Calculation analysis of the processes of boric acid mass transfer in the WWER core in boiling emergency mode

A V Morozov, A V Pityk, S V Ragulin, A R Sahipgareev, A S Soshkina and A S Shlepkin

State Scientific Centre of the Russian Federation – Institute for Physics and Power Engineering named after A.I. Leypunsky, 1, Bondarenko Sq., Obninsk, 249033, Russian Federation

E-mail: sas@ippe.ru

Abstract. In this paper the processes of boric acid mass transfer in a WWER-TOI nuclear reactor core in case of the accidents with main circulation pipeline rupture and loss of all AC power supply are considered. The heat removal from the WWER-TOI reactor in case of an emergency process is determined by the use of the passive heat removal and passive core cooling systems. Passive core cooling system of WWER-TOI consists of three stages of hydro accumulators. These systems provide reactor cooling by feed of boric acid solution with concentration of 16 g H₃BO₃/kg H₂O. In view of length of accident process, the boiling of the coolant with high content of boron and considering low concentration of boric acid in the steam leaving the core, conditions may arise for the possible accumulation and subsequent crystallization of boric acid in the reactor that can lead to a deterioration of the process of core heat removal. To assess the chance of accumulation and subsequent crystallization of H₃BO₃ in the core of the WWER reactor, a hand calculation analysis of the change of concentration of boric acid in the reactor in case of emergency mode was carried out. In accordance with the calculation results, if a boric acid concentration in hydro accumulators of passive core cooling systems is 16 g /kg H₂O, than a large excess of the final boric acid concentration in the core is observed in accidents after approximately 43 hours of an emergency process. The options of reducing the concentration of H₃BO₃ to 8, 4, 2 and 1 g/kg H₂O are considered in the calculation process. The obtained results allow us to conclude that a decrease in the concentration of boric acid in the system of hydro accumulators of the third stage would allow to avoid the crystallization of boric acid in the core in the event of an accident.

1. Introduction

WWER-TOI (Water-Water Energetic Reactor Typical Optimized Informatized), also referred to as AES-2010 is advanced project of NPP with WWER-1200 (V-510 reactor facility) water pressurized reactors executed in the terms of modern informative environment and according to nuclear and radiation safety requirements (figure 1). WWER-TOI project is developed on the basis of the design documents worked-out for AES-2006, considering in maximum experience gained by industry organizations while development of the recent NPP projects based on WWER technology (Novovoronezh NPP-2).
WWER-TOI project takes into account experience in construction and operation of NPP with WWER both in Russia and abroad. Design solutions have been optimized to minimize the failures having a negative effect on Power Unit economic indicators. The construction of the first power units of WWER-TOI project is planned on the site of Kursk NPP-2.

In this NPP project, the cooling of the core of the nuclear reactor in the event of beyond design basis accidents with the rupture of the main circulation pipeline (MCP) and the loss of all AC sources during 72 hours after start of the accident is provided by the operation of passive safety systems. The first, second and third stage accumulator systems (HA-1, HA-2, HA-3) included in the passive core cooling systems, due to the consecutive supply of boric acid solution at a concentration of 16 g H$_2$BO$_3$/kg H$_2$O to the reactor, together with the air-cooled passive heat removal system (PHRS), prevent the core of the nuclear reactor from draining and allow the removal of residual heat from the core in the event of a loss of coolant accident (LOCA) with a total loss of AC power sources [1-5].

In consideration of length of accident process, the boiling of the coolant with high content of boron and considering low concentration of boric acid in the steam leaving the reactor, conditions may arise for the possible accumulation and subsequent crystallization of boric acid in the core. These processes can lead to the formation of flakes of boric acid in the volume of coolant or the appearance of sediment on the surfaces of the reactor internals, which can lead to a deterioration of the process of core heat removal.

The processes of mass transfer of boric acid in the primary circuit of nuclear power plants with a reactor of the WWER type are relevant for many years. This is confirmed by a set of data on the dynamics of the concentration of a solution of boric acid carried out in a number of experimental facilities: AMT, PACTEL, REWET I-III, VEERA, IVO [6]. In some cases, the formation of boric acid crystals in the gaps between the simulators of fuel elements was observed. In connection with all the above, the studies related to the dynamics of the concentration of boric acid solution in nuclear reactors are becoming particularly relevant at the present time in connection with the development of new projects of WWER NPPs with modern passive safety systems [7].

To evaluate the possibility of crystallization of boric acid in the WWER core, a hand calculation analysis of the change of concentration of boric acid in the reactor in case of emergency was performed. In previous calculations, the droplet entrainment of boric acid from the core was assumed constant at the level of 0.2% [8, 9]. The results obtained in these calculations were rather conservative. In this case, a more realistic approach was used for determining the droplet entrainment value.

2. Determination of value of boric acid droplet entrainment

The decrease in the concentration of boric acid in the core in an emergency situation can be accomplished in two ways: by droplet entrainment process in the steam-water mixture and due to the solvent capacity of the steam. In the literature, a number of the quantitative relationships are described that determine the moisture of the steam. They are obtained from the analysis of the equations of motion, the conditions for the fragmentation of a fluid and the differential equation describing the motion of drops in a steam volume. One of these dependences, which establishes the relationship
between the water content of steam and the main quantities determining the droplet entrainment process, obtained as a result of criterial processing of the experimental data obtained at different pressures, and given in [10], has the form:

\[
\omega = 2.75 \cdot 10^8 \frac{N^{2.3}}{Ga^{1.1} \left( \rho' / (\rho' - \rho^*) \right)^{0.25}},
\]

(1)

where \( \omega \) is water content of steam, \( N = w_0^2 / (\varphi g H) \), \( w_0 \) is superficial velocity of steam, \( \varphi \) is actual volumetric content of steam, \( g \) is the gravity factor, \( H \) is height of the steam space, \( Ga \) is the Galilean number, \( \rho' \) is water density, \( \rho^* \) is density of steam.

It should be noted that the above dependence can be used only in a limited range of parameters and is not always applicable for calculating the drop entrainment process from the WWER reactor in the event of an accident with a MCP rupture. One of these parameters is the height of the steam volume. It was noted in [10], that the maximum height of the lifting steam section should not be more than 1 m. This is much less than the height of the steam-water mixture rising in the WWER reactor vessel - from the evaporation mirror to the nozzle of the MCP.

Moreover, there are formulas that allow us to calculate the steam content in the stream of a mixture of water and steam \( x \). One of them, given in [10], has the form:

\[
x = 0.26 \left( w_0^2 / g \sqrt{\sigma / g (\rho' - \rho^*)} \right)^{0.36} \left( \frac{\rho'}{(\rho' - \rho^*)} \right)^{0.12},
\]

(2)

where \( \sigma \) is the liquid surface tension coefficient.

The analysis shows that when calculating the moisture content in the steam and the steam content at the outlet from the core of the WWER, in the event of an accident, according to dependences (1) and (2), the discrepancy between the results obtained can reach 30%. In addition, it must be taken into account that the calculation of the parameters of the steam-water mixture by these formulas is possible only at a certain intensity of evaporation rate. In [10], the boundary conditions are defined for which the formulas presented are valid, however, in case of exceeding the boundary parameters, the calculated dependences are not proposed, although it is said that the intensity of the droplet entrainment is higher. The analysis showed that during boiling a solution of boric acid in the reactor in the event of LOCA, the evaporation rate exceeds the limits of applicability of these dependences in a significant time interval.

3. Calculation of the mass transfer processes of boric acid in the WWER core

Taking into account the above, to use formulas (1) and (2) for calculating the processes of droplet entrainment at an early stage of the LOCA is impossible. Therefore, during the analysis, the emergency process was divided into two different stages. In the early stage of the accident, a very high steam content is observed in the volume of core, which leads to an increase in the level of the foamed liquid above the level of upper perforation of the reactor barrel, and the steam-water mixture splashes out of the reactor into the containment through a break pipeline. This stage lasts approximately 7 hours. In length of time, the intensity of residual heat release decreases, consequently the steam content in the reactor decreases, and the boric acid solution level is stabilized at the height of the broken MCP pipe.

A number of assumptions were made during the calculation, either because of the complexity of the processes occurring in the reactor, or because of the inadequacy of data on the properties of solutions of boric acid [11]:

1. Two regions were allocated in the reactor vessel during calculations: the reactor core volume (C) and the reactor pressure chamber volume (RPC).
2. For all the emergency process, the pressure in the system is assumed to be 0.3 MPa.
3. Density and viscosity of the boric acid solution are considered equal to the water parameters under the appropriate conditions.
4. The calculation did not take into account the dissolution of boric acid in the steam.

In the calculation, it was assumed that the reactor rated power before the accident is $3.2 \times 10^9$ W. The law of change of the residual heat removal ($N_{RC}$) in the reactor core is presented in [12]. As the initial data for the calculation, the flow-rate characteristics of the HA-2 and HA-3 passive core cooling systems and the concentration of boric acid in the hydraulic accumulators were used [13, 14].

Boric acid concentration in the core in the first stage of the emergency process, when liquid level in the reactor locates above the upper raw of holes in the reactor barrel, is calculated by the formula:

$$
C_{(H_3BO_3)} = \frac{(m_{RC} + m_{RPC})C_{(H_3BO_3)} + \Delta m_{in}(H_3BO_3)}{m_{RC} + m_{RPC} + \Delta m_{in}(\text{solution}) - \Delta m_{in}(H_2O)},
$$

where $m_{RC}$ and $m_{RPC}$ are masses of the solution of boric acid in the reactor core and RPC respectively, $\Delta m_{in}(H_3BO_3)$ is mass of boron coming to the reactor from HA-2 and HA-3 systems, $\Delta m_{in}(\text{solution})$ is overall mass of boric acid solution coming to the reactor from the HA-2 and HA-3 systems and mass of the pure condensate from the steam generator (SG) working in condensing mode due to the PHRS operation, $\Delta m_{in}(H_2O)$ is mass of water evaporated in the reactor during a period of time $\Delta \tau$.

All of the above values can be calculated by the following formulas:

$$
\Delta m_{in}(H_3BO_3) = G_{HA} \cdot C_{HA}(H_3BO_3) \cdot \Delta \tau,
$$

$$
\Delta m_{in}(\text{solution}) = (G_{HA} + G_{PHRS}) \Delta \tau,
$$

$$
\Delta m_{in}(H_2O) = \frac{N_{RC} \cdot \Delta \tau}{h'' - h_{RPC}},
$$

where $h''$ is steam enthalpy on saturation line (kJ/kg), $h_{RPC}$ is enthalpy of solution of boric acid in RPC (kJ/kg), $G_{HA}$ is flow-rate of boric acid solution from HA-2 and HA-3 systems (kg/s), $G_{PHRS}$ is flow-rate of condensate coming from SG due to operation of PHRS (kg/s), $C_{HA}(H_3BO_3)$ is boric acid concentration in the tanks of HA-2 and HA-3 systems (kg/kg).

Gradually, the power of residual heat will decrease, and therefore the level of the foamed liquid in the reactor vessel will also fall. The length from the heads of the fuel assemblies to the top perforation in reactor barrel is 2.77 m. The distance between the lower generatrix of the "cold" branch of the primary circuit pipeline and the upper row of perforated holes in the reactor barrel is 1.845 m. Therefore the critical steam content when liquid level will stand above the top row of holes in the barrel in the event of an emergency with a rupture of "cold" MCP leg break is $\varphi_{cr} = 1.845/2.77 = 0.666$. Steam content is calculated by the dependence (2).

At the second stage of the accident, which begins after the steam content falls below the critical value, the volumes of the reactor core and RPC are considered separately. At this stage, the energy of the core residual heat will be consumed to heat the boric acid solution, coming into the core from the RPC and evaporating it:

$$
N_{RC} = G_{S} r + G_{12} \left( r + h'' - h_{RPC} \right),
$$

where $G_{S}$ is flow-rate of steam (kg/s); $G_{12}$ is flow-rate of boric acid solution from RPC to the core (kg/s), $r$ is specific heat of evaporation (kJ/kg), $h''$ is enthalpy of saturated water (kJ/kg), $h_{RPC}$ is enthalpy of solution of boric acid in RPC (kJ/kg).

The dependence for calculating the change in the mass of boron in the core volume over a time interval $\Delta \tau$ was obtained in [8] and can be written as:

$$
\Delta m_{RC}(H_3BO_3) = (G_{12}C_{RPC} - G_{RC}C_{RC}) \Delta \tau,
$$

where $C_{RPC}$ is boric acid solution concentration in RPC (kg/kg), $C_{RC}$ is boric acid solution concentration in the core (kg/kg), $G_{RC}$ is the flow-rate of boric acid from the core due to process of droplet entrainment.
The change in the concentration of boric acid in the core of reactor over $\Delta \tau$ will be as follows:

$$\Delta C_{RC}(H_3BO_3) = \frac{\Delta m_{RC}(H_3BO_3)}{m_{RC}}.$$  

4. Results of calculations

The above stated formulas were used to determine the concentration of boric acid in the RPC and the core. Changing of the parameters at the $i$-th step of the computation along the time interval $\Delta \tau$ were calculated successively. The obtained results were used for calculations at the next interval of time. Calculations were carried out for five different concentrations of $H_3BO_3$ (16, 8, 4, 2, 1 kg/kg $H_2O$) in the tanks of the HA-3 system. The results of calculation of boric acid solution concentration in the reactor core are shown in figure 2.

As can be seen from the graph, if $C(H_3BO_3) = 16$ g/kg in the system of the third stage hydroaccumulators, then the $C_{3BO_3}$ concentration at the end of 72 hours of emergency process will be approximately 1.13 kg/kg $H_2O$, which greatly exceeds the limiting concentration of boric acid ($C_{lim}$), which at the parameters under consideration is about 0.415 kg/kg $H_2O$.

As the graph shows, if the concentration of boric acid in the accumulators decreases, the value of the final concentration of $H_3BO_3$ in the core also decreases. It is necessary to point out that in all scenarios after 24 hours of emergency process boric acid concentration in the reactor core is $\approx 190$ g/kg and does not reach solubility limit.

As can be seen from the results of calculations, if $C(H_3BO_3) = 16$ g/kg in the system of the third stage hydroaccumulators, then after approximately 43 hours after the start of an accident, the solubility limit of boric acid is reached in the reactor core. For this reason, the processes of crystallization and precipitation of $H_3BO_3$ start. As mentioned above, boric acid deposits in the core have a significant effect on heat transfer during the accident, so, the calculation of the mass of the boric acid precipitate was also carried out. Mass of deposits ($m_{dep}(H_3BO_3)$) was calculated by the formula:

$$m_{dep}(H_3BO_3) = m_{RC} \cdot (C_{RC}(H_3BO_3) - C_{lim}).$$

The results of the calculations of boric acid deposits mass are shown in figure 3. As can be seen from the graph, the mass of boric acid deposits in the reactor core at the end of the 72 hour accident is about 7150 kg in the case of $C(H_3BO_3)$ in the HA-3 system equal to 16 g/kg. When the concentration in the HA-3 is decreased to 8 g/kg, the mass of boric acid deposits in the core is reduced to 1620 kg. With further decrease in the concentration of boric acid in the passive core flooding system, precipitation does not occur in the core.
5. Conclusion

Study of boric acid mass transfer processes in the reactor is of great importance for the analysis of emergency processes in new generation WWER. The calculated estimation showed that if $C(\text{H}_3\text{BO}_3)=16$ g/kg in the system of the third stage hydro accumulators, an excess of the boric acid concentration limit in the core of the WWER-TOI reactor takes place about 43 hours after the onset of the beyond design basis accident with rupture of main circulation pipeline. This process can cause its crystallization and deterioration of heat removal processes from the reactor core. One solution to this problem is to reduce the concentration of boric acid in the HA-3 system to below 8 g/kg. As the results of calculations show, in this case, practically no deposits of boric acid are present in the core.

In the course of the calculation analysis, it was found that at the moment there are issues that require additional experimental studies:
- data on the concentration of boric acid in the steam. In literature there are no dependences of the concentration of boric acid in steam on the concentration and temperature of the boric acid solution;
- transfer of boric acid in the primary circuit of the nuclear power plant at the BDBA in the steam-drop mixture and in steam;
- the effect of the presence of boric acid in a steam on heat exchange in steam generators.

These issues are of decisive importance for the analysis of the processes of mass transfer of boric acid in the reactor core. To eliminate the existing uncertainties, experimental research of the heat and mass transfer processes of $\text{H}_3\text{BO}_3$ with parameters specific for the accidents of WWER are necessary.

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