Hydrogen Safety in Design of the Nuclear Power Plant

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ABSTRACT

In Russian project AES-2006 (NPP-2006), the overall safety concept for the nuclear power plant (NPP) is based on the in-depth defense principle, which implies the system of multiple barriers preventing the spread of ionizing radiation and radioactive substances into the environment. The last barrier preventing the release of fission products into the environment is the nuclear reactor building containment. During a severe accident like LOCA (Lost Of Coolant Accident), a large amount of hydrogen is produced in core reflooding and in oxidation of Zr fuel cladding by steam. When hydrogen appears inside the containment compartments, it mixes with steam and air thereby producing combustible mixture prone to detonation. In this paper, we present 3D simulation results of hydrogen-air-steam combustion in the NPP containment compartments using specialized 3D code FIRECON 1.0, with the complex geometry and a wide range of combustion regimes (from slow combustion to detonation) taken into account. Three scenarios are considered: (i) severe accident with break of pressurizer surge line accompanied by failure of active Emergency Core Cooling System (Large Break, LB LOCA); (ii) small leakage (Small Break, SB LOCA) from the cold loop thread with pressurizer failure, and (iii) uncontrolled severe accident (UnSA). The software is validated, and the dynamic loads imposed on the containment walls and inner structures are analyzed.

KEYWORDS: Hydrogen combustion, nuclear safety, CFD.

NOMENCLATURE

C_{H_2}, C_{O_2}, C_{H_2O} volume fractions of H_2, O_2, H_2O (steam) (-)
E internal energy (J)
e specific internal energy (J/kg)
K momentum ((kg·m)/s)
L characteristic linear size (m)
Le Lewis number (-)
M mass (kg)
P pressure (Pa)
S surface area (m2)
T temperature (K)
t time (s)
V volume (m^3)
u, v, w velocity vector components (m/s)

Greek

α molar fraction of combustion products (-)
δ laminar flame thickness (m)
η H_2/O_2 molar ratio (-)
λ detonation cell size (m)
ρ density (kg/m^3)
σ reactant/product density ratio (-)
σ^* critical density ratio (-)

Subscripts

i gas mixture component
x, y, z Cartesian coordinates

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INTRODUCTION

Investigations of severe accidents made in recent years for pressurized water reactors show that in case of meltdown accidents, ignition and subsequent detonation of hydrogen-containing mixtures may cause the integrity violation of Nuclear Power Plant (NPP) containment, followed by the radionuclide release into the atmosphere and radioactive contamination of the environment.

During severe accident such as LOCA (Lost Of Coolant Accident), that is, loss of the coolant, as a result of dehumidification of the reactor core and vapor oxidation of the zirconium fuel cell shells, a large amount of hydrogen is produced. In the course of further development of the accident, hydrogen can penetrate into the containment compartments and form combustible mixtures with air and steam. From the point of view of severe accidents analysis, the most dangerous case is the detonation of such mixtures, since in this case the building structures inside the containment are subjected to the greatest dynamic load.

According to the requirements of national supervisory authorities, the rationale for hydrogen explosion protection must be fulfilled in the design of the nuclear power plant and presented in the safety justification report. At present, numerical modeling is one of the effective methods for such a justification. During the analysis of hydrogen safety, all possible scenarios of emergencies are modeled, and a technical solution is chosen that contributes to reducing the threat of possible combustion and detonation.

There are many different computer codes that are used to analyze severe accidents for different types of nuclear power plants. The application of these codes includes research and development, safety analysis regarding the introduction of hydrogen suppression systems, licensing or periodic safety assessment.

Depending on the mathematical models embedded in the codes, some codes are used to model all aspects of hydrogen safety (hydrogen generation, propagation, combustion, suppression), some codes are used only to calculate the formation of hydrogen inside the reactor facility, thus giving the boundary conditions for the codes, which simulate the spread, combustion and removal of hydrogen.

There are codes specifically designed for modeling combustion and in particular hydrogen detonation, which require as input data information on the distribution of hydrogen inside the nuclear power plant containment [1].

One of the first numerical approaches to simulate combustion processes in large scale facilities was provided by Efimenko and Dorofeev [2]. They combined a system of criteria and combustion models into a computer code CREBCOM for conservative estimates of possible pressure loads resulting from combustion of fuel-air mixtures. These models were validated on experimental data and then successfully employed in several industrial CFD (Computational Fluid Dynamics) codes, such as TONUS [3] and COM3D [4].

Interesting results according flame acceleration and deflagration to detonation (DDT) phenomena in APR1400 containment were obtained in [5]. As calculation tool the open-source CFD package OpenFOAM was chosen.

ACCIDENT SCENARIO

According to the dynamics of the coolant and hydrogen outlet inside the containment, the heavy accidents considered can be divided into two main groups:

- Accidents with a small leakage of the coolant and an accident with a complete blackout of the station;

- Accidents with a large leakage of the coolant.

Accidents with small leakage and accidents with complete blackout are characterized by a continuous release of the coolant into the leak with a low emission intensity and the greatest integral yields of hydrogen. Accidents with a large leakage of the coolant, on the contrary, are characterized by a high emission intensity at individual time intervals and smaller integral hydrogen outputs to the interior of the containment compartments. That was proved in many simulation tests, carried out for Nuclear Power Plant design solutions justification.

The choice of scenarios for the calculation of severe accidents is determined by the objectives of the deterministic analyzes being performed. The safety analysis should focus on quantifying station safety stocks and demonstrating that a certain degree of defense in depth is provided for this class of accidents.

As calculation scenarios, severe accidents with break of pressurizer surge line accompanied by failure of active Emergency Core Cooling System (Large Break, LB LOCA) and the small leakage (Small Break, SB LOCA) from the cold loop thread with pressurizer failure with the failure of the active part of the emergency cooling system active zone of the reactor were chosen. A characteristic feature of these accidents is the high hydrogen content in the steam generator room, where the leak from the pipeline rupture is directly modeled and the complexity of managing these accidents.

In addition to the calculations for the above scenarios, an uncontrolled severe accident (UnSA) calculation was performed that did not take into account the work of severe accident management systems such as the hydrogen removal system and the passive heat removal system from the containment. This calculation was interesting from the point of view of the possibility of the software used to simulate the combustion of hydrogen-containing gas mixtures under such conditions.

The initial parameters for combustion calculating are the results of a calculation analysis of the propagation, accumulation of hydrogen, and changes in the parameters of the environment in the containment compartments during the development of the emergency scenario in question, performed using the Russian code in the lumped parameters KUPOL-M [6] (not presented here because of paper volume limitation). Then, for each time point, an analysis was made of the possible burning regimes in the containment compartments and a time cut was selected in which combustion or detonation of the gas mixture is possible. For this time cut three-dimensional modeling of combustion in the containment compartments was carried out.

The resulting dynamic loads on the walls of the containment compartments can be used in the subsequent strength analysis, which shows the level of effect of combustion of the hydrogen-containing steam-air mixture on the integrity of the nuclear power plant containment.

SIMULATION METHODOLOGY

To simulate the combustion of hydrogen-containing gas mixtures in closed volumes of complex geometry in a wide range of combustion regimes (from slow combustion to detonation) and subsequent analysis of dynamic loads on the walls of a nuclear power plant, 3D computer code FIRECON 1.0 was developed by Russian Federal Nuclear Center in Sarov city with the participation of Joint Stock Company “Atomproekt” specialists [7].

As basic equations describing non-steady-state 3D multi-material gas flows relations expressing the laws of conservation for a motionless volume were taken:

$$\frac{d\vec{K}}{dt}+\int_S \rho\left(\vec{u},\vec{u}\right)d\vec{s}=-\int_S Pd\vec{s}\ , \qquad (1)$$

$$\frac{dM_i}{dt} + \int_{S_i} \rho_i \vec{u}_i d\vec{s} = 0, \tag{2}$$

$$\frac{dV_i}{dt} + \int_{S_i} \vec{u}_i d\vec{s} = 0, \tag{3}$$

$$\frac{dE_i}{dt} + \int_{S_i} \rho_i e_i \vec{u}_i d\vec{s} = -\int_{V_i} P_i div(\vec{u}_i) dV, \tag{4}$$

The system (1-4) is closed by the equation of materials state:

$$P_i = P_i(\rho_i, T_i, \alpha_i). \tag{5}$$

Differential equations describing the propagation of turbulent deflagration and detonation in gas mixtures are approximated using the method of decomposition to several steps logically related to certain physical processes. The values of quantities calculated at a certain step are used as initial data for the subsequent step.

The basic system of Eq. (1) – (4) calculated at first step is equivalent to the following system:

$$\frac{d\vec{u}}{dt} = -\frac{1}{\rho} grad(P), \tag{6}$$

$$\frac{d\rho_i}{dt} = -\rho_i div(\vec{u}_i), \tag{7}$$

$$\frac{d\beta_i}{dt} = \beta_i \left(div(\vec{u}_i) - div(\vec{u}) \right), \tag{8}$$

$$\frac{de_i}{dt} = -\frac{P_i}{\rho_i} div(\vec{u}_i). \tag{9}$$

The combustion model of hydrogen-containing mixtures in the code FIRECON 1.0 is based on a criterial approach similar to that used in [8-10] and is intended for practical use in calculations of hydrogen combustion in a nuclear power plant containment for the purpose of safety analysis.

There are three possible combustion regimes:

- Slow combustion;
- Fast combustion;
- Detonation.

To determine the limits of flammability at various temperatures and pressures, the experimental dependences of the lower and upper limits of hydrogen-air mixture flammability on the temperature and pressure of the surrounding medium are used.

The criterion for the flame acceleration is the fulfillment of the following inequality:

$$\sigma > \sigma^*.$$

Deflagration to detonation transition (DDT) is possible under fulfillment of the inequality:

$$L > 7\lambda.$$

The flame front in this model is treated as a hydrodynamic discontinuity. It propagates through the parent mixture with velocity S_t (turbulent flame velocity) relative to the matter before flame front, and this velocity depends on the parameters of the parent mixture immediately before flame front.

The flame front moves perpendicular to its surface. The initial flame front location is specified in simulations.

In two regions (strong and weak turbulence), the flame velocity is defined in different ways.

For the S_t/S_u ratio, we use the relationships from [9].

In the strong turbulence region, where $L/\delta > 500$:

$$\frac{S_t}{S_u} = 0.5(\sigma - 1)\left(\frac{L}{\delta}\right)^{1/3} \mathrm{Le}^{-2/3}. \tag{10}$$

In the weak turbulence region, where $L/\delta < 500$:

$$\frac{S_t}{S_u} = \begin{cases} 8 \cdot 10^{-4} (\sigma - 1)^3 \left(\frac{L}{\delta}\right), & \eta > 1 \\ 1, & \eta \le 1 \end{cases}, \tag{11}$$

where S_u is the laminar flame velocity.

The code FIRECON was specially developed for the architecture of cluster computing systems with mass parallelism and distributed random access memory, so all calculations were performed using a supercomputer.

The calculation scheme of containment compartments should generally simulate all characteristics of a real object with sufficient accuracy (free room volumes, space between buildings, building structures and large equipment located in containment compartments).

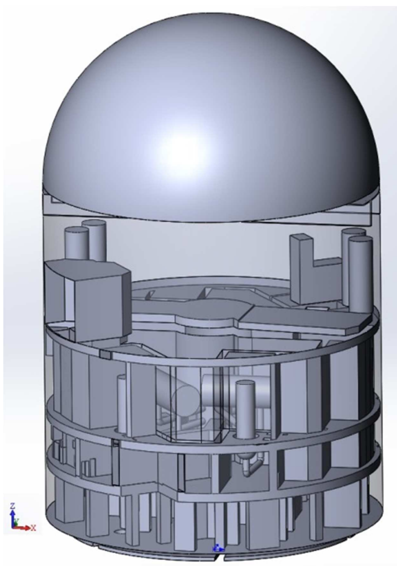

Fig. 1. NPP containment 3D CAD model.

Figure 1 shows the Russian project AES-2006 (NPP-2006) NPP containment 3D CAD (Computer Aided Design) model, which was used for simulation. To decrease calculation time costs we used rough computational grid of containment, but preliminary tests and convergence analysis proved, that its accuracy is enough to get relatively good results. The number of nodes in the computational grid was ~ $1.3 \cdot 10^6$.

The ignition point can be set in any room. In this case, the initiation of combustion can occur both in one counting cell and in a certain volume specified earlier. At the external boundary of the system, the condition of non-flow (a rigid wall) is used as the boundary condition, that is, the normal velocity component equals to zero. The leakage condition can also be specified inside the region along certain faces of the grid, which are the boundaries of the fictitious incompressible components.

SIMULATION RESULTS

On the basis of the hydrogen distribution inside NPP containment compartments analysis results, the room with the highest concentration of hydrogen in mixture was chosen, in which combustion was initiated (i.e., the ignition point was set). According to hydrogen distribution analysis in most cases the highest amount of hydrogen is accumulated in steam generator room. The mixture parameters (component concentrations and initial pressure) in chosen room for each severe accident are given in Table 1.

Table 1. Mixture parameters (obtained from hydrogen distribution calculations)

Accident scenario	C_{H2}, % vol.	C_{O2}, % vol.	C_{steam},% vol.	P_0, MPa
SB_1	12.5	10.9	34.6	0.16
SB_2	15.3	8.95	37.2	0.22
LB_1	13.0	7.2	52.9	0.24
LB_2	19.0	7.9	43.4	0.23
LB_3	10.1	7.4	53.3	0.22
UnSA	21.5	10.0	25.5	0.15

The general views of the burning pattern in a containment at different times for a different scenario are shown in Fig. 2-7, which show the boundary (concentration iso-surface - highlighted in red) of the burned mixture. According to the iso-surface of the formation of combustion products, one can judge the flame front propagation. The most intensive flame propagation within the containment compartments can be seen in the case of UnSA (Fig. 7).

To estimate the dynamic load during the combustion of the mixture in different containment areas, the pressure values at the preselected control points were calculated. Figure 8 shows the maximum pressure values in steam generator room and pressure drops on the outer containment wall for different variants of severe accidents. The results of the calculations showed that the maximum inner pressure within containment from hydrogenous mixture fast deflagration is about 0.36 MPa (LB_1 case) and the maximum pressure at the outer containment wall differs from the atmospheric by 0.29 MPa (SB_2 case) and does not exceed the design allowable value (0.6 MPa).

In the case of UnSA absence of severe accident management systems led to sharp pressure spike at the beginning of the accident, which is characteristic to detonation regime. Pressure drop value on the outer containment wall exceeds the overpressure value (0.6 MPa), laid in the station design (Fig. 9).

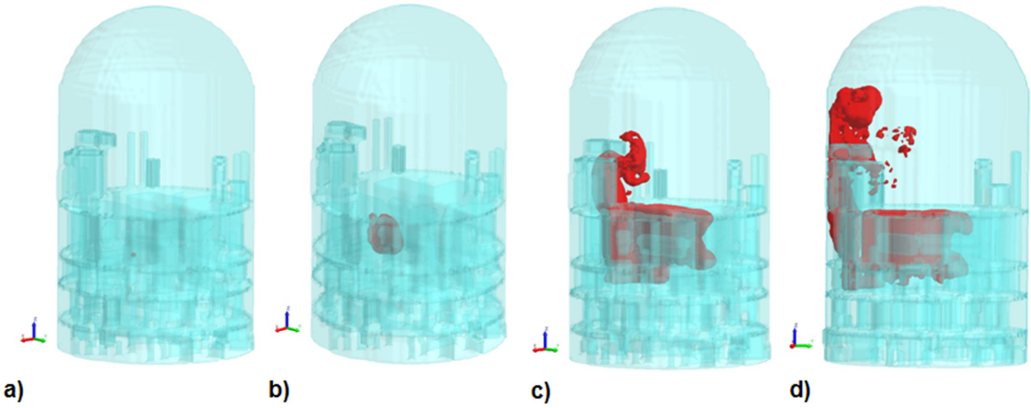

Fig. 2. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (SB1).

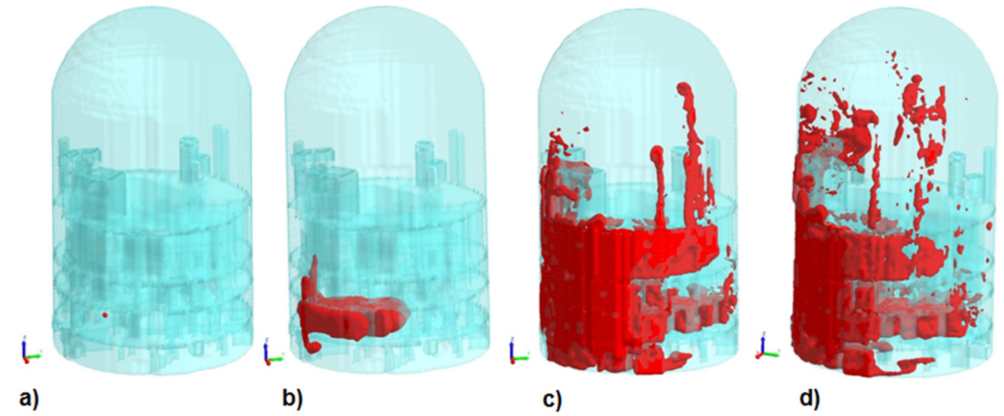

Fig. 3. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (SB2).

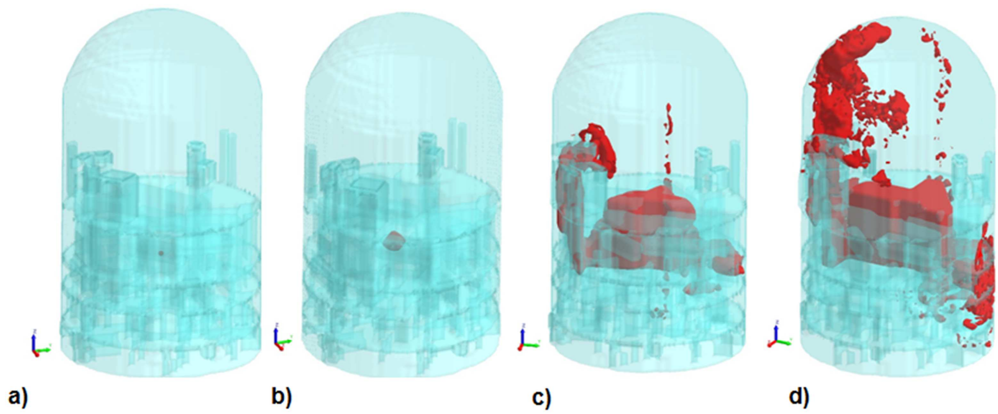

Fig. 4. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (LB1).

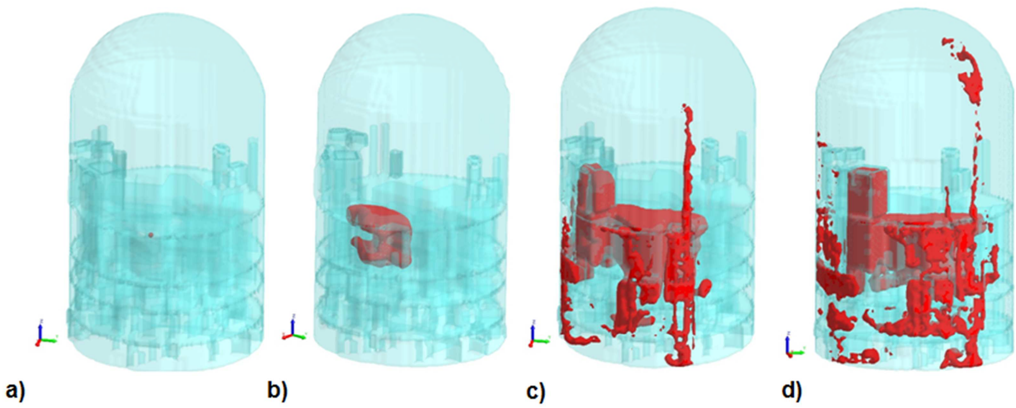

Fig. 5. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (LB2).

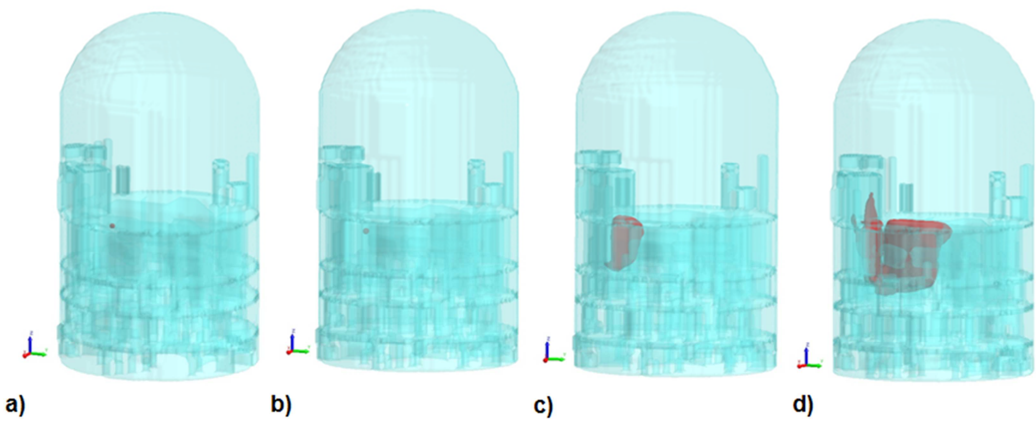

Fig. 6. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (LB3).

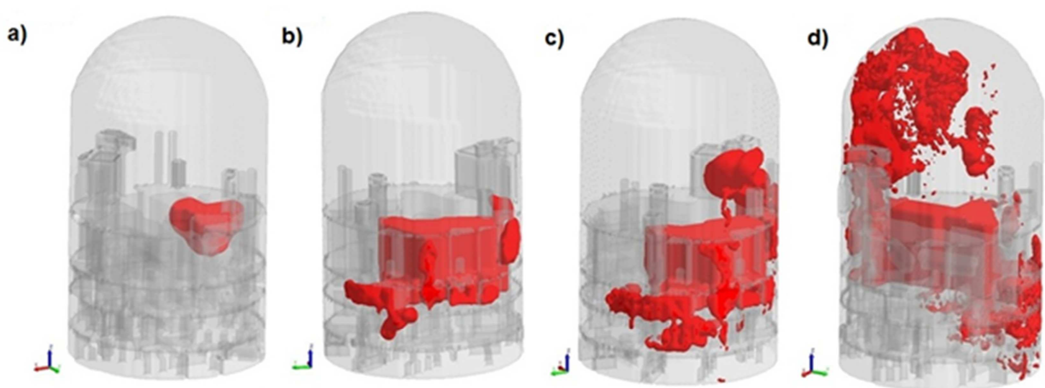

Fig. 7. The iso-surfaces of the burnt mixture concentration for different time instants: a) 0.0 s; b) 0.1 s; c) 0.5 s; d) 1.0 s (UnSA).

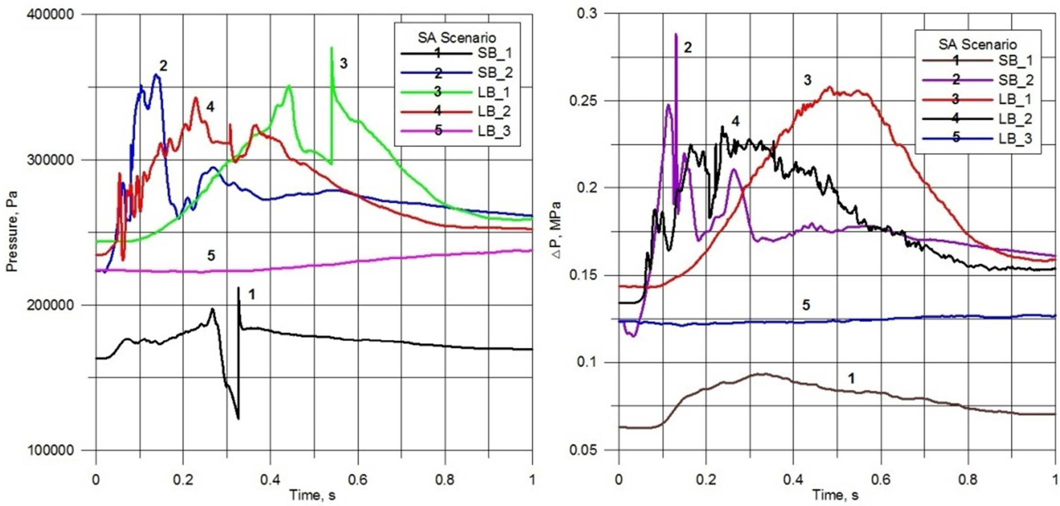

Fig. 8. Maximum pressures in steam generator room (left) and pressure drops on the outer containment wall (right) for different scenarios.

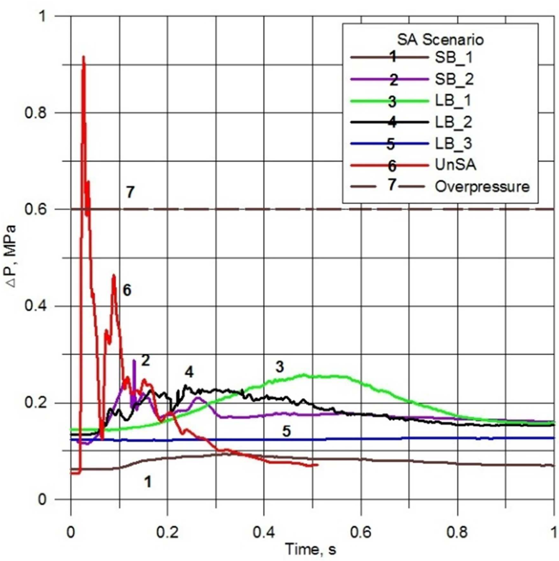

Fig. 9. Pressure drops on the outer containment wall for different scenarios (with UnSA and overpressure value).

CONCLUSION

Within the framework of the NPP safety, a three-dimensional modeling of the hydrogen-air-steam mixture combustion in the containment compartments was carried out. For the calculation, five scenarios of severe accidents (two with small collant leak and three with large leak) were considered, as well as an example of a hypothetical accident in which work of severe accidents control systems was not deliberately taken into account.

The results of the calculation showed that the operation of severe accident management systems incorporated in the plant design makes it possible to avoid formation of explosive hydrogen-containing gas mixtures. The magnitude of the pressure drop on the external wall of the containment for accidents with large and small leaks does not exceed the excess value required by the plant design.

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