Severe Accident Analyses for Shutdown Modes and Spent Fuel Pools to Support PSA level 2 Activities

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Abstract:
In the field of Level 2 PSA at GRS two projects are being performed in order to investigate both shutdown modes and severe accident sequences following from external hazards of nuclear power plants as well as spent fuel pool behavior under severe accident conditions. These works are being done for both PWR and BWR respectively. For both projects, deterministic severe accident analyses using the MELCOR code are a main part of the activities in order to support the probabilistic part of these projects.
The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Office for Radiation Protection (BfS) financially support a project regarding deterministic analyses of severe accident sequences during shutdown modes and external hazards (flooding, aircraft crash, earthquakes and explosions pressure wave). These results can be used for supporting future Level 2 PSA studies.
Within a research project financially supported by the German Federal Ministry of Economics and Technology (BMWi) an extension of probabilistic analyses of spent fuel pools is being performed. Appropriate methods for the consideration to spent fuel pools inside a PSA Level 2 will be developed. The main goals are the identification of the impact of severe accidents inside spent fuel pools onto the plant behavior and the quantification of related releases of radionuclides into the environment.
Results of MELCOR analyses done for the two projects mentioned above are presented. First, preliminary results of a severe accident sequence initiated by a loss of decay heat removal of a PWR shutdown mode are discussed. Following, preliminary results of the PWR spent fuel pool behavior after a “Station Black-out” are shown.
It could be shown that the integral code MELCOR is able to calculate the accident progression of an event starting from a shutdown mode of a PWR and the severe accident sequence inside of a PWR spent fuel pool. The results seem to be realistic from an engineering judgment point of view. Both projects are ongoing and thus, several improvements of the analyses will be expected.

1 ACCIDENT ANALYSES FOR SHUTDOWN MODES

In Germany plant specific PSA has to be performed within the periodic safety assessments as follows:

- PSA Level 1 for plant internal initiating events and a selection of plant external initiating events (airplane crash, explosion, high flood and earthquake, for full power and shut down states).
- PSA Level 2 for plant internal initiating events for full power states only.

As a consequence, there is not much experience available with severe accident analyses including fuel melt for shut down states and for sequences following from external hazards. In order to gain related knowledge, BMU/BfS has commissioned GRS to perform related analyses in the framework of contract 3612R01361. The project started in 2012 and will end in 2015. In a first step, the most relevant accident scenarios have been identified. In a second step, a selection of the relevant sequences is being analyzed with the MELCOR code.

For PWR in shutdown mode, the following relevant sequences have been identified:

- Erroneous triggering of **e**mergency **c**ore **c**ooling **s**ystem (ECCS),
- Failure of decay heat removal pumps (**r**eactor **p**ressure **v**essel (RPV) open),
- Failure of decay heat removal pumps (RPV closed),
- station blackout, and
- 25 cm^2 leak in a decay heat removal loop inside the reactor building and failure of leak isolation.

For BWR in shutdown mode, a similar event list has been generated. Regarding external events at full power operation mode, also two lists of sequences have been set up for PWR and BWR, respectively.

Several of these scenarios will be analyzed within the project using MELCOR 1.8.6. Currently, the scenario “Failure of decay heat removal pumps at mid-loop operation (RPV open)” is in an advanced state of analysis, and the related preliminary results will be presented.

1.1 Initiating Event and Boundary Conditions

As an example, first results of the calculation of the failure of **r**esidual **h**eat **r**emoval (RHR) pumps during mid-loop operation and open reactor circuit is shown. The used boundary conditions are listed in table 1.1. All available RHR pumps fail due to common cause failure of 3 pumps and a random failure of the emergency RHR pump. The fourth RHR pump is out of operation due to maintenance.

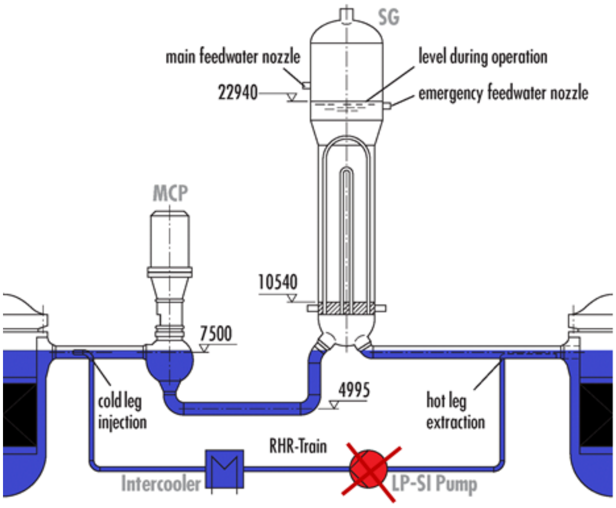
Table 1.1: Boundary Conditions for the event „Failure of Decay Heat Removal“

Failure of Decay Heat Removal, mid-loop operation, RPV open	
Initial event:	Failure of 3 RHR pumps by CCF and 1 RHR pump due to maintenance; additional failure of one emergency RHR pump
Water level in primary circuit:	Mid-loop
State of RPV lid:	removed
Time after shutdown (begin of operational mode):	40 hours
Decay heat (beginning of scenario):	17.75 MW
Miscellaneous actions:	Accumulator injection (6 of 8) at the beginning of the scenario

1.2 Results

Both the state of the primary circuit at event initiation and the calculated events of the severe accident sequence respectivelly are depicted in figure 1.1. It is assumed that the mid-loop operation has been reached about 40 hours after reactor scram. With the initiation of the event the injection from 6 accumulators occurs. The onset of core uncovery is calculated 13:23 h after event initiation. The first failure of fuel rodes occurs at 14:31 h. After 17:14 h, the core is fully uncovered and a significant relocation of molten core / debris starts. The failure of reactor pressure vessel occurs 25 hours after event initiation and **m**olten **c**ore **c**oncrete **i**nteraction (MCCI) is initiated. Due to gas releases from MCCI the containment pressure continiously increases. Thus, filtered containment venting has to be started at 7 bar about 262 hours after event initiation. The venting line stays open for about 13:20 h.

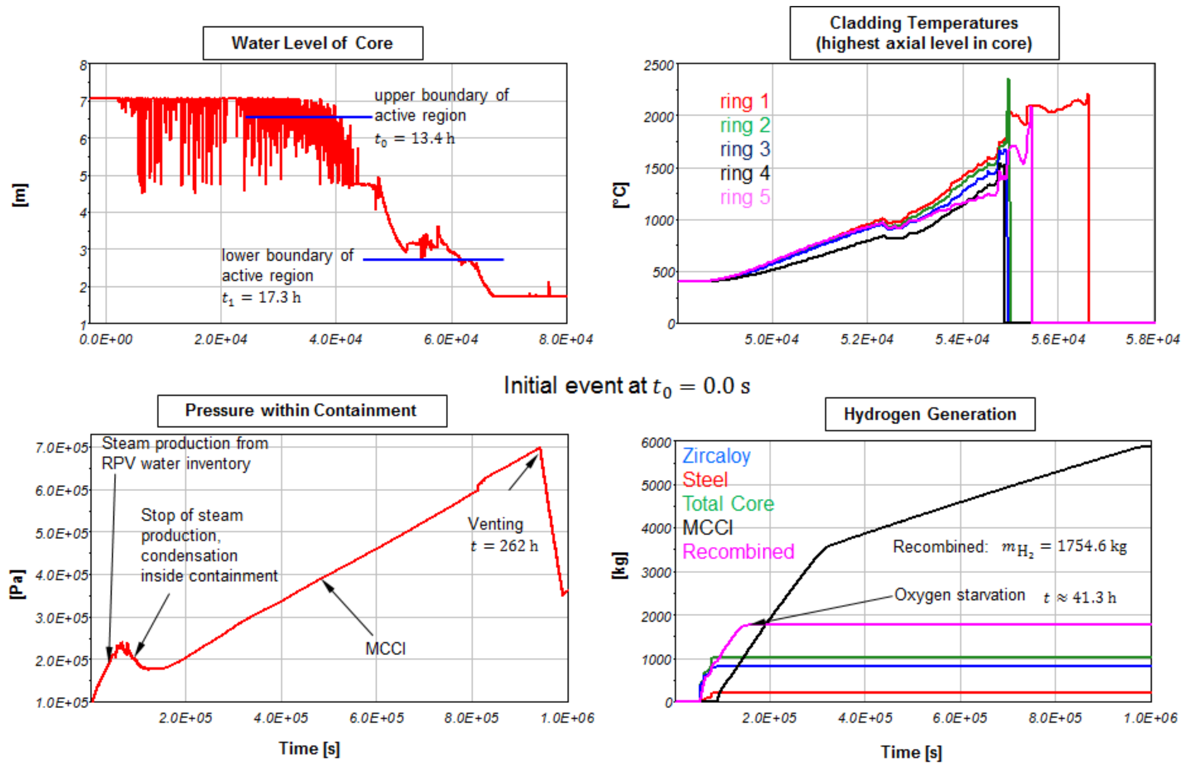
Figure 1.1: State of the primary circuit at the beginning of analysis and calculated events of the sequence



Event	Time
Shutdown	-40:00 h
Accu injection (assumption)	00:00 h
Begin of core uncovery ($L_{RPV} \leq 6{,}63$ m)	13:23 h
Gap release	14:31 h
Exposure of core ($L_{RPV} \leq 2{,}73$ m)	17:14 h
Failure of lower core grid	21:25 h
Dry out of lower plenum	22:00 h
Melt ejection into cavity	25:01 h
Begin of venting ($p_{initiation} = 7.0$ bar)	262:01 h
end of venting ($p_{end} = 3.5$ bar)	275:21 h

More detailed results are shown in the figure below.

Figure 1.2: Detailed results regarding water level, containment pressure, cladding temperatures, and hydrogen generation



At the beginning of the sequence the pressure inside containment is increasing due to the evaporation of primary coolant after failure of RHR. After evaporation of all the coolant and in combination with steam condensation inside the containment, the containment pressure starts to decrease. With the onset of MCCI the containment pressure starts to increase again. The long lasting increase in pressure can only be stopped by the initiation of filtered containment venting. The calculated cladding temperatures show the temperature escalation by oxidation of fuel rods and the subsequent failure and relocation of the rods. Regarding the hydrogen production, about 1000 kg of hydrogen are generated during the oxidation inside the core. With the onset of MCCI additional hydrogen is continiously generated. In total about

1755 kg of hydrogen are recombined by the passive autocatalytic recombiners installed inside containment. Due to oxygen starvation reached at 41.3 hours after event initiation, the recombination of hydrogen is stopped. But, hydrogen production due to MCCI still goes on.

2 ACCIDENT ANALYSES FOR SPENT FUEL POOL

Within a research project financially supported by the German Federal Ministry of Economics and Technology (BMWi) an extension of probabilistic analyses of spent fuel pools is being performed. Appropriate methods for the consideration of spent fuel pools inside a PSA Level 2 will be developed. The main goals are the identification of the impact of severe accidents inside spent fuel pools onto the plant behavior and the quantification of related releases of radionuclides into the environment.
Deterministic analyses of both the accident progression inside the plant and the structural behavior of the pool structure under melt attack will be performed. For the deterministic work regarding the accident progression, the MELCOR code is being applied. Scenarios with uncovering of spent fuel by a postulated "Station Black-out" in combination with failure of accident management measures are investigated.
First preliminary results of MELCOR analyses of a severe accident sequence inside the spent fuel pool of a generic German PWR are presented here. The objective of that MELCOR analysis was to show the applicability of the code on spent fuel pools.

2.1 Initiating Event and Boundary Conditions

Following, first results of a MELCOR analysis of the PWR spent fuel pool are shown. The calculation has been performed up to 125 h after event initiation. Furthermore, a loading of the pool with the whole core of a PWR has been assumed leading to about 12.3 MW decay heat inside pool, in total. The pool is separated from the flooding volume above RPV. For that calculation the spent fuel assemblies of previous cycles usually embedded in the pool were not considered because the plant data were not available. As the objective of the first MELCOR analyses is to show the applicability of the code on spent fuel pools, the assignment of the fuel assemblies to the radial rings presently still agree with the assignment of the fuel assemblies used for reactor analyses. A re-arrangement is being carried out during the final adjustment of the deck currently which is currently underway.

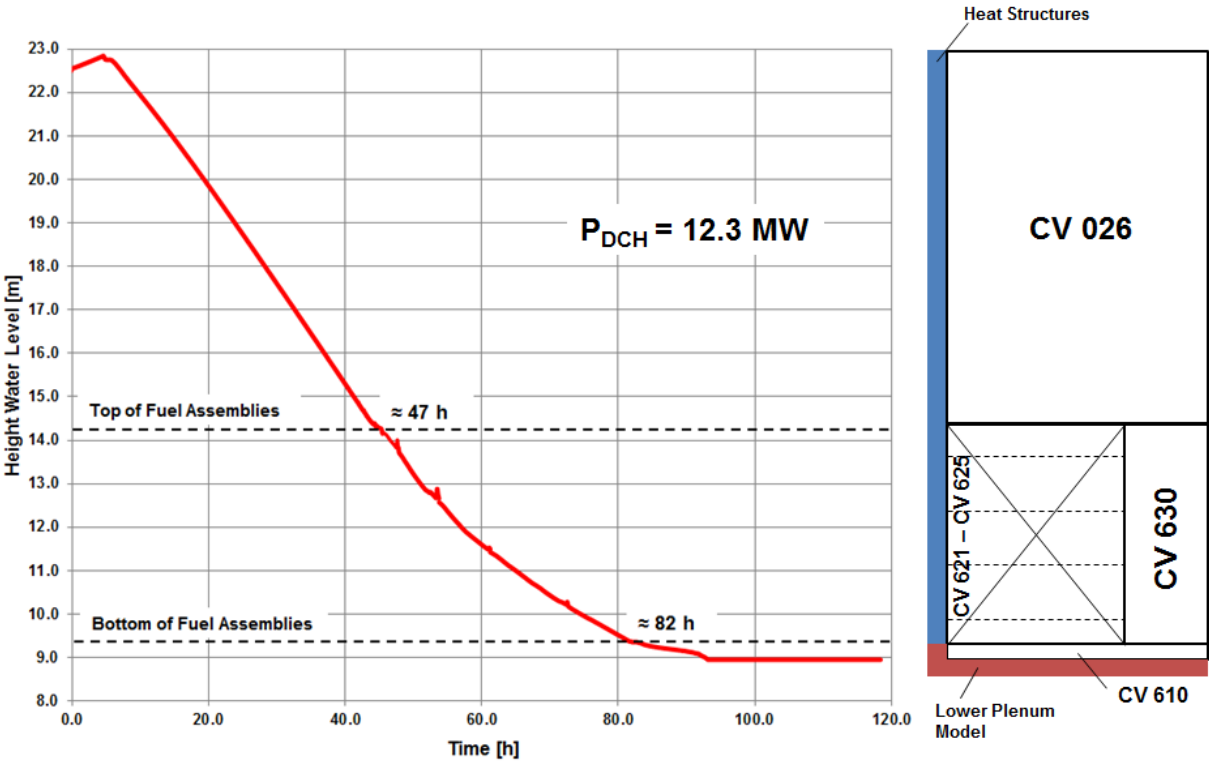
2.2 Results

Following, selected preliminary results of the „Station Black-out" event inside a PWR spent fuel pool are discussed. Section 2.2.1 depicts the results concerning the thermal-hydraulics of the pool. The calculated melt behavior as well as the predicted hydrogen generation inside the pool and due to MCCI are discussed in section 2.2.2. Calculated releases of radionuclides are shown by section 2.2.3.

2.2.1 Thermal-hydraulics

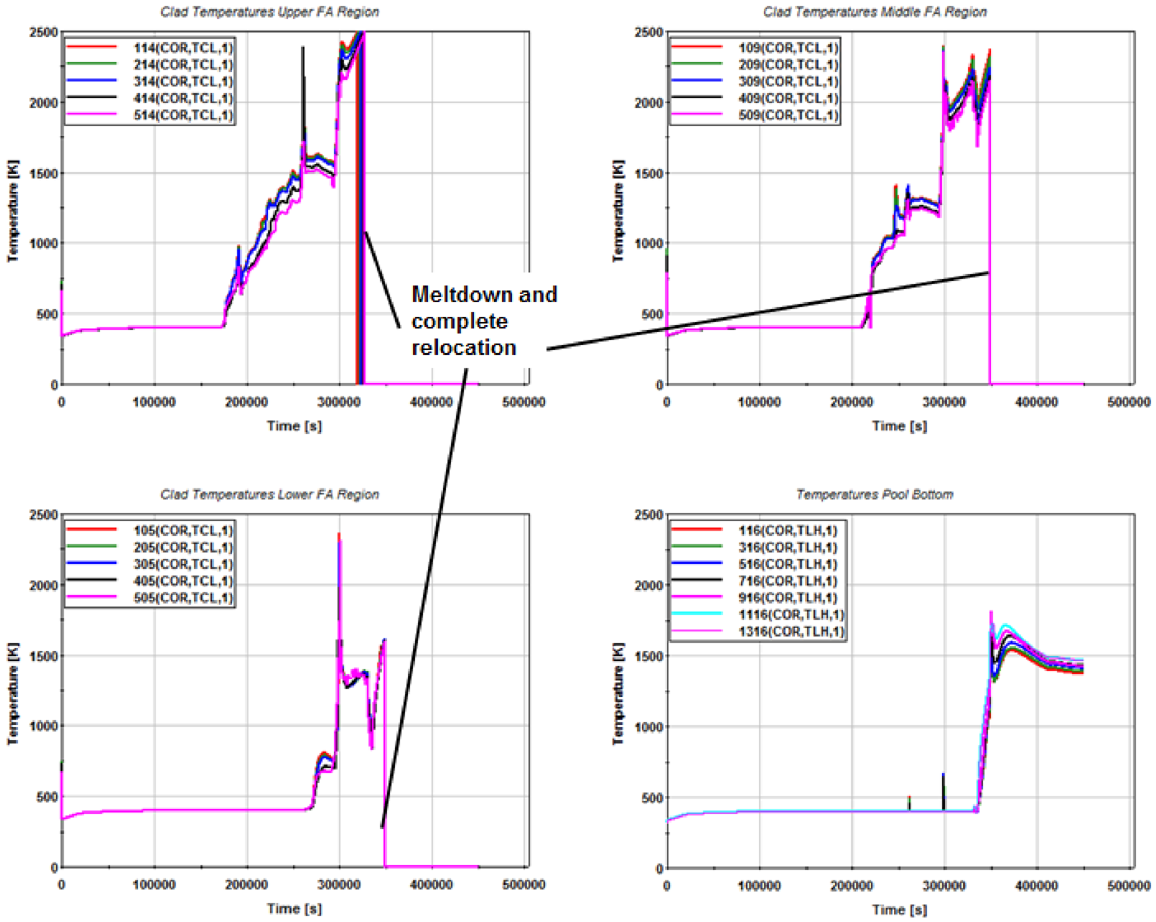
The calculated progression of the water level of the pool is shown in figure 2.1. During the heat-up of the water inside the pool its level increases for about 4.5 hours. With reaching the saturation conditions, the boil-off of the pool water starts. At about 47 hours after event initiation the water level reaches the top of the fuel assemblies. About 82 hours after event initiation the fuel assemblies are fully uncovered. The time span during boiling-off shows, that in case of the "Station black-out" event enough time (approximately 36 h; minimum of 2 m water column above the fuel assemblies) should be available for the realization of emergency management measures like feeding the pool from the top by water hoses. Under radiological safety aspects, such measures have to be carried out with a sufficient water column above the top of the fuel assemblies in order to minimize the radiological consequences for the personnel. Under consideration of the thermal condition inside containment may be much earlier.

Figure 2.1: Calculated water level in the PWR spent fuel pool at 12.3 MW decay heat for SBO scenario



The calculated temperatures of both the fuel assemblies (upper, middle and lower part) and the steel liner of the bottom are depicted by figure 2.2. Simultaneously to the water level falling below the top of the fuel assemblies their heat-up starts in the upper region of the embedded structures. Above approximately 1000 K, the oxidation of the Zircaloy cladding under steam atmosphere increases resulting in an accelerated heat-up of the fuel rods. An escalation of the cladding temperatures can be observed. Later a combined oxidation under steam and air atmosphere occurs. Between 83 hours and 96.7 hours after event initiation the fuel assemblies are totally destroyed and relocated onto the steel liner at the bottom of the pool. The bottom region totally dries out and the steel liner temperatures escalate. By reaching the melt temperature of the steel liner the molten core concrete interaction starts generating both burnable gases like hydrogen and carbon monoxide as well as other non-condensable gases like carbon dioxide. As the containment is closed for that analysis the containment pressure starts to continuously increase again starting from 1.5 bar at initiation of molten core concrete interaction due to the release of gases mentioned before.

Figure 2.2: Calculated cladding temperatures and spent fuel pool bottom temperatures for SBO scenario



2.2.2 Melt Behavior and Predicted Hydrogen Generation

Snapshots of the material distribution in the lower pool region (lower 8 meshes) are depicted in figure 2.3. The first relocation of debris / melt occurs at 83 h after event initiation. At about 91.7 h first material has been relocated to bottom of pool. Up to 96.7 h (348,008 s) a larger amount of debris / melt has been gathered onto the pool bottom. Short time later at 348012 s the whole structure of the upper region of the pool falls down and is distributed on the bottom of the pool. The failure of the steel liner can be seen at 97.1 h. At that point in time the melt is transferred into the cavity model of the MELCOR code, where the MCCI is calculated.

The calculated hydrogen behavior inside the closed containment is shown in figure 2.4. The generation of 960 kg of hydrogen due to the oxidation of zircaloy and steel inside the rack region is calculated. An additional significant hydrogen amount is produced after the onset of MCCI. Up to the termination of the calculation at 125 h after event initiation about 1162 kg of hydrogen has been recombined by the passive autocatalytic recombiners installed inside containment.

Figure 2.3: Snapshots of calculated mass distribution inside the lower eight meshes of the spent fuel pool

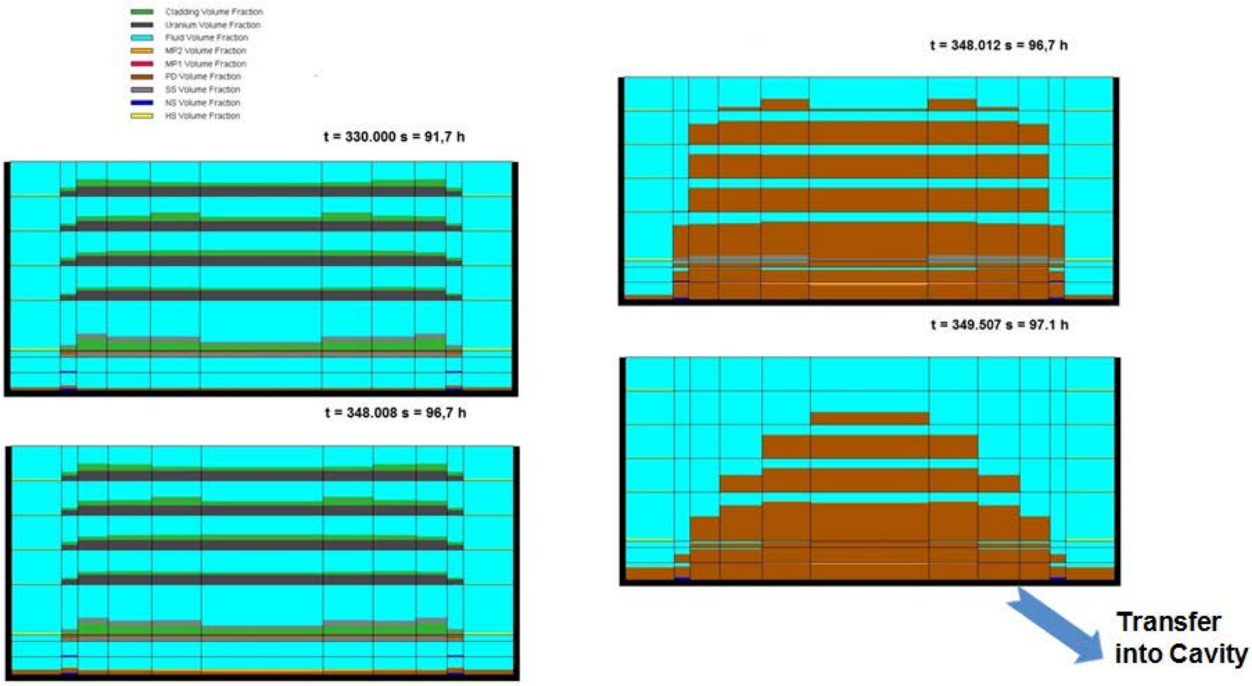
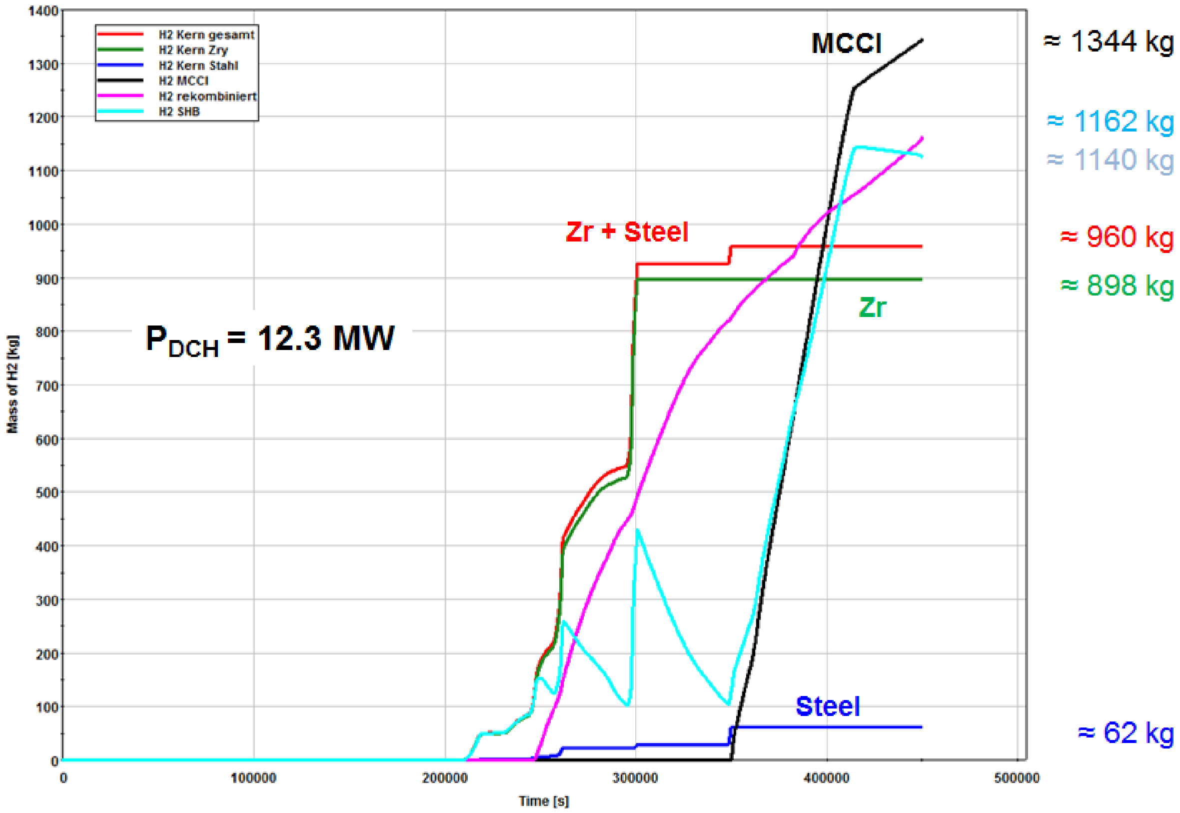


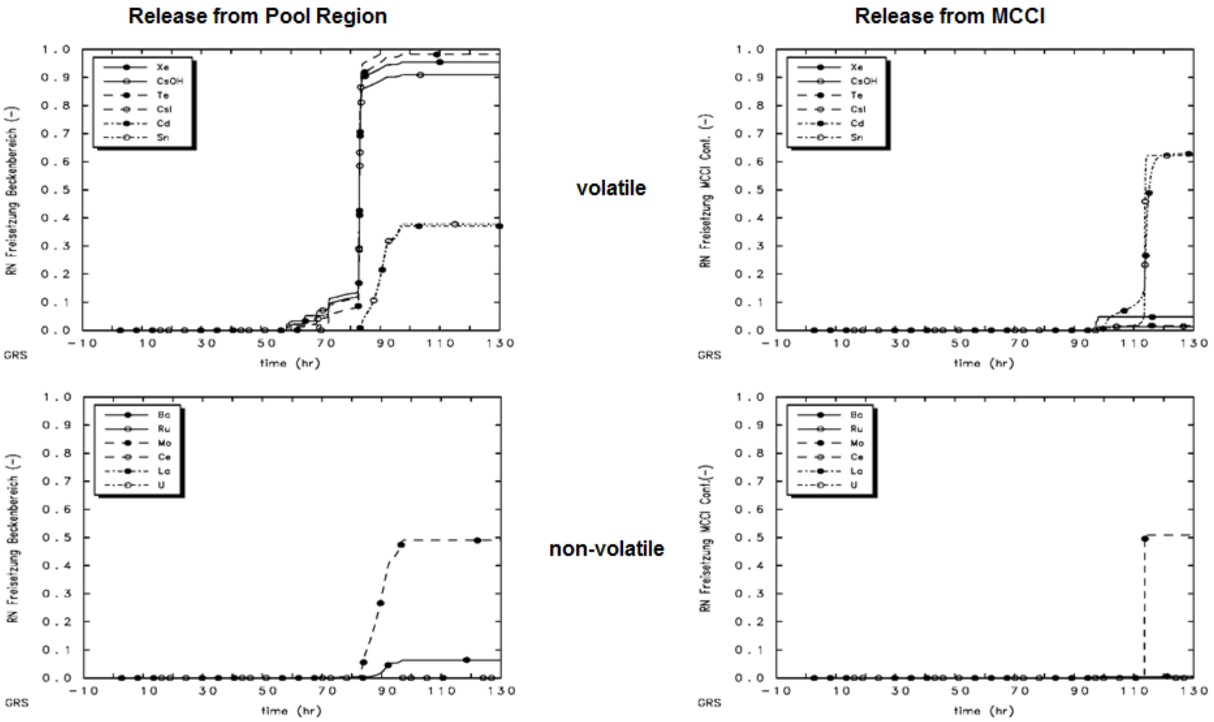
Figure 2.4: Calculated hydrogen masses generated and recombined



2.2.3 Radionclides

The calculated release of radionuclides from the pool region as well as due to MCCI is depicted in figure 2.5. The results are subdivided regarding volatile and non-volatile species.

Figure 2.5: Calculated release of radionuclides from spent fuel pool region as well as due to MCCI



Regarding the volatile radionuclides noble gases as well as the aerosols Te, CsI, and CsOH are already fully released during the degradation in the pool region. About 38 % of Cd and Sn are released in the pool region, too. Due to MCCI the remaining amounts of the aerosols Cd and Sn are released. Regarding the non-volatile species, most of the aerosols are retained inside the debris/melt.

3 CONCLUSIONS

Deterministic integral analyses of the accident progression during shutdown modes of a PWR and inside spent fuel pools are being performed in the frame of two projects at GRS. The results of these analyses could be used for supporting Level 2 PSA studies. In the frame of this paper, first preliminary results of MELCOR calculations of a severe accident sequence during shutdown phase of a PWR and inside a spent fuel pool have been shown. For the event of the shutdown mode the failure of the residual heat removal during mid-loop operation and opened RPV has been assumed. For the calculation of the spent fuel pool which was fully loaded with the whole core of a generic PWR reactor (no consideration of the spent fuel assemblies from previous cycles for that example) a long-term “Station Black-out” event has been postulated.

It could be shown that the integral code MELCOR is able to calculate the accident progression for both cases. From a point of engineering judgement the results seem to be reasonable. As both projects are still going on, several adjustments of the input deck will be performed and therefore some improvements of the calculational results can be expected for both cases.

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