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INFLUENCE OF CORROSION OF THE FIRST CIRCUIT ELEMENTS ON THE DISTRIBUTION OF SEDIMENTS IN THE CIRCULATION TRACT OF THE SMR 160 REACTOR

The object of research is the circulation path of a water-water small modular reactor. The work is aimed at assessing the influence of corrosion intensity on the formation of sediments on the surfaces of the first circuit of the SMR 160 reactor module. The analysis of the circuit structure was performed, the intensity of corrosion destruction and the intensity of sediments on the local sections of the circuit are evaluated. The circulation circuit of vertical architecture, the movement of the coolant in which excites thermal pressure, created by heating in the core and cooling in the steam generator.

The methodology is based on the principle of material balance of the transition of corrosion products into the coolant and their sediment on the circuit surface. To estimate the speed of corrosion the results of complex studies conducted at stations in normal operation and on the physical models of sections of the first circuit in the laboratory were used. Estimation of the speed of sediments is performed according to the ratios that take into account the impact of the concentration of the sedimented substance in the coolant, the thermal load of the site and the consumption of the coolant.

The calculations showed that the main source of iron oxides in the circuit is the surface of the steam generator, causing the average value of their concentration in the final areas, and zirconium oxides come from the surface of the core and retain the concentration close to the average along the entire tract.

The research results showed that the high corrosion stability of the structural materials of the circuit significantly limits the transition and accumulation of corrosion products in the coolant. In turn, low concentrations of corrosion products in the coolant restrain the formation of their sediments on the surfaces of the core and steam generator. The values of the surface density of sediments and their average thickness are estimated.

Analysis of corrosion processes of structural materials and the distribution of their sediments in the circuit allow to predict the level of radiation contamination and to plan the service life of the system.

The presented technique allows to evaluate the effectiveness of the water-chemical regime used.

Keywords: *modular reactor, water-chemical regime, corrosion, sediment, austenitic steel, zirconium.*

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1. Introduction

The SMR-160 (USA, project) light-water modular pressurized water reactor, with a capacity of 160 MW of electrical energy (525 MW of thermal energy) with fuel based on low-enriched uranium, belongs to the PWR-type nuclear reactors [1].

During the operation of reactor plants with a water coolant, changes in the composition of the latter are caused by the transition of oxides of structural materials from surfaces to the liquid phase, as well as the interaction of the components present in it. These are salts of the feedwater and primary filling, corrective impurities, as well as accidental contaminants that enter the circuit during installation and repair. Their interaction can produce compounds that precipitate on the surfaces of the circulation circuit.

The efficient operation of a nuclear power plant is ensured by the regulated composition of the coolant and the mode of its use, i. e. the organization of the appropriate water chemical regime (WCR).

In the first circuit of the considered type of reactors, a reductive weakly alkaline hydrogen-lithium or ammonia-potassium water-chemical regime is used [2]. The PWR reactor coolant differs from the PWR reactor coolant in the composition of corrective additives:

– to suppress the formation of oxidative radiolysis products at PWR NPPs, gaseous hydrogen is dosed into the first circuit, at WWER NPPs – ammonia, which decomposes with the release of hydrogen during the radiolysis process;

– to neutralize the acidic effect of boric acid and create a weakly alkaline reaction of the medium, lithium hydroxide is dosed into PWR NPPs, and potassium hydroxide into WWER NPPs.

Impurities that migrate in the first circuit, passing through the reactor core, are activated, and, being sedimented on the circuit elements, increase the power of ionizing radiation from these elements, creating significant problems during the operation of the NPP [3].

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The problems of activated sediments become especially significant with increasing operation duration and longer fuel cycles, which is typical for SMR-type reactors.

Therefore, the analysis of corrosion processes of structural materials of the primary circuit and the distribution of their sediments in the circuit seems to be very relevant in view of the prospects for the widespread introduction of small modular reactors into power systems.

The object of research is the circulation path of a water-water small modular reactor.

The subject of research is the processes of corrosion degradation of surfaces and the regularities of sediment formation in the circulation path of a water-water small modular reactor.

The aim of research is to assess the intensity of corrosion processes and sediment formation on the surfaces of the primary circuit of the SMR 160 reactor module.

To achieve the aim, it is necessary to solve the following objectives:
– calculation of the amount of corrosion products passing into the coolant, by sections of the path;
– calculation of the concentration of corrosion products in the coolant, by sections of the path, depending on the number of coolant rotation cycles in the circuit;
– calculation of the thermal load of the surfaces of the sections of the path and the coolant flow rate;
– calculation of the intensity of the formation of sediments on the surfaces of the sections depending on the type and concentration of the impurity, thermal load and coolant flow rate;
– assessment of the final concentration of corrosion products in the coolant, as well as the amount and thickness of the layer of sediments depending on the time of operation of the circuit.

2. Materials and Methods

The architecture of the first circuit of the SMR reactor complex is vertical biaxial (Fig. 1). On parallel axes at different levels are located: on the lower one – the core 2 with the control rod control device and on the upper one – the steam generator 6 with the pressure compensator 5.

The coolant from the antechamber 1 enters the core 2 and then sequentially passes through all sections of the path, according to the scheme (Fig. 1). After the coolant exits the collection chamber 7, through the return channel 8, it again enters the antechamber 1 [3].

The formation and entry of corrosion products into the coolant, as well as the rate of formation of sediments in the sections and their accumulation, is estimated by summing the corresponding indicators over the number of circulation cycles.

The increase in corrosion products in the coolant flow and the decrease in coolant impurities as a result of sediment on the surfaces are estimated by the relationship of the form [4]:

$$\Delta = \upsilon \cdot F / D, \tag{1}$$

where Δ – the gain/loss of the component in the corrosion/sediment processes; υ – the process speed (υ^k – corrosion, υ^s – sediment); F – the contact surface of the section with the coolant; D – the mass flow rate of the coolant in the section.

The change in the content of the coolant impurity component during the passage of the circuit section is determined by the material balance:

$$C_i^{out} = C_i^{in} + v_i^k - v_i^s, \tag{2}$$

where, respectively, the concentration of the component at the inlet and outlet of the section.

Corrosion products in the coolant have two components: soluble and insoluble. The soluble part does not participate in the sediment formation. The insoluble part, consisting of colloidal and suspended substances, is able to interact with the surface of the circuit sections in the processes of diffusion, adsorption and crystallization, sediment formation.

Known models of sediment formation reflect, mainly, processes in pipes [5]. The regularities of mass transfer with a coolant moving in a pipe and containing suspended particles reflect the accumulation of sediments by the ratio:

$$A = 10^{-3} \cdot \frac{\beta \cdot q}{v_l} \cdot C \left(\frac{\partial v}{\partial i_l} \right)_p, \tag{3}$$

where β – the ratio of the outer and inner diameters of the pipe; C – the concentration of corrosion products in the coolant; ν, ν_l – the specific volumes of the coolant in the flow core and in the near-wall layer, respectively; i_l – the enthalpy of the coolant in the near-wall layer.

The surface density of sediments, taking into account the residence time of the impurity in the coolant volume, is determined by the expression [5]:

$$A = 0.8 \cdot 10^{-14} \cdot R \cdot C_0 \cdot q^2 \cdot \frac{z^2}{u^2} \cdot \tau, \tag{4}$$

where R – the pipe radius; C_0 – the initial concentration of the substance in the coolant; z – the longitudinal coordinate; u – the flow velocity; τ – the time of the impurity in the coolant volume.

The circuit sections do not always correspond to the "pipe" definition (a long hollow object, usually of circular cross-section, for carrying something), and the presence of parameters that are ambiguously defined complicate the application of relations (3), (4).

Existing models of sediment formation assume that the determining factors of the process are the electrostatic interaction of particles with the surface and the intensity of the heat flow through it [5]. Based on this, experimental dependences were assumed to describe the rate of sediment formation in the form of equations [5]:

$$A = k_1 \cdot q^2 \cdot C, \tag{5}$$

$$A = k_2 \cdot q \cdot (C - C_p) \cdot \rho \cdot \frac{d\nu}{di}, \tag{6}$$

where A – the rate of formation of corrosion product sediments; k_1, k_2 – proportionality coefficients; q – the heat flux; C – the concentration of corrosion products in water; C_p – the concentration of dissolved corrosion products; ρ – the coolant density; ν – the specific volume of the coolant; i – the coolant enthalpy.

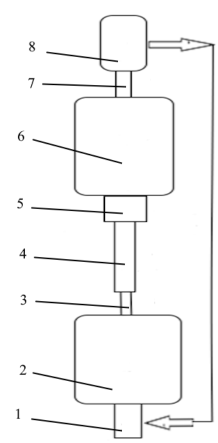

Fig. 1. Structural diagram of the first circuit of the SMR-160 reactor: 1 – pre-chamber of the entrance to the core; 2 – core; 3 – coolant discharge from the cavity of the control rods; 4 – coolant lifting pipeline in the steam generator (SG); 5 – pressure compensator rotary chamber; 6 – pipe area of the steam generator heat exchanger; 7 – cooled coolant collection chamber; 8 – coolant return channel to the core

Geometric characteristics of the elements of the first circuit and the approximate values of the operating parameters were determined by a large-scale analysis of the module description (Tables 1, 2)

Table 1

Geometric characteristics of the elements of the first circuit

Site	Height, m	Diameter, m	Perimeter, m	Surface, m^2	
				steel	zirconium
Core, frame	2.1	1.05	3.3	3.47	211
Core, FA	2.1	1.05	3.3	3.47	1062
Core drain	7.2	0.42	1.32	9.5	–
Top of reactor	3.9	0.42	1.32	5.15	–
Drain	1.05	0.35	1.1	1.16	–
Lift	6.7	0.35	1.1	7.37	–
Invert	2	1.1	4.04	8.08	–
SG	19.7	–	–	1402	1402
Camera	3.4	1.29	4.04	13.74	–
Drain	9.9	0.23	0.72	14.26	–

Note: FA – fuel assembly, SG – steam generator, C – core

Table 2

The approximate operating parameters of the circuit have the following values

Pressure, MPa	Temperature, °C		Flow rate, kg/s
	input	output	
15.5	285	315.5	$4.1 \cdot 10^3$

The characteristics of the reactor core and steam generator (Tables 3, 4) required for the analysis were obtained in previously performed thermal hydraulic calculations [6].

Table 3

Characteristics of the reactor core

Specific load, N_υ^{av}	Volume, V_c	Diameter, D_c	Height, H_c	Speed, w_c	FA number, n_{as}
MW/m^3	m^3	m	m	m/s	items
85	6.6	2.13	1.85	0.77	58

Table 4

Steam generator design characteristics

Coolant flow rate	Heat transfer pipe		Average speed	Heat transfer area	Pipe length
	diameter	quantity			
G_T, kg/s	W_{SG}, m/s	N_{SG}, items	W_{SG}, m/s	S_{SG3}, m^2	L_{SG3}, m
1479	1.6	14080	1.43	1402	20.36

The structures of the primary circuit components are traditionally formed from high-strength and chemically resistant austenitic steels. The sections of the circulation circuit are made of alloyed carbon steel, while the internal surfaces in contact with the coolant are covered with a cladding layer of chromium-nickel steel 05Х19Н10Г2Б or its analogue.

The enclosure of the core, as well as the entire circuit, is made of chromium-nickel steels (04Х20Н10Г2Б, 15Х2НМФА, 08Х18Н10Т), in which the iron content is 70–90 %.

The core is constructed mainly from zirconium-based alloys (alloy E-635 or analogues) with the following weight content of elements: Fe – 0.50 %, Zr – 98.47 %, Nb – 1.00 %, Hf – 0.03 %.

The main characteristic of structural materials, necessary for assessing the corrosion degradation of the structure and the sediment formation, is the corrosion rate. For stainless steels, the corrosion rate at 300 °C varies in the range of 0.2–0.8 $g/(m^2 \cdot day)$ (8.33–33.3 $mg/m^2 \cdot h$) [7]. Systematized average values of the corrosion rate depending on the pH are given in Table 5.

Table 5

Average values of the corrosion rate of chromium-nickel steels, $mg/(m^2 \cdot h)$

pH	12Х18Н10Т	08Х18Н10Т	06Х18Н10Т
5	0.023314	0.015605	0.013912
7.2	0.04075	0.029299	0.022308
10	0.06987	0.059143	0.050986

The corrosion rate of low-alloy pearlitic steel under ammonia-boron-potassium conditions is 0.3–0.4 $g/(m^2\text{-}day)$. Corrosion occurs evenly, up to 80 % of the formed corrosion products pass into the water [8].

The corrosion of zirconium alloys intensifies with an increase in the temperature of the medium above 300 °C and leads to the formation of a loose film that crumbles [8]. The maximum application temperature of zirconium 320–330 °C is limited by corrosion resistance. Any deterioration in heat removal or a temporary increase in the content of aggressive impurities in the circuit water can lead to the formation of a loose film.

The transfer of zirconium corrosion products into water under the operating conditions of the first circuit of the WWER is about 3 $mg/(m^2\text{-}day)$ at a corrosion rate of about 200 $mg/(m^2\text{-}day)$ [9].

3. Results and Discussion

In the process of coolant circulation in the circuit, the consequence of its contact with the surfaces is the formation of corrosion products. Part of these formations is able to pass into the coolant, and with sufficient accumulation in the liquid phase, be sedimented on the surfaces of the circuit.

A simplified assessment of the corrosion processes and the distribution of sediments in the first circuit is advisable to perform according to the structural diagram (Fig. 1), for which the geometric, hydraulic, thermal and corrosion parameters of the structures and the coolant are determined by sections.

In the path 1 of the circuit, there are 2 sections with surfaces significantly larger than the others, which are the main sources of corrosion products: the core and the steam generator. The initial calculation point of the calculation is the intersection of the entrance to the antechamber of the core, which is characterized by the lowest concentration of corrosion products.

The distribution of concentrations of corrosion products of iron and zirconium, which are the main components of structural materials forming the path 1 of the circuit, calculated using relations (1), (2), (4), is shown in Fig. 2, 3.

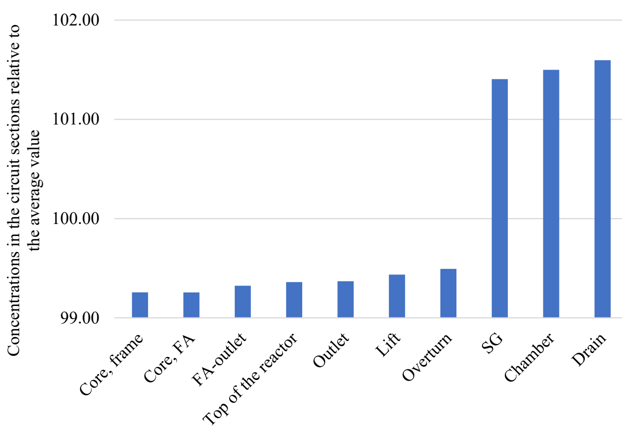

Fig. 2. Distribution of iron corrosion product sediments along the circuit areas

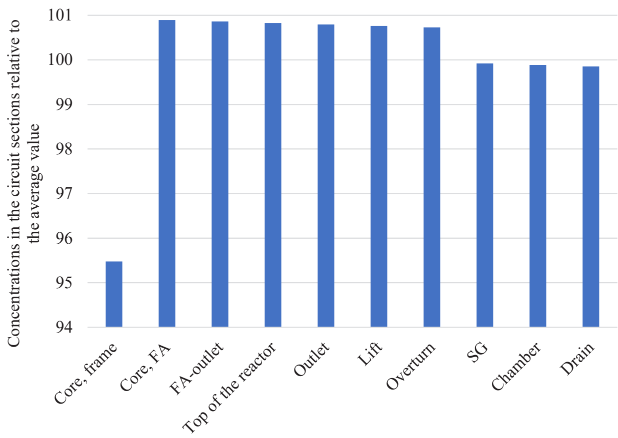

Fig. 3. Distribution of zirconium corrosion product sediments along the circuit areas

From Section 2 on the design and operating characteristics given in the circulation circuit, allow to state that the structure of the distribution of concentrations in the tract is formed in the first 4–5 cycles of circulation of the coolant volume. The steam generator, which is a source of iron corrosion products, is located in the final zone of the tract. From the graphical dependence it follows that in the first section 99.25 % is achieved relative to the average concentration in the tract. Along the entire tract it monotonically increases to 99.5 %. In the steam generator, the concentration increases by 2 % and continues to monotonically increase in the last sections by 0.2 %. Upon entering the core space, the entire insoluble component of corrosion products from the coolant is sedimented on its surfaces and the process is repeated. The high corrosion resistance of austenitic steels limits the amount of sediments along the path 1 of the circuit.

The change in the concentration of corrosion products along the path relative to the average value from the space of the core (C) to the lower chamber of the flow inlet in the C does not exceed 2.25 %. The largest increase of ~2 % is observed in the SG.

The intensity of the increase in the Fe concentration in the steam generator, obtained by approximating its values calculated step by step according to formulas (1)–(4), is reflected by the ratio:

$$C_{SG} = 7.9537 \cdot \ln(\tau) - 19.332, \tag{7}$$

where C_{SG} – the concentration of corrosion products, mg/kg; τ – the process duration, h.

Zirconium corrosion products appear in the core, located in the initial section of the path, and reach more than 95 % of their average concentration along the circuit. Directly in the core, the concentration, due to the fuel element surface, increases to 101 % of the average value.

Further, a decrease of 0.2 % of the average value is observed before the SG, and in the SG the decrease is about 1 %, after which the decrease does not exceed 0.1 %.

Using the ratios (1) and (4), the surface densities of sediment accumulation on the circuit surfaces were calculated according to the expression:

$$\Delta m = S_{Fe} \cdot \tau, \tag{8}$$

as well as the concentration accumulation, it is represented by a logarithmic ratio of the form:

$$\Delta m = 0.0392 \cdot \ln(\tau) - 0.005, \tag{9}$$

where Δm – the specific density of sediment accumulation; S_{Fe} – the sediment formation rate of corrosion products; τ – time.

The surface density of iron corrosion products on the steam generator surfaces gradually decreases and stabilizes at a level of less than 0.55 mg/m^2 (Fig. 4).

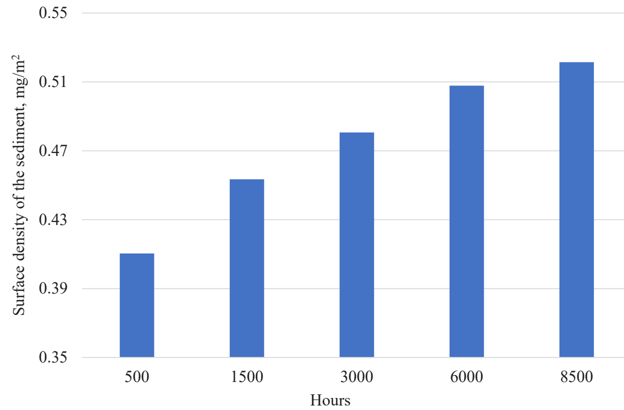

Fig. 4. Surface density of iron corrosion products sediment on the surfaces of the steam generator

The diagram shows that the annual accumulation of iron corrosion products on the surfaces of the steam generator does not exceed 0.5 mg/m^2:

$$\Delta h = 0.007 \cdot \ln(\tau) + 0.0297. \tag{10}$$

The sediments of zirconium corrosion products on the surfaces of the core and the steam generator differ significantly (Fig. 5). Their higher concentration in the core results in a higher sediment rate than in the steam generator.

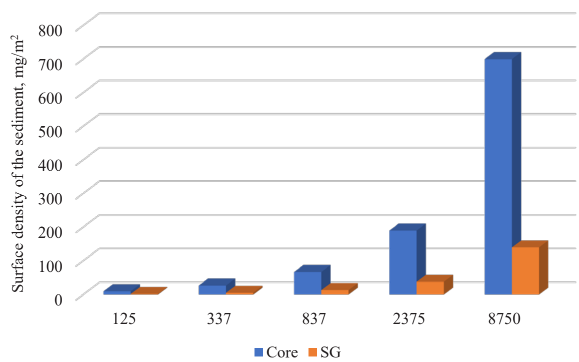

Fig. 5. Sediment of zirconium corrosion products on the surfaces of the core and steam generator

The annual accumulation of zirconium corrosion products on the surfaces of the core is 700 mg/m^2, and on the steam generator pipes it does not exceed 140 mg/m^2.

The thickness of the layer of iron corrosion products on the surfaces of the steam generator has a character similar to the surface density of sediments (Fig. 6).

The thickness of the iron oxide layer after the end of the one-year period, calculated as the ratio of the total volume of sediments to the surface, did not exceed 0.1 nm or 1 Å (Fig. 7). With the dimensions of the magnetite cell parameter $a = 8.397$ Å, it can be stated that the coating is not continuous [10].

The thickness of the zirconium sediment layer after the end of the one-year service life, calculated as for iron oxides, for the core and steam generator surfaces is, respectively, 150 and 40 nm (Fig. 7).

The practical significance of the results obtained lies in the possibility of predicting the terms of operational maintenance of the sections of the first circuit of a promising modular reactor, taking into account radiation contamination.

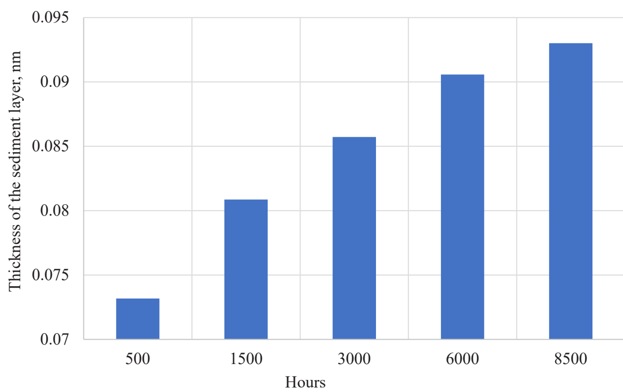

Fig. 6. Thickness of the iron corrosion product layer on the steam generator surfaces

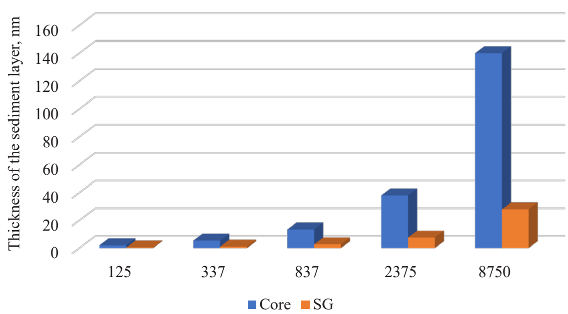

Fig. 7. Thickness of the zirconium corrosion product layer on the surfaces of the core and steam generator

Research limitations. The use of the results obtained in computational studies is limited by the architecture (vertical with direct-flow steam generators), the indicators of thermal and hydrodynamic modes (natural circulation), as well as the range of structural materials (austenitic stainless steels, zirconium alloys) in the circuit circulation path.

Prospects for further research. Further research is advisable to conduct in the areas of evaluating the resource indicators of the circulation path of the 1st circuit to determine the term of its reliable operation, as well as the terms of routine maintenance and repairs of sections of the path.

4. Conclusions

The studies have proven that the amount of corrosion products passing into the coolant in sections of the path depends on the corrosion resistance of the structural materials from which they are formed. The use of highly resistant alloys causes a slight influx of oxides into the coolant and the rapid establishment of a stable concentration distribution in the path. The deviation of concentrations from the average value does not exceed 2 %.

The critical elements of the first circuit path should be considered the core and the steam generator, which differ significantly in surface sizes, thermal load, coolant consumption and the resistance of structural materials from other sections.

The surface density of sediments of corrosion products of steels does not exceed 0.5 mg/m^2 with a thickness of the layer of sediments of no more than 0.1 nm. The surface density of sediments of corrosion products of zirconium in the core does not exceed 650 mg/m^2, and on the pipes of the steam generator – less than 140 mg/m^2 with a thickness of the layer of sediments, respectively, 150 and 40 nm.

The insignificant inflow of oxides of structural materials into the coolant determines their high corrosion resistance and contributes to the rapid establishment of a stable concentration distribution along the path.

The research results will be useful for substantiating water-chemical regimes and terms of operational flushing of the first circuit.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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