Analysis of beyond design basis accident with hydrogen explosion in the at-reactor spent fuel storage pool of NPP with RBMK-1000

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Abstract. The article evaluates the consequences of a hydrogen explosion in an at-reactor spent fuel storage pool due to the development of a beyond design basis accident with a complete long-term blackout. Two scenarios of hydrogen generation in a spent fuel storage pool with a subsequent hydrogen explosion are considered. In the first scenario, the formation of radiolytic hydrogen occurs in the undried storage pool. In the second scenario, hydrogen is formed as a result of the steam-zirconium reaction in the dried storage pool when the cooling water is supplied to the walls of the emergency storage pool. The maximum explosion pressure is calculated using the shock Hugoniot adiabat. The calculations of initial static load taking into consideration hydrogen explosion exposure for each scenario were performed using the equivalent static load method. This method consists in the switch from a dynamic task to a static one, in which the maximum deflections are equivalent. The calculation of the stress-strain state of spatial structures is carried out in the ZENIT-95 program. It is shown in the work that not in all cases of hydrogen explosion, destruction of structures occurs.

1. Introduction
Interest in hydrogen explosion safety increased after the accident at the Fukushima Daiichi nuclear power plant on March 11, 2011. Over the past ten years, the main tasks have been formulated, the solution of which is aimed at increasing hydrogen safety. Research on formation, accumulation and explosion of hydrogen at NPP continues ([1], [2], [3], [4] and others). The IAEA documents SSR–2/1 (Rev. 1) [5], SSG–2 [6] contain the requirements and recommendations, which in particular state “…to control the concentrations of hydrogen, oxygen and other substances in the containment atmosphere in accident conditions so as to prevent deflagration or detonation loads that could challenge the integrity of the containment”. Modern requirements of norms and rules in Russian Federation NP–040–02 prescribe the elimination of hydrogen-containing mixtures detonation during

¹ Federal Nuclear and Radiation Safety Supervision Authority of Russian Federation 2002 Rules for hydrogen explosion protection assurance at nuclear power plants. NP-040-02 Federal rules and regulations in the field of atomic energy use [in Russian].
design basis and beyond design basis accidents. Moreover, it is obvious that not every explosive process must necessarily lead to serious destructive consequences.

This paper presents the results of a hydrogen explosion analysis and the impact of a shock wave on the slatted ceiling in the at-reactor spent fuel storage pool of RBMK-1000.

The calculation of the maximum explosion pressure in a stoichiometric gas-air and vapor-air mixture in a closed volume was carried out using the shock Hugoniot adiabat. The assessment of the explosion overpressure on the slatted ceiling of the spent fuel storage pool was carried out according to the method described in the Russian standard for fire safety of technological processes GOST R 12.3.047–2012. The accounting for short-term dynamic loads caused by shock waves was carried out using the method of equivalent static loads. This method consists in finding the dynamic factor, which allows to reduce a dynamic problem to a static one. This method is based on the energy conservation law. The kinetic energy of the explosion is converted into the potential energy of deformation of the slatted ceiling beams.

The calculation of the stress-strain state of the supporting structure of the slatted ceiling was carried out using the certified software “ZENIT-95”.

2. Object of research
The standard spent fuel storage system at NPPs with RBMK-1000 reactors provides storage in two at-reactor storage pools of canisters with spent fuel assemblies (SFA) and SFAs without canisters in the amount of 828 pieces for one spent fuel storage pool or 1656 pieces for one power unit. Within the central hall of the NPP unit, there are two storage pools with the following dimensions: length – 10.3 m; width – 4.2 m; depth – 17.2 m. To provide biological protection, the pools are filled with water.

Slatted ceiling of storage pool is made of cantilever beams fixed in the wall of storage pool and reinforced with struts made of stainless steel pipes. The cantilever beams form two rows of slats along the storage pool with a step of 250 mm, separated by a central slot. The length of the beams is 2 m. The slatted ceiling is closed by hinged stainless steel covers. Removable and hinged covers partially prevent the escape of steam and "dirty" gases into the central hall, and also protect the stored spent fuel from falling objects.

The list of initiating events of a beyond design basis accident with a complete long-term blackout selected for modeling includes a hydrogen explosion in the spent fuel storage pool, formed due to
1. the release owing to the radiolysis reaction at the stage of heating water in the storage pool and the release of hydrogen dissolved in water when the storage pool is heated;
2. exit owing to the steam-zirconium reaction at the stage of cooling the SFAs heated to a high temperature.

As part of the work, the damage to the slatted ceiling of the storage pool is assessed.

3. Hydrogen generation and its explosion

3.1. Generation of radiolytic hydrogen (1st scenario)
As the first scenario, the initial stage of a beyond design basis accident with a complete long-term blackout of the NPP unit, including the failure of the ventilation system of the storage pool space above water surface, is considered. At this stage, the water in the pool is heated in the at-reactor storage pool. The main source of hydrogen is its generation under the action of $\gamma$-radiation and the formation of radiolytic hydrogen. Additional heating of water leads to a decrease in the solubility of hydrogen in it. In an accident with a loss of power supply, the heating time up to 100 °C is about 70 hours. This corresponds to the hydrogen generation rate from water of $0.3 \cdot 10^{-5}$ kg/s. In this case, the

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2 Federal agency on technical regulating and metrology of Russian Federation 2014 Occupational safety standards system. Fire safety of technological processes. General requirements. Methods of control. GOST R 12.3.047–2012 [in Russian].
release of hydrogen due to the radiolysis of water for storage pool with a power of 500 kW is 
0.47 \times 10^{-5} \text{ kg/s}.

With such a generation rate and closed hinged covers of the storage pool, an explosive 
concentration of hydrogen in the space above water surface (4 vol.%) will be obtained in about 
2 hours. There will not be enough time for a significant change in the water level in the pool. In this 
case, we will assume that the entire free volume under the covers is filled with an explosive mixture of 
hydrogen with air (conservatively, the presence of water vapor is not taken into account). This volume 
is about 28 m³. Thus, the partial minimum explosive volume of hydrogen under the 
slatted ceiling is 1.12 m³ (under normal conditions ~ 0.1 kg H₂).

3.2. Hydrogen generation caused by zirconium-steam reaction (2nd scenario)

As a result of rapid dehydration or slow evaporation of water from the pool, the SFA 
s will begin to heat up. To limit the growth and decrease in temperature in the emergency at-reactor 
storage, the design provides for the supply of cooling water to the walls of the emergency storage 
pool. In this case, the generated steam will interact with the heated surface of the fuel rod zirconium 
cladding, as a result of which, at this stage of the accident process, an additional source of hydrogen 
appears due to the steam-zirconium reaction. The steam generation rate at this stage is 
\sim 0.2 \text{ kg/s}. Due to the late application of mobile equipment and the supply of cooling water to the 
already heated storage pool, there is a possible area for the localization of the explosive concentration: 
in the space of the storage pool under the slatted ceiling.

The estimated time for which the lower flammability limit of 4 vol.% is reached in the volume of 
fuel storage pool (~ 728 m³) is \sim 3 minutes. The maximum mass of hydrogen under the slatted ceiling 
for the calculation period was 0.42 kg.

3.3. Approach for calculating the maximum explosion pressure (Hugoniot adiabat)

The behavior of the gas-air system after chemical detonation can be analyzed using a mathematical 
technique – the shock Hugoniot adiabat [7]:

\[ p_2 - p_1 = \frac{2 h_2 - h_1}{v_2 + v_1} = 0, \quad (1) \]

where \( p \) — gas pressure; \( h \) — specific enthalpy of gases; \( v \) — specific volume of gases. Parameters 
with index “1” refer to the initial state of the system, with index “2” refer to the final state of the 
environment (after the explosion).

Stationary equations of conservation of mass, momentum and energy for a gas medium, which 
result in the Hugoniot equation, have many solutions. This means that after an explosion, its products 
can be in different states, according to these stationary equations. In reality, there will be the only 
solution, which is determined by the tangent line – the Rayleigh-Michelson line drawn from the point 
corresponding to the initial conditions of the hydrogen-air system to the adiabat.

Equation (1), together with the constitutive equation of substances for density \( p = \rho(p, T) \) and 
enthalpy \( h = h(p, T) \), determines the dependence \( p = p(v) \), the Hugoniot adiabat, on which all possible 
values of the mixture parameters are located behind the shock wave.

Mixtures of hydrogen with oxygen (or air) are extremely chemically active. Their interaction under 
certain conditions can proceed in an explosive manner with the release of heat into the environment. 
The most explosive mixtures are those with a composition close to stoichiometric. To maintain the 
chain reaction of H₂ combustion, it is necessary to fulfillment of the ratio

\[ \frac{m_{H_2}}{m_{O_2}} = \frac{4}{32}, \quad (2) \]
where \( m_{H_2} \) — mass of hydrogen in this mixture; \( m_{O_2} \) — mass of oxygen consumed for hydrogen combustion.

Oxyhydrogen gas is capable of burning in a wide range of hydrogen concentrations in air: from 4 vol.% in poor mixtures and up to 75 vol.% in rich mixtures. It is also capable of detonating approximately within the same limits [8].

To solve the problem of the propagation of a shock wave in a combustible mixture using the Hugoniot adiabat approach, a conservative case is considered in the first approximation, during which detonation occurs when pure oxygen and hydrogen interact.

The combustion of hydrogen is formally expressed by the reaction

\[
2H_2 + O_2 = 2H_2O
\]

Performing a number of transformations of equation (1) taking into account equation (2), we obtain the dependence \( p_2(v_2) \) in the case of chemical detonation in the general form

\[
p_2 = \frac{C + p_1v_2}{v_1 + Dv_2}
\]

where the constants \( C, D \) are determined depending on the thermophysical properties of the reacting substances.

Figure 1, (a) shows the shock Hugoniot adiabat calculated using equation (4) for the case of a stoichiometric mixture (equation (2)). The detonation pressure in this case was 16.8 bar. The parameters of the explosion were also estimated for two scenarios of the gases interaction in the hydrogen-oxygen mixture with an excess of \( O_2 \) (for the 1st scenario: \( m_{H_2} = 0.1 \text{ kg}, m_{O_2} = 32 \text{ kg} \); for the 2nd scenario: \( m_{H_2} = 0.42 \text{ kg}, m_{O_2} = 871 \text{ kg} \)). In the first scenario the pressure was 2.72 bar (figure 1, (b)), in the second scenario the pressure was 1.47 bar. With an increase in the mass of oxygen in the mixture, a decrease in the dynamic effect from the shock wave is observed, since an increase in the gas content prevents the propagation of shock waves.

![Figure 1](image_url)

**Figure 1.** Shock Hugoniot adiabat for a) stoichiometric mixture; b) gas mixtures with an excess of oxygen (example for the 1st scenario).
3.4. Calculation of explosion overpressure for combustible gases

The calculation of the explosion overpressure is carried out in accordance with the Russian standard for fire safety of technological processes GOST R 12.3.047–2012:

$$
\Delta P = \left( P_{\text{max}} - P_0 \right) \cdot \frac{m \cdot Z}{V_\text{f}_\text{v}} \cdot \frac{100}{C_{st}} \cdot \frac{1}{K}, 
$$

where $P_{\text{max}}$ – maximum explosion pressure of a stoichiometric gas-air mixture in a closed volume, kPa (in the absence of data, it is allowed to take $P_{\text{max}} = 900$ kPa); $P_0$ – initial pressure, kPa (it is allowed to take $P_0 = 101$ kPa); $m$ – mass of combustible gas released into the room as a result of the accident, kg; $Z$ – coefficient of participation of the fuel in the explosion (according to GOST R 12.3.047–2012 for hydrogen: $Z = 1.0$); $K$ – coefficient taking into account the leakage of the room and non-adiabatic combustion process (according to GOST R 12.3.047–2012: $K = 3$); $V_\text{f}_\text{v}$ – free volume of the room, m$^3$; $\rho_s$ – density of a gas or vapor at a design temperature $t_d$ (°C), kg/m$^3$, where

$$
\rho_s = \frac{M_s}{V_M} = \frac{M_s}{V_0 \cdot (1 + 0.00366 \cdot t_d)},
$$

where $M$ – molar mass of gas or vapor, kg/kmol; $V_0$ – molar volume under normal conditions, equal to 22.413 m$^3$/kmol; $C_{st}$ – stoichiometric concentration of flammable gases or vapors of flammable liquids, vol.% ($\beta$ – stoichiometric oxygen coefficient in the combustion reaction equation, which according to GOST R 12.3.047–2012 for hydrogen: $\beta = 0.5$)

$$
C_{st} = \frac{100}{1 + 4.84 \cdot \beta}.
$$

For both scenarios, the explosion overpressures were calculated using formulas (5) – (7). The values of the maximum explosion pressure of the hydrogen-air mixture were calculated using the approach presented in section 3.3. For 1st scenario (explosion of radiolytic hydrogen formed in the storage pool during prolonged blackout), the excess pressure was $\Delta P = 8.37$ kPa, for 2nd scenario – $\Delta P = 0.364$ kPa. In addition to the main calculation, the conservative case was considered, in which for both scenarios the maximum explosion pressure was taken $P_{\text{max}} = 900$ kPa.

4. Calculation of the stress-strain state of the slatted ceiling beams of storage pool

4.1. Calculation method. Initial data for the calculation

To carry out calculations, the program "ZENIT-95" was used, designed to perform calculations of the stress-strain state of structures and certified by Rostekhnadzor (Federal Environmental, Industrial and Nuclear Supervision Service of Russian Federation) to justify the safety of nuclear facilities.

The cantilever beams are designed for hanging SFAs in canisters or without canisters during storage in the spent fuel pool. These beams with stainless steel covers form a slatted ceiling that separates the storage pool space above water surface from the volume of the central hall. Up to 28 SFAs can be placed in a half-row of the slatted ceiling.

The calculations were carried out for one cantilever beam of the slatted ceiling of storage pool, conservatively loaded with 28 SFAs, placed along a triangular lattice of 130×130×130 mm. A maximum of 28 assemblies (SFA and additional absorber assembly) can be located in one half-row of the slatted ceiling with the help of suspensions along a triangular lattice 130×130×130 mm. We accept conservatively that only SFAs are located on the cantilever beams. In the calculations, a downward distributed force $q_\text{c}$ is applied from the edges of the bottom of the beam at two locations, as shown in figure 2. Each of the two loads applied from each edge is equal to half the $q_\text{c}$. The distributed load $q_\text{c}$
arises as a result of the action of the gravity force of 28 SFAs with suspensions through the support bars that are spaced to the lower chord of the cantilever beam of the slatted ceiling of storage pool.

The theoretical design of structures exposed to explosive loads is carried out for a particular combination of loads, consisting of static and short-term dynamic loads caused by shock waves. The calculation for a special combination of loads was carried out using the method of equivalent static loads.

Equivalent static load is understood as a static load that causes the same maximum forces and displacements in structures as a dynamic load. Equivalent load calculations performed by static methods make it possible to assess the state of structures by the maximum forces in their sections. The value of the equivalent static load per unit surface area is

\[ p_{eq} = p \cdot K_d, \]  

where \( p \) – maximum pressure under dynamic load (overpressure of the explosion), \( K_d \) – dynamic factor.

The calculation of the dynamic factor under shock load was carried out using the formula [9]

\[ K_d = 1 + \sqrt{1 + \frac{T_0}{\Delta U}}, \]  

where \( T_0 \) – explosion energy per one beam, \( \Delta U = (U_p - U_0) \) – change in the potential deformation energy of the beam with a static load (shock wave) \( U_p \) and without it \( U_0 \).

In the explosion of an explosive mixture containing \( 1 \) kg of hydrogen (provided that the entire hydrogen reacts), an energy of \( 1.2 \times 10^8 \) J is released. It follows that the explosion energy in the 1st scenario will be \( 1.2 \times 10^7 \) J, and in the 2nd scenario – \( 5.04 \times 10^7 \) J. From the ratio of the external surface area of the storage pool free volume and the slatted ceiling per one cantilever beam, the energy will be \( 1.53 \times 10^4 \) and \( 1.21 \times 10^4 \) J, respectively.

In order to calculate the dynamic factor, it is necessary to calculate the potential energy of elastic deformation of the beam:

\[ U_b = \frac{1}{2EJ_x} \int_0^L M_x^2(z)dz, \]  

where \( E \) – elastic modulus (\( E = 200 \) GPa), \( J_x \) – main moment of inertia of the beam section, \( L \) – beam length (\( L = 2 \) m), \( M_x(z) \) – bending moment. The moment \( M_x(z) \) arises under the action

- the transverse distributed force \( q(z) \) from the SFA (we assume a uniform distribution of assemblies along the beam (see figure 3) and the fact that the SFA are not located close to the storage pool wall, but at a distance of \( l' = 0.120 \) m)

\[ q(z) = \begin{cases} 0, & \text{for } 0 \leq z < l', \\ q_z, & \text{for } l' \leq z \leq L; \end{cases} \]  

- the gravity of the beam itself,
- pressure of a shock wave \( p \) on the lower edge of a beam with width \( b \).

\[ M_x(z) = -q(z) \cdot (L - z) \cdot \frac{(L - z)}{2} + p \cdot b \cdot (L - z) \cdot \frac{(L - z)}{2} - \rho \cdot S \cdot (L - z) \cdot g \cdot \frac{(L - z)}{2} = \]

\[ = -(q(z) - p \cdot b + \rho \cdot S \cdot g) \cdot \frac{(L - z)^2}{2}, \]  

(12)
where \( \rho \) – the steel density, \( S \) – cross-sectional area of the beam, \( g \) – acceleration due to gravity. Substituting the expressions for the moment \( M_x(z) \) and the distributed force \( q(z) \) into equation (10) for the potential deformation energy \( U_b \), we obtain

\[
U_b = \frac{1}{2EI_x} \left[ (\rho S g - \rho b)^2 L^3 + q_x (q_x + 2\rho S g - 2\rho b) (L - l')^3 \right]
\]  

\[
(13)
\]

Figure 2. Kinematic diagram of loading of the slatted ceiling beams.

In the first scenario, the case is considered when SFAs are located in undried storage pool. To calculate \( q_z \), it is necessary to take into account the buoyancy force (the Archimedes force). Knowing the mass of SFAs with a suspension and the mass of displaced water, taking into account the area near the wall of storage pool without support bars \( (l') \), as well as the number of SFAs, the value of \( q_z \) is 21.9 kN/m. In the second scenario, the spent fuel assemblies are located in the drained storage pool. In this case, the Archimedes force will not act on the SFA, and the \( q_z \) value is 28.5 kN/m.

To calculate the stress-strain state, the ZENIT-95 program was chosen.

Figure 3. The finite element model of the cantilever beam with strut.
Figure 3 shows a finite-element model of the cantilever with strut of the slatted ceiling. The allowable stress \([\sigma]\) for the cases under consideration for the emergency situation, according to [10], is 220.5 MPa, the creep stress is 245 MPa.

4.2. Results of calculations for the strength of a cantilever beam

The values of the equivalent static pressure \(p_{eq}\) are calculated based on equations (8), (9) and (13). As a result of the calculations performed according to ZENIT-95 for the 1st scenario under the action of \(p_{eq} = 0.652\) MPa, it was obtained that the maximum equivalent stress according to the Huber-Mises criterion arises in the area of contact between the beam and the strut and is 42.7 MPa. For this design case with undried storage pool, the structural strength criterion is fulfilled, since the allowable stress is not reached: \(\sigma_{max} < [\sigma] = 220.5\) MPa. The distribution of equivalent stresses is shown in figure 4. (Note that the calculated maximum stress for an undried storage pool without hydrogen explosion pressure is 40.4 MPa.)

As a result of calculations for the 2nd scenario, the maximum stress was 41.7 MPa, which also does not exceed the permissible stress \(([\sigma] = 220.5\) MPa). The distribution of equivalent stresses in the design model is shown in figure 5. Thus, for the explosion of hydrogen in a dried storage pool the strength criterion is fulfilled: \(\sigma_{max} < [\sigma]\).

Since the additional forces from the pressure (at small values up to \(p \sim 0.41\) MPa) resulting from the explosion of hydrogen in the space under the slatted ceiling are directed in the opposite direction relative to the gravity force of the beam and the gravity force of the SFA \((q_z)\), the beam will be unloaded, and the stresses in the beam decrease in comparison with the stresses arising in the beam before the hydrogen explosion. It should be noted that the calculated maximum stress for the dried storage pool without the effect of the hydrogen explosion pressure is 55.5 MPa.

Figure 4. Equivalent stresses for the first scenario: undried storage pool, \(q_z = 21.9\) kN/m, \(p_{eq} = 0.652\) MPa.
The results of the strength analysis of the cantilever beams of the storage pool slatted ceiling, carried out using the ZENIT-95 software tool, are presented in table 1.

| Scenario            | $p_{\text{max}}$, kPa | $\Delta p$, kPa | $q_z$, kN/m | $p_{\text{eq}}$, MPa | $\sigma_{\text{max}}$, MPa | Fulfillment of the strength criterion: $\sigma_{\text{max}} < [\sigma]$ |
|---------------------|------------------------|------------------|--------------|-----------------------|-----------------------------|---------------------------------------------------------------------|
| The 1st scenario    | 272                    | 8.37             | 21.9         | 0.652                 | 42.7                        | Yes                                                                  |
| (undried storage    |                         |                  |              |                       |                             |                                                                     |
| pool                | 900                    | 39.1             | 21.9         | 1.479                 | 201.3                       | Yes                                                                  |
| The 2nd scenario    | 147                    | 0.364            | 28.5         | 0.105                 | 41.7                        | Yes                                                                  |
| (dried storage      |                         |                  |              |                       |                             |                                                                     |
| pool                | 900                    | 6.32             | 28.5         | 0.443                 | 55.5                        | Yes                                                                  |
|                     | -                      | -                | 28.5         | 0                     | 55.5                        | Yes                                                                  |

5. Conclusions
Analysis of the hydrogen explosion consequences in a spent fuel pool showed that:

- the explosion of hydrogen formed due to the reaction of radiolysis and a decrease in its solubility in water due to heating at the initial stage of the accident at the moment of reaching the lower concentration limit, the resulting dynamic effect should not lead to the destruction of the structure of the slatted ceiling;
- the explosion of hydrogen formed due to the vapor-zirconium reaction at the stage of cooling the spent fuel assemblies heated to high temperatures does not lead to a dynamic effect capable of destroying the structure of the slatted ceiling.

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