

# Investigation of hydrogen distribution in Ignalina NPP ALS using COCOSYS code

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The Accident Localisation System (ALS) of the Ignalina NPP is a “pressure suppression” type confinement which protects the population, employees and environment from the radiation hazards.

According to the Safety Analysis Report for the Ignalina NPP, ~ 110 m<sup>3</sup> of hydrogen is released to ALS compartments during the Maximum Design Basis Accident. If the volume concentration of hydrogen in the compartment reaches 4%, there is a possibility for a combustible mixture to appear. However, the flammability of hydrogen depends on the air and steam concentrations [1].

In the NPP hydrogen appears due to: 1) water radiolysis during normal operation and 2) steam interaction with zirconium (this mechanism is related to severe accidents).

In this paper, the calculation results of hydrogen distribution in the Ignalina NPP ALS during Maximum Design Basis Accident (MDBA) are presented.

**Key words:** accident localisation system, hydrogen, Maximum Design Basis Accident

## 1. INTRODUCTION

Various risk studies have shown that early containment failure due to hydrogen combustion without using a sufficient H<sub>2</sub> mitigation system could be a major cause of a large off-site release in case of severe accident [2]. Therefore it is necessary to simulate the major physical processes involved, namely hydrogen distribution, ignition and combustion, which can range from slow deflagration to fully developed detonation.

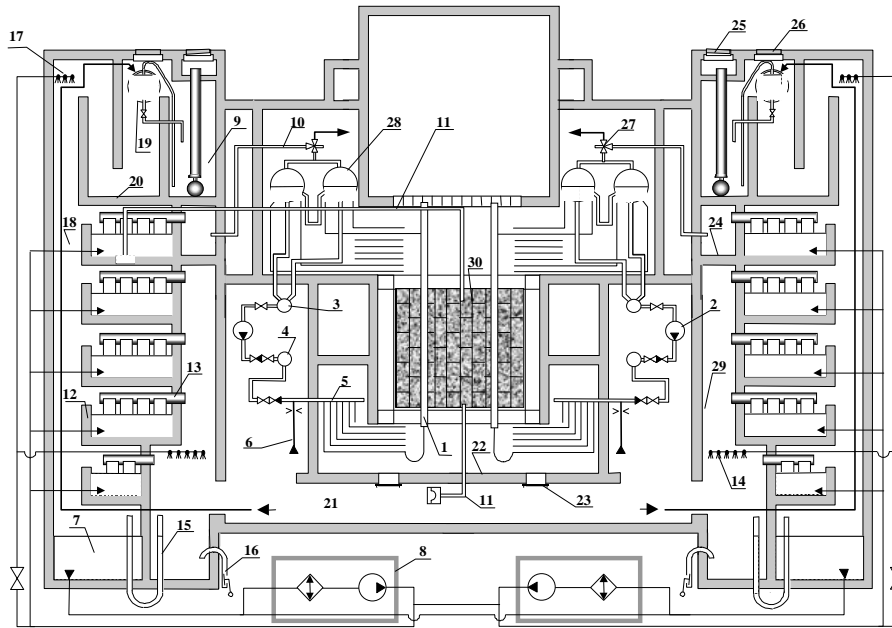
The current analysis was performed for the RBMK-1500 type reactor of the Ignalina NPP Unit 2. The paper presents an analysis of hydrogen distribution in the Ignalina Nuclear Power Plant (INPP) ALS compartments in case of MDBA, *i.e.* guillotine rupture of pressure header of the Main Circulation Pump (MCP). At the beginning of the analysis there was no severe accident scenario defined for an RBMK-1500 type reactor. Therefore the design data on hydrogen release were taken from the report of safety justification of the Symptom Based Emergency Operating Procedures [3] and considered for the analysis. This analysis does not aim to provide a safety assessment; it is devoted to development and validation of the model.

The objective of the presented analysis was to develop a reliable nodalisation of ALS for COCOSYS code to be able to simulate the distribution of hydrogen in case of an accident.

## 2. “CONTAINMENT” OF IGNALINA NPP

A characteristic feature of the major light water reactors is the containment, which protects workers, public and environment from radiation hazard. This is a large, strong, steel and reinforced concrete building, which encloses the reactor and its cooling circuits. Formally, the Ignalina NPP does not have a containment, but the major part of the Main Circulation Circuit (MCC) is enclosed by the ALS, which performs a function of containment.

The ALS of the Ignalina NPP consists of a number of interconnected compartments with 10 condensing pools to condense the accident-generated steam and to reduce the peak pressures that can be reached during any loss of coolant accident (LOCA) (Fig. 1). In this respect, the ALS of the Ignalina NPP is a pressure suppression type containment. The condensing pools are located at five elevations in two ALS towers. In the case of MCP pressure header rupture, the accident-generated steam is direc-



**Fig. 1.** Principal scheme of the Ignalina NPP Accident Localisation System  
 1 – fuel channel, 2 – main circulation pumps, 3 – MCP suction header, 4 – MCP pressure header, 5 – group distribution header, 6 – ECCS headers, 7 – hot condensate chamber (HCC), 8 – CTCS pumps and heat exchangers, 9 – discharge pipes section, 10 – pipe from the steam relief valves, 11 – steam gas mixture from the reactor cavity, 12 – condensing pools, 13 – steam distribution headers, 14 – bottom steam reception chamber (BSRC) sprays, 15 – water seals/S traps between HCC and BSRC, 16 – BSRC vacuum breakers, 17 – air removal corridor sprays, 18 – air venting channel, 19 – gas delay chamber tank, 20 – gas delay chamber, 21 – reinforced, leak tight compartments, 22 – Lower Water Piping compartments, 23 – steam relief valves from Lower Water Piping to reinforced leak tight compartments, 24 – top steam reception chamber, 25 – tip up hatches, 26 – knock down hatches, 27 – main safety valve and fast acting steam discharge valve, 28 – drum separators, 29 – BSRC steam distribution corridors, 30 – core

ted to four bottom condensing pools in both ALS towers. The other pools are designed for the condensation of steam released through the MCC overpressure protection system and do not participate in the MDBA sequence. To maintain the water level of 1.05 m, there are two holes 50 mm in diameter in each overflow barrier of the condensing pools. Two rectangular holes, distributed at an elevation of 1.1 m in each overflow barrier, allow the condensate overflow to the hot condensate chamber (HCC) in the case of water level increase in the condensing pool.

In each pool of the 2, 3 and 4 levels there are 10 steam distribution devices, each about 20 m long. The bottom pool has 7 devices 20 m long and 3 devices 10 m long. The steam distribution devices are pipes 800 mm in diameter connected to rectangular, steel metal downcomers (vent pipes) which under normal operation conditions are submerged to a depth of 0.85–1 m in the water of condensing pools. At the exit end the vent pipes are provided with a saw-tooth edge to ensure a better steam distribution and reduction of condensation type oscillations. To avoid boiling of the water in the con-

densing pools, the Condensing tray Cooling System (CTCS) provides water to these pools. Heat exchangers of CTCS are cooled with service water.

The characteristic feature of ALS is that in the initial phase of the accident, clean air from the wet-well is pushed away to the environment by the air from the drywell. This helps to reduce the peak pressure in compartments. The isolation of ALS from the environment is achieved by the floating ball-type valves. A detailed description of the Ignalina NPP can be found in [4].

The volume of compartments in front of condensing pools (drywell) is 20600 m<sup>3</sup> and behind the condensing pools 28330 m<sup>3</sup> [4]. The water volume in the condensing pools is 2800 m<sup>3</sup> [4].

Control of H<sub>2</sub> concentration in the ALS compartments is provided by the hydrogen concentration control and dilution system.

If hydrogen concentration reaches ~0.4% of the volume, then the exhaust ventilation system is activated to discharge hydrogen to the environment. If hydrogen concentration increases above the water of the condensing pools, it is diluted by the compressed air and discharged to the environment by the ventilation system.

### 3. THE INPP ALS MODEL FOR THE COCOSYS CODE

COCOSYS is a lumped-parameter code for the comprehensive simulation of all relevant phenomena, processes and plant states during severe accidents in the containment of the light water reactors, also covering the design basis accidents [5].

Considering that the most probable hydrogen accumulation places are the top compartments of the ALS towers, *i.e.* before and behind the steam condensing pools [3], these compartments were modelled in more detail. The refined ALS model allows possible convection loops, which can have a significant influence on the H<sub>2</sub> distribution in a long-term accident.

This refined ALS nodalisation was based on a previously developed ALS model for calculation of the thermalhydraulic parameters in ALS during MDBA. A detailed description of the ALS model, which was used as a basis for the current simulation, can be found in [6].

The model of the Ignalina NPP ALS for the code COCOSYS used in the analysis consists of 109 nodes, 291 junctions of different type, including pumps and 341 structures to consider heat transfer to the building's structures. The model includes all the accident-affected ALS compartments, the condenser tray cooling system, drainage and other related systems. The model includes the Emergency core cooling system (ECCS), which uses ALS as a water reservoir.

The refined model of the bottom steam reception chamber (BSRC) and the condensing pools of ALS towers are presented in Fig. 2. In the previous model the current compartments were modelled as two equivalent compartments. To estimate the probable convection in these compartments, the condensing pools were modelled according to their real location. The BSRC was subdivided according to location of condensing pools as well (Fig. 2).

As described in 2, there are 5 condensing pools in each tower of ALS, and in case of a pressure header (PH) rupture only the four lower pools are steam loaded in the accident sequence. Therefore, the pressure suppression pool zone model DRASYS of the COCOSYS code [5] was applied to simulate the four lower condensing pools (nodes PSS1–PSS4 and PSSR1–PSSR4 for the left and right ALS towers, respectively). The 5th condensing pool was simulated as a NONEQUILIB zone model of the COCOSYS code [5] node (PSSL5 and PSSR5 for the left and right ALS towers (ALT) respectively) considering the water mass and the volume of atmosphere above the water surface. The headers of the steam distribution devices (SDD) were simulated as a separate node for each condensing pool (COLL\_L1 to COLL\_L4 and COLL\_R1 to COLL\_R4 for the left and right ALS towers, respectively).

The BSRCs were split in 10 nodes each, *i.e.* according to the height and into two sides located left and right of the condensing pools (nodes BSRC\_L1 to BSRC\_L10 and BSRC\_R1 to BSRC\_R10 for the left and the right ALTs, respectively). In the previous analyses, the hot condensate chamber (HCC) and the air venting channel (AVC) in each ALS tower were combined to one node including also the volume and structures of the 5th condensing pool. For the intended hydrogen distribution analysis these compartments were simulated by several nodes. The AVC is split in upward direction according to the location of the condensing pools. Additionally the AVC was split into two parts – one close to the

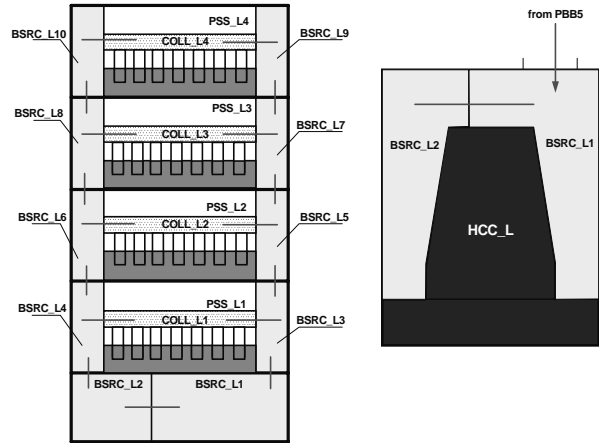


Fig. 2. Nodalisation of the BSRC and condensing pools in the left tower of ALS

condensing pool and the other close to the outer “cold” wall of the ALS tower. Such subdivision allows formation of possible convection loops. The lowest nodes (HCC\_L and HCC\_R) represent the HCC including water pools and are simulated applying the NONEQUILIB [5] zone model.

The junctions are subdivided into three groups: atmospheric junctions, drain junctions (including junctions simulating water overflow from condensing pools) and pump systems. Ventilation was not considered, because it turns off automatically closing the fast-acting isolation valves. These valves close when the overpressure in the compartments rises to 0.02 bar, what happens in case of PH break immediately at the beginning of the accident.

The sprays are part of the CTCS, *i.e.* in each ALT there is one special branch of the CTCS piping system supplied by the same pumps and coolers. In the input deck CTCS sprays are simulated as separate systems consisting of a cooler, a pump and a valve each. Energy and mass transfer between spray droplets and node atmosphere is simulated applying the IVO [5] model of COCOSYS. The initial diameter of the spray droplet was defined as 1 mm. Spray paths were given representing the droplet falling through the different nodes of the AVC compartment.

The walls, ceilings and floors of the ALS are represented in the input deck by structures. Heat transfer to structures, energy conduction in solid materials and wall temperature profiles are calculated in the COCOSYS code for energy sink/source evaluation. The large number of different compartments with the complex geometry of the Ignalina NPP ALS involves considerable surface areas and a mass of structures. The massive concrete walls may not have great influence on the short-term accident analysis, but they play an important role representing a significant energy sink in the long run. The linear initial temperature profile across the walls between two nodes is assumed, whereas a constant initial

temperature is defined for inner walls. The free convection, forced convection and condensation heat transfer models were applied for all simulated walls. The simulation of water drainage from the condensing pools to HCC appears along the side walls of the pools. Therefore, a specific CDW heat transfer model of the COCOSYS code [5] was applied for the walls, which separate condensing pools from the AVC.

Until now there is no severe accident scenario defined for the RBMK-1500 reactor. For the presented simulation, the  $H_2$  release rate is available from the report for the justification of the Symptom Based Emergency Operating Procedures [3]. In the report it is given that in case of a PH rupture the hydrogen release rate can be described by the formula  $G = 0.29/\sqrt{t}$  [m<sup>3</sup>/s], where  $t$  is the time from the beginning of the accident. Further on it is stated that the hydrogen production proceeds for 10 hours and later the  $H_2$  release is terminated. During this period ~110 m<sup>3</sup> of hydrogen is released to the ALS (Fig. 3).

In the present analysis, the hydrogen control system including compressed air supply for hydrogen dilution.

#### 4. CALCULATION RESULTS

The break of MCP pressure header (see 4 in Fig. 1) of the left MCC loop was selected for the analysis. The most representative compartments of ALS in this case are: 1) the accident compartment, which is part of the reinforced leak-tight compartments designed for an absolute pressure of 4 bars; 2) the Bottom steam reception chamber 29, which is the last compartment before condensing pools 12 and is designed for 2 bars of absolute pressure; 3) the Air venting channel 18 is located beyond the condensing pools (wet-well) and is designed for 1.8 bars of absolute pressure.

A detailed thermal hydraulic analysis of the Ignalina NPP ALS was performed and presented in [7]. It showed that the limiting design pressures in ALS compartments are not reached and a challenge of the structural integrity of the building is not expected. Therefore, only some of the thermal hydraulic results of the performed analysis are presented. The results of the analysis are presented in Figs. 4 to 8.

Figure 4 presents the pressure history in the leak-tight compartment located close to the break (zone PPB) and left ALS tower (ALT) compartments.

The maximum pressure in the break node PPB5 was calculated to be 2.45 bars (corresponds well with the result of the previous COCOSYS analyses (2.4 bars, [5]) and occurs at 1.5 s. Thus, the refined nodalisation has only a small influence on the maximum pressure. The maximum pressure in the

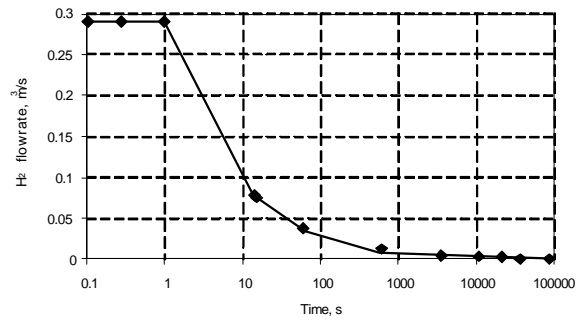


Fig. 3. Hydrogen release rate to the ALS

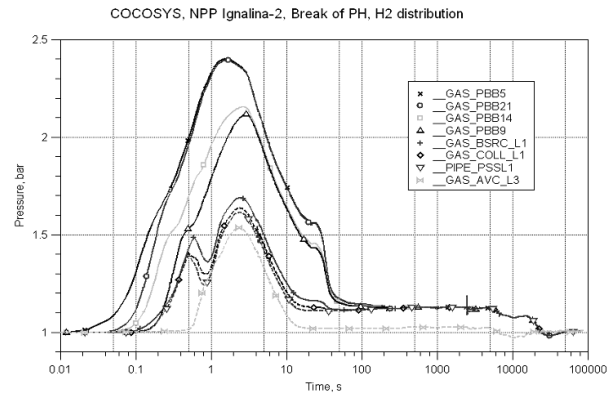


Fig. 4. Pressure histories in ALS compartments

neighbouring zone PPB21 is quite close to this value. Pressure maximums in the other compartments are below 2.1 bars. After reaching the maximum value the pressure reduces due to:

- decreasing mass and energy release from the break;
- condensation of steam in the condensing trays;
- release of air to the environment in the initial stage of accident.

In the period from 100 s to approximately 15000 s (~4 h) the process is characterised by a stable pressure level in all compartments between 0.98 and 1.15 bars, *i.e.* the accident-generated energy is absorbed by the structures, condensing pools and spray systems [7]. Moreover, the consideration of leakages in compartments behind the water layer leads to the sucking of air from the environment under the effect of the spray system.

After 4 h the thermal energy of the graphite stack was largely dissipated and decay heat diminished. The capacity of the energy sinks in the ALS exceeded the release from the break and, consequently the pressure in compartments before the condensing pools decreased. At that time the pressure in compartments behind the condensing trays was already close to atmospheric pressure. Opposite to the compartments in front of the pressure suppression system (PSS) the pressure decrease here is mainly caused by cooling down the gas by the spray system and cooling the HCC water by CTCS and by periodical cold water injection from HCC make-up systems.

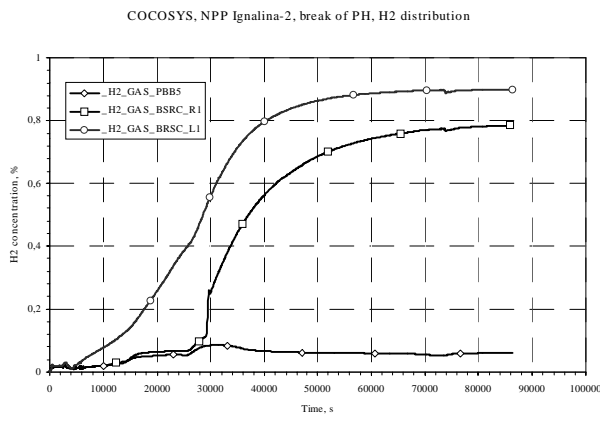


Fig. 5. Hydrogen volume concentration in PBB5 and BSRC compartments

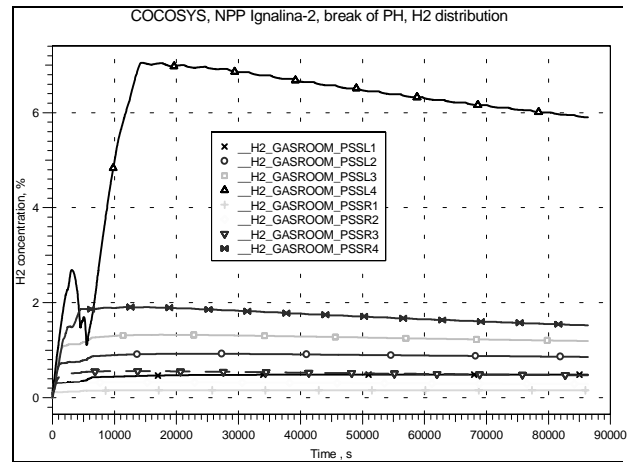


Fig. 6. Hydrogen volume concentration in space above condensing pool water

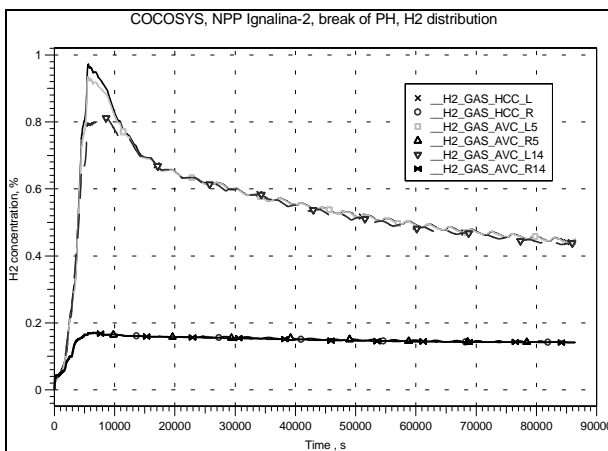


Fig. 7. Hydrogen volume concentration in AVC

Figures 5 to 8 present the first results of hydrogen distribution inside the ALS. Therefore it should be mentioned that a detailed analysis of the hydrogen distribution will be performed in further calculations. The main aim of the current analysis was to compile the INPP ALS model to allow investigation of  $H_2$  distribution during MDBA and further, including corresponding changes, during severe accidents.

Figure 5 shows that the volume concentration of  $H_2$  in the reinforced leak-tight compartments (PPB nodes) reaches  $\sim 0.1\%$  after 30000 s and later decreases and stabilises.

The volume concentration of  $H_2$  in BSRC of the left ALT (BSRC\_L1) in the long approaches 0.9% and in the BSRC of the right ALT (BSRC\_R1) 0.8%. The discrepancies between  $H_2$  concentrations in both ALT could be explained by the fact that the postulated break is located near the left ALT (Fig. 1), *i.e.* the node BSRC\_L1 is closer to break than zone BSRC\_R1. After 80000 s the hydrogen concentration in the compartments stabilised due to termination of the hydrogen release through the break.

Figure 6 shows the history of  $H_2$  distribution in the gasrooms of different condensing pools. Accord-

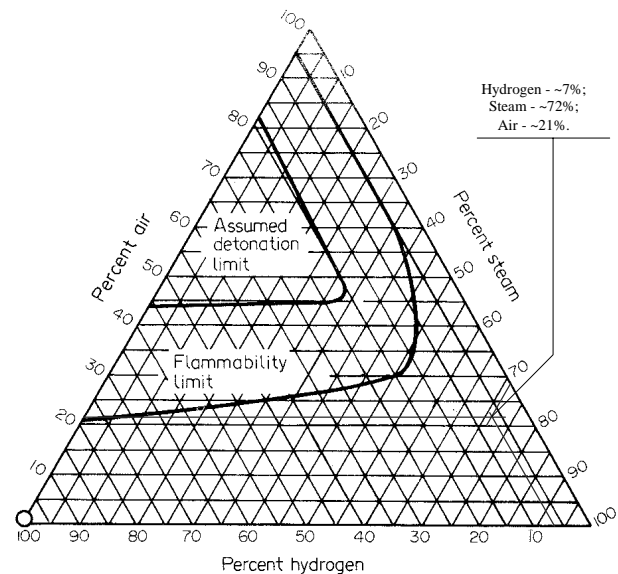


Fig. 8. Flammability and detonation limits for mixtures of air, hydrogen and steam

ing to [3], the most probable locations of hydrogen accumulation in the INPP are the volumes above the upper condensing pools of the ALS. In the present case, in the upper condensing pool of the left ALT (PSSL4) the hydrogen concentration of approximately 7% is reached. The hydrogen concentration in the upper pool of the right ALT is about 2%. As was expected, according to [3] hydrogen accumulates in the upper volumes of the both ALT. The difference between hydrogen concentrations in the left and right ALT is reasonable. The left ALT, which includes the upper condensing pool (PSSL4), is located closer to the assumed break location. According to that, the biggest part of the accident generated steam and hydrogen will be discharged in the left ALT. It should be mentioned that the hydrogen control system, which could decrease the hydrogen concentration, was not simulated.

H<sub>2</sub> concentration in the AVC behind the condensing pools is shown in Fig. 7. A maximum value of less than 1.0% is reached in the left ALT. The significant discrepancies between hydrogen concentrations in both ALS towers could result from the postulated break located closer to the left ALT (Fig. 1). After 5000 s the hydrogen concentration decreases due to a decrease of the H<sub>2</sub> release flow through the break (see Fig. 3).

Figure 8 estimates H<sub>2</sub> flammability in the gasroom of the upper condensing pool at the time when H<sub>2</sub> concentration is the highest (Fig. 6), *i.e.* 15000 s. The hydrogen flammability and detonation limits in Fig. 8 are taken from [1]. As was already mentioned and is shown in Fig. 8, if the volume concentration of hydrogen in the compartment reaches 4%, there is a possibility for a combustible mixture to appear. But the flammability of hydrogen depends on the air and steam concentrations. The performed analysis shows that the maximum hydrogen concentration of 7% is reached when the air and steam concentrations are 21% and 72%, respectively. This point is indicated in Fig. 8, and one can see that with such gas content hydrogen combustion is not expected.

However, the performed analysis was conservative, because the hydrogen control system, which could decrease the hydrogen concentration, was not simulated. The simulation of the hydrogen control system is foreseen in the future.

## 5. CONCLUSIONS

A refined nodalisation of the Ignalina NPP Accident Localisation System was developed for the analysis of hydrogen distribution using the COCOSYS code.

The results of the analysis show that during MDBA the highest hydrogen concentration (7%) appears in the gasroom of the upper condensing pool of the ALS tower which is closer to the ruptured pressure header, but the hydrogen flammability limit is not reached.

The calculated maximum pressure in case of a MCP pressure header rupture corresponds well with the result of the previous analyses [7], *i.e.* refined nodalisation has a negligible influence on the pressure behaviour.

The developed nodalisation of the Ignalina NPP ALS, after including the hydrogen control system, will be used for the simulation of hydrogen distribution in the case of beyond design basis accidents.

## ABBREVIATIONS

ALT	– accident localisation tower;
AVC	– air venting channel;

BSRC	– bottom steam reception chamber;
CTCS	– condensing tray cooling system;
ECCS	– emergency core cooling system;
HCC	– hot condensate chamber;
INPP	– Ignalina Nuclear Power Plant;
LOCA	– loss of coolant accident;
MDBA	– maximum design basis accident;
MCC	– main circulation circuit;
MCP	– main circulation pump;
NPP	– nuclear power plant;
PH	– pressure header;
PPB	– Russian abbreviation for leak-tight compartments;
SDD	– steam discharge device.

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## **VANDENILIO PASISKIRSTYMO IGNALINOS AE ALS PATALPOSE ANALIZĖ PANAUDOJANT PROGRAMINĄ PAKETĄ COCOSYS**

### Santrauka

Ignalinos AE Avarijų lokalizavimo sistema (ALS) – tai „slėgio mažinimo“ apsauginis gaubtas, kurio paskirtis apsaugoti gyventojus, darbuotojus bei aplinką nuo radiologinio pavojaus.

Ignalinos AE saugos analizės ataskaita rodo, kad maksimalios projektinės avarijos metu á ALS patalpas patenka ~ 110 m<sup>3</sup> vandenilio. Jeigu tūrinė vandenilio koncentracija patalpoje pasiekia 4%, vandenilis gali savaime užsidegti. Todėl būtina įvertinti vandenilio pasiskirstymą patalpoje. Būtina pabrėžti, kad kriterijus 4% tūrinės vandenilio koncen-

tracijos savaiame nenusako vandenilio užsidegimo arba spro-gimo galimybės. Žiuo atveju turi būti atsiųvelgta á oro ir garo koncentracijas.

Galima išskirti du pagrindinius vandenilio susidarymo branduolinėse jėgainėse mechanizmus:

1) dėl vandens radiolizės normalios eksploatacijos metu;

2) dėl garo reakcijos su cirkoniu, kai pasiekiamos aukštos kuro apvalkalo temperatūros (šis mechanizmas būdin-gas sunkioms avarijoms).

Điame straipsnyje pateikti vandenilio pasiskirstymo Ig-nalinos AE ALS patalpose maksimalios projektinės avari-jos atveju analizės rezultatai.

**Raktaþodþiai:** avarijø lokalizavimo sistema, vandenilis, maksimali projektinė avarija

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#### АНАЛИЗ РАСПРЕДЕЛЕНИЯ ВОДОРОДА В ПОМЕЩЕНИЯХ СЛА ИГНАЛИНСКОЙ АЭС С ПРИМЕНЕНИЕМ ПРОГРАММНОГО КОДА COCOSYS

Резюме

Система локализации аварий (СЛА) Игналинской АЭС – это защитная оболочка типа „снижения

давления“, который предназначен для защиты населения, персонала и окружающей среды от радиологического загрязнения.

Согласно Отчету по анализу безопасности для Игналинской АЭС, ~110 м<sup>3</sup> водорода выбрасывается в помещения СЛА при максимальной проектной аварии. Если объемная концентрация водорода в помещении достигает 4%, возникает возможность для образования горючей смеси. Поэтому необходимо проанализировать распределение водорода в помещениях. Следует отметить, что концентрация водорода непосредственно не определяет возможность образования горючей смеси. В данном случае необходимо учесть концентрации воздуха и пара в этом помещении [1].

На атомных электростанциях водород появляется из-за: 1) радиолиза воды при нормальной эксплуатации станции и 2) взаимодействия пара с цирконием (этот механизм связан с тяжелыми авариями).

В настоящей статье представлены результаты анализа распределения водорода в СЛА Игналинской АЭС при максимальной проектной аварии.

**Ключевые слова:** система локализации аварий, водород, максимальная проектная авария