Estimation of pressure during steam explosion in the sub-reactor room of NPP with RBMK-1000

D V Finoshkina¹,², O I Melikhov¹ and A M Osipov²
¹ National Research University Moscow Power Engineering Institute, 14, Krasnokazarmennaya, Moscow 111250, Russia
² National Research Center «Kurchatov Institute», 1, Akademika Kurchatova pl., Moscow, 123182, Russia
E-mail: dfinosh@gmail.com

Abstract. The article analyzes the scenario of a severe beyond the design basis accident with core melting at a nuclear power plant with RBMK-1000. Molten reactor core falls into the sub-reactor space filled with a steam-water mixture. The interaction of melt core and the coolant can lead to the creation of conditions for the occurrence of a steam explosion. Parameters of this steam explosion have been evaluated by Hugoniot adiabat method. Such approach considers the steam explosion as detonation phenomenon, where shock wave impacts initial multiphase mixture and initiates melt droplets fragmentation and high heat flux from melt to water. Mass, momentum and energy conservation equations for initial mixture and for equilibrium explosion products mixture lead to Hugoniot equation for the adiabat. The tangent from initial point (initial mixture) on the plane “mixture volume-mixture pressure” to the Hugoniot adiabat determines Chapman – Jouguet point, which characterizes steam explosion parameters. Our calculations have demonstrated that obtained values of steam explosions do not exceed dangerous limits.

1. Introduction
The development of Russia's nuclear power industry in the medium term involves the construction of VVER generation III+ (AES-2006, VVER-TOI) reactor plants. At the same time, research is being actively carried out in the field of development of power plants with heavy liquid metal coolant (BN-1200, BREST-OD-300). Activities continue on projects for floating nuclear thermal power plants (FNTPP) that have no analogues in the world.

There are no plans to build new nuclear power plants with RBMK-type reactors, and the design lifetimes of existing power units with RBMK are expiring. However, due to the substantial part of power generation at RBMK-1000 nuclear power plants in the total volume of nuclear power in Russia, as well as the lack of replacement power in the short term, the question of the possibility of extending their operation is particularly relevant.

According to the requirements of the IAEA, licensing the operation of a nuclear power plant unit must be accompanied by a full safety assessment, including in case of severe beyond design accidents.

2. Possible scenarios for the development of a severe accident at NPP with RBMK-1000
Currently NRC "Kurchatov Institute" is analyzing two cases of the development of a reactor severe accident at a NPP with RBMK at the stage of severe core damage:
1. The core melt will slowly flow through the technological channels into the zone of the hydroseals of the lower water communications (LWC). The high-temperature melt will almost immediately melt the walls of the LWC pipes and enter the under-reactor compartment in small portions ~150-200 kg, distributed over a grid of graphite stacks 250x250 mm (figure 1). The "OR" scheme will be heated due to heat conduction. The metal structure of the "OR" scheme is made in the form of a drum 14.5 m in diameter and 2 m high. The scheme serves as a support for the graphite stack and other metal structures of the reactor. Also, the "OR" performs the functions of the lower biological protection of the reactor. The sub-reactor room is a special compartment for the LWC (height — 6 m, diameter — 14 m);

![Figure 1. Scheme of the flow of fuel-containing masses into the RBMK-1000 sub-reactor compartment.](image1)

2. The reactor core will be heated up and the fuel elements will be melted and drain into the lower part of the reactor into the region of the support structure — the "OR" scheme. The supporting metal structure of the reactor will be heated up and drop under the weight load of the core. The core melt and the elements of the reactor support structure will fall into the sub-reactor compartment as a solid mass (figure 2).

![Figure 2. Scheme of the flow of fuel-containing masses into the RBMK-1000 sub-reactor compartment.](image2)

After the appearance of fuel-containing masses (FCM) in the sub-reactor space, they will interact with the concrete of the reactor base. For power units of the second generation, it is typical to place a bubbler pool filled with water in compartments under the LWC compartments. Thus, there is a potential danger of the concrete slab melting and the fall of the FCM into the water of the bubbler pool.

As the main strategy for the FCM keeping within the boundaries of the reactor space, it is envisaged to decay heat removal from the damaged reactor and cool the supporting metal structures by supplying water.
There are two options for cooling the "OR" scheme:

1. "from above" — by supplying water to the gas cavity between the graphite of the bottom reflector and the upper plate of the "OR" scheme;
2. "from below" — by supplying water to the bottom plate of the "OR" scheme to prevent it from heating up.

During the implementation of the second cooling option, the sub-reactor space will be filled with water, and if measures to localize the FCM within the reactor space are unsuccessful, conditions will be formed for a steam explosion as a result of the interaction of the flowing FCM with water in the sub-reactor compartment.

3. Steam explosion phases
Steam explosion occurs under interaction of high-temperature (~3000 K) molten reactor core (corium) and coolant. Under certain conditions, such interaction can proceed in an explosive manner with an increase in pressure up to hundreds and thousands of atmospheres. In steam explosions, heat transfer between the melt and the coolant is so intense that the time scale for heat transfer is shorter than the time scale for pressure relief. This can lead to the formation of shock waves, that may endanger surrounding structure.

Large scale steam explosion development goes through the following phases [1]:

1. **The premixing phase.** Formation of coarsely mixed region of melt and coolant as a result of breakup of melt jet pouring into water. The length scale of the melt droplets is in the range of centimeters. Stable steam film around the melt droplets causes relatively low heat transfer between the melt and the coolant. The time scale of the premixing phase is in the range of seconds.
2. **The triggering phase.** The triggering event produces the destabilization of steam film around the melt droplets, allowing direct melt-water contact and local fine fragmentation of the droplet. Local enhanced heat transfer and pressurization generates subsequent large scale steam explosion. Different mechanisms can lead to the film destabilization, for example, collision of the melt with the bottom of the vessel.
3. **The propagation phase.** Steam explosion is realized as detonation wave, propagating through melt-coolant premixture. Fine melt fragmentation (length scale is 0.1 mm) and high heat transfer from the melt take place in the wave to provide self-sustaining thermal detonation propagation. Melt thermal energy transfers to kinetic energy of steam explosion products. (steam-water-fine melt fragments mixture).
4. **The expansion phase.** The expansion of the high-pressure mixture behind the detonation wave front against the surrounding constraints determines the damage potential of a steam explosion.

More details on the physical and hydrodynamic processes accompanying a steam explosion phenomenon can be found in [2-7].

This paper considers a steam explosion at the stage of a beyond design basis accident at a NPP with RBMK. During this accident molten fuel-containing masses fall into the sub-reactor compartment filled with water. It is conservatively assumed, that the melt completely fragments when it enters water, forming a coarsely dispersed mixture with water. Then some event is realized that initiates an explosive interaction between corium and water.

4. **Estimation of steam explosion parameters by the Hugoniot adiabat method**
To estimate the explosion parameters, we will use the Hugoniot adiabat method, which is widely used in studies of detonation in combustible gas mixtures [8]. This method for the analysis of a large-scale
steam explosion was first applied in the work [9], in which the Hugoniot adiabat was developed for a mixture of a melt with a coolant, based on the similarity of the processes of thermal detonation and chemical detonation. Explosion parameters for specific mixtures were also calculated in [9]. Then it was used in a number of works [7, 10-12].

It is assumed that a steam explosion is realized in the form of a thermal detonation wave, which makes it possible to formulate equations for the conservation of mass, momentum, and energy that relate these quantities in the initial mixture of the melt with water and in the state when the equilibrium state of the mixture components is achieved (Chapman-Jouguet plane).

The laws of conservation of mass, momentum, and energy are formulated in the coordinate system associated with a moving stationary thermal detonation wave. In this system, the wave front, on which discontinuities of pressure, temperatures, velocities, and other parameters of the mixture occur, is fixed; and the initial mixture moves towards it with the velocity of the detonation wave $u_0$. Since water, when mixed with the melt, receives heat from it and boils with the generation of steam, then we will take into account the presence of steam in the initial mixture.

Conservation equations for the mass of the melt (index $m$) and for the mass of the steam-water mixture (index $w$):

$$\alpha_m \rho_m u = \alpha_{m0} \rho_{m0} u_0,$$

$$\alpha_w \rho_w u = \alpha_{w0} \rho_{w0} u_0.$$

By summing equations (1) and (2), we can obtain the equation for the conservation of the mass of the mixture:

$$\rho u = \rho_{0} u_0,$$

where the mixture density is determined by the following formula:

$$\rho = \alpha_m \rho_m + \alpha_w \rho_w.$$

Since momentums of phases are exchanged in the zone of melt fragmentation and interphase interaction, the momentum of each individual phase is not conserved, but is changed; but the momentum of the entire mixture is conserved:

$$\rho u^2 + p = \rho_{0} u_0^2 + p_0.$$

Equations (3) and (5) lead to the following important relations for the velocity of the detonation wave and the velocity of the mixture in the equilibrium plane:

$$u_0 = v_0 \sqrt{\frac{p - p_0}{v_0 - v}},$$

$$u = v \sqrt{\frac{p - p_0}{v_0 - v}},$$

where $v = \rho^{-1}$ is specific volume.

Likewise, the energy of each phase is not conserved due to interfacial heat transfer and friction; however, energy conservation is performed for the entire mixture:

$$h + u^2 / 2 = h_0 + u_0^2 / 2,$$
where the specific enthalpy of the mixture is determined as follows:

\[ h = \left( \alpha_m \rho_m h_m + \alpha_w \rho_w h_w \right) / \left( \alpha_m \rho_m + \alpha_w \rho_w \right). \quad (9) \]

Conservation equations (3), (5) and (8) lead to the following relation:

\[ p - p_0 - 2\left(h - h_0\right) / \left(v + v_0\right) = 0, \quad (10) \]

which, together with the volume conservation equation \( \alpha_m + \alpha_w = 1 \) and the equations of state for substances \( \rho_i = \rho_i(p, T) \) and \( h_i = h_i(p, T) \) (where \( i = m, w \)) determines the parameters of possible states of an equilibrium mixture, which on the plane "specific mixture volume – mixture pressure" are depicted by a curve called the Hugoniot adiabat \( p = p(v) \).

Equation (6) determines the velocity of the detonation wave \( u_0 \), which on the plane \( p - v \) is defined as the slope of a straight line (Rayleigh line), connecting the point describing the initial mixture and the point on the Hugoniot adiabat. It is known from the theory of detonation of combustible gases [8], that the equilibrium state, which is realized in reality, corresponds to that point on the Hugoniot adiabat, where the Rayleigh line (6) becomes tangent to the Hugoniot adiabat (10). This point is called the Chapman-Jouguet point (plane), and further denoted as C-J.

To obtain the Hugoniot adiabat, equation (8) was solved numerically by the bisection method.

It was conservatively assumed that corium consists of pure dioxides \( \text{UO}_2 \) and \( \text{ZrO}_2 \) in a percentage ratio of 80.3/19.7%. The thermophysical properties of liquid and solid corium were taken constant [13]: \( C_{p,\text{liq}} = 565 \text{J/(kg·K)} \) is specific heat of liquid phase; \( C_{p,\text{sol}} = 445 \text{J/(kg·K)} \) is specific heat of solid phase, heat of corium fusion \( \Delta h_{\text{cor}} = 0.362 \cdot 10^6 \text{J/(kg·K)}. \)

Water and steam thermophysical properties were found using the program Water Steam Pro.

5. Problem parameters and analysis results
It was considered the melting of 167 fuel assemblies (~10% of the total number in RBMK-1000) with a total mass of 23 tons in a flat zone and their subsequent cave in to the sub-reactor compartment.

At the initial moment of time, a steam-water mixture at a pressure of \( p = 1 \text{ bar,} \) consisting of water at a temperature of \( T_w = 323 \text{ K} \) and superheated steam at a temperature of \( T_v = 1661 \text{ K} \) (void fraction \( \varphi_0 = 0.1 \)) fills the compartment. The temperature of superheated steam is defined as the average between the temperatures of water and corium \( (T_{\text{cor}} = 3073 \text{ K}) \). The initial void fraction is an uncertainty parameter; its value was estimated based on the results of FARO experiments [3].

For the given initial parameters, the Hugoniot adiabatic curve was obtained and the Rayleigh line was drawn (figure 3).
Figure 3. Hugoniot adiabatic curve at $\varphi_0$.

At the value of the specific volume $v = 9.15 \text{ cm}^3/\text{g}$, a sharp bend in the adiabatic is observed, which corresponds to the transition between a two-phase steam-water mixture and single-phase water.

The parameters of the explosive interaction were determined using graphical analysis. Thermal detonation occurs at a pressure of 156 kPa at the Chapman-Jouguet point, which corresponds to 56 kPa overpressure. The velocity of the detonation wave is 29 m/s.

When the parameter $\varphi_0$ is varied, an inversely proportional relationship is observed for the detonation rate: at $\varphi_0 = 0.05$ the velocity reaches about 119 m/s and at $\varphi_0 = 0.15$ — 20 m/s, however, the pressure at the C-J point in both cases changes slightly. This is consistent with the idea of thermal detonation and the conclusions drawn from the analysis of FARO experiments [3].

Analyzing the design values of the ultimate load of the elements of the equipment compartment of power units No. 1-2 of the Kursk NPP and No. 1-2 of the Leningrad NPP, it can be concluded that the value of overpressure pressure of 56 kPa is below the maximum permissible values (Table 1).

| Structural element                        | Ultimate pressure (kPa) |
|-------------------------------------------|-------------------------|
| Wall towards the spent fuel assemblies    | 180                     |
| Wall to the side of the turbine compartment| 710                     |
| Fragment of compartment overlap           | 180                     |

6. Conclusion
As a result of the work performed, the behavior of the corium-coolant system after a steam explosion in the sub-reactor compartment of a nuclear power plant with RBMK was investigated using the Hugoniot adiabat method. The parameters of the explosive interaction were determined by the method of graphical analysis at the given parameters of the coolant. The resulting excess pressure was 56 kPa, which is lower than the design value of the ultimate bearing capacity of the elements of the equipment compartment of power units with RBMK reactors.

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