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Statistical analysis of the early phase of SBO accident for PWR

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HIGHLIGHTS

- Best estimate model of generic German PWR is used in ATHLET-CD simulations.
- Uncertainty and sensitivity analysis of the early phase of SBO accident is presented.
- Prediction intervals for occurrence of main events are evaluated.

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ABSTRACT

A statistical approach is used to analyse the early phase of station blackout accident for generic German PWR with the best estimate system code ATHLET-CD as a computation tool. The analysis is mainly focused on the timescale uncertainties of the accident events which can be detected at the plant. The developed input deck allows variations of all input uncertainty parameters relevant to the case. The list of identified and quantified input uncertainties includes 30 parameters related to the simulated physical phenomena/processes. Time uncertainties of main events as well as the major contributors to these uncertainties are defined. The uncertainty in decay heat has the highest contribution to the uncertainties of the analysed events. A linear regression analysis is used for predicting times of future events from detected times of occurred/past events. An accuracy of event predictions is estimated and verified. The presented statistical approach could be helpful for assessing and improving existing or elaborating additional emergency operating procedures aimed to prevent severe damage of reactor core.

1. Introduction

A widespread practice of using best estimate codes to analyse reactor safety tasks in a conservative (deterministic) way reflects existing uncertainties related to implemented reactor models (uncertainties in the input data), including initial and boundary conditions, as well as to intrinsic phenomenological models of the codes (uncertainties in closure relations, e.g., heat transfer correlations). The uncertainties relevant to the analysed case are taken into account within this approach through conservative assumptions, resulting in a single deterministic simulation which predicts the most unfavorable conditions for reactor operation. The results of conservative analyses can be assessed against corresponding acceptance criteria, but they basically cannot be interpreted in probabilistic terms.

Last years, due to the progress in development of BE codes together with availability of new experimental data, the practice in performing reactor safety analyses is moving towards a more realistic, statistical approach aimed at reduction and quantification of conservatism in obtained results (Glaeser, 2008a; Martin and O'Dell, 2005). This statistical method also relies on BE computer codes and models, but together with quantified uncertainty parameters (pre-defined variation ranges and probability density functions) to which simulation results are sensitive. Generally, a set of uncertainty parameters is based on a PIRT relevant to the analysed safety task (e.g., the analysis of LOCA or SBO accidents) and determined by engineering (expert) judgement. The reliability of analysis results depends on the PIRT completeness (Kozmenkov and Rohde, 2013, 2014) and proper quantification of identified uncertainty parameters, especially their variation ranges (Glaeser, 2013).

In this paper, the statistical approach is applied to analyse the uncertainties (first of all operational or time uncertainties) of the SBO accident progression for a generic KONVOI-type PWR.

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Acronyms

AC	Alternating Current
BE	Best Estimate
ECCS	Emergency Core Cooling System
E.D.F.	Empirical Distribution Function
EJ	Engineering/Expert Judgement
EOP	Emergency Operating Procedure
HA	Hydro-Accumulator
HTC	Heat Transfer Coefficient
I&C	Instrumentation and Control
LOCA	Loss-Of-Coolant Accident
NPP	Nuclear Power Plant
PCC	Partial Correlation Coefficient
PDF	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
PSD	Primary Side Depressurization
PWR	Pressurized Water Reactor
SAMG	Severe Accident Management Guidelines
SBO	Station Blackout
SUSA	Software for Uncertainty and Sensitivity Analysis

The analysis is performed for the early phase of this accident, prior notable core degradation, and mainly focused on potential emergency operating procedures aimed to prevent severe core damage. According to IAEA (2009), "the use of conservative assumptions may sometimes lead to the prediction of an incorrect progression of events or unrealistic timescales, or it may exclude some important physical phenomena. The sequences of events that constitute the accident scenario, which are important in assessing the safety of the plant, may thus be overlooked." These are convincing arguments in favor of using best estimate analysis together with evaluated uncertainties (instead of deterministic conservative approach) for the tasks focused on the measures which may be taken to prevent or mitigate the consequences of severe accidents. Potentially BE statistical method is able to reduce and quantify the conservatism of results making them more realistic and reliable.

2. Accident scenario and reactor model

Detailed information regarding the analysed accident and the relevant reactor model is given in Tusheva et al. (2015), where the accident scenario is referred as the "Case 2" of SBO. For this reason, we restrict ourselves here to a brief summary of it.

A generic model of German PWR KONVOI for simulations of SBO (and also LOCA) scenarios has been developed for calculations using ATHLET-CD Mod 3.0 Cycle B (code version released for WASA-BOSS project (Austregesilo et al., 2014)). The model includes main components of the nuclear power plant as well as the safety systems and parts of the reactor control and protection system relevant for the simulated accident scenario. The primary and secondary systems are represented by two loops. The pressurizer is connected to the single loop, while the second (triple) loop of the model combines remaining three loops of the plant. The safety and relief valves of the primary and secondary systems with their functions for pressure limitation and pressure reduction in the SBO scenario are modeled as well. For the reactor core, a six channel representation is used, and the channels are interconnected by cross connection objects. In axial direction, the core is subdivided into 22 nodes (20 of them contain fuel). The core bypass is modeled by a separate channel. On primary side both active and passive emergency core cooling systems are modeled - high and low pressure injection trains for active, and the hydro-accumulators for passive safety injection.

The following assumptions have been made for the simulated SBO scenario:

(1) Initial event: total loss of AC power supply (loss of the offsite electric power supply concurrent with a turbine trip and unavailability of the emergency power supply),
(2) Unavailability of all active ECCSs and total loss of feedwater supply to steam generators; only passive safety systems and systems powered by batteries are available,
(3) The pressurizer relieve/safety valves and the secondary pressure regulation are available,
(4) Secondary bleed and feed is not considered,
(5) Primary bleed and feed is considered: primary system depressurization (permanent opening of the pressurizer valves) is initiated when the maximum coolant temperature at the outlet of the most heated core channel exceeds 400 °C (Roth-Seefrid et al., 1994), and passive feeding from hydro-accumulators starts after sufficient primary pressure reduction (below 26 bar).

3. Identification and quantification of uncertainty parameters

The key physical phenomena and processes observed during the early phase of the accident and associated list of uncertainty parameters are presented in Table 1. These phenomena/processes include: thermal power generation in the core, energy accumulation by the primary system, critical discharge flows from the primary and the secondary systems, circulation of the primary coolant, heat transfer, coolant transport from the emergency core cooling system to the primary system, control of the primary pressure, and interphase energy/mass transfer. All identified uncertainty parameters can be varied directly in the employed ATHLET-CD input deck. They were quantified according to the data from the references given in Table 2 and, partly, to engineering judgement.

4. Results of uncertainty and sensitivity analysis

A series of 181 SBO calculations with different vectors of uncertainty parameters was performed. This number of runs corresponds to the Wilks' formula of the 5th order for 95%/95% coverage/confidence level (Glaeser et al., 2008b). According to Kozmenkov and Rohde (2014), "the reliability of the sensitivity analysis in case of a high number of varied parameters could be improved using the Wilks' formula of the 4th (or higher) order." Besides that, for a fixed coverage/confidence level, results of the uncertainty analysis become less conservative when the Wilks' formula of a higher order is used.

The corresponding set of 181 input files for SBO analysis were generated by EXCEL-integrated software SUSA (Kloos, 2008). The input decks differ from each other by the values of 30 uncertainty (input) parameters described in Tables 1 and 2. The vectors with random values of these parameters were calculated by SUSA based on the quantifications given in Table 2.

All of 181 runs were finished successfully (without abnormal terminations). Otherwise, simulation crashes may indicate possible problems associated whether with the input deck (reactor model) or with the computation tool (code models). Even in the case of relatively low number of crashed simulations in comparison with the total number of runs, like e.g. in Klein-Heßling et al. (2014), the