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ASSESSMENT OF THE OPERATING TEMPERATURE OF ABSORBER ASSEMBLY STRUCTURAL COMPONENTS AND CONFIRMATION OF THEIR COOLING RELIABILITY IN VVER-440 REACTOR CORE

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The specific energy release in the structural materials of the absorber assembly (control part of the accident control assembly – ACA, also known as the shim assembly) has been calculated. It depends on the power of the fixed fuel assemblies (FAs) in adjacent cells. The value of the energy release is 17.5 W/cm^3 on the most loaded section of the boron absorber insert for an average Kq=1.28 over sectors. The total energy release in the structural materials of the absorber assembly, in the coolant, and in the connecting bar material is 229 kW for fully inserted controls and 64 kW for controls lifted up by 154.8 cm from the core bottom. The surface temperature distribution in the absorber insert along the absorber assembly height is conservatively calculated based on the total energy release in the absorber insert material and the amount and rate of coolant flow through it. At a coolant temperature around the absorber insert corresponding to the maximum coolant heating in adjacent fixed FAs (46.6 °C), and in the absence of axial heat exchange, the maximum surface temperature of the absorber insert for fully inserted controls will be 312.7 °C (outer surface), and for controls lifted from the core bottom to 154.8 cm – 317.1 °C (inner surface), giving a margin to saturation of 14.3 °C and 9.9 °C, respectively, at a coolant saturation temperature of 327 °C. In the most conservative case considered in this paper, the maximum surface temperature of the absorber insert is lower than the coolant's saturation temperature. This indicates the absence of bulk and surface boiling of the coolant under operation of the most energy-loaded component, i.e., the absorber insert of the absorber assembly, meaning that the structural components of the absorber assembly will be reliably cooled in the VVER-440 reactor core.
Keywords: *VVER-440; Accident control assembly; Absorber assembly; Absorber insert; Energy release; Cooling*
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INTRODUCTION

The structural materials of the reactor core operate for long periods under severe mechanical loads, neutron irradiation, high coolant parameters, and significant thermal loads. The absorber assembly of the follower fuel assembly is an integral part of the VVER-440 nuclear fuel cycle and is operated in Units 1 and 2 of the Rivne NPP.

Reactor irradiation results in a series of phenomena that cause energy release not only in the core's structural materials but also in the coolant. In this regard, each structural component must be reliably cooled by the coolant flow, and there must be sufficient coolant volume to prevent boiling on its surface. The design of a core component must be sufficient to prevent any of its parts from melting, even under conservative operating conditions.

At present, the issue of justifying the implementation of nationally produced absorber assemblies is relevant for Ukrainian NPPs with VVER-440 reactors. This requires work to be done to justify their corrosion and radiation resistance, the compatibility of materials at contact temperatures, and specify the adequacy of mechanical characteristics to maintain the structural integrity of the absorber assembly components under all static and dynamic loads. Most of the listed phenomena and mechanisms depend on the temperature of the material, and corrosion resistance also depends on the state of the coolant (i.e. water, steam). The work to justify safe operation requires specifying the temperatures of the absorber assembly structural materials in a mixed core (fuel produced by JSC TVEL and Westinghouse). This will enable further materials research at temperatures close to real ones and justify its reliable cooling.

1. GENERAL DESCRIPTION OF THE VVER-440 ABSORBER ASSEMBLY DESIGN

The accident control assembly (ACA) is the actuating component of the VVER-440 control and protection system. The ACA consists of a follower fuel assembly (the fuel part) and an absorber assembly (the control part). ACAs are the reactivity control components (controls) of the reactor control and protection system and 37 of them are the part of the VVER-440 reactor core [1].

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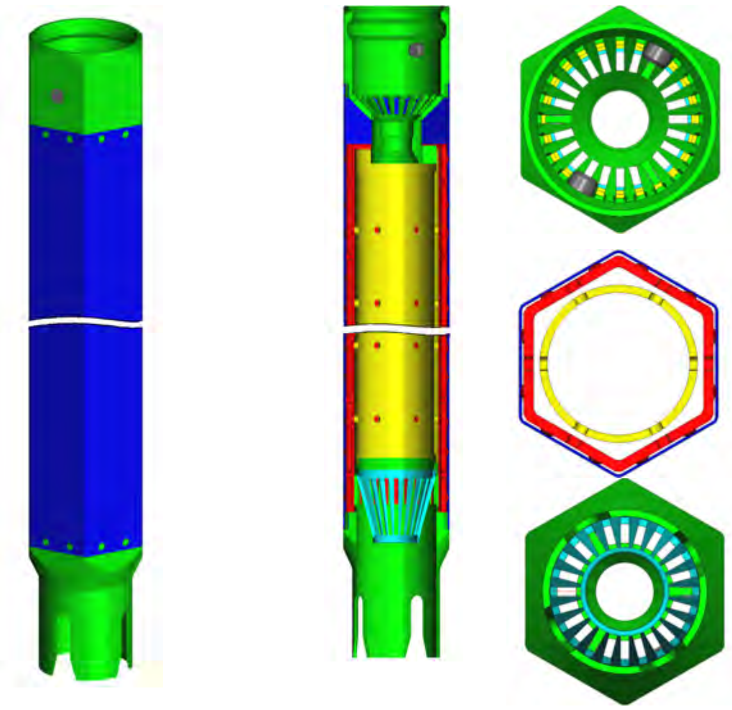
The follower FA and the absorber assembly of the ACA are connected by a connecting bar. The absorber assembly (Fig. 1) has a welded structure with a total mass of 110 kg. It is made of stainless steel and contains a boron steel hexagonal insert. The components of the absorber assembly are made of the following materials [2]:

- shroud – steel X6CrNiTi18-10 (1.4541);
- absorber insert – boron stainless steel (1.6…2.0% of boron);
- central tube and flow limiter – steel X6CrNiTi18-10 (1.4541);
- top nozzle – steel X6CrNiTi18-10 (1.4541);
- bottom nozzle – steel X6CrNiTi18-10 (1.4541).



a b c

Figure 1. Schematic view of the absorber assembly: a – general view; b – vertical section; c – top view, cross-section, bottom view

The connecting bar linking the follower FA to the absorber assembly is made of 08Cr18Ni10T steel. As shown below, it is the chemical composition of the material and the position of the absorber assembly components in the reactor core that account for the energy release in it.

ACAs can move in a vertical channel formed by six adjacent fixed FAs, a hexagonal slot in the bottom plate of the core basket, and the bottom tubes of the core barrel (Fig. 2). When the ACA is in the lower position, the fuel part is located in the core barrel bottom tubes and the absorber assembly is in the core. In this position of the ACA, energy release in the absorber assembly materials will be maximal and the coolant temperature at the inlet will be minimal. The main positions of the ACA, namely full and partial insertion, are shown schematically in Fig. 2. Above the core, there is a protective tube unit that separates the fixed FAs and has protective tubes in which the ACAs can move vertically.

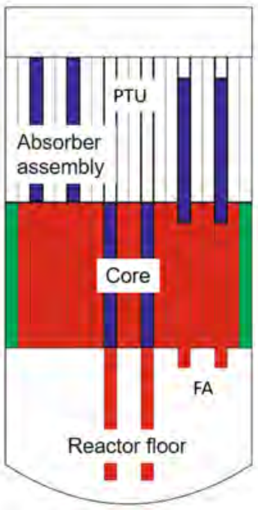


Figure 2. Schematic view of the lower part of the reactor pressure vessel and various positions of the ACAs

The design features of the VVER 440 reactor core affect the energy released in the absorber assembly materials and the coolant temperature at the inlet. Therefore, they are important for determining the operating temperature and ensuring cooling reliability.

2. ENERGY RELEASE IN THE ABSORBER ASSEMBLY MATERIALS

Reactor irradiation results in a series of phenomena that cause the release of energy in the core materials. For structural materials, this interaction involves γ-quanta and electrons; for neutron-absorbing materials, it also involves neutrons. In an operating reactor, γ-quanta and electrons are generated by the nuclear interaction of neutrons with fissile isotopes and are also emitted by radioactive decay products. During power operation, the fraction of fissionable sources is much larger than that of decay sources; therefore, the latter can be disregarded. The power of fission sources is proportional to the neutron flux density, which in turn is proportional to the energy release power of the nuclear fuel in the axial zone (according to the energy release profile at different heights (Kz)) in which the irradiated material is located.

The energy release profile for each stage of reactor core operation is characterized by a curve fitting the maximum energy release values along the height of the fuel assemblies from the same year of operation. These profiles were calculated for the beginning (BOC), middle (MOC), and the end (EOC) of the fuel cycle for assemblies in the first to fifth/sixth years of operation [3]. The BOC is characterized by a single-maximum profile with a maximum Kz close to

1.2, and the EOC – 1.1, which is less conservative for further calculations. Considering this, to calculate the energy release in the absorber assembly components, the profile with the maximum Kz (1.1985), which is typical of a "fresh" assembly at the BOC, was used (Fig. 3).

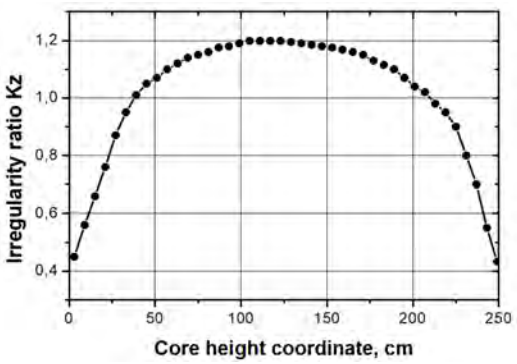


Figure 3. Distribution of relative energy release by height of the core at the BOC [3]

Reactor irradiation results in a series of phenomena that cause the release of energy in the core materials. For structural materials, this interaction involves γ-quanta and electrons; for neutron-absorbing materials, it also involves neutrons.

The absorber assembly materials do not contain fissile materials. The total energy release in the absorber assembly materials, which can result in heating of the coolant passing through it, depends on the energy release power of the fixed FAs located in adjacent cells. The Kq of the six assemblies in adjacent cells varies significantly, ranging from 1.4 to 1.1. It is assumed that the average Kq over sectors is 1.28.

For the absorber insert material, which is made of stainless steel containing 1.6-2.0% boron, energy release will also be due to neutron absorption and interaction with γ-quanta and electrons. For boron (B), the main energy release reaction is the interaction of a neutron with the ^{10}B isotope: n + ^{10}B => ^{7}Li + ^{4}He + 2.78 MeV.

Using the calculation model developed in the HELIOS software (Fig. 4), the energy release in the absorber material containing 1.8% natural boron, with a ^{10}B isotope content of 19.8%, was calculated (Table 1).

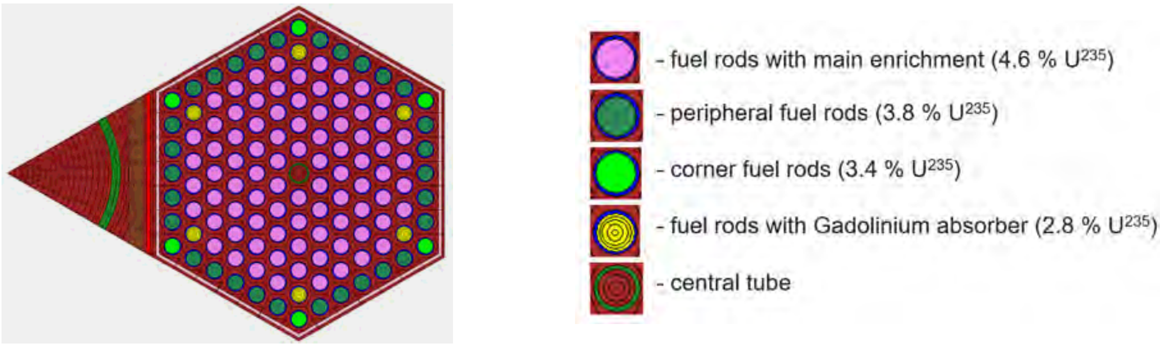


Figure 4. Calculation model of the absorber assembly segment at the level of the absorber inserts next to the fixed FA 427WN, implemented in the HELIOS software

The calculations reveal that, for the case considered in this paper, the maximum averaged over sectors specific energy release power in the most loaded part of the boron absorber insert is 17.5 W/cm^3. The energy release is almost the same across different sectors of the radial and azimuthal cross-sections of the absorber insert. Considering that the absorber insert material is mainly stainless steel, which has a high thermal conductivity, the average energy release across the cross-section of the absorber insert was used for further calculations.

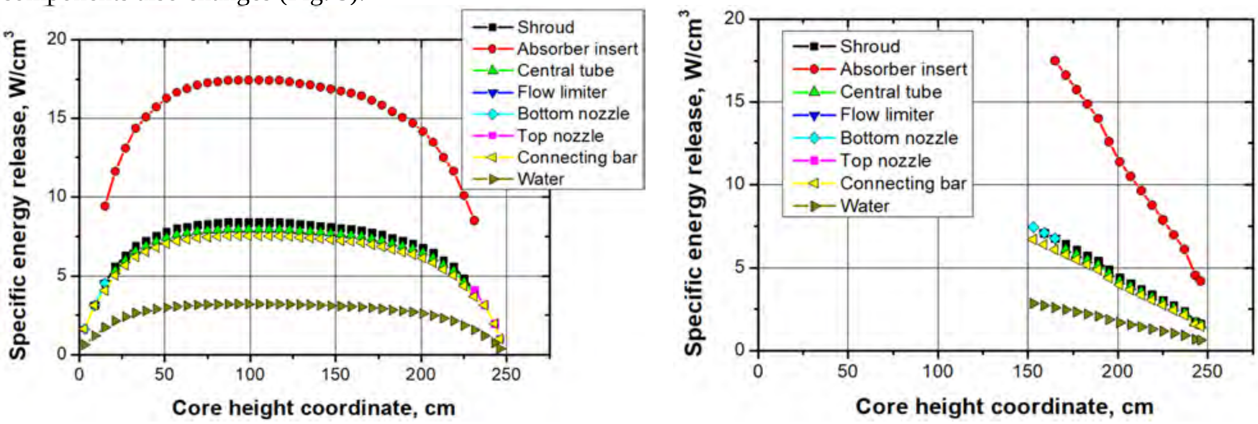
Table 1. Energy release in the absorber inserts material of the absorber assembly

Energy release, W/cm^3							
	Cell number in the radial direction						
Cell number in the azimuthal direction		6	5	4	3	2	1
	1	**17.03**	**16.69**	**16.73**	**16.96**	**17.45**	**18.28**
	2	**17.05**	**16.79**	**16.86**	**17.15**	**17.73**	**18.72**
	3	**16.98**	**16.79**	**16.91**	**17.26**	**17.90**	**18.94**
	4	**17.00**	**16.82**	**16.95**	**17.31**	**17.96**	**19.01**
	5	**16.98**	**16.79**	**16.91**	**17.26**	**17.90**	**18.94**
	6	**17.05**	**16.79**	**16.86**	**17.15**	**17.73**	**18.72**
	7	**17.03**	**16.69**	**16.73**	**16.96**	**17.45**	**18.28**

When calculating energy release in the materials of the absorber assembly structural components, two positions of the controls in the VVER-440 reactor core during operation at the corresponding power level were considered:

- full insertion. The absorber insert of the absorber assembly is located in the middle of the core (in the area of maximum energy release);
- partial insertion (operating condition). The controls are partially inserted in the core to a lower position of 154.8 cm (from the core bottom).

In addition to the structural materials of the absorber assembly main components (Section 1), the coolant flowing through the absorber assembly will also be heated by the connecting bar and the energy release in the water (coolant) itself. The distribution of specific energy release power by height of the absorber assembly structural components for the fully inserted and lifted to 154.8 cm controls is shown in Fig. 5. Accordingly, with a change in the height of energy release in adjacent assemblies in the core (Fig. 3), the energy release in the materials of the absorber assembly structural components also changes (Fig. 5).



a b

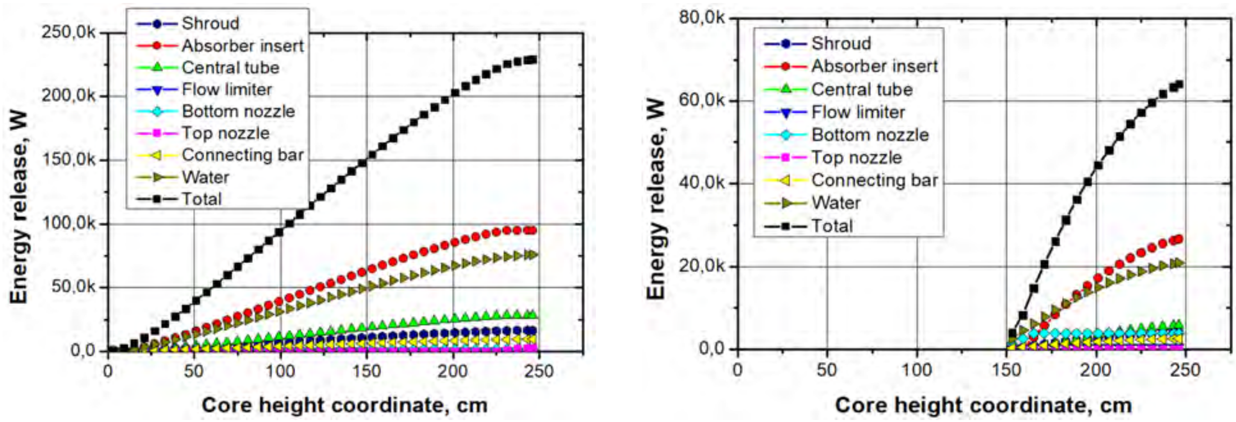
Figure 5. Distribution of specific energy release power by height of the absorber assembly structural components for the controls fully inserted (a) and lifted to 154.8 cm from the core bottom (b)

A comparison of the specific energy release in materials of the VVER-440 absorber assembly structural components and materials of the VVER-1000 rod cluster control assembly (RCCA), presented in the paper [4] shows that for fully inserted controls, the specific energy release in the structural materials (except for the absorber material) and water is comparable to the data given in the above-mentioned paper. This comparability may be due to the comparable neutron flux density in the mentioned reactors. However, the specific energy release in the VVER-1000 RCCA absorber (B_4C) is significantly higher than for the absorber material of the VVER-440 absorber assembly, which is due to the higher boron content per unit volume of the absorber.

The total energy release power in the absorber assembly materials at full insertion of the controls is 229 kW, and the maximum energy release is in the absorber insert material (95 kW) (Fig 6a, Table 2).

Table 2. Energy release in the absorber assembly structural materials for fully inserted controls

Structural component	Volume, cm^3	Total energy release, W
Shroud	2291	16388
Absorber insert	6265	95220
Central tube	3974	28116
Flow limiter	55	233
Bottom nozzle	447	1518
Top nozzle	899	2436
Connecting bar	1537	9452
Coolant	28845	75986
Total		**229 349**



a b

Figure 6. Distribution of total energy release power by height of the absorber assembly for the controls fully inserted (a) and lifted to 154.8 cm from the core bottom (b)

The total energy release in the absorber assembly materials of the lifted to 154.8 cm controls is 64 kW, while the maximum energy release in the absorber insert material is 26 kW (Fig. 6b, Table 3).

Table 3. Energy release power in the absorber assembly structural materials for the controls lifted to 154.8 cm

Structural component	Volume, cm^3	Total energy release, W
Shroud	907	4025
Absorber insert	2429	26680
Central tube	1484	5732
Flow limiter	55	422
Bottom nozzle	536	3816
Top nozzle	0	0
Connecting bar	609	2534
Coolant	11754	20911
Total		**64 120**

In both cases, the highest energy release occurs in the absorber insert material. It is reasonable to calculate the margin to the saturation temperature for the most heat-loaded component of the absorber assembly, i.e., the absorber insert.

3. COOLANT HEATING IN THE ABSORBER ASSEMBLY

Based on the data on the total volume of coolant flowing through the absorber assembly and the distribution of the total energy release power in the absorber assembly, the distribution of the coolant heating temperature along the height of the absorber assembly and the maximum coolant heating temperature in it are calculated.

The calculation assumes that all the heat from the absorber assembly structural components is spent on heating water in the absorber assembly channel. There is no heat exchange through the shroud. In accordance with [1], the coolant flow rate through the fixed FA and follower FA is not less than 100 m^3/hour. All coolant flowing through the follower FA also flows through the absorber assembly. According to Tables 3.3–3.8 of [5], the average coolant temperature at the reactor inlet is 266 °C, and the average coolant temperature at the outlet of the follower FA fuel rod bundle of the most heat-loaded second-generation ACA, manufactured in the russian federation and the NOVCC manufactured by Westinghouse, does not exceed 310 °C in all cases.

According to the basic thermal-hydraulic characteristics of the Rivne NPP Unit 1 reactor [6], the coolant flow rate through the follower FA is not less than 120 m^3/hour, and for the Rivne NPP Unit 2 [5] is 123 m^3/hour. In accordance with the operating conditions of the absorber assembly specified in the technical specifications [2], the minimum coolant flow rate through the follower FA and the absorber assembly is 100 m^3/hour, which at a coolant density of 0.777 g/cm^3 is 21.6 kg/s.

The water heat capacity (C_P) is 4936 J/(kg·°C) at temperatures above 266 °C and 6199 J/(kg·°C) at the maximum coolant temperature at the assembly outlet (310 °C). Coolant heating is described by the following expression:

$$\Delta T = \frac{Q}{(C_P \cdot m)}, \quad (3.1)$$

where:

ΔT – coolant heating, °C;

Q – total heat release capacity, W;

C_P – water heat capacity, J/(kg·°C);

m – coolant flow rate through the absorber assembly, kg/s.

The calculation results demonstrated that, in the absence of heat exchange through the absorber assembly shroud, the maximum coolant heating would be 1.9 °C for the fully inserted controls and 0.53 °C for the controls lifted to 154.8 cm (Fig.7, Table 4).

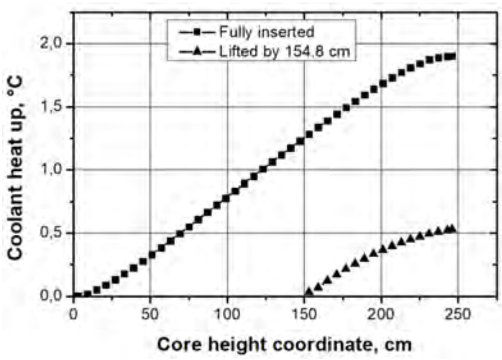


Figure 7. Coolant heating in the absence of heat exchange through the absorber assembly shroud

An increase in energy release in six fixed FAs located in adjacent cells, with the averaged for these FAs Kq = 1.28, to a value corresponding to Kq = 1.47 will result in increased energy release in structural materials. In the absence of heat exchange, this will cause the coolant to heat up to 2.4 °C in the case of a full insertion of the controls.

In the absence of heat exchange through the shroud, the coolant heating is insignificant, and the temperature at the outlet of the absorber assembly will be controlled by the temperature at the outlet of the follower FA. For the case of fully inserted controls, with a residual energy release in the follower FA of 250-300 kW, the coolant temperature at the inlet to the absorber assembly will be approximately ~2 °C higher than the coolant temperature at the inlet to the adjacent fixed FAs.

Table 4. Parameters for calculating coolant heating

Parameter	Fully inserted controls	Controls lifted to 154.8 cm
Coolant temperature at the inlet of the absorber assembly, °C	268	266
Coolant flow rate through the absorber assembly, kg/s	21.6	21.6
Total heat release in the absorber assembly, W	229349	64120
Coolant heating in the absorber assembly, °C	1.90	0.53

When the absorber assembly is partially inserted, due to significant energy release in the follower FA, the heating of the coolant flowing through the follower FA will be significant. The maximum heating of the coolant in the most thermally loaded follower FA is in the range of 40-41 °C (depending on the FA type, their number and positions in the mixed core). For the most conservative calculation (minimum coolant flow, etc.), the maximum heating reaches 44.4°C [5].

For further calculations of the cooling reliability of the absorber insert, which is the most energy-loaded structural component, it can be conservatively assumed that the coolant temperature at the inlet of the absorber assembly will correspond to the temperature at the outlet of the follower FA with heating in it, which is characteristic of this axial area and has a maximum of 44.4 °C at full withdrawal of the absorber assembly.

4. MAXIMUM TEMPERATURE OF THE ABSORBER INSERT AND MARGIN TO THE SATURATION TEMPERATURE

To increase the calculations' conservatism, it was assumed that the temperature of the shroud and coolant near the absorber insert corresponds to the coolant temperature of the adjacent fixed FAs, taking into account the corresponding axial position. According to Report [5], the maximum heating temperature of the Rivne NPP Unit 2 reactor core is 46.6 °C. In further calculations, it is assumed that the coolant heating temperature in all adjacent fixed FAs is 46.6 °C.

The surface temperature of the absorber insert was assessed for each segment with a characteristic specific energy release. As the absorber insert is a semi-hexagonal prism, temperature calculations were performed for a flat wall with two-sided cooling by solving conventional one-dimensional inhomogeneous differential equations for a steady-state case (axial heat flow was conservatively not taken into account).

The absorber inserts were conventionally divided into 5-6 cm segments by height, which conventionally have similar specific energy release power (Fig. 5) and heat transfer coefficient (coolant parameters) by height.

Taking into account that the heat fluxes from the considered wall on the outer surface (in the gap between the absorber insert and the shroud) and the inner surface (the gap between the central tube and the absorber insert) are different, the maximum temperature across the radial cross-section of the absorber insert (due to internal sources of energy release, the dependence is parabolic) is not located in the middle, but is offset from the center. In this regard, the wall thickness (δ) was conventionally divided into two zones by a floating point (with coordinate r). For the inner zone ($x \in 0 \ldots r$) of the absorber insert, the temperature distribution across the cross-section was obtained by solving the equation:

$$\frac{d^2T(x)}{dx^2} + f = 0, \tag{4.1}$$

boundary conditions:

$$\left(\frac{dT(x)}{dx}\right)_{x=r} = 0, \tag{4.2}$$

$$\lambda \left(\frac{dT(x)}{dx}\right)_{x=0} = \alpha_1 (T_{IS} - T_C), \tag{4.3}$$

where:

f – specific energy release power;

T_{IS} – inner surface temperature of the absorber insert;

T_C – coolant temperature;

λ – thermal conductivity factor of the absorber insert material;

r – coordinate of the maximum temperature in the cross section of the absorber insert along its thickness;

α_1 – heat transfer factor from the inner wall to the coolant.

For the outer zone ($x \in r \ldots \delta$) of the absorber insert, the temperature distribution across the cross-section was obtained by solving equation (4.1) for $x \in r \ldots \delta$ with the following boundary conditions:

$$\left(\frac{dT(x)}{dx}\right)_{x=r} = 0 \tag{4.4}$$

$$-\lambda \left(\frac{dT(x)}{dx}\right)_{x=\delta} = \alpha_2 (T_{OS} - T_C) \tag{4.5}$$

where:

δ – absorber insert wall thickness;

T_{OS} – outer surface temperature of the absorber insert;

α_2 – heat transfer factor from the outer wall to the coolant.

The coordinate of the maximum temperature "r" for each segment by height was obtained from the condition of temperature equality at point "r", obtained from two expressions, which are the solutions of equation (4.1) with boundary conditions (4.2, 4.3) and (4.4, 4.5):

$$r = \frac{\frac{\delta}{\alpha_2}+\frac{\delta^2}{2\lambda}}{\frac{1}{\alpha_1}+\frac{1}{\alpha_2}+\frac{\delta}{\lambda}} \quad (4.6)$$

In further calculations, it was assumed that the thermal conductivity of the absorber insert material is 20 W/(m·°C).

The heat transfer factors for each of the absorber insert surfaces were obtained from the following expression:

$$\alpha_i = \frac{l_i}{d_e} \cdot Nu_i, \text{ [W/(m}^2\text{·°C)]} \quad (4.7)$$

where:

i – absorber insert segment number by height,

l_i – coolant heat transfer factor on the segment i;

Nu_i – Nusselt number on the segment i;

d_e – equivalent (hydraulic) diameter.

The Nusselt number was calculated by the formula for ring-type cross-section channels (tube-in-tube [7]):

$$Nu_i = 0.017 \times Re_i^{0.8} \times Pr_i^{0.4} \times \left(\frac{d_{ida}}{d_{odt}}\right)^{0,18} \quad (4.8)$$

where:

Re – Reynolds number;

Pr – Prandtl number;

$\frac{d_{ida}}{d_{odt}}$ – the ratio of the absorber insert inner diameter to the tube outer diameter was calculated as the ratio of the wetted perimeters of the absorber insert inner surface to the outer perimeter of the central tube.

The Reynolds number depends on the coolant flow rate and parameters:

$$Re_i = \frac{\rho_i v_i d_{ei}}{\eta_i} \quad (4.9)$$

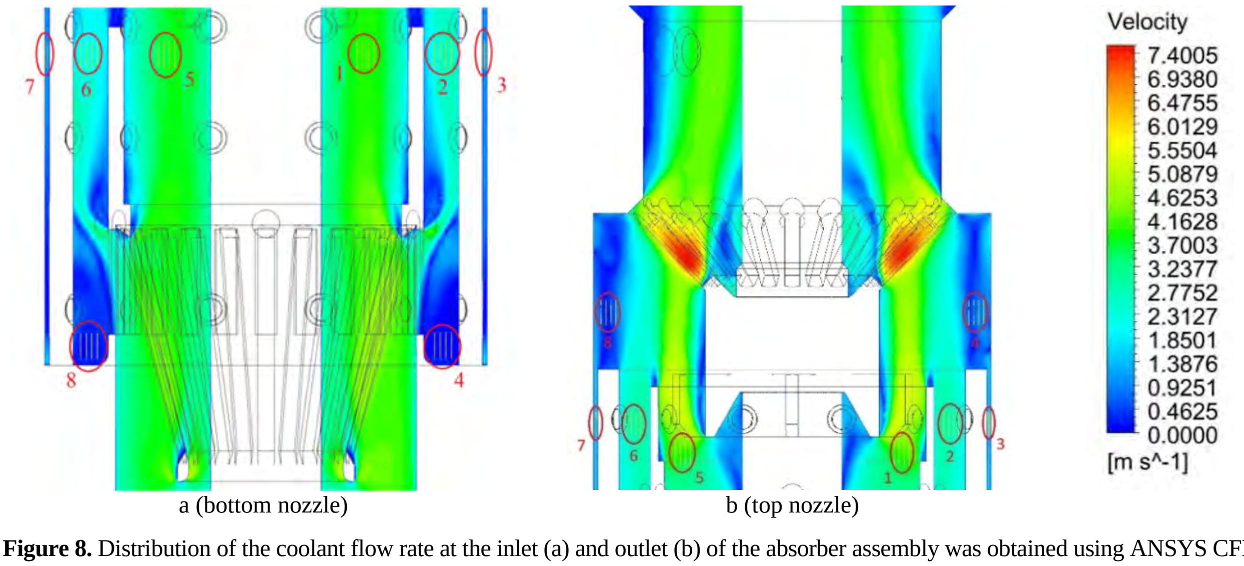
where:

ρ – coolant density;

v – coolant flow rate;

η – coolant dynamic viscosity.

Using the ANSYS software package [8] by the finite element method, a detailed calculation of the coolant flow rate throughout the entire volume of the absorber assembly was performed at a coolant flow rate through the ACA (follower FA + absorber assembly) of 100 m³/hour. The coolant flow rate distribution at the most interesting segments of the absorber assembly (i.e. the coolant inlet (bottom nozzle) and outlet (top nozzle)) is shown in Fig. 8 and Tables 5 and 6.



a (bottom nozzle) b (top nozzle)

Figure 8. Distribution of the coolant flow rate at the inlet (a) and outlet (b) of the absorber assembly was obtained using ANSYS CFD

Table 5. Coolant flow rate in the bottom nozzle area

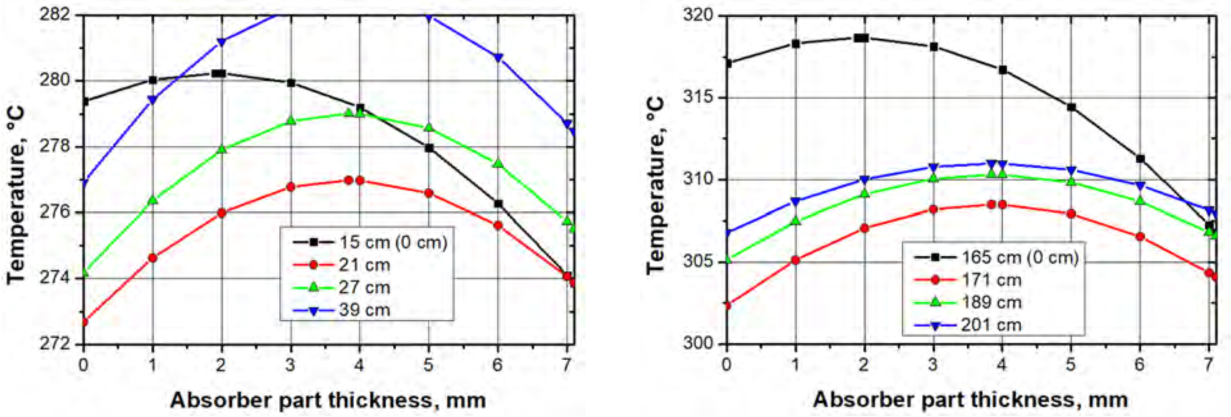
Gap	Average rate, m/s
Connecting bar – central tube (1 and 5 positions)	3.77
Central tube – absorber insert (2 and 6 positions)	2.30
Absorber insert – shroud (3 and 7 positions)	0.95
Stagnant area (4 and 8 positions)	0.14

Table 6. Coolant flow rate in the top nozzle area

Gap	Average rate, m/s
Connecting bar – central tube (1 and 5 positions)	3.90
Central tube – absorber insert (2 and 6 positions)	2.71
Absorber insert – shroud (3 and 7 positions)	1.36
Stagnant area (4 and 8 positions)	0.57

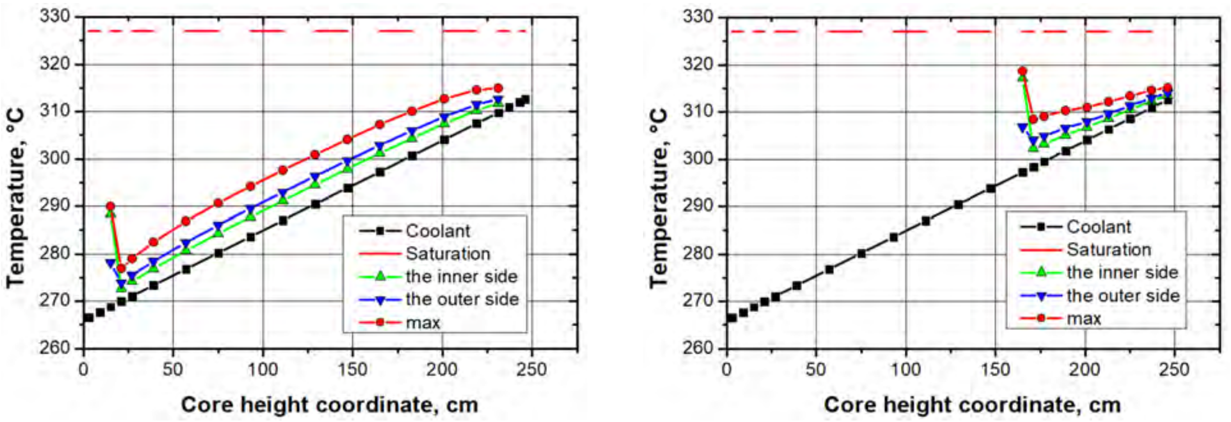
Based on the data obtained (Tables 5, 6), it can be assumed that the most heat-loaded area of the absorber assembly will be near the bottom nozzle, since it is characterized by the highest energy release when the controls insertion is different from zero, and the lowest coolant flow rate is in the area of the absorber insert, as well as the presence of an area with a low coolant flow rate in contact with the absorber insert (stagnant area (positions 4 and 8) Table 5). The stagnant area in the upper part of the absorber assembly (top nozzle) will not affect the cooling of the absorber insert (Fig. 8.b). The top nozzle of the absorber assembly is located outside the fuel-containing core area when the controls insertion is different from zero. Therefore, in further calculations of the temperature on the surface of the absorber insert, the coolant flow rate values obtained for the lower part of the absorber assembly are used.

The calculations demonstrate (Fig. 9) that the lower part of the absorber insert (0 cm), in the stagnant area (positions 4 and 8), which is characterized by a low coolant flow rate in the inner part (0.14 m/s), the temperature of the inner surface of the absorber insert is higher than the temperature of the outer surface, and their difference for fully inserted controls (100%) will be ~5 °C, and ~10 °C for controls lifted to 154.8 cm from the core bottom. The difference is due to the different specific energy release values (Fig. 5) for fully and partially inserted controls.



a (100%) b (154 cm)

Figure 9. Temperature distribution across the absorber insert wall cross-section at different axial positions of the absorber assembly in the reactor core for controls fully inserted (a) and lifted to 154.8 cm from the core bottom (b)



a (100%) b (154 cm)

Figure 10. Distribution of the coolant temperature on the absorber insert surface along the core height for fully inserted (a) and lifted to 154.8 cm (b) controls

With an increase in the axial position along the height of the core, the temperature of the inner surface of the absorber inserts decreases due to the increased coolant flow rate in the gap between the central tube and the absorber insert (positions 2, 6) (Fig. 9). The distribution of coolant temperature on the surface of the absorber insert along the height of the core for fully inserted and lifted to 154.8 cm controls is shown in Fig. 10.

The calculation results indicated that, at the coolant temperature around the absorber insert corresponding to the maximum coolant heating in adjacent fixed FAs (46.6 °C), the maximum surface temperature of the absorber insert will be 312.7 °C for fully inserted controls, and 317.1 °C for controls lifted to 154.8 cm from the core bottom, which at a coolant saturation temperature of 327 °C gives a margin to saturation of 14.3 °C and 9.9 °C, respectively.

Table 6. Results of calculating the cooling of the absorber insert

Parameter	Fully inserted	Lifted to 154.8 cm
Coolant temperature at the absorber assembly inlet, °C	268	295
Coolant flow rate through the absorber assembly, kg/s	21.66	21.66
Coolant temperature at the outlet from adjacent fixed FAs, °C	312.6	312.6
Max. surface temperature of the absorber insert, °C	312.7	317.1
Axial position of max. temperature, cm	~231	~165
Coolant saturation temperature, °C	327	327
Margin by saturation temperature, °C	14.3	9.9

According to the calculations, the maximum surface temperature of the absorber insert does not exceed 317.1 °C at a coolant saturation temperature of 327 °C for different controls' positions. This indicates the absence of bulk and surface boiling of the coolant during operation. Therefore, the absorber insert is reliably cooled in the VVER-440 reactor core. Increasing the energy release in six fixed FAs located in adjacent cells, with an average value of Kq=1.28 for these fixed FAs, to a value that corresponds to Kq=1.47, will cause an increase in energy release in the absorber insert material and an increase in its temperature from 317.1 °C to 320.1 °C, which is also below the saturation temperature (327 °C).

CONCLUSIONS

1. The specific energy release power in the structural materials of the absorber assembly depends on the power of the fixed FAs located in the adjacent cells. For the most loaded part of the boron absorber insert, with average Kq = 1.28 across sectors, the energy release is 17.5 W/cm^3. The total energy release power in the structural materials of the absorber assembly, coolant, and connecting bar material is 229 kW for fully inserted controls and 64 kW for lifted by 154.8 cm from the core bottom.
2. If no heat exchange occurs through the absorber assembly shroud, the maximum heating of the coolant due to energy release in the structural materials, at a conservative coolant consumption rate of 100 m^3/hour, will be 1.9 °C for fully inserted controls and 0.53 °C for controls lifted to 154.8 cm from the core bottom. In the most conservative case involving an increase in energy release in the adjacent fixed FAs to a value corresponding to Kq=1.47, the coolant heating does not exceed 2.4 °C. Due to the large area and the coolant's parameters, heat transfer through the shroud will cause the coolant in the gap between the shroud and the absorber insert to heat. To increase the conservatism of subsequent calculations, it was assumed that the shroud and surrounding coolant temperatures would correspond to the coolant temperature in the adjacent fixed FAs, for which the maximum allowed heating temperature is 46.6°C.
3. At a coolant temperature around the absorber insert that corresponds to the maximum coolant heating in adjacent fixed FAs (46.6 °C), and with no axial heat exchange, the maximum surface temperature of the absorber insert for fully inserted controls will be 312.7 °C (outer side), and 317.1 °C (inner side) for controls lifted to 154.8 cm, which at a coolant saturation temperature of 327 °C gives a margin to saturation of 14.3 °C and 9.9 °C, respectively. An increase in energy release in six fixed FAs located in adjacent cells with average Kq=1.28 to a value corresponding to Kq=1.47 will cause an increase in energy release in the absorber insert material and an increase in its temperature from 317.1 °C to 320.1 °C, which is also below the saturation temperature (327 °C).
4. The calculations and analysis performed reveal that the absorber insert, specifically its lower part when controls are partially inserted, is the most heat-loaded component of the absorber assembly structure. This position is characterized by high energy release and high coolant temperature at the inlet to the absorber assembly. For the most conservative case considered in this paper, the maximum surface temperature of the absorber insert remains below the coolant saturation temperature. This indicates an absence of both bulk and surface boiling of the coolant when the most energy-loaded component (i.e., the absorber insert) is in operation, confirming that the absorber assembly components will be reliably cooled in the VVER-440 reactor core.

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ВИЗНАЧЕННЯ ТЕМПЕРАТУРИ ЕКСПЛУАТАЦІЇ ЕЛЕМЕНТІВ КОНСТРУКЦІЇ НАДСТАВКИ, ПІДТВЕРДЖЕННЯ НАДІЙНОСТІ ЇХ ОХОЛОДЖЕННЯ В АКТИВНІЙ ЗОНІ ВВЕР-440

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Розрахунковим шляхом визначено питому потужність енерговиділення в конструкційних матеріалах надставки АРК, яка залежить від потужності робочих касет, що знаходяться у сусідніх комірках. Для найбільш навантаженої частини борного вкладиша, для усередненого по секторам Kq=1,28, енерговиділення становить 17,5 Вт/см^3. Загальна потужність енерговиділення в конструкційних матеріалах надставки, теплоносії та матеріалі штанги проміжної становить 229 кВт для повністю зануреного та 64 кВт для піднятого на 154,8 см ОР СУЗ. Спираючись на загальне енерговиділення в матеріалі вкладишу надставки АРК, кількість та швидкість теплоносія, що його омиває, консервативно визначено розподіл температури поверхні вкладишу по висоті надставки АРК. За температури теплоносія навколо вкладиша, що відповідає максимальному підігріву теплоносія в сусідніх РК (46,6 °C), та відсутності аксіального теплообміну, максимальна температура поверхні вкладиша для повністю зануреного ОР СУЗ становитиме 312,7 °C (зовнішня сторона), а для піднятого на 154,8 см – 317,1 °C (внутрішня сторона), що за температури насичення теплоносія 327 °C дає запас до насичення 14,3 °C та 9,9 °C відповідно. Для найбільш консервативного випадку, розглянутого в даній роботі, максимальна температура поверхні вкладишу нижча, ніж температура насичення теплоносія. Це свідчить про відсутність об'ємного та поверхневого кипіння теплоносія під час експлуатації найбільш енергонавантаженого елемента – вкладиша надставки. Тобто елементи конструкції надставки будуть надійно охолоджуватися в активній зоні ВВЕР-440.
Ключові слова: *ВВЕР-440; касета АРК; надставка; вкладиш; енерговиділення; охолодження*