International Conference
Nuclear Energy for New Europe 2006
Portorož, Slovenia, September 18-21, 2006
http://www.djs.si/port2006

Ignalina NPP Confinement Response in Case of Large LOCA and Failure of Water Injection to RCS

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ABSTRACT

The question of the RBMK power plants response to Beyond Design Basis Accidents (BDBA) and especially to Severe Accidents is very important. Until now very little attention was paid to it and much speculation remains after the Chernobyl accident.

This paper aims to present the current knowledge regarding the response of Ignalina NPP confinement (it is titled as Accident Localisation System (ALS) to severe accident. A large Loss-of-Coolant Accident with failure of pumped water injection to Reactor Cooling System was selected for the analysis. The analysis was performed using a detailed nodalisation developed for COCOSYS code.

The analysis showed that many uncertainties remain in the BDBA phenomena analysis for the RBMK reactors and the work should be continued investigating other accident scenarios, e.g. station blackout, multiple rupture of fuel channels, etc.

1 INTRODUCTION

At present a lot of scientific efforts around the world are concentrated on the analysis of the key phenomena during severe accident in nuclear reactor and containment; nevertheless still many questions remain unsolved. The Network of Excellence SARNET was created in the frames of FP6 program in order to integrate research performed in European organisations in solving the remaining safety issues. The severe accident research for channel type reactors CANDU and RBMK is not so well developed and very little information is available in the open literature.

Even though many safety improvements were implemented at NPPs with RBMK reactors many speculations, that are caused by the most severe accident in the world, i.e. Chernobyl accident, arise about severe accidents in such power plants. In order to have scientific arguments the analysis has to be performed considering the current status of knowledge about the NPP with RBMK-1500 reactor.

This paper presents the analysis of the large LOCA scenario with loss of coolant injection to the core. This is the first paper, which presents the analysis of fission product (FP) transport in the confinement of Ignalina NPP. The analysis is performed until the fuel melting started (53500 s). It should be noted that this paper does not aim to answer all the questions regarding severe accidents in RBMK but rather to identify the key phenomena, expected timing of the key events and assess the possibility of hydrogen deflagration in the confinement and assess the effectiveness of FP retention in confinement. Considering that this is the first analysis the results should not be considered as final. The confinement analysis will be continued in the frames of the ongoing Phare project.

2 APPROACH TO CONFINEMENT ANALYSIS

RBMK is a boiling light water reactor with nominal power of 4800 MW_{th} (1500 MW_{el}). After the Chernobyl accident the maximal allowed power is set to 4200 MW_{th} i.e. Ignalina NPP is operating at the power below its nominal. The moderator in RBMK reactor is graphite. The specific features of RBMK-1500 reactor related to severe accidents and it's comparison with the vessel-type Light Water Reactors are presented in [1].

The Accident Localisation System (ALS) is a pressure suppression type confinement. Since the Reactor Cooling System (RCS) consists of two symmetric circuits, the ALS is also divided into two almost identical parts. The condensing pools at Ignalina NPP are located in two similar in design ALS towers. These towers are adjacent to the system of reinforced leaktigh compartments. The Main Circulation Pumps (MCP) with it's suction and pressure headers, the group distribution headers, other piping and major RCS components are located in the reinforced leaktight compartments of ALS.The total volume of ALS is ~48000 m^3 from which ~20000 m^3 is the drywell and ~28000 m^3 is the wetwell. Description of the ALS and its comparison with the containments/confinements of other NPPs is presented in [2]. The specific feature of ALS is that in case of an accident the clean air, which fills the wetwell during normal operation, is released to the environment and then the ALS is isolated. In the wetwell there is a Gas Delay Chamber (GDC), which consists of several sections sometimes called "labyrinth" to provide a long flow path for fission products. Condensing Tray Cooling System (CTCS) simultaneously supplies water to the condensing pools and sprays located in wetwell. As well the operator can connect another branch of this system by opening the valve and supply water to sprays located in the drywell.

H_2 concentration in ALS is monitored in ALS towers before and behind the condensing pools. If H_2 concentration in BSRC increases to 0.5% then the exhaust ventilation system is activated to remove the gases and the drywell sprays are activated to condense the steam and prevent it entering the ventilation system and clogging the iodine and aerosol filters. If H_2 concentration above the condensing pools increases to 0.4% then the compressed air system injects air to the place of increased H_2 concentration. This is done to sweep H_2 from there to the large volume of the air venting channel, where it can be mixed avoiding large concentrations. If the H_2 concentration above condensing pool increases to 1%, then the exhaust ventilation is activated to remove the gases from the Gas Delay Chamber.

The analysis of the processes in the ALS was performed employing the recently issued COCOSYS code version 2.3v7 developed at GRS mbH (Germany). COCOSYS (Containment Code System) 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.

The developed ALS nodalisation consists of 87 nodes, 246 junctions to simulate the water and gas flows between nodes and 268 structures (heat slabs) to simulate the heat exchange between nodes (see Figure 1). It includes all the ALS compartments, considers operation of the related systems, e.g. CTCS, ALS drainage, clean air release, etc. Each condensing pool is simulated separately providing possibility of taking into account the elevation effect on the gas flows. Special model of the condensing pool, which is available in COCOSYS and was tested in simulation of the real transient at Ignalina NPP [3], was used in the performed analysis. The ALS towers were internally subdivided to simulate the convective flows inside the compartments. These flows are important to calculate the local hydrogen and fission product concentrations.

The initial water level in the condensing pools is assumed to be minimal according to normal operation procedures. Initial pressure in ALS is atmospheric, gas temperature in the drywell – 50 °C, wetwell – 35 °C. Relative humidity in all the ALS assumed 90%. The service water temperature used for cooling of CTCS heat exchangers is 18 ^{o}C. All six CTCS pumps and eight heat exchangers are in operation to provide cooled water for the condensing pools and sprays located in the wetwell and drywell. The last section of the Gas Delay Chamber is filled with water in 300 s after the accident start, thus, closing the relief path to the environment and isolating the ALS.

The MCP pressure header rupture is assumed to occur in zone PBB5 (see Figure 1), i.e. on the left RCS loop.

The core inventory of isotopes of the Ingnalina-2 NPP was calculated and provided by GRS mbH in the frames of bilateral cooperation project. For the analysis it was assumed that the reactor is fully loaded with nuclear fuel of 2.6% enrichment. The special core inventory library is used in the FIPISO module to consider the decay of up to 1296 fission product and their energy release into the ALS.

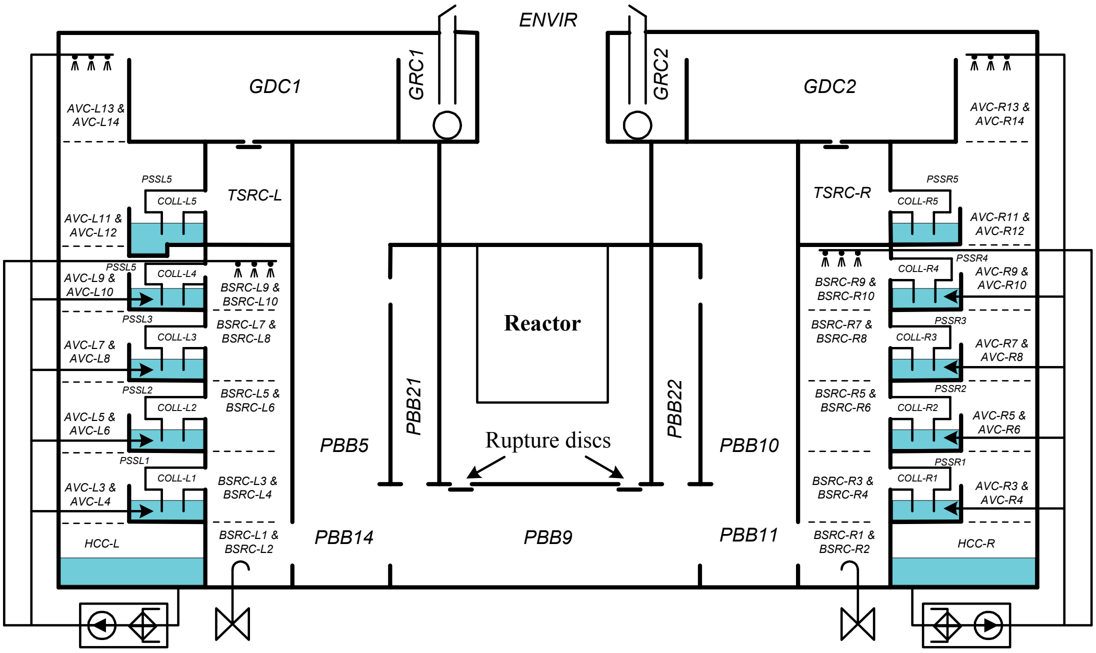


Figure 1**:** ALS nodalisation scheme for COCOSYS code

The coolant and hydrogen release rates to ALS were obtained from the performed RELAP5/SCDAPSIM analysis and are presented in Figure 2. After the rupture occurs the coolant is released from RCS to confinement and in the initial phase coolant mass flow reaches ~27000 kg/s, but in 10 s this flow decreases to 9000 kg/s, in 200 s – 1000 kg/s. During this period the ECCS hydroaccumulators are exhausted and because all the pumps fail to start the coolant injection terminates and mass flow through the break decreases as well. It is assumed that after 6500 s the coolant release through the break terminates and is not restored until the end of calculations. When the fuel cladding temperature increases to 700 ^{o}C H_2 generation starts, but remains slow. When fuel cladding temperature increases above 900 ^{o}C a significant H_2 generation due to steam-Zr reaction starts. After 33500 s the H_2 generation decreases almost to zero. By the end of calculations there is 3751 m^3 of H_2 released to ALS.

Fission Product and aerosol release rates are defined based on the requirements of U.S. NRC document [4] and on the performed RELAP5/SCDAPSIM analysis. It is assumed that the reactor is loaded with nuclear fuel UO2 of 2.6% enrichment. The average burnup of the fuel in the reactor is assumed 10 MWd/kg.

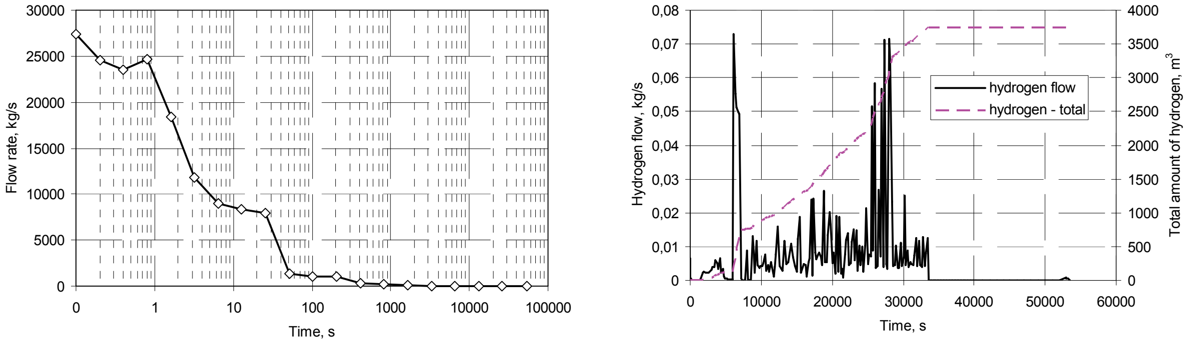


Figure 2**:** Coolant and hydrogen release rates

3 DISCUSSION OF RESULTS

The results of the performed confinement analysis are presented in Figure 3 - Figure 11. Figure 3 presents the pressure behaviour in the drywell and wetwell during the analysed period. The maximum pressure of 2.75 bar was reached in the break node PBB5 and is far below the design pressure of 4 bar for the PPB compartments. The maximum pressure in BSRC is 1.49 bar and this is below the design pressure of ALS tower of 2 bar. The maximum pressure in compartments behind the condensing pools is 1.29 bar this is below the design pressure of ALS tower of 1.8 bar as well. The pressure difference between the compartments before and behind the condensing pools until ~5000 s corresponds to a level to which the nozzles of Steam Distribution Devices (SDD) are submerged to the water of the condensing pools, i.e. ~1 m. Due to continued release the H_2 concentration in drywell (PBB and BSRC nodes) increases to 0.5% (H_2 concentration will be discussed further) and at 4800 s the exhaust ventilation and sprays in BSRC are activated to remove H_2 from there. The operation of sprays causes the condensation of steam in drywell, which leads to pressure decrease there. Due to steam condensation the pressure difference on the SDD nozzles changes its direction what causes 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 lower ends of SDD nozzles are reached the gases start flowing from the wetwell to BSRC and the pressures in these compartments equalises and further gradually decreases to atmospheric. It should be noted that the pressure in the wetwell compartments after the initial blowdown phase decreases close to atmospheric. This is a specifics of ALS and “clean air release” approach implemented in ALS. During initial 300 s the clean air is released through the opened tip-up hatches whereas the steam released from the ruptured MCP pressure header is condensed in the condensing pools. This causes low pressures in ALS in the long-term period. In the analysed case the pressure increase in long-term is not observed therefore it can be concluded that during the analysed period the design pressure limits are not violated in any part of ALS with sufficient safety margin.

Figure 4 presents the water temperature behaviour in condensing pools and Hot Condensate Chambers (HCC) of both ALS towers. Only the upper pools of the left and right ALS towers reach the boiling temperature during the period 1500 – 3500 s. The higher temperatures are observed in the left ALS tower because this tower is located closer to the rupture location. The higher loading of the upper condensing pool appears when the steam flow in the compartments before the condensing pool and the pressure difference across the SDD is small. In this case the heat becomes a dominating effect, i.e. the hot steam flows up in the steam distribution corridors and condenses in the upper condensing pool. This causes less steam inflow to lower pools, where the temperature starts decreasing, and more steam injection to the 4th condensing pool, where the temperature increase continues. The cooling water supplied by CTCS is distributed among four condensing pools equally. When the steam release through the ruptured pipe terminates then the CTCS capacity is enough to cool all the condensing pools and the water temperature starts decreasing until it reaches the temperature of the service water (18 °C). In the analysis it is assumed that CTCS continues operation until the end of the calculation.

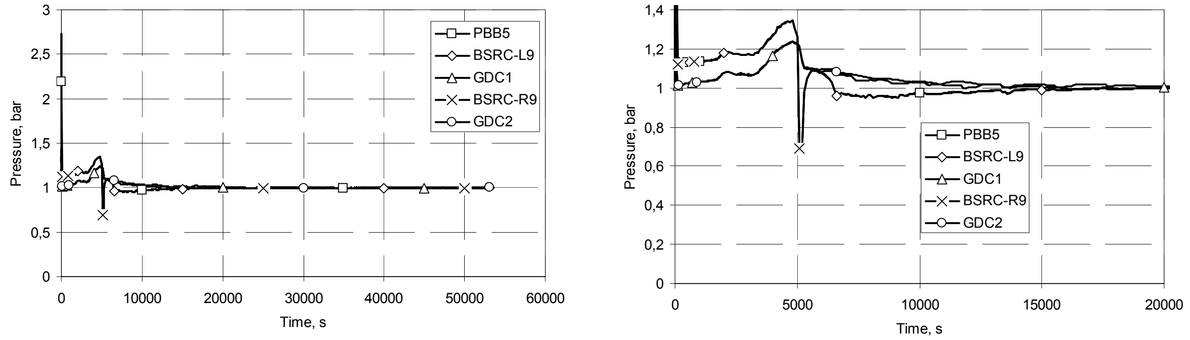


Figure 3: Pressure in the ALS compartments

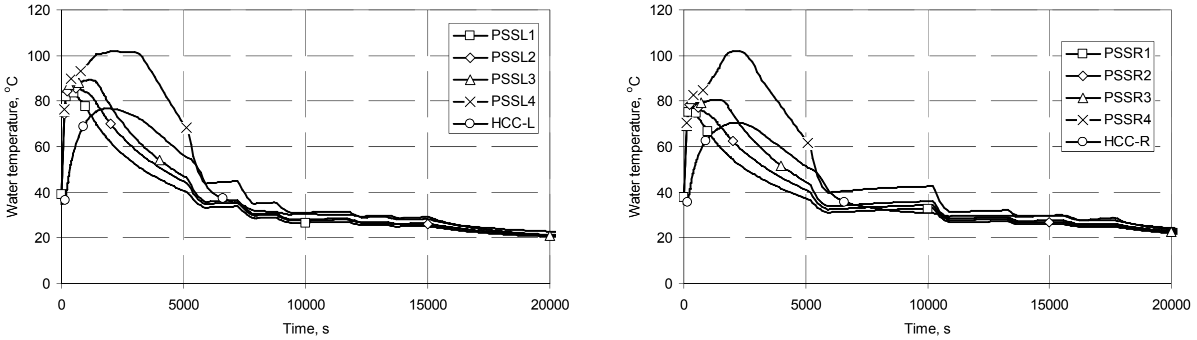


Figure 4: Water temperature in the condensing pools

Figure 5 presents the water level in condensing pools and Hot Condensate Chamber (HCC) of the left ALS tower. Before the reverse water flow from the condensing pools to BSRC appears the water level in the pools is determined by the CTCS operation and location (i.e. elevation) of the overflow gaps. The water level in this period is ~1.2 m. The water level in HCC increases due to overflow of the condensed steam from the pools and reaches ~2.9 m. At ~5000 s the water level in the pools start sharply decreasing due to reverse water flow from the pools to the upstream located BSRC. This causes the emptying of HCC because the water flow from the pools (and the pools feeding by the CTCS from the HCC) is higher than the make up rate to the HCC. When the water level in the condensing pools reaches the lower ends of the SDD nozzles, gas flow starts equalising the pressures before and behind the condensing pools. The water flow from condensing pools to the BSRC stops. After that the restoration of the water level in the condensing pools and in HCC starts. This restoration takes some time but after 15000 s the water level in the condensing pools becomes nominal and stable.

Figure 6 presents H_2 concentrations in the ALS compartments. Figure 6a presents the reinforced leaktight compartments. Significant H_2 release to ALS compartments starts at 1540 s and the H_2 concentration in the reinforced leaktight compartments slowly increases as the release is small. H_2 concentration in these compartments is limited by the presence of steam, which at this moment fills the drywell. When the drywell sprays activate and the reverse flow from the condensing pools appears the steam is condensed and H_2 concentration sharply increases to ~17%. Later H_2 concentration increases due to increased H_2 generation rate in the core (see Figure 2) and in node PBB5 it reaches 53%. Most of H_2 is concentrated in the left ALS side (see nodes PBB5, PBB14, PBB21) and in the corridor PBB9. On the right side of ALS the H_2 concentration is less due to its larger distance from the release location (higher flow losses). The maximal H_2 concentration in the right side of ALS reaches 12%. These results show that there is nearly no mixing between the compartments of the left and right ALS side, isolated by the in-between located zones PBB14, PBB9 and PBB11.

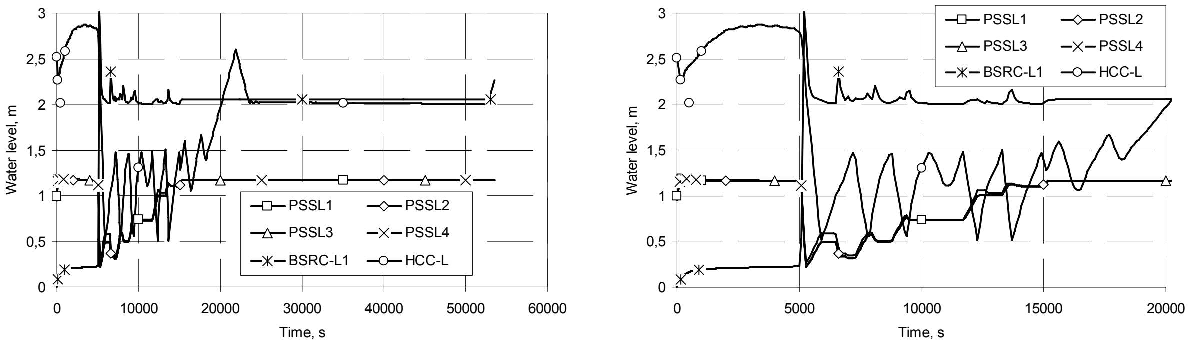


Figure 5: Water level in the condensing pools and BSRC

At ~5000 s the CTCS sprays had start and reverse water flow from condensing pools occurred and caused a strong steam condensation, which consequently caused H_2 concentration increase in PBB zones and short-term peaks in BSRC zones. After 35000 s the H_2 generation rate becomes very small and concentration in PBB zones starts decreasing while in BSRC zones it is still increasing. This is caused by the operation of the exhaust ventilation system, which takes gases from the top part of BSRC (BSRC-L9 and BSRC-R9 for the left and right ALS towers respectively). In the BSRC compartments of the left ALS tower the maximal concentration of 38% is reached at ~50000 s (Figure 6b), while in the right ALS tower the maximal H_2 concentration is only 8.5% at ~40000 s. The concentration difference between top BSRC-L9 and bottom BSRC-L1 parts of BSRC is not large, just 2% and it shows that there is no stratification in these compartments. At the end of the performed analysis the H_2 concentration in the drywell of the left ALS tower is still rather high ~30%.

The (Figure 6c and Figure 6d) presents H_2 concentration in the gasrooms of the condensing pools of both ALS towers. In the analysed case after about 6500 s there is no steam release and only small flow of hydrogen to ALS, therefore there are just small gas flows between ALS compartments and only a small amount of H_2 reaches the condensing pools. In the condensing pools of the left ALS tower H_2 concentrations are rather uniform and close to 0,35%. The maximal H_2 concentration above the condensing pools reaches 0.4% after ~2000 s and the compressed air supply system was activated. The activation of the system helps to reduce the H_2 concentration to 0.35% i.e. to a level when compressed air injection assumed to terminate. Thus, there is no danger for hydrogen deflagration or detonation in the wetwell of ALS. It is not presented here but H_2 concentrations in the rest volume of wetwell (AVC and GDC nodes) do not exceed 1%, i.e. there is no danger for H_2 deflagration or detonation.

Ternary diagram in Figure 7 presents the assessment of the possibility for H_2 deflagration or detonation to occur in the ALS compartments where the H_2 concentration was maximal. It could be seen that in 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 detonation region, but H_2

deflagration is possible. Therefore it could be concluded that the current system for H_2 concentration control in ALS of Ignalina NPP in a case of BDBA is not capable to maintain the H_2 concentrations below the deflagration limits in the drywell compartments.

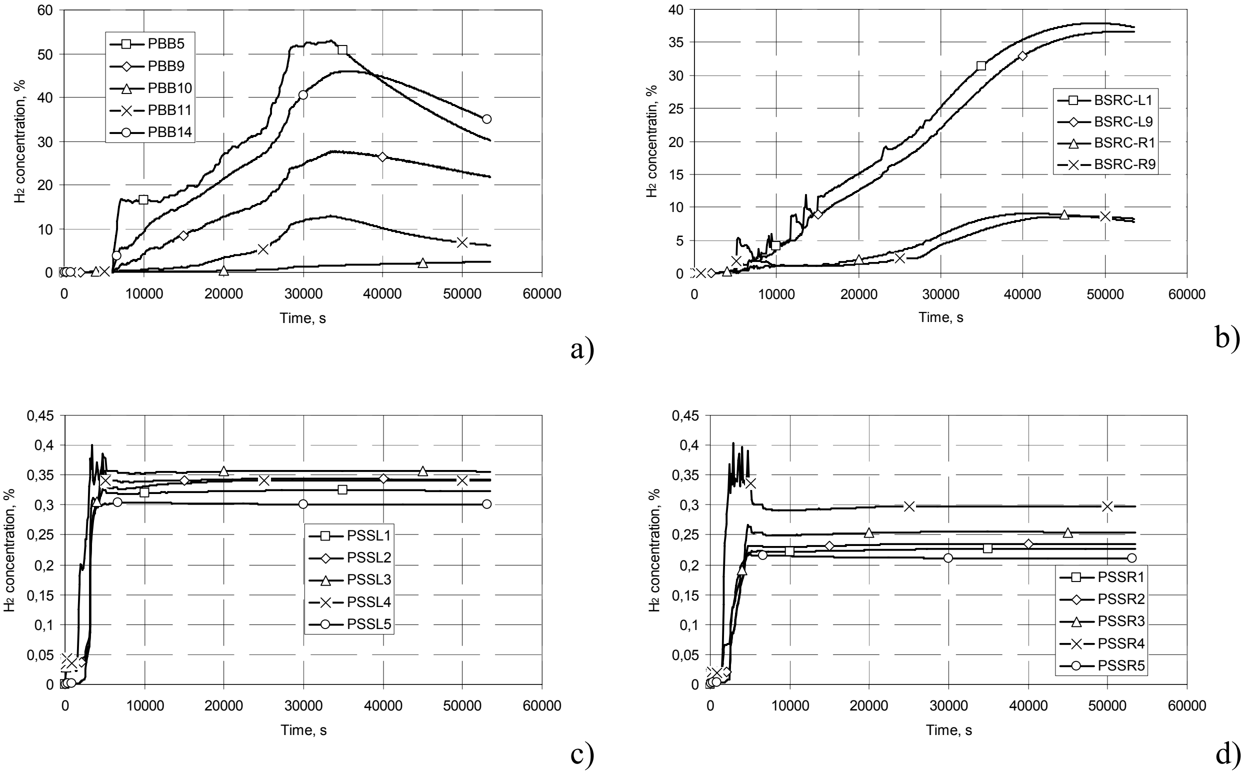


Figure 6: Hydrogen concentrations in compartments

a) Reinforced Leaktight Compartments;
b) Bottom Steam Reception Chambers;
c) and d) gasrooms of condensing pools in left and right ALS towers respectively

Figure 8 presents the distribution of Cs-137 isotope, which was selected as representative of all particulate FP, in the ALS compartments. As it was expected from the calculated aerosol concentration most of FP are deposited in the accident compartment (zone PBB5) and just a little part is transported to neighbouring compartments. Very little amount of caesium is transported to wetwell, i.e. to compartments behind the condensing pools. The mass, which reaches gaseous space of bottom condensing pool of the left ALS tower is at least 8 orders of magnitude lower compared to accident compartment. Even less particulate FP reach the other zones of the wetwell.

For the analysis of transport of gaseous FP it was decided to select isotope Xe-135. Gaseous FP does not deposit on the structures therefore there could be expected different FP distribution in compartments compared to aerosols. Figure 9 presents distribution of Xe-135 in the ALS compartments. Nevertheless, it can be seen that most of gaseous FP are located in the accident compartment (zone PBB5) and 6 times less mass is transported to neighbouring compartment PBB14. The mass, which reaches gaseous space of bottom condensing pool of the left ALS tower is at least 7 orders of magnitude lower compared to accident compartment. The received results indicate that the reason for such small transport of FP is little pressure difference between the compartments, which causes little mass flows.

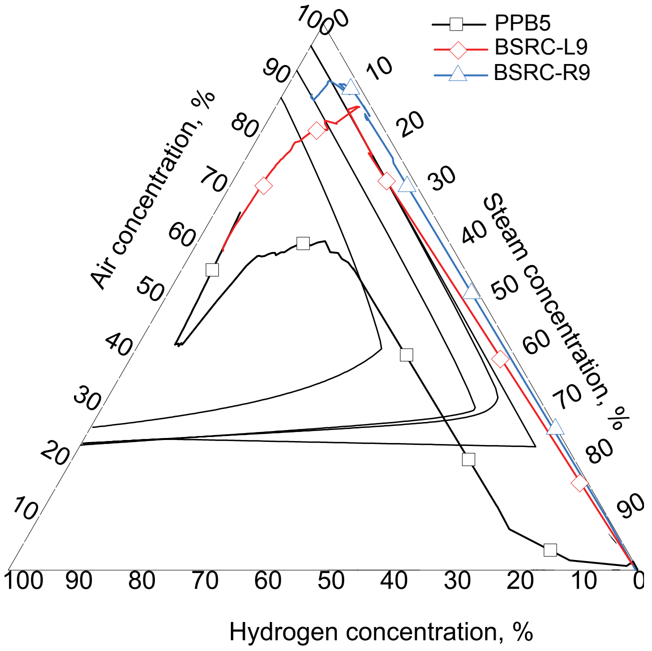


Figure 7: Assessment of possibility for hydrogen deflagration and detonation

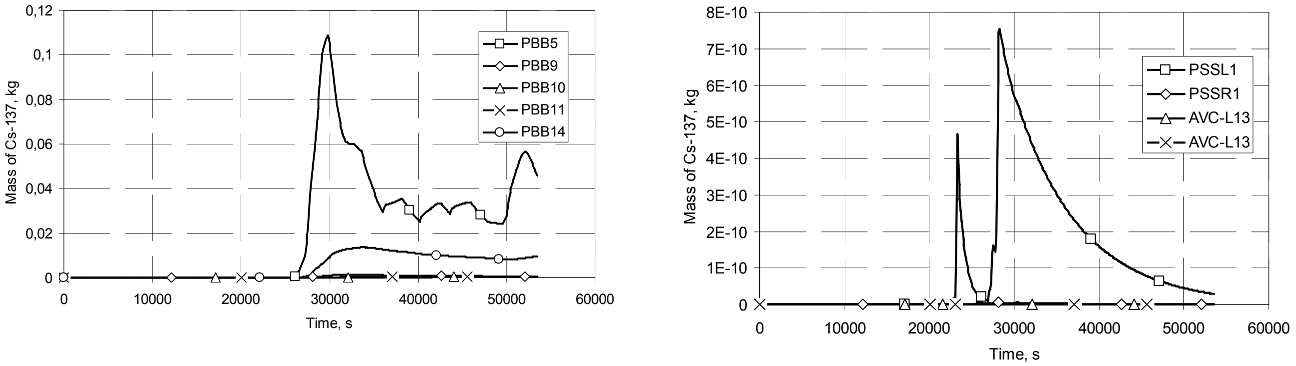


Figure 8: Distribution of Cs-137 in drywell and wetwell

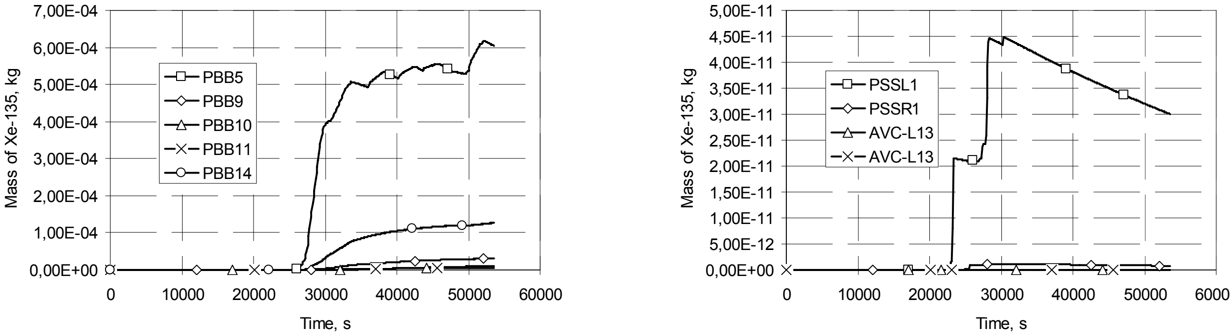
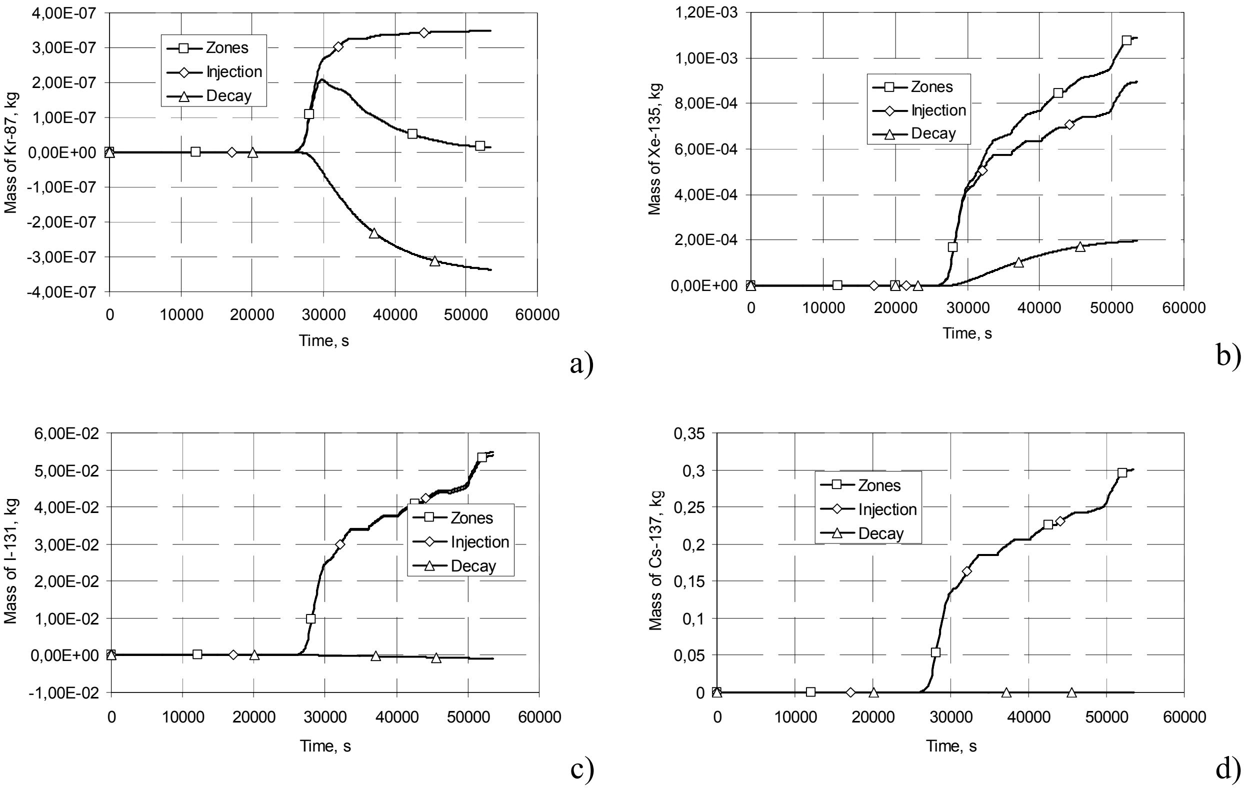


Figure 9: Distribution of Xe-135 in drywell and wetwell

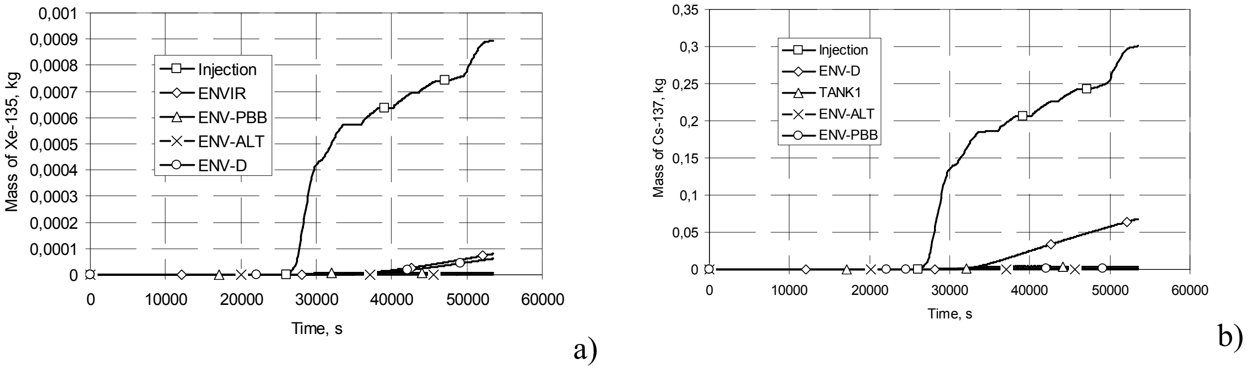
Figure 10 presents the mass balance of several isotopes considered in the analysis (Kr-87, Xe-135, I-131 and Cs-137). The negative decay shows that due to decay processes the mass of the isotope decreases. Analysing the figure Figure 10a it is evident that Kr-87 decays quickly. Figure 10b presents the other gaseous isotope Xe-135. This isotope shows completely different behaviour, i.e. due to decay it's mass increases. Figure 10c presents the isotope of iodine I-131. This isotope has a half-life of 8 days therefore it's decay is very small and the amount available in the zones is close to the released amount. The isotope Cs-137 has a half-life of 30 years therefore the mass injected to the ALS compartments is equal to the mass available in the zones (Figure 10d). The decay heat from the radioactive fission products is released to the zones atmosphere and water sumps or into the structures according to their calculated mass and isotope distribution. The analysis of the mass balance shows that the balance of the isotopes was maintained during the performed analysis.

The most important question for the analysis of FP transport in the confinement is how much FP is released from the confinement. Figure 11a presents the distribution of the Xe-135, which represents the gaseous FP. As it can be seen most of the Xe-135 is released through drainage and this result at first seems to be surprising as the gaseous FP are not transported by water. This result can be explained considering that significant amount of Xe-135 appears due to decay of it's parent isotope I-135, which has a half-life of 6.57 hours. The other path for the release of gaseous FP is the exhaust ventilation, which operates to remove H_2 from the ALS (see curve ENVIR). It should be noted that the exhaust ventilation system 2WZ56 is equipped with the filters for retention of the aerosols and iodine, but they were not considered in the current analysis. From the presented figure it follows that the release of noble gases through the existing structural leakages of ALS is very small. Only ~1.4% of noble gases are released through the leakages of the reinforced leaktight compartments and nothing is released to the environment through the structural leaks of ALS towers.



a) b) c) d)

Figure 10: Mass balance of isotopes: a) Kr-87; b) Xe-135; c) I-131; d) Cs-137



a) b)

Figure 11: Release paths from ALS

CONCLUSIONS

The performed analysis shows that the confinement of Ignalina NPP in the case of the analysed scenario (large LOCA with failure of ECCS except hydroaccumulators) performs its functions of fission products confinement effectively.

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

During the simulated accident period most of the 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 for hydrogen concentration decrease in ALS of Ignalina NPP in a case of BDBA is not capable to maintain the hydrogen concentrations below the deflagration limits in the drywell compartments.

ACKNOWLEDGMENTS

The work was performed in co-operation between GRS mbH and the LEI within the BMU-Project INT 9161 and in the frames of project financed by the Lithuanian State Science and Studies Foundation.

The author gratefully acknowledges the contribution of the experts S. Arndt and H. Wolff from GRS mbH for providing the FIPISO library with Ignalina-2 core isotope inventory and valuable comments regarding development of first input deck to simulate the aerosol and fission products transport in the confinement of Ignalina NPP.

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