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Level 2 PRA for a German BWR

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ABSTRACT

A concept for a Level 2 Probabilistic Risk Assessment (L2 PRA) for a German Boiling Water Reactor (BWR) has been developed taking into account the role of L2 PRA within the German regulatory landscape. According to this concept, a plant specific evaluation of the severe accident phenomenology as well as analyses of the accident progression for the severe accident scenarios has been performed. Furthermore a plant specific MELCOR 1.8.6 model has been developed and special MELCOR source term calculations have been performed for the different release paths. This paper will present examples from the different areas described above.

1 INTRODUCTION

A L2 PRA aims at the quantification of the frequency and magnitude of radiological releases into the environment. Usually the emphasis of an L2 analysis will be on early releases, which will result in more severe consequences than late releases as evacuation and other measures to protect the public can possibly not be carried out in a timely manner. Within the framework of a L2 PRA information about the system availability associated with the endpoints (core damage state) of the L1 PRA, information about the plant behaviour under severe accident conditions, information on the likelihood of phenomena associated with severe accident conditions to occur, information on available procedures to mitigate consequences and information on the characteristics of the different possible release paths for radio nuclides need to be combined.

2 CONCEPT FOR A L2 PRA FOR A GERMAN BWR

From the perspective of German utilities the insights gained from a L2 PRA are limited, because the analysis only concerns hypothetical and very rare incidents with core melt, and thus events which lie far beyond the legally necessary damage precautions.

The behavior of nuclear power plant during core melt accidents has been examined in Germany for more than the last two decades within the framework of national and international research projects. Although a basic understanding was achieved, substantial uncertainties still exist regarding the quantification of complex physical phenomena, which will arise under severe accident conditions. This is why the force of expression of a L2 PRA is limited. Thus if reliable insights are to be gained from the L2 PRA the goal of the L2 PRA needs to be limited to determining the frequency ranges of probabilistically relevant accident branches, which can lead to early, important radiological releases of fission products, as well as calculating the resulting source terms. The results are represented in principle by point values. When certain accident paths show a high importance additional evaluations should be done or more detailed information should be taken from available technical literature.

The concept followed for the described L2 PRA ensures, that the results are provided to a level of detail, which enables the evaluation of whether beyond the damage precaution administrative or technical measures should be implemented, if the relation of cost versus safety improvement is appropriate. This is particularly important if the NPP under investigation has a very low core damage frequency (CDF) as a starting condition for the L2 evaluations.

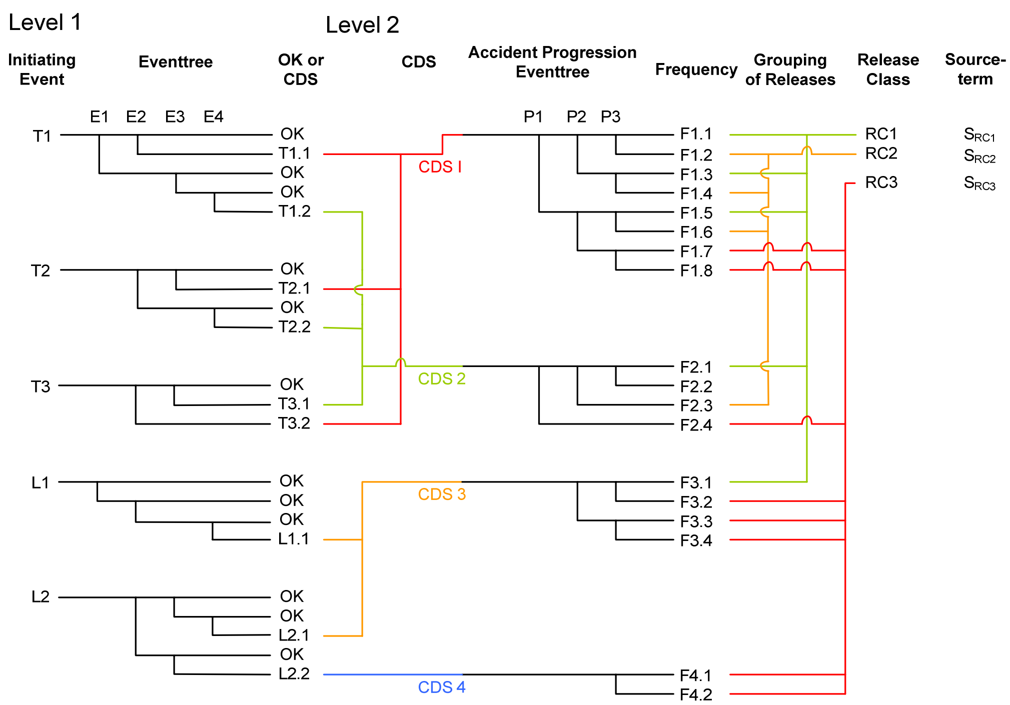

Figure 1: Schematic of the integrated approach for the L1 to L2 transition. The core damage sequences are grouped to core damage states (CDS) and passed on to the accident progression event trees (APET). The endpoints of the APET are grouped into release classes for which frequencies and source terms are calculated.

The described concept for the L2 PRA is based on using an integrated probabilistic model (see Figure 1), which directly connects the L2 accident progression event trees (APET) for the L2 PRA to the endpoints of the L1 event trees. Using this approach the information on failed equipment in the L1 PRA is directly passed to the L2 PRA. This approach offers the opportunity to focus the grouping of the core damage on aspects driving the accident progression like inerting the containment via steam (large LOCA) rather than needing to take into account a lot of information on system availability. When developing the APET linking the core damage states to the final releases emphasis was put on identifying the driving aspects for the accident progression. This is why before developing the logic of the APET a thorough analysis of the severe accident phenomenology was performed to identify the parameters driving the associated consequences. Having identified the driving parameters for the accident progression, a plant specific MELCOR model was designed, which was geared at reliably predicting the relevant parameters identified in the studies above and representing all of the specific identified release paths. When performing plant specific MELCOR calculations and analysing the evolution of parameters as predicted by MELCOR, care was taken to identify mechanisms, which may lead to different behavior. Having a good understanding of the mechanisms translates to correct conclusions on the applicability of derived split fractions under varying conditions within the core damage group and the different branches of the APET. Guided by the principles described above it was possible to screen out uncertain parameters with minimal influence on the accident progression and the expected releases in advance on a clean physical basis. In the following chapters examples will be given from the above areas which illustrate how the clear focus on the accident driving parameters helped to arrive at conclusive results.

3 ANALYSIS OF THE SEVERE ACCIDENT PHENOMENOLOGY

Performing the analysis of the severe accident phenomenology within the plant specific context the following phenomena have been considered:

- In-Vessel and Ex-Vessel steam explosions
- Direct Containment heating
- In-Vessel Recriticality
- Coolability of Debris in the Control Rod Drive Room
- Reactor Vessel Failure Modes
- Core-Concrete Interaction
- Hydrogen Combustions
- Lower Head Coolability

Performing the studies on these phenomena the current experimental and theoretical knowledge has been collected and was compared to the actual situation in the specific plant. After the plant specific governing conditions for the different phenomena had been identified split fractions have been developed. The plant specific results for the German BWR are in line with internationally commonly accepted facts on the issues. For example the impact of in- and ex-vessel steam explosion on the containment integrity has been analyzed and found not to be risk significant. Thus it was excluded from the probabilistic analysis.

As an example for such a phenomenological analysis the in-vessel recriticality after reflooding a partly destroyed core will be discussed. It will be shown that a through understanding of the system capabilities narrows the success criteria in a way which will keep the parameters well out of the ranges with uncertain consequences. The key is to distinguish the aspects of a prompt recriticality from the aspects of fission power after the core became recritical in addition to decay heat. Performing the analysis it was found that the later aspect provides more severe restrictions, which may be calculated in very straightforward way. When evaluating the potential for a prompt recriticality one needs to take into account the mechanisms adding and diminishing reactivity. Important aspects in the analysis are the different time scales on which these effects take place. Here the different aspects increasing and diminishing reactivity will be listed before the resulting limiting condition from prompt recriticality is given:

- Lack of control rod material (melting, dilution)
- Addition of water to the core (flooding delayed by the quenching of the core)
- Fuel temperature
- Formation of void in the core
- Loss of geometry in the core

- Xenon build up / decay

Just taking into account the aspects adding reactivity and the formation of voids in the core which balances with the increased reactivity results in a plant specific minimum addition rate of 370 kg/s needed to generate a prompt recriticality. Other studies [1] taking into account degraded core geometries conclude for similar conditions, that even at water addition rates up to 2100 kg/s the probability for a prompt recriticality might be as low as 1 % (50 % for a non degraded core). It should be noted, that most water supply system are not able to provide water addition rates of that magnitude to the pressure vessel.

4 CONSTRUCTING THE ACCIDENT PROGRESSION EVENT TREE (APET)

The APET provides a structured framework for organizing and evaluating the alternative accident progressions that may evolve from the individual core damage accident sequences given the conditions that exist in the reactor vessel and inside containment at the onset of core damage and that are attributable to the initiating sequence. Besides a thorough understanding of the severe accident phenomenology, a detailed understanding of the plant conditions associated with the different groups of core damage sequences is needed. To achieve this understanding the sequences contributing to the groups have been individually examined down to a level at which the sum of the remaining sequences contributes less than 1 % to the total frequency of the group. Screening has been performed on the remaining sequences searching for conditions, which might result in significant deviations concerning releases. As the major contributions to the core damage frequency are due to common cause failures which at the same time influence the system availability for mitigative actions, the sequence analysis in some cases reached down to the details of the cut set level, even though an integrated approach was used. In case of the supported L2 PRA a lot of suitable mitigative actions were readily available from the emergency operating procedures (EOP). A lot of these strategies were not credited in the L1 PRA either due to the fact that the systems were specially designed for the mitigation of severe accidents and thus are not used in normal operating conditions or due to the short timeframe available during L1. As a core may be retained in the RPV even if minor core damage has occurred, the timeframe to execute the predefined measures in the mitigative context is longer than credited in L1. Before the capabilities of the venting system as a typical system solely aimed at severe accident conditions are discussed it should be noted that for certain sequences passed on from L1 the predefined actions in the EOPs offer more than four general system alignments which may be used to establish injection to the RPV and which were not credited in the L1 (i. e. injection using the mobile fire pump, injection using the primary filling pumps of the decay heat removal system, injection of secondary shell water, injection using the drain pump of the wet well).

When constructing the APET to account for the effects of operating the containment venting system the following aspects have to be considered:

- Operation of the venting system will prevent over-pressure failure of the containment due to generation of non condensable gases and steam produced at rates consistent with a decay heat level about 4 hours into the accident.
- Operation of the venting system means non-condensable gases are removed from the containment atmosphere. This might cause an under-pressure condition in the containment if containment sprays are operated using water with a temperature less than 100 °C.

- Operation of the venting system leads to the loss of water inventory due to the steam vented from the containment, which may lead to uncovering previously cooled core debris.
- Operation of the venting system keeps the absolute pressure in the containment low in order to keep the saturation temperature of water below 150 °C.

The MELCOR calculations done for the L2 PRA indicate that there is no under-pressure issue as long as the defined opening and closing pressures for the venting system are obeyed. The non-condensable gases produced during core degradation and molten core concrete interaction (MCCI) ensure that the fraction of non condensable gases (see Figure 2) stays high enough to prevent under-pressure. (In the MELCOR calculations some cases were identified where the production of non condensable gases may be not sufficient to prevent under-pressure. In these cases large pools of water with temperatures well above 100 °C exist, which will prevent under-pressure by boiling.) This means that the under-pressure issue must not be included in the APET.

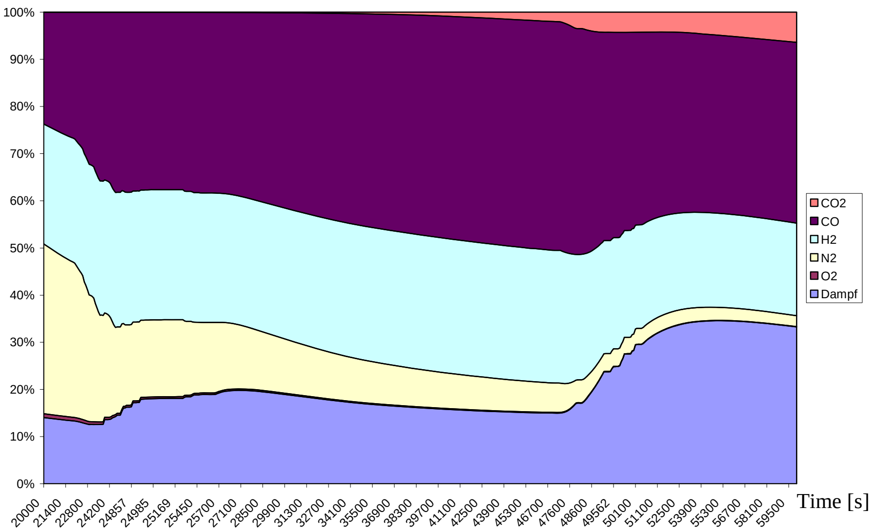

Figure 2**:** Composition of the atmosphere in the wetwell. Even during the second venting cycle (13 h after the initiating event) the peak fraction of condensable gases ("Dampf") is low enough to prevent containment under-pressure issues. (After 6 h the vent was opened for the first time.)

If venting and in-vessel retention of the core are not successful, the containment will ultimately fail due to overpressurization by non condensable gases. This fact is included in the logic of the APET.

In more than 30% of all core damage sequences of the L1 PRA venting shows a much stronger capability in mitigating severe accidents than might have been expected. In these sequences the loss of injection to the RPV is due to high temperatures in the condensation pool. The high temperature leads to a failure of injections to the RPV taking suction from the condensation pool as well as failure of injections from outside the containment which may not have sufficient pump head to inject at resulting elevated containment pressures. If the venting system is operated, the condensation pool may not reach the respective temperatures and injection will continue, which may be credited conservatively as regaining injection early into the accident progression. When implementing this fact into the APET the loss of water inventory due to steaming needs to be accounted for, which is factored into the APET by considering the systems available to replenish the water inventory. Considering just the latter fact the venting system may be expected to guarantee minimal release for about one quarter of all core damage sequences. (This does not include the benefits from avoiding over-pressure failure of the containment, which is the primary design purpose of the venting system.)

5 DEVELOPING A PLANT SPECIFIC MELCOR MODEL

A detailed plant specific MELCOR model has been developed using well documented plant data. For the core model the radioactive inventory has been calculated for 10 typical fuel elements including mixed oxide fuel at different burn up states. Special care was taken that the model is able to cope with all of the phenomena which have been identified in the phenomenological analysis and which are identified during the APET construction. The level of detail in modelling the containment and the surrounding reactor building and the turbine hall was chosen to reflect all the different release paths identified. While the reasons for the high detail level chosen for modelling the RPV are well established the following example will explain the plant specific reasons for choosing a higher detail level than is usually done when modelling the wetwell.

During the analysis a passive plant feature came to attention, which under certain conditions will assist mitigative operator actions to flood the lower drywell. In case of an over-pressure in the wetwell compared to the drywell piping exists, which in addition to mitigative actions will provide passive injection of water to the drywell. The following aspects govern how much water will be ejected from the wetwell.

- Over-pressure in the wetwell compared to the drywell
- Waterlevel in the wetwell
- Average density of the water

The first aspect requires a detailed model accounting for the different pressure relief mechanisms operating at different pressure levels and different mass flow rates. The last aspects means that the model needs to be constructed in such detail, that the average density of the water column in the piping connecting the wetwell to the lower drywell is not influenced by the steam being passed to the condensation pool via the spargers, but may be influenced by the void introduced, when the water boils, because of entering a zone with lower ambient pressure i.e. the drywell.

Apart from properly taking into account all the effects in the model the grouping of the core damage states also needs to support the relevant differences. This is why the following groups of core damage states need to be distinguished:

- Core damage states with the condensation pool at saturation temperature
- Core damage states with the steam produced in the RPV dumped directly to the condensation pool via the SRVs
- Core damage states with the steam and non condensable gases being delivered to the wetwell via the condensation pipes or being expelled to the environment

6 PLANT SPECIFIC SIMULATIONS OF THE ACCIDENT PROGRESSION

MELCOR calculations were performed in order to establish the timing of the accident progression for the different core damage sequence groups. The analyses are used to quantify major parameters during the accident progression. It is also important to identify the driving phenomena of the accident progression. The identification of the main factors influencing the relevant results can be used to replace Monte Carlo samplings of the input parameter space by a well founded analysis of the bounding conditions with a limited set of variations. This results in a reliable prediction of split fractions for the phenomenological branches.

An example for such an analysis would be the timing of important phenomena predicted by MELCOR e.g. with respect to the over-pressure failure of the containment in case of a late failure of the safety injection to the RPV. (Failure of pool cooling and containment venting is assumed in this sequence.) In this special case MELCOR predicts a late failure of the containment. The driving parameters for this prediction are the pressure for a containment failure and a suppression pool heated to over 150 °C. This means that the energy introduced into the containment is completely absorbed by the pool. Aspects which will change the timing thus are a less complete absorption of the energy in water pools not being heated to saturation temperature and the possibility of more energy being introduced to the containment e.g. by higher fission power or by injection of water of higher temperature e.g. main feed water into the containment. By definition of the core damage sequence group the condensation pool is heated up to 150 °C and the reactor is successfully shut down. Further more the conservative ansatz for the MELCOR calculation considers the maximum amount of hot main feed water to be injected to the RPV and thus maximises the energy injected to the containment in this respect. Thus the prediction of containment static over-pressure failure only occurring late into the accident is valid at all branch points for this core damage sequence group.

Within the plant specific MELCOR calculations the potential for improving the capabilities of the plant for a reduction of the consequences of L2 scenarios have also been investigated. Though the plant has very strong potential for retaining the core debris inside the reactor vessel by early recovery of injection to the vessel, there exist some sequences in which the molten core may challenge the containment integrity. The time at which the challenge to the containment occurs might be delayed by introducing for example a small chamotte barrier, which would hold back the molten corium. This would provide up to 14 h of extra time for mitigative actions depending on the specific sequence. Figure 3 shows the radial erosion of the CRD room's concrete in the case of a complete loss of injection. The containment would be protected until a radius of 3.9 m is reached in either the CRD room or the sump i.e. for more than the 24 h shown in the plot.

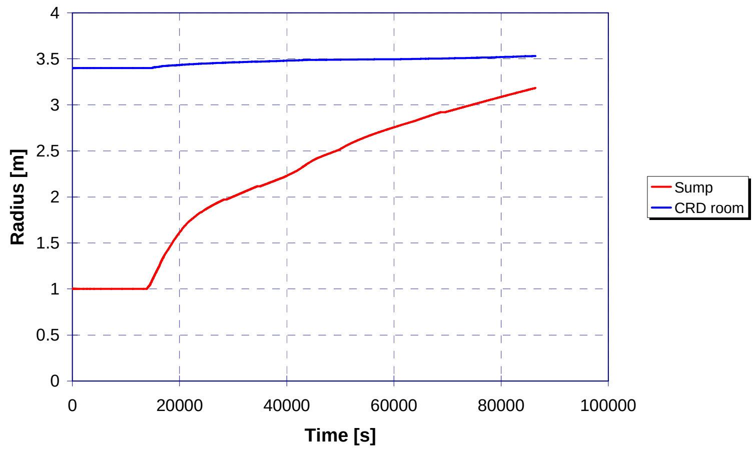

Figure 3: Radial ablation of the lower portion of the CRD room and the containment sump by molten corium for a total loss of injection to the RPV.

7 CONCLUSIONS

The analysis based on the integrated approach to the L2 PRA was beneficial showing specific failure conditions which can be mitigated easily and very effectively with the result of minimal to no radioactive releases.

Further more the approach to first clearly identify the driving conditions for the relevant phenomena and the results of model calculations resulted in a good understanding of the limits of applicability of split fractions derived from MELCOR calculations and helped to avoid extensive use of Monte Carlo methods. Using a well-tested MELCOR model comprising all the relevant L2 phenomena and release paths, which has been built with the details driving the accident progression in mind, adds to the confidence in the results produced by the MELCOR runs.

During the analysis a lot of measures already defined in the EOPs were found to be useful for mitigative actions and systems not credited in the L1 were found to be highly effective for mitigating severe accident conditions. For example the venting system might be used to prevent loss of injection to the RPV in a significant number of core damage states.

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