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# A Formal Guidance for Handling Different Uncertainty Sources Employed in the Level 2 PSA

**Kwang-Il Ahn, Joon-Eon Yang, and Jae-Joo Ha**
Korea Atomic Energy Research institute
150 Dukjindong, Yuseong-gu, Daejeon, 305-353, Korea
kiahn@kaeri.re.kr

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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 CET/APET 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 to provide a formal guidance for quantifying 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, CET/APET, uncertainty characterization and propagation, PSA qualification, formal guidance

## 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) (called accident progression event tree (APET) in some applications) 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. This means that 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/APET.

Although the above concept of the Level 2 PSA appears to be currently standardized in a formalized fashion [1-5], there have been different opinions in the way the sources of uncertainty are characterized and treated [6-8]. 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 [9-11] 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 to provide a formal guidance for quantifying 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 Uncertainties in Level 2 PSA

The Level 2 CET methodology embraces the definition of initial conditions, criteria for selecting top events, probabilistic quantification of top event branch probabilities, and the interpretation and propagation of uncertainties. After all, uncertainties may be addressed in every step and element of the CET analysis. Because these uncertainties make the Level 2 analysis results greater or less unsubstantiated, their existence should explicitly be explained in the Level 2 PSA. 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. For the convenience of discussion, the former part of this section gives a brief introduction to the formal modeling approach of the Level 2 PSA. In the last two parts of this section, we explore the potential possibilities for various uncertainty sources that would often be addressed in the quantification process of the Level 2 PSA.

### 2.1. Overview of the Existing Level 2 Accident Progression Modeling

#### 2.1.1. Formal Integration of the Level 2 Risk

The quantitative result of the Level 2 risk analysis is the frequencies of various CET end points that are grouped into source term release categories (STCs). In the conventional Level 2 PSA, the end states of the Level 1 PSA extended to containment mitigation systems, so called plant damage states (PDSs) represent the entry points into the Level 2 CET model. The PDSs are used as pinch points between the plant model and the containment model so that all the input information required by the containment models is contained in the definition of the PDS. When the Level 2 quantification is decoupled from the Level 1 model, the only information transferred from the Level 1 model to the Level 2 model is the information in these PDSs. Then, the source term release frequency can be determined by combining the frequencies of PDSs with the conditional probabilities of STCs for each PDS. The resultant mathematical formulation of the STC frequencies is given in the following form [12]:

$$R_k = \sum_{i=1}^{n} F_i \times C_{i,k} \qquad (1)$$

where

$R_k$ = Release frequency for STC $k$ (per reactor year): STC frequency vector

$F_i$ = Frequency of PDS $i$ (per reactor year): PDS frequency vector

$C_{i,k}$ = Conditional probability of STC k, given PDS $i$ : containment matrix

#### 2.1.2. 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 [11,13-15]. 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 aforementioned 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. Whereas, 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 [9-11]. 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' .

### 2.1.3. Modeling of Accident Progression Events in the CET

The CET relates a given accident class (i.e., PDSs) to a number of potential containment failure modes, by specifying various top events associated with the interrelation between the physical processes, containment equipment performance and operator actions after core damage. Typically, the foregoing CET top events can be classified into four broad categories [13-15]: (a) The containment structural function bypassed from the beginning of the accident, (b) The containment structural function that is initially effective but degrades during the course of the accident, (c) Failure of equipment induced by various phenomenological impacts expected after core melt (not explicitly defined in the PDS), and (d) initial containment status and recovery actions (explicitly defined in the PDS). The first category is either due to human error or containment equipment failure, e.g., containment bypass due to a significant main steam isolation valve (MSIV) leakage and a steam generator tube rupture (SGTR). Probabilities of those events are quantified within the system analysis with the help of a fault tree approach. The second category is made up of failure modes caused by various phenomenological processes during severe accident progressions, e.g., steam explosions, hydrogen burn, high pressure melt ejection, and slow overpressurization by the build up of steam or noncondensible gas. The magnitude of these challenges when compared with the containment capacity will determine whether or not containment failure will occur and if it does, the time at which the failure is reached. For each of the two decision parameters to determine the containment failure probability (one for failure pressure and the other for peak pressure), a state-of-knowledge uncertainty distribution is developed and the failure fraction is determined by the convolution of the two distributions. The third category includes temperature-induced reactor coolant pump (RCP) seal failure, temperature-induced SGTR, temperature-induced reactor coolant system (RCS) pipe break, and melting or creep failure of reactor pressure vessel (RPV). Probabilities of those events are also derived either by the aforementioned detailed probabilistic analysis whenever possible or with the help of an engineering judgment when no alternative approach exists. The fourth category is used as a prior condition to specify the occurrence of the subsequent events conditionally and recovery actions for severe accident mitigation. The representative recoveries for core damage prevention and severe accident mitigation are RCS depressurization preventing delayed core damage and high-pressure melt ejection, recovery of containment spray in recirculation mode, and active cavity flooding for preventing the failure of reactor vessel. The probability of those events in the CET has either 1 or 0, depending upon the given PDS sequence.

Concerning the layout of various top events in the CET, however, it is a matter of individual preference whether or not to include questions associated with an active system status or operator actions in the containment event tree. If the foregoing questions are included in the CET, the underlying branch probabilities must be either 0 or 1 to distinguish them from the deterministic physical processes.

## 2.2. Phenomenological and Modeling 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 type of phenomenological uncertainty in the Level 2 PSA. Also, such kind of phenomenological uncertainty is considered as 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 [16].

### 2.3. Random and 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.

The first possibility 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 [14]. 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 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. The second possibility that in the CET analysis some phenomenological factors could be treated as a stochastic process comes from the limited resolution of the initiating events [17]. 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. The third possibility that some phenomenological factors leading to core melt are involved in the subsequent accident progression can be subjected to a stochastic nature in part [18]. 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

The potential sources of the Level 2 uncertainties were explored in the previous sections. Because it is not easy to handle all the sources of uncertainty, we have to determine which sources of uncertainty must be explicitly handled in the quantification process and which sources do not need to do so. As mentioned in the previous section, it is generally accepted that major sources of the Level 2 uncertainty primarily come from the uncertainty of our understanding of the phenomena and the uncertainty rather then random/stochastic nature of some events. Then, the subsequent steps are to answer on how to propagate these dominant uncertainty sources addressed in the model inputs to qualify the CET analysis results and how they impact on the results of the analysis. This section a formal guidance on how to characterize major sources of the Level 2 uncertainty and propagate them through the CET model to determine the frequencies of the CET end states.

### 3.1. Characterization of the Level 2 Uncertainty Sources

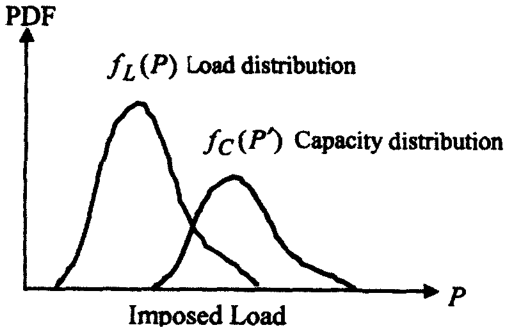
As mentioned before, the Level 2 CET branch probability is regarded as a measure of subjective uncertainty for the occurrence or nonoccurrence of the underlying phenomenological branch event. Thus, the transition of the Level 2 phenomenological accident analysis results into the corresponding CET branch 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.

#### 3.1.1. Phenomenological and Modeling 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) [13-15]. However, the main difficulty in estimating them is when 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 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. In the accident progression analysis, two typical examples of the foregoing approach are the evaluation of (a) probabilities for a specified containment failure mode during accident progression and (b) probabilities of temperature-induced RCS boundary failure after core damage.

**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 gives 0.0 < $p_{cf}$ <1.0. |




**Mean probability of a given structure,**

$$p_{fail}(m_i) = \int_0^{\infty} f_L(\tau) \int_0^{\tau} f_C(m_i \mid \tau) d\tau' d\tau$$

**Structural failure probability of a given $P$,**

$$p_{fail}(m_i \mid P) = \int_0^{P} f_L(\tau) \int_0^{\tau} f_C(m_i \mid \tau') d\tau' d\tau$$

**$f_L(P)$ = probability distribution (PDF) for the imposed load $P$**

**$f_C(m_i \mid P)$ = capacity (or strength) distribution (PDF) of a given failure mode $m_i$**

**$m_i$ = failure mode (e.g., leak, rupture, or catastrophic rupture in the containment structure)**

**$P$ = load (or stress) imposed to a given structure (e.g., pressure, temperature)**

**Fig. 1. Determination of the Level 2 CET Branch Probability (split fraction)**

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. As shown in Fig.1, then a probabilistic combination of both probability distributions 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 | $[p^l, p^u]^{(1)}$ | 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): $l$, 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. When an expert gives his probability for the CET branch event, for example, he might understand which physical laws could be applied and have an opinion as to which physical law is more likely. If information is very limited, however, the expert might rarely ascertain a unique belief to his estimate for the branch probability. As a result, an expert often does not have a unique belief because of less confidence in his judgment of the branch probability, but instead suggests his probability in the form of an interval probability with a different degree of a possibility in his mind. This does not mean the expert is uncertain of the belief in the sense of probability; rather it means the value of the belief is uncertain. Of course, the importance of taking into account such an uncertainty will also depend in the degree of the confidence of the different probability values, the importance of the decision to be made, and the need for an explicit treatment of the uncertain probabilities.

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 [7]. These ranges in probabilities are used to give a single representative estimate of the qualitative probability (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 because there is no reason for assigning his/her degree-of-belief about the degree-of-belief. 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 [19-20] show a wider variation especially when the branch probability is judgmentally assigned rather than when it is based on a detailed engineering analysis.

### 3.1.2. 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 [16,21-22]. 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 [22]. These additional uncertainties addressed in the judgmental process are 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.

### 3.2.1. Statistical Propagation of Branch Probabilities and Parameters

As mentioned previously, the CET branches can be modeled with either a direct assignment of branch probability or the use of phenomenological parameters such as 'pressure' by which branch probabilities of the subsequent top event

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

<table>
<tr><th>Event Type</th><th colspan="5">Branch Model (zero / one frequency format)</th><th colspan="3">Composite Form of Uncertainty Distribution of Branch Frequencies</th></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></td><td>Branch 1</td><td>Branch 2</td><td>Branch 3</td></tr>
<tr><td>Uncertainty</td><td></td><td></td><td></td><td></td><td>$p_1$</td><td>$p_2$</td><td>$p_3$</td></tr>
<tr><td>Frequency</td><td>1</td><td>0</td><td>0</td><td>$p_1$</td><td></td><td></td><td></td></tr>
<tr><td>Frequency</td><td>0</td><td>1</td><td>0</td><td>$p_2$</td><td></td><td></td><td></td></tr>
<tr><td>Frequency</td><td>0</td><td>0</td><td>1</td><td>$p_3$</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="5">$p_1 + p_2 + p_3 = 1.0$<br>All pI' s are subjective probability</td><td colspan="3"></td></tr>
</table>

associated with failure modes of a given structure can be evaluated. A typical example of the latter case is a determination of probabilities for each containment failure mode. In the latter case, uncertainty propagation is a greater or less different with the former case.

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. 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. 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 [7,16,21].

Statistical Propagation of Phenomenological Parameters

In most cases, the impact of phenomenological parameters expected during the accident progression is implicitly reflected in the corresponding CET branch probabilities. When all CET branch inputs are treated with the subjective probabilities, the uncertainty analysis can be made through the aforementioned uncertainty propagation of branch probabilities. However, when a pressure load itself imposed to the containment is explicitly used for some intended purposes of the CET evaluation, an additional step is required to determine statistically the subsequent containment failure modes. In that case, the currently available approach for the uncertainty analysis is to utilize "containment failure probability" curves and conditional probability curves for the underlying containment failure modes. These probability curves are can be obtained from the expert elicitation process as implemented in the NUREG-1150 Surry APET analysis [7] or the use of individual probability distributions for each failure mode that can be obtained from the structural analysis [23]. Once the probability distributions for the containment failure and conditional probability distributions for each failure mode were obtained, whether the containment fails or not at a given pressure could be determined in the following distinct ways:

- The question of the failure mode is dealt with entirely on the basis of a conditional probability. The conditional probabilities for each failure mode are a breakdown of the probability between containment failure modes (such as leak, rupture, and catastrophic rupture), given that a failure occurs. The containment failure mode is subjected. Depending on accident progressions, the containment failure may be subjected to leak mode only or both leak and rupture modes.
- The load and failure pressures are statistically sampled from their own probability distributions through a sampling procedure. If the load pressure is less than the containment failure pressure, the containment does not fail for a given pair of pressure samples, the definition is binary (i.e., deterministic) as given in the case 1 of Table 1.
- If the load pressure is greater than or equal to the containment failure pressure, the containment fails. If the containment fails, then containment failure for a given pressure is treated as if the load is applied statistically. For this, the random number between zero and one is used to determine the resultant failure mode. If the random number is less than the leak conditional probability, the failure mode is leak. If the random number is greater than the leak conditional probability but less than the sum of the leak and rupture conditional probabilities, the failure mode is rupture. If the random number is greater than the sum of the leak and rupture conditional probabilities, the failure mode is catastrophic rupture.

The foregoing approach in the uncertainty analysis makes it possible to consider accident sequence-to-sequence dependency of phenomeno logical inputs employed in the CET. For instance, an accident sequence of the CET may be subjected to some degrees of dependency with another sequences, resulting in a similar trend of pressure loads. In that case, the dependency among those sequences can be quantitatively treated by the use of correlation coefficients in the stage of statistical sampling for uncertainty analysis [7,24].

### 3.2.2. Statistical 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 [16,19]. 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.

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 [16], 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

**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 |

by the relative magnitude of importance measures mentioned in the previous section.

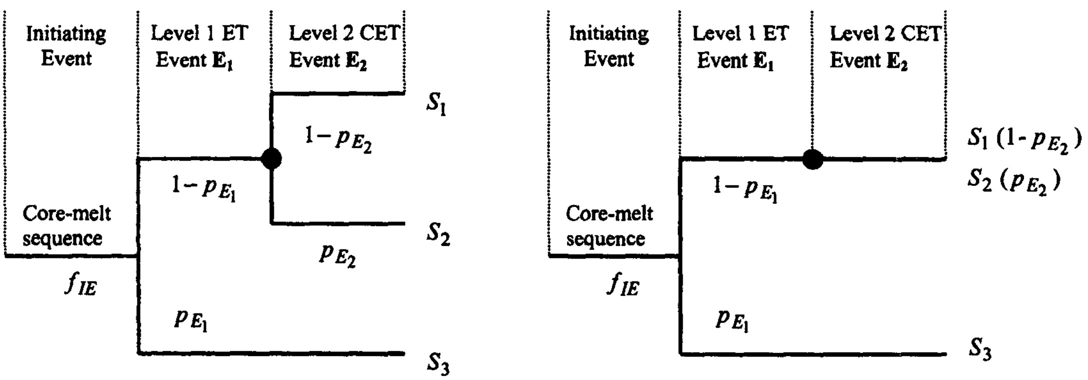
## 4. Formal Link of Level 1 and 2 Uncertainties to Level 2 Risk

When a point estimation for the Level 1 accident sequences and the Level 2 accident progressions is made, the distinction between the random/stochastic events and the deterministic events is only conceptual and makes does not results in any difference for the frequencies of CET end points. However, 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. The former part of this section describes an important implication when the Level 1 random and Level 2 subjective probabilities are combined to obtain the Level 2 risk results. The latter part focuses on how to propagate the Level 1 and Level 2 uncertainties into an uncertainty distribution for the Level 2 risk results.

### 4.1. Link between Level 1 and Level 2 Point Probability Estimates

For the purpose of point estimation for the Level 2 risk results, let' s consider two types of the CET structure as shown in Fig.2, whose branch probabilities have two different interpretations of the probability (one for the relative frequency and the other for the subjective probability). In the CET Type 1, the frequency $f_{IE}$ of the core-melt sequence (i.e., initiating event) and relative probability $p_{E_1}$ on the success or failure branch $E_1$ of the Level 1 system event tree are stochastic in nature. Also, the end point of the CET Type 2, $S_1$, is given with a probability of $1-p_{E_2}$, whereas $S_2$ has a probability $p_{E_2}$, corresponding as they do to the CET end points based on the assumption of the nonoccurrence and occurrence of a particular phenomenon leading to a containment failure (CET top event $E_2$), respectively. As given in the subsequent formulation 1, the two different results are then expected for the frequency of the CET end points $S_i$.

<u>Formulation 1</u> : Frequencies for the CET End Points (or STCs) $S_i$




**(a) CET Type 1: All branch probabilities are characterized as relative branch probability**

**(2) CET Type 2: Mixture of relative branch probability and subjective**

**Fig.2 Impacts of Different Branch Types on the CET End Points**

$$\text{Type 1: } f_{S_1}^{(1)} = f_{IE}(1-p_{E_1})(1-p_{E_2}),\quad f_{S_2}^{(1)} = f_{IE}(1-p_{E_1})p_{E_2},\quad f_{S_3}^{(1)} = f_{IE}p_{E_1} \tag{2.1}$$

$$\text{Type 2: } f_{S_1}^{(2)} = f_{IE}(1-p_{E_1}),\quad f_{S_2}^{(2)} = f_{IE}(1-p_{E_1}),\quad f_{S_3}^{(2)} = f_{IE}p_{E_1} \tag{2.2}$$

In the above formulation 1, $f_{S_i}^{(1)}$ and $f_{S_i}^{(2)}$ represent the frequencies of the CET end points $S_i$ for each of the CET Types 1 and 2, respectively. As given in CET Type 2 of formulation 1 above, when $p_{E_2}$ is interpreted as a subjective probability, the frequencies of the CET end points $S_1$ and $S_2$ are equal and we have a frequency distribution with two distinct parts of the CET, one with a probability $p_{E_2}$ and the other with a probability $1-p_{E_2}$. In this case, the role of $p_{E_2}$ is not to alter the frequency of the STCs but to parameterize the level of confidence in the two conflicting hypothesis (i.e., nonoccurrence and occurrence of the CET top event $E_2$) about the CET end points they represent. However, if a point estimate (e.g., mean value) is all that is required for the CET end point frequency, the foregoing two distinct parts of the CET must be combined into a single representation of the CET. As mentioned in the previous section, the two branch probabilities $p_{E_2}$ and $1-p_{E_2}$ can be then regarded as mean frequencies for the nonoccurrence and occurrence of the CET top event $E_2$, respectively. As a result, formulation 1 above results in the same CET end point frequencies for Type 1 and Type 2. That is,

$$\text{Type 2: } f_{S_1}^{(2)} = f_{IE}(1-p_{E_1})(1-p_{E_2}),\quad f_{S_2}^{(2)} = f_{IE}(1-p_{E_1})p_{E_2},\quad f_{S_3}^{(2)} = f_{IE}p_{E_1} \tag{2.3}$$

On the other hand, a point estimate of the Level 2 source term risk is given in formulation 2 below. As given in Types 1 and 2 of formulation 2, the choice of interpretation need make no difference numerically and the subjective probability does not alter the risk of the specified source term $S(x)$.

Formulation 2: Risk for a specified source term $S(x)$ (defined as the sum of the source term consequences for all possible accidents with the contribution of each accident weighted by the probability of the occurrence of that accident)

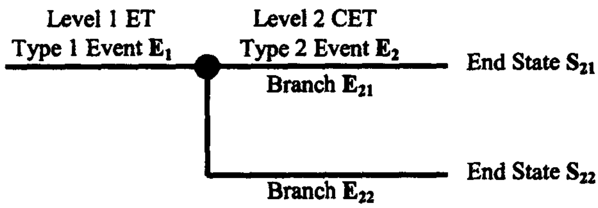
$$\text{Type 1: } R_{S(x)}^{(1)} = f_{IE}(1-p_{E_1})(1-p_{E_2})S_1(x) + f_{IE}(1-p_{E_1})p_{E_2}S_2(x) + f_{IE}p_{E_1}S_3(x) \tag{3.1}$$

$$\text{Type 2: } R_{S(x)}^{(2)} = (1-p_{E_2})\left[f_{IE}(1-p_{E_1})S_1(x)+f_{IE}p_{E_1}S_3(x)\right] + p_{E_2}\left[f_{IE}(1-p_{E_1})S_2(x)+f_{IE}p_{E_1}S_3(x)\right] \tag{3.2}$$

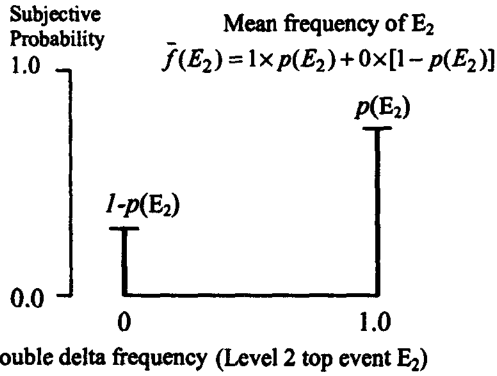
In the above formulation 2, $R_{S_{(x)}}^{(1)}$ and $R_{S_{(x)}}^{(2)}$ represent the risks of the source term $S(x)$ for each of the CET Types 1 and 2, respectively.

### 4.2. Link Between Level 1 and Level 2 Uncertainties

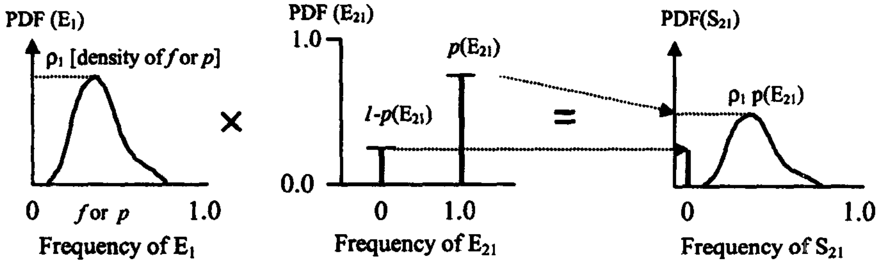
When the Level 1 and Level 2 uncertainties are propagated into an uncertainty distribution for the Level 2 risk results, there is a significant difference with the point estimation explained in the above section. In the CET Type 1, it is logical to estimate the uncertainties for all the parameters ($f_{IE}$, $p_{E_1}$, $p_{E_2}$) and propagate them through the CET model to obtain the (relative) frequencies of the three CET end points. In the CET Type 2, uncertainty distributions for $f_{IE}$ and $p_{E_1}$ may be constructed and propagated to give the probability distributions for the specified source term risk, but $p_{E_2}$ is already an expression of the uncertainty:



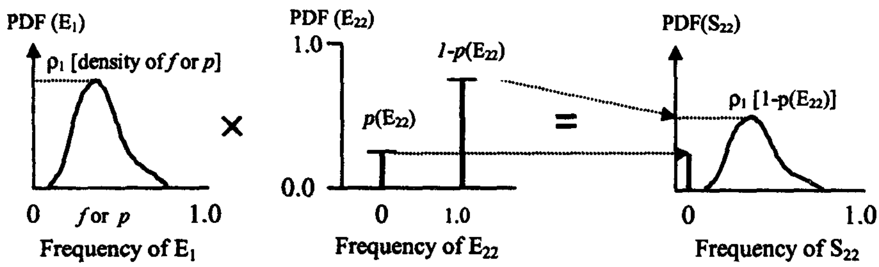

**(a) A Combined Model of Level 1 System ET and Level 2 CET**




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




**(c) Propagation of E1 and E21 Uncertainties into the End State S21**




**(d) Propagation of E1 and E22 Uncertainties into the End State S22**

**Fig.3 Propagation of Type 1 and Type 2 Uncertainties Through the Level 2 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 $0<p_{E_1}<1$ U-distribution (PDF) $f_1= f(p_{E_1})$ | Relative frequency (2-branches) $E_2 = \begin{cases} E_{21} = 1 \\ E_{22} = 0 \end{cases}$ U-distribution (DUD) $f_2 = \begin{cases} p_{E_2}, \text{ if } E_2 = 1 \\ 1 - p_{E_2}, \text{ if } E_2 = 0 \end{cases}$ | |
| Point estimate $p_1 = E[p_{E_1}]$ | Point estimate $p_2 = \begin{cases} 1 \times p_{E_2} + 0 \times (1-p_{E_2}), \text{ if } E_2 = 1 \\ 0 \times p_{E_2} + 1 \times (1-p_{E_2}), \text{ if } E_2 = 0 \end{cases}$ | Point estimate $p_{stc} = p_1 \times p_2$ |
| Point estimate $p_1 = E[p_{E_1}]$ | Uncertainty (-th sample) $p_2^j = \begin{cases} 1, \text{ if } E_2 = 1 \text{ ,weighted by } p_{E_2} \\ 1, \text{ if } E_2 = 0 \text{ ,weighted by } 1- p_{E_2} \end{cases}$ | Level 2 uncertainty only $p_{stc}^j = p_1 \times p_2^j$ |
| Uncertainty (-th sample) $p_1^i = p_{E_1}^i$ | Point estimate $p_2 = \begin{cases} 1 \times p_{E_2} + 0 \times (1-p_{E_2}), \text{ if } E_2 = 1 \\ 0 \times p_{E_2} + 1 \times (1-p_{E_2}), \text{ if } E_2 = 0 \end{cases}$ | Level 1 uncertainty only $p_{stc}^i = p_1^i \times p_2$ |
| Uncertainty (-th sample) $p_{E_1}^i = p_{E_1}^i$ | Uncertainty (-th sample) $p_2^i = \begin{cases} 1, \text{ if } E_2 = 1 \text{ ,weighted by } p_2^E \\ 1, \text{ if } E_2 = 0 \text{ ,weighted by } 1- p_{E_2} \end{cases}$ | Combined uncertainties of Level 1 and 2 Events $p_{stc}^k = p_1^i \times p_2^j$ |

Note:

(1) $E_1$ = 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.

(2) 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

(3) 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.

(4) 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.

thus there is no logical reason for assigning a probability distribution to $p_{E_2}$. That is to say, the Level 2 source term risk given in the CET Type 2 is not reduced as in the CET Type 1 results, but instead the uncertainties of the risk increase.

In order to explain explicitly the aforementioned situation of the Level 2 uncertainty analysis, let' s take a typical example that propagates the Level 1 and 2 uncertainties through a Level 2 CET model (i.e., CET Type 2). Fig. 3(a) as a portion of Fig. 2(b) shows an example event tree linking a Level 1 end sequence and a Level 2 CET top event. Fig. 3(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. 3(c) and Fig. 3(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. In Fig. 3(c) and Fig. 3(d), the uncertainty distribution for Type 1 event $E_1$ is defined as a probability density function (PDF) of the frequency $f_{E_1}$ (or relative probability $p_{E_1}$), which is random/stochastic in nature. Also, the uncertainty distribution for Type 2 event $E_2$ is defined as a double-delta form of PDF in the frequency level of the subjective probabilities for the deterministic branch event $E_{21}$ or $E_{22}$. Based on the frequency format of subjective probability, the frequency of Type 2 event $E_2$ is characterized as either zero or one. Then, the formal integration of uncertainties addressed in both Type 1 and Type 2 events is made in the frequency (or relative probability) levels, with probability densities $\rho_1$ for Type 1 event $E_1$ and $p(E_2)$ for Type 2 event $E_2$. Fig. 3(c) and Fig. 3(d) give a conceptual framework for a formal integration of both types of uncertainty distributions. In real applications, the impact of the probability densities is reflected in the stage of statistical sampling for uncertainty analysis. For an additional purpose of illustration, four distinctive mathematical formulations for combining statistically the Level 1 and Level 2 uncertainties through the CET model are explicitly given in Table 5.

## 5. Summary and Concluding Remarks

The primary concern of this paper was to give a formal guidance for a consistent treatment of different uncertainty sources addressed in the Level 2 PSA, particularly with respect to their characterization, propagation, interpretation, and impact on the PSA Level 2 decision-making process. In the former part of this paper, we have systematically clarified potential sources of epistemic and random aleatory uncertainty that would often be addressed in the Level 2 PSA and provided some insights on their implications on the Level 2 risk quantification process. As a result of the former part, clearer answers have been given for the question on why uncertainties arise in the Level 2 PSA, which kind of uncertainty sources exists, and which uncertainties are explicitly accounted for in real applications and which ones are not. Concerning the aforementioned questions, major findings drawn from this study can be suumarized as follows,

- 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 although epistemic uncertainty for modeling and phenomenological events tends to become much more important.
- 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 addition, the possibility of the stochastic variability in the Level 2 events is greatly reduced with a systematic description of the Level 2 initial conditions.

The above findings mean that the quality of the Level 2 PSA may be more controlled by epistemic uncertainty rather than by random/stochastic uncertainty. Based on the foregoing clarification of uncertainty sources, we have provided a formal guidance for handling two representative sources of epistemic uncertainty (one is the phenomenological and modeling uncertainty source and another for the judgmental uncertainty source). In the Level 2 PSA, both uncertainty sources arise from (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.

An additional concern of this paper was to give a formal approach on how to combine random uncertainties addressed in the Level 1 PSA with subjective uncertainties addressed in the Level 2 PSA. In the latter part of this paper, a formal approach for integrating consistently the uncertainties of the Level 2 uncertainties with the Level 1 uncertainties has been provided, based on a strict distinction between the two different interpretations of probability (i.e., subjective probability and relative frequency) and a frequency format of subjective probability. 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 forgoing 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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