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Effectiveness of SFP Spray Cooling during Loss of Coolant Accidents

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ABSTRACT

For a large Spent Fuel Pool (SFP) loss of coolant accidents, properly sized SFP spray can slowdown or possibly preclude fast heat-up of spent fuel. The MELCOR 2.1 model of NPP Krsko pool was developed and tested for cases of loss of cooling accidents. The simple spray system with spray nozzles distributed at specified location at the top of the pool was added to the model. Different loss of coolant rates where studied for different fuel heat loadings, and different openings and flow rates of the spray nozzles. Traditionally, spray nozzles able to produce larger diameter droplets are used close to the fuel locations with higher heat loadings. According to preliminary results, spray nozzles that will be installed are able to limit or delay long-term heat-up of the spent fuel, but in the case of late actuation it is possible to have temporary high oxidation rates and corresponding production of hydrogen.

Keywords: *SFP, large loss of coolant, MELCOR, spray nozzles*

1 INTRODUCTION

In NEK, the SFP is located in separate building near the Reactor Containment, the Fuel Handling Building (FHB). The SFP is generic pool with the depth approx 12 m with concrete walls, thickness approx 2 m, with the stainless steel construction on the inner side of walls. Fuel assemblies (FAs) are located in racks that sustain FAs in the vertical position. Additionally, they have to enable adequate FAs cooling. The rack is divided in cells of appropriate dimensions to enable coolant flow and to disable criticality. Moreover, the subcriticality is achieved with special metal materials for racks (Boraflex) and the boron acid addition in the water. For the safety proposes, the water level above the FAs should be at least 3 m to ensure that the radiation is at the appropriate level for the workers at the operating deck.

During the refueling outage, the FAs are withdrawn from the reactor and there are very radioactive due to the decay heat production that is the main problem with the nuclear fuel. After withdrawal, the FAs are placed in the SFP, therefore, the SFP has to ensure adequate cooling with the heat exchangers and natural circulation. The coolant in the SFP uses natural circulation to cool the FAs, the warm flow rises through the length of the rack, mixes with the cold coolant above the rack and returns down to the bottom of the rack. This process is supported with the cooling system that intakes the warm coolant above the racks and directs it through the heat exchanger (it is cooled with the Component Cooling Water or Essential Service Water). During the loss of SFP cooling, the coolant starts to heatup and it can lead to the fuel rod heatup and therefore to the radioactive release.

The coolant temperature, during normal condition, is below 50 ^{0}C and it can rise to max 80 ^{0}C, after which the evaporation heat removal starts.

The U.S. Nuclear Regulatory Commission (NRC) has identified nine possible initial events for the SFP accident. Some of those are: loss of power, fire, loss of cooling, loss of coolant, seismic event, airplane crash. They can be sorted in two consequence groups: loss of cooling and loss of coolant inventory. On the other side, they can be sorted from the perspective of the natural coolant circulation to: partial loss of cooling and total loss of cooling. During the total loss of cooling, the natural air circulation is formed, the air is heated through the length of the rack and it cools with the cold air above racks. During the partial loss of cooling, the hot air circulation is disabled leading to the cladding heatup once the water level drops below the half the length of the rack.

The activities that limit the loss of cooling consequences are: the coolant make up, the good fuel distribution in the SFP, the spray system, the FHB ventilation, etc. The coolant make up is the most logical action to limit the accident propagation. This action is efficient only until the water level drops below the 60 % of the active FA length. If the coolant is lost rapidly, the coolant make up can disable the natural air circulation. The worst FAs distribution in SFP is the uniform configuration because the fresh (the hottest FAs) is surrounded by warm FAs. The best configuration (from heat generation point of view) is 1x4 where the fresh FA is surrounded by 4 cold FAs. This way, the radial heat transfer from hot to cold FA, significantly increases the cooling possibility. The spray system possibility will be described later in details. If the FHB ventilation is inappropriate, then the FHB will heatup. Therefore, the ideal ventilation configuration has to intake cold air at the bottom of the FHB and release the hot air at the top of the FHB.

2 SPENT FUEL POOL MELCOR 2.1 MODEL

MELCOR code was developed at Sandia National Laboratories and sponsored by U.S. NRC. It is a fully integrated, engineering-level computer code for BWR and PWR severe accident phenomena. MELCOR has been designed to facilitate sensitivity and uncertainty analyses through the use of sensitivity coefficients. Many parameters in correlations, which are made constant in most codes, are implemented as sensitivity coefficients in MELCOR. MELCOR is executed in two parts. The first is called MELGEN and in it the majority of input is specified, processed and checked. When the input checks are satisfied, a Restart File is written containing initial conditions for the next calculation. The second part is MELCOR program itself which executes the problem based on the MELGEN and MELCOR input. In this paper, version 2.1 is used.

The NEK SFP was originally designed to store the limited number of FAs. Those FAs had to be withdrawn, after some cooling interval, due to permanent storing. According the original design, the SFP had to be filled until 2003. This meant that the NEK had to shutdown because the regulatory guides require that the SFP has to have free space for the total core inventory in the emergency (ECU – emergency core unloading). The NEK had to undergo the reracking of the SFP that had to achieve the possibility store all spent fuel during the whole NPP life (40+20 years). The original SFP had 12 racks. During the reracking, 3 of 12 racks were replaced with 9 new racks. At the moment, there are 9 old racks in NEK SFP that have larger rack cell area and contain newly extracted fuel from the core. There are also 12 new racks that have smaller rack cell area and contain older FAs. New racks have smaller rack cell area and higher density because they have special boraflex plates.

The fuel transfer from the reactor core to the SFP is through the Transfer Canal that is flooded to maintain radioactive protection. A part of the SFP is the Cask Loading Area where the fuel is loaded for dry storage. The control volume (CV) 110 represents the volume where the higher power fuel is located (the fresh fuel) and the CV 210 is the associated bypass for that area. CV 120 represents the volume where the old fuel is located and the CV 220 is the associated bypass for that area. The CV 299 is the coolant volume between the rack and the SFP walls (the downcomer). A part of that volume is extracted to model the downcomer above racks (CV 301). The CV 300 models the coolant volume above racks and CV 100 is the coolant volume below the rack's baseplate.

The spent fuel is modeled in similar way as the active core in COR package. The fuel is divided in 3 rings and 14 axial divisions. First 3 axial divisions model part below the baseplate, and next 10 model the active fuel and the last 2 model upper plenum. That is old way of SFP modeling.

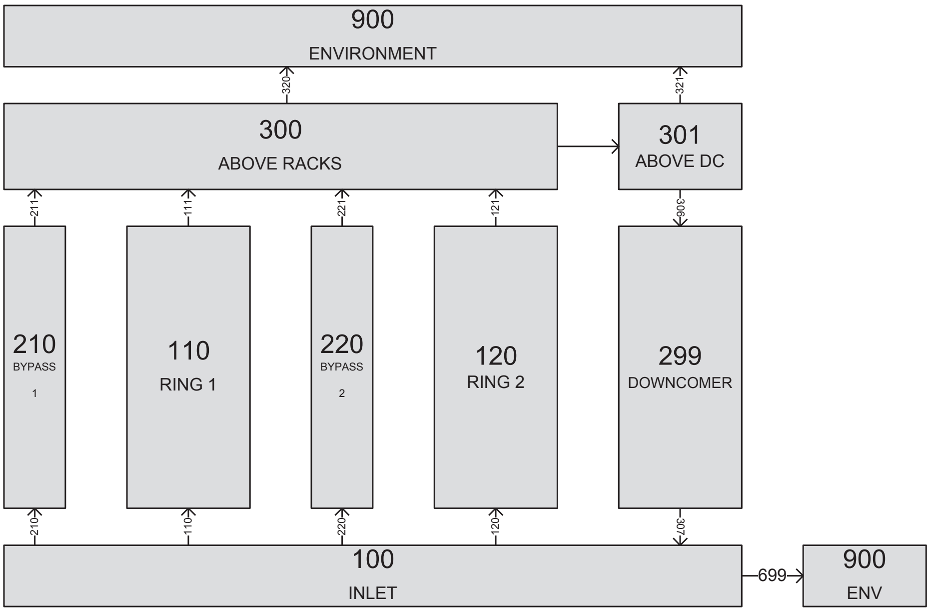

Figure 1: NEK SFP - Control volumes and flow paths

The cooling of the SFP based on spray nozzles will be introduced as part of NEK safety upgrade program [1]. The spray system will be located along the north and south wall of the SFP on the elevation 115.55 m. Both spray lines will have valves for spray pressure control that will discharge water in the SFP when the pressure setpoint is obtained. If all spray nozzles fail, the water will be discharged in the SFP through the relief valves. The water source for spray nozzles will be fire protection water or water from Sava river. The spray system will be divided in low (3 m^3/h), medium (25.4 m^3/h) and high (59.2 m^3/h) mass flow rate nozzles. Every type has 4 nozzles and they are located as shown in Figure 2. Low mass flow rate nozzles are associated with the new racks because there is old cooled fuel. Medium and high flow rate are associated with the old racks where the fresh fuel is located.

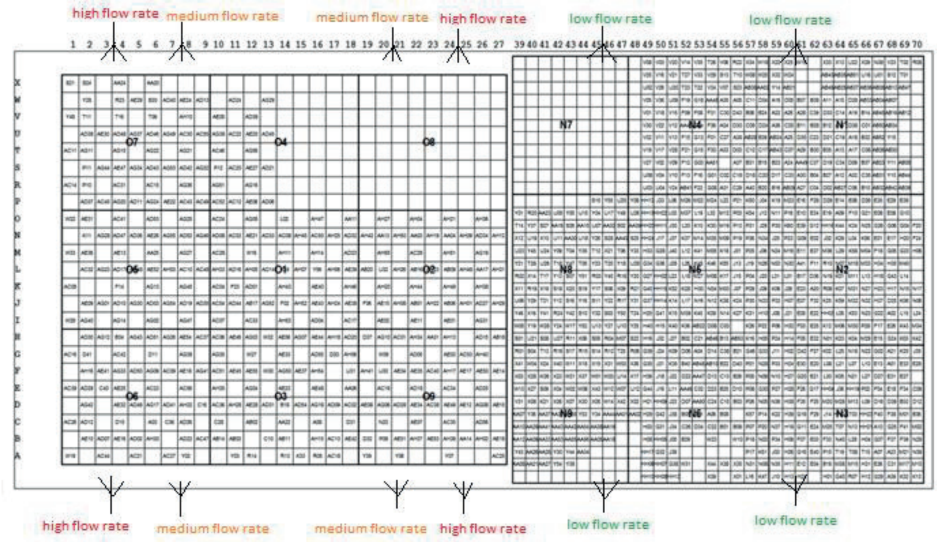

Figure 2: Spray nozzle arrangement above the SFP

The spray system in MELCOR is modeled with two separate sprays, one above the old part of the SFP and another above the new SFP. Spray for the old part of SFP is located in the CV 300 on the elevation 11.7 m, and its mass flow rate is 84.6 m^3/h (that is sum of medium and high mass flow rate nozzles). Spray for the new part of SFP is also on the elevation 11.7 m, and its mass flow rate is 3 m^3/h. For both spray, fractions of spray droplets that reach the certain volume are defined through the input cards. The CV 100 is the control volume containing the sump where all water that did not evaporate flows. The spray is controlled with the control function that starts spray at the certain time after the accident initiation.

A control function is also used to model opening of the blow out panels in FHB. Due to the SFP spray operation, a hydrogen production is expected. Therefore, a part of the SFP modification was to install blow out panel in the FHB that could decrease the pressure increase in the SFP due to hydrogen generation. They open at approximately 1800 s and stay opened the whole accident. The ideal ventilation configuration is to intake cold air from the FHB bottom and to exhaust hot air at the FHB top. In the NEK, that is simulated with big FHB door that are used for the fuel transfer and the blow out panels at the top.

Argonne National Laboratory (ANL) has made tests that showed that a smoother change from pre-breakaway to post-breakaway oxide layer gave a better fit to experimental data. The results of the SFP experiments suggest that a maximum lifetime of 1.2 gives a better fit for the default breakaway parameters than 1.0 what was used before. This newly implemented MELCOR model calculates the maximum lifetime for breakaway in each cell using the local cladding temperature. In this paper, the breakaway oxidation was modeled with control functions that compared accumulated damage for clad component in each COR cell with 1.0. The fuel collapse time is defined as the function of cladding temperature and it is applied only when the unoxidized Zircaloy thickness is less than 0.1 mm. When this is satisfied, the model calculates the damaged fuel fraction for every time interval and adds it to the previously calculated damage. When the cumulative fuel damage reaches 100%, the fuel in the SFP MELCOR model collapses.

3 CALCULATION RESULTS

The time selected for calculation is 09.10.2016., the moment when the fuel, during the refueling outage, was transferred from the reactor to the SFP. The SFPFA program was used to obtain data for the current SFP inventory, its decay heat and the time to boiling. The program is very easy to use and it uses simple conservative models to estimate basic data for the SFP safety. Figure 3 top shows how many days the spent fuel was in SFP (the span is from 9 to 12150 days), whereas the bottom side shows the spent fuel decay heat. The decay heat for old racks is between 98 W and 52.82 kW (5.71 MW total) and for new racks is between 89 W and 2.03 kW (0.573 MW total).

The first observed transient is loss of coolant due to 1 cm^2 break at the SFP bottom. That break size is used in SFP loss of coolant standard analyses. The transient was simulated for 600000 s. Figure 4 shows the start of the fuel heatup for the case without the spray. The fuel temperature distribution is given for every axial division of the active fuel. As expected, the highest fuel division starts to heatup first as the coolant level drops during the accident. Figure 5 shows the comparison of the SFP water level without and with the spray. This figure demonstrates the effectiveness of the spray system in the SFP during the loss of coolant accident. For the case B (with the spray), the water level starts to decrease later than for the case without the spray, therefore the SFP integrity is longer maintained.

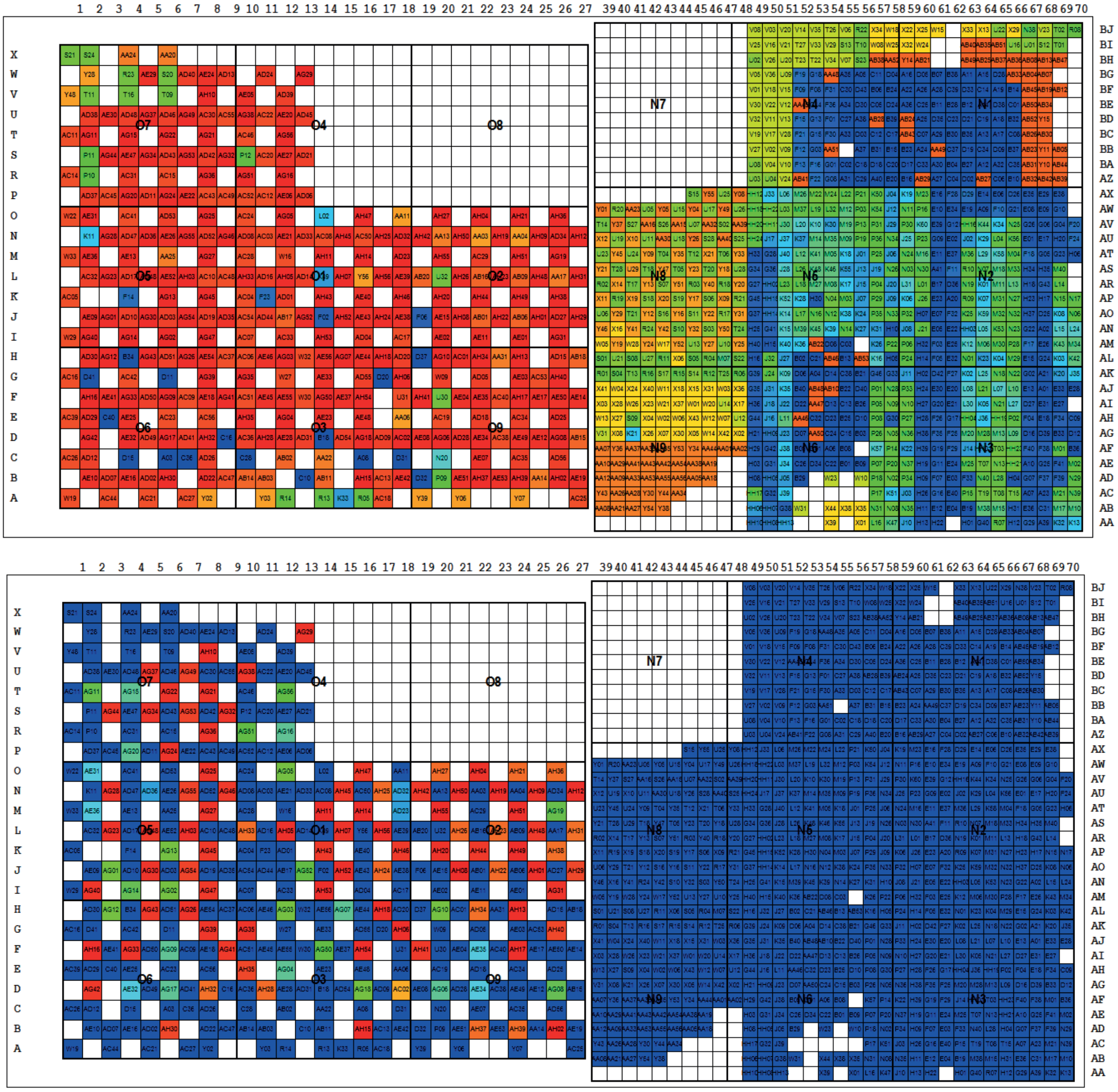

Figure 3: SFPFA calculation results (time and power)

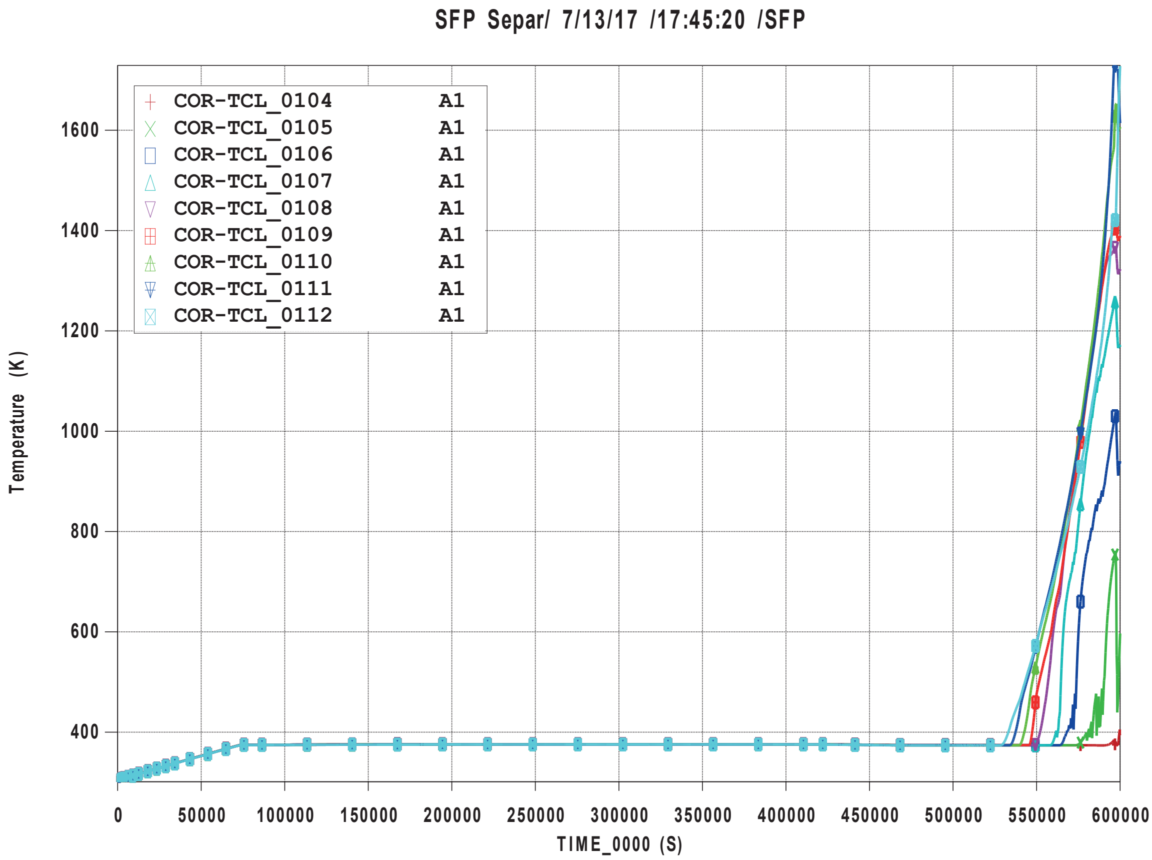

Figure 4: The start of fuel heatup without spray (1 cm^2 break)

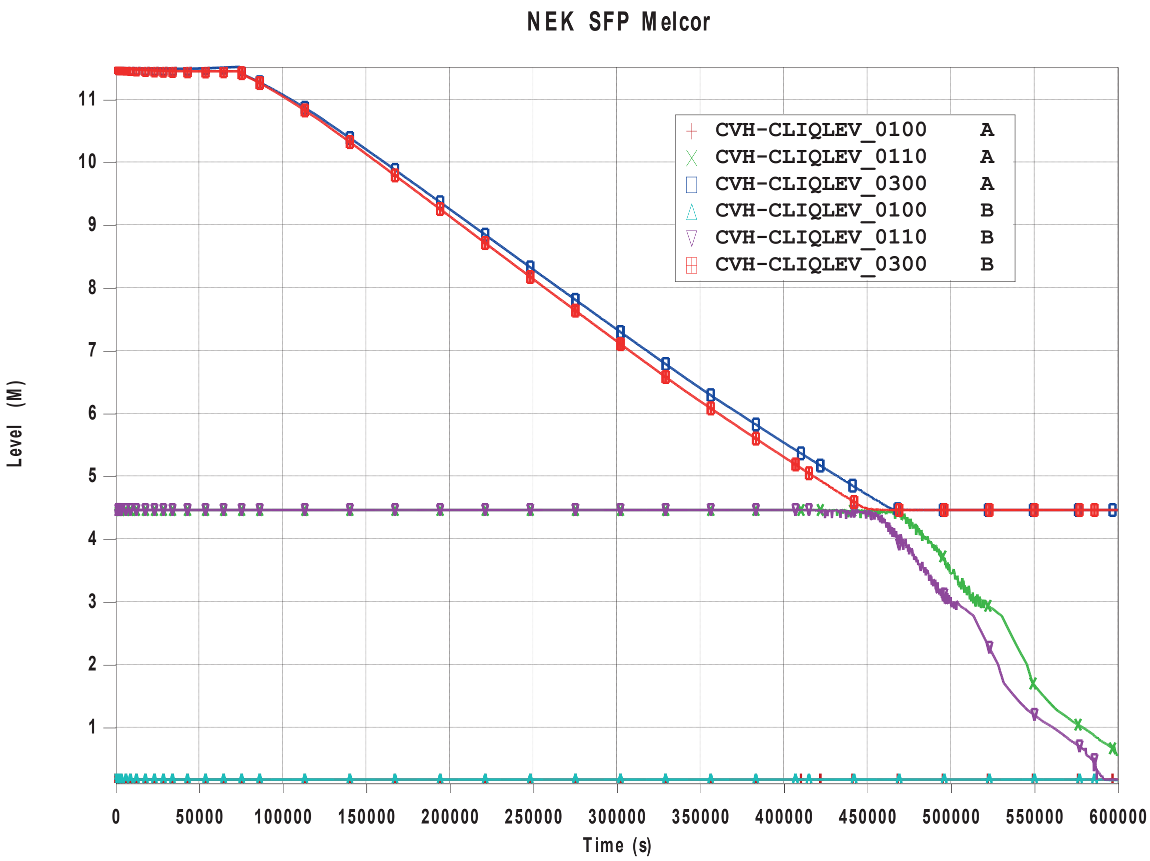

Figure 5: The comparison of the SFP water level without and with the spray (1 cm^2 break)

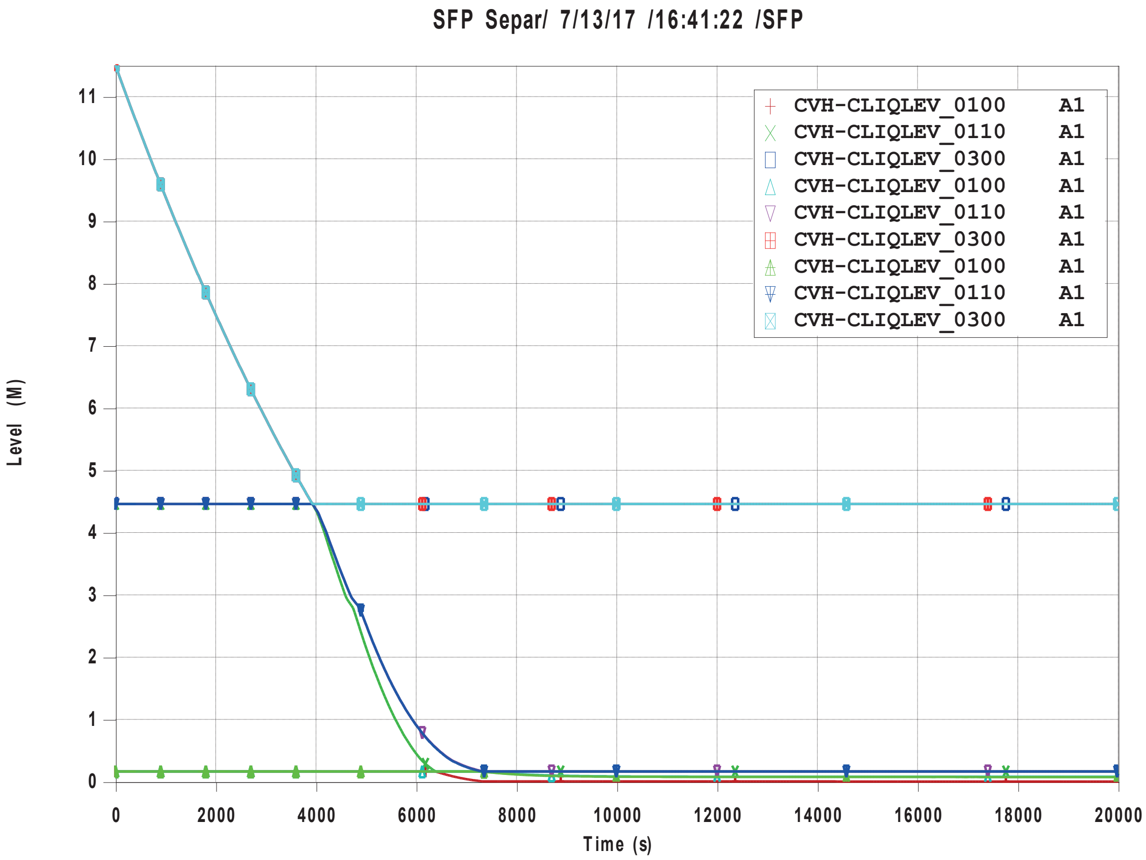

Figure 6: The comparison of the SFP water level without and with the spray (10 cm^2 break)

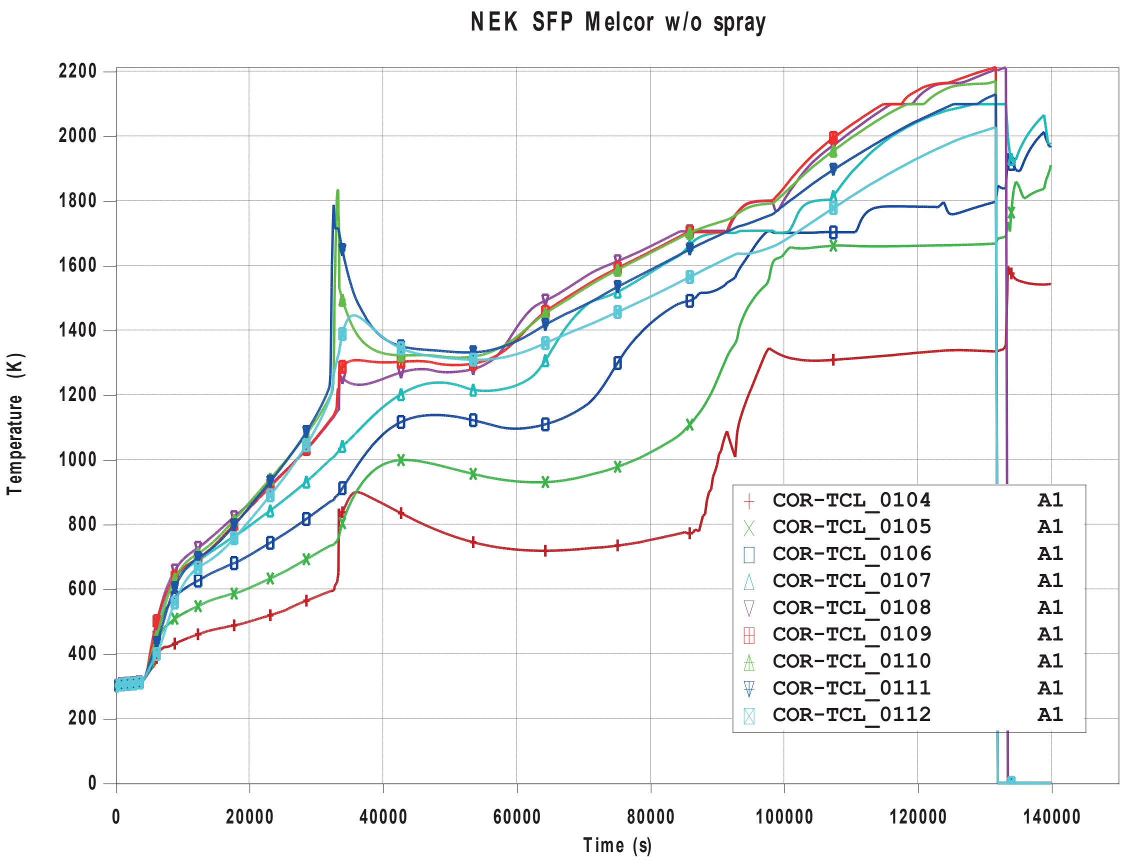

Figure 7: The fuel heatup without spray (10 cm^2 break)

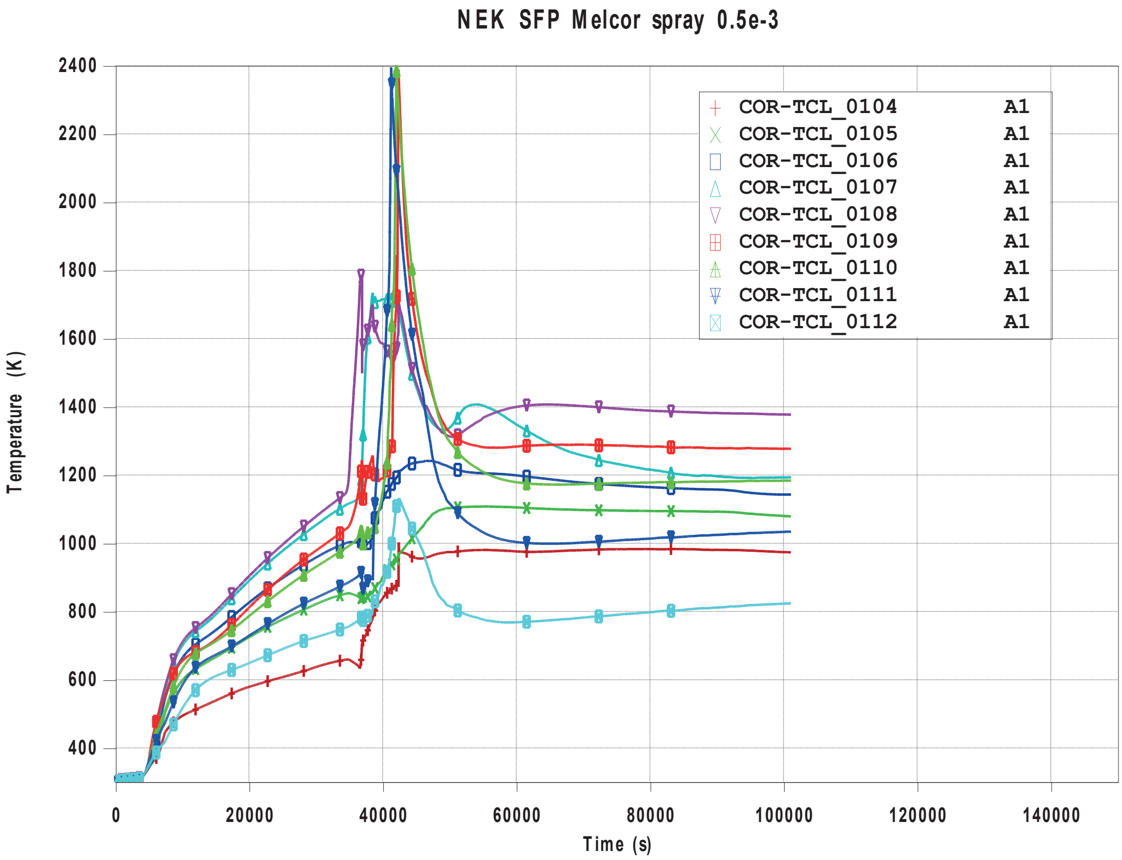

Figure 8: The fuel heatup with spray droplet of 0.5 mm diameter (10 cm^2 break)

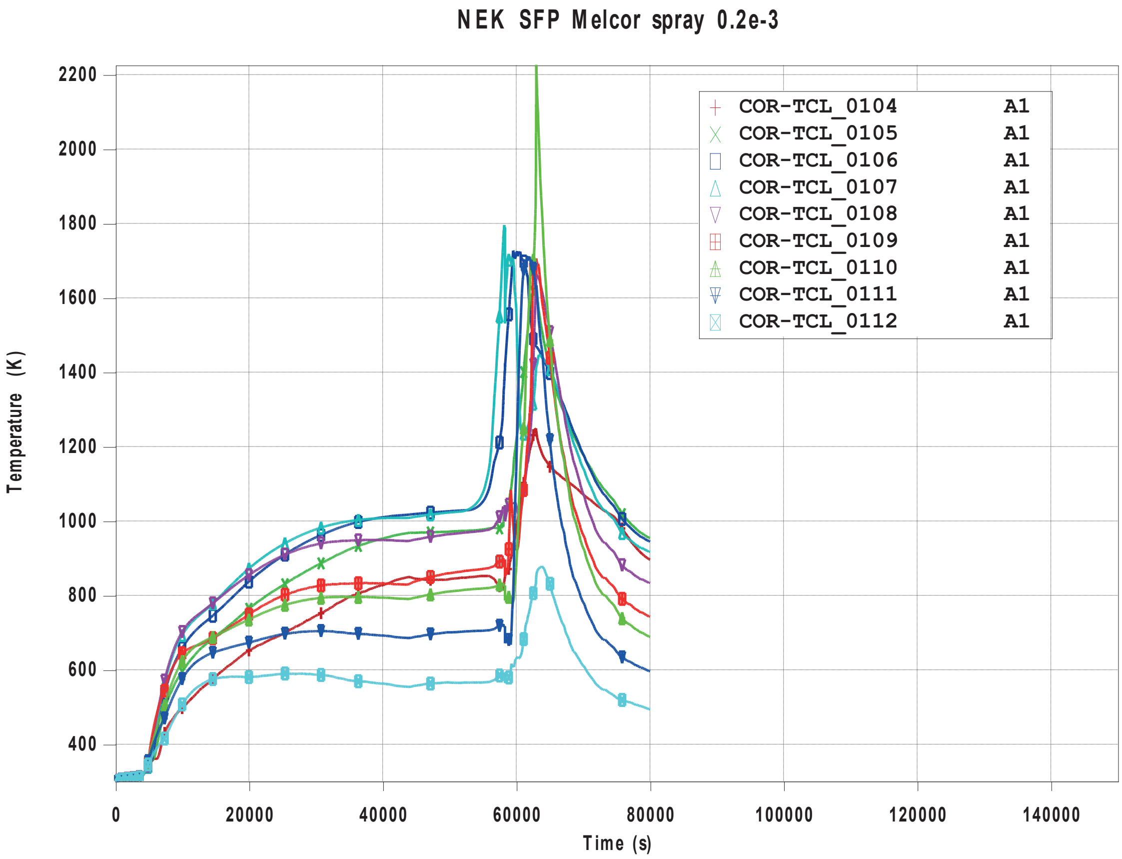

Figure 9: The fuel heatup with spray droplet of 0.2 mm diameter (10 cm^2 break)

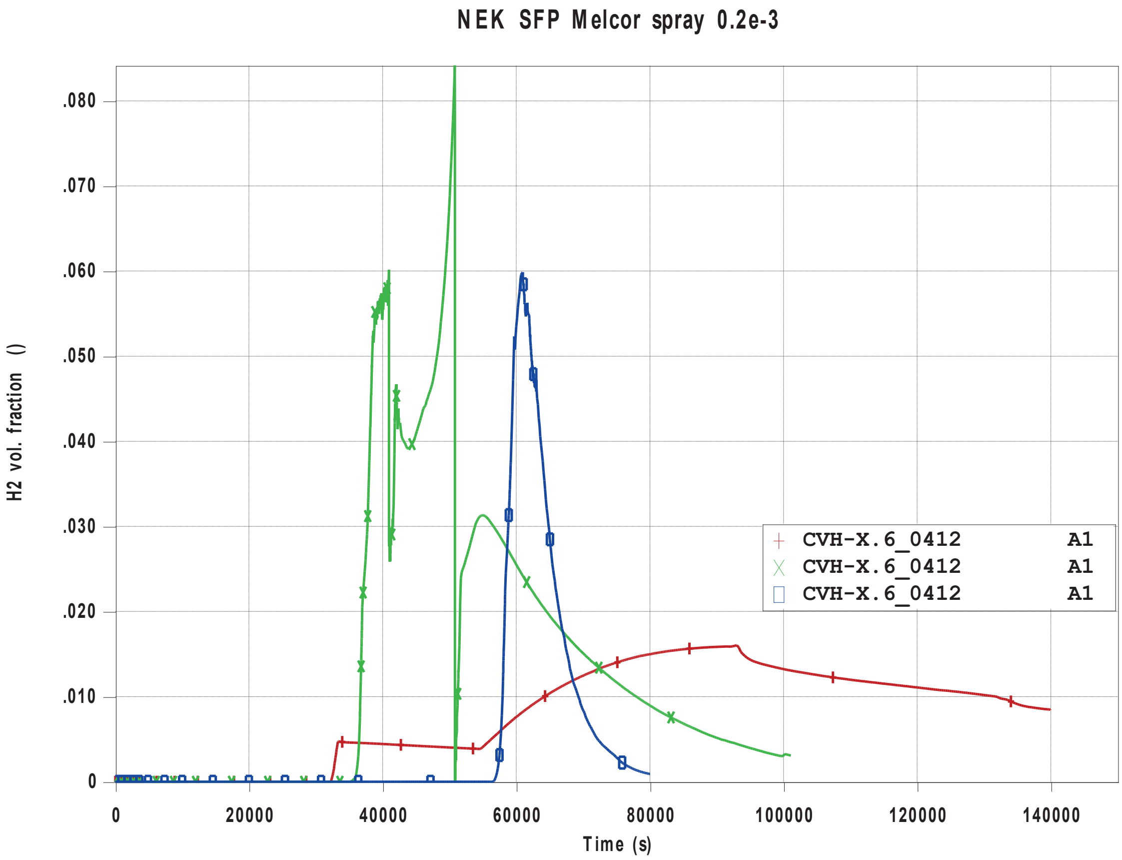

Figure 10: Hydrogen fraction without and with spray - 0.2 and 0.5 mm (10 cm^2 break)

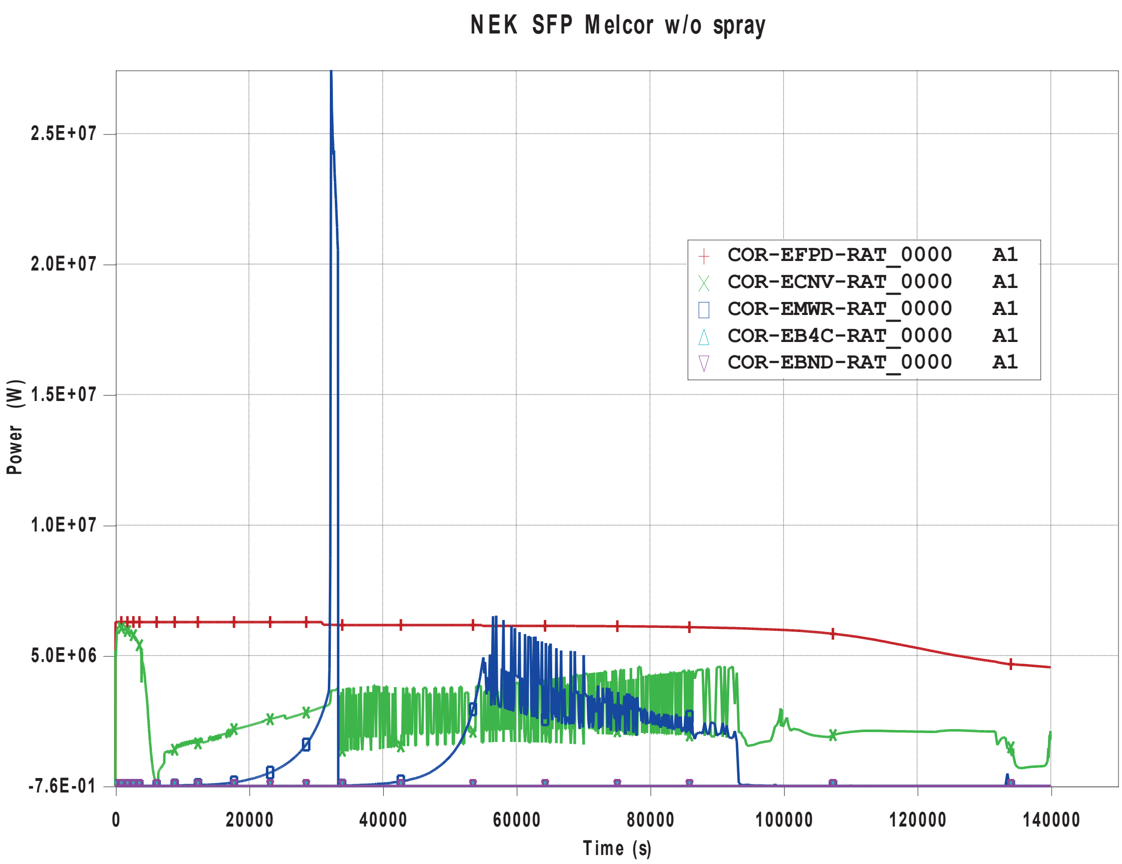

Figure 11: The power distribution for the case without spray (10 cm^2 break)

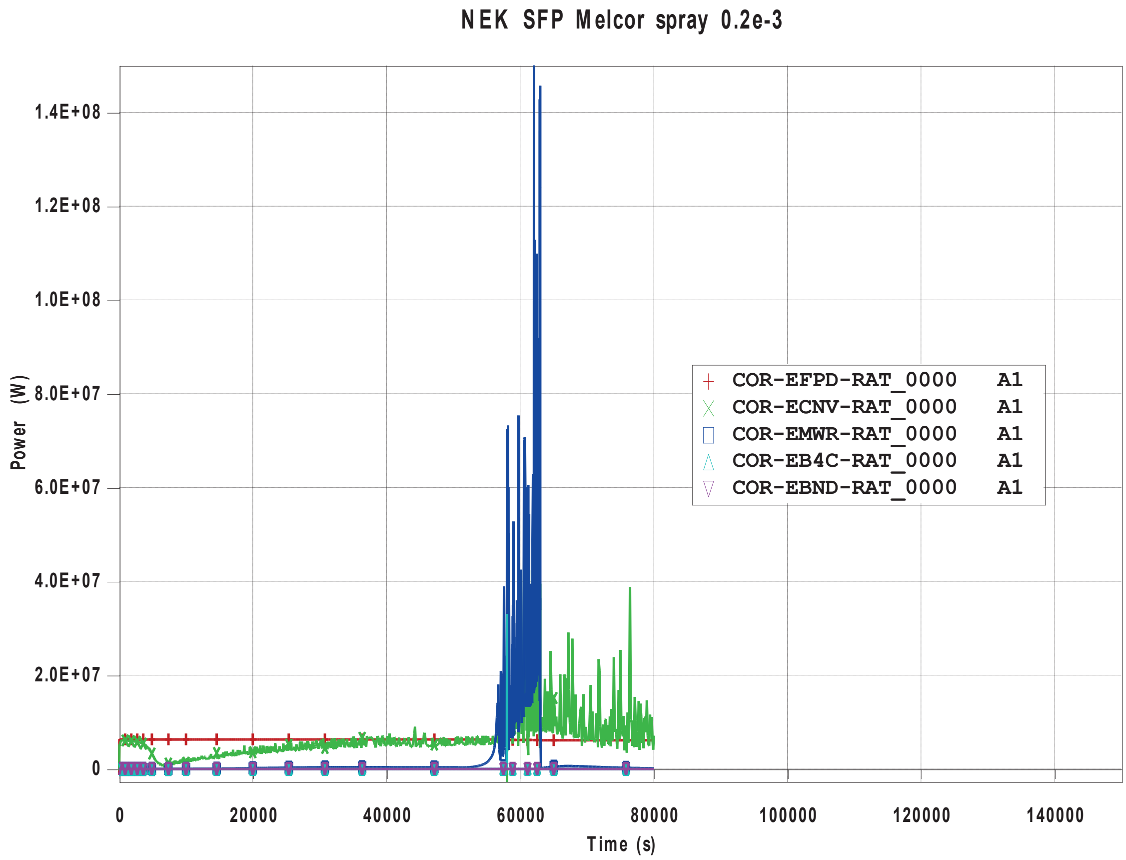

Figure 12: The power distribution for the case with 0.2 mm diameter spray droplets (10 cm^2)

The second observed transient is loss of coolant due to 10 cm^2 break at the SFP bottom. The transient was simulated for 140000 s. The break flow rate is much higher than in the first observed transient due to larger area break. The comparison of the SFP water level for the case without and with the spray is shown in Figure 6. Like for the 1 cm^2 break, the water level starts to decrease later for the case with the spray. The water level in the SFP, due to spray, stabilizes above zero, whereas for the case without the spray, the water drains completely out of the SFP. Figure 7 shows the fuel heatup for the case without the spray. The fuel temperature for all axial division is shown and again the highest divisions start to heatup first. The first peak is reached at approx 30000 s. In that moment, the effect of the breakaway cladding oxidation is noticeable leading to the fuel temperature decrease. Afterwards, the fuel temperature starts to increase until the fuel melts and begins to relocate.

For the same break size, the effectiveness of the spray system was demonstrated. It is initiated with the control function at the 3900 s when the fuel starts to uncover. Figure 8 shows the fuel heatup when the spray system is installed with the spray droplet of 0.5 mm diameter. As expected, the first peak is reached later than in case without spray (at approx 40000 s). This demonstrates that installed spray system can prolong the heatup start and therefore give time to operators to plan an action to prevent severe accident.

For this transient, a case with spray droplet of 0.2 and 0.5 mm diameter was observed to estimate the cooling effectiveness on the droplet size. Figure 9 shows the fuel heatup with spray droplet of 0.2 mm for the same break size. The fuel heatup starts at approx 60000 s that is much later than for the 0.5 mm diameter droplet showing that the smaller droplet can more effectively cool the fuel in the SFP. As a consequence of using the spray, hydrogen is generated due to exothermic steam oxidation. Figure 10 shows the comparison of hydrogen distribution during the accident without spray and with spray droplets of 0.2 and 0.5 mm diameter. In the case without the spray, the smallest amount of hydrogen is generated, whereas the bigger droplet size generates more hydrogen. Figure 11 and 12 show the power distribution for each type of heat transfer for the case without spray (Figure 11) and for the case with 0.2 mm diameter droplets (Figure 12).

4 CONCLUSION

The most critical SFP accidents are loss of cooling and loss of coolant. One of activities that can prolong the fuel heatup in the SFP is spray system. The aim of this paper was to demonstrate the effectiveness of the installed spray system in the SFP. Efficiency of spray system in SFP depends on several parameters, especially on the diameter of spray droplets. The calculations conservative and uses old ring based approach to SFP modelling.

This preliminary calculations show that spray system is eventually capable of limiting fuel temperature increase in SFP, but depending on time of actuation and droplets size can cause hydrogen generation.

Acknowledgements:

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