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Safety Analysis at Increasing Heat Conductivity of Uo2-Fuel of Nuclear Power Plants

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One of the modern directions of improving the safety and operational efficiency of nuclear UO2 fuel is related to the modernization of its thermal conductivity. However, an increase in the thermal conductivity of UO2 fuel, ceteris paribus during accidents with violations of heat removal from the reactor core, can lead to a corresponding increase in the temperature of the cladding of fuel rods and a violation of safety conditions for the maximum allowable temperature of the cladding of the fuel rods. In this case, design basis accidents become trans-design basis and a corresponding decrease in the overall level of nuclear safety occurs.Such provisions determine the need to optimize the modernization of increasing the thermal conductivity of UO2 fuel.Based on the previously developed express method of safety analysis during the modernization of nuclear power plants and the known results of computational modeling with the RELAP5 / M3.2 code of the maximum design basis accident (with two-sided rupture of the main circulation pipe) for serial power units with VVER-1000, it was determined that a rational increase in the thermal conductivity UO2 -Fuel is not more than 100% of the design.With a large increase in the thermal conductivity of UO2 fuel, the safety conditions are violated for the maximum permissible temperature of the zirconium cladding of the fuel elements.

Key words: *optimization, thermal conductivity, UO2 fuel, nuclear power plant.*

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I. RELEVANCE

One of the drawbacks of uranium oxide nuclear fuel (UO2 fuel) is its relatively low thermal conductivity. Due to the low thermal conductivity of UO2 fuel, even in normal operating conditions at the rated power of the reactor in the fuel matrix (about 4 mm thick), the temperature difference is more than 1000 degrees, and the maximum temperature in the central part of the fuel matrix is about 1900 ° C [1]. In emergency conditions with a violation of the heat removal from the fuel rods, the fuel temperature in the central part of the fuel matrix can exceed the maximum permissible values (more than 2800 ° C) at which the melting and destruction of UO2 fuel begins.Therefore, one of the main modern tasks of modernizing the thermophysical properties of UO2 fuel is associated with an increase in its thermal conductivity. At present, it is considered as the main direction for solving this problem - the modernization of UO2 fuel by doping it with metal oxides with high thermal conductivity (chromium, beryllium, etc.). So, according to the results of well-known programs for creating nuclear UO2 fuel with high thermal conductivity, the use of chemical additives from beryllium oxide can increase thermal conductivity by 50%.An increase in thermal conductivity even by 5% makes it possible to increase nuclear safety by reducing the maximum fuel temperature in normal and emergency conditions, as well as increasing the efficiency of using UO2 fuel [2].

However, an increase in the thermal conductivity of nuclear fuel can also have a negative effect in accidents with impaired heat removal from the reactor core. The increased thermal conductivity of the fuel matrix in such accidents determines the relative increase in the temperature of the cladding of the fuel elements, ceteris paribus. The maximum permissible temperature of zirconium claddings of fuel rods is 1200 ° C. In this case, design basis accidents due to violations of the heat removal from the core of a reactor with high-conductivity nuclear fuel can go into the status of beyond design basis accidents with violation of the safety criterion for the maximum allowable temperature of the claddings of fuel elements.

Therefore, the introduction of modernization to increase the thermal conductivity of nuclear fuel requires an additional analysis of the safety and rationality of the values of the thermal conductivity coefficients, which determines the relevance of the proposed work.

BASIC PROVISIONS AND RESULTS OF EXPRESS ANALYSIS OF SAFETY AND OPTIMALITY OF MODERNIZATION OF THERMOPHYSICAL PROPERTIES OF UO2-FUEL

Traditionally, the analysis of nuclear safety of nuclear power plants (NPPs) comes down to probabilistic and deterministic modeling of all possible initial emergency events [3]. With numerous upgrades of nuclear power plants (including the optimization of the thermophysical properties of nuclear fuel), the traditional approach of safety analysis leads to an unreasonable increase in the volume of computational modeling and material costs.

In [4], the authors proposed an express method of nuclear safety analysis during modernization of nuclear power plants, which is based on the known results of computational modeling by traditional deterministic methods (codes) for the design of nuclear power plants (basic version) and analytical estimates of the impact of a particular modernization on the change in maximum fuel temperature and fuel cladding in relation to design conditions. The express method [4] avoids the unreasonably large volume of computational modeling of emergency processes by traditional methods of safety analysis with numerous upgrades of nuclear power plants.

In accordance with the express method, the difference between the maximum temperatures of the nuclear fuel Tm and the cladding of the Tom fuel rods for the modernized (M) and design (P) states of the nuclear power plant is determined by the integral (in time t) analytical expressions:

$$T_{\text{тm}}(\text{M}) - T_{\text{тm}}(\Pi) = \Delta T_{\text{тm}} =$$

$$f_1 \begin{Bmatrix} T_{\text{тm}}(t=0); t; K_1\left[\text{Nu}, r_{\text{т}}, \lambda_{\text{т}}, \rho_{\text{т}}, C_{p\text{т}}, R_T\right]; \\ K_2\left[N_{\text{т}}(t), \text{Nu}, T_{\text{тн}}, \lambda_{\text{т}}, \rho_{\text{т}}, C_{p\text{т}}\right]; \vec{K}_{\text{м}} \end{Bmatrix}, (1)$$

$$T_{\text{om}}(\text{M}) - T_{\text{om}}(\Pi) = \Delta T_{\text{om}} = f_2\left\{T_{\text{om}}(t=0); t; \text{Nu}; f_1; \vec{K}_{\text{м}}\right\} \quad (2)$$

where the determining parameters of the design design / state of the nuclear power plant: Nu = αdRt - Nusselt's criterion; α is the coefficient of external heat transfer on the surface of the fuel element; d, Rt - diameter and thermal resistance of a fuel element, respectively; rt is the radius of the fuel matrix; λт, ρт, Срт - thermal conductivity coefficient, density, specific heat of fuel, respectively; Ttn is the temperature of the coolant at the entrance to the reactor core; N is the heat output of the reactor.

Modernization parameters $\vec{K}_{\text{м}}$ reflect the ratio of modernized and design determining parameters.

The specific form of the integral functions f_1 andf_2 is given in [4].

When upgrading the increase in thermal conductivity of nuclear fuel and other things being equal, the modernization parameter:

$$K_\lambda = \frac{\lambda_{\text{т}}(\text{M})}{\lambda_{\text{т}}(\Pi)}; K_c = \frac{C_p(M)}{C_p(\Pi)}; K_\rho = \frac{\rho(M)}{\rho(\Pi)}. \quad (3)$$

Necessary security conditions for modernization:

$$T_{\text{om}} / T_{\text{ocr}} < 1, \quad (4)$$

$$T_{\text{тm}} / T_{\text{тcr}} < 1, \quad (5)$$

where T_{ocr}, $T_{\text{тcr}}$is the maximum permissible temperature of the claddings of fuel rods and fuel, respectively. For UO2 fuel and zirconium shells:T_{ocr} = 1200 °C and$T_{\text{тcr}}$ = 2290 °C.

In accordance with the known results of computational modeling of design basis accidents at nuclear power plants with VVER-1000 (reviews are given, for example, in [3, 5]), the maximum temperatures of the claddings of fuel rods and fuel can be during initial events of a bilateral guillotine rupture of the main circulation pipeline (the maximum design basis accident is MPA).

The results of computational modeling of the effect of the modernization parameterK_λ on changes in maximum temperatures at MPA according to equations (1) and (2) are shown in Fig. 1. As a basic version of the design estimates of $T_{\text{тm}}$ and T_{om}, we used the results of computational modeling of MPA with the RELAP5 / M3.2 code for VVER-1000 serial power units [6]. From the presented results it follows that an increase in K_λ unambiguously leads to a decrease in Tm. However, this leads to an increase in Tm and, at K_λ> 2.0, the safety condition (4) is violated.

Thus, the rational value of the parameter of modernization of increasing the thermal conductivity of UO2 fuel:

$K_\lambda < 2{,}0.$

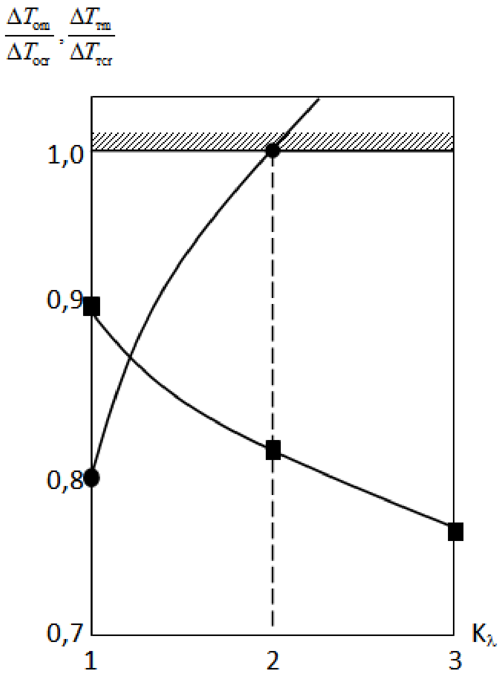

Fig. 1. The dependence of the maximum temperatures of nuclear fuel and fuel cladding in the MPA process on the parameter of modernization of thermal conductivity K_λ: ● – T_{om}/T_{ocr}, ■ – T_{mm}/T_{mc}.

II. MAIN CONCLUSIONS

1.One of the modern directions of improving the safety and operational efficiency of nuclear UO2 fuel is associated with the modernization of its thermal conductivity. However, an increase in the thermal conductivity of UO2 fuel, ceteris paribus during accidents with violations of heat removal from the reactor core, can lead to a corresponding increase in the temperature of the cladding of fuel rods and a violation of safety conditions for the maximum allowable temperature of the cladding of the fuel rods. In this case, design basis accidents become trans-design basis and a corresponding decrease in the overall level of nuclear safety occurs.

Such provisions determine the need to find rational ways to increase the thermal conductivity of UO2 fuel.

2. Based on the previously developed express safety method for modernizing nuclear power plants and the known results of computational modeling with the RELAP5 / M3.2 code of the maximum design basis accident (with two-sided rupture of the main circulation pipeline) for serial power units with VVER-1000, it was determined that a rational increase in the thermal conductivity UO2 fuel ceteris paribus is not more than 100% of the design. With a large increase in the thermal conductivity of UO2 fuel, the safety conditions are violated for the maximum permissible temperature of the zirconium cladding of the fuel elements.

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