Journal of Energy

VOLUME 66 | 2017

journal homepage: http://journalofenergy.com/

JOSIP ĐAKOVIĆ*

josip.djakovic@fer.hr

DAVOR GRGIĆ*

davor.grgic@fer.hr

*** University of Zagreb Faculty of Electrical Engineering and Computing**

ANALYSIS OF SPENT FUEL POOL LOSS OF COOLANT INVENTORY ACCIDENT PROGRESSION

SUMMARY

The Spent Fuel Pool (SFP) in a nuclear power plant is a robust structure designed to withstand large seismic loads. After the terrorist attacks on September 11 and the accident in the Fukushima nuclear power plant, special attention was focused on safety assessments and taking measures to mitigate possible accidents related to the spent fuel pool. This paper will provide an insight into spent fuel pool loss of coolant phenomenology and consequence mitigation strategies. Model of NPP Krško SFP was presented in MELCOR code which has been used as a case-study for evaluating accident propagation. The calculations were carried out using the latest version of MELCOR code which was updated for the analysis of severe accidents in nuclear spent fuel pools.

Key words: Spent Fuel Pool; Loss of Coolant accident; fuel heatup, cladding oxidation, decay heat, NPP Krško

1. INTRODUCTION

Spent Fuel Pool (SFP) is a storage space in nuclear power plant where fuel elements are temporarily discharged (during fuel exchange) or permanently after the fuel reaches a certain burnup. The fuel is placed in metal racks which hold it in the vertical position in the pool. The purpose of the racks is to support fuel weight and ensure the subcritical conditions with adequate cooling. It is possible that the SFP in certain circumstances (disturbances or accidents) remains without an external cooling system, which is acceptable for a shorter period of time. If a cooling and water makeup has not been established for a long period of time (from a few days to a week), fuel uncovery can lead to zirconium rod oxidation, and in severe accidents ignition of fuel elements, radioactivity release and hydrogen explosion [1]. A sudden loss of water from the pool can be cause by a fracture of the pool walls due to a major earthquake or other catastrophic event. The probability of radiological release from the SFP due to severe seismic accidents is estimated at one in 10 million years (for some power plants). Despite the very low chance of such an event, experience has shown that weather disasters can lead to the severe accidents that can affect both nuclear reactor and spent fuel pool (Fukushima). The aim of this paper is to evaluate the response of a NPP Krško SFP to a loss-of-coolant inventory accident (LOCA). The paper is divided into three main sections. The first section explains phenomenology associated with different types of spent fuel pool failures, i.e. the rate of coolant leakage. In addition, measures for accidents mitigation and their effectiveness on a certain type of failure are listed. The second section describes the NPP Krško SFP model in the MELCOR code. The last section provides the results and discussion of accidental parameters for the different sizes and locations of the SFP cracks.

2. LOSS OF COOLANT INVENTORY ACCIDENTS

From the perspective of natural circulation and phenomenology, SFP loss of coolant accidents are divided into two categories:

1) Complete loss of coolant inventory accident;
2) Partial loss of coolant inventory accident.

In a complete-loss-of-pool-coolant scenario, most of the oxidation of zirconium cladding occurs in an air environment:

$$Zr + O_2 \rightarrow ZrO_2 \qquad (1)$$

For a partial-loss-of-pool-coolant scenario (or slow drainage in a complete-loss-of-pool-coolant scenario), the initial oxidation of zirconium cladding will occur in a steam environment:

$$Zr + 2H_2O_{steam} \rightarrow ZrO_2 + 2H_2 \quad (2)$$

Both reactions are highly exothermic, although Zirconium oxidation in the steam produces less heat energy per mole of Zircaloy than in the air, since part of the energy is spent on water dissociation to hydrogen and oxygen. The zirconium-steam reaction leads to the formation of hydrogen, which can undergo rapid deflagration in the pool building, resulting in overpressures and structural damage. This damage can provide a pathway for air ingress to the pool, which can promote further zirconium oxidation and allow radioactive materials to be released into the environment. Debris from the damaged building can fall into the pool and block coolant passages.

2.1 Mitigation Strategies for Spent Fuel Pool LOCA

Loss of coolant accident has been analyzed through numerous tests, using data from operable PWR and BWR power plants. The recent study [2] analysed a wide spectrum of accidental scenarios and phenomenological uncertainties for determining the most important factors affecting the progression of accidents and fuel coolability. Based on the analyses carried out, activities that could influence the consequences of an accident are identified: adding makeup water, optimal pool configuration, dispersed fuel loading patterns, spray nozzles, building ventilation. At least two mitigation strategies are available to mitigate a loss-of-coolant event in a spent fuel pool: Repair the leak that is causing water to be lost and/or add makeup water. In the absence of leak repair, the location, size of the leak, magnitude of decay heat in the pool, and rate and timing of makeup water addition determines the effectiveness of the mitigation strategy. In the case where a spent fuel pool drains completely, adding makeup water will cover the lower portions of the fuel assemblies and block air convection. This could lead to rapid heat-up of the fuel and production of hydrogen as a result of zirconium-steam reaction, loss of coolable geometry in the assembly, and eventually self-sustaining oxidation of zirconium. The flow of makeup water must be high enough to cover a certain portion of the active fuel height before these conditions occur. Spraying water on top of the fuel assemblies may also be an effective strategy to provide additional cooling if makeup water capabilities are inadequate to maintain pool water levels above the tops of the fuel racks. Spraying the fuel can be an effective strategy for maintaining coolability of the fuel depending on droplet size, effect of counterflowing steam and fuel loading configuration.

3. SFP MODEL IN MELCOR

The MELCOR code was originally developed for analysis of severe accidents in BWR and PWR reactors [3]. The code is based on control volumes connected by flow paths (junctions) with specified frictional losses. Flow areas are either given or are determined as degraded material relocates. Generally, one-dimensional (1D) flows are considered. Since the version 1.8.6 MELCOR has been updated for use in investigating conditions in spent fuel pools under various loss-of-coolant conditions. The last version of MELCOR includes models for:

- Air and steam oxidation;
- Radiative, convective, and conductive heat transfer;
- Hydrogen production and combustion;
- Fuel degradation;
- Boiling and two-phase thermal hydraulics;
- Fission-product release and transport.

3.1 NPP Krško Spent Fuel Pool model

Spent fuel pool and associated building has been modeled as control volumes with the lumped parameters. The control volume geometry is mostly rectangular or cylindrical. The pool volume is divided into 9 control volumes, while the building is divided into 2 volumes, as shown in Fig 1. The outer space is modeled as a time-independent volume ('ENVIRONMENT').

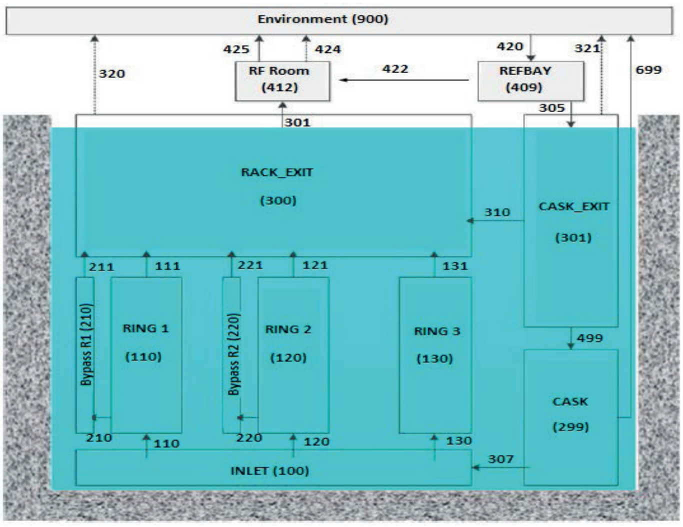

Fig. 1 Control volumes and flow paths in SFP model

Warm water in its natural circulation comes out of racks, enters the RACK_EXIT volume, radially extends to the edge of the pool and enters the CASK_EXIT volume. Furthermore, the water descends to the CASK volume, passes through the INLET at the bottom and re-enters the racks. The space inside the metal racks is divided into 3 Rings and 2 Bypass. The volumes are interconnected by the flow paths, shown by the arrows in Fig 1.

The spent fuel inside the pool is modeled in a similar way to the core in the reactor using the COR package [4]. Due to initial program constraints, fuel is modeled as a cylindrical structure with axial and radial splits. The fuel is divided into 14 axial layers and 3 radial rings (Fig 2.). For large pools the new approach using interacting channels instead of the fuel rings is able to provide more realistic results.

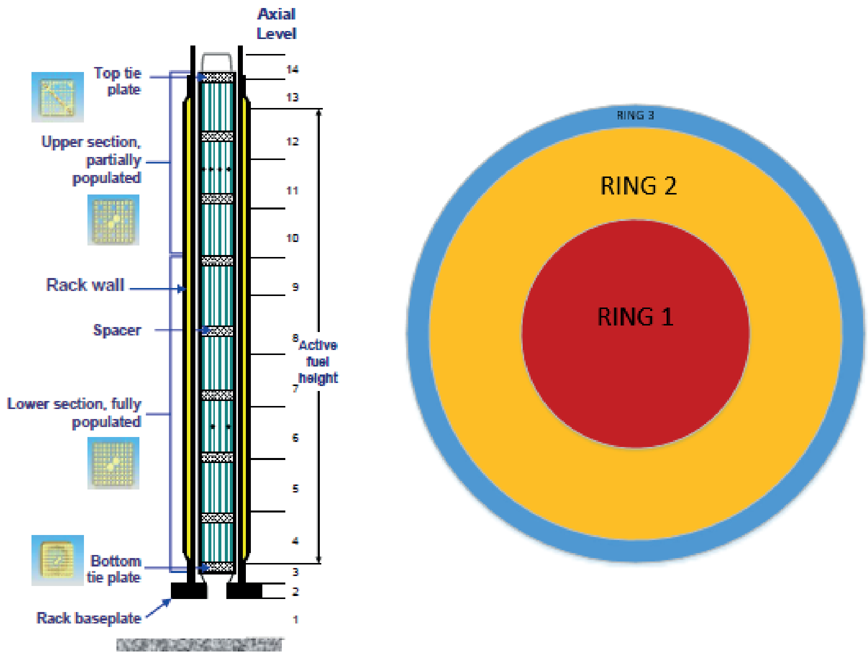

Fig. 2 Spent fuel model

The current configuration of NPP Krsko SFP, having old and new racks, is result of first phase of reracking program. The first ring (Ring 1) is made up of all fuel elements in the old section of the SFP (old racks), i.e. the fuel with larger decay heat. The second ring consists of cooler elements in the new section of the SFP, while the third ring represents a small amount of water between racks and side walls of SFP.

Concrete walls of SFP with metal liner, metal walls of FHB (Fuel Handling Building) and concrete floors on top of the pool (operating deck) represent the heat structures modeled in the HS package [5]. The concrete floor of SFP is modeled in the COR package due to the requirement to define the lower plenum and the reactor cavity below the fuel in MELCOR. Four concrete floors at the elevation of the pool top (11.8 m) were defined, with a total thickness of 0.5 m, surrounding all sides of SFP. Floors are rectangular geometries in which 9 temperature nodes are defined. The boundary condition on the left (inner) side were set as the convective heat transfer coefficient calculated by the HS package. On the right (outer) surface, a symmetric boundary conditions were defined, which represents an isolated surface. Due to program requirements, it was necessary to divide the side walls of the pool on the 17 axial layers and define the boundary (metal) structures above each radial ring of the fuel model in the COR package. Depending on the type of defined boundary condition, it was necessary to define the associate control volume for some heat structures. Therefore, the lowest two wall segments are connected with the INLET volume, the next 14 segments are connected with the RING 3 volume, while the last three segments are connected with the RACK_EXIT volume (Fig. 3).

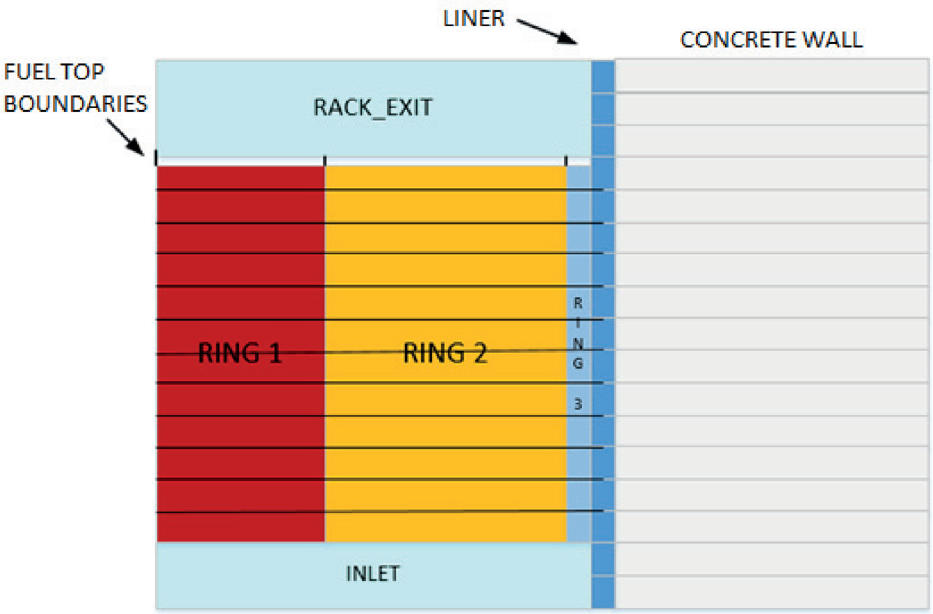

Fig. 3 Heat structures and neighboring volumes

4. RESULTS AND DISCUSSION

The calculations were carried out for a moment in which the fuel, during the refueling, was completely transferred from the reactor to the pool (09.10.2016.). The total decay heat in the old part of the pool was 5.71 MW, with the total fuel mass (metal uranium) 147.315 t, while the decay heat in the new part was 0.573 MW with a uranium mass of 372.035 t. Some MELCOR calculation results were compared with an application that uses simple conservative models (mass and energy balances) for estimating basic data related to the safety of the spent fuel pool - SFPFA.

4.1 Loss of coolant through a 1 cm² crack

This scenario describes the loss of the coolant through the hole at the bottom of the pool having cross section area of 1 cm^2. A hole of such size is used in NEK in design bases water pool drainage analyzes. Fig. 4 depicts the inventory loss of the pool by the height of water in the control volumes 300, 110 and 100 (they extend through the entire height of the pool). The result shows that the water after 6.0e5 s drops to 0.5 m height. Fig. 5 shows comparison of MELCOR and SFPFA results. In the MELCOR results, the effect of water level stagnation to about 7.0e4 s is noticed even though the mass is lost, which can be explained by the increase in water volume due to heating, i.e., density reduction (Fig. 6).

Fig. 7 shows the temperature of the axial segments of the fuel rod cladding, showing a sudden rise of the temperature after the fuel has become uncovered.

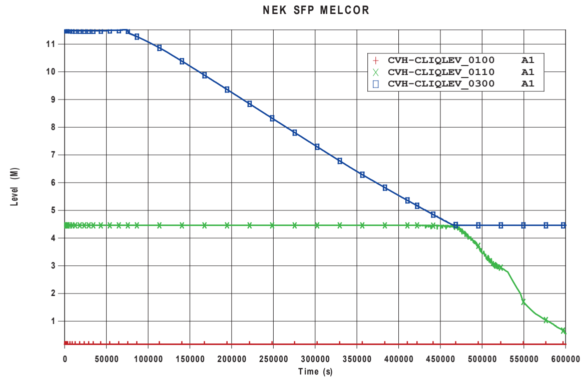

Fig. 4 Water elevation change in MELCOR

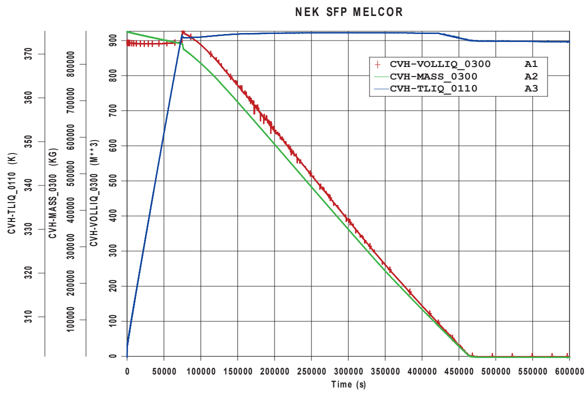

Fig. 6 Water level swelling explanation

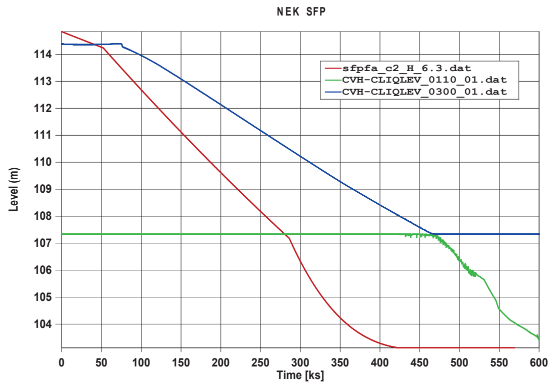

Fig. 5 MELCOR and SFPFA water elevation comparison

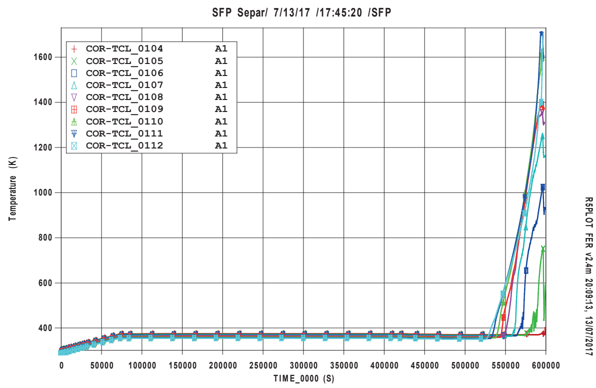

Fig. 7 Fuel cladding heatup in Ring 1

4.2 Loss of coolant through a 0.23 m² crack

The second case analyses the crack of a very large cross section located at the bottom elevation and at 0.5 m above the bottom. The crack of such size area is possible only during major seismic event (beyond design bases event), but it shows the fuel behavior in the case of almost instantaneous loss of coolant inventory. Water drains from the pool after 600s, except in the case of hole at 0.5 m where it stagnates below that elevation (Fig. 8). The water mass flow rate through the crack is exceptionally high (initial flow rate about 3000 kg/s) as can be seen in Fig. 9. The temperature of the fuel cladding in region 1 (Ring 1) is shown in Fig. 10 and 12. On those figures can be observed the effect of breakaway oxidation, which influences the significant cladding temperature rise. Fig. 11 shows the heat produced and exchanged within SFP by various types of heat transfer. The decay heat power (EFPD-RAT) is shown, which due to radionuclide release partially decreases over time. In addition, the convective heat transfer from the fuel, water oxidation, and heat transfer to the surrounding heat structures are shown. Fig. 13 shows the energy balance of the COR model.

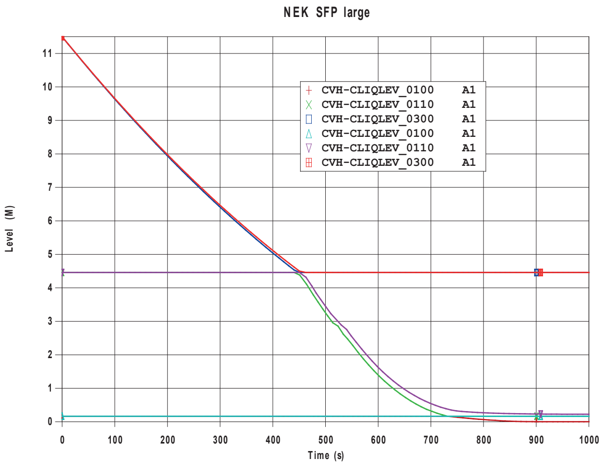

Fig. 8 Crack position impact on water level

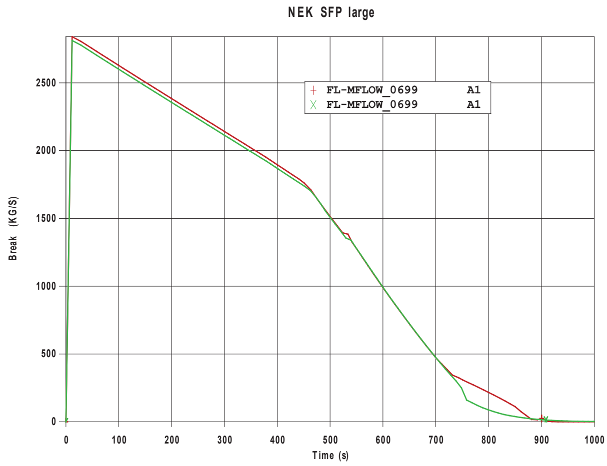

Fig. 9 Water flow through liner crack

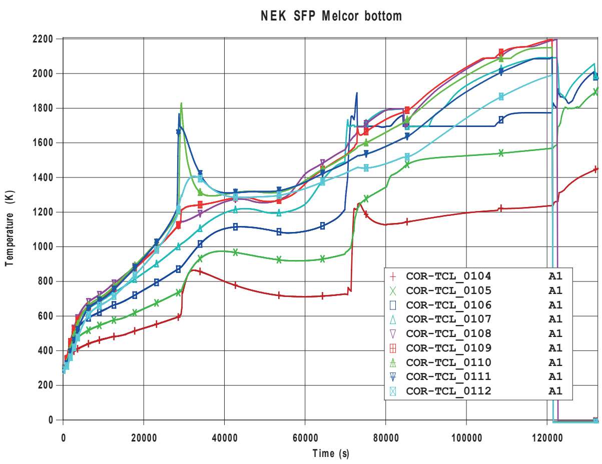

Fig. 10 Cladding temperature in Ring 1 (crack on bottom)

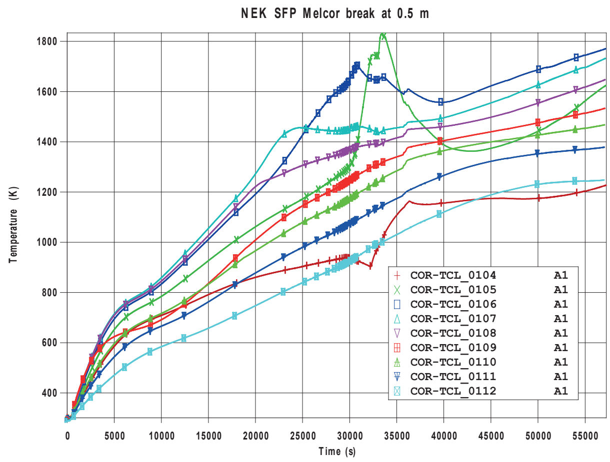

Fig. 12 Cladding temperature in Ring 1 (crack at 0.5m height)

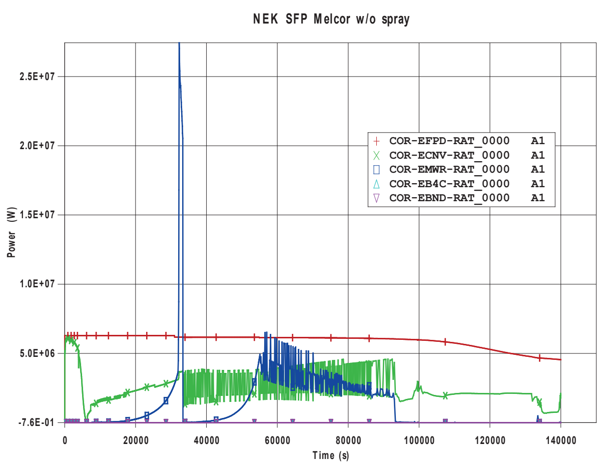

Fig. 11 Heat balance of pool contents - power

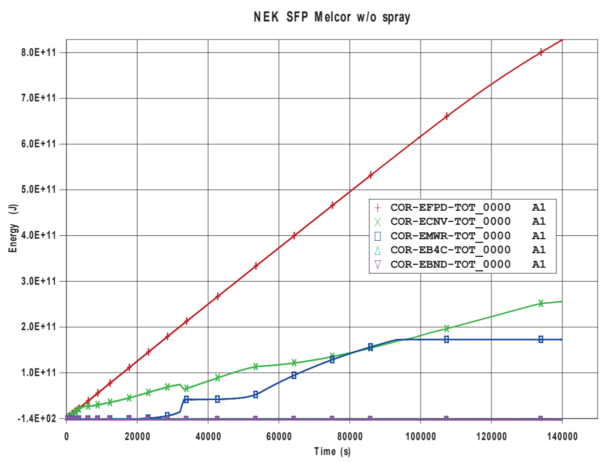

Fig. 13 Heat balance of pool contents - energy

5. CONCLUSIONS

In this paper the Spent fuel pool model of the NPP Krško was used for evaluation of loos-of-coolant inventory accident response using severe accident code MELCOR. Model has been used for partial (slow water drainage) and compete loss of coolant analysis. The case of coolant loss through a small hole prolongs fuel uncovery and consequent fuel heat-up. If the sudden loss of the coolant from the SFP occurs, natural circulation of air is established through the racks, but the results show that it is insufficient to prevent the overheating of the fuel elements with high decay heat. Accident mitigation measures should prevent fuel uncovery in case of partial loss of coolant by enabling water makeup. Due to the different phenomenology of the complete loss of coolant accident, the uncovered fuel should be cooled by allowing convective airflow through the racks, which can be achieved by the implementation of spray nozzles.

6. REFERENCES

[1] Wagner, K. C., Gauntt, R. O. Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents And Extension of Reference Plant Analyses to Other Spent Fuel Pools. SANDIA Letter Report revision 2, Sandia National Laboratories, November 2006.

[2] Barto, et all. Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor. NUREG-2161, US Nuclear Regulatory Commission, September 2014.

[3] Humphries, L.L., B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips. MELCOR Computer Code Manuals; Vol. 1: Primer and Users' Guide; Version 2.1. SAND2015-6691R, Sandia National Laboratories, 2015.

[4] Cardoni, Jeffrey. MELCOR Model for an Experimental 17x17 Spent Fuel PWR Assembly. SAND2010-8249, Sandia National Laboratories, November 2010.

[5] Kromar, Marjan, Kurincic, Bojan. Criticality Safety Analysis of the NPP Krško Storage Racks. Nuclear Energe for New Europe 2002, Kranjska Gora, Slovenia, 2002.