Performing an Accident Sequence Precursor Analysis with the ADS-IDAC Dynamic PSA Software Platform

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Abstract: An accident sequence precursor is defined as an observed event that combined with one or several postulated events could lead to core damage, while an accident sequence precursor analysis is a probabilistic safety assessment performed to obtain the conditional probability of a core damage accident given an initiating event and identify the dominant event sequences. The current discrete dynamic probabilistic safety assessment techniques are generally used to simulate accident scenarios and their probability of occurrence. They are an appropriate tool for performing an accident sequence precursor analysis that can capture realistic scenarios in a transparent manner. One such platform is ADS-IDAC – the accident Dynamics Simulator coupled with the Information, Decision, and Action in a Crew context cognitive model, and a mature nuclear power plant thermal-hydraulic model. Rich contextual scenarios are algorithmically generated using a relatively small set of branching rules that cover both stochastic and deterministic interactions between the system and the crew evolutions. Moreover, thermal-hydraulic success criteria are explicitly represented in the simulation. This paper provides details about how to perform an accident sequence precursor analysis with ADS-IDAC. Additional information is included regarding the recommended analysis team, the necessary information for performing the analysis, when to use ADS-IDAC, and the advantages and limitations of using it.

Keywords: Dynamic PSA, Accident Sequence Precursor, Simulation HRA.

1. INTRODUCTION

The Accident Sequence Precursor (ASP) Program is one of the critical United States Nuclear Regulatory Commission (NRC) programs focused on continuously assessing the risk significance of performance deficiency or degraded conditions of Nuclear Power Plants (NPPs). It uses retrospective event and condition assessment to identify and rank the operational events that could potentially lead to a core damage state and eventually release of fission products. Conventional Probabilistic Risk Assessment (PRA) employing event trees (ETs) and fault trees (FTs) remains the standard approach used to support these activities. There is no simulation-based PRA platform developed that can facilitate ASP. An ASP is defined as an observed event that combined with one or several postulated events could lead to core damage. An ASP analysis is a PRA performed to obtain the conditional core damage probability (CCDP) given an initiating event and identify the dominant event sequences [1]. The use of simulation-based PRA tools such as ADS-IDAC can aid in solving some of the challenges of conventional methodologies. However, it is critical to emphasize that the reasons for doing dynamic ASP, that is ASP analysis with dynamic PRA tools are mutually beneficial. The narrow scope of an ASP analysis aligns particularly well with the dynamic PRAs that can be resource intensive since the analysis is intended to be limited only to the operational event of interest with a few postulated complications. Therefore, this is one of the drivers of the work behind the latest version of ADS-IDAC. This paper aims to describe and to demonstrate why, when, and how ADS-IDAC can be used for dynamic ASP analysis studies. It is intended to be the starting point for performing an ASP analysis.

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2. OVERVIEW OF ADS-IDAC

As in the accident at Three Mile Island (TMI) Unit 2 in 1979, the crew can fail to make the correct situational assessment of the NPP by inadequately perceiving the critical system information and executing the wrong recovery strategy or bypassing important safety systems [2]. Although no similar accident has occurred since 1979 in the United States, the challenge of correctly predicting and mitigating the human performance remains. ADS-IDAC attempts to resolve this challenge. It was developed to tackle the shortcomings of the previous generation of human reliability analysis methods (e.g., THERP, SPAR-H), which include the inability to integrate the so-called 'errors of commission'. ADS-IDAC was and remains revolutionary for being the only simulation-based HRA method that transparently predicts and quantifies the time-dependent crew behavior by simulating both the crew and system behavior. It is one of the most mature dynamic platforms with an evolution that spans more than 25 years as illustrated in Figure 1.

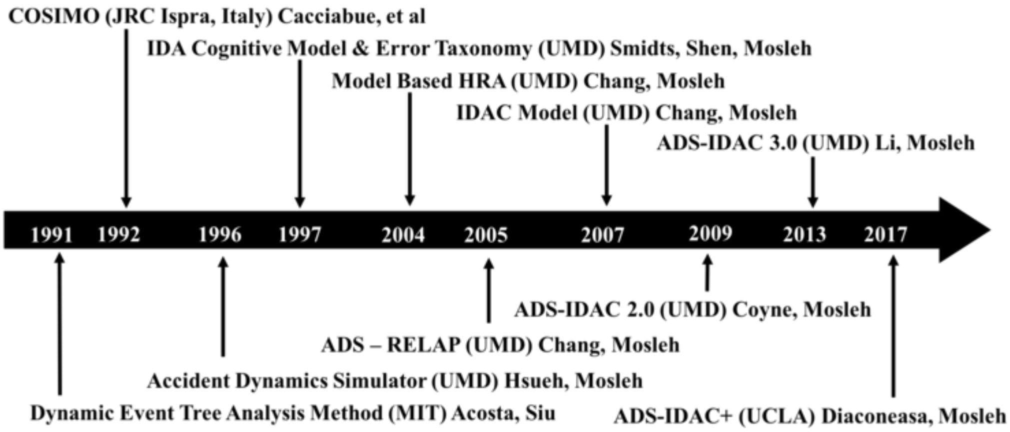

Figure 1 ADS-IDAC Development History [1-7]

ADS-IDAC is a simulation engine that uses the IDAC operator response model and the RELAP5/MOD3.3 thermal hydraulic code to generate discrete dynamic event trees (DDETs) containing contextually rich scenarios that could occur given an initiating event (Figure 2). Its modular structure and the flow of information between modules are shown in Figure 3. A scheduler module coordinates the interactions between all the other modules and generates the DDETs. The probability of each scenario/sequence is calculated as the product of conditional probabilities of its constituent branches (as is the case for conventional ETs). The indicator module simulates the control panel indicators' states driven by information from the system module. The hardware reliability module simulates the failure probabilities of the system's and control panel's components.

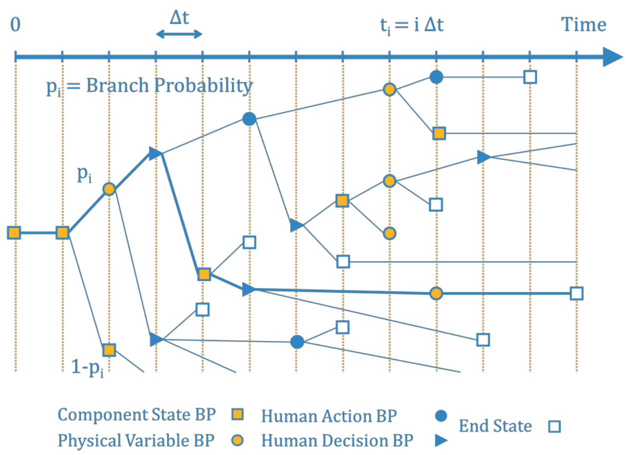

Figure 2 Discrete Dynamic Event Tree Generated by ADS-IDAC

The RELAP5/MOD3.3 system code is a light water reactor (LWR) best estimate transient simulation tool for modeling the behavior of the reactor coolant systems (RCSs) and the core during postulated events such as loss-of-coolant accidents (LOCAs), loss of offsite power (LOOP), loss of feedwater (LOFW), or loss of flow operational transients [10].

The system module exposes all the thermal-hydraulic system model variables and controls to the control panel module, which in turn acts as the interface to the human operators. The control panel module is also linked to the hardware reliability module and Hybrid Causal Logic (HCL) module used to model component failures, either part of the frontline systems or support systems. A wide range of hardware failure events is supported by ADS-IDAC [11].

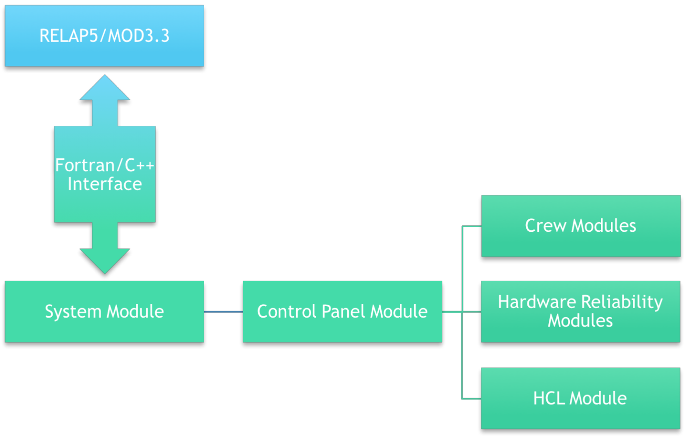

Figure 3 ASD-IDAC Architecture

At a high level of abstraction, IDAC is composed of models for information pre-processing, decision-making, and action execution of a crew. Together with the mental state and the reasoning module, they constitute the main parts of the IDAC model as shown in Figure 4. Given incoming information, the crew model generates a probabilistic response, linking the context to the decisions and actions through explicit causal chains.

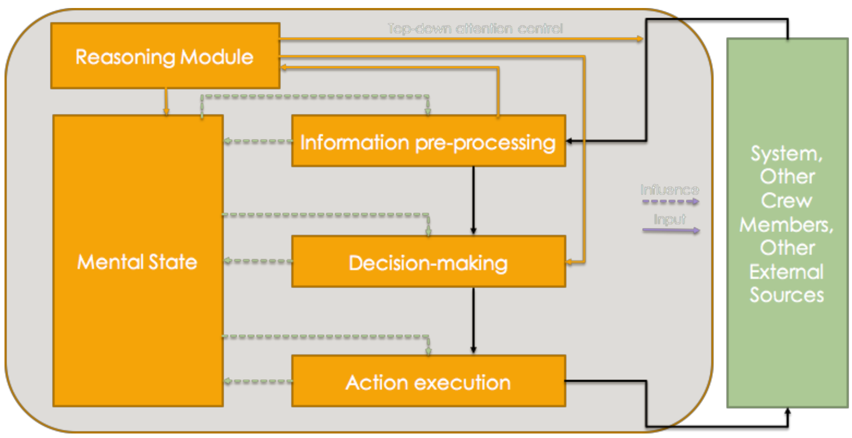

Figure 4 IDAC Architecture

The simulation model requires either the heuristic cognitive engine or the reasoning module to guide operator decision-making. The cognitive engine forms a situational assessment from perceived information to identify and select suitable goals using the situational assessment, to identify and select suitable strategies for obtaining goals, and to prioritize and resolve conflicts among the selected goal/strategy sets [8]. The cognitive engine is based largely on a recognition primed naturalistic decision-making model [12]. The recognition primed naturalistic decision-making model, mainly used to simulate the behavior of experienced decision makers under time pressure, was enhanced to capture the variability in human decision-making. As an example, variation in timing of operator response was included through stochastic models. By selecting the reasoning module as the engine of cognition, the operators' knowledge-based behavior is greatly augmented through an embedded attention mechanism in information perception channels, better capturing cognitive resource limitations, and top-down attention control [9]. This module also captures how the crew analyze the perceived information, connecting different pieces of information to form a big mental picture of the plant situation, and making accident diagnoses. Both decision-making engines support the following of written procedures if the crew decide they are appropriate given the perceived plant state.

Overall, ADS-IDAC is a very powerful simulation platform that is capable of modelling plant and crew behavior, including their interactions given abnormal conditions. From previous studies (8, 9, 13), the following conclusions can be made:

- ADS-IDAC can model the direct effect of crew behavior on the plant recovery given abnormal conditions.
- ADS-IDAC can model the decision-maker's underlying cognitive processes.
- ADS-IDAC can capture the variability in crew decisions and behaviors by using a relatively small number of branching rules.
- ADS-IDAC can quantify the probability of hardware and human failure events.

3. ACCIDENT SEQUENCE PRECURSOR ANALYSIS

As already mentioned in the introduction, the ASP Program is an important United States NRC program focused on continuously assessing the risk significance of performance deficiency or degraded conditions. Retrospective event and condition assessments are used to identify and rank the operational events that could potentially lead to accident conditions. The narrow scope of an ASP analysis is compatible with the dynamic PRA resource demanding needs since the analysis is intended to be limited only to the operational event of interest with only a few postulated abnormal conditions. It is worth mentioning that the remarks given in the next section are generally applicable to any dynamic PRA analysis with ADS-IDAC.

3.1. The Recommended Analysis Team

As with any other PRA or HRA method, a multi-disciplinary team is recommended to be available for the necessary background knowledge of the accident under investigation. However, the actual collection of data and implementation of the model can be performed by any of the team members alone (to be called the "ADS-IDAC analyst").

The recommended analysis team should include people with sufficient knowledge and expertise to supply information about the accident under investigation to build the ADS-IDAC model. Typical skillsets and specialists include:

- a PRA analyst,
- an HRA analyst,
- a thermal-hydraulics engineer providing the RELAP5 or alternative assistance,
- a reactor operations trainer, and
- a reactor operator.

3.2. Necessary Information for Performing the Accident Sequence Precursor Analysis with ADS-IDAC

The multi-disciplinary team of experts should provide knowledge on a wide range of topics necessary for performing the analysis by the ADS-IDAC analysist. It is the responsibility of the ADS-IDAC analyst to understand the ADS-IDAC methodology for collecting the appropriate information, perform expert elicitation, and training the other team members on ADS-IDAC if needed. In general, the following types of information are needed to perform an ASP analysis with ADS-IDAC:

- existing plant-specific PRA;
- underlying ADS-IDAC methodology;

- plant behavior (including both frontline and support systems);
- operator training programs;
- plant procedures and guidelines; and
- plant operational history.

The easiest was to perform an analysis with ADS-IDAC is to check existing simulation models for the design and scenario under investigation in the ADS-IDAC installation folder under 'testcases'. One such model is referenced in [13]. If such simulation models are available, minimal changes are required and the analyst can proceed directly to add new conditional events. By running the simulations, the analysts can immediately assess how the added conditional events or plant conditions contribute to the overall plant and crew performance and, ultimately, to the core damage frequency.

Until a comprehensive database of ADS-IDAC simulation models becomes available, it is likely that the analysts would need to create a new simulation model that matches their needs. On demand, a step-by-step guide can be provided. It is intended to help the analysts understand how such simulation models could be created and the exact information needed to complete it. It is expected that this guide would be followed sequentially as some model elements may depend on other elements that need to be defined in advance (e.g., conditional failure events cannot be defined for components that are not already created in the control panel).

3.3. Advantages and Limitations of Using ADS-IDAC for Accident Sequence Precursor Analysis

ADS-IDAC offers several key advantages over the conventional ET and FT PRA methods:

- it can capture the impact of event sequence timing,
- it provides a better representation of thermal-hydraulic success criteria,
- it permits more detailed and realistic modeling of operator response,
- the complexity of enumerating scenarios is delegated to scenario generating algorithms,
- it reduces analyst-to-analyst variability of the results; and
- it allows heterogeneous models of various phenomena to be devolved and used at different levels of detail (simulation tracking can provide desired information on nature of scenarios – "white box" simulation).

Nonetheless, ADS-IDAC shares the following limitations with all other discrete dynamic PRA models:

- the physical models can be resource intensive to develop and difficult to validate (particularly for rare events);
- obtaining a complete risk profile (i.e., ensuring that a complete solution space is explored and representative samples are chosen) requires further research;
- efficient methods for uncertainty analysis do not exist as certain types of uncertainty and variability can alter the structure of risk scenarios as they evolve over time; and
- possible "scenario space explosion" noting that "smart" algorithms have been explored that produce dominant risk scenarios at reasonable simulation times.

3.4. When to Use ADS-IDAC for Accident Sequence Precursor Analysis

Given ADS-IDAC's benefits and limitations, it is reasonable to ask, "when should one use ADS-IDAC?" Considering that ADS-IDAC has thus far only been used for validation and testing purposes, this question does not have a straightforward answer. For existing ADS-IDAC models or separate RELAP5 physical models, it should be apparent that ADS-IDAC is a very powerful tool given the advantages listed in the previous section.

Even if new ADS-IDAC models are needed, there are certain situations when the effort to build the model will be worthwhile. In general, these cases have some of the following characteristics that are necessary to be captured in the analysis:

- control loops;
- complex hardware – human interactions;
- multiple plant conditions or aleatory influences that may affect the operator behavior;
- operator-to-operator variability; and
- complex design or procedural changes that may affect the operator behavior.

3.5. Creating a New ADS-IDAC Model

If an ADS-IDAC model is not readily available for the application under study, a new model would have to be created starting from a RELAP5 model. ADS-IDAC has complete guidance for creating such a model part of the graphical user interface.

Moreover, the ASP analysis sequence of interest can be used as input for the dynamic PRA model to constrain the simulation to the solution space of interest. To be more precise, in ADS-IDAC, by simulating the plant and crew response models, and using the generic branching rules, the initial sequence of events is expanded into a DDET capturing both the initial sequence and various other sequences with different timing of failures, order of failures, degrees of component degradation, time and degree of recovery, human actions, human decisions, or physical variable thresholds. This can be encapsulated in the cut set diffraction phenomenon graphically shown in Figure 5.

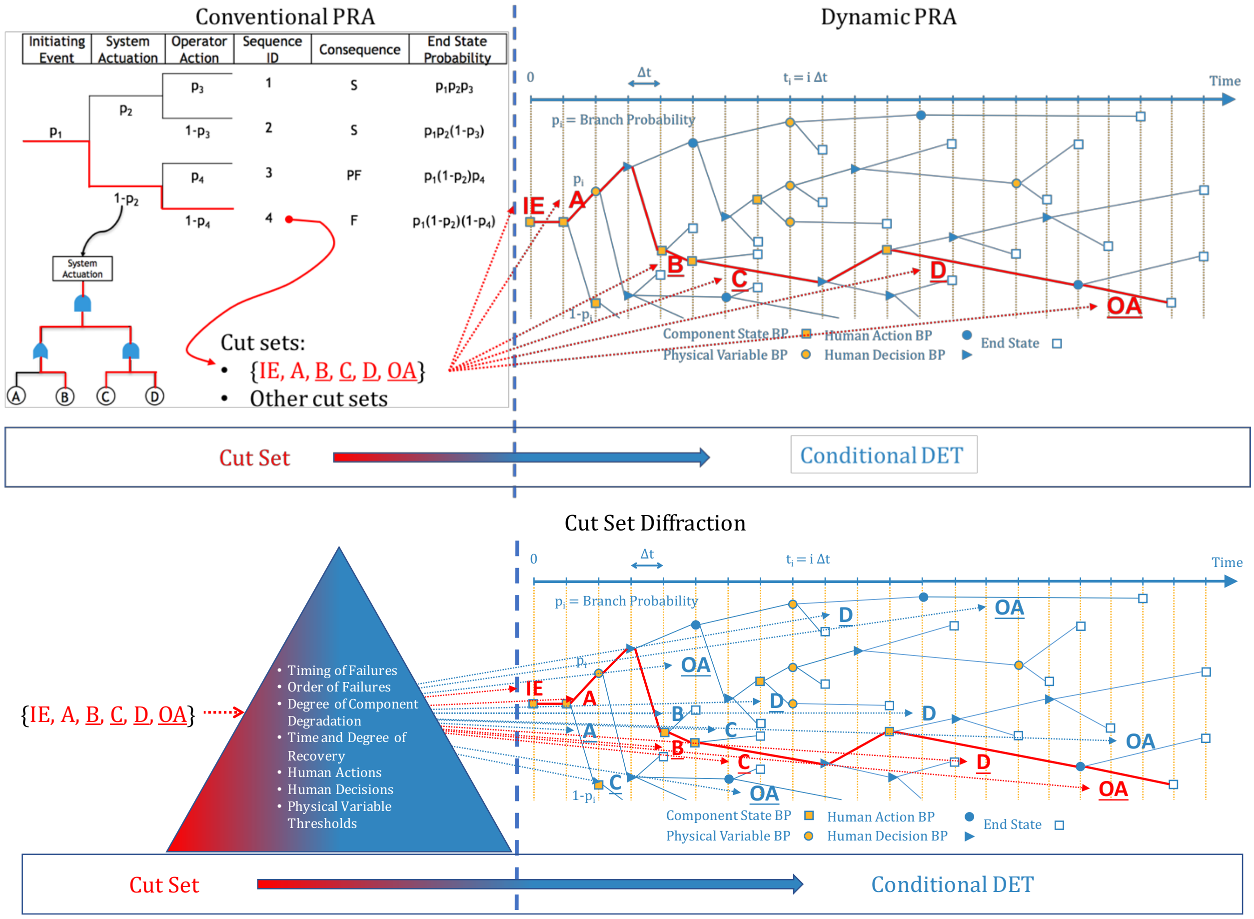

Figure 5 Cut Set Diffraction Phenomenon [14]

Given the availability of a complete ADS-IDAC model, the scope of the ADS-IDAC analysis is defined by activating branching rules and setting sequence termination conditions. Multiple runs of the simulation model can be performed in which the input conditions are varied. This effectively allows the analyst to investigate various "what if?" scenarios and compare the results between similar conditions with slightly altered precursors.

4. CONCLUSION

In this paper the details about how to perform an accident sequence precursor analysis with ADS-IDAC have been given. Additional information is included regarding the recommended analysis team, the necessary information for performing the analysis, when and how to use ADS-IDAC, and the advantages and limitations of using it. Ideally, this paper should be the starting point for performing an ASP analysis.

Acknowledgements

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