https://doi.org/10.46813/2024-152-040

UDC 621.039

COOLING OF CONTROL RODS AND SPECIFICATION OF CRITICAL TEMPERATURES TO JUSTIFY SAFE OPERATION

V.A. Zuyok[1], V.V. Gann[1], V.V. Zigunov [1], A.D. Dzhamirzoiev[1],
O.S. Mazurok[2], O.V. Godun[3], A.A. Makarenko[4]
[1]National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;
[2]ES Group LLC, Kyiv, Ukraine;
[3]Scientific and Technical Center, JSC "NNEGC "Energoatom", Kyiv, Ukraine;
[4]Scientific and Technical Complex "E.O. Paton Electric Welding Institute" of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
E-mail: valeriyz@kipt.kharkov.ua

The paper analyzes the cooling conditions of the control rods in the mixed core of the WWER-1000 reactor containing fuel assemblies of different vendors (TVSA, WFA/RWFA). The coolant heat-up in the guide thimbles due to own energy release in control rod materials and control rod temperatures required to justify safe operation were calculated for the most conservative case, when the core consists only of TVSAs with a standardized guide thimble inlet plug of NCCP. The energy release was obtained using the calculation method for the boron carbide absorber (B_4C), dysprosium titanate ($Dy_2O_3 \cdot TiO_2$), control rod cladding (42CrNiMo), water gap between the cladding and the guide thimble and in the guide thimble (zirconium alloy), fully immersed and 70% immersed RCCA 10th control group. The highest calculated energy release will be observed in fully immersed control rods with boron carbide material at the height position corresponding to the zone of maximum neutron fluence and will be 43.8 W/cm^3. The maximum energy release of the 70% immersed (from the bottom of the core) 10th control group is 29.4 W/cm^3 for fresh B_4C. For the condition of the reactor facility at which the temperatures in FA guide thimbles are maximum, for a "fresh" control rod characterized by maximum energy release in the neutron-absorbing material, the maximum coolant heat-up in the guide thimbles does not exceed 28.9 °C, with the maximum coolant heat-up in FAs being 44 °C, and the maximum control rod cladding temperature not exceeding 335.6 °C at a coolant saturation temperature of 345.8 °C, which indicates that there will be no coolant boiling in the guide thimbles under operation. The maximum temperature typical for the central part of the control rod absorber and for the most conservative calculation for a "fresh" absorber is 529.6 °C, which is significantly lower the melting point of boron carbide, which is ~2350 °C. The maximum calculated temperature in the contact zone of the B_4C absorber with control rod cladding is 348 °C. The performed calculations and further analysis of the results confirm that during operation of the RCCA control rods with both "fresh" and "burned-up" B_4C, there will be no boiling of the coolant and melting of the absorber in the central part of the control rod. This means that the VVER-1000 core with TVSAs and WFAs/RWFAs and the RCCA rods are reliably cooled.

INTRODUCTION

Structural materials of the reactor core operate under extremely severe conditions during a long period of time at high coolant parameters and significant thermal loads. The rod cluster control assembly (RCCA) is an integral part of the WWER-1000 nuclear fuel cycle. The modern control rod (CR) of the RCCA consists of a cladding made of chromium-nickel alloy 42CrNiMo and a neutron-absorbing mandrel combined in height with dysprosium titanate powder ($Dy_2O_3 \cdot TiO_2$) in the lower part and boron carbide powder (B_4C) in the upper part. The CR is sealed with appropriate end plugs. The cladding of the RCCA control rod must meet many requirements, be mechanically reliable and ensure the stability of the shape, dimensions and tightness of the control rod during long-term operation in the reactor. Some characteristics of structural materials (e.g., mechanical) depend on temperature. Irradiation results in the degradation of the initial characteristics of structural materials, and the phenomena such as the evolution of point defects, phase transformations, radiation hardening, swelling and embrittlement, which also depend on temperature. For austenitic structural materials, most of these phenomena are observed in the temperature range from 300 to 400 °C. Given that the temperature of the WWER-1000 primary coolant can reach almost 350 °C, determining the temperature at which each of the CRs is operated is important for understanding the processes that occur in them and makes it possible to predict their performance.

Reactor irradiation leads to a number of phenomena that cause energy release not only in the reactor core structural materials, but even in the coolant. In this regard, each structural component must be reliably cooled by the coolant flow, and its amount must be sufficient to prevent its boiling on the surface of the structural component. The design of the core component should be such that even under conservative operating parameters, no melting of any of its elements is possible. This statement applies not only to the protective structural components, such as the fuel cladding and CR cladding, but also to the materials inside them, such as the fuel pellet or neutron-absorbing material. When justifying the safe operation of fuel, the temperature in the center of the fuel pellet must be calculated, which, under some operating parameters, can reach the melting point (~2805 °C).

Reactor irradiation of CRs results in significant energy release, and for CRs with "fresh" neutron-absorbing material in the fully immersed 10th group of the RCCAs, reaches 4.5 kW with a maximum local linear energy release of 20 W per 1 cm of control rod length. Long-term operation of the RCCAs in the reactor core results in some decrease in neutron absorption efficiency, and hence to a decrease and redistribution of energy release in the neutron-absorbing material along the rod cross section.

The temperature of control rod materials is affected not only by the energy release in them but also by the conditions of their cooling in the guide thimbles (GT). Ukrainian nuclear power units operate fuel assemblies from different vendors: TVSA by JSC TVEL and WFA/RWFA by Westinghouse, which have differences in certain structural components and hydraulic resistance. TVSAs supplied for the needs of Ukrainian NPPs have three modifications of the GT inlet plugs that limit the flow of coolant into the GTs for cooling of the CRs. That is, the CRs in different fuel assemblies with different GT inlet plugs designs will be cooled differently. Moreover, the presence of fuel assemblies of different designs (vendors) in the reactor core will also affect the cooling conditions for CRs, since they have different hydraulic resistance.

Currently, Ukrainian NPPs with WWER-1000 reactors face the issue of extending the service life of the already operating RCCAs and justifying the implementation of nationally fabricated RCCAs. This will require the justification their corrosion and radiation resistance, justification material compatibility at the contact temperature, and estimation the sufficiency of mechanical characteristics to maintain the integrity of the CR cladding and other RCCA components under all static and dynamic loads. These activities require calculation of the temperatures of CR structural materials in a mixed core (TVSAs and WFAs/RWFAs). This will enable further material science studies for the temperatures close to real ones and justify reliable cooling of CRs.

1. CALCULATION OF ENERGY RELEASE BY RADIUS AND HEIGHT POSITION OF B_4C ABSORBER

Reactor irradiation results in a number of phenomena that induce energy release in core materials. For structural materials, this is the interaction with γ-quanta and electrons, and for neutron-absorbing materials, this is also the interaction with neutrons. In an operating reactor, γ-quanta and electrons are produced as a result of nuclear interaction of neutrons with fissile isotopes and are emitted by radioactive products during decay. When a reactor operates at power, the proportion of fission sources is much higher than that of decay sources. The power of fission sources is proportional to the neutron flux density, which in turn is proportional to the power of nuclear fuel release in the axial zone in which the irradiated material is located (Fig. 1).

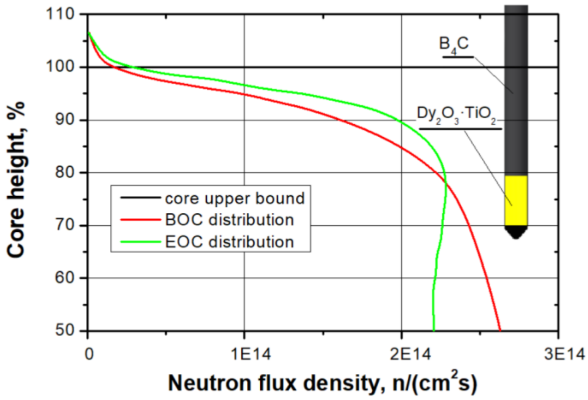


Fig. 1. Schematic axial distribution of fast neutron flux density by core height [1]

During operation, the neutron-absorbing materials of CRs are exposed to intense neutron irradiation in the reactor core and, due to a large cross section of thermal neutron absorption, they release intense heat. For boron carbide (B_4C), the main energy release reaction is the interaction of a neutron with a single neutron-absorbing isotope ^{10}B: $n + {}^{10}B \Rightarrow {}^{7}Li + {}^{4}He + 2.78$ MeV. For dysprosium titanate ($Dy_2O_3{\cdot}TiO_2$), this is a series of reactions with a number of dysprosium isotopes. With the same neutron flux density, the energy release in B_4C is about 5 times higher than that in $Dy_2O_3{\cdot}TiO_2$, and it is the energy release in B_4C that will play a key role in the overall energy release in the structural materials of CRs.

For the CRs immersed by 70% from the bottom of the core, which is the conservative case considered for WWER-1000 reactor (see Fig. 1), the dependence of the average energy release power in the CR sections on the height position for different points of operation time is shown in Fig. 2. Based on the results obtained, for fresh neutron-absorbing material B_4C, the energy release in the lower, most loaded part of the neutron-absorbing stack is 29 W/cm^3.

Boron carbide is a burnable neutron absorber because the products of ^{10}B and neutron interaction do not possess a significant neutron absorption cross section. The density of ^{10}B decreases, which leads to a decrease in neutron absorption efficiency and, as a result, a decrease in energy release over the operating time (Fig. 3).

The decrease in energy release is uneven for the entire absorber volume. The interaction cross section of B_4C with neutrons is quite significant (for a material with a natural boron isotope content it is ~ 760 barn). For fresh B_4C, neutrons are absorbed mainly by the outer layers of the material. The energy release in the lower part of the neutron-absorbing stack of B_4C in the peripheral layer reaches 86 W/cm^3 (Fig. 4,a).

The contribution of the B_4C peripheral layers to the total neutron absorption decreases over the operation time, which leads to a decrease in energy release.

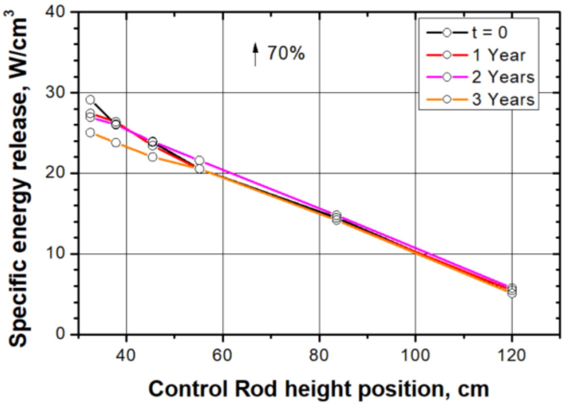


Fig. 2. Dependences of the specific energy release in the sections of CRs with B_4C on the height position for different periods of operation

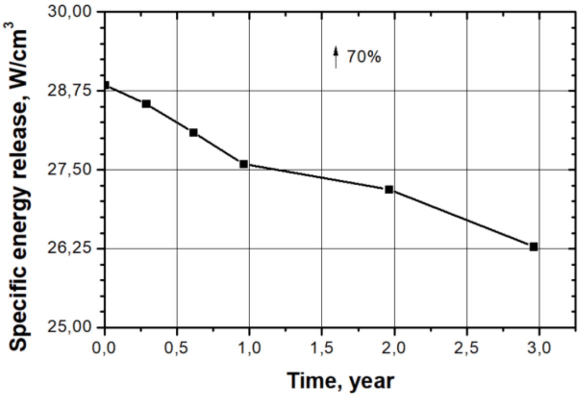
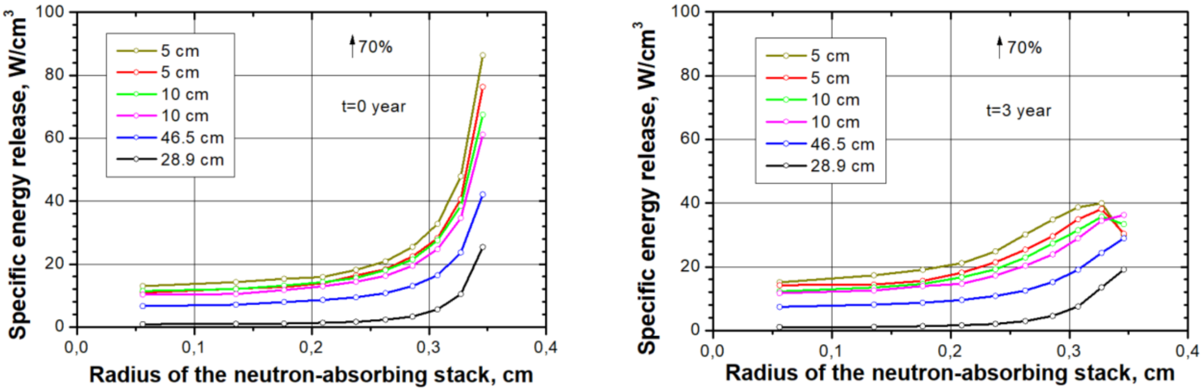


Fig. 3. Dependence of the average specific energy release on the operating time in the core at the 70% immersion depth of the RCCAs

After 3 years of operation, the energy release in the lower part of the peripheral layer will decrease from 86 to 30 W/cm^3. The middle and inner layers of B_4C will contribute more to the neutron absorption efficiency (see Fig. 4,b). Since the thermal conductivity of vibro-compacted boron carbide is only 0.3 W/(m·K) (573 K) [2], the shift of energy release to the central part of the CR can cause intense heating, which should be taken into account in further calculations.



a *b*

Fig. 4. Distribution of specific energy release by the radius of the B_4C neutron absorbing stack for different height sections of the CRs for time points t = 0 years (a) and t = 3 years (b)

The calculations showed that, with respect to the conservatism, further thermal calculations should be performed for fresh non-irradiated neutron-absorbing material, since it is characterized by the highest energy release, and the calculation of the temperature in the center of the B_4C absorber should also be performed for the material with the highest burnup by ^{10}B (after 3 years of operation).

2. COOLING OF THE CONTROL RODS AND CALCULATION OF TEMPERATURE ON THE CLADDING SURFACE

In the calculations, it is expedient to consider two positions of the RCCA control group in the reactor core:

– full immersion of the 10th control group (immersion at 0% from the bottom of the core, lower limit switch);

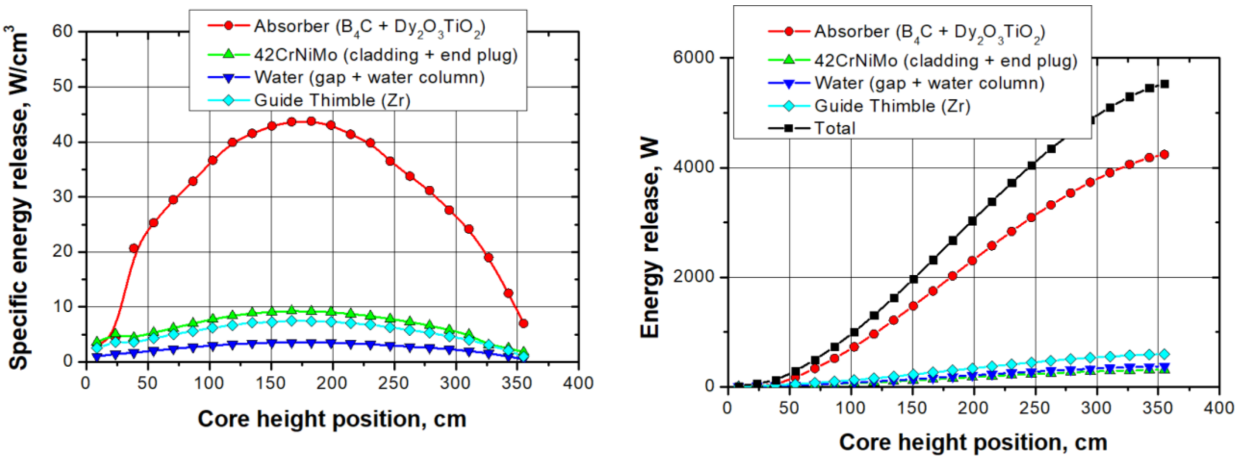
– partial immersion (operating state) of the 10th control group (70% immersion from the bottom of the core).

The calculations were performed for those zones along the CR height that overlap with the FA fuel stack. The total energy release, which results in the heat-up of the coolant in the GTs, comprises the energy release in the neutron-absorbing material (B_4C, $Dy_2O_3 \cdot TiO_2$), in the CR cladding (42CrNiMo alloy), in the water gap, and energy release in the GT material (zirconium alloy) for a fully immersed control group in FAs, in which the RCCAs with Kq = 1.35 are positioned (Fig. 5,a).

The results of the calculation of the total energy release power for the entire volume of material that can come into contact with the coolant in the GTs are shown in Fig. 5,b and Table 1.

Generalization of the calculation results for the energy release in different materials revealed that the total energy release power of GT and CR materials is 5513 W and is contributed primarily by the energy release in B_4C absorber (see Fig. 5,a), the contribution of other materials is much lower.

For the 70% immersed RCCA control group for the FA, in which the RCCA with Kq = 1.35 is positioned, the calculation results for the specific energy release are shown in Fig. 6,a. The results of the total calculation of the energy release by the entire volume of material that can come into contact with the coolant in the GT are shown in Fig. 6,b and Table 2.



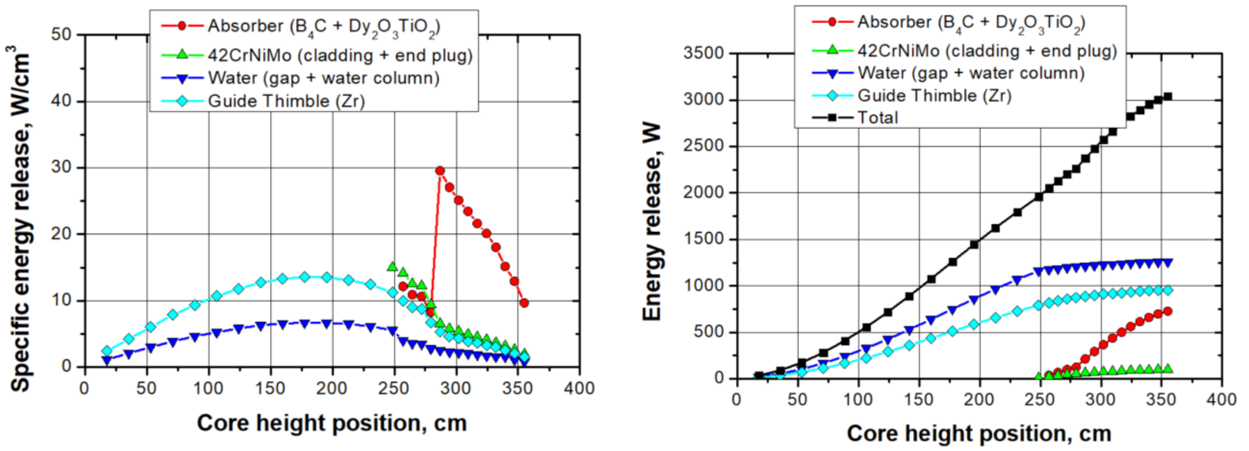
a *b*

Fig. 5. Distribution of specific energy release power (a) and energy release power (b) by height position at full immersion of the RCCA 10th control group

Table 1

Energy release power in GT and CR structural materials at full immersion of the RCCA 10th control group

Material	Total energy release power, W
Absorber ($Dy_2O_3{\cdot}TiO_2 + B_4C$)	4241
Alloy 42CrNiMo (cladding + bottom end plug)	311
Water	366
GT material	594
Total	**5513**



a *b*

Fig. 6. Distribution of specific energy release power (a) and energy release power (b) by height position for the 70% immersed RCCA 10th control group

Table 2

Energy release power in structural materials of the GTs and CRs for 70% immersed RCCA 10th control group

Material	Total energy release power, W
Absorber ($Dy_2O_3{\cdot}TiO_2 + B_4C$)	728
Alloy 42CrNiMo (cladding + bottom end plug)	99
Water	1258
GT material	959
Total	**3041**

Generalization of the calculation results for the energy release by different materials revealed that the total energy release power of GT and CR materials is 3041 W and is contributed primarily by the energy release in water and GT material (see Fig. 6,b), the contribution of other materials is much lower.

The temperature of CR materials is influenced not only by the energy release in it but also by the conditions of its cooling in the GT. Currently, Ukrainian NPPs operate Westinghouse fuel of RWFA and WFA modifications. The designs of the GTs and the plugs are identical in these FAs. At the same time, compared to TVSAs, the hydraulic resistance coefficients of WFAs and RWFAs are higher [3], and therefore the CR cooling conditions in WFAs and RWFAs are better than in TVSAs. The TVSAs supplied for the needs of

Ukrainian NPPs have three modifications of fuel inlet plugs, which can be conditionally labeled “Standardized NCCP”, “MSZ Bolt” and “NCCP Bolt” by their design features.

The inlet plug of the GT affects significantly on the volume of coolant that passes through the GT. The analysis of the GT inlet plugs design differences enables to arrange the plugs in the following row by decreased hydraulic resistance coefficient (HRC): “Standardized NCCP”, “MSZ Bolt” and “NCCP Bolt”. Taking into account the above, the TVSA with the GT plug “Standardized NCCP”, which has a central hole with diameter of 2 mm and the highest hydraulic resistance, should be considered as a limiting factor in terms of the cooling conditions of the CRs.

With an increase in the number of RWFAs in the core, which exhibit a higher hydraulic resistance, the cooling conditions for CRs in TVSAs will be improved. Taking into account the above, a homogeneous core with TVSAs is considered as a conservative case.

According to the report [4], during the tests of TVSA with the inlet plug “Standardized NCCP”, the coolant consumption and rate were measured for three positions of the RCCA, where for the fully immersed RCCA the coolant flow rate is 0.033 kg/s, for the partially immersed RCCA – 0.044 kg/s, and for the fully withdrawn RCCA – 0.047 kg/s.

The distribution of the coolant heat-up temperature in the GT along its height and the maximum heat-up temperature in the GT are calculated based on the data regarding the volume of coolant flowing through the GT, and taking into account the distribution of the total energy release power in the GT, in the CR, and in the water gap (Fig. 7).

For the calculation, it was assumed that all the heat from the GT is consumed to heat up the water in the GT. Heat exchange through the GT is absent. The coolant consumption corresponds to the data given in [4].

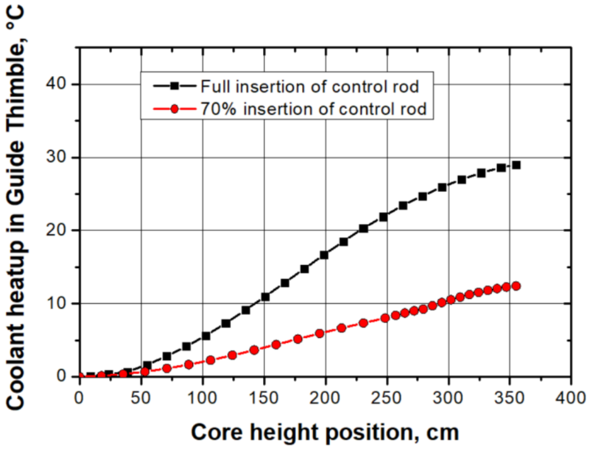


Fig. 7. Coolant het-up along the GT height with no heat exchange through the GT from/to the main coolant flow in FA

The coolant heat-up is calculated by the following expression:

$$\Delta T = \frac{Q}{(C_P \cdot m)}, \quad (1)$$

where ΔT – heat-up of the coolant, °C; C_P – heat capacity of water, J/(kg·°C); m – coolant consumption through the GT, kg/s.

The calculation results revealed that in the absence of heat exchange through the GT from/to the main coolant flow in the FA, the maximum heat-up of the GT coolant at the GT outlet would be 28.9 °C for a fully immersed CR and 12.4 °C for a 70% immersed one (Table 3).

Table 3

Parameters for calculation of the coolant heat-up

Parameter	Fully immersed CR	70% immersed CR
Coolant temperature at the GT inlet, °C	290	290
Coolant consumption through the GT, kg/s	0.033	0.044
Total heat release in the GT and CR, W	5513	3041
Coolant heat-up in the GT, °C	28.9	12.6

That is, for the most conservative case, for a fully immersed CR, the coolant heat-up in the GT due to energy release in the GT and CR does not exceed 28.9 °C. The coolant temperature on the outer side of the GT is higher than on the inner side when the reactor is at power operation. The maximum coolant heat-up at the FA can be up to 44 °C (temperature difference at the inlet and outlet of the FA) [5]. This will result in heat exchange through the GT and additional heat-up of the coolant inside the GT. For a fully immersed CR, such heat-up will be insignificant, since the temperature drop through the GT is insignificant, and for a 70% immersed CR, such heat exchange will be crucial for heating up the coolant column in the lower part of the GT (from the bottom of the GT to the bottom of the CR), 11350 W is required (with an average C_P=5490 J/(kg·°C)) to heat up the coolant in the GT by 44 °C (coolant consumption in the GT is 0.047 kg/s), with the fully withrdawn control rod. At the same time, the total energy release in the GT and CR structural materials is lower.

Depending on the immersion depth of the CR, the contribution of heat exchange to the overall heat-up of the coolant in the GT will differ and will contribute to the equalization of the external and internal temperatures. However, heat exchange cannot result in overheating of the coolant in the GT above the temperature of the main coolant flow. That is, to calculate the temperature on the surface of the CR cladding, to increase the conservatism of calculations, it can be assumed that the coolant heat-up temperature in the GT is equal to (or not greater than) the coolant heat-up temperature in FA (~ 44 °C), which is a conservative assumption for calculating the maximum temperature of the CR cladding outer surface.

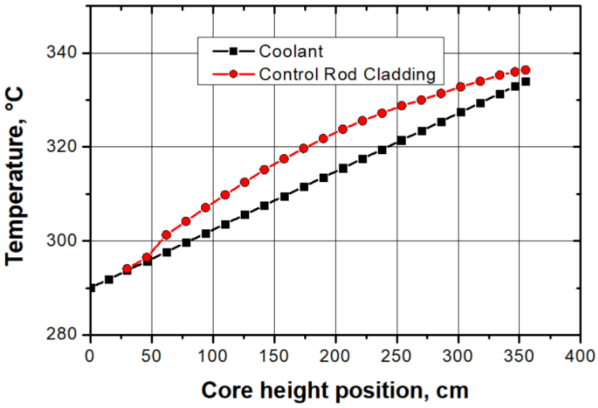
The temperature of the CR cladding outer surface, at each segment with a characteristic specific energy release power, was estimated by the formula:

$$t_i^s = t_i^{clnt} + \frac{q_i \cdot d_{CR}}{4 \cdot \alpha_i}, [^{\circ}C], \quad (2)$$

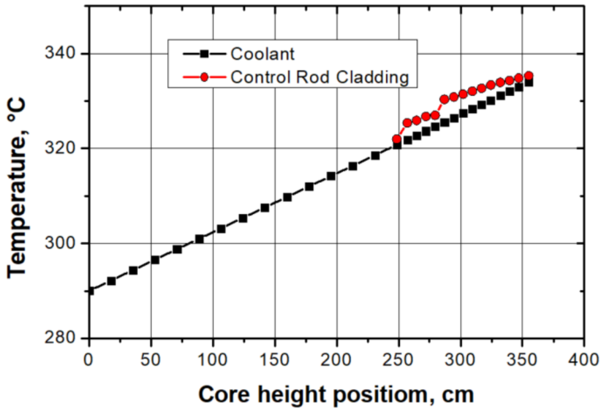
where t_i^s – temperature of the CR cladding outer surface in segment i; t_i^{clnt} – coolant temperature in segment i; q_i – specific energy release power of the CR in segment i; d_{CR} – diameter of the CR; α_i – coefficient of heat transfer from the CR to the coolant in segment i.

The table characteristics of the coolant were used for the calculations [6]. The parameters of the coolant for shorter temperature segments were calculated by approximating the data.

The heat transfer coefficient ranges from 11400 W/(m^2·°C) in the lower part of the GT to 12800 W/(m^2·°C) in the upper part of the GT under the coolant parameters in the GT. The specific energy release power in the CRs (CR + cladding) is shown in Figs. 5,b and 6,b. The temperature distribution of the coolant and CR cladding by core height for a fully immersed and 70% immersed RCCAs is shown in Fig. 8.



a



b

Fig. 8. Temperature distribution of the coolant and CR cladding by the core height for fully immersed (a) and 70% immersed (b) RCCAs

The calculation results showed (Table 4) that at a coolant temperature of 290 °C at the GT inlet and maximum coolant heat-up of 44 °C in FA and GT, the maximum temperature of the CR cladding for a fully immersed CR would be 335.6 °C, and for the CR immersed by 70% from the core bottom – 335.3 °C, which, at a coolant saturation temperature of 345.8 °C, gives a saturation margin of 10.2 and 10.5 °C, respectively.

Table 4

Calculation results for the CR cooling

Parameter	Fully immersed CR	70% immersed CR
Coolant temperature at the GT inlet, °C	290	290
Coolant consumption through the GT, kg/s	0.033	0.044
Coolant temperature at the GT outlet, °C	334	334
Coolant temperature at the FA outlet, °C	334	334
Maximum temperature of the CR cladding, °C	335.6	335.3
Coolant saturation temperature, °C	345.8	345.8
Saturation temperature margin, °C	10.2	10.5

3. ESTIMATION OF THE BORON CARBIDE ABSORBER TEMPERATURE

The maximum temperatures of the powder absorber in the central part of the neutron-absorbing B_4C stack and at the interface of B_4C – CR cladding were calculated. To calculate the maximum temperatures, there were used the calculation data of the specific energy release power distribution along the radius of the B_4C powder backfill with a density of 1.7 g/cm^3. These temperatures are necessary to confirm that the absorber temperature does not exceed the melting point (~2350 °C [2]) and for further studies of the boron carbide absorber compatibility with cladding materials (42CrNiMo, Cr18Ni10Ti).

The calculations are based on the model of heat transfer by conductivity (Fourier's law) for a long cylinder in a stationary mode (as the most conservative), taking into account the distribution of energy release power along the radius of the absorber. The temperature of the CR cladding outer surface was used as boundary conditions.

In order to verify the adequacy of the chosen method of estimation, a verification was performed by comparing the result of fuel pellet (fresh fuel) temperature calculation with generalized data for fuel. According to generalized literature data, the temperature in the center of a fuel pellet is 1379 °C for a fuel rod consisting of a fuel pellet, a cladding and a gap with helium, with a linear energy release of 341.5 W/cm and an external cladding temperature of 346.1 °C. And the calculations performed using the proposed model yielded a temperature of 1397 °C. Such a small difference between the generalized and calculated data confirms the reliability of the proposed computational model.

3.1. CALCULATIONS FOR CRS WITH FRESH POWDERED ABSORBER

The thermal conductivity of boron carbide powder depends to a greater extent on the density of the filling, and to a lesser extent on the particle size distribution in the powder. In addition to the above, the thermal conductivity of the vibration-compacted powdered B_4C used as a neutron-absorbing stack of the CR also depends on the pressure of helium gas under the CR cladding and should be obtained experimentally.

The thermal conductivity of the powdered absorber in the range from 100 to 600 °C, obtained by approximating the experimental data presented in [2], is described by the equation:

$$\lambda_{ap}(T) \approx 0.0004 + 9 \times 10^{-6} \times \mathrm{T}, \ \mathrm{W/(cm{\cdot}°C)}, \quad (3)$$

where T – temperature, °C; $\lambda_{ap}(T)$ – thermal conductivity of the powdered absorber (boron carbide) as a function of temperature, W/(cm·°C).

Experimental data on the thermal conductivity of 42CrNiMo alloy in the temperature range from 300 to 400 °C [7] can be approximated by a linear expression:

$$\lambda_{cl}(T) \approx 0.06 + 0.0003 \times \mathrm{T}, \ \mathrm{W/(cm{\cdot}°C)} \quad (4)$$

where T – cladding temperature, °C; $\lambda_{cl}(T)$ – thermal conductivity of the cladding (42CrNiMo) as a function of temperature, W/(cm·°C).

According to the results of the calculation of energy release in the B_4C absorber, for a fully immersed CR, the maximum energy release in fresh B_4C is at a height position of 190 cm from the CR bottom. The maximum calculated temperature (actual) of the cladding outer surface at the indicated height position is 321.8 °C. For the B_4C absorber in the CR, which is part of the 10th control group, immersed at 70% from the core bottom, the maximum energy release in fresh B_4C is located in the lower part, which corresponds to the height position of 287 cm. The maximum cladding temperature is 330.4 °C. The saturation temperature of the core coolant is 345.8 °C, which can be considered the maximum temperature of the CR cladding for conservative calculations.

The calculation results for the temperature distribution along the CR radius in the zone of maximum energy release are shown in Fig. 9. The maximum temperature of the powder filling is typical for the CR with the maximum conservative cladding temperature for the central part of the absorber of 529.6 °C (see Fig. 9,a). For the maximum calculated temperature of the cladding outer surface, the temperature in the center of the cladding will be 515.6 °C. The temperature in the contact zone of B_4C with the cladding depends on the temperature of the cladding outer surfaceand is 348 and 324 °C for realistic and conservative calculations, respectively.

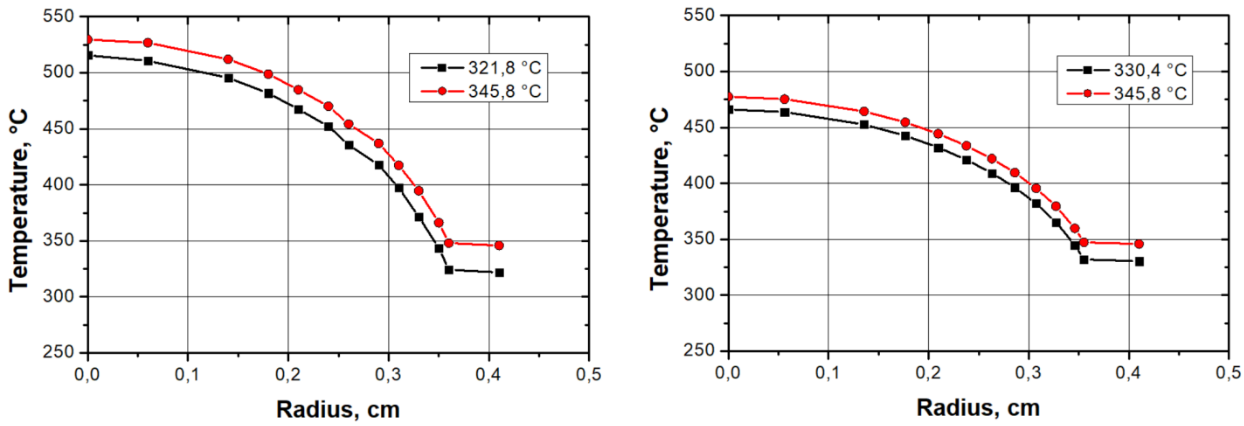
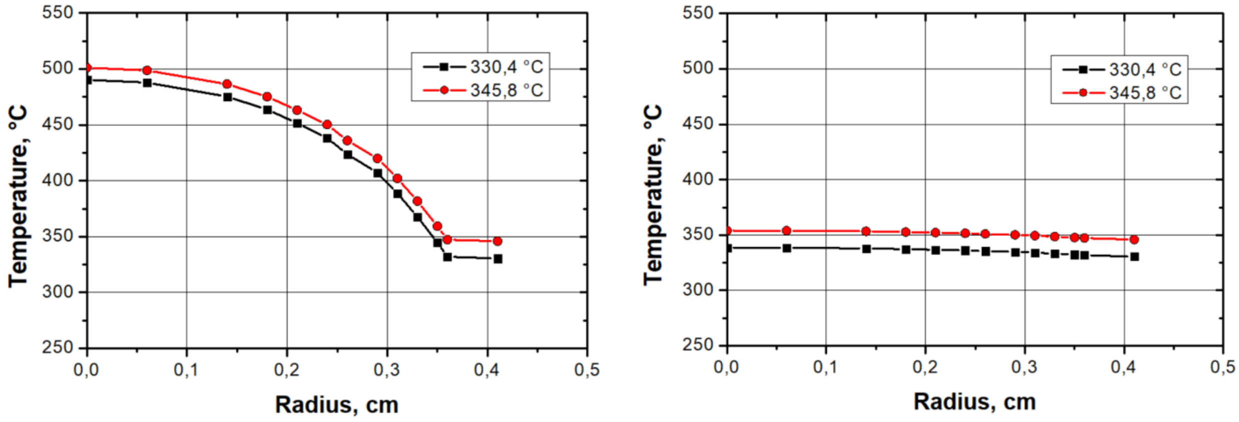


Fig. 9. Temperature distribution in B_4C absorber along the CR radius at different temperatures of the cladding outer surface for a fully immersed group (a) and 70% immersed (b) RCCAs

For a CR immersed by 70%, in the zone of maximum energy release in B_4C and at the temperature of the cladding outer surface corresponding to the saturation temperature of the coolant (345.8 °C), the temperature in the center will be 477.5 °C (see Fig. 9,b). The calculated temperature in the contact zone of B_4C with the CR cladding, will be 347.3 °C for the conservative case. For the actual temperature of the CR cladding, these temperatures will be lower.

3.2. CALCULATIONS FOR CRS AFTER 3 YEARS OF OPERATION WITH A POWDERED AND SINTERED ROD ABSORBER

The performed calculations enabled to obtain the temperature distribution along the radius of the "fresh" CR absorber for a fully immersed and 70% immersed RCCAs. For a "fresh" B_4C absorber, the main energy release is in the peripheral layers of the absorber. The isotopic composition of B_4C changes with the operation time. After 3 years of RCCA operation in the automatic control mode at 70% immersion, in the lower, most loaded part of the boron absorber, the averaged ^{10}B burnup by volume will be 40…42%. And the energy release power shifts to the central layers of the absorber. This redistribution of energy release power leads to an increase in the temperature in the central part of the CR to 501.1 °C (for a "fresh" CR absorber under similar conditions, it is 477.5 °C).



a *b*

Fig. 10. Temperature distribution of B_4C absorber along the CR radius at different temperatures of the cladding outer surface for a 70% immersed RCCAs after 3 years of operation, for powder (a) and sintered (b) absorber

When B_4C is burned up by ^{10}B for more than 35...40%, the powder turns into a monolithic mandrel. The thermal conductivity of sintered boron carbide differs significantly from that of powder [8], so the temperature in the center of the absorber will also differ. In the temperature range from 300 to 600 °C, the thermal conductivity of the mandrel can be described by the following expression:

$$\lambda(T) \approx 0.1198 - 7 \times 10^{-5} \times T \text{ , W/(cm·°C).} \quad (5)$$

Based on the calculated temperature distribution along the CR radius, for the RCCA control group immersed by 70% from the bottom of the core, the maximum temperature of the sintered B_4C after 3 years of operation is observed in the center of the absorber and, for the most conservative case, is not greater than 354 °C.

CONCLUSIONS

1. The energy release was obtained using the calculation method for the boron carbide absorber (B_4C), dysprosium titanate ($Dy_2O_3·TiO_2$), CR cladding (42CrNiMo), water gap between the cladding and the guide thimble and in the guide thimble (zirconium alloy), fully immersed and 70% immersed RCCA 10th control group.

2. The highest calculated energy release will be observed in fully immersed CRs with boron carbide material at the height position corresponding to the zone of maximum neutron fluence and will be 43.8 W/cm^3. The maximum specific energy release of the 70% immersed (from the bottom of the core) RCCA 10th control group is 29.4 W/cm^3 for fresh B_4C.

3. Taking into account the conservatism, it is expedient to perform thermal calculations for "fresh" non-irradiated neutron-absorbing material B_4C, since it is characterized by the highest energy release, and to obtain the temperature in the center of B_4C absorber also for the material with the highest burnup by ^{10}B (after 3 years of operation), since the energy release in it shifts to the central layers of the absorber.

4. Taking into account the main features and differences of TVSA and WFA/RWFA designs, it is concluded that the thermal calculation of TVSA with a standardized GT end plug of NCCP should be considered as limiting in terms of cooling conditions for the RCCA CRs. And with RWFAs present in the core, which exhibit a higher hydraulic resistance, the cooling conditions for CRs in TVSAs are improved.

5. For the condition of the reactor facility, at which temperatures in the GTs of FAs are maximum, for a "fresh" CR, which is characterized by maximum energy release in neutron-absorbing material, the maximum value of the CR cladding temperature does not exceed 335.6 °C at a coolant saturation temperature of 345.8 °C, which indicates that there will be no boiling of the coolant in the GTs under operation. This means that the WWER-1000 core with TVSAs and WFAs/RWFAs, which contain RCCAs, is reliably cooled.

6. Despite the radial zone of maximum energy release in B_4C ("fresh" or "burned up" absorber), for all the cases considered, the maximum temperature is observed in the center of the CR absorber and for the most conservative calculation for the "fresh" absorber it will be 529.6 °C, which is significantly lower than the melting point of boron carbide, which is ~ 2350 °C.

7. The maximum calculated temperature in the contact zone of B_4C absorber with CR cladding is 348 °C, which must be taken into account when justifying their compatibility.

8. The performed calculations and further analysis of the results confirm that during operation of the RCCA control rods with both "fresh" and "burned up" B_4C, there will be no boiling of the coolant and melting of the absorber in the central part of the CR. This means that the WWER-1000 core with TVSAs and WFAs/RWFAs and the RCCA rods are reliably cooled.

REFERENCES

1. V. Zuyok, O. Mazurok, O. Godun, M. Chaikovskyi, M. Tretyakov. Materials Science Analysis of RCCA Structural Materials and Calculations for Lifetime Extension // *Nuclear and Radiation Safety*. 2024, v. 101 (1), p. 38-48; https://doi.org/10.32918/nrs.2024.1(101).04

2. B.A. Kushunin. *Boron carbide filler for control rods of VVER-1000 reactor*: Verification report. M., 1999.

3. I.A. Shevchenko, Y.Y. Vorobiev. Verification of Safety Criteria for Mixed Nuclear Fuel Loading for

VVER-1000 Reactors // N*uclear and Radiation Safety*. 2015, v. 66 (2), p. 3-7.

4. *Thermal-hydraulic calculations of control rod cooling and determination of coolant heating in TVSA for variants of GC tips*: Report. Inv. No. 10581, Afrikantov OKBM, 2006.

5. *Technological Regulations for Safe Operation of Rivne NPP Unit 4. 4-R-RNPP*.

6. S.L. Rivkin, A.A. Aleksandrov. *Thermophysical properties of water and water vapor.* M.: “Energia”, 1980.

7. M.I. Solonin, V.P. Rondrat`ev, V.N. Rechitsky, et al. KhNM-1 alloy as a promising structural material for water-cooled fusion reactjr components // *Journal Nuclear of Materials*. 1996, v. 233-237, p. 586-591.

8. V.D. Rysovanyi, A.V. Zakharov, E.P. Klochkov. *Absorbing materials and control rods of nuclear reactors: textbook for universities.* MPEI Publishing House, 2012, p. 392.

Article received 05.07.2024

ОХОЛОДЖЕННЯ ПЕЛ ТА ВИЗНАЧЕННЯ ВАЖЛИВИХ ТЕМПЕРАТУР ДЛЯ ОБҐРУНТУВАННЯ БЕЗПЕЧНОЇ ЕКСПЛУАТАЦІЇ

В.А. Зуйок, В.В. Ганн, В.В. Зігунов, А.Д. Джамірзоєв, О.С. Мазурок, О.В. Годун, А.А. Макаренко

Проаналізовано умови охолодження ПЕЛ ПС СУЗ у складі змішаної активної зони реактора ВВЕР-1000, що містить палива різних виробників (ТВЗА, ТВЗ-W/WR). Для найбільш консервативного випадку, коли активна зона складається лише за палива ТВЗА з уніфікованим вхідним наконечником НК НЗХК, визначено підігрів теплоносія в НК за рахунок власного енерговиділення в матеріалах ПЕЛ та розраховано температури ПЕЛ, необхідні для обґрунтування безпечної експлуатації. Розрахунковим шляхом визначено енерговиділення для поглинача карбіду бору (B_4C), титанату диспрозію ($Dy_2O_3{\cdot}TiO_2$), оболонки ПЕЛ (42ХНМ), водяного зазору між оболонкою та напрямним каналом та в напрямному каналі (сплав цирконію), для ПЕЛ повністю зануреної та зануреної на 70% 10-ї регулюючої групи. Найбільше розрахункове енерговиділення спостерігатиметься при повному зануренні ПЕЛ з матеріалом карбіду бору на висотній позначці, яка відповідає зоні максимального флюенсу нейтронів та становить 43,8 Вт/см^3. Максимальне енерговиділення зануреної на 70% (від низу активної зони) 10-ї регулюючої групи для свіжого B_4C становить 29,4 Вт/см^3. Для стану реакторної установки, при якому температури у НК ТВЗ максимальні, для «свіжого» ПЕЛ, що характеризується максимальним енерговиділенням у нейтронно-поглинаючому матеріалі, максимальний підігрів теплоносія у НК не перевищує 28,9 °С при максимальному підігріві теплоносія на ТВЗ 44 °С, а максимальне значення температури оболонки ПЕЛ не перевищує 335,6 °С за температури насичення теплоносія 345,8 °С, що свідчить про відсутність кипіння теплоносія у НК під час експлуатації. Максимальна температура характерна для центральної частини поглинача ПЕЛ та для найбільш консервативного розрахунку для «свіжого» поглинача становить 529,6 °С, що значно нижче температури плавлення карбіду бору, яка становить ~ 2350 °С. Максимальна розрахункова температура в зоні контакту поглинач B_4C-оболонка ПЕЛ становить 348 °С. Проведені розрахунки та подальший аналіз результатів підтверджують, що під час експлуатації ПЕЛ ПС СУЗ як зі «свіжим», так і з «вигорілим» поглиначем B_4C буде відсутнє кипіння теплоносія та розплавлення поглинача в центральній частині ПЕЛ. Це значить, що активна зона ВВЕР-1000 з ТВЗА та ТВЗ-W/WR та сам ПЕЛ ПС СУЗ надійно охолоджуються.