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Research Article

# Hydrogen explosion safety for the Bilibino NPP EGP-6 reactor in conditions of a beyond design basis accident*

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## Abstract

The paper presents the results of simulating a beyond design basis accident with regard to radiolytic hydrogen transport and analysis of hydrogen explosion safety in the reactor cavity and in the central reactor hall of the Bilibino NPP. The KUPOL-M code, version 1.10a, is used as the calculation tool for justifying hydrogen explosion safety. The accident under investigation is a beyond design basis accident, the initial event for which is spontaneous travel of two pairs of automatic control rods and a failure of the reactor scram system. The accident leads to the maximum possible release of positive reactivity, mass destruction of fuel elements, and escape of radiolytic hydrogen, as part of the gas mixture, into the reactor cavity and the central hall and further, through the broken windows, into the atmosphere. The calculation results show that no explosive concentrations of hydrogen are formed in the reactor cavity and in the central hall. Therefore, hydrogen explosion safety is ensured throughout the duration of the design basis accident for the Bilibino NPP unit with the EGP-6 reactor.

## Keywords

boiling water reactor, radiolysis products, radiolytic hydrogen, Bilibino NPP, EGP-6, hydrogen explosion safety, beyond design basis accident, KUPOL-M code

## Introduction

The formation of an explosive mixture and its explosion may lead to the wall and equipment breakdown and, further, to the release of radioactive fission products (RFP) into the environment, so hydrogen explosion safety justification issues are indispensable in the NPP design and safe operation justification (NP-040-02 2002). The Shapiro-Mofette ternary diagram (Shapiro and Moffette 1957), showing graphically the concentration limits for the explosive mixture combustion and detonation to start, is broadly used for analyzing hydrogen explosion safety.

Explosive safety of hydrogen-containing mixtures is characterized by the following criteria:

- smallest possible explosive content of oxygen – 5 vol.%;
- hydrogen inflammation region – 4 vol.%;
- phlegmatization by steam during its concentration – over 55 vol.%.

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The state of the art in ensuring hydrogen explosion safety at NPPs and an overview of respective regulatory documents are provided in Kirillov et al. 2017. The KUPOL-M code, version 1.10.a, certified by SEC NRC (the KUPOL-M hereinafter) was used by the authors as the analytical tool for the hydrogen explosion safety justification (KUPOL-M version 1.10a 2018).

The paper considers a beyond design basis accident (BDBA) at a reactor facility with the EGP-6 reactor leading to the maximum release of positive reactivity due to the spontaneous travel of the automatic control rods in response to the scram failure. The BDBA scenario was described earlier in Parafilo et al. 2018, that deals with analyzing the radiological consequences of an accident. This paper considers the BDBA scenario as regards the hydrogen explosion safety.

In reactor conditions, hydrogen is produced as follows in the process of water radiolysis:

$$2H_2O \rightarrow 2H_2 + O_2.$$

After the heat sinks is lost and the FA cladding fails at 800 to 1100 °C, hydrogen is produced as the result of the steam interaction with the magnesium the fuel composition contains according to the following reaction:

$$Mg + H_2O = MgO + H_2.$$

# BDBA scenario

The scenario for the beyond design basis accident (BDBA) under consideration is presented in Parafilo et al. 2018. The initial state of the power unit prior to the BDBA is 100% rated power operation with all parameters meeting the nominal steady-state condition. In addition, it is conservatively assumed that the plant power is lost and the plenum and exhaust ventilation systems are out of operation.

An accident involving the insertion of the maximum possible positive reactivity and the scram system failure leads to a neutron power growth to 419% of the rated power and the gradual cladding failure in up to 126 FAs. The cladding heat removal is lost within 30 seconds after the CRs start to move upwards in a spontaneous manner, which leads to a departure from nucleate boiling (DNB) and a surge of coolant boiling. This, in turn, leads to a rapid pressure growth (to 10 MPa), and the reactor circulation circuit rupture and voiding. The DNB leads to the FA cladding overheating and a failure of about a half of all FAs. Hydrogen is produced as the result of the evaporating coolant interaction with the fuel's magnesium matrix.

The duration of the BDBA under consideration is 1000 s.

Fig. 1 shows an overall view of the simulated central hall (CH) at the Bilibino NPP. Seen on the right are the CH windows that serve as safety structures.

**Figure 1.** Bilibino NPP's central hall with four EGP-6 reactors [www.fotoalbom.su].

Fig. 2 presents a sectional view of the EGP-6 reactor (Kashirin et al. 2013). In the course of service, the reactor has had its flowchart modified from that at the time of the start of the operation (Chapter 1.9. Operation experience of Bilibino ATEC 1987) to the Bilibino NPP's flowchart with the EGP-6 reactor (Dolgov 2004) after 30 years of service.

Conditionally, the development of a beyond design basis accident can be divided into three stages.

**Stage I.** This stage involves massive fuel cladding failure in 16 maximum-power FAs, this leading to a steam-gas-water mixture (that containing radiolytic hydrogen) formed in the reactor. An abrupt reactor pressure growth of 0.24 MPa causes the welded joint between the reactor's top plate and the reactor vessel thermal expansion compensator to break down and the plate to lift. The steam-gas-water pressure growth in the space between the reactor head and the upper safety plate leads to the steam-gas-water mixture entering the central hall.

At this stage, hydrogen is produced as the result of the water boiling and the release of the radiolytic hydrogen dissolved in water. Hydrogen is produced additionally as the result of the fuel magnesium matrix reaction with the coolant in 16 FAs whose cladding has failed.

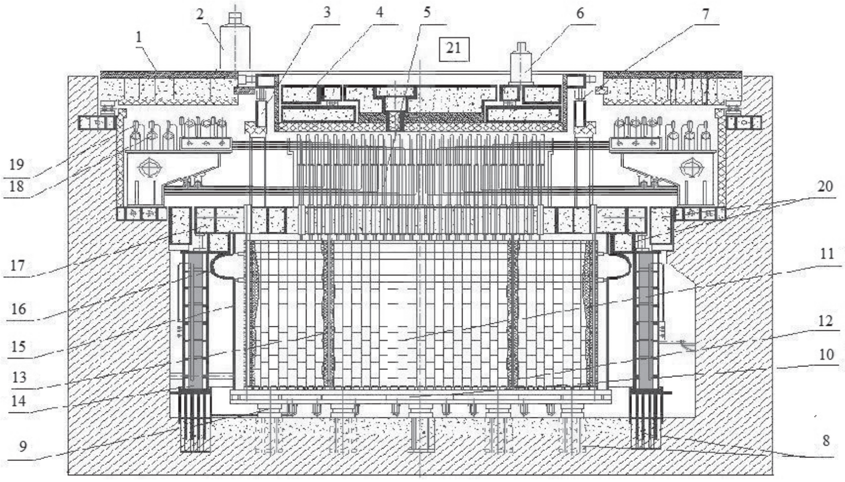

**Figure 2.** Sectional view of the EGP-6 reactor: 1 – upper side plate; 2 – larger rotary plate drive; 3 – central frame with supports; 4 – central rotary plate; 5 – risers; 6 – smaller rotary plate drive; 7 – roller bearing; 8 – inserts; 9 – support assemblies; 10 – lower plate; 11 – graphite stack; 12 – CPS channel; 13 – FA; 14 – biological shielding tank; 15 – shroud; 16 – reactor vessel compensator; 17 – upper plate; 18 – group headers with working pipelines;19 – stop valves; 20 – lower layer of safety plate; 21 – central hall (CH).

**Stage II.** An abrupt pressure increase in the CH leads to the central hall windows broken and a steam-gas-water mixture released into the atmosphere. As more primary coolant is lost, the FA cladding temperature grows to 900 °C, which leads to some 100 average-power FAs failing further by the 100th s. The process involves the steam-gas-water mixture escaping additionally, through the graphite stack, into the reactor cavity, the assembly space, the space between the reactor head and the upper safety plate and, further, into central hall and, through the CH windows, into the atmosphere.

**Stage III.** After the primary coolant is lost in full by the 100th second, 126 FAs fail additionally due to the FA heating to 1100 °C.

Fuel cladding failure was investigated experimentally at IPPE to analyze the consequences of a beyond design basis accident (Baranaev et al. 1993). The findings have made it possible to define the yield of hydrogen from the steam-steel reaction in conditions of the BDBA in question as negligibly small. This is explained by the small reactor power and a small amount of heat stored due to low working temperatures.

Paper Kazantsev et al. 2022 presents the authors' estimates for the sources of hydrogen as the result of radiolytic processes in the course of the coolant boiling in the Bilibino NPP's EGP-6 reactor FA fuel tubes.

# Kupol-m calculation of the central hall processes

The estimate provided in Mukhamadeev and Baranaev 2019 for the beyond design basis accident at the Bilibino NPP under consideration is as follows: "The amount of hydrogen produced, according to conservative estimates, will be 2.5 m$^3$". When all this hydrogen enters the central hall (CH) (see Fig. 1) and mixes uniformly, its average concentration will amount to 0.02 vol.% (Mukhamadeev and Baranaev 2019). The KUPOL-M calculation (KUPOL-M version 1.10a 2018) led to a more precise estimate since the calculation for the change of the hydrogen volume fraction as a function of time makes it possible to take into account the maximum concentration of hydrogen at the leakage point and its further spreading through the CH nodalization model volumes.

The flow rate of the steam-water mixture entering the central hall is shown in Fig. 3 (Parafilo et al. 2018). The flow rate change in time was estimated using the RELAP5/Mod3.2 code (RELAP5/MOD3.2 2012).

The release of hydrogen from the reactor cavity into the central hall is defined by two processes: the release of dissolved radiolytic hydrogen in the process of water boiling and the release of hydrogen due to the fuel's magnesium matrix reaction with steam after some of the FA claddings fail. And the amount of hydrogen resulting from the fuel matrix interaction will be several times as large as the amount of radiolytic hydrogen.

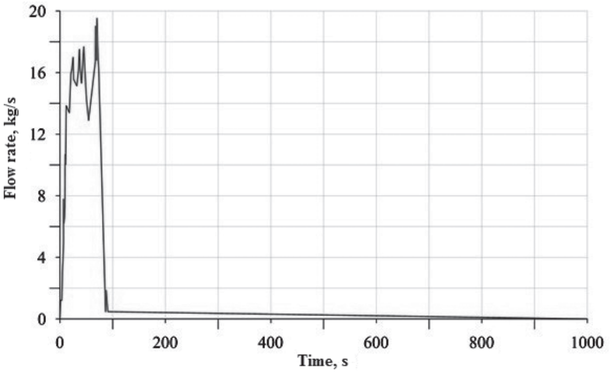

**Figure 3.** Flow rate of the steam-water mixture entering the CH.

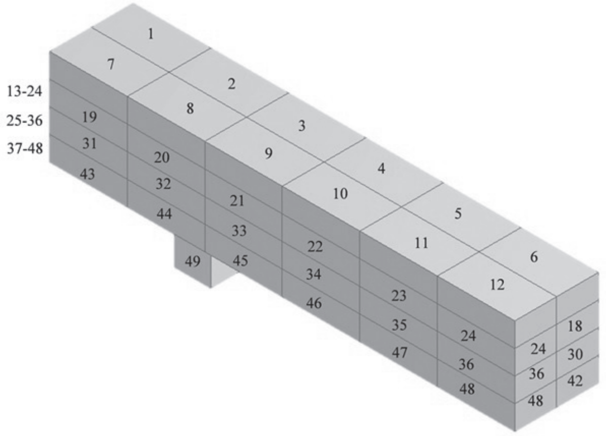

**Figure 4.** Nodalization model used for the KUPOL-M calculations.

The nodalization model used for the KUPOL-M calculations is shown in Fig. 4. The nodalization model included 50 inner boxes connected through 202 couplings. The central hall space is simulated by 48 boxes. The source is in box No. 49 that simulates the space above the reactor. Box No. 50 simulates the atmosphere.

Figs 5 through 8 present the results of the computational simulation for the change in the gas environment parameters in the reactor cavity and in the CH during the accident. Fig. 5 shows the CH pressure change in time. It is roughly at the 28th second that a pressure drop of 3 kPa is observed at which the safety structures (CH windows) break down; the total area of the broken CH windows is 240 m$^2$. After that, the above parameters in the CH tend to reach the atmospheric values. Fig. 6 present the temperature changes in boxes Nos. 45 and 9 (see Fig. 4) in the CH.

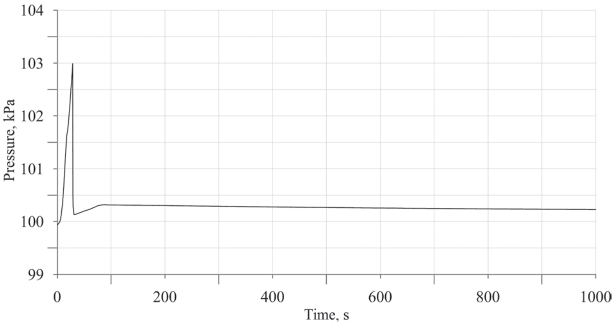

**Figure 5.** CH pressure change.

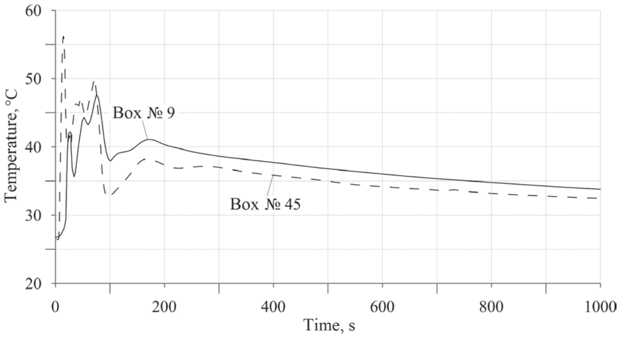

**Figure 6.** CH environment temperature change.

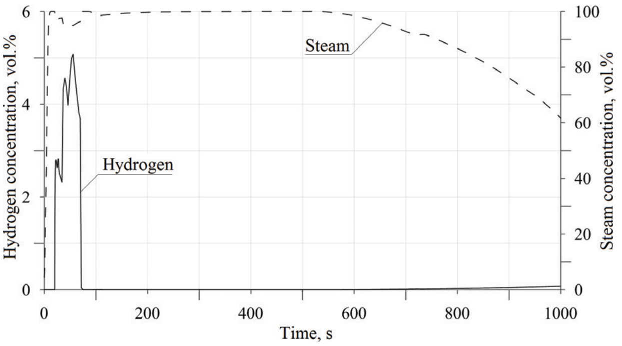

**Figure 7.** Hydrogen and steam concentration in the reactor cavity.

Fig. 7 presents the changes in the hydrogen and steam concentration (the right-hand axis) in the space above the reactor. It can be seen in the figure that, due to the phlegmatization by steam, as its concentration exceeds 55 vol.%, hydrogen safety is ensured in the space above the reactor across the accident simulation interval.

Fig. 8 shows the changes in the hydrogen concentration in some of the calculated volumes in the CH atmosphere. The hydrogen concentration in box No. 45 (that adjoining the box with leaking coolant) is observed to be higher than in box No. 9 in the upper part of the CH space. Fig. 8 demonstrates that the concentration of hydrogen does not exceed 0.46 vol. % in all of the calculated CH volumes, which is an order of magnitude as small as the threshold concentration of 4 vol.%, that is, hydrogen explosion safety is ensured across the accident simulation interval.

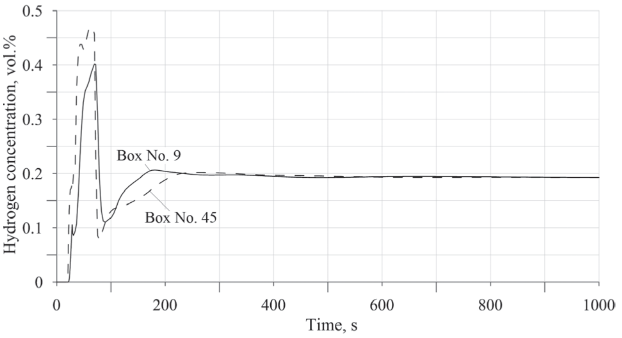

**Figure 8.** CH hydrogen concentration change.

# Conclusions

An analysis of the calculation results obtained using the KUPOL-M code has shown that the concentration of steam in the reactor cavity during the accident exceeds 55 vol.%, which ensures hydrogen explosion safety at the BDBA stage discussed.

The volume concentration of hydrogen in the central hall is an order of magnitude as small as the threshold concentration of 4 vol.%, so, accordingly, hydrogen explosion safety is ensured across the simulation range of a beyond design basis accident.

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