen NPP, Switzerland, as shown by the calculated TCR dependences in the design documentation. The data on the PWR reactor fuel TCR dependences on power and fuel burn-up has also been provided by the Gösgen experts.

Based on the calculated Gösgen TCR dependences, the authors suggest that, with high burn-up values and a high intensity of the gaseous fission product accumulation (at a high specific power), gases pass through the radial cracks reaching the fuel pellet periphery and the swelling process slows down. This process is illustrated in Fig. 1. In this case, as a minimum, the gas gap width decrease decelerates.

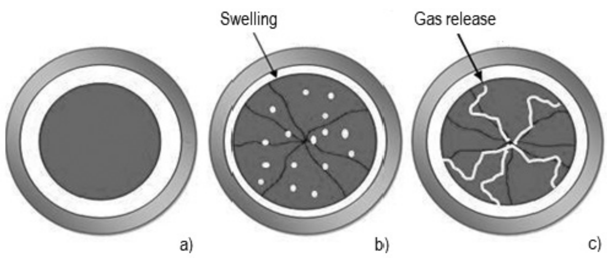

Figure1. Variation in the cladding – fuel pellet gap width at high specific power $Q_L > 400$ W/cm, for a PWR reactor: a) – fresh fuel; b) – fuel with burn-up; c) – high burn-up fuel

Computational model

Data from the Bushehr NPP final safety analysis report was analyzed (Rahgoshay and Rahmani 2007, 2011). It was used as the basis for building the approximation for the gap conductance dependence on burn-up using a polynomial approach and the linear power effect on the gap conductance was determined more accurately for fresh fuel. Such approach has led to fully adequate results for the approximation built based on the safety report data and has explained the behavior of the gap conductance depending on burn-up and specific power outside the approximation region. The approximation built for the dependence of the gap conductance on fuel burn-up was included in the PROSTOR code (Vygovskiy et al. 2004) which is the software core for the primary circuit models in the full-scale simulators (FSS) at units 2, 3 and 4 of the Kalinin NPP and in the FSSs at units 3 and 4 of the Rostov NPP. Fig. 2 presents the TCR dependences on linear power for fresh fuel (based on data from chief designer) and burn-up at a specific power of 448 W/cm, as result from the Bushehr safety report data approximation.

The conductance processes in a fuel element were simulated using the procedures to calculate Thermal conductivity coefficient for uranium fuel (UO_2) without taking into account the dependence on fuel burn-up and temperature (see Fig. 3) (Lucuta et al. 1996, Wiesenack 1998). These calculation procedures were also included in the PROSTOR reactor core model.

The gap TCRs were calculated as a function of burn-up at different specific power values based on the developed approximation and compared against the TCRs for the PWR-1000 KONVOI-series fuel dependence (*Western dependence* hereinafter) (Tong and Weisman 1996, Mesquita Amir et al. 2007, Medvedev et al. 2003, Yousef et al. 2014, Geelhood and Luscher 2014). Fig. 4 presents calculated dependences of the gap thermal resistance value obtained for the VVER-1000 and PWR-1000 fuel.

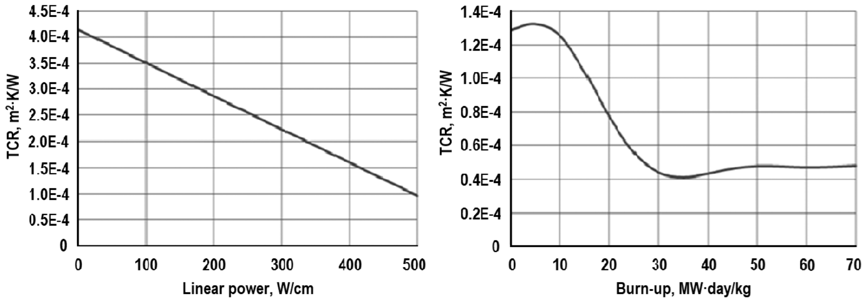

Figure 2. Fuel gap TCR s as a function of linear power for fresh fuel (based on chief engineer's data) and of burn-up at linear power 448 W/cm (based on the Bushehr NPP final safety report data)

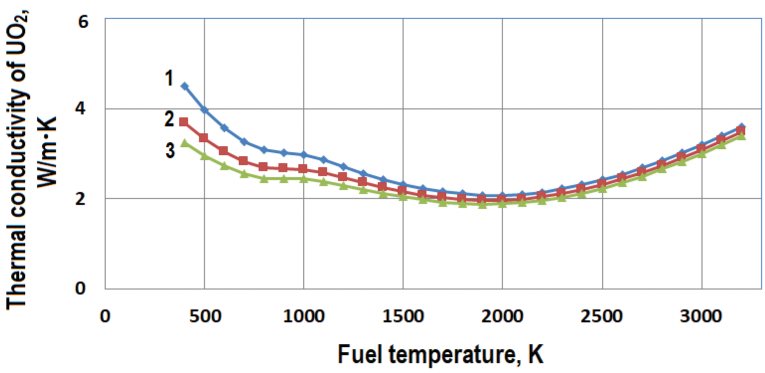

Figure 3. Thermal conductivity coefficient of UO2 as a function of temperature at different burn-up values: 1 – 20 MW·day/kg U; 2 – 40 MW·day/kg U; 3 – 60 MW·day/kg U

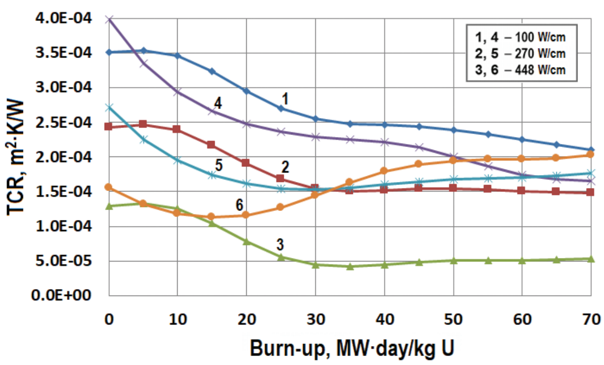

Figure 4. Gap TCRs as a function of fuel burn-up at different levels of linear power on fuel elements in VVER-1000 (semi-empiric dependences **1**, **2**, **3**) and in PWR-1000 (Western dependences **4**, **5**, **6**)

Calculation of fuel burn-up

With regard for the dependences of the TCR and Thermal conductivity coefficient on temperature and burn-up, computational studies were performed, using the PROSTOR code, to determine the extent to which these dependences affected the reactor core neutronic performance. In the first place, a study was conducted to investigate the influence the gap conductance dependence on burn-up has on the VVER-1000 core steady-state characteristics during burn-up or, more specifically, on the duration of the reactor fuel cycle and the spatial neutron field distribution across the core. The fuel burn-up was calculated for the stationary fuel load in one of Russian NPPs. This load is a generalized example of fuel loads in VVER-1000 during the transition to an 18-month fuel cycle. The calculations used the gap conductance dependences on fuel temperature, based on data from chief engineer, without taking into account the dependence on burn-up (option 1) Gap Conductance Coefficient taking into account the dependence on burn-up (option 2). The calculations were performed for the base power of 3120 MW and fuel cycle extension due to the power reactivity effect at a power reduction to 75% of the nominal value.

Fig. 5 presents the results of calculating the maximum difference between the calculated linear power of fuel element and the maximum allowable at the end of the cycle for stationary fuel loading: $Dif_{max} = \max(Q_L(x, y, z) - Q_{L\,lim}(x, y, z))$. The presented time interval has been chosen from the condition of achieving the maximum value of the difference between the calculated and the maximum allowable fuel element load across the burn-up interval. This turns out to be the time interval as the end of cycle. The maximum difference is observed in the upper part of the reactor core, in the 7th region of the core detectors channel. The magnitude of this difference does not exceed 1 W/cm.

Fig. 6 presents the results of calculating the critical concentration of boric acid during fuel burn-up at the end of the cycle. The difference in the concentration values between the two options is about 0.1 g/kg. Extrapolation to zero concentration of boric acid leads to a difference in the duration of the reactor cycle about 4-5 eff. Days.

It can be concluded from the calculation results that there is a small increase in the duration of the reactor cycle for stationary fuel load, with regard for the dependence of conductance on fuel burn-up, which is explained, on the one hand, by a decrease in the effective fuel temperature which improves the neutron multiplying properties of the VVER fuel lattice (Kudrov et al. 2017, Vygovskiy et al. 2016). On the other hand, however, a change in the isotopic composition during fuel burn-up leads, as the burn-up grows, to a decrease in the conductance of the fuel as such due to which the average fuel temperature increases and the multiplying properties of the fuel lattice worsen. Both phenomena are caused by the Doppler effect (Weinberg and Wigner 1961, Bartolomey et al. 1982) but act oppositely on the fuel lattice multiplying properties. This makes up for a great deal of the fuel TCR reduction effects, which explains a small difference in the values of the linear power on the fuel elements and the critical concentration of boric acid.

Despite of a small decrease in the linear power margin, it needs to be noted that this leads to somewhat worsened conditions of the reactor core safe operation. Though the extent of the variations obtained is small, the effects the gap conductance dependence on burn-up has on the local power axial distribution across the reactor core shall not be neglected.

Dynamic calculations of the xenon process

The effects the dependence of the gap conductance on burn-up has both on the characteristics and the dynamics of in-core xenon processes has been investigated.

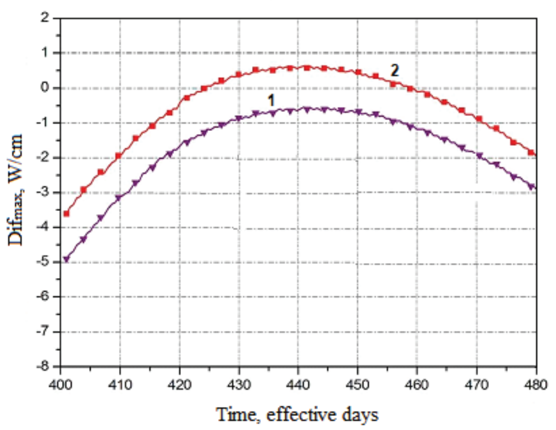

Figure 5. The maximum difference between the calculated and the maximum allowable linear power on the fuel element of the VVER-1000 at the end of the cycle for stationary fuel loading.: 1 – Gap Conductance Coefficient without taking into account the dependence on burn-up; 2 – Gap Conductance Coefficient taking into account the dependence on burn-up

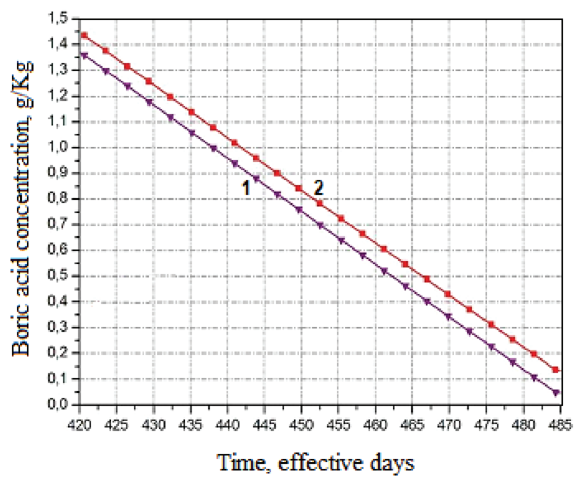

Figure 6. Dependence of boric acid concentration on the operating time of stationary fuel loading of the VVER-1000 at the end of the cycle: 1 – Gap Conductance Coefficient without taking into account the dependence on burn-up; 2 – Gap Conductance Coefficient taking into account the dependence on burn-up

Calculations were performed for stationary fuel load with a base power of 3120 MW for an 18-month fuel cycle in different moments of the cycle. The configuration of the in-core axial neutron field was changed by the 20% insertion of the group of regulating control rods and retained in the resultant position for three hours. The reactor power was set as equal to and kept at 75 % of the nominal value by changing the critical concentration of boric acid. Calculations were performed for the moment of cycle: 150, 350 and 485 effective days. The dependences of axial offset on time for 485 effective days are presented in Fig. 7.

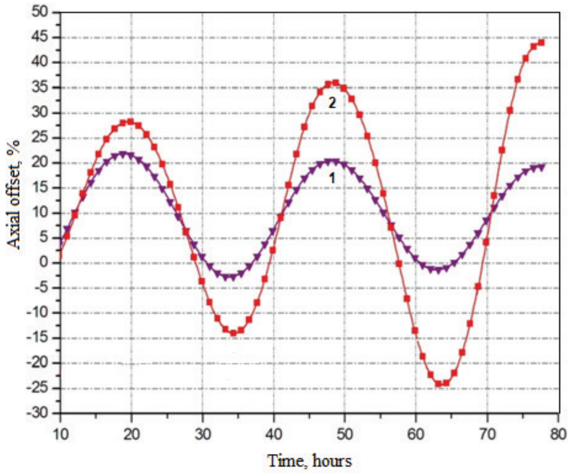

Figure 7. Axial offset as a function of time for stationary fuel loading of the VVER-1000 at 75 % of nominal power: 1 – Gap Conductance Coefficient without taking into account the dependence on burn-up; 2 – Gap Conductance Coefficient taking into account the dependence on burn-up

Findings

The need for taking into account the dependence of the gap conductance on fuel burn-up is explained by the fact that a high burn-up leads to the greatest possible change in the gap conductance values with, accordingly, the maximum influence on the radial temperature distribution in the fuel pellet. The effect of the thermal contact resistance reduction is comparable with that from the decrease in the fuel conductance. Therefore, it is critical to take into account the dependence of the gap conductance on fuel burn-up leading to a change in the radial temperature distribution in fuel such that the average temperature and, accordingly, the effective fuel temperature decrease as compared to the calculation of the temperature fields in fuel without this effect taken into account. The Doppler effect improves to a certain extent the reactor core's neutron multiplying properties and leads to increase in the duration of the reactor cycle and a local power growth in the core's upper and lower parts. The presence of this effect reduces the reactor stability to the local power xenon oscillations in the core at the end of cycle.

Calculations to justify safe operation of the NPP equipment involve the so-called principle of conservatism that can be briefly described as follows. When employed, any approximations and simplifications in the calculation procedures for the nuclear plant safety justification can reduce the nuclear safety level. A valid conclusion on the nuclear safety during calculation of a phenomenon can be made if the calculations really show a safe operation level. And where they provide the results leading indirectly to an increased level of the nuclear safety, approximations and simplifications are better not to be used. It follows from this that there is a need for an increased calculation accuracy of the gap conductance with its dependence on fuel burn-up. These facts should be into consideration in design of engineering codes, that used to support the operation of the VVER-1000 (1200) and full-scale simulators.

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