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INTRODUCTION

Standardized Plant Analysis Risk (SPAR) models are a set of linked fault tree/event tree PRA models that have been used by the Nuclear Regulatory Commission (NRC) to evaluate the risk of operations at U.S. nuclear power plants since 1990s. The models use the Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) code developed by the NRC and Idaho National Laboratory (INL). SAPHIRE, currently Version 8, is a powerful software with advanced features to perform separated or integrated Level 1, Level 2, internal events, external events, at-power, and low power shutdown PRA [1]. One of its features is the availability of three different approaches to model the success branch of a top event in event tree: delete term, complement of system logic, and developed event. Improper choosing of the approach and modeling success branch might yield unexpected and incorrect results. This paper will discuss the two most often used success branch modeling approaches, delete term and developed event, and provide recommendations for using proper approaches in different models. A potential SAPHIRE code enhancement is also presented to efficiently address the impact brought by the developed event approach.

SUCCESS BRANCH MODELING

SAPHIRE Process Flags

SAPHIRE uses the process flag field in basic event definition window to determine how to solve event tree accident sequences and fault tree logic. The default sequence process flag is blank which will use system logic for failure branch and delete term for success branch (Failure => System Logic, Success => Delete Term). If the sequence top event fails (failure branch), SAPHIRE will expand and solve the fault tree with the same name as the top event to generate sequence failure cut sets; if the top event succeeds (success branch), SAPHIRE will use the delete term process to expand the sequence fault tree, evaluate the cut sets belonging to systems that are successful in the sequence, and remove these success cut sets from the list of failure cut sets to generate sequence cut sets.

If the process flag is set to “W”, SAPHIRE will still expand and solve the fault tree for the failure branch, but will treat the top event as a basic event (i.e., developed event) for the success branch and use the complement of the event for the branch probability. This approach can be represented as Failure => System Logic, Success => /Developed Event.

Several other process flag types exist for different modeling needs. Table I provides a summary of the process flags currently available in SAPHIRE.

Table I. Sequence Top Event Process Flags

Process Flag	Failure Branch	Success Branch	
Blank (Default)	System Logic	Delete Term	remove successful top event cut sets from the list of failure cut sets
I	System Logic	/System Logic	solve complement fault tree logic
W	System Logic	/Developed Event	Treat success as a basic event with complement value of failure branch
X	Developed Event	Delete Term	same as default *
Y	Developed Event	/Developed Event	same as W *

* X and Y process flags use the same success branch but different failure branch modeling approaches as the default and W flags, respectively.

Considerations of Success Branch

With the default sequence process flag, SAPHIRE does not quantify the success branches of an event tree. Instead, delete term process is performed to remove success cut sets from the list of failure cut sets to get the sequence cut sets. This approach usually causes little problem in an internal events, at power model as

(1) the failure branch probabilities of event tree top events are generally in the range of 10^{-3} or smaller (i.e., success branch very close to 1.0);
(2) the success branch sequences with end state of OK do not need to be quantified.

The error brought by using delete term and not calculating success probability is normally negligible in core damage frequency quantification for an internal events, at power model.

This is not the case, however, when the PRA is expanded to include external events (especially seismic) modeling and Level 2 modeling. The failure branch probability of an event tree top event may go up to the range of 10^{-2} or even 10^{-1}. For example, failures of reactor pressure vessel, reactor internals and core assembly, steam generator, and reactor coolant pump due to a seismic event are assumed to cause core damage directly in a seismic PRA. Their generic failure probabilities at 0.707g (BIN-3 of a three-bin model) are 1.20E-2, 3.08E-2, 5.77E-3, and 5.77E-3, respectively [2]. In a specific five-bin SPAR seismic model, the probabilities at 1.00g (BIN-5) are even greater at 9.88E-2, 2.13E-1, 4.47E-1, and 2.52E-2, respectively. Also, in a Level 2 model, when the core damage sequences are transferred to Level 1/Level 2 bridge tree, plant damage status event tree, and containment event tree, each Level 2 sequence in these Level 2 event trees has to be accounted for. In either situation, using delete term without success probability evaluation or consideration would bring unexpected results.

Using the “W” (or “Y”) process flag to treat the event tree top event as a developed event and solve/assign the success probability to the success branch would address the above issue with failure branch probability being too large. After the failure probability of a top event is calculated, its complementary (or success probability), which is no longer as close to 1.0 as in typical internal events, at-power models, will be assigned to the success branch to be accounted for in the sequence cut sets.

To use the developed event approach would result in another issue though. By introducing success branch probability into sequence cut sets, SAPHIRE does not perform the delete term process. The success cut sets are not removed from the list of failure cut sets. The resulting sequence cut sets may thus include non-coherent cut sets. For example, consider an event tree with top events A and subsequent B. Suppose component M failure would fail both A and B. For sequence /A * B (A success and B fails), with the delete term process, any cut sets including component M failure would be removed from sequence cut sets as it should be (however, the probability of /A is not calculated and accounted for in sequence frequency determination). With the developed event process, the probability of /A is calculated and included in the cut sets, but those non-coherent cut sets including component M failure may now reside in the sequence cut sets. Table II provides a summarized comparison between the delete term and developed event processes.

Table II. Comparing the Processes

	Delete Term	Developed Event
Pros	Coherent cut sets	Success branch probabilities are accounted for
Cons	Success branch probabilities are not accounted for, which may cause unacceptable error in quantification results.	Non-coherent cut sets could exist when one basic event failure may result in more than one top event failure.

Recommendations

With the issues might have been brought by using either the delete term or developed event process, improper choosing of the process and modeling success branch might yield unexpected and incorrect results. The following recommendations are provided for modeling consideration.

(1) If the failure probability of an event tree top event is very small (for example, in the range of 10^{-3}), use the SAPHIRE default process, i.e., delete term. This is the usual case for most tops in Level 1 internal events, at-power model, external events model except severe seismic event categories, and Level 2 bridge tree.

(2) If the failure probability of an event tree top event is large (for example, greater than $5x10^{-2}$ as suggested in NRC’s RASP Handbook [3]) AND the tops do not share the same basic events that would fail them, use the developed event process (i.e., use “W” or “Y” process flag). This includes applicable top events in Level 1 external events models such as some fire event trees and severe seismic event trees, and Level 2 PDS event tree, and containment event tree.

(3) If the failure probability of an event tree top event is large (for example, greater than $5x10^{-2}$) BUT the tops share the same basic events that would fail them, one may either use the delete term or use the developed event process. Both processes may warrant processing results to get more accurate results by using SAPHIRE post-processing rules.

   a. If the developed event process is used, carefully review the cut sets to remove non-coherent cut sets manually with post-processing rules.

   b. If the delete term process is used, add the success branch probabilities manually to applicable cut sets with post-processing rules such as

```
if system(/ET_TOP) then
  recovery = /ET_TOP_Succ_Prob;
endif
```

   c. Method (b) is preferred as reviewing cut sets in method (a) to find out and remove non-coherent cut sets is more resource intensive and error-prone.

(4) SAPHIRE code could also be enhanced to automatically resolve the non-coherent cut set issue brought by the current developed event process. For example, if the “W” process flag is chosen, the enhanced code would
    a. first process with the default delete term approach to remove success cut sets from the list of failure cut sets and create correct sequence cut sets; and
    b. then process with the original developed event approach to calculate the success branch probability and include it in the proper sequence cut sets.

SUMMARY

SAPHIRE is able to model the success branch of a top event in an event tree with one of three approaches: delete term, complement of system logic, and developed event. Improper choosing of the process to model the success branch might yield unexpected and incorrect results. This paper reviews the issues in using the delete term and developed event processes, provides recommendations for using proper approaches in different kinds of SPAR models, and proposes a potential SAPHIRE code enhancement to efficiently address the impact brought by the developed event approach.

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