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Analysis of core degradation and relocation phenomena and scenarios in a Nordic-type BWR

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HIGHLIGHTS

- A data base of the debris properties in lower plenum generated using MELCOR code.
- The timing of safety systems has significant effect on the relocated debris properties.
- Loose coupling between core relocation and vessel failure analyses was established.

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ABSTRACT

Severe Accident Management (SAM) in Nordic Boiling Water Reactors (BWR) employs ex-vessel cooling of core melt debris. The melt is released from the failed vessel and poured into a deep pool of water located under the reactor. The melt is expected to fragment, quench, and form a debris bed, coolable by a natural circulation and evaporation of water. Success of the strategy is contingent upon melt release conditions from the vessel and melt-coolant interaction that determine (i) properties of the debris bed and its coolability (ii) potential for energetic melt-coolant interactions (steam explosions). Risk Oriented Accident Analysis Methodology (ROAAM+) framework is currently under development for quantification of the risks associated with formation of non-coolable debris bed and occurrence of steam explosions, both presenting a credible threats to containment integrity. The ROAAM+ framework consist of loosely coupled models that describe each stage of the accident progression. Core relocation analysis framework provides initial conditions for melt vessel interaction, vessel failure and melt release frameworks. The properties of relocated debris and melt release conditions, including in-vessel and ex-vessel pressure, lower drywell pool depth and temperature, are sensitive to the accident scenarios and timing of safety systems recovery and operator actions. This paper illustrates a methodological approach and relevant data for establishing a connection between core relocation and vessel failure analysis in ROAAM+ approach. MELCOR code is used for analysis of core degradation and relocation phenomena. Properties of relocated debris are obtained as functions of the accident scenario parameters. Pattern analysis is employed in order to characterize typical behavior of core relocation transients. Clustering analysis is employed for grouping of different accident scenarios, which result in similar core relocation behavior and properties of the debris.

1. Introduction

Severe Accident Management (SAM) in Nordic Boiling Water Reactors (BWR) relies on ex-vessel core debris coolability. In case of core degradation and vessel failure, corium is poured into a deep pool of water located under the reactor in the lower dry well (LDW). The melt is expected to fragment, quench, and form a debris bed, coolable by natural circulation and evaporation of water. Success of the strategy is contingent upon melt release conditions from the vessel and melt-coolant interactions (Frid, 1991; Kudinov et al., 2014), which determine (i) properties and thus coolability of the ex-vessel debris bed (Yakush et al., 2013a; Yakush and Kudinov, 2014, 2009); and (ii) potential for energetic interactions (steam explosions) (Grishchenko et al., 2015). Timing of the events and phenomena at early stages of the accident progression can

Abbreviations: ROAAM, Risk Oriented Accident Analysis Methodology; SM, surrogate model; PSA, Probabilistic Safety Assessment; EOP, Emergency Operation Procedures; SAMG, Severe Accident Management Guidelines; CDF, core damage frequency; PDS, plant damage state.

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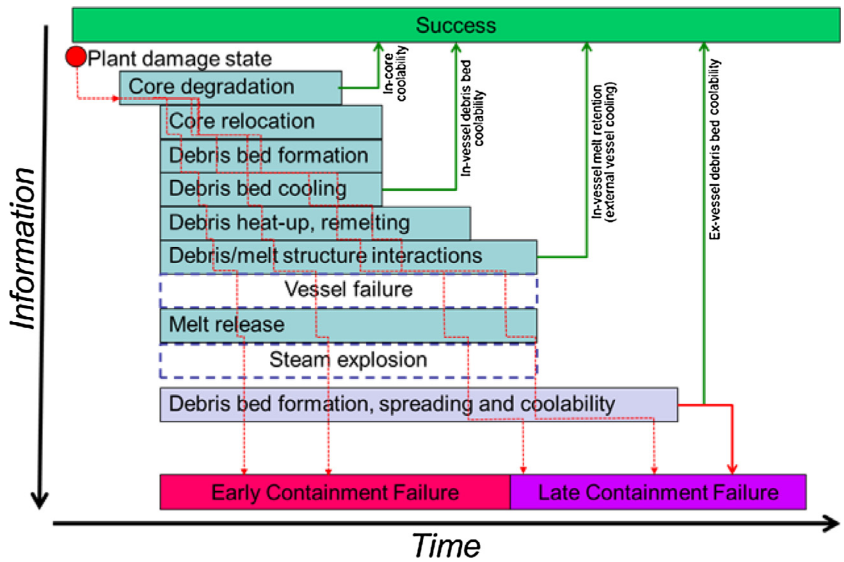

Fig. 1. Severe accident progression in Nordic BWR (Kudinov et al., 2014).

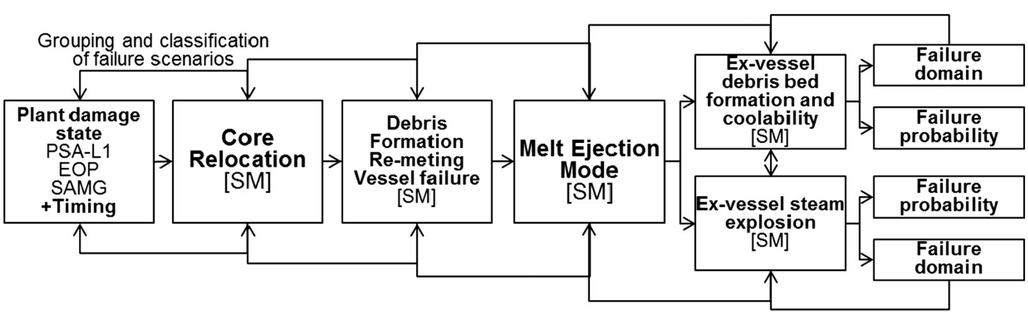

Fig. 2. ROAAM+ framework for Nordic BWR (Kudinov et al., 2014) for "forward" (failure probability) and "reverse" (failure domain) analysis (SM – Surrogate Model; PSA – Probabilistic Safety Assessment; EOP – Emergency Operation Procedures; SAMG – Severe Accident Management Guidelines).

significantly affect accident progression at the later stages (see Fig. 1). Thermal hydraulic conditions in the reactor pressure vessel (RPV) after accident initiation determines conditions for degradation of the core material and its relocation to the lower plenum. Formation of in-vessel debris bed, debris remelting and melt pool formation in the lower plenum, provide conditions for thermos-mechanical loads on the lower head wall and structures (such as instrumentation guide tubes (IGTs) and control rod guide tubes (CRGTs)). Vessel failure and melt release conditions determine ex-vessel melt-coolant interactions, debris bed formation and energetics of steam explosion. Different time-dependent trajectories of the accident scenarios with the same logical sequence can result in different outcomes (see red and green arrows in Fig. 1 that represent possible severe accident progression paths that can be different due to timing of the events and specific conditions for the accident phenomena leading to possible success or failure of SAM strategy). For instance, large mass of core melt released from the vessel creates larger risks of formation non-coolable debris bed (Yakush et al., 2014). The effect of timing is not straightforward. For instance, timing of operator actions can affect vessel failure timing and respective decay heat and melt temperature. In case of later melt release smaller decay heat is better for ex-vessel coolability, while higher melt temperature would increase the risk of debris agglomeration (Kudinov et al., 2013; Kudinov and Davydov, 2013, 2014), which can hinder coolability of the debris bed (Yakush and Kudinov, 2009), and also could increase energetics of the steam explosion.

Risk Oriented Accident Analysis Methodology (ROAAM+) is currently under development (Kudinov et al., 2014) for assessment of the effectiveness of Nordic BWR SAM strategy in preventing containment failure. The framework is an extension of the ROAAM approach originally proposed by prof. Theofanous (Theofanous, 1996). Deterministic and probabilistic analyses are integrated in ROAAM+ framework in order to address the impact of both phenomena (epistemic) and scenarios (aleatory) uncertainties. ROAAM+ (Fig. 2) is designed to model the multistage path (Fig. 1) from initial plant damage states, identified in Probabilistic Safety Assessment (PSA) Level 1 to the ex-vessel phenomena that can threaten containment integrity. The framework is used to quantify uncertainty in failure probability and to identify failure domains in the space of scenario parameters employing so called "forward" (from initiating events to containment failure) and "reverse" (from containment failure to initiating events) analyses (see details in (Kudinov et al., 2014)) respectively.

High computational efficiency of the framework is a must for quantification of the uncertainties. Loose coupling established through initial conditions between individual frameworks in ROAAM+ (Fig. 2) enables decomposition of the complex problem, in this way the key sources of uncertainty can be identified and addressed separately. Necessary computational efficiency is achieved by employing surrogate modeling approach (Kudinov et al., 2014) for each individual framework. Additional benefit of such "loose coupling" and surrogate modeling approach is high computational efficiency in quantification of uncertainty which