SIMULATION OF CONTAINMENT HYDROGEN CONTROL
SYSTEM AT IGNALINA NPP

Egidijus Babilas, Egidijus Urbonavicius, Sigitas Rimkevicius
Laboratory of Nuclear Installation Safety, Lithuanian Energy Institute

1. INTRODUCTION

Various risk studies have shown that the containment failure due to H\textsubscript{2} combustion without using a sufficient H\textsubscript{2} mitigation system could be a major cause for large off-site release in case of an accident [1]. Even through Ignalina NPP with RBMK-1500 reactor formally does not have full-scope containment, the ALS performs a function of containment. ALS is a “pressure suppression” type confinement, which protects the population, employees and environment from the radiation hazards. Therefore it is necessary to investigate H\textsubscript{2} distribution and capability of hydrogen control system to maintain the acceptable H\textsubscript{2} concentration in the ALS compartments during the transient processes.

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

A detailed nodalisation is required in order to consider a formation of the convection loops and other local effects.

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

The present paper presents the analysis of H\textsubscript{2} distribution and H\textsubscript{2} control system operation in the INPP ALS compartments in case of the maximum design basis accident (MDBA). The design data on H\textsubscript{2} release was taken from the safety justification of the Ignalina NPP design [3] and considered for the presented analysis.

The nodalisation of Ignalina NPP ALS considering the operation of the H\textsubscript{2} control system was developed for COCOSYS code [4]. The current nodalisation allows simulating the local H\textsubscript{2} distribution and assessing the efficiency of the H\textsubscript{2} control system. The operation of the related safety systems is considered as well.

2. NOMENCLATURE

ALS Accident Localisation System
ALTs ALS towers
3. **“CONTAINMENT” OF IGNALINA NPP**

A characteristic feature of the major light water reactors is the containment, 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, Ignalina NPP does not have 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 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 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 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 of 50 mm diameter in each overflow barrier of 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 better steam distribution and 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 CTCS are cooled with service water. The characteristic feature of ALS is that in the initial phase of the accident a 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 Ignalina NPP can be found in [5].

The volume of compartments in front of condensing pools (drywell) is 20600 m³, behind the condensing pools – 28330 m³ [5]. The water volume in the condensing pools – 2800 m³ [5].

During normal operation several ventilation systems provide 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 under pressure 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.

4. HYDROGEN CONCENTRATION CONTROL IN ALS

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 Ignalina NPP is performed in the following compartments:
Technical section

- bottom steam reception chambers,
- gas space of each condensing pool,
- 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 the hydrogen concentration decreases to 0.4 % the ventilation and BSRC sprays are stopped manually. If the hydrogen concentration increases in the compartments behind the condensing pools, then the operator

![Fig. 1 Principal scheme of the Ignalina NPP Accident Localisation System](image)

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

Dysnai - 2005
starts to supply 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. The capacity of the exhaust ventilation system 2WZ56 is from:

- reinforced leak tight compartments – 19000 m³/h,
- BSRC of each ALS tower – 400 m³/h,
- group distribution header compartments – 4500 m³/h,
- each ALS tower – 7500 m³/h.

The 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 m³/h, i.e. the maximal possible supply of compressed air to both ALTs is 4000 m³/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 m³/h. The spray nozzles are installed close to the 1st condensing pool at the elevation of 9.5 m.

The operation of these systems is considered in the model.

5. ACCIDENT SCENARIO AND INJECTION RATES

Until the current analysis any quantitative information was 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 simply transferable to RBMK and also the developed analysis tools are not appropriate without some modifications.

Therefore, at the moment for the analysis of the hydrogen distribution in the Ignalina NPP ALS the maximum design basis accident - rupture of a MCP pressure header - was selected. The analysis of MCC behaviour in case of a PH rupture was performed employing the code RELAP5 [3]. The boundary conditions of this analysis were defined as ALS conservative (all safety systems operate as designed) resulting in the largest coolant release to the ALS and, thus, leading to higher loads. This mass and energy release (MER) was already applied for the analysis of the ALS thermal
hydraulic behaviour with RALOC and COCOSYS [6]. Taking the same scenario it will be possible to evaluate the influence of H₂ on the thermal hydraulic results.

A H₂ release rate is available from the report for the justification of the Symptom Based Emergency Operating Procedures [2]. In the report it is given that in case of a PH rupture (with different boundary conditions compared to [3] - i.e. with an additional failure of one check valve in the reactor cooling circuit) the hydrogen release rate can be described by the \( G = 0.29/t \) where “t” is the time from the beginning of the accident. Further on is stated that due to the steam-zirconium reaction the hydrogen production is relatively high for 10 hours and later the H₂ release is terminated. During this period \( \approx 110 \text{ m}^3 \) of hydrogen is released to the ALS. The report [2] provides also a rough conservative estimate on possible hydrogen concentrations in the ALS compartments and possible loadings if a combustible mixture appears.

The break of the MCP pressure header, i.e. the release of the coolant together with hydrogen was assumed to occur in the left loop of the reactor cooling circuit. The MER is given in Fig. 2 and the considered H₂ release rate is shown in Fig. 3.

![Fig. 2 Coolant mass flow rate and specific enthalpy calculated with RELAP5](image)

6. INPP ALS 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 containment of light water reactors, also covering the design basis accidents [4].

Considering that the most probable hydrogen accumulation places are the top compartments of the ALS towers, i.e. before and behind of steam condensing pools [2], these compartments were modelled in more detail. The refined ALS model allows possible convection loops, which can have a significant influence for the H₂ distribution in long term.

This refined ALS nodalisation was based on previously developed ALS model for calculation of the thermalhydraulic parameters in ALS during MDBA. Detailed
description of the ALS model, which was used as a basis for the current simulation, can be found in [7].

The model of 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 the heat transfer to building structures. The model includes all the accident-affected ALS compartments, 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.

![Fig. 3 Hydrogen release rate to the ALS](image)

The refined model of the bottom steam reception chamber and condensing pools of ALS towers are presented in the Fig. 4. 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. 4).

![Fig. 4 Nodalisation of the BSRC and condensing pools in the left tower of ALS](image)

Dysnai - 2005
As described in Section 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 [4] was applied to simulate the four lower condensing pools (nodes PSSL1 - PSSL4 and PSSR1 - PSSR4 for left and right ALS towers respectively). The 5th condensing pool was simulated as a NONEQUILIB zone model of COCOSYS code [4] node (PSSL5 and PSSR5 for 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 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 left and 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. AVC is split in upward direction according to the location of the condensing pools. Additionally the AVC was split into two parts – one is close to the condensing pool and the other is 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 [4] zone model.

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 closes, when the overpressure in the compartments rises to 0.02 bar, what happens in case of PH break immediately at the begin of the accident.

The sprays are a 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 sprays droplets and nodes atmosphere is simulated applying the IVO [4] 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.

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 complex geometry of the Ignalina NPP ALS causes considerable surface areas and mass of structures. The massive concrete walls may not have the large influence on the short-term accident analysis, but they
Technical section

play an important role representing significant energy sink in the long-term. 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 COCOSYS code [4] was applied for the walls, which separate condensing pools from AVC.

7. SIMULATION OF THE HYDROGEN CONTROL SYSTEM

The operation of the hydrogen control system is controlled by the operator depending on the local concentration measured. This is realized in the COCOSYS input deck by "EXTERNAL EVENTS" [4]. At the NPP the hydrogen concentration is monitored in compartments corresponding to nodes BSRC-L9 and BSRC-L10 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 the hydrogen concentration in the BSRC of both ALTs is monitored only in nodes BSRC-L9 and BSRC-R9. Such assumption allows decreasing the number of external events in the input deck and does not have a large impact on the results because the conditions of the neighboured nodes BSRC-L10 and BSRC-R10 are similar.

Usually, the operation of 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 with hydrogen concentration control.

The intakes of the ventilation system are located in BSRC on both sides of the condensing pools, i.e. in the nodes BSRC-L9 and BSRC-L10 in the left ALS tower, and 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 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 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 nodes GDC1 and GDC2 in the left and 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. The air supply is assumed from the node ENVIRON, which simulates a second environment independent from the node ENVIR. There are no junctions modelled between ALS compartments and ENVIRON. This way, 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 a numerous switching 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 pump systems SP_BSRC-L and SP_BSRC-R for the left and 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 steam/gas mixture from BSRC, i.e. activated when the volume concentration of hydrogen reaches 0.5 % and turned off when it decreases below 0.4 %.

RESULTS

A detailed thermal hydraulic analysis of an anticipated MCP pressure header break in the Ignalina NPP ALS was already performed and presented in [6]. The main results of the analysis are presented in Fig. 5 – Fig. 8. Some results are compared with the results received from the calculation of the MDBA without operation of the hydrogen control system (base case).

Due to the hydrogen concentration increase in the left ALT exceeding 0.4 % already after 305 s the corresponding supply of compressed air and after 770 s (when exceeding 1 %) the exhaust ventilation system should be operated. Fig. 5 represents the mass flow histories of the hydrogen control system (except the CTCS spray branches) and so, gives an outline on operator actions to be done in accordance to the emergency operating procedures [2]. As it can be seen from the figure, already 5 minutes after start of the accident the operator has to switch on different systems for controlling the hydrogen.

The calculation results with regard to the volume concentration of hydrogen in PSS nodes are shown in Fig. 6. As it can be seen from figure, thanks to the operation of the hydrogen control system the maximum concentration in the node PSSL4 was reduced from 6.2 % in the base case [8] to 1.2 % in the current analysis. The very short lasting maximum in the highest BSRC nodes of the left ALT, i.e. BSRC-L9 and BSRC-L10, was reduced from 5.2 % in the base case to 4.6 % in the current calculations. It is impossible to judge about the flammability knowing only the hydrogen concentration, because gas mixtures with high hydrogen concentration might be inerted by steam.
Corresponding information on the explosion is included in the ternary diagrams, given in Fig. 7. In the base case [8] the atmosphere above the 4th condensing pool of the left ALT reaches flammability conditions after about 10000 s. In the same case the uppermost BSRC compartments approach to flammability conditions for a very short period during the reverse flow of water [8]. As shown in the Fig. 7, in the analysed case flammability conditions are suppressed thanks to the operation of the hydrogen control system.
Beside the hydrogen concentration the operation of the hydrogen control system strongly influences thermal hydraulic parameters. At the water supply by operation of the sprays in the BSRC increase the steam condensation rate. Due to increased steam condensation in the BSRC reached the underpressure conditions. Such pressure behaviour in BSRC leads to the reverse water flow from the condensing pools into BSRC.

In Fig. 8 pressure histories of current case (case 2) are compared with results of the base case [8]. Due to the operation of the hydrogen control system, the pressure in the compartment system changes significantly. So, a (partial) reverse flow from the condensation pools occurs earlier and more often than in the base case [8] - after 7 000, 11 000, 21 000, 23 000 and 25 000 s instead of only after 26 400 s [8]. During and/or after reverse flow processes, vacuum breakers open a path from the compartments outside the confinement to the bottom steam reception chambers. Nevertheless, strong pressure drops cannot be avoided this way. After 40 000 s process time, in both cases the general pressure level approaches to normal pressure conditions, i.e. 100 kPa.
CONCLUSIONS

For the current analysis a COCOSYS input deck with a detailed nodalisation, consisting of 109 nodes, 302 junctions including 25 pump systems, 12 fan systems and 341 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 the single condensing pools and of the local accumulation of hydrogen in compartments.

The effectiveness of the hydrogen control system was investigated in the present case, where the system was operated manually (i.e. by operator actions) according to the emergency operation procedures. Comparing the results with those of the base case [8], it appears that the operation of exhaust ventilation and compressed air supply systems leads to a more homogeneous distribution of the hydrogen in ALS and partly removal from the ALS. Thus, the highest hydrogen concentration in the gasroom of the 4th condensing pool and in the highest BSRC nodes in the left accident localisation tower was reduced to 1.2 % and 4.6 % respectively.

An assessment of the explosion of this atmosphere composition can be given with ternary diagrams. Different to the base case [8] the formation of flammable hydrogen mixtures can be suppressed by the hydrogen control system. Comparing base case [8] and present case results, it is visible, that the operation of the hydrogen control system significantly influences the atmosphere conditions and the ALS response at all.

In the analysis hydrogen concentration threshold values were reached already 5 min after accident initiation. According to the emergency operation procedures several operator actions are required to activate/deactivate the exhaust ventilation, the compressed air supply and the CTCS spray systems and or to keep the HCC water level in designed limits in the long term. The realisation of the sequence of actions
supposed seams to be questionable taking into account the stress situation of the staff during an accident. This gives manifold possibilities for variant calculations to investigate the consequences of the corresponding operator actions (delayed action, actions not performed, wrong actions which caused strong sub-atmospheric pressure or a pressure difference between both ALT, …).

REFERENCES