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Prediction of in-vessel debris bed properties in BWR severe accident scenarios using MELCOR and neural networks

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ABSTRACT

Severe accident management strategy in Nordic boiling water reactors (BWRs) employs ex-vessel corium debris coolability. In-vessel core degradation and relocation provide initial conditions for further accident progression. Outcomes of core relocation depend on the interplay between (i) accident scenarios, e.g. timing and characteristics of failure and recovery of safety systems and (ii) accident phenomena. Uncertainty analysis is necessary for comprehensive risk assessment. However, computational efficiency of system analysis codes such as MELCOR is one of the big obstacles.

The goal of this work is to develop a computationally efficient surrogate model (SM) for prediction of main characteristics of corium debris in the vessel lower plenum of a Nordic BWR. The SM has been developed using artificial neural networks (ANNs). The networks were trained with a database of MELCOR solutions. The effect of the noisy data in the full model (FM) database was addressed by introducing scenario classification (grouping) according to the ranges of the output parameters. SMs using different number of scenario groups with/without weighting between predictions of different ANNs were compared. The obtained SM can be used for failure domain and failure probability analysis in the risk assessment framework for Nordic BWRs.

1. Introduction

In Nordic type boiling water reactors (BWRs), severe accident management (SAM) strategy employs ex-vessel corium debris coolability. Different accident scenarios (e.g., timings and available capacity of safety systems) can change drastically conditions for the in-vessel accident progression phenomena and respective outcomes of in-vessel core relocation (Phung, et al., 2016). Properties of corium debris bed in the vessel lower plenum (e.g., mass, composition, thermal properties, timing of relocation, spatial configuration and decay heat) affect melt interactions with the vessel structures, vessel failure, melt ejection mode (Goronovski et al., 2013) (Goronovski et al., 2015) and thus ex-vessel accident progression and respective threats to containment integrity.

Risk Oriented Accident Analysis Methodology (ROAAM) (Theofanous, 1996) combining probabilistic and deterministic approaches has been developed for such cases when both epistemic (modeling) and aleatory (stochastic scenario) uncertainties are significant. It is based on quantification of uncertainty using deterministic models and sampling techniques. This work is a part of the program on development of the ROAAM+ risk assessment framework for severe accident in Nordic BWRs (Kudinov, et al., 2014a). The framework is designed for comprehensive risk assessment and can be used to: (i) characterize failure domains and (ii) estimate failure probability in the space of the accident scenario parameters. In the framework, a set of connected models is used for prediction of different accident progression stages which start from core damage to steam explosion or formation of non-coolable debris bed (Fig. 1).

Reactor system analysis codes such as MELCOR (Summers, et al., 1991) (US NRC, et al., 2005) are often used to quantify effect of the scenarios on the accident progression. The codes employ phenomenological models derived from the data observed in severe accidents and scaled down, separate effect experiments. The codes are complex, highly non-linear, and often use discrete thresholds in the models, e.g. for onset of different failure modes or activation of equipments. As a result, predictions with severe accident analysis codes are computationally expensive and can be sensitive to small variation in the input parameters and numerical discretization, e.g. selection of computational time step.

In ROAAM+, surrogate (simplified) models are developed (Fig. 2) for each stage of the accident progression in order to approximate the response of complex and computationally expensive full modes (such as MELCOR). The purpose of the surrogate

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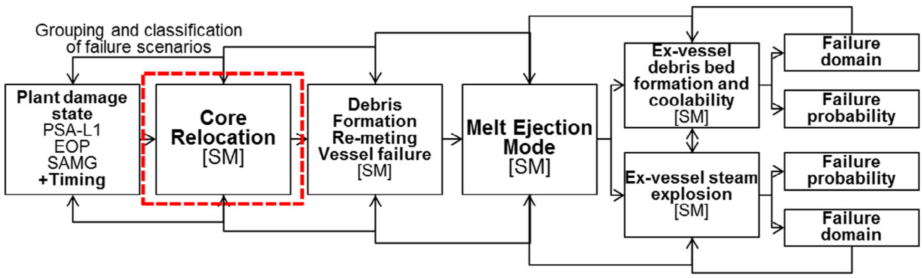

Fig. 1. Risk assessment framework for severe accident in Nordic BWRs (Kudinov, et al., 2014a).

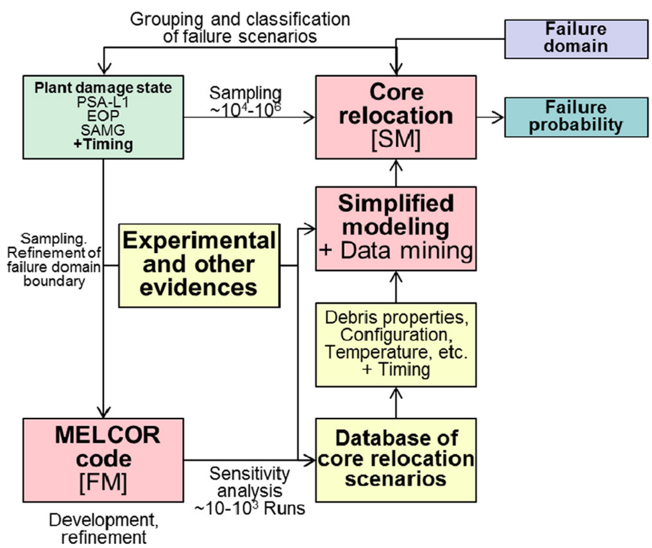

Fig. 2. Full model and surrogate model development (Kudinov, et al., 2014a).

models (SMs) is to improve computational efficiency while maintaining acceptable accuracy for extensive uncertainty and failure domain analyses. Simplified modeling and data mining approaches are used in order to develop the SMs. In the ROAAM + to calculate the failure domain and failure probability, fine sensitivity calculations are required for the core relocation stage. The total number of these calculations could be in the order of 10^6. Performing millions of full model (FM) calculations would not be feasible from the aspect of computational time. Thus the SM is developed to calculate these scenarios (Fig. 2). To train the SM, only $\sim 10^3$ of full model (FM) calculations would be needed (Fig. 2).

Artificial neural networks (McCulloch and Pitts, 1943) have been successfully used in nuclear applications, for example for plant status or transient diagnosis (Bartlett and Uhrig, 1992) (Uhrig and Tsoukalas, 1999) (Santosh et al., 2009) (Mo et al., 2007), for prediction of outcome of different scenarios (Zio et al., 2009) (Na, et al., 2004) (Kim et al., 2015). Recently fuzzy logic (Zadeh, 1965) based approaches have gained considerable attention, for example in (Zio and Baraldi, 2005) (Zio et al., 2007) (Guimarães and Lapa, 2007). Dozens or hundreds of full model simulations is often necessary for development of a reliable SM.

In (Phung et al., 2016), MELCOR was used in order to obtain a database of full model (FM) solutions and improve understanding on how accident scenario parameters can affect characteristics of debris bed in the reactor lower plenum. Station black out scenario with varying delayed power recovery was considered. The FM database has considerable (physical and/or numerical) noise in the response. Sampling was also biased towards regions of scenario parameters of special interest for analysis of the further accident progression (i.e. small or large mass of relocated debris).

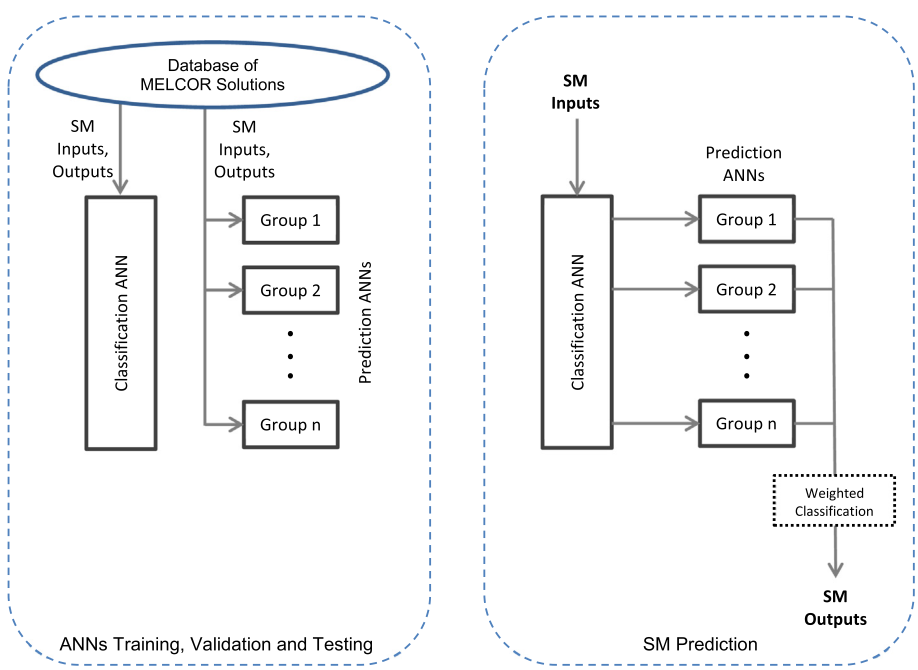

Fig. 3. Flow diagram of ANNs training and SM prediction of in-vessel core relocation.