

Analysis of mass transfer processes in a reactor during a loss-of-coolant accident*

Aleksey V. Kulikov¹, Andrey N. Lepyokhin¹, Vitaly I. Polunichev¹

¹ JSC “Afrikantov OKBM”, 15, Burnakovskiy proezd, Nizhny Novgorod, 603074 Russian Federation

Corresponding author: Aleksey V. Kulikov (bolnov@okbm.nnov.ru)

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Abstract

The purpose of the work was to optimize the parameters of the spillage system equipped with a gas pressure hydroaccumulator for a ship pressurized water reactor in a loss-of-coolant accident. The water-gas ratio in the hydroaccumulator and the hydraulic resistance of the path between the hydroaccumulator and the reactor were optimized at the designed hydroaccumulator geometric volume.

The main dynamic processes were described using a mathematical model and a computational analysis. A series of numerical calculations were realized to simulate the behavior dynamics of the coolant level in the reactor during the accident – by varying the optimized parameters. Estimates of the minimum and maximum values of the coolant level were obtained: depending on the initial water-gas ratio in the hydroaccumulator at different diameters of the flow restrictor on the path between the hydroaccumulator and the reactor. These results were obtained subject to the restrictive conditions that, during spillage, the coolant level should remain above the core and below the blowdown nozzle. The first condition implies that the core is in safe state, the second excludes the coolant water blowdown. The optimization goal was to achieve the maximum time interval in which these conditions would be satisfied simultaneously.

The authors propose methods for selecting the optimal spillage system parameters; these methods provide the maximum time for the core to be in a safe state during a loss-of-coolant accident at the designed hydroaccumulator volume. Using these methods, it is also possible to make assessments from the early stages of designing reactor plants.

Keywords

Accident; coolant leak; coolant level; core; safe state; optimization; spillage system; reactor; hydroaccumulator; design analysis

Problem definition

In the Russian Federation, a civil nuclear fleet has been created and is now successfully operating. It consists of marine reactor plants equipped with pressurized water reactors and gas pressurizers to create pressure in the pri-

mary circuit, made in the form of separate tanks filled with water and nitrogen (IAEA-TECDOC-1451 2005, Zverev and et al. 2012, Fadeev and et al. 2016). One of the main requirements for reactor units is their high safety.

The article considers a potential large-break loss-of-coolant accident in the primary circuit. The long expe-

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rience of analyzing such accidents (Kuul and et al. 1992, Vorobyova and et al. 2008, Lepyokhin and et al. 2009, Vorobyova and et al. 2016, Lepyokhin and et al. 2017) allows us to clearly imagine the course of processes and the characteristic behavior of the main reactor thermohydraulic parameters (see Fig. 1 and 2). These parameters are given in relative units, reduced to the initial values at the time of depressurization.

At the beginning of such an accident, the coolant blowdown occurs before the nozzle is drained. The process is accompanied by a rapid (with typical times of the order

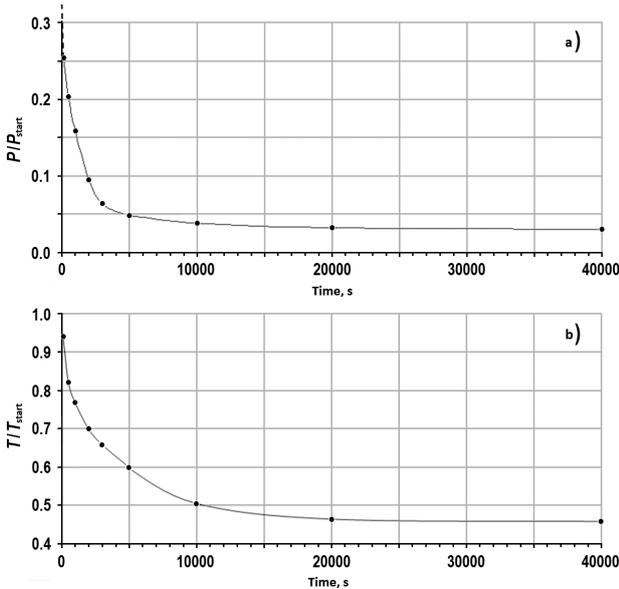


Figure 1. Characteristic time behavior of the main thermohydraulic parameters in the primary circuit during a loss-of-coolant accident: a) relative pressure; b) relative coolant temperature.

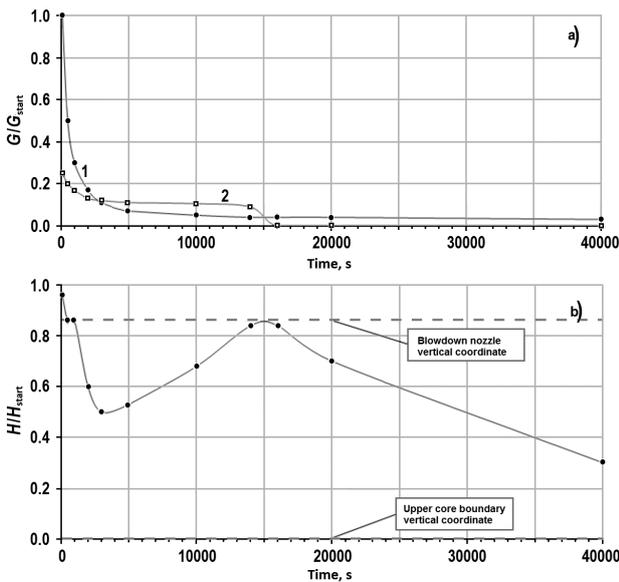


Figure 2. Characteristic time behavior of the main thermohydraulic parameters in the primary circuit during a loss-of-coolant accident: a) relative blowdown (1) and spillage (2) rates; b) relative coolant level.

of tens of seconds) decrease in the pressure and temperature of the primary coolant; the blowdown rate also falls accordingly.

Protective actions in this situation, along with dropping the emergency protection and connecting the reactor shutdown cooling means, include supplying water to the reactor from the passive system, for example, from hydraulic accumulators (HA) (Fadeev and et al. 2016). The system parameters (pressure, water-gas ratio in HAs, hydraulic characteristics of the path from the HA to the reactor, etc.) are optimized, as a rule, subject to the condition that the coolant level in the reactor should be maintained as long as possible above the core (to eliminate its melting) at the specified total HA volume.

As the primary circuit pressure decreases, the coolant in the reactor boils and the gas flows from the pressurizer to the reactor, forming a steam-gas volume under the reactor cover, from which actually the steam-gas mixture blowdown occurs after the level is below the nozzle. After a while, there is a relative balance between the processes of the steam-gas mixture blowdown, coolant boiling and water entering the reactor from the HA. The characteristic times of these processes are several thousand seconds. The change in the coolant level at this stage is mainly determined by the balance between the blowdown flow rate and the water entering the reactor from the HA. Obviously, the closer the values of the blowdown flow rate from the reactor and the water entering the reactor are, the more stable the coolant level in the reactor is.

After the hydraulic accumulator is drained, the water level in the reactor is reduced due to boiling. The time when the core is in safe state is determined by the time when the water level drops to the top of the core. The characteristic times of these processes are tens of thousands of seconds.

Optimization of the spillage system parameters aimed at maintaining the water level in the reactor above the core as long as possible can be carried out within certain ranges of the most significant parameters. These ranges are determined by design capabilities, weight-size characteristics of systems, etc. In this case, it is necessary to fulfill certain conditions, i.e., criteria of keeping running.

The paper discusses possible ways of optimizing the following spillage system parameters:

- the initial water-gas ratio in the HA at the specified total volume: a larger water volume provides a larger time reserve but, at the same time, the initial gas volume decreases, which accordingly affects the dynamics of water flowing from the HA to the reactor and the possibility of maintaining the level in the reactor above the core;
- the hydraulic resistance of the path between the HA and the reactor, which also affects the behavior of water flowing from the HA. The required hydraulic characteristic of the path is generally provided by the flow restrictor.

The criteria that must be met during the accident to ensure the maximum safety time for the core are as follows:

- the coolant level in the reactor should not fall below the core upper boundary;
- the time, during which one the coolant level is above the blowdown nozzle, should be reduced to a minimum and further the coolant level should be maintained below the blowdown nozzle.

Mathematical model for analyzing the dynamics of mass transfer processes

The model describes the following basic processes:

- water/steam blowdown from the reactor (the corresponding flow rates are calculated taking into account possible critical blowdown);
- water supply from the hydraulic accumulator to the reactor;
- pressure change in the reactor and hydraulic accumulator;
- gas volume change in the hydraulic accumulator;
- level change in the reactor.

Mass transfer between the reactor and the pressurizer was not considered in this analysis.

The model corresponding to the stage of water blowdown from the reactor. The design diagram of the model is shown in Fig. 3, where V_{HA}^g is the HA gas blanket, m^3 ; V_1^w is the reactor water volume above the core, m^3 ; P_{HA} , P_1 are the HA and reactor pressures, respectively, Pa; γ_{HA}^w , γ_1^w are the HA and reactor water densities, respectively, kg/m^3 ; G_{blow} is the reactor blowdown flow rate, kg/s ; G_{HA} is the water flow from the HA to the reactor, kg/s ; ζ_{HA} is the hydraulic resistance factor of the spillage pipe (spillage path from the HA); F_{HA} is the passage area, to which the hydraulic resistance on the spillage path from the HA is referred, m^2 .

The HA gas pressure and volume are calculated by the equations:

$$\frac{dP_{HA}}{dt} = -\frac{\kappa \cdot P_{HA}}{V_{HA}^g} \cdot \frac{dV_{HA}^g}{dt} \quad (1)$$

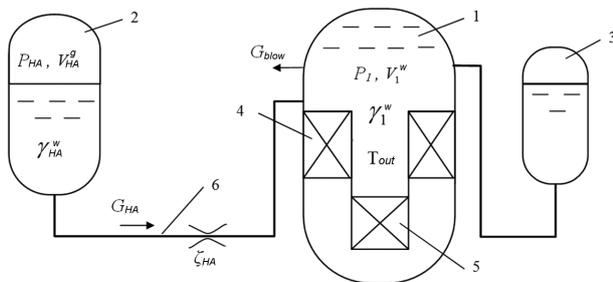


Figure 3. Design diagram of the reactor spillage system (initial state): 1. Reactor; 2. Hydraulic accumulator; 3. Pressurizer; 4. Steam generator; 5. Core; 6. Spillage pipe.

$$\frac{dV_{HA}^g}{dt} = \frac{G_{HA}}{\gamma_{HA}^w} \quad (2)$$

The reactor pressure is calculated by the equation:

$$\frac{dP_1}{dt} = -\frac{G_{HA} - G_{blow}}{V_1^w \cdot \partial \gamma_1^w / \partial P} \quad (3)$$

Water supply from the HA to the reactor is calculated by the equation:

$$G_{HA} = F_{HA} \sqrt{2 \cdot \gamma_{HA}^w \cdot (P_{HA} - P_1) / \zeta_{HA}} \quad (4)$$

The following equation is used to calculate the reactor blowdown flow rate (Idelchik 1990):

$$G_{blow} = \mu \cdot F_{blow} \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \sqrt{\frac{2\kappa}{\kappa+1} \cdot \gamma'(P_1) \cdot P_1} \quad (5)$$

where μ is the flow coefficient; F_{blow} is the nozzle passage area, from where the coolant flows out, m^2 ; κ is the nitrogen adiabatic index (Chirkin 1968); γ' is the water density on the saturation line at the reactor pressure, kg/m^3 (Rivkin and et al. 1980, IAEA-TECDOC-1496 2006).

The model corresponding to the stage of steam blowdown from the reactor. Equations (1) and (2) for gas pressure and volume in the HA, Equation (4) for water flow from the HA to the reactor, and Equation (5) for blowdown flow rate are preserved.

The pressure in the reactor is assumed equal to the saturation pressure at the primary circuit coolant temperature at the core outlet (Rivkin and et al. 1980, IAEA-TECDOC-1496 2006):

$$P_1 = P_s(T_{out}) \quad (6)$$

The primary circuit coolant temperature at the core outlet is assumed to be a boundary condition (a given time function) determined by the power balance of the residual heat release, heat removal through the steam generator and steam entrainment as a result of boiling in the core.

$$T_{out} = f(t) \quad (7)$$

The effects due to the steam condensation on the drained part of the tubular system of the steam generator in the presence of a noncondensable gas are neglected.

Analytical methods and results

A search was made to find the optimal ratio between the initial water and gas volumes in the HA, while maintaining their total volume. The ratio of the initial gas volu-

me to the total HA volume was varied for a certain set of hydraulic characteristics of the path between the HA and the reactor. At the same time, the diameter of the flow restrictor was used as the main parameter determining the hydraulic characteristic of the path. The range of its change was taken from the practice of designing similar systems.

The characteristic behavior of the coolant level when water is supplied from the HA to the reactor is generally as follows: initially, the level is relatively quickly reduced to the minimum value corresponding to the moment of the first equalization of the blowdown and spillage flows; then, it increases due to the fact that the spillage flow rate exceeds the blowdown flow rate, reaching the maximum value corresponding to the moment of the second equalization of the blowdown and spillage flows; and further, the level decreases monotonically after the accumulator is drained. Of course, for certain combinations of parameters, one or even both of the above extremes can be absent. However, in practice, this means that the blowdown flow rate from the reactor and the water supply flow rate from the accumulator are not close, i.e., the spillage system parameters are far from being optimal. Therefore, it makes no sense to use this set of parameters to solve the problem of providing the maximum safe-state time for the core.

Figures 4 and 5 show the results of estimates for the minimum and maximum values of the coolant level depending on the ratio of the initial gas volume to the total HA volume at different diameters of the flow restrictor on the path between the HA and the reactor. These results are also limited by the above criteria for reducing and raising the level – inadmissible areas are outside the shaded area. For the obtained admissible ranges of parameters, the coolant level remains above the core and below the blowdown nozzle during spillage.

Based on the task to maintain the coolant level in the reactor above the core as long as possible, we can, while remaining within the range of parameters shown in Fig. 4, 5, to estimate the maximum possible time of this maintenance. As the volumetric water-gas ratio in the accumulator decreases, its drainage time slightly increases, because,

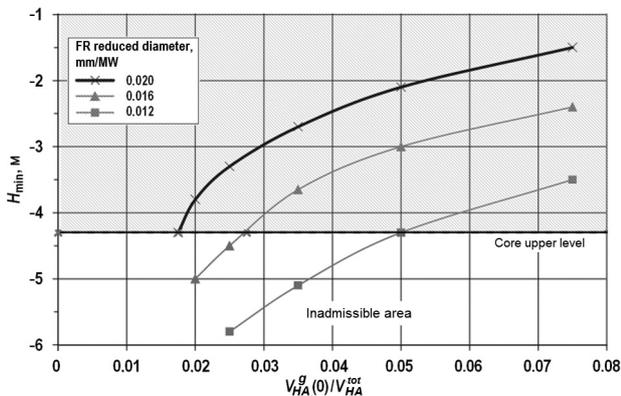


Figure 4. The minimum coolant level depending on the ratio of the initial gas volume to the total HA volume at different diameters of the flow restrictor.

all other things being equal, the available water amount increases. However, when the gas volume decreases, the pressure reduction rate in the accumulator decreases as water flows from it; therefore, the current spillage flow decreases, thus reducing the system efficiency, which is confirmed by the results given below.

Figure 6 shows the dependences of the HA drainage time on the ratio of the initial gas volume to the total HA volume at different diameters of the flow restrictor (the shaded part of the curves corresponds to the restrictions on the level increase). It can be seen that the dependencies have characteristic extreme points indicating a level decrease limitation to the elevation mark of the core upper boundary (the dashes show the continuation of the dependencies constructed with no allowance for this limitation, the dash-dot shows the portions of the curves corresponding to the times for achieving this limitation).

The presence of these extreme points on each curves and their approximate correspondence to the same time point are of a general nature, which can be qualitatively illustrated in Fig. 7.

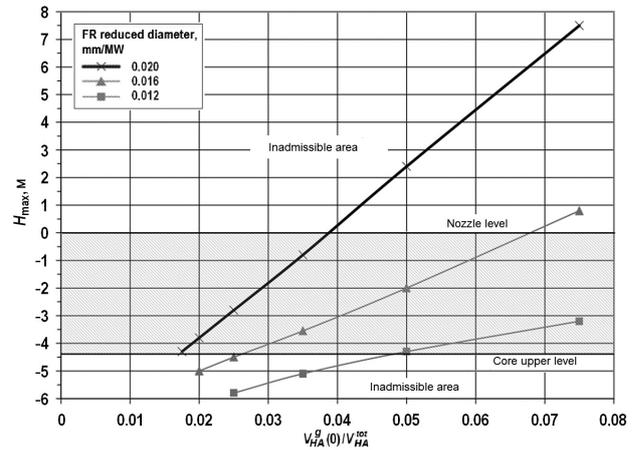


Figure 5. The maximum coolant level depending on the ratio of the initial gas volume to the total HA volume at different diameters of the flow restrictor.

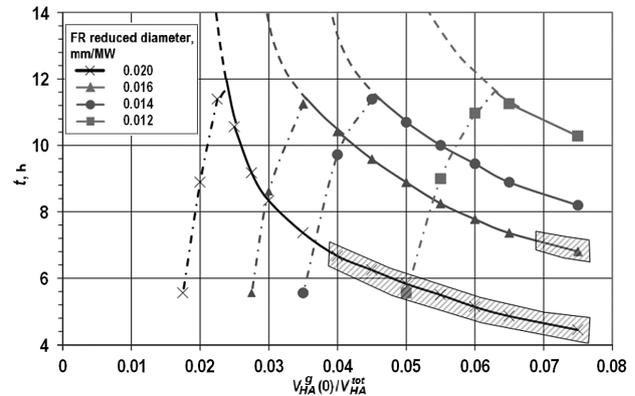


Figure 6. The HA drainage time (or the core uncover start) depending on the ratio of the initial gas volume to the total HA volume at different diameters of the flow restrictor.

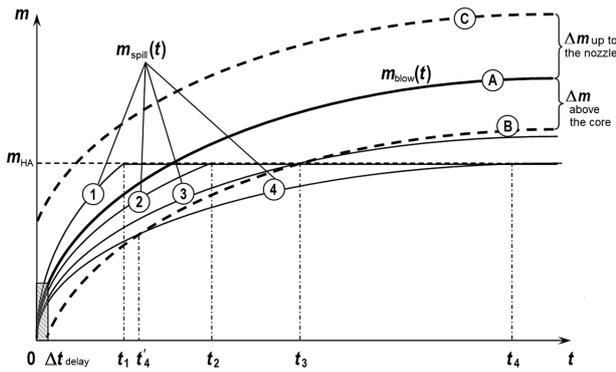


Figure 7. Water mass ingress and entrainment in the reactor. Characteristic times of the HA drainage and the core uncover start.

Dynamics of change in time of the coolant mass leaving the reactor at the blowdown rate $m_{\text{blow}}(t)$ (the curve A in Figure 7), starting from the moment of the steam-gas blanket formation, does not depend on the spillage rate, i.e., an invariant in this problem. The choice of the spillage system parameters determines the dynamics of change in time of the water mass entering the reactor with the spillage rate $m_{\text{spill}}(t)$ (the family of curves 1–4 in Figure 7).

The HA drainage time is determined by the intersection of the curve $m_{\text{spill}}(t)$ and the straight line m_{HA} (the initial water mass in the HA). It should be noted that, with the change by two to three times in the relative gas volume in the HA considered in this task, the absolute value of the initial water mass in the HA varies insignificantly, since in practice the volumetric gas-water ratio in the HA is in principle chosen small (of the order of 0.05–0.1) in order to ensure the maximum water supply. At higher spillage rates, this time is reached earlier (curves 1 and 2, time points t_1 and t_2 , respectively). The initial spillage rate is limited from above by the condition that the nozzle level should not be reached. In Figure 7, this condition corresponds to the bandwidth “ Δm to the nozzle” – between $m_{\text{blow}}(t)$ (the curve A) and the dashed curve C.

Of course, after the HA is drained, the spillage rate is equal to zero and the further growth of the corresponding curve $m_{\text{spill}}(t)$ ceases. If the spillage rate reduces and, accordingly, the growth rate of the curve $m_{\text{spill}}(t)$ decreases, the intersection occurs later (curves 3 and 4, time points t_3 and t_4). This is exactly what happens when the spillage system parameters are optimized in order to increase the HA drainage time.

At the same time, the lower the spillage rate is, the faster the mass difference grows between the water leaving the reactor and the water flowing into it. This difference should be limited based on another chosen criterion by the amount of water mass initially located in the reactor above the elevation mark of the core upper boundary. In the figure, it corresponds to the bandwidth “ Δm above the core” between $m_{\text{blow}}(t)$ (the curve A) and the dashed curve B. Thus, as the spillage flow decreases to a certain value, the float time in the considered accident ceases to be associated with an increase in the HA drainage time,

and the time before the core uncover becomes decisive (see the time point t'_4 instead of t_4 in Fig. 7).

The limiting (mathematically optimal) value of the spillage flow rate is such that the HA drainage time is exactly the same as the core uncover start time (see point t_3 in Fig. 7). This moment is determined by the two constants of the problem: m_{HA} (the initial water mass in the HA) and “ Δm above the core” (the water mass initially located above the core upper boundary). Therefore, it is the same for any curve in Fig. 6. However, it should be noted that in practical terms it is necessary to have some reserve relative to this mathematical optimum. Based on the experience of designing such systems, it is inadvisable to choose the flow restrictor diameter below a certain technically justified value, for example, to exclude possible clogging.

It is possible to somewhat increase the float time in the considered accident due to an introduced delay in connecting the HA. At the same time, on an accident scale, this increase, as a whole, is expected to be insignificant: the permissible delay value Δt_{delay} (the shaded rectangle in Figure 7) is determined by the time when the water mass above the core upper boundary “ Δm above the core”, is removed from the reactor, while the mass change rate at the beginning of the process is maximal.

Conclusions

1. When using passive water supply systems (gas pressure hydraulic accumulators) in primary coolant loss accidents, it is advisable to optimize the parameters of these systems, for example, relating to the initial water-gas ratio for a given total volume or the hydraulic resistance of the path between the HA and the reactor (in particular, the diameter of the flow restrictor on the path).
2. The optimization goal can be achieving the maximum time interval in which the following criteria (limiting conditions) will be satisfied simultaneously:
 - the coolant level in the reactor should not fall below the core upper boundary;
 - the time, during which one the coolant level is above the blowdown nozzle, should be reduced to a minimum and further the coolant level should be maintained below the blowdown nozzle.

If these conditions are met, the coolant level in the reactor can be maintained above the core as long as possible. Thus, it becomes possible to increase the reactor safe-state time during LOCAs.
3. It is shown that there is a limit value of the time interval in which the above criteria are satisfied simultaneously. This value does not depend on the hydraulic characteristics of the path between the HA and the reactor but is determined by the initial water mass in the accumulator and the water mass that initially is above the core upper boundary.

4. Given the limiting time interval and the flow restrictor diameter, it is possible to unambiguously determine the optimum parameters of the reactor spillage system to provide the maximum time for the core to remain in safe state at a specified total accumulator volume.
5. The presented analytical methods make it possible to estimate optimal parameters of the spillage system, starting from the early stages of designing. In order to obtain refined characteristics, for example, when per-

forming a safety analysis, calculations should be made, using system codes (e.g., (Idaho National Engineering Laboratory 1995, Migrov and et al. 2001)) describing the processes as a whole, taking into account heat transfer in steam generators, steam condensation in the presence of noncondensable gas, etc., to confirm the effectiveness of safety systems during loss-of-coolant accidents.

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