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ENSURING SAFE COOLANT CIRCULATION IN THE PRIMARY CORE COOLING LOOP OF THE SUBCRITICAL NUCLEAR FACILITY "NEUTRON SOURCE"

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The paper presents the parameters of the hydraulic circulation system of the coolant in the subcritical assembly tank of the Subcritical Nuclear Facility "Neutron Source". After a prolonged shutdown, tests were performed that confirmed the reliable safe operation of the primary core cooling system of the facility. The obtained numerical characteristics should be verified before the start of pilot operation.

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INTRODUCTION

During 2020–2021, the physical start-up of the subcritical nuclear facility "Neutron source based on the subcritical assembly driven by the linear electron accelerator" (SNF "Neutron Source") was performed at NSC KIPT [1, 2]. The pre-loaded dummies of the fuel assemblies were sequentially replaced by fresh nuclear fuel in the form of single-section fuel assemblies (FAs) of VVR-M2 type [3].

According to the SNF "Neutron Source" design [4, 5], the operational mode includes removal of 260 kW of thermal power from the core by the coolant of the primary cooling loop of the subcritical assembly.

Experimental results on the hydraulic performance of the coolant circulation in the subcritical assembly tank of SNF "Neutron Source" are presented below.

1. DESCRIPTION OF THE SUBCRITICAL ASSEMBLY

At the completion of the physical start-up, the core of the subcritical assembly contained 37 FAs, one fuel dummy and 82 beryllium neutron reflector elements. Subsequently, due to the need to transition the facility to a long-term shutdown mode, two beryllium reflector elements were replaced with absorber rods.

Figs. 1 and 2 show the configuration of the single-section FA of VVR-M2 type and beryllium neutron reflector element, respectively.

The core is in the subcritical assembly (SCA) tank, through which the coolant (demineralized water) circulates as follows (Fig. 3). Water from the tank is drawn by centrifugal pump through the core and the pipeline sections A-B-C-D-E and is then returned to the SCA tank through a heat exchanger. The pump is at elevation of 1.745 m below the water level in the SCA tank. Therefore, one of the safety considerations is the evaluation of the potential drainage of the core resulting from the siphon effect. The water drainage scheme essentially comprises two siphons. One siphon is the section A-C which includes the upper bend. The second siphon is the section C-E which includes the lower bend. Disruption of the first siphon largely depends on the condition of the shut-off valves located in the upper part of the buffer tank (E22), as well as on the parameters of the anti-siphon connection in the SCA tank. The analysis focuses on the hydraulic parameters of the drainage section, which is the most probable location for the formation and loss of the siphon effect in order to prevent the core drainage.

2. HYDRAULIC RESISTANCE PARAMETERS OF THE DRAINAGE SECTION

2.1. HYDRAULIC RESISTANCE PARAMETERS OF THE CORE

The core is assembled from beryllium reflector elements, fuel elements, and fuel dummies with hydraulic characteristics equivalent to those of FAs. As shown in Figs. 1 and 2, from a hydraulic resistance perspective, the core is represented as a set of tubular flow passages with various cross-sections. A total of 522 parallel channels of 500 mm in length are arranged within a hexagonal lattice of 245 mm in diameter (see Fig. 3).

The channel parameters are summarized in Table 1. The calculations were performed using the Darcy equation [6]. For each channel, the pressure drop ΔP_i consists of two components. The first represents frictional losses along the channel length, while the second represents local losses caused by flow disturbances (inlet and outlet effects, as well as changes in flow velocity in both magnitude and direction) [6, 7]:

$$\Delta P_i = \lambda \frac{L}{D_h} \frac{\rho V_i^2}{2} + \xi \frac{\rho V^2}{2}, \quad (1)$$

where λ=64/Re (Re<2300); $\lambda = \frac{0.3164}{Re^{0.25}}$ (Re>4500);
Reynolds number $Re=VD_h/\nu$;
Kinematic viscosity $\nu \approx 0.8 \cdot 10^{-6}$ m^2/s;
Hydraulic diameter of a rectangular channel D_h=2ab/(a+b);
Hydraulic diameter of an annulus $D_h = D_1 - D_2$;
$\xi = 0.5$ for channel inlet;
$\xi = 1$ for channel outlet.

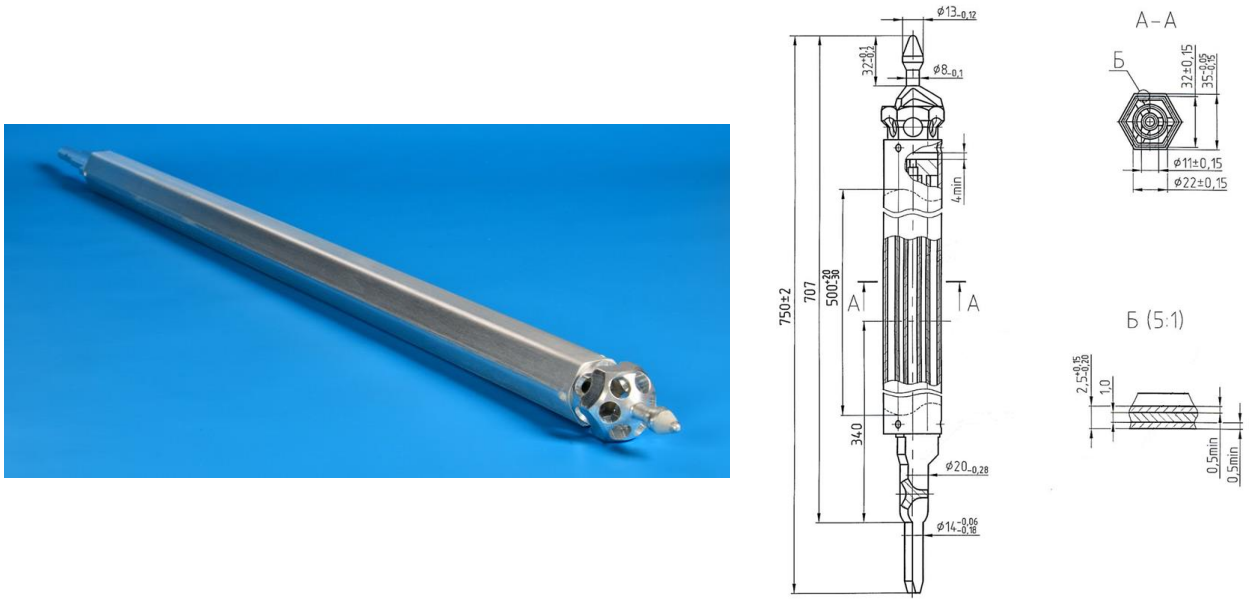


Fig. 1. The single-section FA of VVR-M2 type [3]



Fig. 2. The beryllium neutron reflector element

Table 1

Parameters of cooling channels of the subcritical assembly core elements

Channel type	Number of channels	Area, A, mm^2	Total area, mm^2	Hydraulic diameter D_h, mm	Flow rate, m^3/h	Velocity, V, m/s	Reynolds number, R
Rectangular channel 19.34x1.5 mm	96	29	2784	2.78	4.4	0.44	1529
Rectangular channel 19.34x3 mm	312	58	18096	5.19	39	0.62	4022
Annular channel with a hexagonal D Inscribed in diameter 27 /D 22 mm	38	250.6	9523	6.34	22.6	0.66	5230
Annulus D17 /D 11 mm	38	132	5016	6	11.6	0.64	4800
Cylinder D 6 mm	38	28.27	1074	6	2.5	0.63	4725

The following condition should be satisfied for all channels:

$$Q_{tot} = \sum n_i \cdot Q_i \quad (2)$$

and

$$\Delta P_1 = \Delta P_{2=} \Delta P_i = \cdots = \Delta P \quad (3)$$

For a water flow rate of 80 m^3/h, the following results are obtained. The total flow area of the core is 0.036 m^2. The FA cooling area is 0.022 m^2. At a total flow rate of 80 m^3/h (22 L/s), the flow directed to FA cooling is 48 m^3/h (13.5 L/s). These values are adopted in the design of the SNF "Neutron Source".

Estimates based on the parallel-channel model yield a total pressure drop in the core of 1 kPa. It should be noted that Ref. [3] reports a pressure drop of 11 kPa in the core at a coolant velocity of 2.2 m/s in the channel between FAs. This value is consistent with the pressure drop in the core at a velocity of 0.622 m/s in a similar channel.

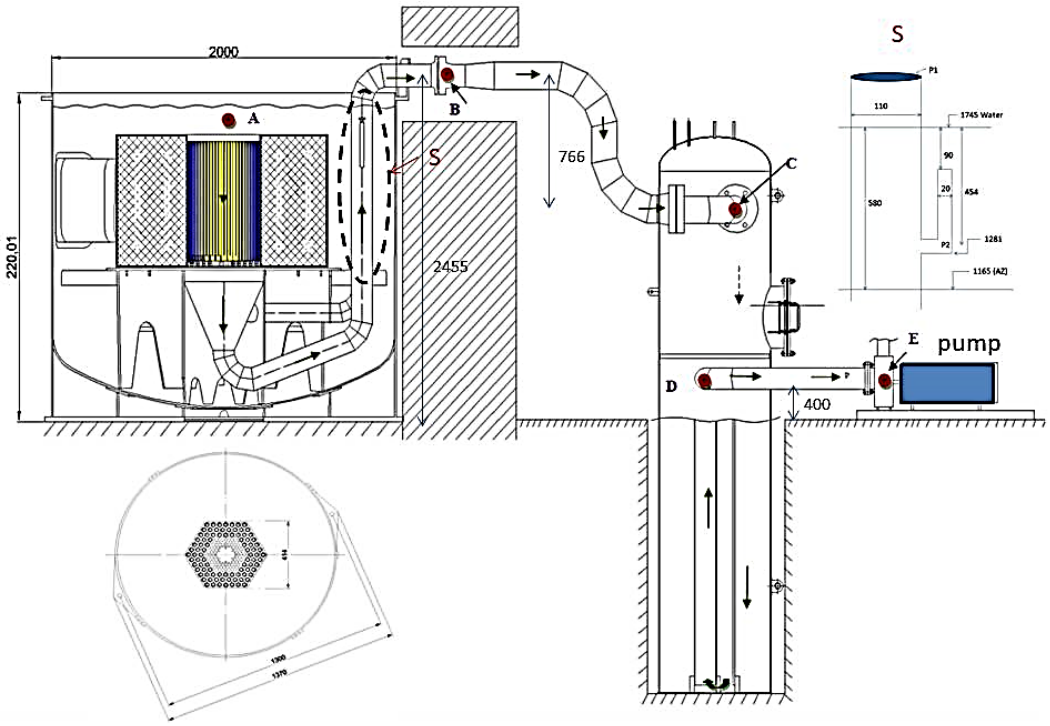


Fig. 3. Coolant flow diagram of the primary cooling loop of the subcritical assembly

Table 2

Parameters of individual sections of drainage line in the primary cooling loop of the subcritical assembly

№	Sections	Diameter, D, mm	Velocity V, m/s	Resist. coef. (λ or ζ)	Losses ΔP, Pa	R/D
1	Core	450	4.4-6.6		1000	–
2	Inlet cone	400→110	0.18→2.34	ζ=0.15	410	–
3	Bend, θ=110°, L=259 mm.	110	2.34	ζ=0.45	1230	1.35
4	Pipe Al, L=627 mm	110	2.34	λ=0.021	325	–
5	Bend θ=45, L=122 mm	110	2.34	ζ=0.45	601	1.41
6	Pipe Al, L=1723 mm	110	2.34	λ=0.021	892	
7	Bend θ=90°, L=177 mm	110	2.34	ζ=0.75	2047	1.03
8	Pipe Al, L=333 mm	110	2.34	λ=0.021	172	–
9	Reducing flange 110→100 L=160	110→100	2.83	ζ=0.1	400	–
10	Cone L=170, θ=13°	100→140	1.44	ζ=0.25	260	–
11	Pipe Al, L=400 mm	140	1.44	λ=0.019	56	–
12	Bend θ=90°, L=140 mm	140	1.44	ζ=0.35	362	1.77
13	Pipe Al, L=227 mm	140	1.44	λ=0.019	32	
14	Bend θ=90°, L=390 mm	140	1.44	ζ=0.35	362	1.77
15	Flange L=177 mm	140	1.44	ζ=0.05	25	–
16	Reducing flange 140→150 mm, 100 L=40	150	1.26	ζ=0.05	40	–
17	Stainless steel pipe, L=280 mm	150	1.26	λ=0.018	26	–
18	Stainless steel bend, θ=90° L=250 mm	150	1.26	ζ=0.7	553	1.06

№	Sections	Diameter, D, mm	Velocity V, m/s	Resist. coef. (λ or ζ)	Losses ΔP, Pa	R/D
19	Stainless steel pipe, L=1900 mm	150	1.26	λ=0.018	179	–
20	Tank inlet (sudden expansion)	150→∞	1.26→0	ζ=1	790	–
21	Pipe inlet (from the tank)	∞→150	0→1.26	ζ=0.5	395	–
22	Stainless steel pipe, L=1850 mm	150	1.26	λ=0.018	179	–
23	Stainless steel bend, θ=90° L=285 mm	150	1.26	ζ=0.55	435	1.21
24	Stainless steel pipe, L=170 mm	150	1.26	λ=0.018	16	–
25	Stainless steel bend, θ=90°, L=250 mm	150	1.26	ζ=0.7	553	1.19
26	Stainless steel pipe, L=100 mm	150	1.26	λ=0.018	9	–
27	Stainless steel bend, θ=90°, L=250 mm	150	1.26	ζ=0.7	553	1.19
28	Stainless steel pipe, L=2250 mm	150	1.26	λ=0.018	212	22
29	Tee connection, perpendicular branch	150→100	1.26	ζ=1.8	1420	–
30	Stainless steel pipe, L=170 mm	100	2.83	λ=0.021	108	–
Total					13642	–

Table 3

Parameters of water level decrease in the SCA tank under gravity drainage

Water level in the SCA tank, mm	Flow rate, L/s	Time, s	Water level change rate in the SCA tank, mm/s	Velocity in the D110 pipe, m/s	Velocity in the D100 pipe, m/s	Negative pressure at the anti-siphon tube insertion, Pa
1745	21.7	0.	6.9	2.3	2.77	2097
1655	21.2	13.1	6.75	2.23	2.7	2639
1281	18.7	72.	5.9	1.96	2.37	4893
1165	17.8	92.	5.6	1.87	2.26	5592

2.2. PRESSURE DROP PARAMETERS – MAIN CIRCULATION PUMP SECTION

Using methodologies presented in [6, 7], the pressure losses in the pipeline from the core to the pump were calculated and summarized in Table 2.

The total pressure losses of approximately 14 kPa are consistent with the design parameters for normal operation (pressure at the inlet of circulation pumps of 0.07…0.08 MPa).

The data presented in Table 2 allow the hydraulic characteristics of both the entire drainage system and its individual sections to be determined. In particular, for the section from the SCA tank free surface to the flange of the circulation pump (see section A–E, Fig. 3), the system characteristic is expressed as follows:

$$\Delta P = P_L \left(\frac{Q}{Q_0}\right)^2 = 13642 \left(\frac{Q}{Q_0}\right)^2 = 27.610^6 Q^2 [Pa], \quad (4)$$

where P_L is the pressure drop in the section at a flow rate Q.

For the section from the SCA tank free surface to the buffer tank E22 (see section A–C, Fig. 3), the system characteristic is expressed as follows:

$$\Delta P = P_L \left(\frac{Q}{Q_0}\right)^2 = 9762 \left(\frac{Q}{Q_0}\right)^2 = 19768050 Q^2 [Pa]. \quad (5)$$

For the section from the SCA tank free surface to the connection point of the anti-siphon tube, the system characteristic is expressed as follows:

$$\Delta P = P_L \left(\frac{Q}{Q_0}\right)^2 = 4066 \left(\frac{Q}{Q_0}\right)^2 = 8233650 Q^2 [Pa]. \quad (6)$$

This characteristic allows the operating conditions of the anti-siphon insert to be determined under various accident scenarios.

The head generated by the water column H is expended to overcome the resistance of the suction pipeline (ΔP) and to produce the kinetic energy of the flow (velocity head at the outlet). The equation is expressed in in meters of water column (m H_2O)

$$\frac{\Delta P}{\rho \cdot g} + \frac{V^2}{2 \cdot g} = H. \quad (7)$$

Resulting in

$$\frac{27625050 * Q^2}{\rho \cdot g} + \frac{8 \cdot Q^2}{g \cdot \pi^2 \cdot D_{out}^4} = H \quad (8)$$

or

$$\frac{27625050 \cdot \pi^2 \cdot D_{out}^4 \cdot V^2}{16 \cdot \rho \cdot g} + \frac{V^2}{2 \cdot g} = H. \quad (9)$$

For this case D_{out} = 0.1 m, the following expression is obtained:

$$Q = 0.0165 \cdot \sqrt{H}\ , \quad V = 2.10 \cdot \sqrt{H}\ . \quad (10)$$

In this case, the flow velocity in the pipe with the anti-siphon branch is

$$V_s = 1.736 \cdot \sqrt{H}. \quad (11)$$

The time dependencies for drainage through a free outlet are expressed as follows.

Rate of decrease of the water level in the tank

$$V_t = \frac{Q}{S_t} = \frac{0.0165}{S_t} \cdot \sqrt{H}\ , \qquad \frac{dH}{dt} = -0.021 \cdot \sqrt{H}, \quad (12)$$

where S_t is the surface area of the SCA tank

$$H = 1.745 - 0.0069 \cdot t + 6.9 \cdot 10^{-6} \cdot t^2. \quad (13)$$

Thus, in the absence of siphon break, the SCA tank will drain relatively quickly. The parameters of this process are presented in Table 3.

Consider the processes that occur when the water level in the SCA tank reaches the anti-siphon tube. The total pressure at the anti-siphon tube insertion is equal to:

$$P = P_a + \rho \cdot g \cdot h_{as} - P_L - \Delta P_{as}. \quad (14)$$

Where P_a is the atmospheric pressure; h_{as} is the depth of the anti-siphon tube insertion (0.4 m); P_L is the negative pressure caused by pressure drop along the suction pipe; and ΔP_{as} is the hydraulic vacuum in the pipe. According to Table 2, at the anti-siphon insertion (section 1-6) P_L = 4000 Pa. Therefore, hydrostatic term ρ g h_{as} ≈ 4000 Pa is compensated.

According to Bernoulli's equation

$$\Delta P_{as} = \frac{\rho \cdot V^2}{2} = \frac{997 \cdot 1.736^2 \cdot \mathrm{H}}{2}. \quad (15)$$

At an elevation of 1651 mm (the top of the anti-siphon tube), air is entrained through a pipe of diameter 0.11 m at a pressure of:

$$\Delta P = \frac{997 \cdot 1.736 \cdot \sqrt{1.655}}{2} = 2639\ [\mathrm{Pa}]. \quad (16)$$

This pressure can be expressed in terms of the dynamic pressure of air

$$\Delta P = \frac{\rho_{air} \cdot V_{air}^2}{2} \rightarrow V_{air} = \sqrt{\frac{2 \cdot \Delta P}{\rho_{air}}}. \quad (17)$$

Thus, air is induced at a velocity of V_{air} = 65.6 m/s. A diaphragm is installed at the end of the anti-siphon tube, allowing the air flow area to be set within the range of 24…314 mm^2. Through an orifice of 84 mm^2, an air flow rate of 5.5 L/s is supplied.

Through an orifice of 314 mm^2, an air flow rate of 20 L/s is supplied.

The volume of water in the pipes forming the upper siphon is approximately 80 L including the E22 buffer tank section of 320 L[3].

Estimate the volume of air injected into the E22 buffer tank during the time required for the water level to drop to 1165 (the top of the core headpieces). According to Table 3, over a time of t = 92 s, an air volume of 92*5.5 L ≈ 500L will be injected. This is valid provided that the upper siphon does not break earlier due to the presence of a large amount of air (> 15% of the liquid volume in the flow). This corresponds to a level in the E22 buffer tank below 750 mm, at which drainage through the upper siphon is no longer possible. Therefore, the SCA tank cannot be drained below the top level of the core. In practice, draining will stop earlier, at approximately the 1300 mm level. Thus, draining of the tank through the siphon formed by the upper bend with an open pump flange is not possible.

3. COOLANT LOSS THROUGH THE PRIMARY COOLING SYSTEM SUPPLY LINE OF THE SCA

Water is supplied to the SCA tank through the piping system of the primary cooling loop, which includes a heat exchanger. The total length of this system exceeds 40 m. Consider the processes that occur in the cooling system during the operation with circulation enabled and gradual coolant loss.

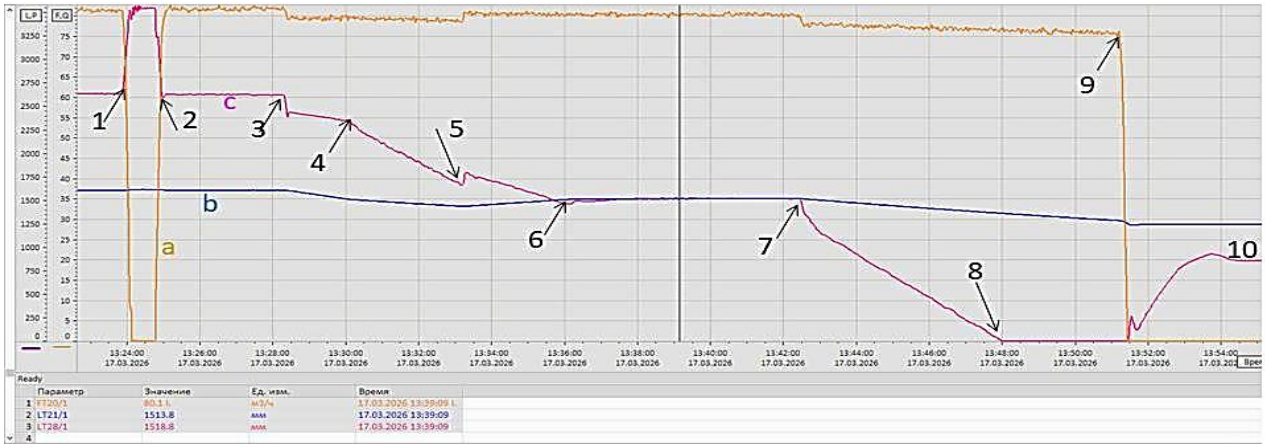


Fig. 4. Operating diagram of the cooling system through the SCA:
a – pump coolant flow rate; b – water level in the SCA tank; c – pressure sensor in the E22 buffer tank

Fig. 4 shows diagrams of sensor parameters at specific locations along the drainage channel.
1-2 – Shutdown of the circulation pump for calibration of the pressure sensor in the E22 buffer tank;
2-3 – Circulation pump operation in a leak-tight loop;
3 – The moment of turning on the leak;
3-4 – Decrease in the SCA tank level due to siphon action, with no air ingress;
4-5 – Operation of the anti-siphon tube (air ingress);
5-6-7 – Intermediate stabilization of levels with the pump in operation and leakage blocked;
7 – Leakage resumption;
7-8 – Decrease in the E22 buffer tank level;
8 – The sensor does not register negative pressure;
9 – Circulation pump shutdown;
10 – Stabilization with a partially empty E22 buffer tank.

The curves corresponding to section 1-2 show the pressure drop between the SCA tank and the E22 buffer tank during pump operation at a flow rate of 80 m^3/h. This pressure drop is equal to 920 mm of water column, which is consistent with the calculated values presented in Table 2. In section 2-3, the system operates without losses, and the coolant levels in the tanks remain unchanged. In section 2-3, with losses present but no air ingress (the anti-siphon branch remains submerged), the coolant level in the SCA tank decreases (1606→1514) by 92 mm. This corresponds to a loss of 3.14 L/s. In addition, the pressure sensor in the E22 buffer tank indicates the same decrease in level (2441→2348). When the water level in the SCA tank reaches 1514 mm (the level of the anti-siphon branch, item 4 in Fig. 4), air ingress begins. During the period from 13:30:00 to 13:33:09 (189 s), the SCA tank level decreased by 79 mm (0.42 mm/s), while the E22 buffer tank level decreased by 680 mm. This indicates that air enters the E22 buffer tank to replace the discharged water at a rate of 1.8 L/s. In section 7-8, the situation is similar: the SCA tank level decreases at a rate of 0.44 mm/s, while air enters the E22 buffer tank at a rate of 2.2 L/s. Thus, on average, the E22 buffer tank will be drained in approximately 900 s (16 min), while the SCA tank level will decrease by 390 mm.

CONCLUSIONS

Experimental start-up of the primary core cooling loop of the SCA demonstrated that, after a prolonged shutdown, the passive safety system “anti-siphon device” remains operational. The system has retained parameters ensuring safe operation; however, it requires more precise adjustment prior to the start of pilot and industrious operation.

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ЗАБЕЗПЕЧЕННЯ БЕЗПЕЧНОЇ ЦИРКУЛЯЦІЇ ТЕПЛОНОСІЯ У ПЕРШОМУ КОНТУРІ ОХОЛОДЖЕННЯ АКТИВНОЇ ЗОНИ ЯДЕРНОЇ ПІДКРИТИЧНОЇ УСТАНОВКИ «ДЖЕРЕЛО НЕЙТРОНІВ»

О.В. Бихун, А.О. Мициков, В.М. Рідозуб

Наведено параметри гідравлічної системи циркуляції теплоносія у баку підкритичної збірки ядерної підкритичної установки «Джерело нейтронів». Після тривалого простою проведено випробування, що підтвердили працездатність безпечної експлуатації системи охолодження активної зони. Отримано чисельні характеристики, що повинні бути підтверджені перед початком дослідно-промислової експлуатації.