Uncertainty Bound due to the PDS Approximation of the Level 1 ET Sequence Cut Sets

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ABSTRACT

While a strict PDS operation requires that all the Level 1 ET core damage sequences are assigned to all the relevant PDS categories and that their sum is equal to the total CDF, the current practices of the Level 1 ET/FT combinations causes an inevitable approximation of the total PDS frequency (PDSF) for the total CDF value. The main objective of this paper is to estimate the type of uncertainty bound generated for the total PDSF (or a degree of a PDSF approximation for the CDF) due to a propagation of the Level 1 ET sequence cut sets into the relevant PDSs, consequently leading to a change of the corresponding Level 2 risk metrics (such as containment failure frequencies or large early release frequency). The plant-specific analysis shows that when the cutoff value of 1.0E-11 is applied, the PDS approximation from the Level 1/2-bridge trees may vary the PDSF value from –1.2% to 2.5%, when compared to the corresponding CDF value (i.e., a CDF value estimated from the Level 1 ET/FT models). A detailed investigation shows that the forgoing uncertainty is mainly caused by a mixed impact of a decrease of the PDSF from a truncation limit and its increase from the potential extra cut sets employed in the PDS model when the Level 1 cut sets are propagated into the PDS model (subsequently the other Level 2 models).

INTRODUCTION

The recent expanded usage of risk-informed applications (RIAs) for a probabilistic safety assessment (PSA) has required dynamic operational models, so that the resultant PSA model can address a variety of plant configurations exemplified in Regulatory Guide 1.174[1] as well as real-time evaluations of a plant risk such as a Core Damage Frequency (CDF) and Level 2 risk metrics such as a Large Early Release Frequency (LERF). Here, the CDF and LERF have been utilized as two surrogate measures for a plant risk[2,3].

The first step for employing the Level 2 portion into the dynamic PSA models is to define the plant damage states (PDSs) as pinch points between the Level 1 plant model and the Level 2 containment model. The conventional concept of a PDS is to map the Level 1 accident sequence cut sets, which have been extended to the containment systems, into similar relevant plant damage states. By doing so, the number of unique accident conditions that need to be considered in the Level 2 PSA is greatly reduced. The role of the interfaces between the Level 1 plant system analysis and the Level 2 containment performance analysis is particularly important from two perspectives. First, the likelihood of a core damage can be influenced by the status of particular containment systems. Second, a containment performance can be influenced by the status of the core cooling systems. The systems availability aspect of the PDS definitions can often be addressed in one of the following ways: (a) by extending the Level 1 event trees (ETs) to include the top events associated with the availability of the containment systems, so that their system fault trees can be linked and their dependencies accounted for during the evaluation of the PDSs, and (b) by using a separate computer program which takes the cut set equation information from the Level 1 ETs, and links then to the fault trees (FTs) for the containment systems and, if appropriate, for the accident management systems, and acts essentially as an extension of the Level 1 PSA. While the PDS operation requires that a sum of all the Level 1 ET core damage sequences that are assigned to the relevant PDS categories is equal to the total CDF, however, the current practices of the ET/FT combinations causes an inevitable approximation of the PDS frequency (PDSF) for the total CDF value. What amount of uncertainty (or approximation) is expected from the conventional PDS binning process or what kind of sources cause such a kind of uncertainty, has been questionable up to now. This information is particularly important when we want to establish a deviation of the PDSF for the CDF when the Level 1 information (more specifically ET sequence cut sets) is propagated into the relevant PDSs.

The main objective of this paper is to estimate the type of uncertainty bound generated for the total PDSF (or a degree of PDSF approximation for the CDF) due to a propagation of the Level 1 ET sequence cut sets into the relevant PDSs, consequently leading to a change of the corresponding Level 2 risk metrics (such as containment failure frequencies or large early release frequency). The propagation of the Level 1 fault trees (or cut sets) to a Level 2 model through a Level 2 process (i.e., PDSs) would be useful to establish the cut sets associated with the Level 2 PSA sequences such as an emergency out of service (EOOS) and the related importance of the Level 1 events to the Level 2 risk metrics.

METHODS AND RESULTS

As a starting point of the Level 2 PSA, the PDS approach provides pinch points between the Level 1 plant model and the Level 2 containment model. Its main concept is to map the Level 1 accident sequence cut sets, which extended to the containment systems, into similar relevant plant states. As a logical tool for the PDS analysis, we utilize a type of Level 1/2-bridge tree (called 'PDS ET'), and a mapping of all the ET sequences to PDS categories to obtain the corresponding single operational FT model[4]. Then, the bridge tree given in the form of 'PDS ET' contains the additional top events needed to define the initial conditions for the accident progression analysis in sufficient detail. With these types of event trees, all the PDS ET sequence cut sets can be transferred into the relevant PDS categories, without a loss of the Level 1 information. With these types of event trees, all the PDS ET sequence cut sets can be transferred into the relevant PDS categories, without a loss of Level 1 information.

Evaluation Approach

With the foregoing approach for the PDS analysis, a type of sensitivity analysis has been implemented to obtain an uncertainty bound for the PDSF of the underlying PDS model, with a one-by-one change of a PDS grouping scheme (e.g., different categorization of the PDSs). Whereas, the bridge trees linking the Level 1 portions with Level 2 themselves remain unchanged for all the sensitivity analyses, and the same cutoff value is applied to identity the impact of the PDS binning scheme itself. Its practical implementation has been made with the help of a coupled software package[5-7], which is currently controlled by 'AIMS-PSA Manager'. The AIMS system has been modified recently to match the end points of the Level 1 ETs (or Level 1/2 bridge trees) with the corresponding PDS categories[8]. For this, a dummy basic event with 1.0 of a probability is incorporated into the end points of the ET (or Level 1/2 bridge tree) sequences, which expresses the PDS categories corresponding to the individual ET sequences. While the dummy event does not change the cut set probability itself, its use makes it possible to sort and gather the ET sequence cut sets with the same PDS category. This approach is particularly useful in a mapping of the Level 1 ET sequences to the corresponding PDS, when a certain type of bridge tree is utilized for a PDS categorization. Fig.1 shows an event tree example to explain the aforementioned approach, and Fig. 2 shows its logical transformation into a fault tree model with sequence numbers.

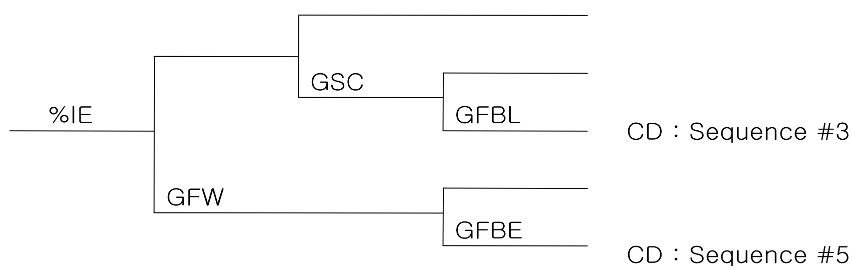


Fig. 1 Example Event Tree

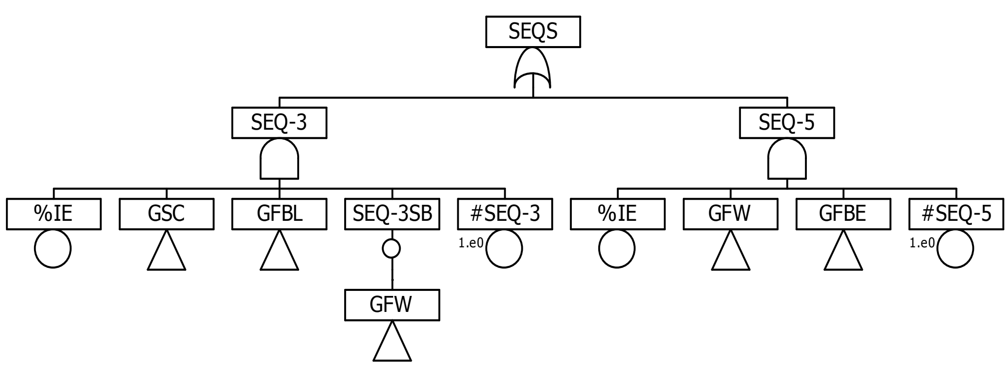
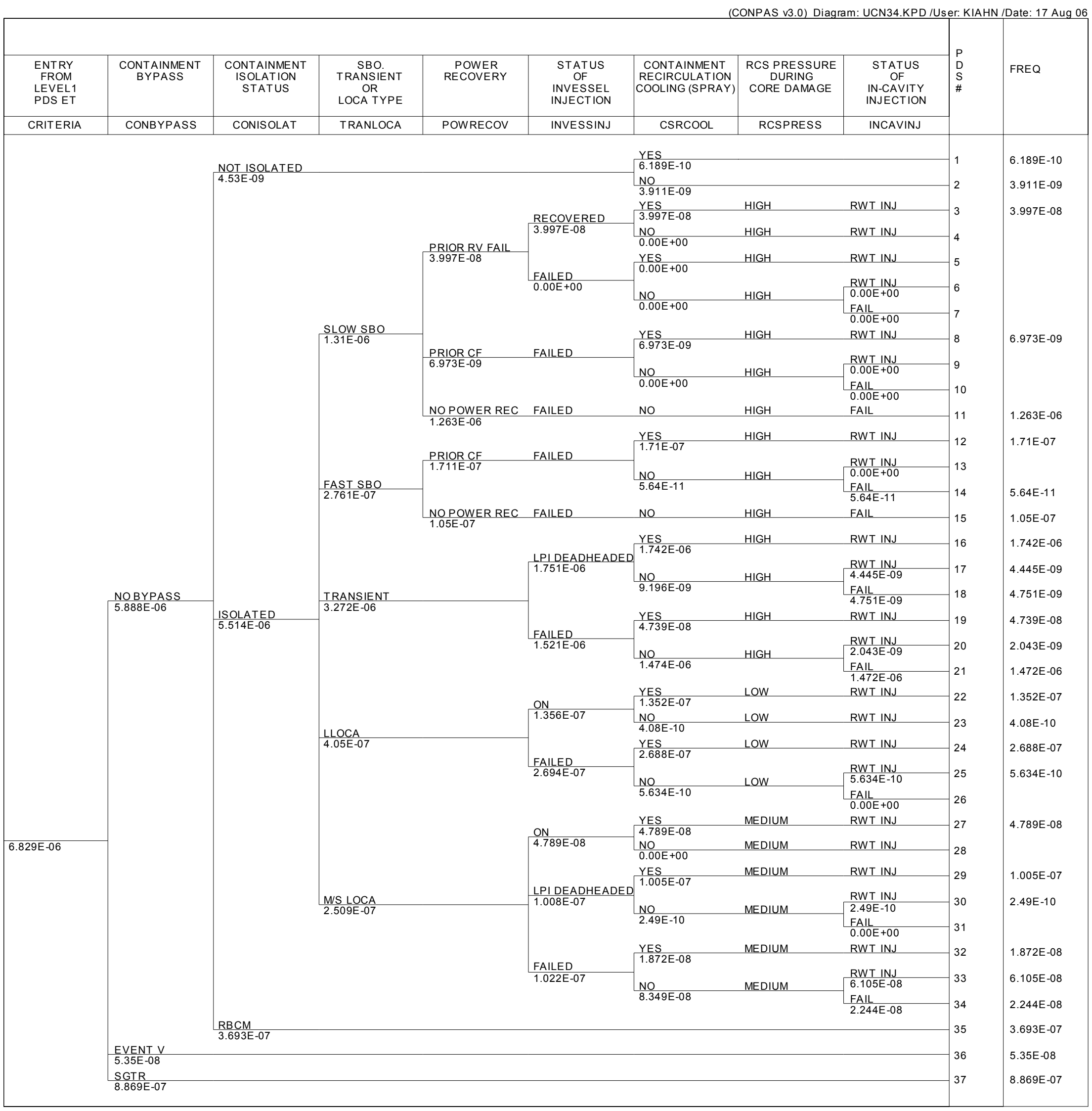


Fig. 2 FT Model with the ET Sequence Numbers

As implemented in most PSAs, the present quantification of an ET/FT with negates is also made by a success operation of (a) use of a 'delete-term procedure' to remove the nonsense cut sets related to the success branches and (b) a 'minimization between sequences' to remove the non-minimal cut sets between the ET sequences. It is noted that when the present PDS binning operation is made, all the ET sequence cut sets obtained from both operations are treated independently.

Evaluation Results

The foregoing approach for the PDS analysis has been applied to the existing UCN 3&4 Level 1/2-bridge trees and PDS logic tree[9] whose models and elements are given in Fig. 3 and Table 1, respectively. A PDS logic tree is utilized systematically to group the Level 1/2-bridge trees into their relevant PDS categories. The PDS logic tree is not quantified by it, but used for the PDS binning from the PDS ET sequences with the user-supplied PDS classification parameters[5].



UCN 34: Internal PDS Grouping Logic Diagram

Fig. 3 UCN 3&4 PDS Logic Tree for the PDS Estimation

Table 1 A Summary of the UCN 3&4-specific PDS ETs and PDS logic tree

PSA Models	UCN 3&4 PSA Model and Event Descriptions
Level 1/2 Bridge Tree *PDS ET/FT*	33 PDS ETs for 16 internal IEs (Large LOCA, Medium LOCA, Small LOCA, Reactor Vessel Rupture, Steam Generator Tube Rupture, Interfacing System LOCA, Large Secondary Side Break, Loss of Main Feedwater, Loss of Condenser Vacuum, Loss of Component Cooling water, Loss of 4.16KV AC Bus, Loss of 125V DC Bus, Loss of Offsite Power, Station Blackout, General Transient, Anticipated Transient Without Scram)
PDS Logic Tree	37 PDS generated by 9 PDS parameters (containment bypass, containment isolation, type of accidents like SBO and LOCA, power recovery, Operability of ECCS after CD, containment recirculation cooling with sprays, RCS pressure after CD, and reactor cavity condition (dry or wet) at vessel breach)

As a result of the sensitivity analysis, Fig. 4 shows a change of the total PDSF according to a different PDS binning scheme from the Level 1/2-bridge trees (PDS ET models). As shown in Fig. 4, the uncertainty bound of the UCN 3&4 PDSF always lies between when a single PDS is utilized and when all the individual ET sequences are treated as the corresponding unique PDS categories. The latter portion is equivalent to the case without a minimization operation between the ET sequences and so all the ET sequences are treated independently. It is also noted that when the cutoff value of 1.0E-11 is applied, the PDSF approaches a CDF value of 6.828E-6 as the number of PDS categories approaches 37, while a sum of all the PDS ETs provides a frequency of 6.746E-06 (this is a CDF-equivalent frequency). The foregoing difference between the PDSFs and the CDF-equivalent frequency is due to two factors: (a) one is an increase of the number of truncated cut sets due to the additional top events considered in the Level 1/2-bridge trees (i.e., loss of truncated frequencies), and (b) another is an increase of the number of individual PDSFs due to an independent treatment of the PDS categories. For the 37 PDS categories utilized for the UCN 3&4 Level 2 PSA, the PDS approximation of the Level 1/2-bridge trees is overestimated by about 1.2%, when compared to the corresponding CDF-equivalent value.

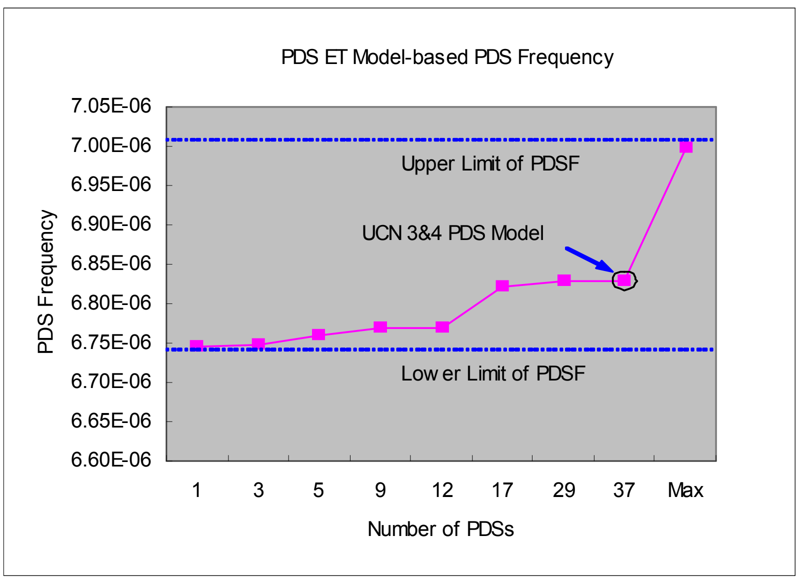


Fig. 4 A Change of the PDS ET-based PDSF with the PDS Level

Another type of sensitivity analysis has been performed to assess an impact of the Level 1/2 ET models on the potential PDSF. For this, the Level 1 ET models for a CDF estimation have been propagated into the same PDS logic tree. The foregoing situation indicates that the number of Level 1 ET sequences to be binned into the PDSF is greatly reduced when compared to that of the Level 1/2-bridge trees. Fig. 5 shows that the resultant change of the PDSF according to a given PDS structure is less sensitive when compared to that of Fig. 4. The difference between the total PDSF due to a PDS approximation of the Level 1 ETs and the CDF value is just 0.3%.

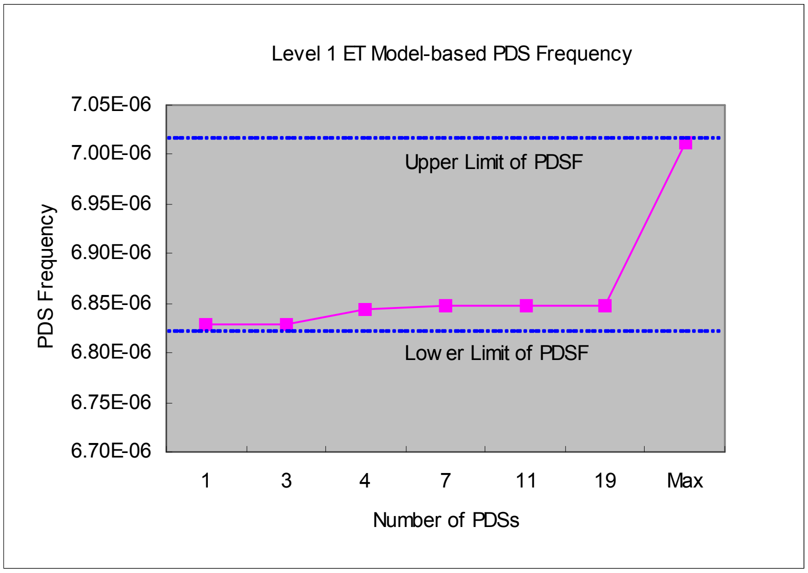


Fig. 5 A Change of the Level 1 ET-based PDSF with the PDS Level

Major Sources for the Two Different Results

There are two potential sources causing the foregoing difference between CDF and PDSF even for the same Level 1 ET/FT model: one is a decrease in the PDSF from the truncation error caused by a fixed cut off value and the other is an increase in the PDSF from the extra cut sets included in the final PDS model. The combined impact of both sources depends upon the levels of (1) the truncation limit and (2) the ET/FT models.

Decrease in the PDSF due to the Truncation Limit

For example, let's consider a simple Level 1 CDF event tree composed of an initiating event '%IE' and its two subsequent branches expressed as 'NB-E' and '/NB-E', respectively. The term '/NB-E' (e.g., success branch) is a complement for the corresponding branch 'NB-E' (e.g., failure branch). It is assumed that the two CDF event tree sequences lead to a core damage. Then both CDF sequences are assigned to each relevant PDS, e.g., $PDS_1 = (\%IE)(NB - E)$, and $PDS_2 = (\%IE)(/NB - E)$. This leads to an exact CDF value expressed as a sum of the frequencies of both branches, i.e., $CDF = (\%IE)(NB - E) + (\%IE)(/NB - E)$. In this case, the corresponding PDSF is exactly the same as CDF, i.e., $PDSF = PDS_1 + PDS_2 = CDF$. When a truncation limit is applied for estimating the CDF (or PDSF) as implemented in most PSAs, the first term of the CDF cut sets can be cut off due to the level of the truncation limit, leading to a CDF value (or PDSF) equal to or less than the exact CDF (or PDSF).

Increase in PDSF due to the Extra Cut Sets

The main reason why the Level 2 PDSF is slightly higher than that of the Level 1 CDF can be explained from the fact that the Level 2 minimal cut set (MCS) may have extra minimal cut sets when compared to the Level 1 MCS. As an example, let's consider the aforementioned Level 1 cut sets with additional events 'NB-T', i.e., MCS_1 = (%IE)(NB-T)(NB-E) and MCS_2 = (%IE)(NB-T)(/NB-E).

When success terms (i.e., '/NB-E' in the present example) are treated by using a delete term as implemented in most PSAs, the practical MCS_2 is given as MCS_2 = (%IE)(NB-T). Then, MCS_1 is no longer minimal when compared to MCS_2 and thus MCS_1 is subsumed by MCS_2 in the final Level 1 cut sets and only MCS_2 remains.

However, if the Level 2 logic (including PDS) is combined with the Level 1 cut set, the present approach utilizes MCS_1 and MCS_2 with a corresponding dummy event PDS_# whose probability is 1.0. Thus, the two Level 2 MCSs originating from MCS_1 and MCS_2 are given as L2-MCS_1 = MCS_1 = (%IE)(NB-T)(NB-E)(PDS_1, prob. =1)(the subsequent Level 2 events) and L2-MCS_1 = MCS_1 = (%IE)(NB-T)(/NB-E)(PDS_2, prob. =1)(the subsequent Level 2 events), respectively. It is obvious that the L2-MCS_1 is no longer a non-minimal cut set when compared to the L2-MCS_2 and thus the L2-MCS_1 will not be subsumed by the L2-MCS_2 in the final Level 2 cut sets. Thus, the Level 2 cut sets will have extra cut sets (L2-MCS_1 in the above case), leading to an equal or greater PDSF (or Level 2 risk metrics) than the corresponding CDF. Even with extra cut sets in the Level 2 model, however, the difference is usually so small that the Level PDSF will approach the corresponding CDF in the case that the extra cutsets are removed. An exact coupling of the Level 1 and Level 2 may require a significant effort since it requires some modifications of both the Level 1 and Level 2 logics.

SUMMARY AND CONCLUSION

Based on the present study, we have drawn the following findings and conclusions:

(1) While a strict PDS operation requires that all the Level 1 ET core damage sequences are assigned to all the relevant PDS categories and that their sum is equal to the total CDF, the current practices of the ET/FT combinations into the relevant PDSs causes a difference between the CDF and the PDSF. The present study has shown that when the Level 1 ET sequence cut sets are propagated into the relevant PDSs, there are two potential sources for causing a difference: one is a decrease in the PDSF from a truncation error caused by a fixed cut off value and the other is an increase in the PDSF from the extra cut sets that would be included in the PDS cut sets.

(2) Even when some extra cut sets are included in the PDS linked with the Level 1 model, however, the difference between the Level 1 CDF and the Level 2 PDSF is usually small and thus the Level PDSF will approach the corresponding CDF in the case that the extra cut sets are removed. Nevertheless, an exact coupling of the Level 1 cut sets and Level 2 PDS (or LERF) model may require a significant effort since it requires some modifications of both the Level 1 and Level 2 logics or more clarification on the nature of the extra cut sets that are inherently included in the Level 2 models.

(3) When implemented with the same cutoff value, the present analysis shows that the resultant PDSF is subject to its upper and lower bound, due to the combined impact of a truncation limit and extra cut sets. That is, the given PDSF always lies between a single-PDS-based PDSF and all the ET sequences-based PDSF. From the numerical aspects, the PDS approximation from the Level 1/2-bridge trees may vary the PDSF value from –1.2% to 2.5% due to a different binning of the PDS, when compared to the CDF value of 6.828E-6 estimated from the Level 1 ET/FT models. Although it is very small in the case of most PSA models, the aforementioned difference would increase due to an additional truncation when it is propagated into the Level 2 model, inevitably requiring a corresponding compensation of said cut off level.

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