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Simulation of hydrogen distribution at the Ignalina NPP confinement during BDBA

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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 radiation hazards. According to the Safety Analysis Report for the Ignalina NPP, ~110 m^3 of hydrogen is released to ALS compartments during the Maximum Design Basis Accident. However, in case of a beyond-design basis accident when zirconium oxidation starts, the amount of generated hydrogen could be significantly higher. If the volume concentration of hydrogen in the compartment reaches 4%, there is a possibility for a combustible mixture to appear.

To prevent the possible hydrogen accumulation in the ALS of the Ignalina NPP during an accident, a H_2 control system is installed.

The analysis revealed places of a possible H_2 accumulation in the ALS compartments during transient processes and assessed the mixture combustibility in these places for a beyond-design basis accident scenario. Such analysis of H_2 distribution in the ALS of the Ignalina NPP in case of BDBA had never been performed.

Key words: confinement, hydrogen, loss of coolant accident

1. INTRODUCTION

Various risk studies have shown that the confinement failure due to H_2 combustion without using a sufficient H_2 mitigation system could be a major cause for a large off-site release in case of an accident [1]. Even though the Ignalina NPP with RBMK-1500 reactor formally does not have a full-scope confinement, the ALS performs its function. The ALS is a "pressure suppression" type confinement which protects the population, employees and environment from radiation hazards. Therefore, it is necessary to investigate H_2 distribution and the capability of the hydrogen control system to maintain an acceptable H_2 concentration in the ALS compartments during the transient processes.

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

To prevent the possible hydrogen accumulation in the ALS during an accident, the H_2 control system, which includes H_2 concentration monitoring, H_2 dilution by the compressed air injection and H_2 exhaust by the ventilation system, is installed. The operation of the ventilation system and a compressed air supply system are foreseen in the symptom-based Emergency Operating Procedures (EOP) [2].

The paper presents an analysis of H_2 distribution in the INPP ALS compartments in case of a beyond-design-basis accident (BDBA). The main goal of the analysis was to improve the COCOSYS model for the Ignalina-2 considering the hydrogen control system and a realistic source term for hydrogen in case of a BDBA scenario.

The nodalisation of the Ignalina NPP ALS considering the operation of the H_2 control system was developed for the COCOSYS code [3]. The current nodalisation allows simulating the local H_2 distribution and assessing the efficiency of the H_2 control system. The operation of the related safety systems is considered as well.

2. CONFINEMENT OF THE IGNALINA NPP

A characteristic feature of the major light water reactors is the confinement which protects the 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 has no confinement, but the major part of the Main Circulation Circuit (MCC) is enclosed by the ALS which performs the function of confinement.

The ALS of the Ignalina NPP (Fig. 1) 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). In this respect, the ALS of the Ignalina NPP is a pressure suppression type confinement. The condensing pools are located at five elevations in two ALS towers. In the case of the MCP pressure header rupture, the accident-generated steam is directed 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 2, 3 and 4 level, 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 800 mm diameter pipes connected to rectangular steel metal downcomers (vent pipes) that 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 in order of improve steam distribution and the reduction of condensation type oscillations. To avoid boiling of the water in the condensing pools, the condensing tray cooling system (CTCS) provides water to these pools. Heat exchangers of the 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 the 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 the condensing pools (drywell) is 20600 m^3 and behind the condensing pools 28330 m^3 [4]. The water volume in the condensing pools is 2800 m^3 [4].

During a normal operation, several ventilation systems ensure the cooling of the ALS atmosphere to maintain a temperature of 50 °C in the compartments before the condensing pools and 35 °C in the compartments behind the condensing pools. The exhaust ventilation systems maintain a slight underpressure in the compartments to avoid any release of radioactive fission products to the environment. These ventilation systems are equipped with iodine and aerosol filters. In case of a LOCA inside the ALS compartments, all the ventilation fans are stopped and the double hermetic valves on the ventilation lines are closed automatically.

3. HYDROGEN CONCENTRATION CONTROL

The operation of the ventilation and compressed air supply systems is an accident management measure for controlling the hydrogen concentration and preventing hydrogen accumulation as well as the formation of combustible mixtures. As foreseen in the EOP [2], the hydrogen concentration control is performed manually and consists of the following subsystems:

- hydrogen monitoring system,
- exhaust ventilation system to remove hydrogen,
- compressed air supply system for hydrogen dilution and
- the branch of the condenser tray cooling system (CTCS) spraying into BSRC.

Hydrogen concentration monitoring in the ALS compartments of the Ignalina NPP is performed in the following compartments:

- bottom steam reception chambers,
- gas space of each condensing pool,

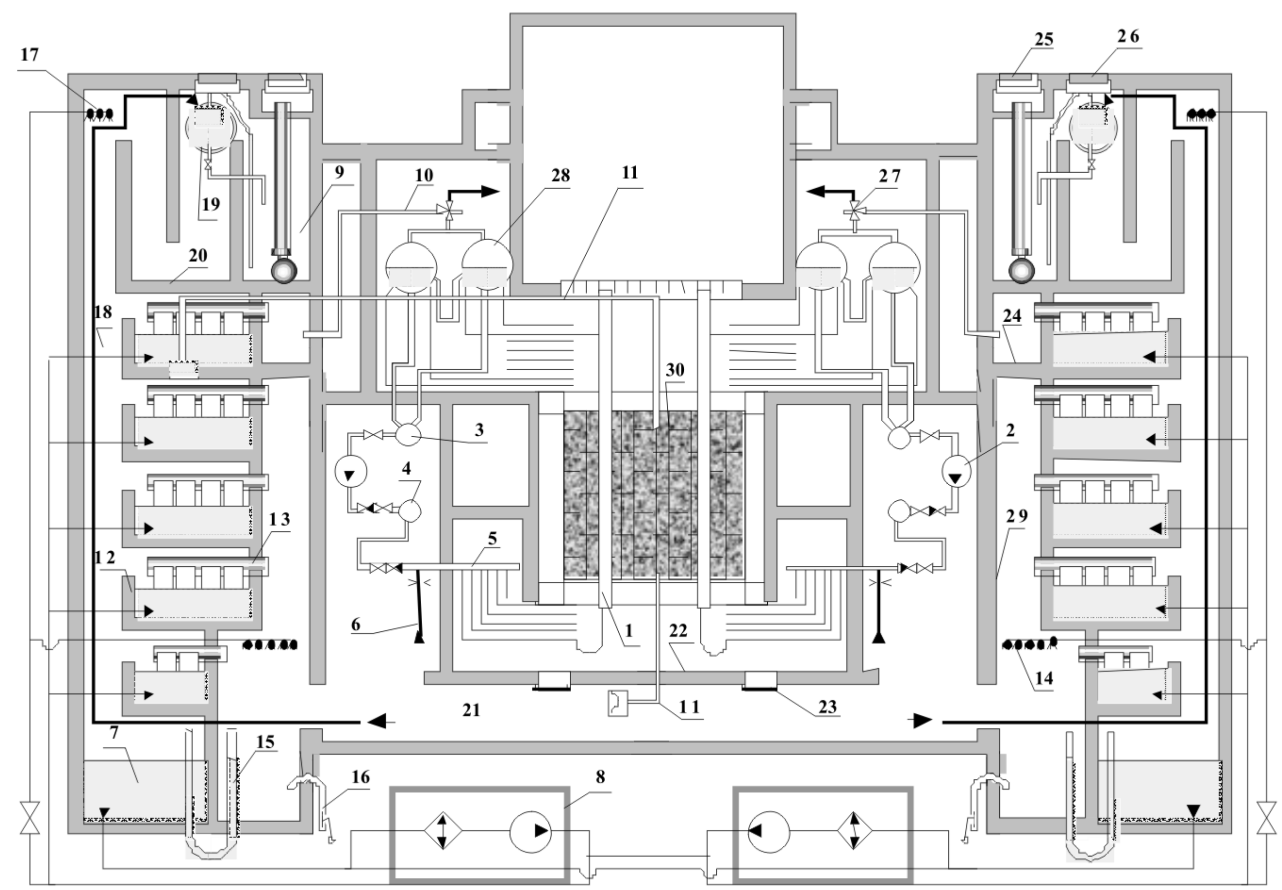

Fig. 1. Principal scheme of the Ignalina NPP Accident Localisation System

- air venting channels and
- gas delay chambers.

If the hydrogen concentration in BSRC reaches a defined set-point, then the operator turns on the fan of the exhaust ventilation system to discharge the steam / gas mixture through the filters to the ventilation stack. At the same time, the sprays that are installed in BSRC are activated to condense the steam. When hydrogen concentration decreases to 0.4%, the ventilation and BSRC sprays are stopped manually. If hydrogen concentration increases in the compartments behind the condensing pools, then the operator starts supplying compressed air to the location with the increased hydrogen concentration and turns on the ventilation to discharge the steam / gas mixture from the gas delay chamber.

Compressed air to the ALS compartments is supplied with a temperature of 15 °C and without prior purification. The air is supplied to the spaces above the water of the condensing pools. To dilute the gas there, the air can be supplied to each condensing pool separately; e. g. if an increased hydrogen concentration is detected in the 1st condensing pool, then the air is supplied only to the space above the water of this pool. The supply rate to each condensing pool is 500 m^3/h, i. e. the maximal possible supply of compressed air to both ALTs is 4000 m^3/h to the pools 1 to 4.

The branch of the CTCS spraying into BSRC is operated manually, too. The total flow rate to BSRC sprays is 250 m^3/h. The spray nozzles are installed close to the 1st condensing pool at an elevation of 9.5 m.

The operation of these systems is considered in the model.

4. ACCIDENT SCENARIO AND INJECTION RATES

Until the current analysis, any quantitative information had been available concerning a severe accident scenario in RBMK type reactors. The reason is the special assembly of the graphite-moderated channel type boiling water reactor. Thus, the phenomena identified for LWR core melt accidents are not just transferred to the RBMK, and the developed analysis tools are not appropriate without some modifications.

The thermal-hydraulic analysis of the reactor cooling system response was performed by employing a full model of RBMK-1500 for RELAP5 and a simplified model for RELAP5 / SCDAP. Simulation of full RCS with the SCDAP code is problematic. Neither was it possible to simulate multiple fuel channels and graphite columns. Therefore, it was decided to use a simplified RELAP5 / SCDAP model where a single equivalent fuel channel is simulated employing SCDAP elements with pressure difference and changing the coolant flow rate in this channel, defined as boundary conditions and extrapolating the results to all 880 FC of the affected RCS loop. These boundary conditions are obtained from calculations using a full model of the RBMK-1500, developed for the RELAP5 code.

Analysis of the guillotine MCP pressure header rupture with the ECCS failure, except hydro-accumulators, was performed until the fuel melting started. The ECCS of the Ignalina NPP could be subdivided into two subsystems: 1) short-term subsystem, which includes the operation of ECCS hydroaccumulators and main feedwater pumps, 2) ECCS pumps and auxiliary feedwater pumps. All of the pumps included in the ECCS operation logics are high-pressure pumps capable to inject into the reactor the cooling circuit operating at a nominal pressure. At present, the RCS depressurisation and injection to RCS with low pressure pumps (usually such procedure is called "bleed and feed") is not foreseen as an accident management measure at the Ignalina NPP.

In the analysis with the RELAP5 code using a full RCS model, it was assumed that both ends of the ruptured pressure header are misaligned so that the coolant is discharged from both unconstrained. During the first second after rupture, the coolant discharges both from the fuel channel side and from the drum separator (DS) side. In the beginning the subcooled water is discharged, therefore the coolant flow rate through the break is maximal and reaches ~37000 kg/s (Fig. 2).

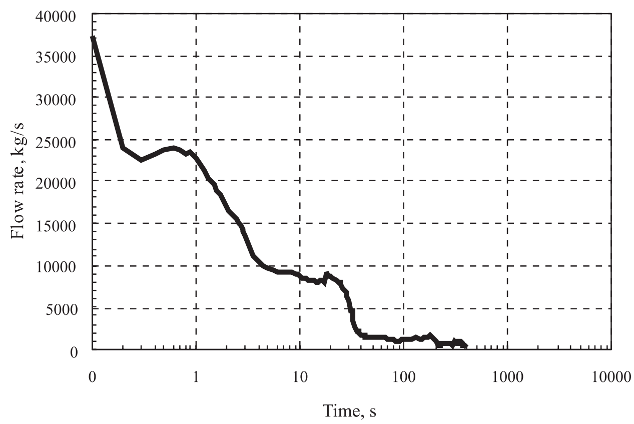

Fig. 2. Coolant mass flow rate and specific enthalpy calculated with RELAP5

Due the rupture of the header, the coolant in the pipelines connecting the MCP pressure header (PH) and the group distribution header (GDH) changes the flow direction and thus causes a fast closing of all check valves in the GDH within 0.1 s. In the beginning of the accident, the pressure in the ruptured header sharply decreases and generates a signal for the ECCS activation on a decrease of pressure difference between the MCP pressure header and the DS. This signal indicates the affected loop of the RCS. The coolant, discharged through the rupture, flows to the ALS reinforced-leak tight compartments. Pressure in these compartments increases and causes the generation of the reactor scram signal.

In the model, it was conservatively assumed that the control rods are inserted only after 1.2 s from the beginning of the accident. The signal of pressure increase in compartments is the second signal for the fast-acting ECCS subsystem activation. According to the ECCS actuation algorithm, water from the hydro-accumulators is supplied only into the GDH of the affected RCS loop. There are two groups with 8 pressurized water tanks. Approximately 175 m^3 of water is injected from these ECCS hydro-accumulators within the first 2 minutes. Later, water supply from the hydro-accumulators is terminated due to water level decrease there. The main feedwater pumps also belong to a fast-acting ECCS subsystem; however, it is assumed that these pumps, as well as the pumps of long-term ECCS subsystem (auxiliary feedwater pumps and ECCS pumps), have failed.

After approximately 50000 s from the beginning of the accident, the fuel and fuel cladding temperatures reach their maximum values and further do not increase. This means that the melting–freezing of the fuel starts.

The temperature increase leads to cladding oxidation after 6000 s from the beginning of the accident. It corresponds to the cladding temperature increase above 900 °C. At the same time, hydrogen generation starts (Fig. 3).

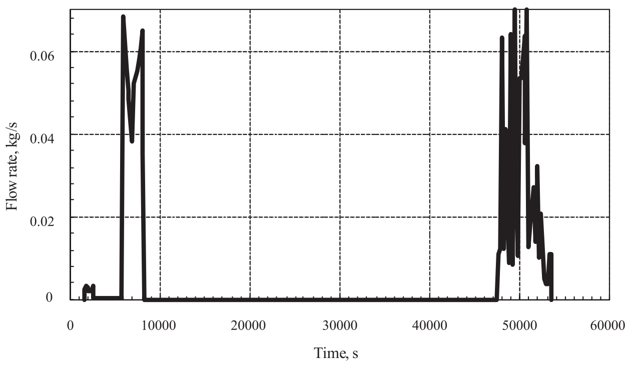

Fig. 3. Hydrogen release rate to the ALS

The hydrogen generation lasts 9000 s because later there is no available steam in the circuit to oxidise zirconium. The second peak of hydrogen generation is related to the beginning of the fuel melting process in the time interval 47000–53000 s.

During the first hydrogen peak 1412 m^3 and during the second hydrogen peak additional 1582 m^3 are released, i. e. the total amount of hydrogen released to the ALS during the analysed accident is 2995 m^3 (~267 kg).

5. INPP CONFINEMENT MODEL FOR THE CODE COCOSYS

COCOSYS is a lumped-parameter code for the comprehensive simulation of all relevant phenomena, processes and plant states during severe accidents in the confinement of light water reactors, also covering the design basis accidents [3].

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 [5], these compartments were modeled in more detail. The refined ALS model allows possible convection loops which can have a significant influence on the H_2 distribution in the long run.

This refined ALS nodalisation was based on the previously developed ALS model for calculating the thermalhydraulic parameters in ALS during a MDBA. A detailed description of the ALS model, which was used as a basis for the current simulation, can be found in [5].

The model of the Ignalina NPP ALS for the COCOSYS code used in the analysis consists of 84 nodes, 210 junctions of different type, including pumps, and 258 structures to consider heat transfer to building 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 and condensing pools of ALS towers is presented in Fig. 4. In the previous model, the current compartments were modelled

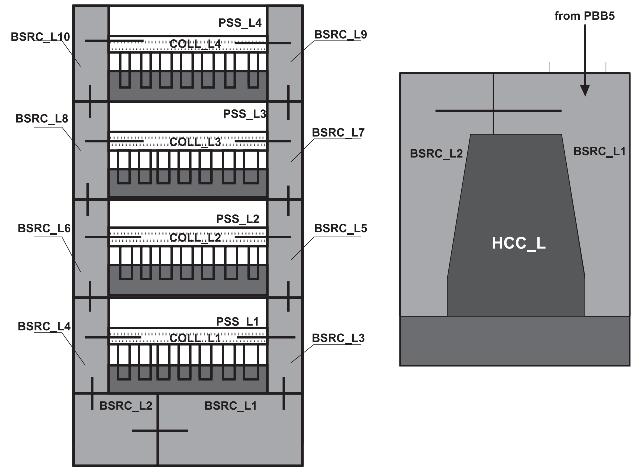

Fig. 4. Nodalisation of the BSRC and condensing pools in the left tower of ALS

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 also according to the location of condensing pools (Fig. 4).

As described in Section 2, there are five condensing pools in each ALS tower. The pressure suppression pool zone DRASYS model of the COCOSYS code [3] was applied to simulate the four lower condensing pools (nodes PSSL1–PSSL4 and PSSR1–PSSR4 for the left and the right ALS towers, respectively). The 5th condensing pool was simulated as a NONEQUILIB zone model of the COCOSYS code [4] node (PSS_L5 and PSS_R5 for the left and the right ALS towers (ALT), respectively) considering the water mass and the volume of the 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 the right ALS towers, respectively). The BSRCs were split into 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).

The detailed nodalisation includes the top steam reception chamber of both ALS towers (see position 24, Fig. 1). The current compartments are modelled as TSRC_L and TSRC_R nodes of the left and the right ALS towers, respectively. The TSRC nodes are connected with the gas delay chamber (see position 20, Fig. 1) by a valve which opens if the pressure in the GDC is 0.015 bar higher than in the TSRC. The top steam reception chambers are connected to the 5th condensing pools of both ALS towers as well. To connect the top steam reception chambers with the 5th condensing pools of both ALS towers, the COLL_L5 and COLL_R5 nodes, which represent steam distribution devices, are included.

In the previous analyses, the hot condensate chamber (HCC) and the air venting channel (AVC) in each ALS tower were combined into 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 the upward direction according to the location of the condensing pools. Additionally, the AVC was split into two parts – one close to the condensing pool and the other close to the outer "cold" wall of the ALS tower. Such subdivision allows the 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 [3] 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 nodes is simulated applying the IVO [3] model of the COCOSYS. The initial diameter of the spray droplet was defined as 1 mm. Spray paths were given representing a droplet falling through 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 the 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 a complex geometry of the Ignalina NPP ALS result in considerable surface areas and mass of the structures. The massive concrete walls may not have a notable effect on a short-term accident analysis, but they play an important role representing a significant energy sink in the long run. A 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 [3] was applied to the walls that separate the condensing pools from the AVC.

6. SIMULATION OF HYDROGEN CONTROL SYSTEM

The operation of the hydrogen control system is controlled by the operator depending on the local concentration. This is realized in the COCOSYS input deck by EXTERNAL EVENTS [3]. At the NPP, the hydrogen concentration is monitored in compartments corresponding to the BSRC_L9 and BSRC_L10 nodes in the left ALS tower, to BSRC_R9 and BSRC_R10 in the right ALS tower and in the gas space above each condensing pool simulated by PSS* nodes. In the input deck, it was assumed that hydrogen concentration in the BSRC of both ALTs is monitored only in the BSRC_L9 and BSRC_R9 nodes. Such assumption allows decreasing the number of external events in the input deck and does has no notable impact on the results because the conditions of the neighbouring nodes BSRC_L10 and BSRC_R10 are similar.

Usually, the operation of the ventilation systems is not considered in LOCA analyses, because they are turned off automatically (confinement isolation). For the current analysis, the operation of the exhaust ventilation system is considered in the ALS model to an extent related to hydrogen concentration control.

The intakes of the ventilation system are located in BSRC on both sides of the condensing pools, i. e. in the BSRC_L9 and BSRC_L10 nodes in the left ALS tower and in BSRC_R9 and BSRC_R10 in the right ALS tower. The ventilation of the BSRC is simulated by the outlet fan systems F-BSRC-L and F-BSRC-R for the left and the right ALS tower, respectively. According to EOP-5 [2], the ventilation system should be activated when the volume concentration of hydrogen in the corresponding tower reaches 0.5% and turned off when it decreases below 0.4%.

The venting of the ALS tower behind the condensing pools is simulated by the outlet fan systems F-GDC-L and F-GDC-R for the left and the right tower, respectively. These ventilation systems are activated, if the volume concentration of hydrogen above any of the condensing pools reaches 1%, and turned off when the concentration above all the pools is less than 0.4%. The intakes of this ventilation system in the gas delay chambers (GDC) are assumed to be located in the GDC1 and GDC2 nodes in the left and the right ALTs, respectively.

Compressed air supply outlets are located above each condensing pool. The inlet fan systems F-PSS* simulate the compressed air injection above the water of the condensing pools. Air supply is assumed from the ENVIRON node which simulates the second environment independent of the ENVIR node. There are no junctions modelled between ALS compartments and ENVIRON. Thus, no gas exchange with ENVIRON, which would influence the calculated gas concentrations, will take place. Activation of each system is controlled individually by the local volume concentration of hydrogen. If the concentration in the gas space above any condensing pool exceeds 0.4%, then the respective fan system is activated to inject air. It should be noted that the switch-off of the compressed air system is not explicitly stated in EOP-5 [2]. Therefore, in order to avoid numerous switchings on and off at 0.4%, it was assumed in the data deck that the system is switched off when the hydrogen concentration decreases below 0.2%.

The CTCS branch connected to BSRC sprays is simulated by the SP_BSRC-L and SP_BSRC-R pump systems for the left and the right ALTs, respectively. The CTCS branch related to BSRC sprays is activated and turned off at the same set points as the exhaust ventilation system taking the steam / gas mixture from the BSRC, i. e. activated when the volume concentration of hydrogen reaches 0.5% and turned off when it decreases below 0.4%.

The full capacity of the compressed air supply system is 4000 m^3/h for both ALS towers. The system supplies compressed air above the water layer of each condensing pool of ALS. If the set point of hydrogen concentration would increase only above one condensing pool, the full capacity of compressed air would be directed above this pool only. In order to ensure the correct system logic, an additional node, NZ1, on the compressed air path was included. The NZ1 node is connected to the gasrooms of all the condensing pools by atmospheric junctions controlled by valves. Compressed air is supplied from the environment to the NZ1 node by an atmospheric junction, and this junction is controlled by a valve as well. If only one gasroom reaches the

H_2 concentration 1%, the flow trough the NZ1 node will be directed to this gasroom, or the flow will be split into several pools, if setpoints are reached in several gasrooms. The additional node, NZ1, should ensure a correct splitting of the compressed air flow.

7. RESULTS

Results of the performed analysis are presented in Figs. 5–15. Figures 5 and 6 present the pressure behaviour in leak-tight compartments, in the nodes before and behind the ALT. Figure 5 presents the pressure behaviour in the leak-tight compartments during a simulated accident. The maximum pressure of 2.75 bar was reached in the break node PBB5, and it corresponds well with the 2.7 bar calculated in the previous COCOSYS analyses [5]. This is not surprising because the mass and energy release during the blowdown phase of the accident is the same. Differences occur only at a later stage when the operation of the pumps included in the ECCS logic should occur. Further on, the modified nodalisation has a minor influence on the maximum pressure. Also, the maximal value of pressure is far below the design pressure of 4 bar for the PBB compartments.

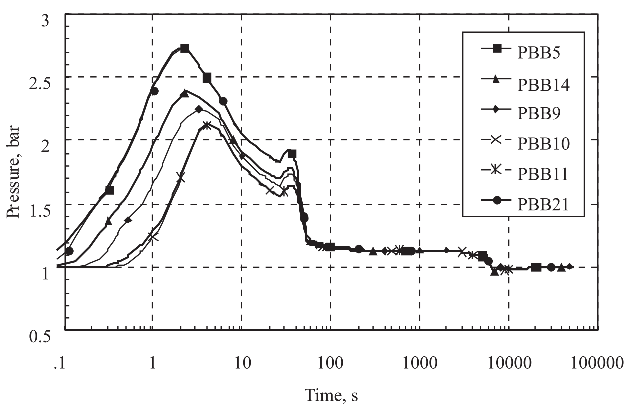

Fig. 5. Pressure in reinforced leaktight compartments

Figure 6 presents the pressure behaviour in ALT compartments before and behind the condensing pools. The results present the pressure behaviour in the compartments of the left ALT because this ALS tower is located closer to the assumed location of the rupture. The maximum pressure in BSRC (nodes BSRC_L1 and BSRC_L9) is 1.49 bar, and this is below the design pressure of ALT (2 bar). The maximum pressure in compartments behind the condensing pools is 1.29 bar, i. e. below the design pressure of ALT as well. The pressure difference between the compartments before and behind the condensing pools until ~8000 s corresponds to a level to which the SDD nozzles are submerged into the water of the condensing pools, i. e. ~1 m. At ~8000 s, the steam injection through the ruptured PH pipe is terminated; the steam condensation in the compartments before the condensing pools starts prevailing, and the pressure there decreases below atmospheric. The pressure difference on the SDD nozzles changes its direction and makes the water to flow from the condensing pools through the SDD to the steam distribution corridors (reverse flow) and then to the BSRC and reinforced leaktight compartments. When the bottom of SDD nozzles is reached, the gases start flowing from the compartments behind the condensing pool to the BSRC; the pressures in these compartments equalise and become equal to atmospheric. It should be noted that the pressure in the compartments behind the condensing pools after the initial blowdown phase decreases close to atmospheric. This is a specific feature of ALS and the "clean air release" approach implemented in ALS. During the initial 300 s, the clean air is released through the opened tip-up hatches, whereas the steam released from the ruptured PH pipe is condensed in the pools, resulting in low pressures in the ALS in a long-term period. Higher pressures could be expected if the condensing pools had been not reliably cooled or a large amount of noncondensible gases was injected. Since the no pressure increase in ALS in the case of the analysed BDBA scenario is observed, it can be concluded that during the analysed period the ALS performs its function, and the design pressure limits are not violated in any part of ALS with a sufficient safety margin.

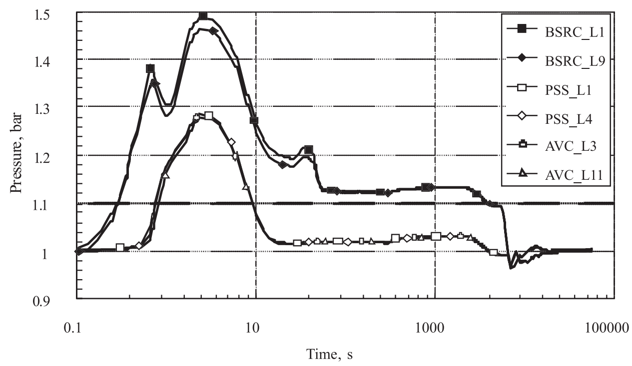

Fig. 6. Pressure in the left ALT compartments

Figures 7 and 8 present the gas temperature behaviour in the PBB and ALT compartments during the postulated accident scenario. As is seen in Fig. 7, the maximum gas temperature of 127 °C is reached in the reinforced leaktight compartments (node PBB5). In the neighbouring compartments, the maximum temperature is in the range of 98 °C to 121 °C and corresponds to saturation conditions. The temperature in node PBB11, which represents the compartment before entrance to the right ALS tower, increases slower and the saturation temperature is not reached. Such temperature difference appears because this compartment is located at a longer distance from the rupture

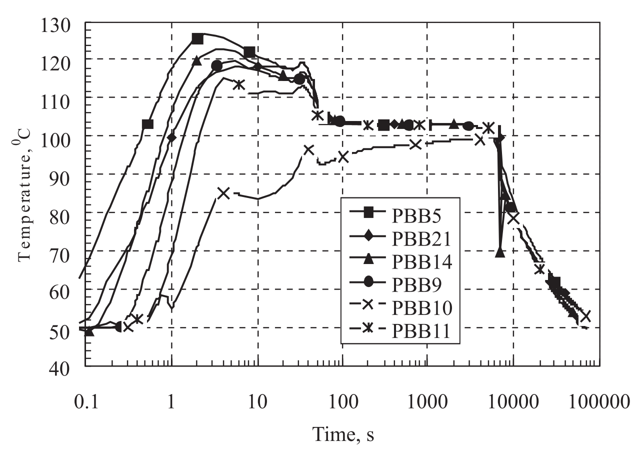

Fig. 7. Gas temperature in reinforced leaktight compartments

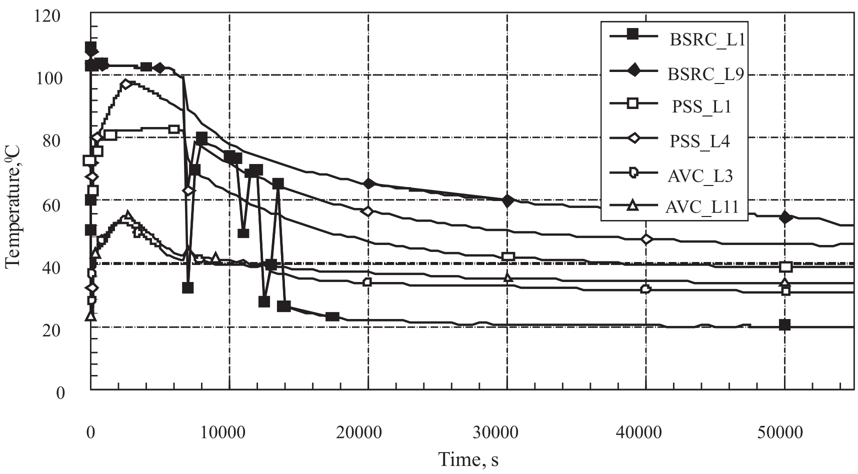

Fig. 8. Gas temperature in the left ALT compartments

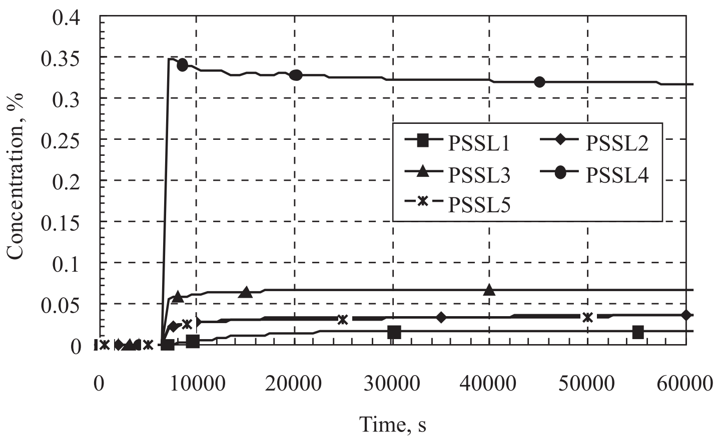

Fig. 9. Hydrogen concentration in PSS nodes of the left ALT

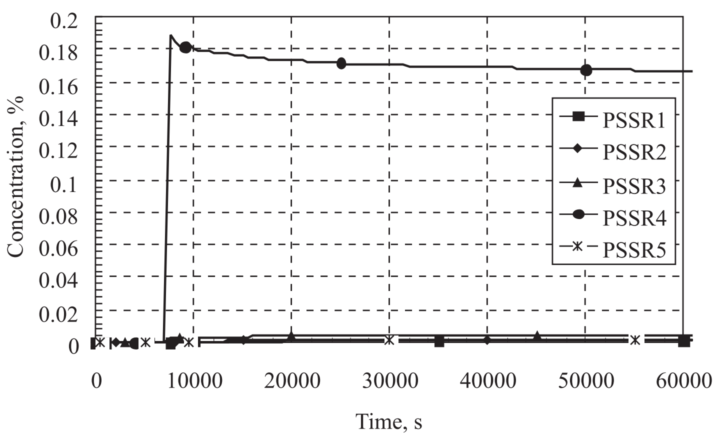

Fig. 10. Hydrogen concentration in PSS nodes of the right ALT

location and more air has to pass through as compared with the left ALS side. When the steam release through the ruptured pipe terminates, steam condensation in the compartments starts prevailing and gas temperatures start decreasing. Almost at the same time (at ~8000 s), i. e. when the water flow from the condensing pools appears, a sharp pressure decrease is observed. But later the gas temperature in the compartments decreases gradually due to steam condensation and heat transfer to the building structures.

Figure 8 presents the gas temperature in the left ALT compartments. The maximum temperature of 109 °C is reached in the BSRC_L1 node in the beginning of the accident, and it corresponds to saturated conditions. The temperature in PSS and AVC nodes is below 100 °C, i. e. saturation conditions are not reached.

The temperature in the gasroom of the condensing pools strongly depends on the heat transfer through the metal of the steam distribution devices, therefore the temperature in this part is high. The gas temperature in the AVC depends on the operation of CTCS sprays which cool the atmosphere. The gas temperature in the AVC in a longer term does not reach 60 °C and later decreases to 30 °C. Figure 8 shows that the temperature in the BSRC-L1 in the period 7000–14000 s sharply decreases several times. Such behaviour is caused by the operation of the

CTCS spray system in this node (Fig. 13). A description of CTCS operation during this period is presented further.

Figures 9 and 10 present hydrogen concentration in the gasrooms of the condensing pools of both ALTs. In the previous analyses [5], the highest hydrogen concentration was reached exactly in these compartments: when the steam gas mixture is injected into the condensing pools, the steam is condensed, and hydrogen enters the gasroom of the pool, leading to a high hydrogen concentration above the condensing pools. In the present case, there is no steam release to ALS after about 6500 s and only a small flow of hydrogen takes place; therefore, there are just small gas flows between ALS compartments, and only a small amount of hydrogen reaches the condensing pools.

Thus, the maximum concentrations in case of the accident scenario under analysis are reached in the upper condensing pools (PSSL4 and PSSR4) of both ALTs with 0.35% and 0.19%, respectively. The maximal H_2 concentration in other condensing pools does not exceed 0.1% in the left and 0.02% in the right ALT. As the maximal H_2 concentration in the compartments behind the condensing pools does not exceed 0.4%, neither the compressed air supply system nor exhaust ventilation for gas removal from the GDC were activated, in contrast to the results of the previous pilot calculation [5] when the highest concentrations were calculated for the gasrooms of the condensing pools. This time, in the pilot calculation a long-lasting mass and energy release from a PH break (DBA scenario) was combined with a hydrogen release for a BDBA due to the absence of a reliable information on a severe accident scenario. This long-lasting steam release forced the hydrogen transport through the condensing pools.

Figures 11 and 12 present hydrogen concentration in the BSRC nodes of both ALTs during the considered BDBA scenario. The maximal concentration is reached in the upper part of the BSRC compartments (BSRC_L9, BSRC_L10) for the left ALS tower and BSRC_R9, BSRC_R10 for the right ALS tower at about

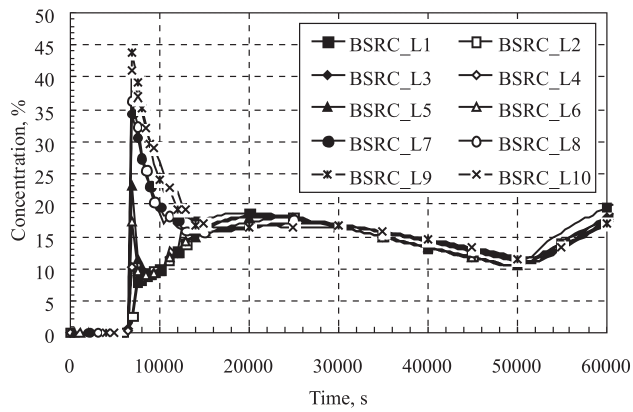

Fig. 11. Hydrogen concentration in BSRC nodes of the left ALT

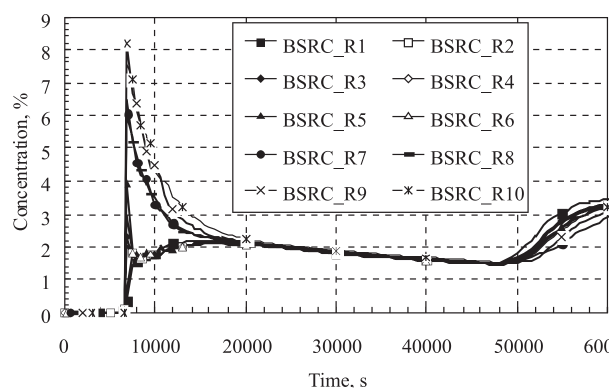

Fig. 12. Hydrogen concentration in BSRC nodes of the right ALT

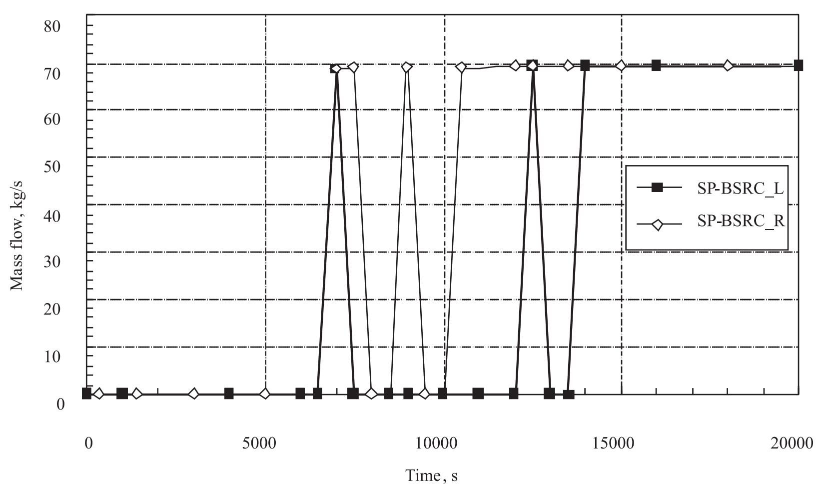

Fig. 13. Mass flow of spray systems in BSRC zones

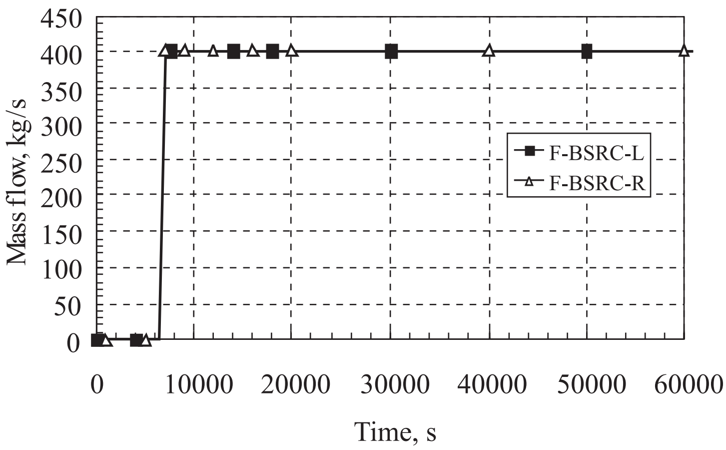

Fig. 14. Mass flow through the exhaust ventilation system

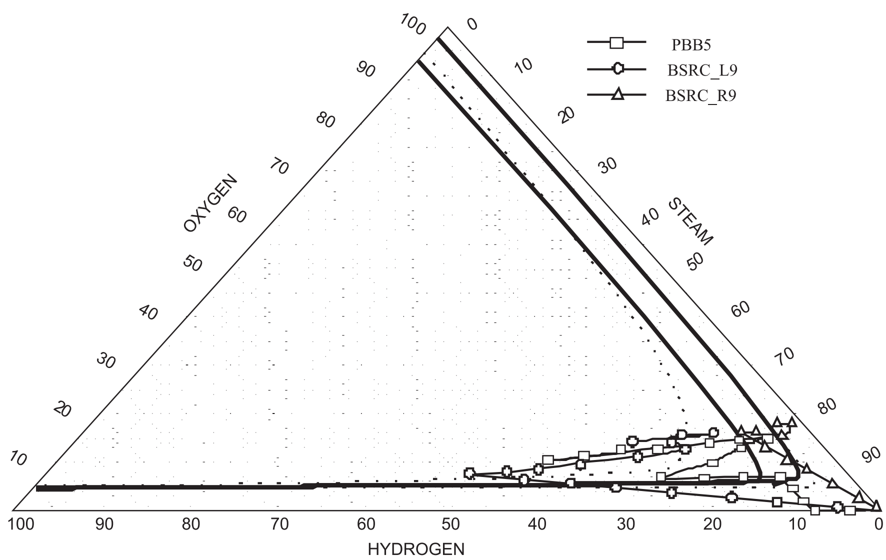

Fig. 15. Assessment of hydrogen deflagration and detonation (hydrogen, oxygen and steam, %)

7000 s when CTCS sprays had started and a reverse water flow from condensing pools occurred, associated with a strong steam condensation.

In the left ALT, the maximal H_2 concentration is 43.7%, while in the right ALS tower the maximal H_2 concentration is only 8.2%. Hydrogen in the lower BSRC nodes is less. Such distribution is caused not only by the different density of gases (H_2, air, steam) but also by the operation of the exhaust ventilation system, which takes gases from the top part of the steam distribution corridors (nodes BSRC_L9, BSRC_L10 and BSRC_R9, BSRC_R10).

After the first peak, hydrogen concentration in all BSRC nodes decreases to ~20%, and in this period in the uppermost nodes H_2 concentration becomes even lower than in the other nodes. The decrease of hydrogen concentration in ALS compartments is very slow. In the period between 20000–50000 s, hydrogen concentration decreases from 20% to 10%. Then, the second H_2 injection appears, and within 60000 s H_2 concentration increases again to 20%.

Figures 13 and 14 present mass flows through CTCS sprays located in BSRC and in the exhaust ventilation in BSRC, respectively. The CTCS sprays are activated together with the exhaust ventilation when hydrogen concentration in the BSRC increases by more than 0.4%. After 6500 s from the beginning of the accident, the concentration in the BSRC of both ALTs increases by more than 0.4% (see Figs. 11 and 12), and the spray systems start operating and supplying cold water to and condensing the steam in the BSRC.

During the accident sequence, there are some periods when the CTCS stops operating. The reason is the low water level in the HCC, which is the source for CTCS. When the water level in the HCC is restored, the CTCS is activated again, but the HCC makeup is less than the capacity of CTCS and the refilling of the condensing pools is not finished, i. e. there is no water backflow from the pools to HCC and the water level there decreases, causing a repeated stop of the CTCS. It should be noted that in such case the operator could switch over the CTCS to take water from the BSRC, but this possibility is not considered in the current ALS model. From the presented results it follows that the activation of CTCS sprays initiates a faster steam condensation in the reinforced compartments and causes the reverse water flow from the condensing pools to the BSRC. The operators of the NPP should be aware of the possibility of such phenomenon in the case of accident.

Figure 14 presents the mass flow through exhaust ventilation in BSRC of both ALTs. The exhaust ventilation is activated depending on the increase of hydrogen concentration in BSRC to more than 0.4%. After 6500 s, the exhaust ventilation starts operating at full capacity – 400 kg/s. As is seen in Fig. 14, the ventilation operates through all the accident time because hydrogen concentration in the BSRC of both ALTs does not decrease below 0.4%.

Figure 15 presents an assessment of the possibility of H_2 deflagration or detonation to occur in the ALS compartments where hydrogen concentration was maximal. In the ternary diagram one can see that in the PBB5 and BSRC_L9 nodes the gas mixture enters the detonation region, i. e. the gas mixture on the left side of ALS is detonable. The gas mixture on the right side of ALS (see node BSRC_R9) does not enter the detonation region, but H_2 burning is possible.

The above results allow concluding that the current system of hydrogen concentration decrease in the ALS of the Ignalina NPP is not capable to maintain hydrogen concentrations below the deflagration limits in case of a BDBA. The application of electric fans in the ventilation systems could be dangerous because they could produce sparks which could initiate the deflagration or detonation of hydrogen. This in turn could lead to a failure of the air ducts of the ventilation systems. As discussed before, the pressure in the ALS compartments during this stage is close to atmospheric. Therefore, considering that the ALS of the Ignalina NPP consists of many interconnected compartments of different geometry, it is difficult to assess the pressure loads on ALS structures in case hydrogen burning occurs.

The high concentration of hydrogen in ALS compartments is caused by the selected accident scenario with multiple failures leading to a long-term loss of reactor cooling and high temperatures in the reactor core. This would lead to the steam–zirconium reaction and an intensive hydrogen generation. Therefore, prevention of high temperatures in the reactor core and the appearance of the steam–zirconium reaction are very important for the power plants with RBMK reactors.

8. CONCLUSIONS

For the current analysis, a COCOSYS input deck with a detailed nodalisation, consisting of 84 nodes, 210 junctions including pump and fan systems and 258 structures, was set up. This input model allows the simulation of convective flows in special regions of the accident localisation system, the calculation of different steam loading of separate condensing pools and of the local accumulation of hydrogen in compartments.

The design pressures were not reached for any ALS compartment during the whole accident sequence. The CTCS performed its functions to maintain the temperature of the condensing pools below saturation.

During the simulated accident period, the bulk of hydrogen is concentrated in the compartments before the condensing pools, and just a small amount of hydrogen enters the compartments behind the condensing pools.

The current system of hydrogen concentration decrease in the ALS of the Ignalina NPP is not capable to maintain hydrogen concentrations below the deflagration limits in case of a BDBA. The application of electric fans in the ventilation systems could be dangerous: they could produce sparks which could initiate the deflagration or detonation of hydrogen. This in turn could lead to a failure of the air ducts of the ventilation systems.

Considering that the ALS of the Ignalina NPP consists of many interconnected compartments of different geometry, it is difficult to assess the pressure loads on ALS structures should hydrogen burning occur.

The prevention of high temperatures in the reactor core and appearance of the steam–zirconium reaction are very important for the power plants with RBMK reactors in order to avoid hydrogen accumulation in the compartments and violation of ALS integrity.

Nomenclature

ALS	Accident localisation system
ALTs	ALS towers
AVC	Air-venting channel
BDBA	Beyond-design-basis accident
BSRC	Bottom steam reception chamber
CTCS	Condenser tray cooling system
ECCS	Emergency core cooling system
EOP	Emergency operating procedure
GDC	Gas delay chamber
HCC	Hot condensate chamber
INPP	The Ignalina nuclear power plant
LOCA	Loss of coolant accident
LWR	Light water reactor
MCC	Main coolant circuit
MCP	Main circulation pump
MDBA	Maximum-design-basis accident
MER	Mass and energy release rate
NPP	Nuclear power plant
PH	Pressure header
RBMK	Russian acronym for "Large Power Channel Reactor"
SDD	Steam discharge device

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VANDENILIO PASISKIRSTYMO IGNALINOS AE APSAUGINIAME KIAUTE ANALIZĖ NEPROJEKTINĖS AVARIJOS METU

Santrauka

Ignalinos AE avarijų lokalizavimo sistema (ALS) – tai „slėgio mažinimas“, kurio paskirtis – apsaugoti gyventojus, darbuotojus bei aplinką nuo spinduliuotės pavojaus.

Ignalinos AE saugos analizės ataskaita rodo, kad maksimalios projektinės avarijos metu į ALS patalpas patenka ~110 m^3 vandenilio. Tačiau įvykus neprojektinei avarijai, dėl kurios prasideda cirkonio oksidacija, susidaro kur kas daugiau vandenilio. Jeigu tūrinė vandenilio koncentracija patalpoje pasiekia 4 %, vandenilis gali užsidegti.

Siekiant užkirsti kelią vandenilio kaupimuisi, Ignalinos AE avarijų lokalizavimo sistemos patalpose yra įrengta vandenilio koncentracijos kontrolės ir mažinimo sistema.

Atlikus analizę buvo nustatytos vandenilio kaupimosi vietos avarijų lokalizavimo sistemos patalpose neprojektinės avarijos metu. Toks vandenilio pasiskirstymas Ignalinos AE avarijų lokalizavimo sistemos patalpose neprojektinės avarijos metu atliktas pirmą kartą.

Raktažodžiai: avarijų lokalizavimo sistema, vandenilis, avarija, kurios metu prarandamas šilumnešis

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АНАЛИЗ РАСПРЕДЕЛЕНИЯ ВОДОРОДА В ЗАЩИТНОЙ ОБОЛОЧКЕ ИГНАЛИНСКОЙ АЭС ВО ВРЕМЯ ЗАПРОЕКТНОЙ АВАРИИ

Резюме

Система локализации аварий (СЛА) Игналинской АЭС – это контайнмент 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^3 водорода выбрасывается в помещения СЛА при максимальной проектной аварии. Но в случае запроектной аварии, когда начинается оксидация циркония, создается намного больше водорода.

Если объемная концентрация водорода в помещении достигает 4 %, то возникает опасность образования горючей смеси.

Для предотвращения накопления водорода в помещениях системы локализации аварии на Игналинской АЭС установлена система контроля и снижения концентрации водорода.

Аналитическим путем были установлены места в помещениях СЛА, где в случае запроектной аварии может накапливаться водород. Такой анализ накопления водорода в помещениях системы локализации аварий Игналинской АЭС выполнен впервые.

Ключевые слова: система локализации аварий, водород, авария с потерей теплоносителя