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Fuel Integrity Under Dry And Wet Storage

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ABSTRACT

This paper describes the limits of storage of spent nuclear fuel under air environment in case of a loss of coolant accident in a spent fuel pool. Different geometries of fuel assemblies used in Swiss nuclear power plants (PWR and BWR) were modelled for the severe accident code MELCOR. Different code versions are used to calculate the accident histories under different heat loads of the spent fuel assemblies. Two extreme storage policies inside the pool (hot neighbor and cold neighbor storage) are modelled to show the effect of additional heat sinks on the accident progression.

1 INTRODUCTION

The most important parameter for the cladding degradation is the temperature of the fuel defined by the remaining decay heat of the fission products. As long as the decay heat can be removed from the fuel assembly (FA) by heat transfer to the coolant medium, no heat up of the cladding and therefore no cladding degradation will happen. This means, for water as coolant medium, no degradation will occur due to the low temperature and the strong heat conduction to the coolant as long as the water will not boil away. The boil down time of a spent fuel pool is in the order of two to four weeks, depending on the total heat load in the pool. This gives enough time to add additional water for the prevention of fuel melting.

For air as coolant medium, the heat conduction to the coolant is much lower and now additional parameters will play an important role. The heat flux at buoyancy driven air-cooling is mostly defined by the convectional heat transfer and therefore by the flow velocity of the coolant through the FA. Severe accident codes normally calculates the flow resistance in a FA from parameters deduced from pipe flow experiments at laminar flow conditions. In a FA additional obstacles, e.g. spacer grids, are increasing the flow resistance and therefore reducing the flow velocity and the convectional heat transfer from the FA. Due to the reduction of the heat transfer, the FA heats up and reaches higher temperatures, which can lead to the onset of oxidation of the cladding material.

Experimental programs conducted at Sandia National Laboratories (SNL) [1,2,3] delivered data to get more realistc buoyancy driven flow calculations for the air flow through different FA's from PWR's and BWR's.

2 FUEL ASSEMBLIES

Two different geometries from Swiss pressurized water reactors are modelled, 14x14 (NPP1) and 15x15 rods (NPP2). Both FA's are with full length fuel rods and they are compared with the 17x17 PWR FA used in the Sandia experiments [2,3] (Sandia Fuel Project, SFP).

Three different geometries are modelled for the Swiss boiling water reactors, 9x9 and 10x10 rods with two different part length rod combinations for the 10x10 rod FA's (NPP3). These calculations are compared with Fukushima (1F4) results, 9x9 full length rods (Tabel 1).

Table 1: Fuel assembly geometries

Description	Rods	Remarks
NPP1 14x14-17	179	
NPP2 15x15-20	205	
SFP 17x17-25	264	
NPP3 9x9-7	66/8	2 water rods
NPP3 10x10-8	78/14	2 water rods
NPP3 10x10-8	78/8/6	2 water rods
1F4 9x9-9	72	water channel

3 STORAGE POLICY

In a spent fuel pool the fuel assemblies can be stored either each cycle together as in the Fukushima unit 4 pool (hot neighbor storage) or distributed between longer stored fuel elements (cold neighbor storage). The latter has the advantage, that the relative hot fuel elements from the latest outage will radiate part of the decay heat to the cold neighbors, which will reduce the heat-up rates in case of a loss-of-coolant accident. The hot neighbor storage is modelled as a single, insulated, FA to be compared with the SFP Phase I experiment [2], and the cold neighbor storage is modelled as one "hot" FA surrounded by 4 "cold" FA's similar to the SFP Phase II experiment [3] (Fig. 1).

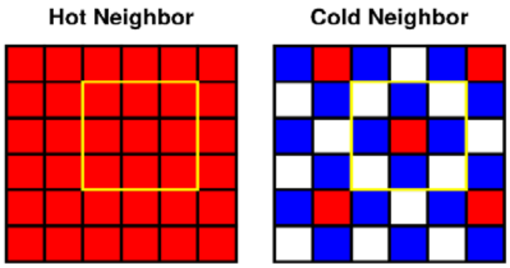

Figure 1: Hot and cold neighbor storage

4 MELCOR MODELLS

For the generation of a MELCOR input deck an EXCEL file is used, where the geometrical data of the FA's are used to calculate the volumes, flow areas, surface areas and masses of the different components as fuel, cladding, channel boxes, rack cells and so on. If once an EXCEL sheet is generated for an input deck, it is relatively easy to get a new input deck by changing only some geometrical parameters. For all the seven FA geometries mentioned in Table 1 each, a hot neighbor and a cold neighbor input deck was produced.

The axial modelling of the FA's was distributed into the inlet and outlet volume, the lower support structure, the non-fueled part below and above the active fuel and ten equidistant nodes for the active fuel.

Input decks for two MELCOR versions, MELCOR 1.8.6 and MELCOR 2.2 were produced for each case mentioned above. The SNAP [4] software was used to translate the input deck from one MELCOR version to the other.

5 RESULTS

In the hot neighbor configuration (Fig. 2) the smallest fuel element of a Swiss NPP shows ignition at all heat loads above 2.5 kW. For the largest Swiss FA, the one from NPP2, a heat load of 5 kW did not lead to ignition (Fig. 3). The reason for this behavior is due to the different heat ratio per mass combined with the different hydraulic diameter (see Table 2). A larger hydraulic diameter means higher convectional heat loss and a larger heat to mass ratio means lower heat capacity and therefore faster heat-up.

At the cold neighbor calculations with the same FA as in Fig. 2 it can be seen, that about three times the heat load is needed to reach ignition of the bundle (Fig. 4).

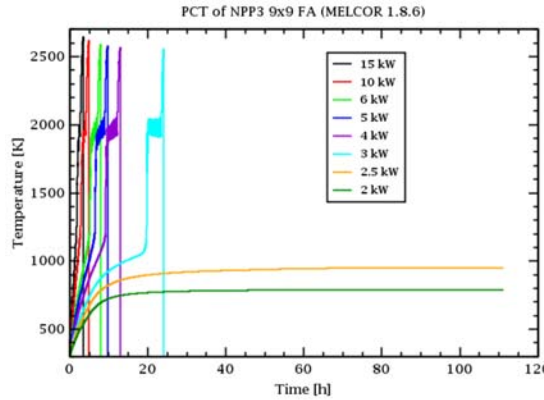

Figure 2: Hot neighbor calculations part 1

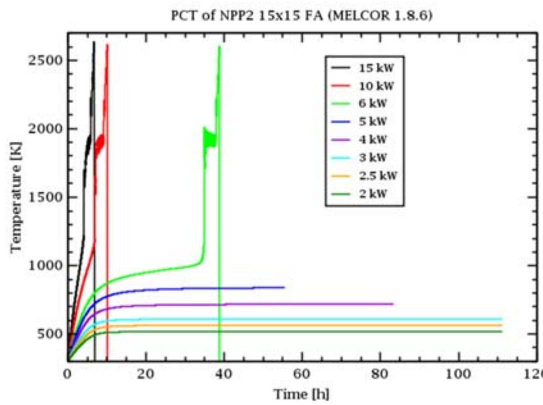

Figure 3: Hot neighbor calculations part 2

Table 2: Fuel assembly parameters

Description	Hydraulic Diameter	Heat ratio
NPP1 14x14-17	1.28 cm	1.305
NPP2 15x15-20	1.40 cm	0.978
SFP 17x17-25	1.24 cm	1.000
NPP3 9x9-7	1.14/1.30 cm	2.472
NPP3 10x10-8	1.03/1.25 cm	2.388
NPP3 10x10-8	1.03/1.12/1.25 cm	2.343
1F4 9x9-9	1.12 cm	2.050

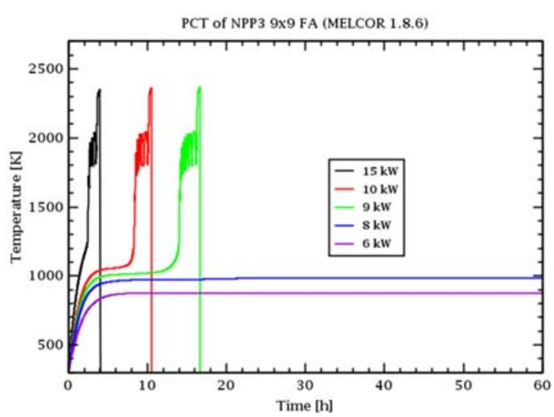

Figure 4: Cold neighbor calculations

The comparison of different code versions of the MELCOR program is shown in Fig. 5. Here a hot neighbor calculation for the FA from KKG is shown with a heat load of 10 kW conducted with four different MELCOR versions. The first version is MELCOR 1.8.6 with the PSI oxidation and break-away model, the second version is with the additional new nitriding model, while the third and fourth versions are official MELCOR releases from MELCOR 2.1 and MELCOR 2.2. Also the two official releases are using the PSI oxidation and break-away model.

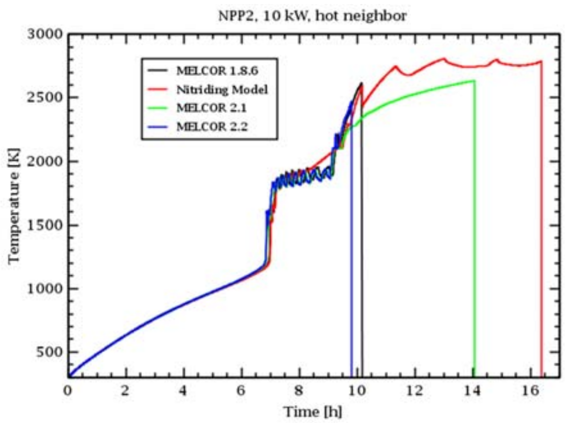

Figure 5: Comparison of MELCOR versions.

As can be seen, the differences are very small. MELCOR 1.8.6 and the nitriding model have identical results until ignition of the FA at about 1200 K. The nitriding model is only activated in the absence of oxygen or steam as main reaction partners. The calculations of the official releases from MELCOR 2.1 and 2.2 show a slightly earlier temperature escalation due to changes of the heat transfer models which were updated for better quenching calculations with the code.

For the comparison of the calculated behavior with experimental data the SFP Phase I [2] and Phase II [3] experiments were used. Both experiments were conducted at Sandia National Laboratories using commercial 17x17 rods PWR fuel elements with MgO as model for the fuel.

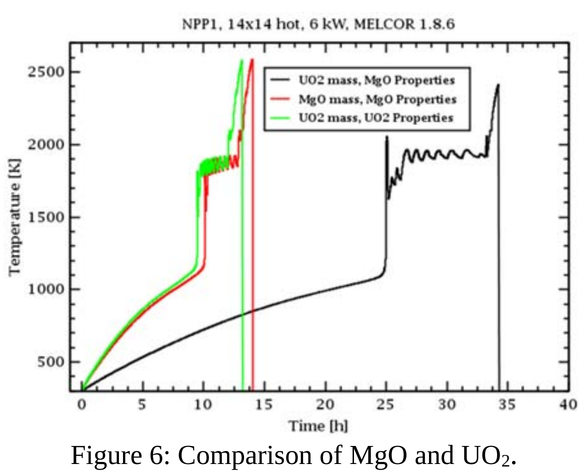

Figure 6: Comparison of MgO and UO_2.

The calculation for the FA of KK1 with 6 kW heat load shows a very good estimation between the UO_2 and the MgO behavior. This demonstrates, that MgO is a perfect model for the fuel in this experiment. The only problem is the missing eutectic reaction between MgO and the cladding material. For the temperatures below ignition of the cladding it does not play any role. The later accident progression may be influenced by the eutectic reaction between UO_2 and cladding.

The other difference between the experiment in Sandia National Laboratories and the behavior of the Swiss spent fuel assemblies are the boundary conditions, which is related to the air pressure in Albuquerque of 830 mbar.

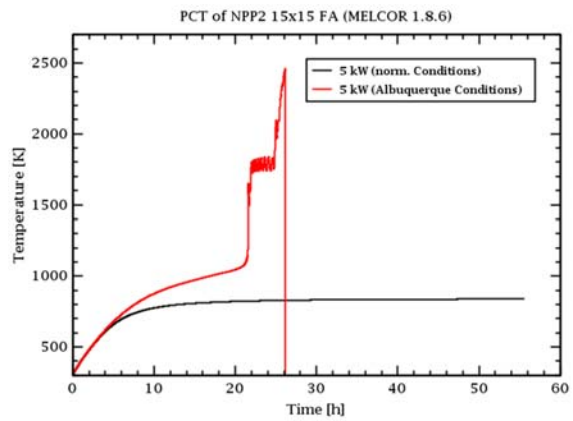

Figure 7: Influence of air pressure on accident progression.

The almost 20% lower air presure in Albuquerque (Elevation about 1600 m) results in a lower heat capacity of the atmosphere and a lower pressure drop, which is responsible for the chimney effect (flow velocity) and so the convectional heat loss ios strongly reduced. Fig. 7 shows a hot neighbor calculation of NPP2 FA under Albuquerque conditions and under Swiss conditions. While ignition is calculated in Albuquerque after about 20 h, there is no ignition under conditions at sea level.

The calculation of the ignition in the upper part of the centered 17x17 rod fuel assembly from the experiment Phase II is shown in Fig. 8. The ignition happens at about 90% elevation of the active fuel, which means in the experiment 90 % of the heated length. Immediatelly after the ignition the starvation of oxygen begins and the zirc fire starts to propagate downwards. It can be observed, that the temperature in the node igniting first is dropping and the fire front is moving to the lower node.

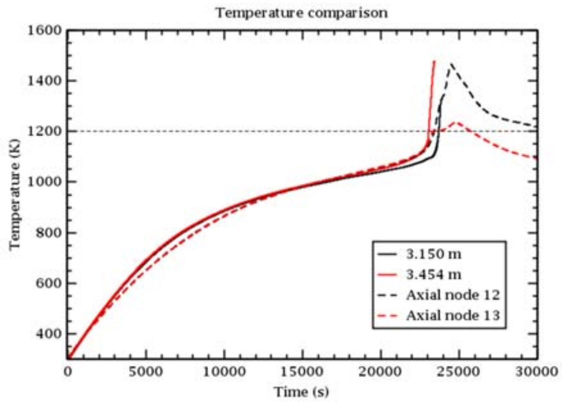

Figure 8: Temperatures of SFP Phase II.

The downward propagation of the zirc fire with complete consumption of the oxygen leaves the upper nodes under oxygen-starved conditions. Regarding the temperature dependent reaction rate of the zirconium nitriding now the remaining cladding material will be nitrided. The off-gas analysis (Fig. 9) shows not only the consumption of oxygen, but also a partial consumption of nitrogen.

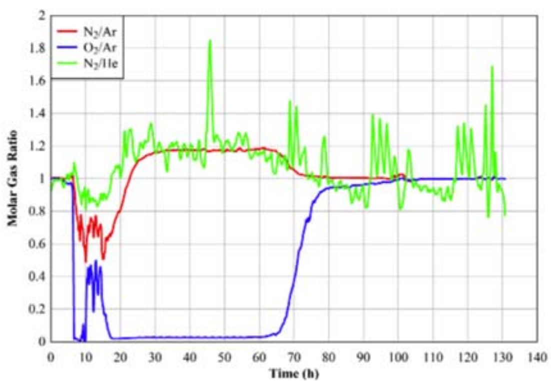

Figure 9: Off-gas analysis of SFP Phase II.

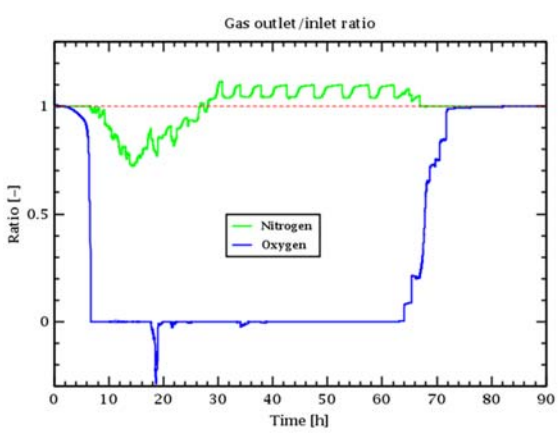

Figure 10: Calculated gas outlet versus inlet ratio.

The calculated behavior of the consumption of the gasses oxygen and nitrogen (Fig. 10) are in qualitative good estimation with the measured data. The oxygen "recovery" after about 10 h can be explained with countercurrent gas flow at the outlet due to the consumption of all the oxygen and some nitrogen as well. The negative value of the oxygen ratio underlines the possibility of a countercurrent gas flow, even if MELCOR is not a CFD tool which could deliver better results for this behavior.

6 CONCLUSIONS

The calculations have shown, in comparison with experimental data, that the cold neighbor storage policy is a good way to enhance the safety of spent fuel in a spent fuel pool. All the investigated MELCOR versions showed very good estimation until the time of zirc fire ignition. After onset of the zirc fire the nitriding model showed good capabilities to describe the accident progression until the end of the experiment inclusive the gas consumption and release in the late phase of oxidation of the zirconium nitride.

ACKNOWLEDGEMENTS

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