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Quantification of Dynamic Event Trees – A comparison with event trees for MLOCA scenario

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ABSTRACT

Dynamic event trees (DETs) provide the means to simulate physical system evolutions, the evolution of system states due to stochastic events, and the dynamic interactions between these evolutions. For risk assessment, the framework avoids the need to specify a priori the sequence of stochastic events prior to the plant response simulation and to iterate between the definition of the sequences and simulation of the responses. For nuclear power plants, DETs have been applied to treat scenarios up to core damage as well as post-core damage accident scenarios. The quantification of the frequencies of the sequences leading to the undesired system outcomes, while conceptually straightforward, faces several implementation issues. These include, for instance, the treatment of support system dependencies and of events characterized by a continuous aleatory variable. Some solutions to these issues are proposed and applied in a case study dealing with Medium Break Loss of Coolant Accident (MLOCA) scenarios. Additionally, the results obtained from DET quantification are compared with those estimated with a "classical" event tree model for these scenarios. This comparison provides some case-specific results on the impact of the improved modeling of dynamics on risk estimates.

1. Introduction

Practically all Nuclear Power Plants (NPPs) perform Probabilistic Safety Assessments (PSAs) to quantify risk. In these PSAs, the risk model is developed using the classical combination of event tree and fault tree analyses. Challenges to this PSA methodology include the treatment of time dependent interactions (accident dynamics) [1–4] and the propagation of physical process uncertainties to risk [5,6]. The Dynamic Event Tree (DET) framework provides a dynamic PSA methodology to address these challenges.

Although dynamic PSA approaches are useful in improved modeling of systems, some issues need to be resolved before these approaches become fully practical and applicable to plant-scale models. The intensive computational requirements and processing of large quantity of information are fairly addressed in the literature, e.g. [7,8], but the literature on the treatment of support system dependencies and safety systems whose response is a continuous stochastic variable is limited.

The primary aim of this work is to address these issues in the quantification of risk in DETs. The Medium Break Loss of Coolant Accident (MLOCA) accident scenario in a NPP is modeled with a DET and the DET has been quantified to estimate the corresponding risk. To see the impact of improved modeling of dynamics on risk, the DET quantification results are compared with the results reported in the literature [9], which used event tree models and success criteria analysis to quantify risk.

1.1. Quantification of risk with DET

The DET is a framework to simulate and analyze the dynamic interactions among the physical process, safety system responses, and operator responses. DET implementation tools include ADS [10–12], MCDET [13,14], ADAPT [7,8,15], SCAIS [16,17], and RAVEN [18]. DETs have been applied for scenarios up to core damage as well as post-core damage accident scenarios [13,15,19,20]. The DET studies reported in the literature have primarily focused on examining the dynamics of scenario and further providing useful information for PSA analysis [11,13,21]. A study in which the DET tool ADS was applied to the Small LOCA scenario focused on variability in operator actions on scenario evolution [11] and reported peak clad temperature (PCT) profiles. A study of Station Blackout scenarios with the MCDET tool, considering stochastic elements of the model [13], reported the conditional distributions of the total generated hydrogen. The literature on studies in which risk has been quantified using DETs, i.e. estimation of core damage frequency or large early release frequency, however, is limited. Chao and Chang [21] quantified the DET for steam generator tube rupture scenarios in a NPP. In their study, conditional probabilities

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for DET pivotal events (branch points) were obtained from offline (pre-simulation) fault tree calculations; the study thus accounted for dependencies among the events but defined success criteria without considering how the sequence dynamics may impact these. Considering the variabilities and accident dynamics, the success criteria definitions may change and therefore they should be verified while calculating conditional probabilities. Cojazzi [22] cautioned about treating continuous stochastic variables in DET simulations, "Failures in-time require an enormous number of sequences to be considered, therefore limiting rules must be developed for limiting the size of the problem". In [22], equipment run-time failures, i.e. after a successful start, were conservatively assumed to occur at the time of the demand; in other words, no operation of the equipment was credited. Turning to the treatment of uncertainties, the ADAPT tool was applied to treat severe accident phenomenological uncertainty in Station Blackout scenarios, dynamically generating accident progression event trees (level-2 PSA) [15] and quantifying probabilities for containment failure modes. Regarding the discretization used and its impact on quantification of risk, this study reports "There is a significant error associated with the choice of only five points to represent fragility curves".

Although these applications of DETs are useful for the examination of scenario dynamics, the end results analogous to PSA results (risk, risk contributors, critical sequences, etc.) have not been reported by any of these studies. The quantification of the frequencies of the sequences leading to the undesired system outcomes in DETs is conceptually straightforward but faces several implementation issues. Two of these are the need to address dependencies among DET pivotal event probabilities such as those arising from support system dependencies among safety functions (e.g. shared power supplies) and the modeling of safety functions whose response involves a continuous aleatory variable (e.g. recovery time or operator response times). These two essential practical problems in DET quantification of risk are acknowledged in [15,21,22]. The challenge with support system dependencies has been only partially addressed in [23] within the context of merging dynamic PSA results with the traditional even-tree/fault-tree approach. This paper demonstrates possible solutions to these issues.

In addition to treating accident dynamics, the DET offers a means to address the bounding issues associated with PSA modeling approaches. For instance, Osborn et al. [24] used DETs to eliminate the bounding of level-2 PSA for the level-3 PSA analysis and Karanki et al. [9] examined success criteria artifacts revealed in level-1 PSA. In classical PSA, the quantification of risk normally requires grouping of sequences and defining bounding success criteria. Bounding assumptions are essential in the process of developing accident sequence models. Bounding is not only difficult but also produces modeling artifacts in certain cases. Although the bounding reduces the number of cases for which success criteria analyses (plant simulations) are needed, it may inadvertently introduce unnecessary conservatism in some cases and underestimation of risk estimate in other cases. DET quantification of risk, where all generated sequences from DET simulations are quantified without sequence grouping and defining bounding success criteria to obtain the total risk, bypasses the risk quantification issues associated with these steps.

1.2. DET quantification of MLOCA risk and its comparison with PSA

Comparisons between dynamic event trees and classical PSA approaches were reported in references [1,22]. Amendola [1] qualitatively discussed the limitations of classical event trees to propose the Dynamic Logical Analytical Methodology (DYLAM), which is subsequently called DETs. Cojazzi [22], extended the DYLAM into a tool and compared its results with event tree results for the simple hold-up tank problem from [25]; a significant difference between DYLAM and event trees is found when the time constant of the system was increased. In addition, the DET quantification issues mentioned above (i.e. dependencies, safety functions with continuous responses) are not present in the simple tank problem. In solving larger-scale NPP scenarios with strong dynamics, the merits as well as the limitations of DETs (or their implementations) compared with classical event trees are further unmasked.

This paper presents an approach for DET quantification and its application to the MLOCA scenario for the Zion NPP, a Pressurized Water Reactor (PWR). The results include conditional core damage probabilities, core damage frequencies, individual break range contributions, contributions of important sequences, and contribution of important events. They are obtained by quantifying all of the sequences generated in the DET simulations, without grouping and defining bounding success criteria.

Because of differences in the boundary conditions, these DET quantification results cannot be compared with the PSA results reported in Ref. [26]. Instead, a comparison is made between the DET quantification results and those reported in [9]. As mentioned, the DET quantification results presented here represent the explicit quantification of all DET generated sequences; in contrast, in [9], the DET generated sequences were used to build a PSA model, including sequence grouping and success criteria definition.

The pivotal events considered here and in [9] include high pressure injection, low pressure injection, manual recirculation, and manual rapid cooldown. Variability in break size, number of available injection trains, and operator responses are also considered in the analysis.

This paper is organized into four sections. Section 2 focuses on practical issues and possible solutions of DET quantification. The two issues in particular, support system dependencies and safety functions with continuous response in DET quantification and their treatment are discussed. The steps involved in DET quantification approach used for MLOCA scenario is explained. A qualitative comparison between dynamic event tree and classical PSA approaches is discussed. Section 3 compares the quantitative MLOCA scenario results obtained with the two approaches; it also discusses the limitations and open challenges in DET quantification. Finally, the conclusions of the study are given in Section 4.

2. DET quantification – practical issues and possible solutions

DET quantification provides a framework to quantify risk, which bypasses bounding issues while considering impacts of accident dynamics. The calculation of risk (e.g. Core Damage Frequency (CDF)) using DET quantification must evaluate all generated sequences, treat support system dependencies among safety functions (e.g. shared power supplies), and also address safety functions whose response is a continuous aleatory variable (e.g. recovery time or operator response times). The next three sections discuss how to deal with these issues in the DET quantification. Section 2.4 gives DET quantification step-by-step, which is applied to MLOCA scenario. A qualitative comparison between DET quantification and PSA approaches is given in Section 2.5.

2.1. Representation of DET sequences

The DET generated through simulation is a large event tree that explicitly represents each sequence. For instance, for a given safety system/function, separate sequences will generally be generated for the cases of 0 trains, 1 train available, 2 trains available, etc. up to the total number of trains. In this implementation, safety functions with continuous responses (in time) are discretized and sequences are generated for each discrete response. The number of sequences