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Abstract. Developing effective accident management strategies with complete loss of long-term power supply at nuclear power plants requires the qualification of existing and promising passive safety systems that do not require power supply. One of the approaches to solving this problem is to qualify the system of pressure compensator for accidents with complete loss of long-term power supply. The original method of qualification of the system of pressure compensator for the conditions of accidents with complete loss of long-term power supply is presented, taking into account the significant dynamics of thermo-hydraulic processes in the reactor. As a result of the computational modeling of the developed method of qualification of the pressure compensator system for the conditions of failure with complete loss of long power supply, it is established that the effective action of the pressure compensator system to maintain the required level of coolant in the reactor is carried out up to 900 s from the beginning of the emergency process.

Keywords: Qualification, Pressure Compensator, Accidents With Complete Loss of Long-Term Power Supply of Nuclear Power Plants

1. Introduction

According to IAEA terminology, qualification refers to a design, experimental, or design and experimental justification of the reliability and performance of systems / equipment in the operational, transient and emergency modes of nuclear power plants (NPPs).

The consequences of the accident with a complete long-term loss of power supply (LLPS) caused by the flooding of the tsunami at the Fukushima-Daiichi NPP site in 2011 were the following: nuclear fuel damage, destructive combined-cycle explosions and catastrophic radioactive pollution of the environment [1]

One of the most important lessons and conclusions of the Fukushima accident is the lack of effective strategies of management of accidents with complete loss of long power supply at NPP. This conclusion was confirmed by double inspections of the US Nuclear Regulatory Authority (NRC) at all US nuclear power plants.

The development of effective strategies of accident management with a complete long-term loss of power supply determines the need for qualification of both new passive safety systems (which do not require power supply) and existing passive safety systems in the conditions of LLPS.

One of these pressing issues is the qualification of a pressurizer system for accident conditions of accident with LLPS in a nuclear power plant. This article is devoted to this article.

2. Analysis of literature data

Design and beyond design basis accidents with deenergizing of nuclear power plants were considered in the reports of the operating organization for safety analysis of nuclear power plants with VVER reactors (VVER) [2, 3, 4].

The main goal of these developments is to determine the acceptable time for restoration of power supply and / or alternative means of accident management (mobile diesel generators, filling the reactor with fire engines and others

However, the analysis of the Fukushima accident determines the insufficient possibility and effectiveness of such measures to prevent damage to nuclear fuel and destructive combined-cycle explosions.

In addition, the methodological support of the calculation justifications does not take into account the possibility of the occurrence and consequences of various types of thermohydrodynamic instability in the equipment / systems of nuclear power plants.

One of the dominant consequences of vibrational and aperiodic thermohydrodynamic instability is water hammers (WH), which can significantly affect the reliability, performance and equipment life of systems that are important for the safety of nuclear power plants. WH are accompanied by a pulsed high-amplitude increase in pressure and a sharp inhibition of the coolant flow [5, 6].

The use of the well-known Zhukovsky formula for calculating the maximum pressure amplitude during water hammer, depending on the density and speed of sound in water, as well as the difference in flow rates before and after the WH in the pressurizer system, is unreasonable for the following main reasons:
- the formula does not determine the reasons and conditions for the formation of the WH in the pressurizer system;
- the formula is justified for stationary conditions of thermohydrodynamic parameters.

For the pressurizer system of a nuclear power plant with VVER, the conditions of the WH on the pressurizer case and on the shut-off elements of the safety valves of the pulse-safety device (SV PSD) of pressurizer are priority. In [5], the boundaries of the regions of conditions for the occurrence of WHs on the PS case were determined in the format of defining criteria K1, K2, K3, K4:

$$\mathrm{K}_1 = \frac{\rho_l \Pi_K}{G_0} \cdot \frac{i_v - i_l}{i_l} \cdot \mathrm{v}_H;\ \mathrm{K}_2 = H_0 / H_K;\ \mathrm{K}_3 = \frac{\xi_K}{2};\ \mathrm{K}_4 = \frac{\rho_l \Pi_K}{G_0^2}\left(P_{vK_0} - P_0\right)$$

where ρ_l – coolant density; i_v, i_l – specific (per unit mass) enthalpies of steam and coolant, respectively; v_H – the rate of rise of the level of coolant in the pressurizer when opening the SV PSD of pressurizer; H_0, H_K – the initial level of coolant in the pressurizer and the total height of the pressurizer, respectively; ξ_K – total coefficient of hydraulic resistance of pressurizer; Π_K – coolant flow area in pressurizer; G_0 – nominal coolant flow in the reactor loop; P_{vK_0}, P_0 – accordingly, the initial vapor pressure in the pressurizer and the pressure in the pressurized tank / bubbler tank of the nuclear power plant, respectively.

In [6], the boundaries of the region of WH in the through section of open SV PSD of pressurizer VS-99 from Sempell were determined in the format of defining criteria:

$$\mathrm{K}_5 = \frac{\rho_0 \mathrm{v}_0^2}{P_{\max}};\ \mathrm{K}_6 = \frac{L_{iK}}{\Pi_{iK}} \cdot \mathrm{grad}_z\left(\Pi_{iK}\right)$$

where L_{iK} – SV confuser length; $\mathrm{grad}_z(\Pi_{iK})$ – the average gradient of the change in the area of the bore along the longitudinal coordinate z in the confuser part of the SV.

However, the boundaries of the WH regions defined in [5, 6] in the pressurizer system do not take into account the dynamics of thermohydrodynamic processes directly in the reactor during accidents with LLPS, which determines the relevance of the work presented.

The main objective of the study is to qualify the reliability and efficiency of the NPP pressure compensator system in the event of an accident with a LLPS.

To achieve this goal, the following tasks must be solved:

- To develop a method for qualifying pressurizer in an accident with a LLPS taking into account the dynamics of thermohydrodynamic processes in a reactor.
- Determination of the conditions for the occurrence of WH in the pressurizer system, taking into account the dynamics of thermohydrodynamic processes in the reactor in the event of an accident with LLPS.
- Determining the time of the effective operation of the pressurizer system for accident management with LLPS.

3. The main provisions of the qualification method of the pressure compensator system for accident management with LLPS.

Key points / assumptions of the method:

1. Timeline of accident sequences with LLPS:

- emergency shutdown of the reactor;
- a complete failure of active safety systems (ASS) using electric pumps to ensure the safety functions for removing residual heat (SF RH) with power *N (t)* and maintaining the required level of feed water in the steam generator (SF SG);
- accident management passive safety systems (PSS) that do not require long-term power supply
- the lack of the possibility of restoring the power supply of own needs and the use of effective alternative means of ensuring the SF RH and SF SG within 72 hours from the beginning of the accident.

2. The failure of the ASS leads to a decrease in the flow of coolant through the reactor, the beginning of vaporization in the active zone, an increase in vapor pressure in the reactor.

3. The influence of “run-out” of the stopped main circulation pump (MCP) and natural circulation in the 1st circuit on the feasibility of SF RH and SF SG are not conservatively taken into account.

4. When the maximum permissible pressure values ($P_{\max}$) are reached in the steam volume of the pressurizer, the safety valves of the pulse-safety device (SV PSD) automatically open and close when the pressure drops below $P_{\max}$.

5. For one channel of the PSD of pressurizer, P_{max} = 18.5 ... 19.2 MPa, and for the other two channels $P_{\max}$ = 19.0 ... 19.6 MPa. Accordingly, at the closure of the SV - 17.0 MPa and 17.4 MPa.

6. When opening / closing the SV PSD of pressurizer, three types of water hammer (WH) may occur, which are critical for the reliability of accident control with LLPS [5, 6]:

- WH on the pressurizer case due to overflow of the full volume of the pressurizer with the coolant (WH type WH1);
- WH when closing the SV PSD of pressurizer, caused by condensation pressure pulses during transonic flow regimes of two-phase flows in the SV flow path (WH type WH2);
- WH when closing the SV, caused by an unacceptable speed of closing the SV (WH type WH3).

The design scheme of qualification of the pressurizer system for accident conditions with LLPS is shown in Fig. 1. The structural and technical data of the reactor and pressurizer required for the design justification of the qualification are given in Tables 1, 2. The structural and technical data of the SVPSD of pressurizer are given in [7].

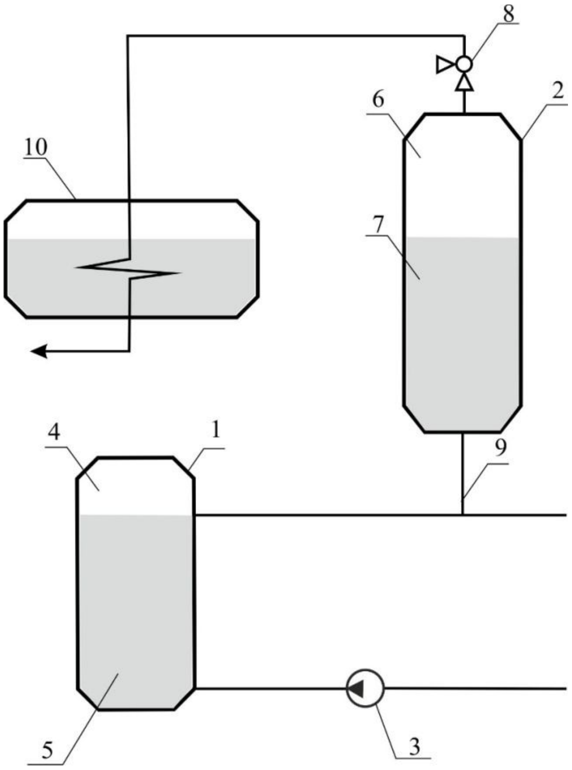

Fig. 1. Calculation scheme of qualification of the pressure compensator system:
1 – reactor (R); 2 – pressurizer; 3 – reactor main coolant pump (MCP); 4 – vapor volume in the reactor; 5 – the volume of coolant in the reactor; 6 – steam volume in pressurizer; 7 – the amount of coolant in the pressurizer; 8 – safety valves of the pulse-safety device of pressure compensator (SV PSD of pressurizer); 9 – connecting line of the pressure compensator with the 1st circuit; 10 – tank bubbler

Table 1. The main structural and technical data of the nuclear reactor VVER 1000

№	Structural and technical parameters	Значение
1	Reactor height	10.897 м
2	Inner diameter	3.680 м
3	Working pressure	15.7 МПа
4	Design pressure	17.7 МПа
5	The temperature of the coolant at the reactor inlet	289.7 °C
6	The temperature of the coolant at the outlet in nominal mode	320 °C
7	Nominal thermal power	3000 МВт
8	Maximum permissible thermal power	3200 МВт
9	Hydraulic resistance (without inlet and outlet nozzles)	0.37+0.06 МПа
10	The coolant level in the reactor at nominal mode	8.747 м
11	Maximum coefficient of hydraulic resistance at the inlet / outlet pipes of the coolant	1.1
12	Total minimum flow rate from pressure compensator to reactor	0.1

Table 2. The main structural and technical data of the VVER 1000 pressure compensator

№	Structural and technical parameters	Value
1	Stationary mode nominal pressure	15.7+0.3 МПа
2	Nominal coolant temperature of stationary mode	346 ± 2 °C
3	Working environment	пар, вода 1-го контура
4	Capacity (full volume)	79 м^3
5	Water volume at nominal mode	55 м^3
6	Pressure Compensator Height	12.940 м
7	Inner diameter	3.000 м
8	Minimum flow rate at the inlet to the 1st circuit	1.0
9	Coolant flow rate in the 1st circuit in nominal mode on the pressure compensator loop	(20…27)·10^3 м^3/час (5.55…7.5)·м^3/сек
10	Diameter of the bore of the connecting pipeline with the 1st circuit	0.35

Mass balance equations for volumes of steam and coolant in pressurizer:

$$\frac{\mathrm{d}(\rho_v V_{vK})}{\mathrm{d}t} = \rho_v \cdot \frac{\mathrm{d}V_{vK}}{\mathrm{d}t} + V_{vK} \cdot \frac{\mathrm{d}\rho_v}{\mathrm{d}P_{\mathrm{vK}}} \cdot \frac{\mathrm{d}P_{\mathrm{vK}}}{\mathrm{d}t} = -\rho_l \Pi_K \frac{\mathrm{d}H}{\mathrm{d}t} - G_{iK} \tag{1}$$

$$\rho_l \Pi_K \frac{\mathrm{d}H}{\mathrm{d}t} = -G_{iK} \tag{2}$$

Start conditions:

$$V_{vK}(t=0) = V_{vK_0}; H(t=0) = H_0(V_{vK_0}) \tag{3}$$

$$P_{vK}(t=0) = P_{vR_0} - \rho_l g(H_0 + L) \tag{4}$$

Mass flow from pressure compensator to the 1st circuit:

$$G_{iK} = \mu_K \Pi_T \sqrt{2\rho_l\left[P_{vK} - P_{vR} + g\rho_l\left(H + L\right)\right]} \tag{5}$$

where ρ_v, ρ_l – the density of steam and coolant, respectively; V_{vK} – pressure compensator steam volume; t – time; P_{vK}, P_{vR} – the pressure in the vapor volume of the pressure compensator and the reactor, accordingly; H, L – the height of the coolant level in the pressure compensator and the connecting pipe (Fig. 1), respectively; Π_K, Π_T– accordingly, the flow area of the pressurizer and the connecting pipeline; g – gravity acceleration ; μ_K–total minimum flow coefficient from the pressure compensator to the 1st circuit (see Table 2); G_{iK} – flow through the system SV PSD of pressurizer:

$$G_K = \begin{cases} \mu_{iK}\Pi_{iK}\sqrt{2\rho(P_{vK} - P_0}\text{, for opened SV PSD of pressurizer } (P_{vK} \geq P_{\max}) \\ 0\text{, for closed SV PSD of pressurizer} \end{cases} \tag{6}$$

where μ_{iK} – flow rate through SV PSD of pressurizer ($P_{vK}<P_{\max}$);Π_{iK} – minimum flow area SV PSD of pressurizer; ρ - density of the medium ; P_0 – containment pressure; $P_{\max}$– the maximum pressure in the vapor volume of pressurizer.

Necessary conditions for the occurrence of water hammer on the body of the pressure compensator and SV PSD of pressurizer [5, 6]:

$$\text{for WH1} - H = H_K \tag{7}$$

$$\text{for WH2 – Mach criterion} \quad \mathrm{M} = \frac{\mathrm{v}\left(\Pi_{iK_0}\right)}{a_{TF}\left(\Pi_{iK_0}\right)} \geq 1 \tag{8}$$

for WH3 – closing speed of SV PSD of pressurizer

$$\frac{\mathrm{d}\Pi_{iK}}{\mathrm{d}t} \geq \frac{2 \cdot \Pi_{iK_0}}{t_0}\left[\frac{2\left(P_{vK}-P_0\right)\rho\Pi^2_{iK_0}}{G^2_{iK}} - \xi_0\right] \tag{9}$$

where H_K – hight of pressurizer; $\mathrm{v}(\Pi_{ik0})$ – two-phase flow rate with fully open SV PSD of pressurizer with a minimum flow area Π_{ik0}; a_{TF} – speed of sound in a two-phase flow; ξ_0 – coefficient of hydraulic resistance when SV PSD of pressurizer fully open; t_0 –pressurizer design opening / closing time.

The condition for the effective influence of the pressure compensator on SF RH:

$$\mathrm{d}H/\mathrm{d}t \leq 0 \text{ при } t \leq t_K \tag{10}$$

Mass balance and thermal energy equations for volumes of steam and coolant in a reactor:

$$\frac{\mathrm{d}(\rho_v V_{vR})}{\mathrm{d}t} = \rho_v \cdot \frac{\mathrm{d}V_{vR}}{\mathrm{d}t} + V_{vR} \cdot \frac{\mathrm{d}\rho_v}{\mathrm{d}P_{v\mathrm{R}}} \cdot \frac{\mathrm{d}P_{v\mathrm{R}}}{\mathrm{d}t} = G_{iv} \tag{11}$$

$$\rho_l \Pi_R \frac{\mathrm{d}h}{\mathrm{d}t} = G_K - G_{iv} + G_{gP}(t) \tag{12}$$

$$G_{iv} \cdot i_v(P_{vR}) + \rho_l \cdot \Pi_R \cdot (i_v - i_l)\frac{\mathrm{d}h}{\mathrm{d}t} = N(t) \tag{13}$$

Under the initial conditions:

$$V_{vR}(t{=}0){=}\ V_{vR_0};\ P_{vR}(t{=}0){=}\ P_{vR_0};\ h\,(t{=}0){=}\ h_0;\ i_v(t{=}0){=}\ i_{v0};\ i_l(t{=}0){=}\ i_{l_0} \tag{14}$$

$$G_{gP} = G_0(1 - t/t_B) \tag{15}$$

where V_{vR}, P_{vR} – steam volume and pressure in the reactor; G_{iv}– vaporization flow rate in the reactor core; Π_R, h– flow area and coolant level in the reactor core, respectively; i_v, i_l – specific (per unit mass) enthalpy of steam and coolant, respectively; $N(t)$ - residual heat power; $G_{gP}(t)$ – run-out flow of the stopped main coolant pump ; t_B – full run-down time of the main recirculation pump .

The maximum water hammer amplitude (ΔP_{gm}) on the pressure compensator body at $H=H_K$ can be determined from the energy conservation equation when the kinetic energy of braking of the coolant level is converted into the energy of the pressure water hammer pulse in the isometric approximation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{\rho_l}{2}\cdot\left(\frac{\mathrm{d}H}{\mathrm{d}t}\right)^2+i_l\right]=0 \tag{16}$$

After the transformations, it follows from (16):

$$\Delta P_{gm}=\int_0^{t_g}\frac{\mathrm{d}P}{\mathrm{d}\tau}\mathrm{d}\tau=-\frac{\rho_l}{\mathrm{d}i_l\mathrm{d}P}\int_0^{t_g}\frac{\mathrm{d}H}{\mathrm{d}\tau}\cdot\frac{\mathrm{d}^2H}{\mathrm{d}\tau^2}\mathrm{d}\tau \tag{17}$$

Where $t_g=H_K/a_l;\, a_l$ – the speed of sound in the coolant.

In the criteria (dimensionless) format of the equation of mass balance and thermal energy:

$$\rho_v\cdot\frac{\mathrm{dV}_{vK}}{\mathrm{dt}}+\mathrm{V}_{vR}\cdot\frac{\mathrm{d}\rho_v}{\mathrm{dP}_{vR}}\cdot\frac{\mathrm{dP}_{vR}}{\mathrm{dt}}=\sqrt{\mathrm{K}_7\cdot\left(\mathrm{P}_{vK}-\mathrm{P}_{vR}+\mathrm{K}_8\cdot\mathrm{H}+\mathrm{K}_9\right)}-\mathrm{G}_{iK} \tag{18}$$

$$\rho_v\cdot\frac{\mathrm{dV}_{vR}}{\mathrm{dt}}+\mathrm{V}_{vR}\cdot\frac{\mathrm{d}\rho_v}{\mathrm{dP}_{vR}}\cdot\frac{\mathrm{dP}_{vR}}{\mathrm{dt}}=\mathrm{K}_{10}\cdot\mathrm{G}_{lv} \tag{19}$$

$$\mathrm{K}_{11}\cdot\frac{\mathrm{dh}}{\mathrm{dt}}=\mathrm{G}_K-\mathrm{G}_{lv}+\mathrm{G}_{gP} \tag{20}$$

$$\mathrm{K}_{12}\cdot\mathrm{G}_{lv}\cdot\mathrm{i}_v+\frac{\mathrm{dh}}{\mathrm{dt}}=\mathrm{N}(t) \tag{21}$$

Initial conditions:

$$\mathrm{V}_{vK_0}=1;\ \mathrm{H}_0=1;\ \mathrm{P}_{vK_0}=\mathrm{K}_{13};\ \mathrm{V}_{vR_0}=\mathrm{K}_{10}^{-1};\ \mathrm{h}_0=1;\ \mathrm{P}_{vR_0}=P_{vR_0}/P_{vK_0};\ \mathrm{i}_{v0}=1;\ \mathrm{i}_{l0}=i_{l0}/i_{v0} \tag{22}$$

where are the similarity criteria:

$$\left.\begin{aligned}
&\mathrm{K}_7=\frac{2\rho_{l_0}^3P_{vK_0}\mu_S^2\Pi_{gP}^2\Pi_R^2h_0^2i_{v_0}^2(1-i_{l_0}/i_{v_0})^2}{\rho_{v_0}^2V_{vK_0}^2N_0^2}\\
&\mathrm{K}_8=\frac{\rho_l gH_0}{P_{vK_0}};\ \ \mathrm{K}_9=\frac{\rho_l gL}{P_{vK_0}};\ \ \mathrm{K}_{10}=\frac{V_{vK_0}}{V_{vR_0}};\\
&\mathrm{K}_{11}=\frac{\rho_{l_0}\Pi_R h_0}{\rho_{v_0}\cdot V_{vK_0}};\ \ \mathrm{K}_{12}=\frac{\rho_{v_0}\cdot V_{vK_0}}{\rho_{l_0}\cdot\Pi_R\cdot h_0(1-i_{l_0}/i_{v_0})};\\
&\mathrm{K}_{13}=\left[P_{vR_0}-\rho_{l_0}g(H_0+L)\right]/P_{vK_0}
\end{aligned}\right\} \tag{23}$$

μ_S – total flow rate at the inlet to the reactor;
Π_{Gp} – flow area of the coolant of the main circulation pipe.

The system of equations (18) - (23) is nonlinear and in the general case can be solved by the numerical Runge-Kutta method.

4. Analysis of the results of computational modeling.

In accordance with (7), (8), (9) and the developed method, the criteria and qualification conditions of pressurizer system for water hammers in the process of an accident with LLPS:

$$\text{for ГУ1 - } \quad \mathrm{K}_{K1} = \frac{H}{H_K}(\mathrm{K}_7,...,\mathrm{K}_{13}) < 1 \tag{24}$$

$$\text{for ГУ2 at } P_{vK} \geq P_{\max} - \quad \mathrm{K}_{K2} = \mathrm{M}(\Pi_{iK_0}, \mathrm{K}_5,...,\mathrm{K}_{13}) < 1 \tag{25}$$

$$\text{for ГУ3 at } P_{vK} \geq P_{\max} - \quad \mathrm{K}_{K3} = \frac{1}{2}\left[\frac{2(P_{\max} - P_0)\rho\Pi^2_{iK_0}}{G^2_{iK}} - \xi_0\right]^{-1} < 1 \tag{26}$$

The feasibility of qualification conditions (24), (25) is determined by the results of integrating the system of nonlinear equations by the Runge-Kutta method.

To verify the proposed method for determining the conditions and parameters of water hammer in a pressure compensator, the well-known experimental data of A.V. Korolev obtained on the model of a pressure compensator VVER-440 were used [8].

Figure 2 shows the experimental data [8] on the relative maximum amplitude of ГУ1 $\Delta\mathbf{P}_{gm} = \Delta P_{gm}/P_0$ for various shutter diameters of the pressurizer VVER-440 model (SV PSD of pressurizer simulator). From the presented results it follows that the calculations according to the well-known formula N.E. Zhukovsky have underestimated $\Delta\mathbf{P}_{gm}$ values with respect to experimental data, and solutions of equations (17), (18) ... (23) have quite satisfactory conservative estimates.

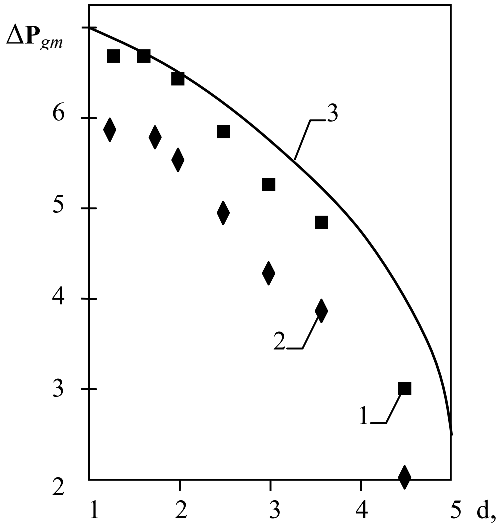

Fig. 2. The maximum amplitudes of the pressure of hydroblow when filling out the experimental model of the VVER-440 pressure compensator depending on the shutter diameter d (SV PSD of pressurizer simulator): 1 - experiment [8]; 2 - calculation by the formula N.E. Zhukovsky; 3 - calculation by formulas (17), (18) ... (23)

The results of computational modeling of steam pressure (P_{vK}) and coolant level (H) in the pressure compensator are presented in Fig. 3.

Figure 3 shows the results of calculating the change in pressure at the outlet of the reactor (P_{vR}) and the coolant level in the pressure compensator during accidents with LLPS. At the initial moments of the accident, the pressure in the reactor decreases due to shutdown of the main coolant pump (MCP).

The rate of P_{vR} decrease is determined by the rate of decrease in pressure head and flow of the MCP during the “run-out” after the MCP shutdown.

The pressure reduction in the reactor, on the one hand, determines the corresponding decrease in the coolant level in the pressure compensator. On the other hand, it intensifies the process of vaporization in the reactor core. The intensification of vaporization determines a corresponding increase in steam pressure at the outlet of the reactor.

From 910 seconds of the emergency process, the second of the above factors becomes dominant and the pressure at the outlet of the reactor, as well as the level of the coolant of the pressure compensator begins to increase. At the 1950 second of the emergency process, the pressure in the steam volume reaches the maximum permissible values and the pressurizer safety valves are actuated, which is accompanied by a sharp increase in the coolant level in the pressurizer and water hammer on the inner surface of the pressurizer case (Fig. 3).

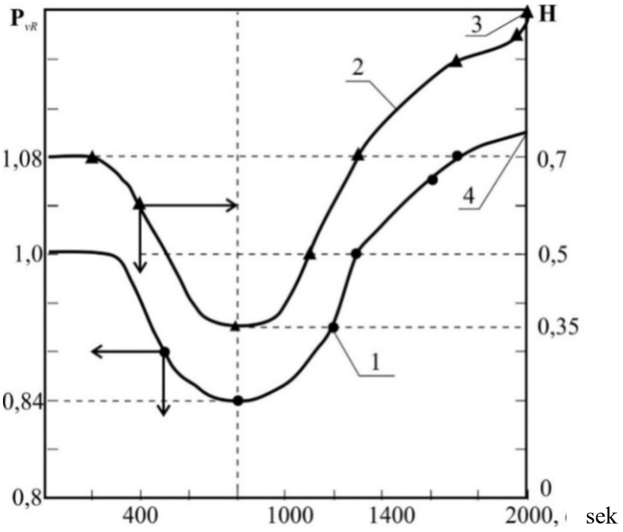

Fig. 3. Change in the pressure in the reactor $\mathbf{P}_{vR} = P_{vR}/P_{R0}$ and the level of the coolant in the pressure compensator $H = H / H_0$ in the event of an accident with the LLPS: 1- $\mathbf{P}_{vR}$; 2 - **H**; 3 - water hammer on the housing of the pressure compensator; 4 - pressurizer SV activation

At the time of the opening of the SV PSD of pressurizer , the qualification condition (24) for the absence of a water hammer due to the overflow of the full volume of the pressure compensator (WH type WH1) with the coolant is not provided.

The qualification results for the conditions of the WH type WH2 are shown in Fig. 4 in the format of criteria K_5 and K_6. From the obtained results of computational modeling it follows that the qualification condition for WH2 (25) is also not provided.

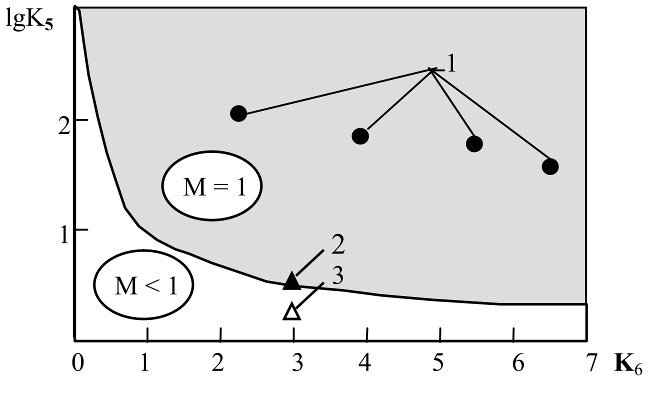

Fig. 4. The range of conditions for the occurrence of water hammer as a consequence of aperiodic instability in transonic flows of two-phase vapor-liquid flows: 1 - experiment 2; 2 - VS-99 at the rated power of the reactor; 3 - VS-99 during tests at the “hot” shutdown of the reactor

The feasibility of qualification conditions (26) for the absence of water hammer due to the accelerated closure of the SV PSD of pressurizer (WH type WH3) is ensured.

Computational models of emergency codes (e.g. 9-15) shall account the supposed passive security system operation.

Conclusions.

1. A conservative estimate of the time of effective operation of a pressure compensator system for management of accident with a complete loss of long-term power supply is about 900 seconds from the start of the emergency process. The conservatism of this estimate is determined by the fact that, according to the accepted assumptions, the influence of natural circulation in the reactor circuit and heat transfer in the volume of the steam generator on the heat transfer conditions in the reactor core were not taken into account in the calculation simulation of the emergency process.

2. In the framework of the developed method, the criteria, conditions and consequences of the occurrence of water hammers due to overflow of the coolant of the pressure compensator, transonic flow regimes of a two-phase flow in the flow part of the safety valves of the pressure compensator and unacceptably accelerated closing of the safety valves when the pressure in the vapor volume of the pressure compensator is less than the maximum allowable values. The obtained criteria, conditions and consequences of water hammer in the pressure compensator system are in good agreement with the known experimental data.

3. As a result of the calculation analysis, it was found that during an accident with a complete loss of long-term power supply, water hammers may occur due to the overflow of the pressure compensator when the safety valves are opened and the transonic modes of the two-phase flow in the flow part of the open safety valves are opened.

4. An effective measure to prevent water hammer in the pressure compensator system is to increase the hydrodynamic resistance in the upper part of the pressure compensator by installing distance gratings.

5. Qualification of alternative passive safety systems is required, providing effective management of accident with a complete loss of long-term power supply from 900 seconds of the onset of the emergency process.

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