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COMPLEX APPROACH TO QUALIFICATION OF EXTENDED TIME OF FUEL CAMPAIGN OF NUCLEAR POWER PLANTS

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A complex approach has been developed to increase the design time of the fuel campaign of nuclear reactors, based on increasing the nominal power and upgrading the thermal resistance of fuel elements. Increasing the nominal power of the reactor can be ensured with upgrading the neutron-physical parameters of nuclear fuel. It has been recognized that the maximum permissible increase in the nominal power is determined by the conditions for the start of thermoacoustic instability of the coolant in the reactor core that can lead to deformation and leakage of the fuel elements. The maximum permissible increase in the nominal power (other things being equal) qualifies the maximum time of the fuel campaign as no more than 15 months. Increasing the time of the fuel campaign with upgrading the thermal resistance of fuel elements can be ensured by optimizing the thermal resistances of the two-phase fuel matrix model. The optimization criterion is the identity of the fuel cladding temperature of the design and upgraded thermal resistances of the fuel elements in the reactor operating modes at the design nominal power. Optimization parameters are the thermal resistances of the surface and central zones of the fuel matrix. The maximum time of the fuel campaign with upgrading the thermal resistance of the fuel elements is 18 months. It has been recognized that a complex approach to increasing the time of the fuel campaign, based on increasing the nominal power and upgrading the thermal resistance of the fuel elements, can provide a maximum time of the fuel campaign of no more than 21 months. The qualified maximum time of the fuel campaign is determined assuming the independence of the burn-up rate of nuclear fuel from temperature. This may be the subject of further study.

INTRODUCTION

Increasing the time of fuel campaigns (TFC) of nuclear power plants (NPPs) is one of the promising approaches to increasing the efficiency of operation of Ukraine's nuclear power industry, because an increase in the time of reactor operation at power (other things being equal) determines an increase in the main indicator of NPP operation efficiency – the installed capacity utilization factor (ICUF).

The prospects of industry-specific TFC programs were previously considered by NNEGC Energoatom on the basis of advanced international experience [1–6]. However, due to various circumstances, TFC programs have not found widespread application in the nuclear power industry of Ukraine.

In today's extreme conditions, Ukraine's energy sector has suffered significant losses of energy capacity, which determines the particular urgency of increasing the ICUF of Ukrainian nuclear power plants (including through the implementation of industry TFC programs).

The implementation of NPP TFC programs requires qualification (substantiation) of the maximum permissible TFC while ensuring the necessary safety conditions in the operating and emergency modes of the NPP, which determines the relevance, goal and objectives of the presented work.

APPROACHES TO QUALIFICATION OF EXTENDED TIME REGIME OF REACTOR FUEL CAMPAIGNS

In the general case, the TFC t_{TK} is determined with the depth H_F and the rate $v_F = dH_F/d\tau$ of nuclear fuel burn-up [1, 5]:

$$t_{TK} = \int_0^{H_F} \frac{dH_F(\tau)}{d\tau} d\tau , \quad (1)$$

where τ is current operating time of nuclear fuel.

In the case of stationary conditions of the TFC for H_F та v_F, expression (1):

$$t_{TK} = \frac{H_F}{v_F} . \quad (2)$$

According to the results of experimental studies (a review of which can be found, for example, in [3, 6, 7]), the empirical dependences for determining H_F and v_F in the general case have the form:

$$H_F = C_1 T_F^n , \quad (3)$$

$$v_F = C_2 T_F^l , \quad (4)$$

where C_1, C_2, n, l are empirical coefficients, which in general depend on the neutron-physical and thermophysical properties of nuclear fuel.

Considering (3) and (4), TFC (2) is:

$$t_{TK} = C_1 C_2^{-1} T_F^{n-l} . \quad (5)$$

Basic qualification provisions and assumptions.

1. The steady-state operating mode of the nominal reactor power is simulated.

2. Heat transfer with thermal conductivity in the fuel element is modelled in a one-dimensional linear approximation, justified for a fuel element diameter much smaller than its height [4–7].

Taking into account the assumptions made, the equation of the fuel element heat balance in the steady-state mode of the reactor's nominal power is [3–7, 11]:

$$N = f_{\mathrm{R}}(R_{\mathrm{F}}, R_g, R_{\mathrm{O}}, \alpha)\left(T_{\mathrm{F0}} - T_{\mathrm{T}}\right), \quad (6)$$

where

$$f_{\mathrm{R}} = (R_{\mathrm{F}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{g}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{O}}A_{\mathrm{O}})^{-1} + (\alpha A_{\mathrm{O}})^{-1}, \quad (7)$$

$R_{\mathrm{F}} = \delta_{\mathrm{F}}/\lambda_{\mathrm{F}}$, $R_{\mathrm{g}} = \delta_{\mathrm{g}}/\lambda_{\mathrm{g}}$, $R_{\mathrm{O}} = \delta_{\mathrm{O}}/\lambda_{\mathrm{O}}$ is thermal resistance of the fuel matrix, gas gap and fuel element cladding; A_{F}, A_{O} is surface area of the fuel matrix and fuel element cladding; δ_{F}, δ_{g}, δ_{O} is thickness of the fuel matrix, gas gap and fuel element cladding; λ_{F}, λ_{g}, λ_{O} is thermal conductivity of nuclear fuel, gas gap and fuel element cladding; N is thermal power of fuel element; T_{F0} is temperature of nuclear fuel in the central zone of the fuel matrix; T_{T} is coolant temperature at the reactor core inlet; α is heat transfer coefficient on the fuel element surface.

After transforming equation (6), we obtain:

$$T_{\mathrm{F0}} = N f_{\mathrm{R}}^{-1} + T_{\mathrm{T}}. \quad (8)$$

Considering (8), TFC (5) as to the temperature of nuclear fuel in the central zone of the fuel matrix:

$$t_{\mathrm{TK}} = C_1 C_2^{-1} (N f_{\mathrm{R}}^{-1} + T_{\mathrm{T}})^{n-l}. \quad (9)$$

Thus, the TFC can be regulated with the thermal power and thermal resistance of the fuel elements.

The efficiency indicator of implementing the increased TFC strategy is the ratio of the modernized TFC (m) to the design TFC (D):

$$P_{\mathrm{e}} = \frac{t_{\mathrm{TK}}(m)}{t_{\mathrm{TK}}(D)}. \quad (10)$$

Taking into account the solution (9) obtained with the developed method the efficiency indicator of the increased TFC strategy for NPP is (10):

$$P_{\mathrm{e}} = \frac{\left[C_1 C_2^{-1} (N f_{\mathrm{R}}^{-1} + T_{\mathrm{T}})\right]^{n-l} (m)}{\left[C_1 C_2^{-1} (N f_{\mathrm{R}}^{-1} + T_{\mathrm{T}})\right]^{n-l} (D)}. \quad (11)$$

Condition for successful qualification of the increased TFC strategy is:

$$P_{\mathrm{e}} > 1. \quad (12)$$

The strategy to increase the TFC can be implemented with two independent approaches:

Increasing the nominal reactor power N;

Increasing the temperature of the nuclear fuel T_{F} with upgrading the thermal resistance of the fuel element.

Approach 1. Increasing the nominal reactor power.

Increasing the nominal reactor power (other things being equal) provides a relative increase in T_{F}, and accordingly the depth of nuclear fuel burn-up. However, a significant increase in the nominal reactor power can lead to a violation of normal operating conditions due to boiling and two-phase coolant. In particular, when a stable vapour phase forms on the fuel element surface (boiling crisis), heat exchange conditions deteriorate, that can lead to a significant relative increase in the fuel cladding temperature and its subsequent damage/ destruction.

According to various estimates (for example, [1–11]), reserve before the coolant boiling crisis conditions in the WWER core is more than 200% of the design nominal power. A significant reserve as to the boiling crisis conditions allows us to assume the possibility of a significant increase in the nominal power of the reactor to increase the TFC.

However, this approach has the following limitations/disadvantages.

1. An increase in the fuel element cladding temperature T_{O} due to increased nominal power in reactor operating modes may lead to a violation of safety conditions in emergency modes. Thus, according to individual results of modelling with deterministic codes of a maximum design basis accident with a rupture of the main circulation pipeline, the “reserve” to the maximum permissible fuel element cladding temperature at the beginning of the intensification of the steam-zirconium reaction (1200 °C) may be less than 100 °C (for example, [4, 5, 11]).

2. At thermal loads on the fuel element surface, much lower than the thermal loads of boiling crisis conditions, conditions of thermoacoustic instability (TAI) of the coolant in the reactor core may occur [12]. Under TAI conditions, high-frequency (hundreds of Hz) and high-amplitude (maximum amplitudes up to 50% of the average value) pressure fluctuations occur in the WWER core, which can lead to deformations/damages/ destruction of fuel element claddings.

The “lower” boundary of the area of the TAI start N_{TA} in the WWER core was determined in [11, 12]:

$$N_{\mathrm{TA}} = 1.25 N_{\mathrm{D}}, \quad (13)$$

where N_{D} is reactor design nominal power.

At the maximum increase in the nominal reactor power N_{TA} (13), the qualification parameter for increasing the TFC (11) is:

$$P_{\mathrm{e}} = \frac{\left[C_1 C_2^{-1} (1.25 N_{\mathrm{D}} f_{\mathrm{R}}^{-1} + T_{\mathrm{T}})\right]^{n-l} (m)}{\left[C_1 C_2^{-1} (N_{\mathrm{D}} f_{\mathrm{R}}^{-1} + T_{\mathrm{T}})\right]^{n-l} (D)}. \quad (14)$$

In the limiting case of the independence of the nuclear fuel burn-up rate (4) from $T_{\mathrm{F}}(l = 0)$, as well as the linear dependence of the nuclear fuel burn-up depth (3) from $T_{\mathrm{F}}(n = 0)$ and $C_1 C_2^{-1} \approx$ const, it follows from the TFC qualification parameter (14) that the maximum TFC with an increase in the nominal reactor power is no more than 15 months.

When $l \geq n$, the qualification condition for increasing the TFC (12) is not met ($P_{\mathrm{e}} \leq 1$).

Approach 2. Increasing the TFC with upgrading the thermal resistance of the fuel element.

According to the efficiency indicator of the increased TFC strategy (11), an increase in TFC can be ensured with appropriate modernization of the thermal resistance of the fuel element (R_{TF}, R_{Tg}, R_{TO}).

Such a strategy for increasing the TFC can be implemented using the example of a promising two-zone fuel matrix [8, 9], which consists of:

- Central (main) zone with reduced thermal conductivity, which provides a relative increase in T_{F} and the depth of nuclear fuel burn-up;
- Surface (rim-) zone with increased thermal conductivity, which reduces damage to the fuel matrix surface.

However, the implementation of the concept of a two-zone fuel matrix can be effective for the increased TFC strategy while ensuring safety conditions in both operating and emergency modes of the NPP.

In this case, the identity of the nominal power and fuel element cladding temperature for the design and modernized thermal resistance of the fuel element may be the safety criteria (conditions):

$$N_{\mathrm{m}}(R_{\mathrm{TFm}}) = N_{\mathrm{D}}(R_{\mathrm{TFD}}),\ \ T_{\mathrm{Om}}(R_{\mathrm{TFm}}) = T_{\mathrm{OD}}(R_{\mathrm{TFD}})\,. \quad (15)$$

Ensuring safety conditions (15) and increasing the depth of nuclear fuel burn-up determines the need in this case to optimize the thermal resistance of the central and rim-zones of the fuel matrix. Then the optimization criterion is the safety conditions of modernization (15), and the modernization parameters are the thermal resistances of the central and rim- zones of the fuel matrix.

In the general case, the fuel element heat balance equation in the design and modernized operating mode of the reactor at a power [7–11] are:

$$N_{\mathrm{FD}} = A_{\mathrm{F}}\left[R^{-1}_{\mathrm{FD}}\left(T_{\mathrm{FD0}} - T_{\mathrm{FDr}}\right) + R^{-1}_{\mathrm{OD}}\left(T_{\mathrm{FDr}} - T_{\mathrm{OD}}\right)\right] + \alpha A_{\mathrm{O}}\left(T_{\mathrm{OD}} - T_{\mathrm{T}}\right), \quad (16)$$

$$N_{\mathrm{Fm}} = A_{\mathrm{F}}\left[R^{-1}_{\mathrm{Fm}}\left(T_{\mathrm{Fm0}} - T_{\mathrm{Fmr}}\right) + R^{-1}_{\mathrm{Om}}\left(T_{\mathrm{Fmr}} - T_{\mathrm{Om}}\right)\right] + \alpha A_{\mathrm{O}}\left(T_{\mathrm{Om}} - T_{\mathrm{T}}\right), \quad (17)$$

where N_{FD}, N_{Fm} is power of nuclear fuel elements in design and modernized operating mode; A_{F}, A_{O} is surface area of the fuel matrix and fuel element cladding; T_{FD0}, T_{Fm0} is maximum temperature of nuclear fuel in the design and modernized operating mode; T_{FDr}, T_{Fmr} is nuclear fuel temperature on the surface of the fuel matrix in the design and modernized operating mode; T_{OD}, T_{Om} is fuel element cladding temperature in the design and modernized operating mode.

Thermal resistances of thermal conductivity of fuel elements in the design and modernized mode in a linear approximation (justified for a fuel element diameter much smaller than its height) are:

$$R_{\mathrm{FD}} = \frac{\delta_{\mathrm{FD}}}{\lambda_{\mathrm{FD}}},\quad R_{\mathrm{Fm}} = \frac{\delta_{\mathrm{FO}}}{\lambda_{\mathrm{FO}}} + \frac{\delta_{\mathrm{Fr}}}{\lambda_{\mathrm{Fr}}},\quad R_{\mathrm{OD}} = \frac{\delta_{\mathrm{g}}}{\lambda_{\mathrm{g}}} + \frac{\delta_{\mathrm{O}}}{\lambda_{\mathrm{O}}} = R_{\mathrm{Om}}\,, \quad (18)$$

where λ_{FD} is thermal conductivity indicator (coefficient) of nuclear fuel in design mode; λ_{FO}, λ_{Fr} is thermal conductivity indicator in the central and rim-zones of the fuel matrix; λ_{g}, λ_{O} is thermal conductivity of the gas gap and fuel element cladding; δ_{FD}, δ_{FO}, δ_{Fr}, δ_{g}, δ_{O} is thickness of the fuel matrix, central zone, rim-zone, gas gap and fuel element cladding.

After transforming equations (16) and (17) taking into account (11) and (18), we obtain that the optimization criteria (15) for the maximum 18-month fuel campaign can be ensured under the condition of modernization:

$$\mathrm{opt}\,R_{\mathrm{Fm}} = 1.5 R_{\mathrm{FD}}\frac{T_{\mathrm{FD0}}}{T_{\mathrm{FD0}} - T_{\mathrm{FDr}}}. \quad (19)$$

The main advantages of approach 2 over approach 1 for the strategy of increasing the TFC of NPPs are as follows.

1. No need to increase the nominal reactor power.

2. Possibility of qualifying for longer fuel campaigns.

The complex approach of the increased TFC strategy is based on the results of both approaches to increase TFC – increase in nominal power and modernization of the thermal resistance of the fuel element. Taking into account (7), (8), (11), and (19), the maximum efficiency indicator of the strategy of complex TFC increase is:

$$\max P_{\mathrm{e}} = \frac{N_{\mathrm{m}} f^{-1}_{\mathrm{Rm}} + T_{\mathrm{T}}}{N_{\mathrm{D}} f^{-1}_{\mathrm{RD}} + T_{\mathrm{T}}}\,, \quad (20)$$

where

$$f_{\mathrm{Rm}} = (\mathrm{opt}R_{\mathrm{Fm}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{gD}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{OD}}A_{\mathrm{O}})^{-1} + (\alpha A_{\mathrm{O}})^{-1}, \quad (21)$$

$$f_{\mathrm{RD}} = (R_{\mathrm{FD}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{gD}}A_{\mathrm{F}})^{-1} + (R_{\mathrm{OD}}A_{\mathrm{O}})^{-1}. \quad (22)$$

Thus, taking into account (13) and (19), a complex approach to increasing the TFC with increasing the nominal power and upgrading the thermal resistance of the fuel matrix of the fuel element can ensure the maximum time of the fuel campaign up to 21 months.

CONCLUSIONS

1. A complex approach has been developed to increase the design time of the fuel campaign of nuclear reactors, based on increasing the nominal power and upgrading the thermal resistance of fuel elements.

2. Increasing the nominal power of the reactor can be ensured with upgrading the neutron-physical parameters of nuclear fuel. It has been recognized that the maximum permissible increase in the nominal power is determined by the conditions for the start of thermoacoustic instability of the coolant in the reactor core that can lead to deformation and leakage of the fuel elements. The maximum permissible increase in the nominal power (other things being equal) qualifies the maximum time of the fuel campaign as no more than 15 months.

3. Increasing the time of the fuel campaign with upgrading the thermal resistance of fuel elements can be ensured by optimizing the thermal resistances of the two-phase fuel matrix model. The optimization criterion is the identity of the fuel cladding temperature of the design and upgraded thermal resistances of the fuel elements in the reactor operating modes at the design nominal power. Optimization parameters are the thermal resistances of the surface and central zones of the fuel matrix. The maximum time of the fuel campaign with upgrading the thermal resistance of the fuel elements is 18 months.

4. It has been recognized that a complex approach to increasing the time of the fuel campaign, based on increasing the nominal power and upgrading the thermal resistance of the fuel elements, can provide a maximum time of the fuel campaign of no more than 21 months.

5. The qualified maximum time of the fuel campaign is determined assuming the independence of the burn-up rate of nuclear fuel from temperature. This may be the subject of further study.

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КОМПЛЕКСНИЙ ПІДХІД КВАЛІФІКАЦІЇ ПІДВИЩЕНОЇ ТРИВАЛОСТІ ПАЛИВНОЇ КАМПАНІЇ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК

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Розроблено комплексний підхід підвищення проектної тривалості паливної кампанії ядерних реакторів, що базується на підвищенні номінальної потужності та модернізації термічного опору твелів. Підвищення номінальної потужності реактора може бути забезпечено модернізацією нейтронно-фізичних параметрів ядерного палива. Встановлено, що гранично допустиме підвищення номінальної потужності визначається умовами початку термоакустичної нестійкості теплоносія в активній зоні реактора, які можуть призвести до деформації та порушення герметичності твелів. Гранично допустиме підвищення номінальної потужності (за інших рівних умов) кваліфікує максимальну тривалість паливної кампанії не більшою за 15 місяців. Підвищення тривалості паливної кампанії модернізацією термічного опору твелів може бути забезпечене оптимізацією термічних опорів двофазної моделі паливної матриці. Критерій оптимізації – ідентичність температури оболонок твелів проектних і модернізованих термічних опорів твелів у робочих режимах реактора на проектній номінальній потужності. Параметри оптимізації – термічні опори поверхневої та центральної зон паливної матриці. Максимальна тривалість паливної кампанії модернізацією термічного опору твелів – 18 місяців. Установлено, що комплексний підхід підвищення тривалості паливної кампанії, що базується на підвищенні номінальної потужності та модернізації термічного опору твелів, може забезпечувати максимальну тривалість паливної кампанії не більшу за 21 місяць. Кваліфіковану максимальну тривалість паливної кампанії встановлено при допущенні незалежності швидкості вигоряння ядерного палива від температури, що може бути предметом подальшого вивчення.