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# A Formal Treatment of Uncertainty Sources in a Level 2 PSA

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## Abstract

The methodological framework of the Level 2 PSA appears to be currently standardized in a formalized fashion, but there have been different opinions on the way the sources of uncertainty are characterized and treated. This is primarily because the Level 2 PSA deals with complex phenomenological processes that are deterministic in nature rather than random processes, and there are no probabilistic models characterizing them clearly. As a result, the probabilistic quantification of the Level 2 PSA is often subjected to two sources of uncertainty: (a) incomplete modeling of accident pathways or different predictions for the behavior of phenomenological events and (b) expert-to-expert variation in estimating the occurrence probability of phenomenological events. While a clear definition of the two sources of uncertainty involved in the Level 2 PSA makes it possible to treat an uncertainty in a consistent manner, careless application of these different sources of uncertainty may produce different conclusions in the decision-making process. The primary purpose of this paper is to characterize typical sources of uncertainty that would often be addressed in the Level 2 PSA and their impacts on the PSA Level 2 risk results. An additional purpose of this paper is to give a formal approach on how to combine random uncertainties addressed in the Level 1 PSA with subjectivistic uncertainties addressed in the Level 2 PSA.

**Key Words**: Level 2 PSA, Uncertainty Sources, Uncertainty Propagation, Formal Treatment

## 1. Introduction

The Level 2 probabilistic safety assessment (PSA) provides a systematic and coherent framework for evaluating nuclear severe accident challenges for the containment integrity and the release of radionuclide source terms. As a logical model for a Level 2 PSA, the containment event tree (CET) has been commonly used to quantify the probabilities of accident pathways causing a containment failure systematically. Then, the CET looks at the severe accident as a series of snapshots in time from the initial conditions to a potential containment failure. The CET top event asks the basic questions that arise in the course of a severe accident progression, many of which are characterized as phenomenological events associated with severe accident progressions within the containment and induced containment failure. Lots of phenomenological subevents with different degrees of possibility for a given top event are modeled as branch points of the CET that are uniquely determined by the prior conditions of the event tree. That is, if the same prior conditions are given exactly, the following accident pathway is always fixed to a specified one. In other words, there is no uncertainty in the choice of CET branch event if and only if the physical conditions involved in severe accidents are completely known for the occurrence of the event. The problem is that a limited knowledge about the prior conditions gives rise to different possibilities of accident progression and it is not easy to clearly specify which condition for a given accident pathway is the correct one. This is the main reason why we need probabilistic analysis for the deterministic accident pathways that are taken into account in CET.

Although the above concept of the Level 2 PSA appears to be currently standardized in a formalized fashion [1, 2], there have been different opinions in the way the sources of uncertainty are characterized and treated [3-5]. This is primarily because the Level 2 PSA deals with complex phenomenological processes in nature rather than random processes, and thus there are no probabilistic models that can tell us with certainty the actual severe accident situation we are trying to predict. As a result, the probabilistic quantification process of the Level 2 PSA is inevitably subjected to two sources of uncertainty: (a) incomplete modeling of CET accident pathways (each incomplete with respect to various aspects of the problem) or different predictions for the behavior of CET top events), and (b) expert-to-expert variation on the CET top event branch probability (judgmental uncertainty). These sources of uncertainty are epistemic or subjectivistic in nature [6, 7] and some phenomena have very different models and magnitudes applied by different experts. We can only recognize the existence of significant state-of-knowledge uncertainties and deal with them as realistically as we can. While a clear definition of the aforementioned sources of uncertainty involved in the Level 2 PSA makes it possible to treat the uncertainty in a consistent manner, careless application of these different sources of uncertainty may produce different conclusions in the decision-making process. Another aspect is the possibility for reducing the uncertainty. If one knows why there are uncertainties and what kinds of uncertainties are involved, one has a better chance of finding the right methods for reducing them and a deeper insight into the decision-making process. A higher qualification of the CET uncertainty analysis process is also needed to qualify the risk-informed decision making process as well as the realistic assessment of the Level 2 risk. The primary purpose of this paper is to characterize typical sources of uncertainty that would often be addressed in the Level 2 PSA and their impacts on the PSA Level 2 risk results. For this, the underlying methodologies of the Level 2 PSA are critically investigated in the former part of this paper. The latter part of this paper describes a formal approach on how to combine random uncertainties addressed in the Level 1 PSA with subjectivistic uncertainties addressed in the Level 2 PSA, so that uncertainties about the final outcomes of the Level 2 PSA are represented in an integrated manner.

## 2. Potential Sources of Various Uncertainties in Level 2 PSA

The existence of uncertainties in every step of the Level 2 analysis.makes the Level 2 results greater or less unsubstantiated. Before tackling the formal quantification of uncertainty sources involved in the Level 2 PSA, it is a natural step to understand why uncertainties arise in the Level 2 PSA, to find the underlying sources of uncertainty, and to identify which uncertainties are explicitly accounted for and which ones are not.

### 2.1 Formal Distinction between System and Phenomenological Events

In performing the Level 2 PSA, we take into account a clear distinction of the two types of events: one is the status of the containment systems that are typically modeled as the plant damage state (PDS) events and the other is the occurrence possibility of phenomenological events that are modeled as CET top events. Keeping such a distinction is for a consistent treatment of the two types of event probabilities that are different in nature [6, 7]. The containment system events are mainly related to the success or failure status of the containment mitigation systems, many of which are estimated on the basis of actual data. As manipulated in the Level 1 system event trees, the occurrence of these events is modeled as a random process and their success or failure probabilities are a property of the event (or a performance of the system). This type of probability is an expression of the relative frequency for the success and failure events in a random/stochastic process. Whereas, the Level 2 phenomenological events that are modeled in the CET are mainly related to the occurrence of physical accident progressions, many of which are estimated under the lack of direct data. The physical accident progressions that are deterministic in nature are governed by laws of physics that are, in principle, amenable to a complete understanding of the physical law. In that case, the underlying probability is fundamentally an expression of an analyst's subjective confidence about the occurrence possibility of the phenomenological events, whose true value is subjected to either an occurrence or nonoccurrence, but not both. The uncertainty about the foregoing true value arises from the fact that, in general, the physical phenomena are rather complex to describe exactly. Thus, an important point to note is that the probabilities characterizing the occurrence of the Level 2 phenomenological events should not be regarded as a type of relative frequency, they are the result of an uncertainty analysis and are more suitably regarded as measures of belief in the various paths of accident progression denoted by the CET top events. Returning back to the CET branch events, the underlying branch point probability is interpreted as a measure of the subjective/epistemic uncertainty. Whereas, the relative probability obtained for the status of the containment systems is in nature random/aleatory, whose uncertainty is expressed as a distribution for the relative probability.

The foregoing interpretation of event probability indicates that the uncertainty for the Level 2 deterministic events would be eliminated if we could resolve all the uncertainties addressed in the physical processes involved in reactor accidents. Normally, the phenomenological CET is quantified separately for each important PDS with regards to the corresponding initial condition of the Level 2 accident progressions. Even though we considered the two types of uncertainty above, it have been generally accepted that at a fundamental level, uncertainty is just uncertainty and all uncertainties come from the lack of knowledge for a given problem. In that case, there is no fundamental reason for distinguishing between different types of uncertainty. The foregoing rigorous classification of the uncertainty type is mainly related to the more practical aspects such as modeling of complex systems and obtaining clearer information for a risk of the system [6, 7]. Another important aspect for exploring different types of uncertainty allows for a proper propagation of different uncertainties in the evaluation process so that consistent decision-making is made for the resulting quantitative uncertainties. When both uncertainties are already mixed up in the course of the analysis without a clear separation, it is not possible to identify the resulting combined effect of the uncertainties of either type. The last aspect of the formal separation is that the approach is very helpful in understanding the nature of the uncertainties and for the estimation of uncertainty measures in practical situations. Through the formal distinction of uncertainties, we can gain clear insights into 'what we know about variability among the occurrences of individuals in the population' or 'how much we know about a fixed but unknown quantity'.

### 2.2 Modeling and Phenomenological Sources of the Level 2 Uncertainty

As mentioned before, it is generally considered that variability in a logical or physical structure of the CET to describe the behavior of a given severe accident progression is characterized as the modeling uncertainty over a right CET structure. Typically, the impact of this type of uncertainty characterized as different CET structures on the Level 2 risk results has been analyzed with the sensitivity analysis for each model. On the other hand, the accident progression addressed in a Level 2 PSA is uniquely determined by the prior conditions and thus if the same conditions are given, the resultant accident progression is always fixed at one. Problem is that a limited knowledge about the prior conditions gives rise to different accident progression possibilities that are characterized with subjective probabilities for a given CET top event branch point. Whenever possible, the branch probability can be obtained by the overlap of a probability distribution for the occurrence criteria of the branch point and a probability distribution of a control parameter that would be used to determine the relative magnitude of the event. Uncertainties addressed in the foregoing two parameters (i.e., one for the occurrence criteria of event and the other for a parameter controlling the relative magnitude of the event) are characterized as a phenomenological uncertainty of the Level 2 PSA. They are a special case of modeling uncertainty. Although the both uncertainties are closely related in the CET analysis, it may be more instructive to manipulate uncertainty over the phenomenology associated with accident progression and modeling uncertainty over structure as distinctively mentioned above. By considering “modeling” and “phenomenology” separately, one can separate the question of how well our models represent a given process from the question as to how well we understand the underlying phenomena for the accident process. The explicit treatment of this modeling uncertainty and the phenomenological uncertainty results in the distinctive phenomenological uncertainty distributions for each of the accident progression models considered [8].

### 2.3 Stochastic Sources of the Level 2 Uncertainty

In general, a formal separation between the stochastic and epistemic portions of uncertainty greatly depends on the level of decomposition and qualification for the events in question. If the underlying events are not clearly defined at the fundamental levels, the potentials for the stochastic portion of the probability are inevitable even for phenomenological events. This would be the same situation even for the Level 2 PSA, most of whose events have been characterized as subjective/epistemic uncertainties. There are three representative cases where the stochastic variability might be addressed in the Level 2 accident analysis.

<u>The first possibility</u> for the potential existence of stochastic variability in the CET analysis could be introduced in the form of a sequence-to-sequence variability of some phenomenological factors [9]. If the same sequence in the CET were executed many times from the same PDS and if the outcome of a top event varies in such an execution, there would be a sequence-to-sequence variability. However, as long as the plant damage states are properly defined and all the top events represent physical processes governed by the laws of physics rather than random events, there is no variability in a CET sequence. If such a variability were observed in a practical experiment, it would in all likelihood be due to a subtle detail in a physical process that is not adequately understood. This would result in the redefinition of either the PDS or the CET. Not knowing what the subtle details could be and lacking any evidence that they may indeed even exist, they are properly treated as an element of uncertainty in the outcome of each top event. <u>The second possibility</u> that in the CET analysis some phenomenological factors could be treated as a stochastic process comes from the limited resolution of the initiating events [10]. A basic assumption for such a case is that the phenomenon can occur in core damage accidents leading to containment failure. Then, the underlying probability becomes an estimate of the fraction of all the Level 1 core damage sequences that result in the phenomenon. This probability describes a stochastic process of a given phenomenon, which is therefore a measure of a physical property of the containment system being studied. When the concept of PDS is introduced as an initial condition of the Level 2 PSA, the details of different accident sequences ending in the same PDS do not have to be retained for the containment model; i.e., a specific sequence can lose its information once it is assigned to its PDS. Probabilistically, this means that there is no variability in the containment response for different plant failure sequences within the same PDS. <u>The third possibility</u> that some phenomenological factors leading to core melt are involved in the subsequent accident progression can be subjected to a stochastic nature in part [11]. In most cases, the description of the factors leading to a containment phenomenon will be of a limited resolution and the accident sequences with it will differ in many details. Even when an initial accident condition is specified in PDS, the question for the peak pressure resulting from the phenomenon neglects the existence of subsequences or phenomena that are unspecified in various ways in the definition of PDS. For example, the description of the aforementioned question says nothing about some factors making them a stochastic process like the initial melt temperature at the time of core melt, and/or the question refers to sequences with the melt exhibiting any technically feasible values. Consequently, a population of values applies such that there is uncertainty as to which value to use in the estimation of the peak pressure to the given accident sequence defined as the specific PDS, i.e., a random/stochastic variability of the peak pressure within the population of initial melt temperatures. Then, the probability of the containment failure branch from the relevant probability distribution is a conditional probability, applied from the conditions of the given PDS sequence.

Even when the stochastic portions of uncertainty are involved in the phenomenological events, there are two reasons why they are no longer taken into account in the CET analysis. The first reason is that in many cases the contribution of the stochastic portion to the CET branch probability is not so much, compared to the phenomenological impact assessed for a specific PDS. The second reason is that a clear separation between the stochastic and phenomenological portions is not easy due to the complexity of severe accident phenomenology. In fact, the ability to estimate uncertainties in physical phenomena at the level of detail at which they enter the total analysis requires considerable knowledge of the physical phenomena, the reactor itself, and the possible accident sequences. Even when the both portions of uncertainty are distinguished, the incorporation of both uncertainty portions into the CET analysis makes it difficult to quantify explicitly the impact of each uncertainty for the CET end points. Due to the aforementioned reasons, the uncertainty is estimated principally for the uncertainty of our understanding of the phenomena and the uncertainty due to random processes are no longer taken into account in CET analyses. Strictly speaking, there is no reason for an analysis of CET accident pathways that cannot be clearly identified.

## 3. Formal Treatment of the Level 2 Uncertainty Sources

Major and minor sources of the Level 2 uncertainties were discussed in the previous sections. The subsequent steps are to answer on how to propagate uncertainties addressed in the model inputs to qualify the CET analysis results and how they impact on the results of the analysis. This section introduces how to propagate these uncertainties through the CET model to determine the frequencies of the CET end states.

### 3.1 Characterization of the Level 2 Uncertainty Sources

As mentioned before, the Level 2 CET branch probability is regarded as a measure of subjective uncertainty for the occurrence or nonoccurrence of the underlying phenomenological branch event. Thus, the transition of the Level 2 phenomenological accident analysis results into the corresponding CET branch probabilities is the first step in the determination of the Level 2 risk and related uncertainties, which is an inductive process of the analyst's confidence in the acceptability of the deterministic predictions of an uncertain phenomenon. There are two types of uncertainty that need to be explicitly handled in the assessment of the Level 2 risk results.

(1) Phenomenological Uncertainty Sources

If possible, the occurrence probabilities of various branch events and phenomena must be determined with the probability distributions for two decision parameters (one for physical impacts imposed on the specified branch event and another for physical criteria on the occurrence of the event) [3-5]. However, the main difficulty in estimating them is that there is no directly applicable database or statistical model with which to estimate these quantities. These deficiencies allow different experts to arrive at different conclusions about the branch probability, and therefore large uncertainties may exist in the realistic prediction of Level 2 risk results. To minimize potential uncertainties resulting from the lack of phenomenological data and subjectivism in making quantitative estimates of the branch probabilities, experiments and code analyses are primarily utilized to simulate the expected behavior of an accident phenomenon to be considered in the CET. For less well-understood accident sequences and the criteria for some branch events, the analyst must place greater reliance on an engineering judgment and assumptions. Then, the final integration of this information in the form of probability distributions can provide a comprehensive description of the state of understanding of these physical events.

Table 1 Different Combination of Containment Peak and Failure Pressures

| Cases | Peak pressure ( $P_{peak}$ ) | Failure pressure ( $P_{fail}$ ) | Containment failure probability ( $p_{cf}$ ) |
|---|---|---|---|
| Case 1 | Point estimate | Point estimate | If $P_{peak} > p_{fail}$ , $p_{cf}$ =1.0<br>If $P_{peak} < p_{fail}$ , $p_{cf}$ =0.0 |
| Case 2 | Uncertainty distribution | Uncertainty distribution | The convolution of the two uncertainty distributions results in 0.0 < $p_{cf}$ <1.0. |
| Case 3 | Point estimate | Uncertainty distribution | The cumulative failure probability for a given pressure results in 0.0 < $p_{cf}$ <1.0. |
| Case 4 | Uncertainty distribution | Point estimate | (a) Obtain point values ( $P_{peak,i}$ , $i = 1$ to n ) from a given peak pressure distribution;<br>(b) The application of Case 1 to each pressure value results in $p_{cf}$ =1.0 or 0.0;<br>(c) The arithmetic average of all $p_{cf}$ gives in 0.0 < $p_{cf}$ <1.0. |

As one example utilizing the phenomenological data, the probability of a high-pressure melt ejection failing the containment is evaluated as follows. The question consists of two parts: firstly, (a) what pressure is generated from the high-pressure melt ejection (i.e., containment peak pressure), and secondly, (b) how is the pressure strong enough to fail the containment in a specific mode (i.e., containment failure pressure). The two resultant probability distributions (one for containment peak pressure and another for containment failure pressure) are regarded as a representation of the analysts' uncertainty for the containment pressure resulting from a high-pressure melt ejection for a specific core melt accident sequence and for the containment failure for a given pressure, respectively. Then, a probabilistic combination of both probability distributions [3-5] gives a single measure (or mean probability) of the analyst's belief that the branch event will occur in a core melt accident as a result of a physical challenge in it. Table 1 summarizes four approaches for determining the containment failure probabilities when the containment peak and failure pressures are subjected to either point values or probability distributions.

Table 2 Different Formulation of Probability Variation in Level 2 PSA

| Expression of Branch Probability | Form of Uncertainty | Variation in Estimated Probability | | |
|---|---|---|---|---|
| | | Expressions | [ $p^{\ell}$ , $p^{u}$ ](1) | Nominal(2) |
| Qualitative (Linguistic) Expression of Branch Probability | Interval Probability | Certain | $p$ =1.0 | 1.0 |
| | | Highly Likely | [0.995, 1.0] | 0.999 |
| | | Very Likely | [0.95, 0.995] | 0.99 |
| | | Likely | [0.70, 0.95] | 0.9 |
| | | Indeterminate | [0.30, 0.70] | 0.5 |
| | | Unlikely | [0.05, 0.30] | 0.1 |
| | | Very Unlikely | [0.005, 0.05] | 0.01 |
| | | Highly Unlikely | [0.0, 0.005] | 0.001 |
| | | Impossible | $p$ = 0.0 | 0 |

Note superscripts (1): $\ell$ , $u$ = lower and upper bounds of interval probability, respectively
(2): Nominal value based on Flat Function in NUREG-1150 study

For less well-understood accident sequences and some branch classification criteria, it is generally accepted that the branch probabilities obtained in such way cannot be rigorously substantiated because the judgment process is not a clearly defined process. However, it may well be the right thing to do in many practical applications when no other alternative means exist. Distinctive qualitative terms have been proposed for the transition of the analyst's confidence into the subjective probabilities and Table 2 summarizes the representative terms that have been widely used for the CET branch probability assignment since the Surry Level 2 PSA [12]. These ranges in probabilities are used to give a single representative estimate (e.g., a nominal value or mid range) that will be used as the corresponding branch probability, but does not have any statistical meaning in a strict sense. In other words, the range in probabilities does not mean any statistical distribution in probability because the subjective probability is already an expression of uncertainty. Past experiences [13-14] show a wider variation especially when the branch probability is judgmentally assigned rather than when it is based on a detailed engineering analysis.

(2) Judgmental Uncertainty Sources

When a judgmental process is concerned with the estimation of the CET branch probabilities, on the other hand, there are two distinct sample spaces of probability judgments [15-16]. The first is the usual sample space over which probabilities are estimated as the space of event conditions, and the second is a new sample space over which the dispersion of opinions are measured as the space of the experts' opinions. While the former asserts the probability of an event by an individual (i.e., personal probability), the latter suggests the different opinions of experts on a chance of the individual probability (i.e., expert-to-expert variation on probability estimates). Moreover, the latter case can be statistically treated, based on the sample space of heterogeneous opinions among the experts [16]. These additional uncertainties addressed in the judgmental process of an individual expert are characterized as expert-to-variability in the subjective estimate, which is different from the uncertainty of the occurrence of the CET branch point as a physical event. The latter type of uncertainty involved inherently in the judgmental process gives additional information on the uncertainty to the Level 2 PSA decision-making process. Because these two types of uncertainty are considered equally important, it is necessary to manipulate them explicitly in the Level 2 PSA.

### 3.2 Propagation of Characterized Uncertainties

In the Level 2 CET, only one accident pathway is physically possible for a specific PDS, but we do not know which one is correct. This feature of CET events has an important implication when their probabilities are propagated in the form of uncertainty through the CET model. If a point estimate (e.g., mean value) is all that is required for the Level 2 risk results, the point estimation of the CET end point (or STC) frequencies is rather straightforward. However, if a full propagation of uncertainties is required to determine the uncertainty distributions for the frequency of the CET end states, then a formal representation of the uncertainty distributions is required.

(1) Uncertainty Propagation of Branch Probabilities

In order to formalize the uncertainty propagation of the CET branch probabilities, let's reset the branch probability in the frequency format of probability, e.g., a deterministic value of one correct accident pathway equal to one and the other pathways equal to zero. This is possible just when we can eliminate all the subjective uncertainties surrounding the occurrence of the branch events. Then, the branch events in question would be either 0 or 1 in the sense of an occurrence frequency [3-5]. Accordingly, the frequency format of a CET branch probability is a kind of double-delta function that expresses the probability that the frequency is either one or zero, and the frequency between zero and one has a zero probability. Consequently, the branch probability itself is interpreted as a mean value of the corresponding branch frequencies (or a weighted average of uncertainty for the frequency of one and uncertainty for the frequency of zero). All the CET branch probabilities are similar in that they originate from the uncertainties in the branch events. The above approach makes it possible to statistically propagate uncertainties of the branch events given in the form of subjective probabilities to determine the uncertainty distributions for the frequency of the Level 2 end states. Table 3 shows an explicit expression of the CET branch probability as a measure of uncertainty in a frequency format. This contrasts with an uncertainty attributable to a random frequency estimated from the stochastic models characterizing a system component failure in a Level 1 PSA, i.e., a probability distribution for the continuous frequency. After all, the uncertainty propagation of the CET branch probabilities is based on the two aforementioned propositions: (a) The CET branch probability is a complete statement of knowledge as the branch probability itself expresses the uncertainty that the event frequency is either one or zero, and (b) This state of knowledge can be interpreted as a double-delta distribution for the occurrence frequency of a specified branch event.

For the Level 2 uncertainty analysis, first, it is required to identify the probabilities of the branch points that are expected to give more impact to the Level 2 risk results. After then, it is required to formulate a single set of aggregate probability estimates for each CET branch point (e.g., mean estimates) so that the best estimate in the branch point probabilities can be illustrated. Finally, in order to obtain the impact of deterministic branch model uncertainties on the Level 2 risk, the different CET structures (more specifically branch models or accident pathways) are then sampled with an appropriately chosen statistical procedure (such as Monte Carlo approach). Then, the relative weights of each branch point sample (i.e., one-zero sample in the frequency format of probability) are designed to reflect the formulated branch probabilities. As a result, a type of probability distributions for the CET end state (or STC) frequencies are obtained in the discrete form of a frequency, and their mean frequencies can be then obtained by aggregating the CET end state frequencies. A type of sensitivity study can be done to determine the CET top event questions with the greatest impact on the Level 2 risk or with the greatest impact on the output uncertainties. For this purpose, each top event under consideration is fixed into its base branch model characterized with the frequency of 0 or 1, one by one, while the remaining branch models are propagated through the CET with their original uncertainties. After that, the branch models with the greatest impact on the uncertainty of CET end states are ranked according to the relative magnitude of importance measures (e.g., difference of the standard deviations for each of the base case and sensitivity results). The aforementioned approach based on mean estimates of the branch point probabilities is the normal way to estimate uncertainties for frequencies of the CET end points [3-5, 8, 12].

Table 3 Expression of CET Branch Probability as a Measure of Uncertainty

<table>
<tr><td>Event Type</td><td colspan="5">Branch Model (zero / one frequency format)</td><td colspan="3">Composite Form of Uncertainty Distribution of Branch Frequencies</td></tr>
<tr><td rowspan="6">Phenomenological Branch Events</td><td colspan="5">Relationship of Branch Events with Uncertainty</td><td colspan="3">Three branches for a given event</td></tr>
<tr><td></td><td>Branch 1</td><td>Branch 2</td><td>Branch 3</td><td>Uncertainty</td><td>Branch 1</td><td>Branch 2</td><td>Branch 3</td></tr>
<tr><td>Frequency</td><td>1</td><td>0</td><td>0</td><td>$p_1$</td><td>$p_1$</td><td>$p_2$</td><td>$p_3$</td></tr>
<tr><td>Frequency</td><td>0</td><td>1</td><td>0</td><td>$p_2$</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>Frequency</td><td>0</td><td>0</td><td>1</td><td>$p_3$</td></tr>
<tr><td colspan="5">$p_1 + p_2 + p_3 = 1.0$<br>All $p_i$'s are subjective probability</td></tr>
</table>

(2) Propagation of Judgmental Uncertainties

When experts are involved in the estimation process of a specific branch probability, the branch probabilities are allowed to vary as each expert may have his own opinion concerning the branch model assumptions with some degree of validity. Table 4 shows a mathematical expression of expert-to-expert variation of a branch probability when experts provide their own probability estimates. The foregoing situation leads to an assessment for the impact of a model-to-model variation of each branch event or expert-to-expert variation of each branch probability on the Level 2 risk results. For the PSA application, the probabilistic formulation of a model uncertainty has been made with the probability (or relative weight) of each model over alternate models, whose values may be equally weighted by the experts. In that case, the probability is regarded as an expression of each analyst's degree of belief in that model as being the most appropriate [8, 17]. This formulation of judgmental uncertainty about the branch probability is fundamentally based on an assumption that each of the underlying branch models can be treated as a probability variable in the framework of uncertainty analysis, with varying degrees of probability estimates or probability distributions. However, it should be noted that the resultant uncertainty is epistemic in nature, and not random/stochastic.

An appropriately chosen statistical procedure for quantifying an overall impact of the experts' different estimates in the branch probabilities produces an envelope of experts' different viewpoints for the Level 2 risk results (e.g., a mean frequency of a specified CET end point). In addition, the impact of such an expert-to-expert variation for the uncertainties of CET end points can be assessed through an additional type of sensitivity analysis (e.g., distributional sensitivity analysis). This type of sensitivity analysis is applicable as long as the branch probability is regarded as a type of uncertainty distribution as mentioned before. According to the definition of distributional sensitivity analysis [8], the discrete distribution given by the first expert is replaced as its base branch model. Then each base model is propagated through the CET model, one by one, while the remaining branch models have their original uncertainties. The resultant CET end states for each branch model vector are characterized as a family of probability distributions. Consequently, the expert-to-expert variation with the greatest impact on the uncertainty of CET end states can be determined by the relative magnitude of importance measures mentioned in the previous section.

Table 4 Expert-to-Expert Variability to the Specified Set of Branch Probabilities

| Source of Variability | Form of Variability | Mathematical Expression |
|---|---|---|
| Experts' Different Weights to Estimated Branch Probability Set | Discrete Weights | Discrete Sets of Branch Probabilities<br>$\sum_i p_{ij} = \sum_j w_j = 1$<br>$p_{ij}$ : Probabilities of *i*-th branch in *j*-th branch set,<br>$w_j$ : experts' weight assigned to *j*-th branch set |

## 4. Formal Link of Level 1 and 2 Uncertainties to the Level 2 Risk

When a full propagation of the Level 1 and Level 2 uncertainties is required to determine the uncertainty distributions for the frequency of the Level 2 end states, a strict representation of the uncertainty distributions for the Level 1 events and for the Level 2 events is required. This section focuses on how to propagate the Level 1 and Level 2 uncertainties into an uncertainty distribution for the Level 2 risk results.

In order to explain explicitly a formal combination of the Level 1 and 2 uncertainties, let's take a typical example that propagates the Level 1 and Level 2 uncertainties through a Level 2 CET model (i.e., CET Type 2). Fig. 1(a) shows an example event tree linking a Level 1 end sequence and a Level

2 CET top event. Fig. 1(b) gives an expression of the CET branch probability in the format of a frequency (i.e., an expression of uncertainty distribution for a subjective probability). Then, Fig. 1(c) and Fig. 1(d) explain how an uncertainty distribution of the Level 1 event ($E_1$) and the uncertainties involved in both the events of the Level 2 CET ($E_{21}$ and $E_{22}$) are propagated through the CET model to obtain the uncertainties of the two CET end states $S_{21}$ and $S_{22}$, respectively. For an additional purpose of illustration, Table 5 shows four distinctive mathematical formulations for combining the Level 1 and Level 2 uncertainties through the CET model.

TABLE 5 Different Combination of PSA Level 1 and Level 2 Uncertainties

| Type of Event and Frequency | | End State of Level 2 CET Quantified STC frequency |
|---|---|---|
| $E_1$: Level 1 Event | $E_2$: Level 2 Event | |
| Relative frequency<br>$0< p_{E_1} <1$<br>U-distribution (PDF)<br>$f_1 \equiv f(p_{E_1})$ | Relative frequency (2-branches)<br>$E_2 \equiv \begin{cases} E_{21} = 1 \\ E_{22} = 0 \end{cases}$<br>U-distribution (DUD)<br>$f_2 \equiv \begin{cases} p_{E_2}, & \text{if } \mathrm{E}_2 = 1 \\ 1 - p_{E_2}, & \text{if } \mathrm{E}_2 = 0 \end{cases}$ | |
| Point estimate<br>$p_1 = E[p_{E_1}]$ | Point estimate<br>$p_2 \equiv \begin{cases} 1\times p_{E_2} + 0\times(1-p_{E_2}), & \text{if } \mathrm{E}_2 = 1 \\ 0\times p_{E_2} + 1\times(1-p_{E_2}), & \text{if } \mathrm{E}_2 = 0 \end{cases}$ | Point estimate<br>$p_{stc} = p_1 \times p_2$ |
| Point estimate<br>$p_1 = E[p_{E_1}]$ | Uncertainty ($j$-th sample)<br>$p_2^j \equiv \begin{cases} 1, \text{ if } \mathrm{E}_2 = 1, \text{ weighted by } \mathrm{p}_{\mathrm{E}_2} \\ 1, \text{ if } \mathrm{E}_2 = 0, \text{ weighted by } 1 - \mathrm{p}_{\mathrm{E}_2} \end{cases}$ | Level 2 uncertainty only<br>$p_{stc}^j = p_1 \times p_2^j$ |
| Uncertainty ($i$-th sample)<br>$p_1^i = p_{E_1}^i$ | Point estimate<br>$p_2 \equiv \begin{cases} 1\times p_{E_2} + 0\times(1-p_{E_2}), & \text{if } \mathrm{E}_2 = 1 \\ 0\times p_{E_2} + 1\times(1-p_{E_2}), & \text{if } \mathrm{E}_2 = 0 \end{cases}$ | Level 1 uncertainty only<br>$p_{stc}^i = p_1^i \times p_2$ |
| Uncertainty ($i$-th sample)<br>$p_1^i = p_{E_1}^i$ | Uncertainty ($j$-th sample)<br>$p_2^j \equiv \begin{cases} 1, \text{ if } \mathrm{E}_2 = 1, \text{ weighted by } \mathrm{p}_{\mathrm{E}_2} \\ 1, \text{ if } \mathrm{E}_2 = 0, \text{ weighted by } 1 - \mathrm{p}_{\mathrm{E}_2} \end{cases}$ | Combined uncertainties of Level 1 and 2 Events<br>$p_{stc}^k = p_1^i \times p_2^j$ |

Note:

(a) $E_1$ = Level 1 random and stochastic event, $E_2$ = Level 2 deterministic event, STC: Level 2 PSA source term category, $p_{E_1}$ = probability of $E_1$ (relative frequency), $p_{E_2}$ = probability of $E_2$ (subjective probability), $E[p_{E_1}]$ = Expectation of $p_{E_1}$, $f_1$, $f_2$ = uncertainty distributions for $E_1$ and $E_2$, respectively, $p_{stc}$ = probability for source term category (STC), DUD= double-delta uncertainty distribution.

(b) Type 1 Event ($E_1$): Random and stochastic event, Different outcomes occur at random (e.g., flipping a two-sided coin, always true or occurring event), Probability used to describe relative frequency of outcomes

(c) Type 2 Event ($E_2$): Deterministic event or parameter value, A single and true, but uncertain outcome (One-sided coin, true or false, occurrence or nonoccurrence), Probability used to describe uncertainty or state-of-knowledge about the outcome.

(d) Results of the Level 2 PSA accident progression and containment analyses through the CET are containment failure modes characterized as STCs and their frequencies and, in some studies, the conditional probabilities of their occurrence.

## 5. Summary and Concluding Remarks

The main concern of this paper was to give a formal guidance for a consistent treatment of different uncertainties addressed in the Level 2 PSA, whose sources come from (a) uncertainty in the phenomenological branch models and (b) uncertainty involved inherently in the judgmental process by an individual or experts. All the uncertainties are in nature epistemic rather than random/stochastic. For this, the former part of this paper mainly addressed the potential sources of uncertainty that would be implicitly or explicitly involved in the Level 2 PSA and their implications on the Level 2 risk quantification. As a result of the former part, clearer answers were given for the question on why uncertainties arise in the Level 2 PSA, to find the underlying sources of uncertainty, and to identify which uncertainties are explicitly accounted for and which ones are not. The latter part of this paper provided a formal guidance for handling different sources of uncertainty that would be addressed in the CET analysis of the Level 2 PSA, particularly with respect to their characterization, propagation, interpretation, and impact on the PSA Level 2 decision-making process. According to the present approaches, uncertainties addressed in the frequency of the CET end points are subjected to two different scales of uncertainty. An additional emphasis of the latter part was related to a methodological framework for the direct link of the Level 2 CET model with the Level 1 event sequence model to obtain the uncertainties of the Level 2 CET end points. This approach is fundamentally based on a strict distinction between the two interpretations of uncertainty. As a result, an answer is given for the question on how to propagate random uncertainties addressed in the Level 1 PSA event sequence models into subjective uncertainties addressed in the Level 2 PSA CET models. The present formulations for the Level 2 uncertainty analysis may provide a deeper insight into the Level 2 PSA, add to the credibility of the results, and aid in the decision making process under uncertainty.

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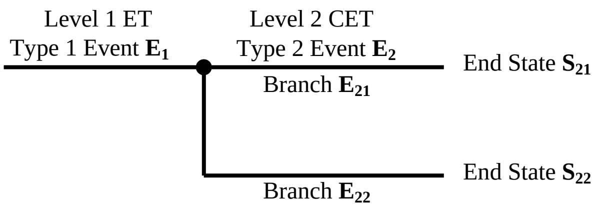
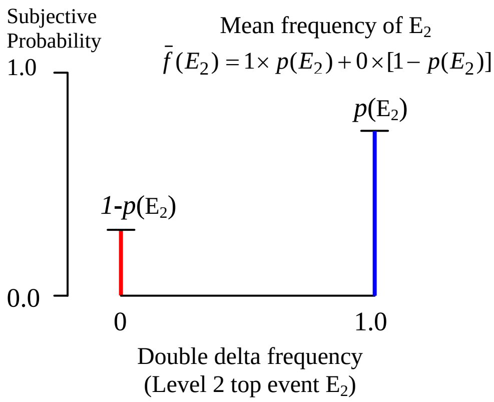
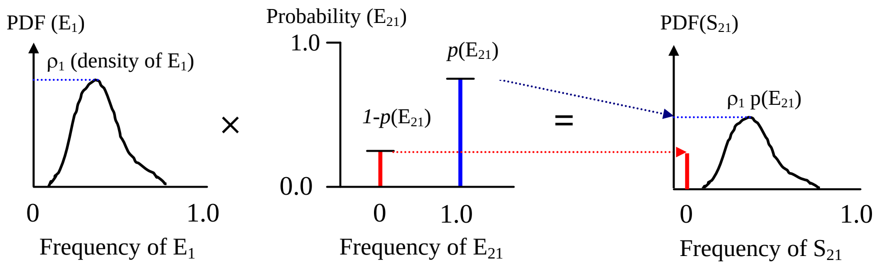


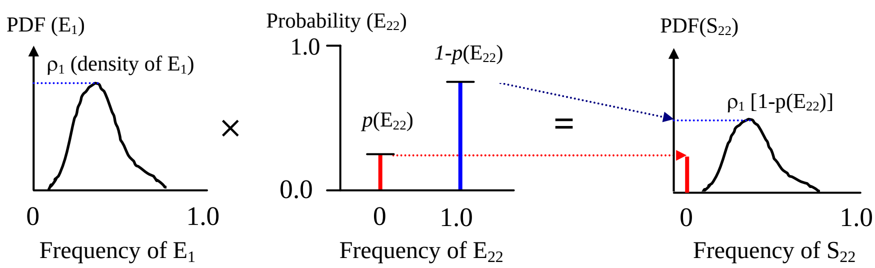

(a) A Combined Model of Level 1 System ET and Level 2 CET




(b) Frequency Format of the Level 2 Top Event Probability
(Phenomenological Uncertainty)




(c) Propagation of $E_1$ and $E_{21}$ Uncertainties into the End State $S_{21}$




(d) Propagation of $E_1$ and $E_{22}$ Uncertainties into the End State $S_{22}$

Fig.1 Propagation of Type 1 and Type 2 Uncertainties through a Level 2 CET Model