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Integrated Framework for Dynamic Safety Analysis

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1. Introduction

In the conventional PSA (Probabilistic Safety Assessment), detailed plant simulations by independent thermal-hydraulic (TH) codes are used in the development of accident sequence models. Typical accidents in a NPP involve complex interactions among process, safety systems, and operator actions. As independent TH codes do not have the models of operator actions and full safety systems, they cannot literally simulate the integrated and dynamic interactions of process, safety systems, and operator responses. Offline simulation with pre-decided states and time delays may not model the accident sequences properly. Moreover, when stochastic variability in responses of accident models is considered, defining all the combinations for simulations will be cumbersome task. To overcome some of these limitations of conventional safety analysis approach, TH models are coupled with the stochastic models in the dynamic event tree (DET) framework, which provides flexibility to model the integrated response due to better communication as all the accident elements are in the same model. The advantages of this framework also include: Realistic modeling in dynamic scenarios, comprehensive results, integrated approach (both deterministic and probabilistic models), and support for HRA (Human Reliability Analysis).

2. Development of ADS-TRACE

2.1 Goal of Development

ADS (Accident Dynamic Simulator) [1] is a software tool based on discrete DET framework for simulation of accident sequences. The integrated response of process, hardware (safety systems), and operator actions for an initiating event is modeled within the tool. The stochastic modeling (for hardware and operator actions) is present within ADS and the deterministic modeling (for the process) is modeled by RELAP5 [2]. The existing ADS has an issue related to the limited computational power since it runs under the Microsoft Windows environment and this is one of the major obstacles for the practical implementation of integrated analysis to industrial scale problems. In addition, since RELAP5 is a legacy code of US NRC and it was decided for US NRC not to support further development of RELAP5, it was decided to replace RELAP5 with a state-of-the-art thermal hydraulic system code, TRACE [3]. Consequently, the final product of the development is ADS coupled with TRACE runs under the Linux environment.

2.2 Coupling Strategy

For efficient dynamic calculations, it is necessary to integrate ADS and TRACE, and let them communicate with each other in real time. In this way, the real-time plant parameters calculated by TRACE can be provided to ADS for operator action modeling and decision-making, and any decision or parameter change done by ADS can be directly implemented into the TH calculation by TRACE. In addition, since ADS plays a role of scheduler as well, it is reasonable approach to integrate TRACE as a sub-program of ADS. Therefore, the final coupling scheme has been decided as depicted in Fig. 1. In this integrated framework, ADS and TRACE have roles of a master program and a sub-program, respectively. An interface subroutine package has been developed for the real-time communication between them. Since ADS and TRACE are written in C++ and FORTRAN90, respectively, mixed language programming has been introduced in the development of the interface subroutine package. The communication between ADS and TRACE happens in every one second of problem time, by default, and a user is allowed to modify the communication interval, if necessary. In addition, since TRACE has been designed as a stand-alone code, it is necessary to modify the code to cope with requirements as a sub-program. The modification includes the time step advancement, preparation of proper failure paths, initialization and deallocation of arrays and parameters, and so on.

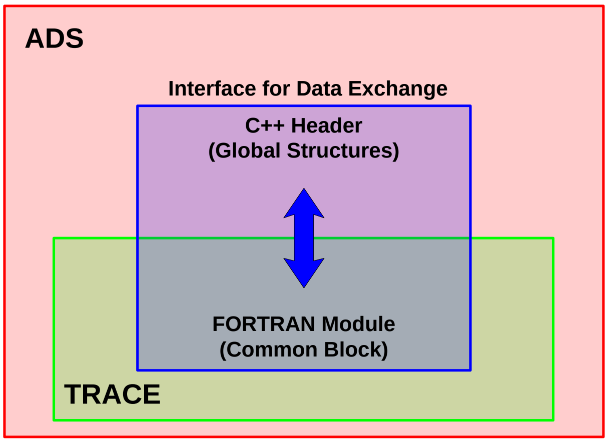

Fig. 1. Coupling scheme

2.3 Calculation Procedure

Calculation procedure in the developed framework starts with input processing for ADS. At first, the scope of analysis is defined, and boundary conditions and assumptions such as safety functions, variability, core damage criteria and sequence truncation criteria are decided. Then input processing for TRACE is conducted to check out the soundness of a TH model. When the TH model is confirmed, information for the required safety signals and TH variables are exchanged between two codes and ADS figures out if all required variables are included in the TH model. A calculation for the first sequence starts when the models in both ADS and TRACE are confirmed, and data exchange and decision-making, if necessary, happen in every one second of problem time.

Whenever a decision-making happens or a hardware malfunction is decided, ADS-TRACE creates a restart file at that moment and keeps calculating the sequence. ADS-TRACE comes back to the latest restart point when the calculation for the sequence is done, and starts a restart calculation for the lower branch with modified boundary conditions considering the decision-making or the hardware malfunction. By repeating the procedure mentioned above, ideally, ADS-TRACE can calculate all necessary sequences. Since it is allowed for ADS-TRACE to consider the random variability, recovery action by operator and human error, it is basically possible to analyze all sequences from each initiating event using ADS-TRACE. When all sequences are evaluated, results are gathered by ADS-TRACE and interpreted for engineering purposes. Examples of output include success criteria, time window for operator action, realistic core damage frequency, and so on.

3. A Case Study using ADS-TRACE

A case study using ADS-TRACE has been carried out for a medium loss-of-coolant-accident of Zion nuclear power plant [4]. In the case study, it was evaluated the effect of break size on the time window for operator action to switch the low-pressure injection pump over from the injection mode to the recirculation mode. The TH model for the analysis has been developed on the basis of a model for OECD/NEA SM2A project [5] and the cooldown by the secondary system was considered when the high pressure injection system is not available. Since it is a case study to demonstrate the capability of ADS-TRACE, in order to simplify the problem, the time window for operator action was selected from a distribution [6], and 5%, 50%, and 95% values have been employed.

The result from the calculations successfully reveals sensitivity by the break size on the time window for operator action and the secondary cooldown timing and rate, as depicted in Fig. 2.

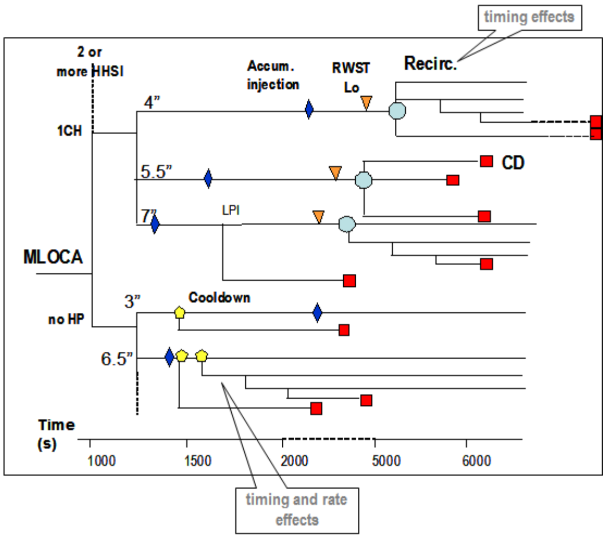

Fig. 2. Example of results from ADS-TRACE

3. Conclusions

An integrated framework for dynamic safety analysis has been developed by integrating ADS and TRACE. The developed code, namely ADS-TRACE, can evaluate real-time dynamic interaction between operator action, random variability, and system behavior. A case study using ADS-TRACE demonstrates the capability of dynamic analysis successfully. Therefore, ADS-TRACE is expected to be used to analyses of time window, success criteria, and more realistic core damage frequency.

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