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Coupling RAVEN to SAPHIRE for Performing Time Dependent Probabilistic Risk Assessment

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INTRODUCTION

Cost Risk Analysis Framework Tool (CRAFT) was recently developed by Idaho National Laboratory (INL) to perform economical risk analysis by combining physics, risk and cost information of components in a Nuclear Power Plant (NPP) that can be quickly deployable through the nuclear industry to evaluate the risk associated to capital projects and asset management [1]. In this framework, RAVEN is coupled with SAPHIRE to perform the time dependent risk/safety assessment of NPPs. Traditionally, the risk associated to the NPPs can be determined by classical Probabilistic Risk Assessment (PRA) tools, such as SAPHIRE, under the assumption that all failure rates are constant over time. In some circumstances, however, the assumption is rendered invalid since that the failure rate of a component may gradually change in a systematic way, for example, because of aging and degradation. In addition, recent data analysis in [2] has suggested decreasing values of failure rates for several important components of NPPs. A PRA that includes these components should employ the time-dependent failure rates in order to accurately estimate the risk at any given time. This time-dependent PRA is achieved by the coupling between RAVEN and SAPHIRE.

RAVEN-SAPHIRE COUPLING METHODOLOGY

SAPHIRE is a software application, funded by U.S. Nuclear Regulatory Commission (NRC) and developed by Idaho National Laboratory (INL), for performing a complete PRA on a personal computer [3]. SAPHIRE can be used to perform all three levels of PRA: 1) model a complex system's response to initiating events, quantify associated damage outcome frequencies, and identify important contributors to this damage (Level 1 PRA); 2) analyze containment performance during a severe accident and quantify radioactive releases (Level 2 PRA); 3) quantify risk in terms of radioactivity release accidents to both the public and the environment (Level 3 PRA). In addition, SAPHIRE can also be used to perform FT/ET uncertainty analysis.

RAVEN is a flexible and multi-purpose framework, also developed by INL, that has been designed to perform uncertainty quantification, regression analysis, PRA, data mining and model optimization [4]. From a CRAFT perspective, the coupling between RAVEN and SAPHIRE can be used to perform the time-dependent safety analysis with uncertainty quantification, integrating the reliability, availability and maintainability models with the time-dependent PRA models that can be used in the cost analysis, and model the time-dependent failure rate or failure probability distribution with Bayesian inference.

When performing time-dependent safety related risk analysis (Fig. 1), Event-Trees and Fault-Trees methods from SAPHIRE are employed to model accident progression while time-dependent components failure data (i.e. failure probabilities and failure rates) generated via RAVEN external model are used to determine the frequency/probability of each accident sequence at particular time.

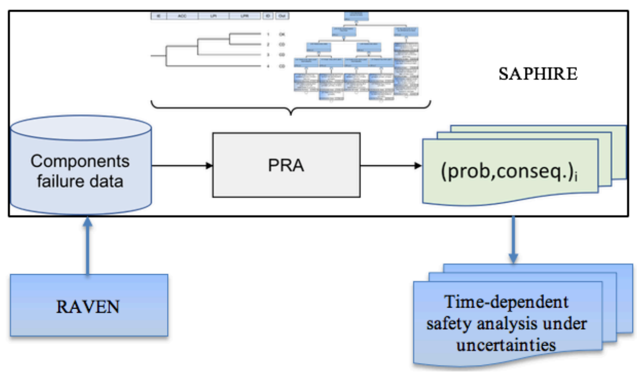

Fig. 1. Time dependent PRA using RAVEN-SAPHIRE.

TEST CASES AND RESULTS

A simple example of PRA model based on ETs and FTs is shown in Fig. 2, Fig. 3 and Fig. 4 for a single initiating event (e.g. Loss of offsite power) is employed to perform the time-dependent risk analysis. The status of each of the two safety systems:

- ECS: Emergency Cooling System
- CCS: Containment Cooling System

dictates the branching condition of the ET and it is modeled through a set of FTs, one for each system. SAPHIRE is employed to calculate the most probable combination of basic events that lead to radioactive releases: Minimal Cut Sets (MCSs). The sum of the probability associated to each MCS determines the probability of radioactive releases given the occurrence of LOSP initiating event. Three outcomes are possible: OK (i.e. no radioactive releases), small-release, and large-release. By observing in Fig. 2, radioactive release outcomes can be avoided only if all the two systems are functioning.

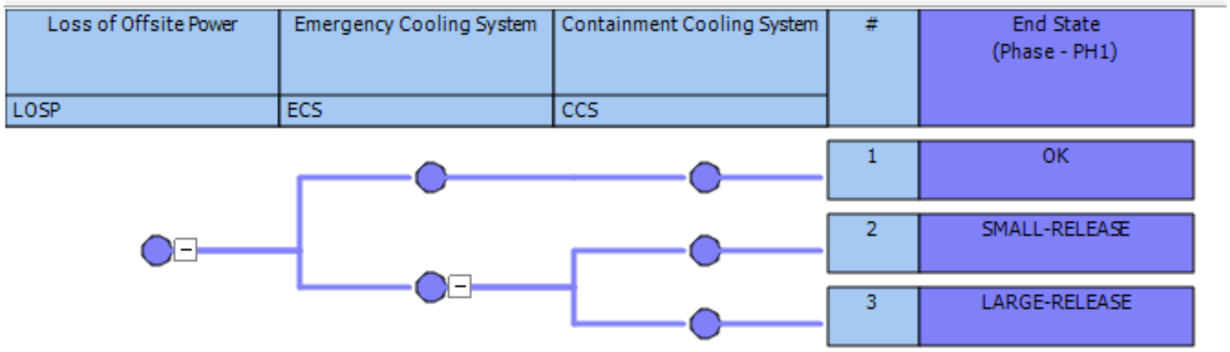

Fig. 2. LOSP Event Tree Model.

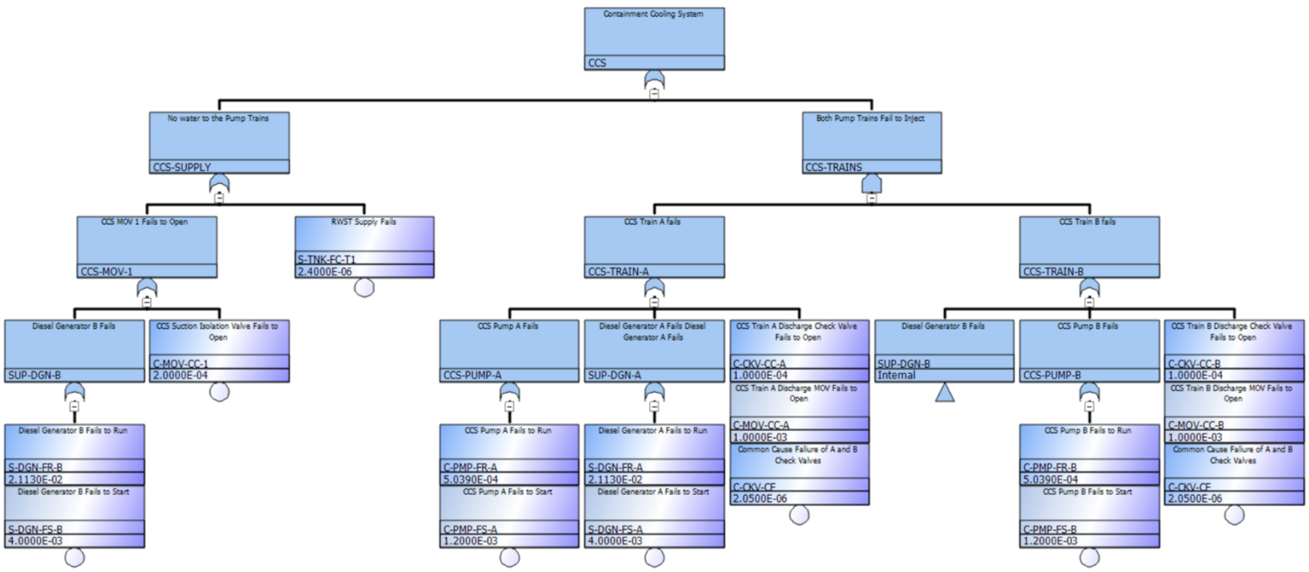

Fig. 3. CCS Fault Tree Model.

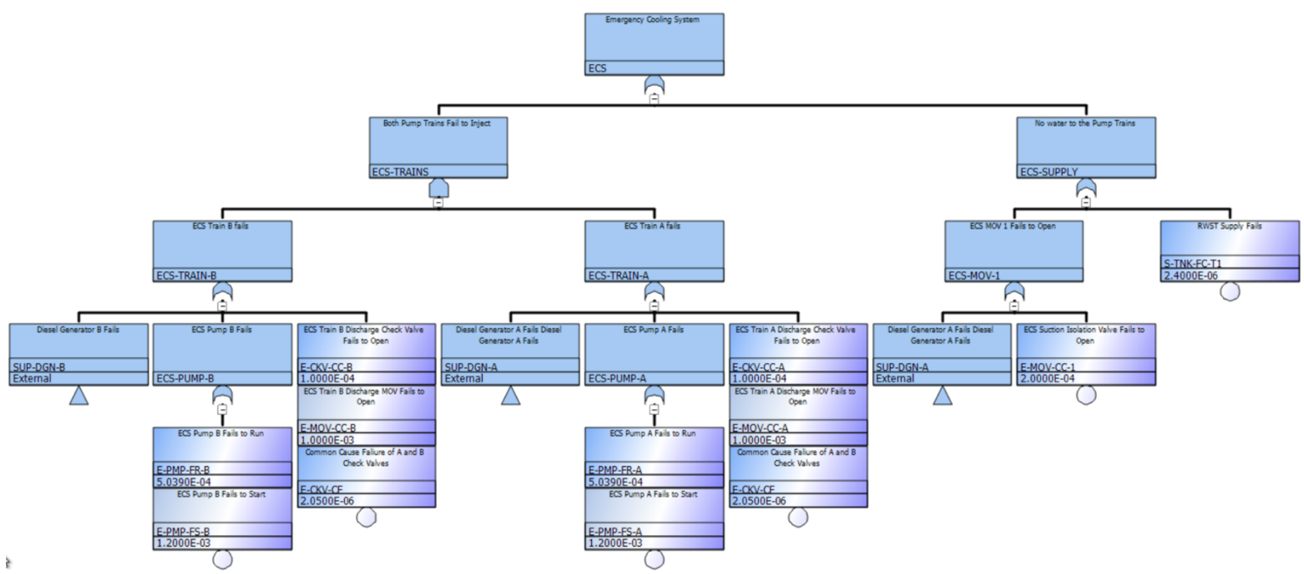

Fig. 4. ECS Fault Tree Model.

The failure model of each basic events in SAPHIRE contains a calculation type selection box. There are two calculation types identified as 1, 3 are employed in this analysis as shown in Table 1.

Table 1. "Basic" failure model employed in ECS/CCS FTs.

Calc. Type	Equation	Description
1	$P = p$	Mean probability
3	$P = 1 - \exp(-\lambda T_m)$	λ: mean failure rate, T_m: mission time. Failure probability of an operating component without repair.

In this example, the time-dependent models of mean failure probability and mean failure rate are employed as shown in the following equations:

- Linear failure probability model: $P(t) = P_0[1 + b(t - t_0)]$
- Exponential failure rate model: $\lambda(t) = \lambda_0 \exp\big(b(t - t_0)\big)$

Here, t_0 is a value selected by the analyst for convenience. In these two models, $P(t)$ or $\lambda(t)$ is increasing if $b > 0$, is constant if $b = 0$, and is decreasing if $b < 0$. P_0 or λ_0 is the value of failure probability/rate at time $t = t_0$. If t_0 is set to zero, $t - t_0$ is the time measured from the component's installation.

SAPHIRE can be used to perform uncertainty analysis of ETs/FTs via Monte Carlo or Latin Hypercube sampling. In other words, the variability of a FT top event or ET sequence end state probability resulting from uncertainties in the basic event probabilities can be quantified. Monte Carlo sampling strategy is one of the most-used sampling strategies. It approximates an expectation by sample mean of a function of simulated random variables based on the laws of large numbers. Latin Hypercube sampling (LHS) is a stratified sampling technique, with the random variable distributions divided into equal probability intervals. In this study, LHS is employed setting a limit of 5000 simulations. Grid-based sampling from RAVEN is employed to perform the parametric analysis of ETs/FTs with respect to time. The time-dependent uncertainty analysis is performed by mean of an equally spaced value grid. Now, ET/FT models are run in a time-dependent fashion by evaluating radioactive releases at specific time instants (e.g., 6 months) over a fixed time scale (e.g., 20 years). The time-dependent failure rates and failure probabilities are generated by RAVEN with external functions as provided in Table 2. Fig. 5 and Fig. 6 illustrate the mean and 5th/95th percentiles of small radioactive releases and large radioactive releases over 20 years. Fig. 7 and Fig. 8 show the mean and 5th/95th percentiles of ECS and CCS over 20 years.

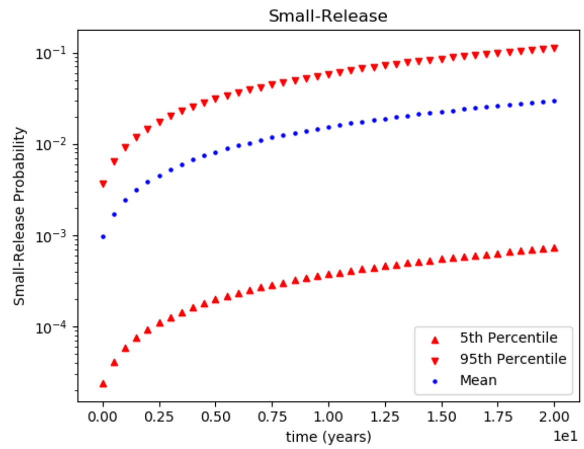

Fig. 5. Time dependent uncertainty analysis of ET: small-release.

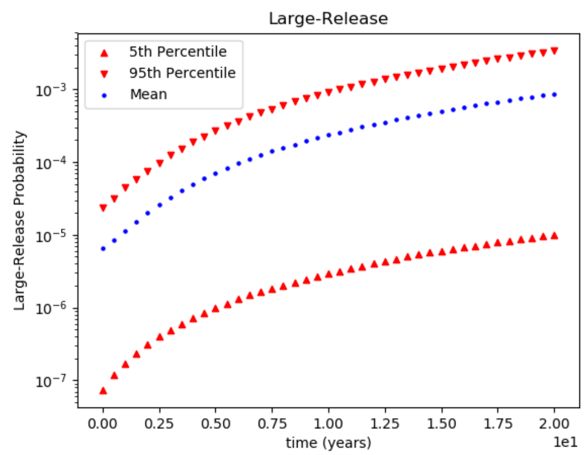

Fig. 6. Time dependent uncertainty analysis of ET: small-release.

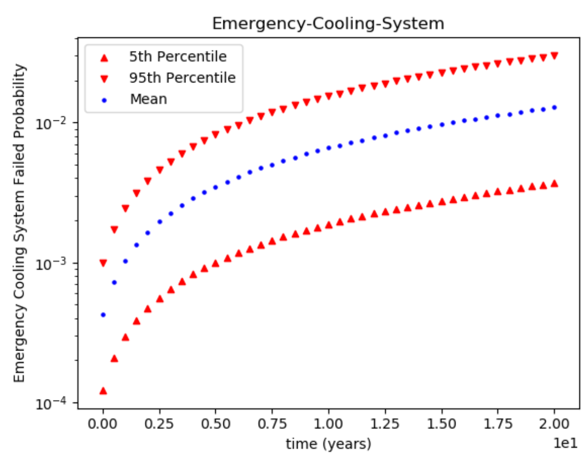

Fig. 7. Time dependent uncertainty analysis of FT ECS.

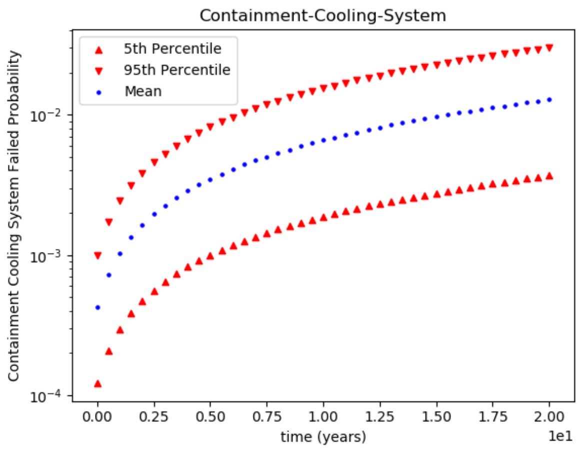

Fig. 8. Time dependent uncertainty analysis of FT CCS.

CONCLUSIONS AND FUTURE WORK

As demonstrated with the simple LOSP PRA model, the coupling of RAVEN and SAPHIRE can be used to perform the time-dependent risk/safety assessment. In the future, the explicit SSC aging or degradation models that explicitly model how the failure rates or failure probabilities change in time can be directly used in PRA of NPP with this coupling capability. The coupling with other commercialized PRA tools, such as CAFTA and RISK SPECTRUM, will also be explored to support the second license renewal of commercial NPPs.

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APPENDIX

Table 2. Basic events employed in CCS/ECS FTs.

Basic Event	Calc. Type	Failure Probability/Rate	Description
CKV-CC-A	1	$P = 1.0E-05+1.45E-05*(t-t_0)$	Train A discharge check valve fails to open
CKV-CC-B	1	$P = 1.0E-05+1.45E-05*(t-t_0)$	Train B discharge check valve fails to open
MOV-CC-1	1	$P = 2.0E-05+2.9E-05*(t-t_0)$	Suction isolation value fails to open
MOV-CC-A	1	$P = 1.0E-05+1.45E-05*(t-t_0)$	Train A discharge MOV fails to open
MOV-CC-B	1	$P = 1.0E-05+1.45E-05*(t-t_0)$	Train B discharge MOV fails to open
PMP-FR-A	3	$\lambda = 2.1E-06*\exp(0.17(t-t_0))$	Pump A fails to run
PMP-FR-B	3	$\lambda = 2.1E-06*\exp(0.17(t-t_0))$	Pump B fails to run
PMP-FS-A	1	$P = 1.2E-04+1.74E-04*(t-t_0)$	Pump A fails to start
PMP-FS-B	1	$P = 1.2E-04+1.74E-04*(t-t_0)$	Pump B fails to start
S-DGN-FR-A	3	$\lambda = 8.9E-05*\exp(0.17(t-t_0))$	Diesel generator A fails to run
S-DGN-FR-B	3	$\lambda = 8.9E-05*\exp(0.17(t-t_0))$	Diesel generator B fails to run
S-DGN-FS-A	1	$P = 4.0E-04+5.8E-04*(t-t_0)$	Diesel generator A fails to start
S-DGN-FS-B	1	$P = 4.0E-04+5.8E-04*(t-t_0)$	Diesel generator B fails to start