Analysis of the influence of mass transfer processes between reactor and containment on the operation of the WWER steam generator in condensation mode

A S Shlepkin and A V Morozov
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. This paper presents an analysis of mass transfer processes between the reactor and the containment of a WWER reactor in case of a loss of coolant accident (LOCA). The effect of the differential pressure arising due to the difference in the densities of the media in the primary circuit and in the containment on mass transfer is considered. A description of the HA-2M test facility used for the study of process between the containment and the reactor is given. The results of analysis of the experimental data are presented.

1. Introduction
The joint use of active and new passive safety systems is one of the innovations of modern designs of WWER reactors [1]. The new systems include the passive core flooding system from the hydro accumulators of the second stage (HA-2) and the passive heat removal system (PHRS).

The passive heat removal system of WWER-1200 consists of four independent channels, one for each steam generator (SG) [2]. In case of a LOCA accident, the PHRS provides the transfer of steam generators to the operation in the condensation mode. Condensate produced by SG feeds the core. As a result of condensation of steam coming from the reactor, water of the second circuit in steam generator is heated to the saturation temperature and turns into steam. Due to the natural circulation in the air-condensate loop of the PHRS, the steam enters into the air heat exchangers. The condensed steam transfer heat to the ambient air, then condensate flows back into the SG. Thus, the efficiency of heat removal from the core in case of an accident depends on the power of the steam generator [3].

The presence of non-condensable gases in the primary circuit of the reactor has a negative impact on the steam generator condensing power. These gases include nitrogen, entering the circuit from the hydro accumulators, products of water radiolysis, and air that can enter through a break in the main circulation pipeline (MCP) from the containment [4, 5]. Due to the accumulation of non-condensable gases in the tube bundle, the steam generator condensation power can be reduced [6, 7].

Investigations of the operability of the WWER steam generator model in case of LOCA accident were carried out at IPPE [8]. It was found that if non-condensable gases enter the steam generator only from hydraulic accumulators and due to gas generation in the reactor, then the SG condensation power does not fall below 80% of the initial level [9, 10]. Thus, to substantiate the operability of the steam generator in condensation mode, it is necessary to study mass transfer processes of non-condensable gases between the containment and the reactor core.
2. Analysis of heat and mass transfer processes between core and containment of WWER – 1200

As it was mentioned above, in the case of LOCA accident the primary coolant boils due to the presence of residual energy release and steam enters the containment through the MCP break. It leads to the increasing of containment pressure up to 0.43 MPa soon after the start of the accident. But after that pressure starts to decline due to: decreasing of decay power in the core, steam condensation inside the containment and operation of the passive heat removal system [11].

After the finish of the initial transient phase of an accident and start of passive system operation, the steam flow rate from the primary circuit to the containment can be calculated from the following balance ratio:

\[ G_{\text{out}} = \frac{N_{\text{out}}}{r}, \tag{1} \]

\[ N_{\text{out}} = N_{\text{core}} - N_{\text{SG}} - G_{HA} (i' - i_{HA}), \tag{2} \]

where \( G_{\text{out}} \) is the flow rate of steam coming from the reactor to the containment through the MCP break, \( N_{\text{out}} \) is the thermal energy of steam leaving the reactor through the break, \( r \) is the heat of evaporation, \( N_{\text{core}} \) is the decay power of the reactor core, \( N_{\text{SG}} \) is the power of steam generators operating in condensation mode, \( G_{HA} \) is coolant flow rate from the HA-2 system, \( i_{HA} \) is enthalpy of water from HA-2 system.

The amount of heat needed to heat the water coming from the HA-2 system to saturation temperature is relatively small. So, it can be said that steam flow rate through the MCP break depends on the ratio of \( N_{\text{core}} \) and \( N_{\text{SG}} \). During an accident, it is possible that the decay power will decrease faster than the condensation power of steam generators. In this case, the steam – air mixture from the containment can enter the reactor volume.

To describe correctly the processes in reactor-containment system, it is necessary to consider the presence of mass transfer due to the difference of densities of primary circuit steam and steam – air mixture in the containment, using the approach described in [12].

Let us define the pressure at the upper and lower parts of the break section as \( P_1 - P_4 \), where \( P_1, P_2 \) are pressures in the upper part of break section from the side of the reactor and the containment respectively, and \( P_3, P_4 \) are pressures in the same points of lower part of break. The value of these pressures along vertical \( z \) axis will be equal to:

\[ P_1 = P_3 - \rho^* \cdot g \cdot z, \tag{3} \]

\[ P_2 = P_4 - \rho_{\text{mix}} \cdot g \cdot z, \tag{4} \]

where \( \rho_{\text{mix}} \) is the density of the steam – air mixture in the containment, \( \rho^* \) is the steam density in the primary circuit.

Because density of steam – air mixture is slightly greater than the density of steam, then primary circuit pressure at the upper part of the break section is higher than the pressure in the containment at the same height. A differential pressure between the media of the primary circuit and the containment is equal to:

\[ \Delta P = P_1 - P_2 = g \cdot z \cdot (\rho_{\text{mix}} - \rho^*). \tag{5} \]

This pressure difference leads to outflow of steam to the containment volume. Its flowrate can be determined by the hydraulic resistance of the break section:

\[ \Delta P_{\text{res}} = \zeta (\rho^* \cdot v^*^2) / 2, \tag{6} \]
where $\xi$ is the coefficient of local hydraulic resistance of the break section, $v^\ast$ is the steam velocity. Equating (5) and (6) we obtain the relation for calculation of steam velocity:

$$v^\ast = \left[ \frac{2 \cdot (\rho_{\text{mix}} - \rho^\ast) \cdot z \cdot g}{(\xi \cdot \rho^\ast)} \right]^{1/2}.$$  \hspace{1cm} (7)

Thus, to start the outflow of air through the break from the containment to the primary circuit, it is necessary that the pressure difference between the containment and the reactor would be more than the pressure difference resulting from the difference in the densities of the media defined by (5). The flow rate could be calculated from the following equation:

$$G_{\Delta p} = \rho^\ast \cdot b \cdot \int_0^h v^\ast (z) \cdot dz,$$  \hspace{1cm} (8)

where $b$ is the width of the break section. In the case of a guillotine break of primary circuit, the rupture will have the shape of a circle and its width will be equal to:

$$b = 2 \cdot \left[ z \cdot (D - z) \right]^2,$$  \hspace{1cm} (9)

where $D$ is the diameter of the rupture.

In this case, after integrating the equation (8), we obtain the dependence of the flow rate of the primary circuit coolant through the break section on the size of the break and the densities difference between the containment and the primary circuit media:

$$G_{\Delta p} = D^{2.5} \cdot \left[ g \cdot \rho^\ast \cdot (\rho_{\text{mix}} - \rho^\ast) \right]^{0.5}.$$  \hspace{1cm} (10)

$$N_{\Delta p} = G_{\Delta p} \cdot r,$$  \hspace{1cm} (11)

$$N_{\text{out}} = N_{\Delta p} + N_{\Delta p} = N_{\text{core}} - N_{\text{SG}} - G_{\text{HA}} (i' - i_{\text{HA}}),$$

$$N_{\Delta p} = N_{\text{core}} - N_{\Delta p} - N_{\text{SG}} - G_{\text{HA}} (i' - i_{\text{HA}}).$$  \hspace{1cm} (12)

Thus, to start the process of mass transfer from the containment to the reactor, it is necessary that the difference between $N_{\text{core}}$ and $N_{\text{SG}}$ exceeds the value of $N_{\Delta p}$.

In order to confirm the presence of mass transfer caused by the difference in the media densities in the reactor and containment, the data obtained at the HA-2M test facility were analyzed.

### 3. Test Facility

At the HA-2M test facility, built in IPPE, the processes of mass transfer between the containment and the reactor were investigated. The main element of the HA-2M large-scale test facility is the metal containment model with a volume of 80 m$^3$. There is a test section inside the containment - steam heated reactor model. This model is a coaxial pipe structure consisting of two pipes of 377x6 mm and 325x6 mm. The boiling of the coolant in the core is simulated using the steam flow from the heat electrical plant. Steam flow rate corresponds to the full-scale in view of the scale factor 1:192.

The model has two MCP break simulators: rectangular nozzles with a height of 850 mm and a width of 14 mm. They are designed to simulate break of the primary circuit hot and cold legs. Each break simulator is equipped with thermocouples, three of which are located at the top of the section and three at the bottom. Figure 1 shows the location of thermocouples in the MCP break simulator.

Except the models of containment and reactor, the facility includes the model of steam generator and PHRS heat exchanger simulator. The more detailed information about the test facility is provided in [13].
A number of parameters were measured and monitored during the tests: temperature, pressure and water level in the models of containment, reactor, and SG; flow rate of steam; flow rate of water in the heat exchanger of PHRS.

Experiments on the test facility were carried out at initial pressure of 0.35–0.39 MPa corresponding to the pressure in the reactor and the containment in case of a LOCA accident. The main task of the experiments was to determine the condensation power of the steam generator model and study the effect of outflow of air-steam mixture from the containment on this power. The concentration of non-condensable gases was determined by the calculations of the 24-hours emergency process, performed by EDO "Gidropress" [14]. At the HA-2 test facility, the experiments simulated accidents with large break LOCA at the cold and hot legs of main circulation pipes were carried out.

4. Experimental results

During the tests, the power of the reactor model simulated an exponential decrease in the decay power during the accident. In the experiments, a four-stage flowrate of the steam from the reactor with steps 184-157-134-103 g s\(^{-1}\) was implemented. The generated steam came either into the containment model through the MCP break simulator or to the steam generator model.

Figure 2 shows the change in the condensation power of the steam generator model in tests No. 1 (rupture of the MCP cold leg) and No. 2 (rupture of the MCP hot leg).
As it can be seen from figure 2, at the end of test No. 1, the value of condensation power was at the level of 85% of the initial one. At the same time, in test No. 2, steam generator power decreased to 77%. It can be assumed that the difference in the dynamics of changes of the condensation power in experiments was caused by the influx of a larger mass of air from the containment model in the test No. 2. This assumption can be confirmed by consideration of changes in the readings of thermocouples installed in the MCP break simulator (Figure 1).

In the tests, the containment model was filled by a steam – air mixture. Since the pressures in the reactor and in the containment are almost the same, then steam – air mixture temperature is obviously lower than the temperature of the steam in the reactor model. Thus, the movement of the steam – air mixture from the containment to the reactor model can be registered by reducing the readings of thermocouples installed in the break simulator. It can be assumed, that the largest inflow of steam – air mixture can be observed during the transition from one steam flow rate stage of reactor model to another. Figure 3 shows the change of temperatures in the upper and lower parts of the MCP break simulator during the transition from the first to the second stage of steam flow rate of reactor model.

![Figure 3](image-url)

Figure 3. The change in the temperatures in the different parts of MCP break simulator during the first transient phase in test No. 1 (a) and test No. 2 (b).

As it can be seen from figure 3, in the test No. 1, a sharp, but short in duration, decreasing of the temperature in the lower part of the break simulator is observed. This can be explained by the movement of steam – air mixture with a lower temperature through the break section from the containment to the reactor model. At the same time, it should be mentioned that the process of air entry into the reactor model in the test is limited in time. When some amount of non-condensable gases enters into the steam generator tube bundle, its power decreases, as does the steam flow rate from the reactor model. For this reason, the pressure in the reactor model increases and at a certain point exceeds the pressure in the containment. After that, air stops flowing into the primary circuit.

Moreover, as it can be seen from figure 3a, the lower thermocouples in the break simulator reacted to the process of steam-air mixture flow from the containment with higher amplitude, while the upper ones did not change theirs readings much. This can be explained according to the formula (5): the greater the distance from the lower generatrix of the break section along the z axis, the greater the differential pressure that must be overcome by air-steam mixture. Therefore, first, air starts to flow through the lower part of the break, and then, when the differential pressure between the containment and the reactor models increases, the area of the break section, through which air flows, increases also.

Another process is observed in test No. 2. As it can be seen from figure 3b, it is impossible to determine the time when air starts to flow from the containment model. However, the temperature in the upper part of the break simulator is higher than in the lower one. This indicates the presence of motion of air – steam mixture in this area.
The amplitude of temperature fluctuations exceeds that in test No. 1, except for the moment of air intake. This allows us to suggest that air from the containment model constantly came into the reactor model by small portions during the test. Therefore, it can be assumed that the following sequence of processes took place during the whole experiment: air intake to SG bundle from containment; SG condensation power is reduced; reactor pressure is increased; the movement of the steam-air mixture into the reactor from containment stops.

**Conclusion**

As a result of the research, the condition of starting the flow of steam – air mixture from the containment to the reactor in case of a LOCA accident was determined.

Experimental data obtained at the HA-2M test facility confirmed that the steam generator is able to operate in the condensation mode even in the presence of mass transfer processes between the containment and reactor. It was found that the location of the primary circuit break significantly affects the flow rate of air coming into the reactor and steam generator condensing power. It was also found that the flow rate of the steam – air mixture into the first circuit occurs unevenly along the height of the rupture. This fact confirms the presence of mass transfer caused by the difference in the densities of media in the reactor and containment.

The results obtained can be used to analyze emergency processes in WWER reactors with operating of passive safety systems.

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