Annals of Nuclear Energy 115 (2018) 55–72

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Dynamic event tree analysis with the SAS4A/SASSYS-1 safety analysis code

Zachary K. Jankovsky [a,b,*], Matthew R. Denman [b], Tunc Aldemir [a]

[a] Nuclear Engineering Program, The Ohio State University, 201 West 19th Avenue, Columbus, OH, USA
[b] Risk & Reliability Analysis, Sandia National Laboratories, 1515 Eubank Boulevard SE, Albuquerque, NM, USA

ARTICLE INFO

Article history:
Received 6 September 2017
Received in revised form 2 January 2018
Accepted 5 January 2018

Keywords:
ADAPT
SAS4A/SASSYS-1
SFR
DET
Dynamic PRA
Transient overpower

ABSTRACT

The consequences of a transient in an advanced sodium-cooled fast reactor are difficult to capture with the traditional approach to probabilistic risk assessment (PRA). Numerous safety-relevant systems are passive and may have operational states that cannot be represented by binary success or failure. In addition, the specific order and timing of events may be crucial which necessitates the use of dynamic PRA tools such as ADAPT. The modifications to the SAS4A/SASSYS-1 sodium-cooled fast reactor safety analysis code for linking it to ADAPT to perform a dynamic PRA are described. A test case is used to demonstrate the linking process and to illustrate the type of insights that may be gained with this process. Newly-developed dynamic importance measures are used to assess the significance of reactor parameters/constituents on calculated consequences of initiating events.

1. Introduction

Computer models (simulators) are used in Probabilistic Risk Assessment (PRA) to inform the likelihood of possible outcomes given an initiating event and set of uncertain parameters. Simulators are regarded as repositories of knowledge of physical phenomena and can provide best-estimate values based on current knowledge (Schmidt et al., 2011). SAS4A/SASSYS-1 is one such simulator for Sodium-cooled Fast Reactors (SFRs) developed by Argonne National Laboratory (Fanning et al., 2017) (an earlier version (Fanning, 2012) has been used for this work). SAS4A/SASSYS-1 deterministically models coupled phenomena in a plant including point kinetics, thermal hydraulics, and mechanical changes such as expansion or failure of structural components. A SAS4A/SASSYS-1 model typically begins with steady-state operation, introduces a transient, and follows the progression of the transient through potential fuel damage and relocation within the core region.

SFRs have traditionally used PRAs to support their licensing process. Clinch River Breeder Reactor (CRBR) conducted a multiple part PRA to evaluate its safety characteristics (Bruske et al., 1983). Power Reactor Innovative Small Module (PRISM) included a Level 3 PRA in its Preliminary Safety Information Document (PSID) submittal to the United States Nuclear Regulatory Commission (NRC) (PRISM Preliminary Safety Information Document, 1987). The general flow of a PRA for an SFR is shown in Fig. 1 (PRISM Preliminary Safety Information Document, 1987). Recently, work has been performed with the goal of developing licensing processes for advanced reactors in the United States (Grabaskas et al., 2016). The work in Grabaskas et al. (2016) includes an attempt to model the potential release and transport of radionuclides from SFR fuel beyond containment in the case of an accident.

The PRA representation shown in Fig. 1 potentially has a number of limitations including possibly subjective ordering of events and difficulty in capturing the effects of event timing, representing logic loops, and accounting for epistemic uncertainties (Aldemir, 2013). These limitations make the process challenging to apply for accident sequences where significant uncertainties exist regarding the behavior of inherent safety systems and/or operator actions (Jankovsky et al., 2015). The objective of this paper is to describe how such a traditional PRA flow can be augmented through a Dynamic Probabilistic Risk Assessment (DPRA) framework using SAS4A/SASSYS-1 simulations.

DPRA is a terminology used to describe methods that explicitly consider the time element in system evolution to account for complex hardware/process/software/human interactions. Among the DPRA methods proposed to date (Aldemir, 2013; Bucci et al., 2008), the Dynamic Event Tree (DET) approach is perhaps the most

* Corresponding author at: Nuclear Engineering Program, The Ohio State University, 201 West 19th Avenue, Columbus, OH, USA.
E-mail address: Zachary.Jankovsky@sandia.gov (Z.K. Jankovsky).

https://doi.org/10.1016/j.anucene.2018.01.001
0306-4549/

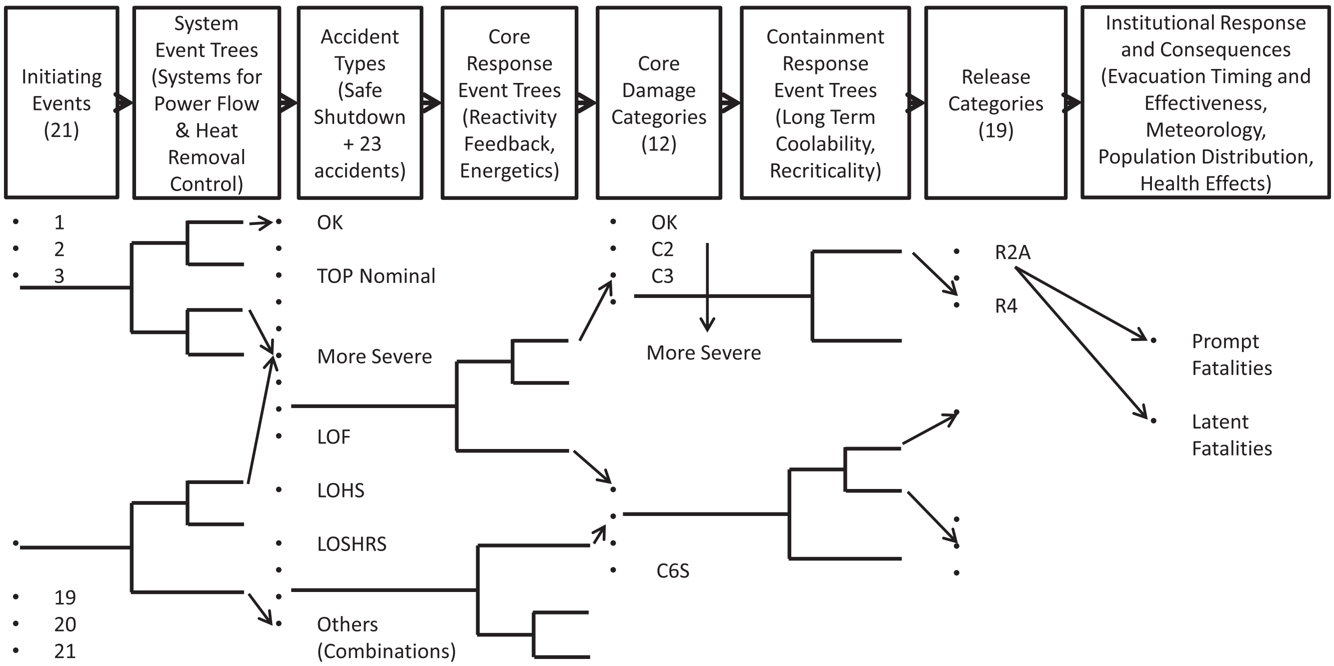

Fig. 1. Risk Model Structure for PRISM, recreated from Ref. PRISM Preliminary Safety Information Document (1987). TOP: transient overpower, LOF: loss of flow, LOHS: loss of heat sink, LOSHRS: loss of shutdown heat removal system.

commonly used one due to its direct integrability into traditional PRA (albeit with some post-processing, see Reference (Aldemir et al., 2009)). A DET may be coupled to existing fault trees to inform branching probabilities (Karanki and Dang, 2016) and may be inserted in the place of a traditional event tree for a specific initiating event while leaving the remainder of the PRA intact (Gil et al., 2012). An example DET is shown in Fig. 2 which covers the *Core Response Event Trees* analysis phase from Fig. 1. The tree splits into new branches (see P_{1121} and P_{1122} in Fig. 2) for each sampled value of an uncertain parameter of interest. Each branch to be explored is accompanied by a conditional probability.

The augmentation of traditional PRA with DPRA methods may be particularly helpful in the analysis of SFRs. Traditional PRA excels at analyzing component failures while DPRA incorporates mechanistic responses to changes in boundary conditions. Modern SFR designs place an emphasis on inherent safety measures in which significant uncertainties exist in the form of continuous parameters, such as heat transfer coefficients, that are difficult to represent in traditional PRA (Brunett et al., 2014). The timing of key events, such as pump recovery, may significantly affect the progression of the accident (Ho and Apostolakis, 1988).

DPRA and a previous application of this methodology to an SFR are briefly described in Section 2. The work performed to enable dynamic manipulation of SAS4A/SASSYS-1 for DET generation and to couple it to the Analysis of Dynamic Accident Progression Trees (ADAPT) DET generator code (Hakobyan et al., 2008) is described in Section 3. The operational status and performance of the systems of interest used in defining branching conditions are given in Section 4 with the key results delineated in Section 5. Section 6 summarizes the contribution of the paper to the state of the art.

2. Dynamic PRA background

Brief descriptions of DPRA and the DET approach specifically are provided in Section 2.1. The operation of ADAPT is explained in Section 2.2. Section 2.3 outlines the history of the use of ADAPT for safety analysis of advanced reactors, including SFRs.

2.1. Dynamic PRA

Traditionally, PRA has been performed using an event-tree/fault-tree framework. Fault trees logically trace the potential causes of the loss of each function of a sub-system. An event tree is used to explore the consequences of events that follow an initiating perturbation of the overall system. Events may represent the failure of a sub-system, recovery by operators, or other events or conditions that are expected to have an impact on the end state of the system. The probability of an event occurrence is informed by its associated fault trees and the current condition of the system. A limitation of traditional PRA is that it relies on the analyst to assemble events on the event tree in an order that reflects reality (Reactor Safety Study, 1975). Given that a PRA may include tens or hundreds of thousands of events and branches, it is difficult to identify all significant sequences with partially subjective judgment. Events where uncertain timing may affect the progression of the accident must be binned and implemented as a series of binary events to fit the framework of a traditional event tree (Bucknor, 2013). Modeling uncertainties that can affect the sequencing of events are hard to capture and interactions among hardware/process and humans are challenging to model (LaChance et al., 2012).

DPRA addresses these challenges by a systematic and mechanistic search of both epistemic and aleatory uncertainty space on a common computational platform. DPRA (Aldemir, 2013) is often implemented using the DET methodology due to ease of integrability of DETs into traditional PRA as indicated in Section 1. The chosen definition of DET in this paper is an analysis in which, "plant parameters are represented as time-dependent variables in event tree-construction with branching times often determined from the severe accident systems analysis code being used to examine the plant" (Hakobyan et al., 2008).

A simulator is used to model the plant-level response to an initial perturbation. The state of the plant before this perturbation is referred to as the first branch. When conditions in the plant as reflected by the simulator are appropriate for an event to occur (referred to as reaching a branching condition) the simulator is stopped and a new set of input is generated for each possible path