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Application Of Dynamic PSA Methods For Accidents In Mid-Loop Operation and Lessons Learned

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Dynamic probabilistic safety analysis (PSA) extends classical, static PSA methods applying event and fault trees to allow for a more realistic modelling of time dependent processes and the corresponding uncertainties. In this respect this tool is particularly useful for analysing accident scenarios strongly affected by the timing of human actions. Such accident scenarios require both deterministic and probabilistic analyses. In the frame of current research activities (Kloos, Peschke, 2015), (Peschke et al., 2018) the dynamic PSA method MCDET (Monte Carlo Dynamic Event Tree) developed by GRS has been further enhanced for performing an Integral Deterministic-Probabilistic Safety Analysis (IDPSA). MCDET is a combination of Monte Carlo simulation and the dynamic event tree method, which can be used to analyse and quantify the influence of (aleatory and epistemic) uncertainties on the behaviour of dynamic systems over time. This especially involves random timing and random ordering of stochastic events and their effect to the progression of a dynamic process. One of the MCDET modules is the Crew Module (Peschke et al. 2018). It has been developed for modelling and simulating time dependent human action sequences. In combination with the main MCDET code the Crew Module can be used to assess the effect of stochastic influences on the total time needed for mitigating human actions. The scenario described in (Mateos Canals et al. 2022) combines the inherent uncertainty regarding the duration and success of human actions with the uncertainties of the failure time of components such as safety and control valves.

In the past, PSA for nuclear power plants (NPPs) revealed a high contribution of accidents during low-power and shutdown operation to the integral frequency of damage states for western design pressurised water reactors (PWRs) (Babst et al. 2003). As decoupling the reactor protection system (RPS) is permitted for German NPPs in the plant operational states (POSs) “cold subcritical / primary system pressure-tight closed” (C) and “cold sub-critical / primary system not pressure-tight closed” (D) (BMUB. 2015), automatic interventions from numerous subsystems are strongly reduced in case of demand. In consequence, the relevance of operator actions increases accordingly. Moreover, spurious actuation of the RPS can lead to a failure of the residual heat removal (RHR) system during mid-loop operation if the RPS is not fully decoupled. The coolant inventory in the primary system is significantly reduced during the above-mentioned POSs compared to system states during full-power operation. This boundary condition as well as the partial or complete unavailability of instrumentation and control (I&C) systems and a possibly increased error probability of the plant operators due to high workload make the analysis of the POSs C and D and particularly of the mid-loop POS relevant from a safety perspective. Due to the high relevance of human actions in this situation, a quantitative assessment of the of operator actions´ effectiveness and their impact on the thermal-hydraulic phenomena within the plant is highly significant for nuclear safety. In the scope of this R&D project, probabilistic assessments regarding the effectiveness of human actions in mid-loop operation for one specified accident scenario have been conducted. This includes the identification of critical points during action sequences and the determination of time safety margins when these actions are performed. In addition, various event sequences and the resulting system states with their occurrence frequencies have been determined.

Deterministic thermal-hydraulic analyses have been performed using the system code ATHLET. The utilised thermal-hydraulic model represents a generic 4-loop western design PWR with an electrical power output of 1300 MW_{el}, adapted for mid-loop operation and a power of 26.07 MW around 20 hours after reactor scram. In addition, an operator action model (OAM) has been derived including aleatory uncertainties for the execution times of human actions, human error probabilities (HEP) and dependencies of human actions on stochastic influences and/or system and process states. These human action sequences, which generally depend on stochastic influences, are decomposed into activities carried out by the plant operators involved. The specified activities are assigned to corresponding execution times the operators need to carry them out. The quantification of HEPs is based on the human reliability analysis (HRA) methods “Accident Sequence Evaluation Program (ASEP)” (Swain, 1987) and “Technique for Human Error Rate Prediction (THERP)” (Swain, Guttmann, 1983).

The complexity of the various uncertainties considered for the duration and success of human actions and connected system processes makes the analysis outlined above a key example for one of the main caveats regarding a dynamic PS. Namely that the time and experience needed for performing a dynamic PSA make it unmanageable in non-academic contexts. The problems encountered when conducting a dynamic PSA have served as starting point for improving and extending MCDET to simplify the performance of a dynamic PSA. One of the observations was that the Crew Module and its interface to MCDET needed to be optimized and the task of modelling the MCDET Crew Module to be simplified. During an earlier MCDET project, the formerly FORTRAN-based Crew Module was rewritten in python and set up to be used like a deterministic simulator, both stand-alone and interfaced to MCDET. Thus, standard post-processing tools can be applied for analysing the results of a combined MCDET Crew Module run. During the reformulation of the Crew Module it became clear that other changes are necessary to improve the usability, e.g. a different approach for modelling the input. The current input of the Crew Module follows the logic of a mind-map. This approach does not support the modelling of divergent action sequences that merge back together or of cyclic action sequences. As part of the new MCDET project, a strategy is currently being developed how human action sequences can be best modelled as state machines, enabling the analyst to model action lists, branch points and cyclic behaviour. This approach also offers the possibility of utilising tools that support the modelling, simulation and testing of the resulting state machines, such as the one described in (Yakindu, 2024).

The presentation will provide first results of the mid-loop scenario analysis and an introduction to the current Crew Module implementation with an example model of the future Crew Module input.

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