Dynamic Methods for the Assessment of Passive System Reliability

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Abstract: Passive systems present certain challenges for conventional reliability assessments due to their ability to fail functionally without any physical component failures. This results in difficulties when modeling the system using fault trees. Also, the behavior of passive systems can be entirely time-dependent, meaning that their representation in conventional event trees where time is not explicitly modeled is ineffective. Dynamic methods, which utilize computer simulations to dictate the timing of events, offer a possibility to alleviate some of these issues. In this work, a methodology is presented for utilizing discrete dynamic event trees (DDETs) to characterize passive system reliability. A demonstration problem has been chosen which analyzes a long-term station blackout (SBO) in a generic advanced small modular reactor (advSMR) coupled with the reactor cavity cooling system (RCCS), a passive cooling system that relies on natural convection and radiation to reject heat from the reactor guard vessel. Uncertainties related to characteristics affecting the performance of the RCCS are identified, and the methodology for addressing uncertainties in the sequencing of events in scenario progression is presented. This work is part of an ongoing project at Argonne National Laboratory to demonstrate methodologies for assessing passive system reliability.

Keywords: PRA, Sodium Fast Reactor, Dynamic PSA, Passive Systems

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1. INTRODUCTION

In more recent years, the nuclear sector has increased its developmental efforts in the areas of small modular reactors (SMRs) and their non-light water counterparts, advanced SMRs (advSMRs). This shift away from the traditional and proven large light water reactor technology is incentivized by the potential benefits of the small, modularized design: decreased capital investment, abbreviated production and construction periods, access to new markets, and the ability to utilize cost-effective technology, such as passive safety systems. However, the current regulatory framework does not adequately detail the licensing process for this new generation of reactor designs. As new licensing protocols are developed, it is anticipated that the regulatory standards will continue to experience a shift towards best-estimate methodologies and risk-based metrics, particularly with regard to the analysis of passive safety system performance and reliability.

The risk-informed analysis of passive system reliability presents a unique challenge, however, that is typically not addressed in traditional risk assessment techniques. Traditional fault and event trees treat active failures, or the physical failure of a specific component or system (e.g. failure of a check valve to open or pump to operate). While this approach is sufficient for systems that rely on the successful operation of specific physical components, this technique is not appropriate for assessing the reliability of systems that maintain no active components and do not rely on operator intervention, such as a passive decay heat removal system prevalent in pool-type advSMR designs. Furthermore, failures in passive systems are often phenomenologically driven, and are therefore time-dependent; traditional event tree analyses do not explicitly consider time, so time-dependent effects are not always adequately addressed. To account for this, the utilization of discrete dynamic event trees (DDETs), which explicitly treat time, allows for a mechanistic and consistent treatment of failures and the phenomenology driving passive systems.

This work presents a dynamic approach to quantifying the reliability of a passive system, which is part of an ongoing project at Argonne National Laboratory to demonstrate various methodologies for assessing passive system reliability. The analysis presented in this paper focuses on the reliability and

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performance of the reactor cavity cooling system (RCCS), a passive system that aids in cooling the cavity adjacent to a small, pool-type sodium fast reactor (SFR) via natural convection. A model is currently being developed in RELAP5-3D [1] of a 100 MWe pool-type SFR that includes treatment of the sodium pool and its associated piping and pumps. This reactor model will be coupled with an existing RELAP5-3D model of the RCCS. The ultimate objective of this analysis is to develop and demonstrate dynamic techniques for the determination of passive safety system reliability, including a consistent treatment of the uncertainties typically associated with these types of systems. This paper is accompanied by a sister paper, titled "The Development of a Demonstration Passive System Reliability Assessment" [2].

2. PASSIVE SYSTEM RELIABILITY ASSESSMENT TECHNIQUES

There currently exist several methodologies for analyzing the reliability and performance of passive systems. A margins-based approach, where the margin to a specific safety goal is assessed for conservative, bounding scenarios, was developed during the licensing process for AP600 [3,4]. This technique, while proven, is similar to the historical regulatory basis that relied on conservative assumptions and deterministic methods. Passive system reliability assessment can also be accomplished using mechanistic methods, where passive system performance is treated deterministically through decomposition techniques and best-estimate parameters. The analysis in [2] presents details of the Reliability Methods for Passive Systems (RMPS) [5] methodology, a mechanistic method, which is being used to concurrently analyze the demonstration problem outlined in this work.

More recently, dynamic methods, and in particular DDETs, have been under development for risk assessment applications in the nuclear sector [6,7,8]. The structure of DDETs exhibits many similarities to its static counterpart, in that the sequence of events leading to a specific outcome (core damage, environmental release, etc.) is described probabilistically in the form of event trees. Construction of conventional event trees tends to rely heavily on expert elicitation and the analyst's judgment with regard to the timing and relative ordering of events, as time is not explicitly modeled in a static event tree. The most obvious criticism of this conventional approach is that when the full range of uncertainties is considered in the analysis, it is possible that the ordering and relative timing of events may change. Also, because the analysis utilizes expert elicitation to treat the progression of key accident phenomenology, scenario evolution can be treated inconsistently. To address these shortcomings, the DDET technique, which explicitly treats time and utilizes deterministic models to describe accident progression, is utilized. A DDET treatment allows for a consistent and mechanistic analysis while still incorporating the probabilistic treatment of uncertainties.

Construction of DDETs is accomplished by coupling a system model with a set of branching rules that describe behavior of the system probabilistically. The analysis begins with a single initiating event and the simulation proceeds in time until a user-defined branching criterion (typically a state variable) is achieved. At this point, the simulation is halted, and the scenario bifurcates to generate two parallel scenarios, where one scenario contains the occurrence of the branching event, and the other does not. The simulations proceed as before, until the next branching criterion is reached, where branching will then occur again.

For many passive systems that rely on natural circulation (such as in-vessel circulation within a sodium pool), establishing operation at 100% capacity can require some prolonged time interval. Typically, the rate of capacity development is heavily dependent on the boundary conditions of the system. Treatment of passive systems by means of DDETs provides an advantage over conventional event trees in that the physical boundary conditions affecting passive system performance can be directly modeled during the simulation, and non-binary operating conditions, representing degraded performance or varying failure modes, can also be treated in the DDET through system modeling and application of uncertainties in the boundary conditions.

3. SYSTEM MODEL AND DEMONSTRATION PROBLEM

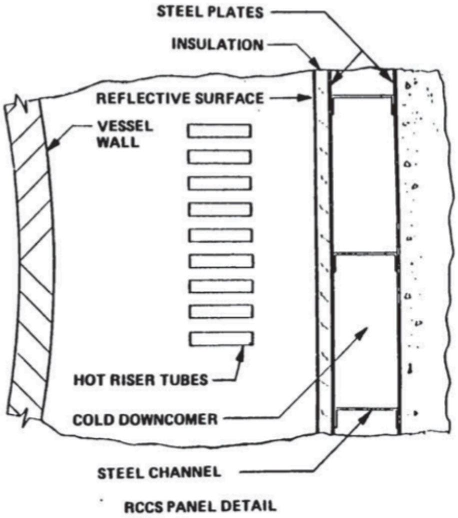
Because the objective of this analysis is to develop and analyze techniques for passive system performance assessment, a generic design is utilized in this analysis, rather than a specific reactor. In this work, a small pool-type advSMR with the passive RCCS will be used to model the response of the plant to a station blackout (SBO) in RELAP5-3D. The design characteristics of the generic advSMR used in this analysis are presented in Table 1. For the primary system model, representations of the sodium pool, heat rejection to a secondary loop via intermediate heat exchangers (IHX), core inlet and outlet plenums and primary pump are included. In this model, the core is not explicitly modeled. Instead, during unprotected transients, changes in reactivity will be modeled using integral reactivity feedback coefficients that treat core power as a function of temperature. During protected cases, decay heat generation will be modeled.

Table 1: Design characteristics of the generic advSMR used in this analysis.

Feature	
Power Rating	250 MWth/100 MWe
Primary Coolant	Sodium
Primary System Type	Pool
Primary Coolant Flow Rate	~1270 kg/s
Coolant Pump Type	Electromagnetic
Number of Coolant Pumps	4
Primary Vessel Height	10 m
Core Inlet/Outlet Temp.	~400°C/~550°C

The primary system model will be directly coupled with an existing RCCS model. The RCCS is a passive cavity cooling system originally included in the General Atomics Modular High Temperature Gas cooled Reactor (GA-MHTGR) design [9]. In this system, shown in Figure 1, a series of hot riser tubes in the reactor cavity cool the reactor vessel through natural convection and radiation. Cooling air from the atmosphere enters the RCCS by means of the downcomer, and then travels through the risers before it is ultimately rejected to the atmosphere. RCCS contains no active components and is therefore functioning during normal operation; however, the system is primarily intended to remove decay heat during accident scenarios.

Figure 1: Plan view of RCCS located within reactor cavity [9].



With regard to accident scenario selection, a long-term SBO sequence, where all offsite and onsite AC power is lost, was chosen for this analysis. This specific scenario was selected as it represents an ideal scenario in which passive systems such as the RCCS are expected to function at a specified level of performance. Furthermore, it is anticipated that SBOs will receive increased attention in new regulatory requirements, as indicated by the NRC's Near-Term Task Force report [10], issued in 2011 in response to the Fukushima Dai-ichi accident.

4. SCENARIO PROGRESSION AND TREATMENT OF UNCERTAINTIES

This section contains a description of the components comprising the dynamic analysis. The first section describes the top events that are considered to be a factor in this analysis. The uncertainties addressed in this analysis are described in Section 4.2. The methodology for the construction of the DDETs, which combines both the top events identified in Section 4.1 and the uncertainties identified in Section 4.2, is described in the final part, Section 4.3.

4.1. Top Events

Construction of the DDETs in this analysis requires the identification of events relevant to an SBO that have the potential to lead to core damage. To accomplish this, the SBO system response tree for PRISM [11] is utilized as a reference. The events considered in the PRISM response tree that are being applied to this analysis are listed in Table 2; these events are largely related to the SCRAM status of the reactor, pump trip and coastdown, and the removal of operating power heat. Additionally, for the purpose of this dynamic analysis, power recovery and the delayed actuation of active heat rejection to an ultimate heat sink via IHX is considered in the scenario progression, and is also listed in Table 2. It is anticipated that active heat removal late in the scenario may introduce undesirable temperature feedback effects in the core, thereby inherently increasing core power as the primary pool is cooled.

Table 2: Events considered in DDET SBO analysis.

Top Events	Comment
RPS signal to RSS for shutdown	RPS signal required for control rod insertion
Enough control rods inserted by RSS	If RPS signal fails, assume failure to SCRAM
Pump trip	Assumed to have likelihood of unity, due to loss of power
Pump coastdown	Considers successful coastdown of *n* of 4 pumps, where $n = 0, 1, \ldots 4$
Operating power heat removal failure	Likelihood assumed to be unity, pumps dependent on AC power
RCCS operating	Assumed to have likelihood of unity in this analysis
Power recovery	Time-dependent event
Actuation of active heat removal via IHX	Dependent on power recovery and bulk pool temperature being greater than 600°C

For the top events listed in Table 2, unless otherwise noted, frequencies of these events will be obtained from data found in the NRC's "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants," NUREG/CR-6928 [12], the Preliminary Safety Information Document for PRISM [11], and other SFR PRAs, as necessary. It is assumed that if the reactor protection system (RPS) signal to the reactor shutdown system (RSS) fails, that the reactor will fail to SCRAM, (i.e. the top event "Enough Control Rods Inserted by RSS" in Table 2) with a probability of unity. Because this analysis utilizes an SBO as an initiating event, the likelihood of pump trip is assumed to be unity, since the electromagnetic pumps require AC power for operation.

Also, it is assumed that the EM pumps, which do not provide inertial force due to the lack of moving parts, are equipped with the appropriate coastdown mechanisms, where a coupled flywheel-generator system is typically utilized to simulate the inertial coastdown of a traditional mechanical pump. Since a generic system model is utilized for this analysis, specific details regarding the number of primary system pumps required for successful system coastdown, or specific coastdown characteristics are not available. For that reason, pump coastdown failure will be treated as the failure of n of four pumps to successfully coastdown, where $n = 0, 1, \ldots, 4$. Therefore, for this specific event, the tree will contain five branches.

It is also assumed that operating power heat removal, which relies on AC power for pump operation in the secondary loop, fails with a likelihood of unity. Due the nature of this analysis, where the objective is to demonstrate an analysis technique for passive system reliability, it is currently assumed that the RCCS successfully operates at full capacity with a likelihood of unity. There is the potential that in future work in FY15, the effects of RCCS operating at degraded capacities or successful reestablishment of full capacity at varying times will be addressed in additional dynamic analyses.

For this analysis, the likelihood of power recovery will be treated as a function of time. It is assumed that power to the site is restored via the successful implementation of FLEX equipment. The FLEX strategy [13], developed by the industry in response to Fukushima, utilizes portable equipment stored both onsite and offsite as a potential backup to maintain core cooling and/or containment integrity. For the final event listed in Table 2, the actuation of heat removal via IHX, it is assumed that this event can occur only if power is successfully recovered and if the primary sodium temperature achieves a temperature of 600°C, where this threshold is listed as the maximum primary sodium temperature operational requirement in [11]. During a severe accident, it is assumed that some operator intervention will be attempted to prevent primary vessel and fuel damage by activating an available active heat removal system. However, these systems will not be utilized unless the bulk sodium temperature is sufficiently high, so as to prevent overcooling of the sodium which may introduce undesirable reactivity feedback effects.

For the majority of the top events listed in Table 2, their timing does not need to be explicitly modeled in the RELAP5-3D simulation. Events related to reactor SCRAM, pump trip, and removal of operating heat are assumed to occur effectively instantaneously upon the initiating event trip signal. Pump coastdown is assumed to occur on the order of minutes following the initiating event. The timing of power recovery and activation of heat removal systems in the secondary loop is assumed to occur on the order of several to tens of hours, as this is considered to be a long-term SBO with limited reestablishment of power.

4.2. Uncertainty Quantification

In this analysis, uncertainties affecting both the RCCS performance and overall plant behavior will be considered. These characteristics, shown in Table 3, were chosen as uncertainties for this analysis such that both aleatory variability in the behavior of the system and epistemic uncertainty, related to a lack of knowledge regarding specific phenomena, would be sufficiently addressed. Bounding quantities for some uncertainties in Table 3 have been obtained from supporting documentation for PRISM [11]. Probability distributions representing the uncertainties in Table 3 have been developed based on engineering judgment, and the parameters of the distributions (mean and standard deviation) are shown in Table 3. For uncertainties related to the RCCS performance, modifications of bounding values may be necessary as experimental data is obtained from ongoing experiments at the Natural convection Shutdown heat removal Test Facility (NSTF) [14] at Argonne. The NSTF facility is designed to perform scaled experiments of the RCCS with regard to flow characteristics in the system during normal and accident conditions.

Table 3: Uncertainties considered in DDET analysis.

Uncertainty	Characterization	Comment
Ambient temperature	$U(-30.0, 45.0)$	Assume conservative bounds, °C.
Primary vessel emissivity	$N(0.77, 0.035)$	Mean and bounding percentiles from [11].
Primary vessel thermal conductivity	$N(1.0, 0.0125)$	Scaling factor, assume limits are ±2.5% of mean.
Guard vessel emissivity	$N(0.77, 0.035)$	Mean and bounding percentiles from [11].
Guard vessel thermal conductivity	$N(1.0, 0.0125)$	Scaling factor, assume limits are ±2.5% of mean.
Duct surface roughness	$\ln N(3.45, 0.70)$	Large range of uncertainty due to weathering, bounding values of 10 μm, 100 μm.
Power recovery time	$U(4.0\ 24.0)$	Represents timeframe of interest, hrs.
Initial power level	$N(1.0, 0.025)$	Scaling factor, limits are ±5% of mean.
Decay heat curve	$N(1.0, 0.025)$	Scaling factor, limits are ±5% of mean.
Pump coastdown failure	$P(1/4) = 1.000$ E-4 $P(2/4) = 3.267$ E-6 $P(3/4) = 1.108$ E-6 $P(4/4) = 8.420$ E-7	Failure per pump considered to be several orders of magnitude larger than value utilized in [11]. Failure of multiple pumps treated using alpha factor model for common cause failures.

For this analysis, data from [11] was utilized to determine the uncertainty in emissivity; the conservative value reported in the supporting PRISM PSID documentation was used as the 5th percentile to develop the normal distribution. Thermal conductivities will be treated as a scaling factor for the existing correlation in RELAP5-3D, and it is assumed that the uncertainty will vary by a maximum of 2.5% of the mean value, as thermal conductivities are not anticipated to change greatly over the lifetime of the material, and variances in the manufacturing process are expected to dominate the uncertainty space. It is anticipated that variations in the surface roughness of the duct will be large over the lifetime of the facility, where the variations are largely due to accumulation of particulate and debris on surfaces. Variations in the manufacturing process can also contribute to the uncertainty in surface roughness. For these reasons, bounding surface roughness values of 10 μm and 100 μm are used for the 5th and 95th percentiles, respectively. The ambient temperature is assumed to vary uniformly between -30°C and 45°C; these values were chosen to represent conservative seasonal changes and are not climate-specific, but it would be possible to utilize a distribution representing daily atmospheric changes for a specific location, if desired. The uncertainties in initial power level and decay heat are treated using scaling factors, where it is assumed that the uncertainty will vary by a maximum of 5% of the mean value.

With regard to pump coastdown failure, it was assumed that common cause would dominate the likelihood in the failure of multiple pumps. In this case, common cause is considered as failures not explicitly modeled in the analysis (e.g. incorrect installation, maintenance errors, etc.). The alpha factor model with staggered testing for common cause failures was utilized to calculate the discrete probabilities for multiple pump failures [15]. For the failure of a single pump, a value several of orders magnitude larger than the value utilized in [11] was chosen, as the analysis in [11] received criticism for the use of unrealistic likelihoods [16].

In this analysis, power recovery times have been selected between 4 hr and 24 hr after the initiating event. These times are based on the anticipated NRC rulemaking regarding loss of AC power coping capabilities that is expected in response to Fukushima [17]. For the purpose of this analysis, it is assumed that FLEX equipment will be utilized to provide power to the active heat removal system, as a massive grid failure has prevented offsite power recovery for up to 72 hr. Power recovery will be considered at 4 hr intervals following the initiating event. The actuation of active heat removal will be treated as a conditional event, where both power recovery and achievement of the threshold bulk sodium temperature are required.

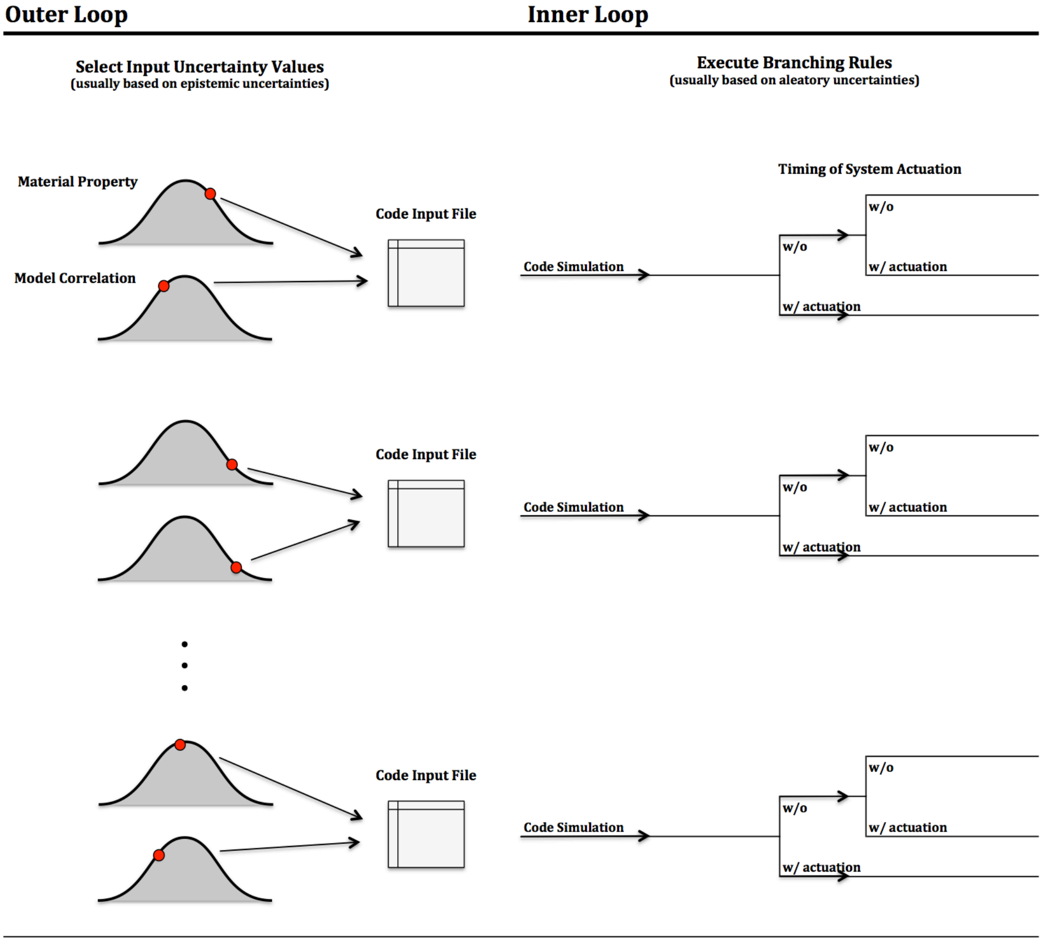
4.3. DDET Generation

To generate the DDETs, the uncertainties identified in Table 3 will be treated within the context of the scenario described by the top events listed in Table 2. An iterative inner-outer loop approach will be utilized, where typically aleatory variability (such as the timing of active heat removal) will be treated with inner loops, and the epistemic uncertainties will be treated using outer loops. In this technique, a single DDET with a specified set of system parameters is generated for a given set of aleatory uncertainties, otherwise known as an inner-loop iteration. To then treat the epistemic variability, several outer-loop iterations are performed where system parameters (such as material or heat transfer characteristics) are systematically varied. During outer-loop iterations, several DDETs are generated, where each DDET pertains to a specified set of system parameters and contains a range of aleatory uncertainties. This inner-outer loop iteration process is shown in Figure 2.

In this analysis, the primary inner-loop uncertainty is considered to be the timing of power recovery. The remaining uncertainties listed in Table 3 will be treated as epistemic uncertainties, and will therefore be treated in outer-loop iterations. Pump coastdown is not considered to be an aleatory uncertainty in this analysis since successful coastdown of a specified number of pumps is of interest, rather than the relative timing or rate of coastdown.

Prior to beginning any simulations, samples will be independently and randomly drawn from the distributions describing the uncertainties listed in Table 3. A single set of draws, one from each probability distribution, will be used to characterize the model parameters for a single DDET. In this way, outer-loop iterations will be performed to generate numerous DDETs. For consistency, the same variables for each draw will be utilized in both the mechanistic analysis presented in [2] and in this analysis, so that comparisons regarding the RCCS performance and its effect on primary system behavior can be made. While this analysis includes only one inner-loop uncertainty (IHX actuation times), future analyses in FY15 will consider failure of the RCCS structure, including degraded capacities, and varying times of RCCS recovery as inner-loop uncertainties.

Figure 2: Strategy for treatment of uncertainties in DDET analysis [18].



Given a specific set of model parameters, input preparation will be accomplished via a simple, automated process utilizing Python scripting. A standard input deck will be prepared with user-specified keywords replacing input variables of interest. These keywords will then be modified as necessary according to the random draws from the uncertainty distributions, which will act as input to the script. Simulations will be executed in batch on a Windows cluster located at Argonne.

Key metrics of interest in the analysis include vessel temperature and the traditional failure metric of peak cladding temperature. For protected scenarios where the reactor SCRAMs successfully, peak cladding temperatures are anticipated to be below the failure limit with a significant margin; unprotected scenarios with some limited establishment of flow may encroach on the safety limit, however. Vessel temperature is of high importance in this analysis due to its long-running nature. For unprotected scenarios with reduced flow, there is a possibility of prolonged elevated vessel temperatures, which could violate the vessel design limits as specified in [11], and may even induce vessel creep failure. The performance of the RCCS relative to this analysis will also be tracked, so as to determine the coupled effects of primary system behavior and the RCCS performance.

While runtimes are anticipated to be on the order of hours for a single scenario, the simulation times for a single DDET can be abbreviated through the use of restart files. For example, if IHX actuation is desired to occur at 4 hr, 8 hr and 12 hr within a DDET experiment, then a single simulation anticipating IHX actuation at 4 hr can be executed for the time up to 4 hr and halted. The restart file produced from this single simulation can then be duplicated and modified to reflect IHX actuation at the remaining two times. These two new restart files can then be launched on their respective hosts, without the need for running the simulation from time zero for all three scenarios.

5. CONCLUDING REMARKS

In this paper, a methodology for assessing the reliability of a passive system using dynamic methods was presented. The RELAP5-3D model currently under development is intended to serve as a relatively fast-running representation of an advSMR; furthermore the model will be capable of treating natural circulation in the sodium pool with sufficient detail such that its effect on the RCCS performance can be determined. The events selected for inclusion in the DDET are expected to sufficiently describe the key phenomena in SBO progression in an advSMR and serve as a surrogate example for more complex, inclusive analyses that encompass the entire plant. Similarly, the uncertainties selected for this analysis are expected to describe the process of uncertainty identification and quantification and their treatment in an iterative inner-outer loop type of dynamic analysis such that the same technique can be applied to a more complex analysis of passive system reliability.

As several thousand scenarios are expected to be generated in this analysis, it is anticipated that substantial amounts of data will be generated in this process. Various data mining techniques are currently under consideration, including clustering techniques that aggregate data based on several user-defined criteria. In this case, importance ranking could be utilized to determine the relative importance of certain phenomena or events in scenario progression to improve the clustering results.

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