Investigation of the Effect of the Spent Fuel Pool Configuration on Fuel Degradation

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ABSTRACT

The accident in the nuclear power plant Fukushima Daiichi in 2011 highlighted the importance of the safety of nuclear spent fuel pools. Fortunately during the accident the fuel inside the spent fuel pool was not damaged, however awareness rose regarding a possible meltdown scenario inside a spent fuel pool.

In general, special dedicated codes (e.g.: MELCOR, ASTEC, ATHLET-CD/AC2) are used to analyze the very complex phenomena that can occur during a severe accident. These codes are, however, optimized for reactor configurations. The core region is divided radially into concentric rings, axially into many levels. This code characteristic is not well suited for the typically not cylindrical geometry of the spent fuel pools.

An option was implemented into the developer version of ATHLET-CD (which is the module in AC2 responsible for the simulation of phenomena that occur during a severe accident) that departs from the ring-like structure of the core nodalization and allows the user to use flexible nodalization inside the fuel region. This option makes simulations in spent fuel pools easier and more adequate.

A set of calculations with different configurations were performed using the flexible nodalization to analyze the effects of the fuel assembly positioning on a hypothetical accident scenario inside a generic spent fuel pool. Results of these calculations as well as the required model changes due to the flexible nodalization are going to be presented, which could give new information about the coolability of spent fuel pools.

KEYWORDS
heat radiation, spent fuel pool, ATHLET-CD, AC^2

1. INTRODUCTION

The environmental consequences of the nuclear accident at the Fukushima Daiichi power plant unfolded from the processes related to the degradation of the fuel assemblies in the reactor vessel. Parallel to these events the cooling of the spent fuel pools (SFP) was interrupted. The outage was fortunately not long enough to uncover the fuel assemblies, so fuel damage was avoided.

However, scenarios are possible, where the cooling outage is long enough to uncover the fuel assemblies, which then can lead to fuel degradation and fission product release. Simulating such events was not in the focus of research, but the events in Fukushima Daiichi highlighted the possibility of severe accidents in spent fuel pools, thus giving the spent fuel pool a large safety relevance.

The evolution of accidents in a spent fuel pool are slow compared to the accidents inside a reactor, but the environmental impact of such accidents can be significant, especially for spent fuel pools that are not inside the containment. This gives good motivation to analyze severe accidents also in spent fuel pools.

Codes however, that can simulate severe accident phenomena were developed and optimized mostly for reactor configurations: cylindrically symmetrical loading, no large empty (water filled) volumes. Generic spent fuel pools have mostly a rectangular geometry, which makes the adequate modelling using the typical "ring-like" nodalization of the severe accident codes difficult.

A new option was developed for ATHLET-CD (which is part of the code system AC^2, developed by GRS), which allows the user to define flexible nodalization in- and outvessel. The new option doesn't use the typical ring-line nodalization of the core region. The new nodalization allows therefore a better representation of severe accidental processes inside a reactor vessel or in a spent fuel pool, where cylindrically symmetrical conditions are not applicable.

This paper presents the basic idea of the new nodalization scheme and the model changes that were necessary for its implementation. The functionality of the new nodalization is going to be presented on a series of spent fuel pool calculations. The aim of these calculations was to analyze how the position of the different fuel assemblies with different decay power influence the accident scenario.

2. MODELLING SEVERE ACCIDENTS IN SPENT FUEL POOLS

Analyzing severe accidents in spent fuel pools is possible using the existing major severe accident codes (for example: MELCOR, ASTEC, ATHLET-CD) [1,2,3], but requires the user to make simplifying assumptions, mostly because of the non-cylindrical geometry of the spent fuel pool and the non-uniform power distribution of the stored fuel assemblies. Such configurations are unlikely/nonexistent in reactor cases. Historically, the severe accident codes were developed for reactor applications, thus the fuel region is typically nodalized horizontally into radial rings, axially into many levels. The fuel rods that are inside a horizontally and axially defined "ring-node" are assumed to be behaving identically. This is a valid assumption, because the fuel rods inside a reactor vessel are organized azimuthally symmetrically. To apply the ring-like nodalization scheme for a typically rectangular spent fuel pool geometry is difficult (Figure 1).Some parts of the spent fuel pool covered by a "ring-node" are empty (filled only with water), while different ring segments have fuel assemblies with high or low decay power. Defining all these different zones into one ring creates an average of the different spent fuel pool zone properties. Some parts of the "ring-node" are even outside of the physical boundaries of the fuel pool. To be able to use the ring-like nodalization adequately for spent fuel pool configurations the fuel assemblies must be repositioned artificially so that fuel assemblies with similar properties can fit into a ring-like node. This however is not resembling most of the real spent fuel pool loadings. Changing the positions of the fuel assemblies can influence the accident scenario. One of the aims of this paper is to demonstrate this effect.

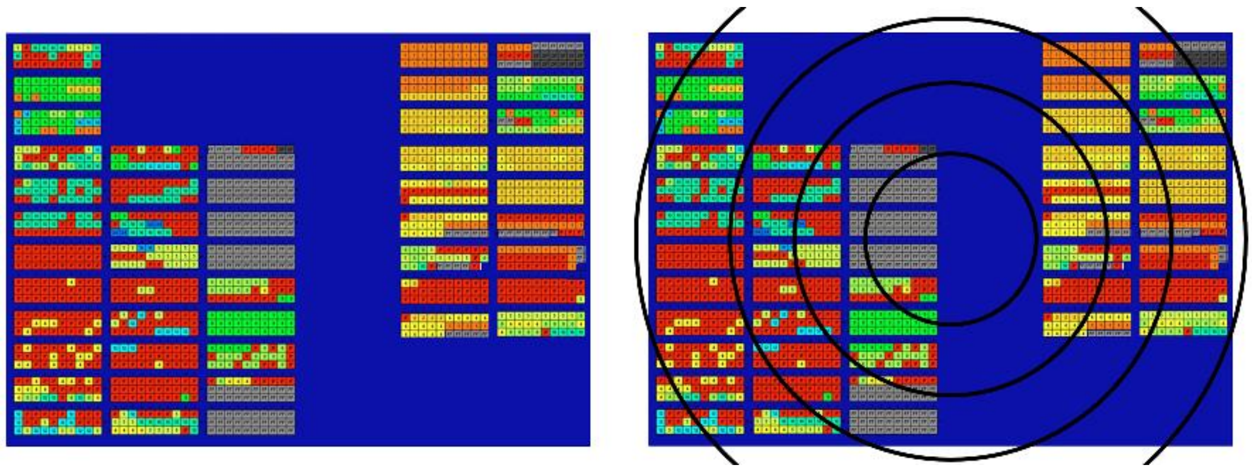

Figure 1, Spent Fuel Pool Nodalization Using the Standard Ring-Like Method

The developer version of ATHLET-CD has a new feature that allows the user to use a non ring-like nodalization within the core region. Figure 2shows an example of the flexible nodalization. The user can explicitly input the coordinates of the desired rectangular nodes (nodes do not have to be of equal size). With this option the typical rectangular geometry of the spent fuel pool can be represented without averaging large different areas and without violating the physical boundaries of the spent fuel pool.

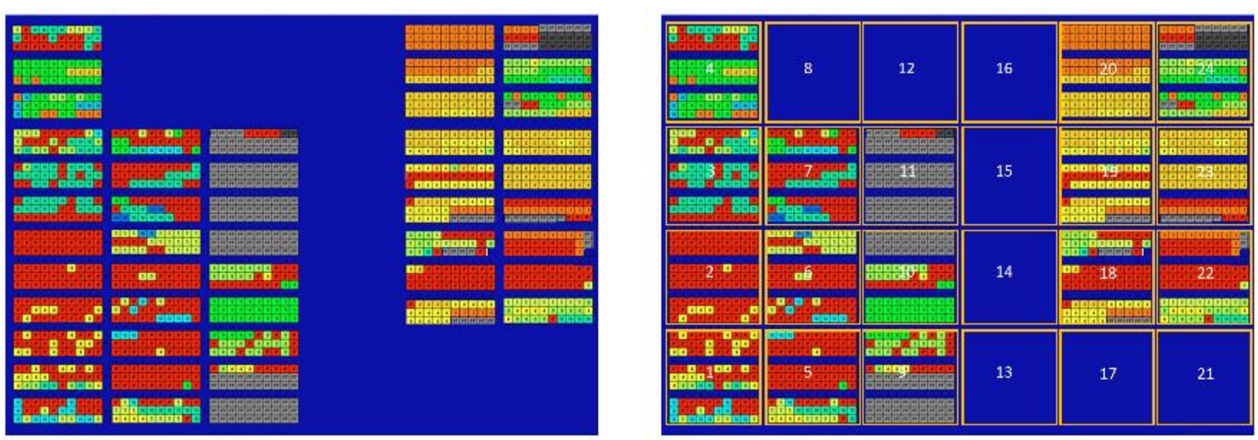

Figure 2, Spent Fuel Pool Nodalization Using the Flexible Nodalization Method

Changing the hardcoded ring-like nodalization of ATHLET-CD had some consequences on the existing models. Fortunately, only some models took advantage of the typically cylindrically symmetrical configurations. The following conclusions were made [4]:

- Inside a node many of the phenomena are calculated pinwise and the results are multiplied by the number of rods defined in the node. These phenomena are: convective and conductive heat transfer, deformation, oxidation, fission product release and axial melting processes.
  - Nodalization change only affects the number of rods inside a node, no changes of the physical models are necessary.
- The thermohydraulic properties of the core can be flexibly defined by the user.
  - Nodalization change does not effect the physical models.
- Communication between core nodes via radiation or radial movement of molten material.
  - Change is necessary, because current models take advantage of the cylindrically symmetric configuration

Therefore a new heat radiation model was developed that can calculate the radiative heat transfer in a possibly complex, non-cylindrical geometry, while taking core degradation processes into account. The horizontal movement of molten material between nodes is yet only available for ring-like nodalization, therefore in this article only axial melt relocation is considered.

2.1. New Heat Radiation Model [5]

In ATHLET-CD radiative heat transfer is considered between nodes. If a node melts, then heat radiation is automatically calculated towards the next node. To calculate the radiative heat transfer equation 1 is solved in every timestep:

$$\frac{Q_{node}}{dt} = \sum_{i}^{\substack{source\\sides}} \sum_{j}^{\substack{target\\sides}} VF_{i-j} * \sigma * \varepsilon_i * \varepsilon_j * A_i * \left(T_i^4 - T_j^4\right) \quad (1)$$

Where:

- VF_{i-j} is the view factor from side i to side j
- A_i is the area of the side [m^2],
- σ is the Boltzmann constant [J/K],
- ε_i, ε_j is the emissivity of source/target [-],
- T_i, T_j is the temperature of source/target [K],
- Q_{node} is the energy transferred from/to source [J],
- dt is the time step [s].

The main difficulty for the radiative heat transfer calculations is the determination of the view factors of the communicating surfaces. The view factor between surfaces X and Y is the proportion of the radiation which leaves surface X and strikes surface Y. Its value only depends on the current geometry. In a cylindrically symmetric configuration it is possible to determine the view factors analytically. Also, the identification of the free surfaces after core melt is relatively easy, no shadowing effects can occur (or are very unlikely).

Using the flexible nodalization in the core region, the calculation of radiative heat transfer between nodes can be very complex, due to the geometry changes in the core during a severe accident. Figure 3 shows that after the melting of a node (indicated with red zones in the top views, with empty zones in the side view) new heat radiation paths become available.

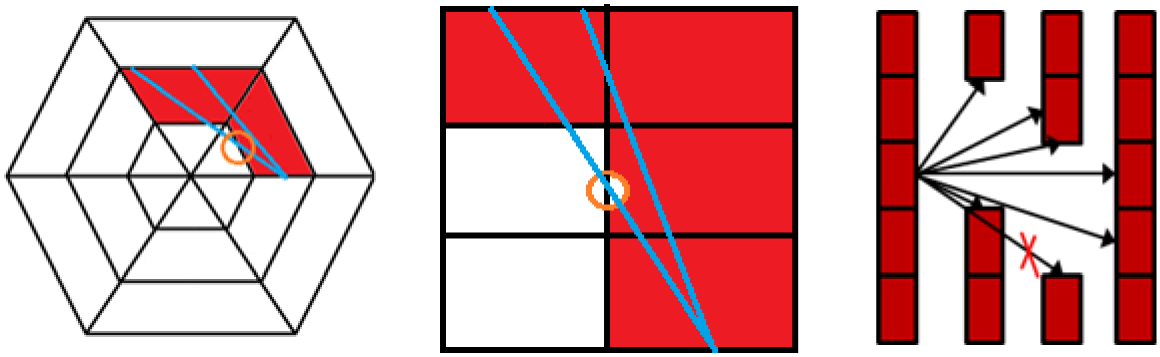

Figure 3, Top and Side View of a Partially Molten Reactor / Spent Fuel Pool Using the Flexible Nodalization - Heat Radiation Paths with Shadowing -

Configurations can occur, where heat radiation between two sides is blocked (shadowed) by a still intact side. This shadowing effect of course has to be taken into account in the determination of the heat radiation, three-dimensionally.

There is no analytical solution for all the possible configurations. That is why a numerical method was implemented into the developer version of ATHLET-CD to determine the view factors for the radiative heat transfer calculations. View factors for a constantly changing geometry can be determined numerically by solving equation (2), as follows:

$$VF_{X-Y} = \frac{1}{\pi * A_X} * \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\cos(\theta_X) * \cos(\theta_Y) * block}{S^2} * dA_j * dA_i \quad (2)$$

Where:

- A_X is the side area [m^2],
- dA_i, dA_j is the area of the subsurface [m^2],
- Θ_X, Θ_Y is the angle of the line connecting the two subsurfaces to the normal vector of the surface [°],
- S is the distance of the two subsurfaces [m],
- N is the amount of subsurfaces [-],
- block is the blockage indicator; its value is 1 or 0 [-],
- VF_{X-Y} is the view factor from surface X to surface Y [-].

The developed model takes the sides of the nodes as flat surfaces into account. It is a valid assumption, because inside a node all the fuel rods have the same temperature and due to the many rows of fuel rods the heat radiation cannot pass through a node. That is also a limitation of the model. The basic logic of the model is valid as long as there are at least three rows of fuel rods defined in a node. These are assumed to block any radiation between adjacent regions. The equation 2 is visualized in Figure 4.

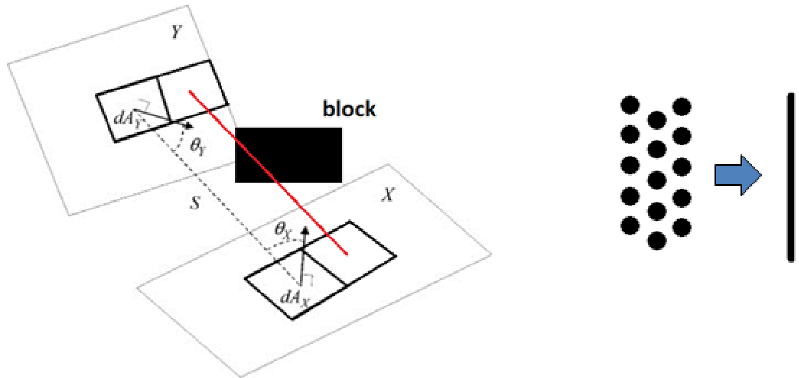

Figure 4, Visualization of Equation 2 (left) and Node Surface Assumption (right)

To calculate the view factor from one side to another both surfaces have to be divided into small subsurfaces and the sub view factors have to be calculated between all subsurfaces. The sum of these sub view factors is the view factor which is used during the thermal radiation calculations. During the calculation it is checked, whether the line between the centers of the sub surfaces passes through a still intact object, which can block the radiation between the two surfaces. If that is the case, the contribution of that sub view factor to the general view factor is zero. After the calculation is done a check is performed. The sum of all view factors from one side equals one, at all times, in any configuration. If the calculated sum of view factors for a side is within the range 0.9 – 1.1, the calculation is considered accurate enough. If it is outside this range, then a more detailed subdivision of the surfaces is needed.

Using flat surfaces as boundary for the nodes makes the numerical calculation reasonably fast, however it cannot be performed in every timestep. View factor calculation is performed if the geometry changes significantly, which means, after 70% of the node is already relocated.

Furthermore, the following assumptions are made for the determination of the radiative heat transfer between the nodes:

- The fluid is completely transparent, the emissivity of the structures is user input.
- Currently only the temperature of fuel, cladding and structure material is considered, heat transfer to melt and crust is taken only into account in an indirect way (radiation to structures, heat transfer from structures to melt/crust). Radiation directly to melt/crust is topic of future development.
- Heat radiation horizontally to the core surroundings is considered, however those structures cannot melt if they reach their melting temperature.
- In spent fuel pool calculations the heat radiation to the environment above and below the pool is calculated using a user defined temperature.

3. SPENT FUEL POOL ACCIDENT SIMULATIONS USING THE FLEXIBLE NODALIZATION

3.1. Model and scenario description

In order to demonstrate the importance of the adequate spent fuel pool nodalization and the functionality of the new model, a series of simulations are presented. Each simulation calculates the same scenario at the same spent fuel pool, the only difference between the calculations is the power and spatial distribution of the stored fuel assemblies. The simulations were terminated after the molten mass reached 50% of the total mass in the spent fuel pool.

A generic spent fuel pool model was developed, with a side ratio of 6.75m x 9.87m. The total power of the simulated spent fuel pool was 2.345 MW and 1440 out of the possible 2160 spent fuel assemblies were stored in it. These parameters are comparable with the parameters of the spent fuel pool of Fukushima Daiichi Unit 4. [6] The postulated accident is a loss of coolant scenario, the assumed leak mass flow was 10 kg/s. The spent fuel pool was divided into 24 equal rectangular nodes, using the new, flexible nodalization method. Each node consists of 90 fuel assembly positions.

Three different fuel assembly configurations were analyzed, they are depicted in Figure 5. “Configuration 1” is the closest to the spent fuel pool configuration of Fukushima Daiichi Unit 4 regarding fuel assembly and power distribution. “Configuration 2” had the same spatial distribution of fuel assemblies as “Configuration 1”, but a perfect mixture of fuel assemblies was assumed, creating an average power for all non-empty nodes. “Configuration 3” has a new spatial distribution of the fuel assemblies. The aim was to distribute the empty spaces along the spent fuel pool to be able to analyze the potential cooling effect of the empty nodes. Still, all the non-empty nodes have the same power. The used power distribution in the different configurations is summarized in

Table I. If the power of a node is 0 then there were no structures defined, they are considered empty (blue nodes in Figure 5). Exception is the node 11 in “configuration 1”, because it represents a node filled with fresh fuel, without any decay power.

Thermohydraulically, all nodes are connected with all their neighbouring nodes, however cross-flow is limited, as long as canister walls are intact in the nodes. Figure 5 shows only the top view of the fuel assembly region, there are two other water volumes, one above this region and one below this region. Along the sides of the pool four downcomer nodes are defined. ATHLET-heat objects are defined in the downcomer nodes, they represent the walls of the spent fuel pools. They are simulated as a flat wall, with 1 cm thickness of steel and 1 m thick concrete. The outside temperature is set as a boundary, at 20 °C. Above the pool air is defined, with atmospheric pressure. The leak is defined at the bottom of the pool.

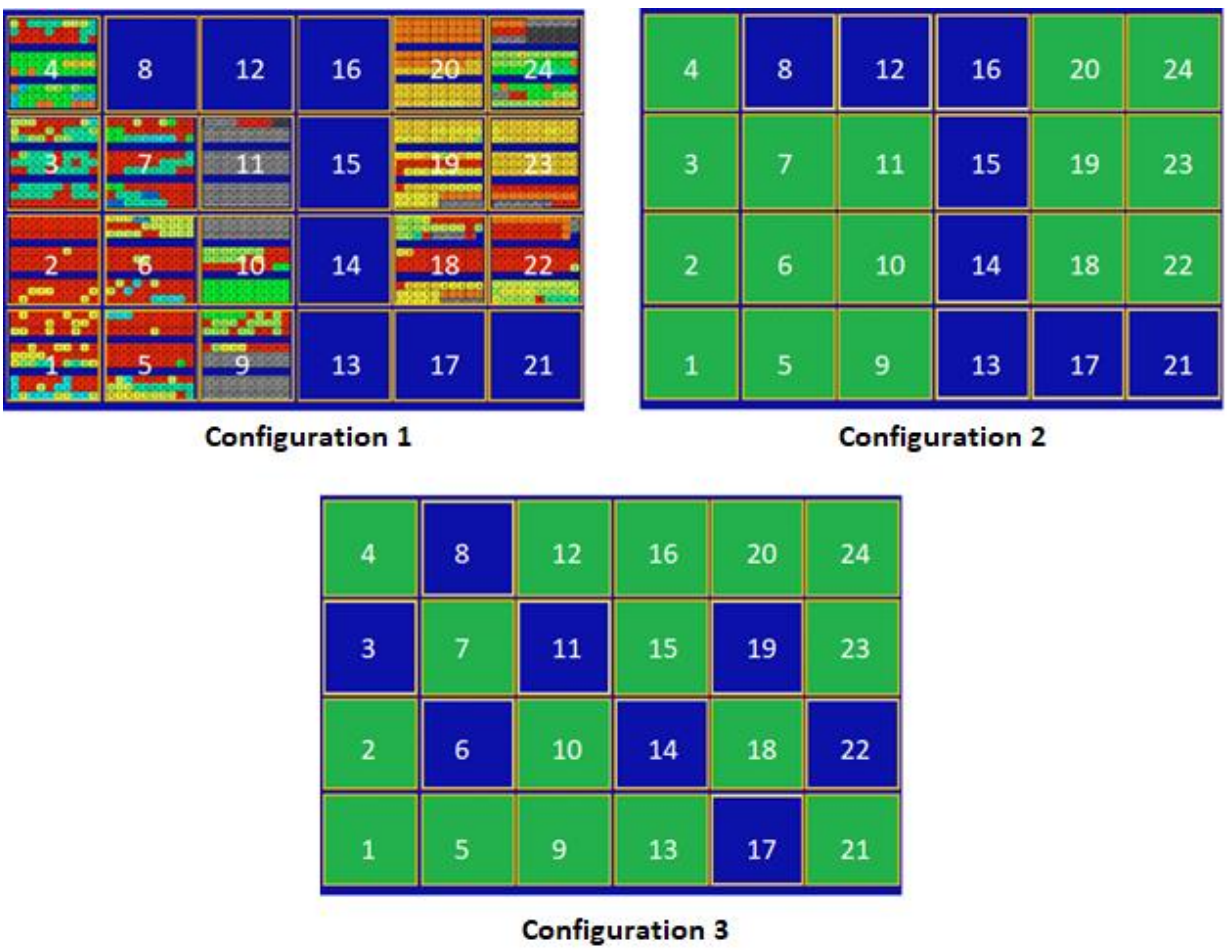

Figure 5, Top View of the Analyzed Fuel Assembly Configurations in the Spent Fuel Pool
(Colors indicate the power of the node: red – high power, yellow – medium power, green – low power, dark blue – empty node (filled with water))

Table I. Power distribution of the spent fuel pool in different cases

	Power (W) "Configuration 1"	Power (W) "Configuration 2"	Power (W) "Configuration 3"
1	186230	146572	146572
2	304800	146572	146572
3	135710	146572	0
4	177240	146572	146572
5	297270	146572	146572
6	287160	146572	0
7	192140	146572	146572
8	0	0	0
9	63790	146572	146572
10	64640	146572	146572
11	0	146572	0
12	0	0	146572
13	0	0	146572
14	0	0	0
15	0	0	146572
16	0	0	146572
17	0	0	0
18	155790	146572	146572
19	79280	146572	0
20	76260	146572	146572
21	0	0	146572
22	186600	146572	0
23	90250	146572	146572
24	47990	146572	146572
Sum of power (W):	2345150	2345152	2345152

3.2. Simulation results

Figure 6 shows the evolution of the maximum cladding temperature in the different configurations. As it is clearly visible, as long as the fuel assemblies are covered by water, their cooling is sufficient. The water level reaches the top of the fuel assemblies at approximately 30000 seconds after the start of the LOCA scenario. The heat up of the upper parts of the fuel assemblies is not significant at the beginning, due to their relatively low decay power and due to the fact that the parts below are still cooled. The generated heat can be removed by axial conduction. As larger parts of the fuel are uncovered, the temperatures rise and the first differences occur due to the unequal effectivity of the cooling via heat radiation. At about 64000 seconds after the initiating event the whole fuel assembly is uncovered. The disappearance of the water plug in the bottom part of the fuel assemblies allows the air to flow through completely. This leads to a natural circulation, which increases the coolability of the spent fuel assemblies. The cooling effect of the natural circulation can be seen in Figure 6 at around 64000 seconds, because the maximum cladding temperatures decrease temporarily. The natural circulation is, however not strong enough to cool the spent fuel pool in the long term, therefore after a short temperature decrease the fuel assemblies start to heat up again.

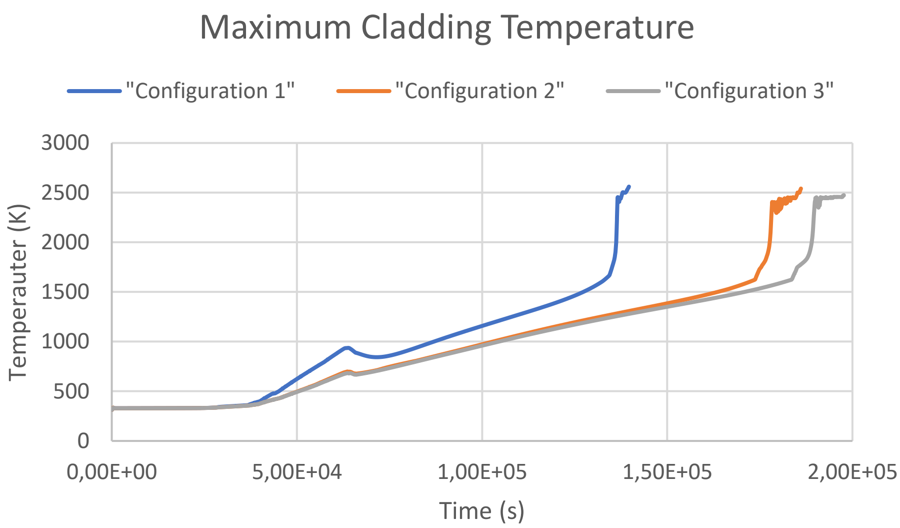

Figure 6, Evolution of Maximum Cladding Temperatures in Different Configurations

The slow but continuous temperature increase lasts until the temperature of the hottest zone reaches the breakpoint, where oxidation processes start to dominate. There are, however, significant time differences when this point is reached.

Figure 7 shows the evolution of molten masses in the spent fuel pool. At around the start of oxidation the canister walls melt, then after an excessive heat generation due to the oxidation, also the cladding and the fuel start to melt.

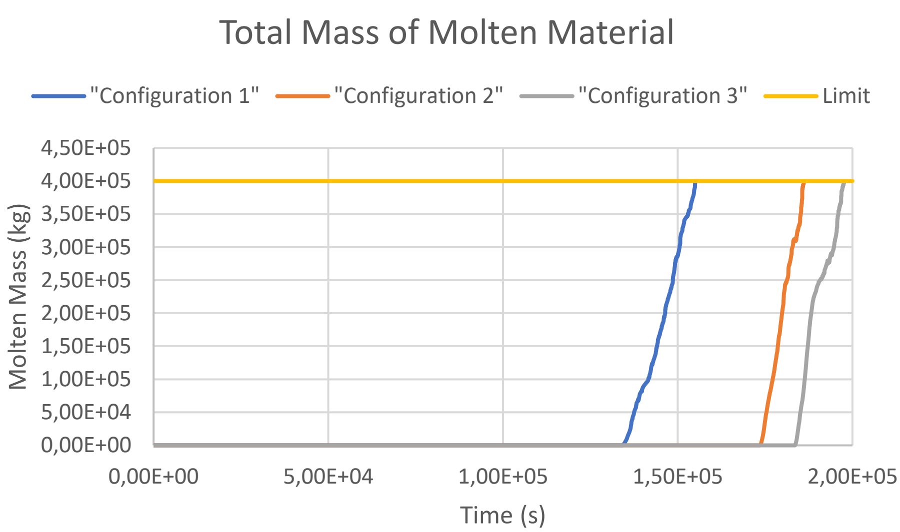

Figure 7, Evolution of Molten Mass in Different Configurations

As it was expected, the earliest melt formation is in “Configuration 1” and the first melt formation occurs in the node 6 at around 135000 seconds. In “Configuration 1” that node has one of the highest power and its neighbours have also relatively high decay power. Therefore, it can not be cooled effectively by thermal radiation, which leads to an early melt formation. In “Configuration 2” all the nodes have the same decay power, but node 6 is the only node that has no cold neighbours. Therefore, in this configuration also the first melt formation occurs in the node 6. However, approximately 40000 seconds later than in “Configuration 1”. In “Configuration 3” the first melt occours later, at around 184000 seconds in the node 16. In “Configuration 3” this node has the least cold neighbours (similarly to node 9, which melts soon after node 16).

The main events of the accident scenarios for the different configurations are summarized in Table II.

Table II. Summary of main events in different configurations

	Configuration 1	Configuration 2	Configuration 3
Water level at the top of fuel assemblies	30000 s	30000 s	30000 s
Water level at the bottom of fuel assemblies	64000 s	64000 s	64000 s
Excessive oxidation start	135000 s	175000 s	185000 s
First melt occurrence	135000 s	175000 s	185000 s
First node to melt	6	6	16 / 9
50 % melt mass limit reached	156000 s	186000 s	198000 s
Time between first melt occurrence and 50 % melt mass limit reached	22000 s	12000 s	14000 s

The simulations showed that spent fuel pool configurations can have a big influence on the accident evolution. Distributing spent fuel assemblies uniformly in a spent fuel pool can give considerate amount of extra time to prevent fuel degradation. But if melt starts to form in a spent fuel pool with uniformly distributed fuel assemblies then the rate of melt formation is faster, due to the more or less equal power distribution the temperature of the stored fuel is similar.

The simulations were done using the newly implemented external numerical toolkit of ATHLET-CD [7]. The numerical toolkit “ATHLET-NuT” could accelerate the calculations by approximately 30%. Simulating the scenarios for the different configurations took about 2.5 days each, on a normal PC. Dividing the spent fuel pool into 24 core nodes and defining cross connection between all nodes is maybe more detailed than it is needed for plant applications. Using this detailed subdivision of the spent fuel pool could however demonstrate the applicability of the new nodalization method in spent fuel pool configurations and show possible future applications. Also, the simulations delivered expected results qualitatively, therefore the study could have been also used for verification purposes.

4. CONCLUSIONS

A new nodalization method was implemented into the developer version of ATHLET-CD. The departure from the typical ring-like nodalization required some model changes which were also demonstrated. This new method can be used to nodalize and analyze accident scenarios in a spent fuel pool more adequately than before. Three spent fuel pool simulations were presented in this paper, that demonstrated the applicability of the new model in spent fuel pool configuration and could be used as verification. Also, the simulations delivered some interesting results regarding optimal spent fuel pool configurations.

The new nodalization method and the developed new models deliver promising results, some other tests are however still required before this new option is released.

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