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Assessment of Model Uncertainties In Regulatory Decisions Involving PRA Results*

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Abstract – *This paper explores the feasibility and options for developing a systematic methodology for assessing the plant specific importance of model uncertainties and its use in regulatory decisions involving PRA results. Risk importance ranking of the various phenomenological issues that are considered in a plant PRA model is also discussed. Such risk importance measures for phenomenological issues can be helpful for developing research priorities to reduce the overall model uncertainty.*

I. INTRODUCTION

Probabilistic Risk Assessment (PRA) is being used increasingly as an important element in regulatory decisionmaking. In the US, for example, the Nuclear Regulatory Commission (NRC) is moving toward an expanded use of PRAs in what is termed risk-informed regulatory approach. In 1995, the NRC adopted a policy [1] that promotes increased use of probabilistic risk analysis in all regulatory matters to the extent supported by the state-of-the-art to complement the deterministic approach.

The safety decisions, whether risk-informed or not, are made in the face of uncertainties and within the boundaries of the state of knowledge of nuclear power plants and how they behave under both normal and accident conditions [2]. Both deterministic and probabilistic safety evaluations must deal with uncertainties. However, the uncertainty should be examined in the context of a decision, focusing on the uncertainties that have impact on the outcome of the decisionmaking process.

Various classifications of uncertainty have been reported in the literature [3-6]. Two major groups of uncertainty that have been recognized are aleatory (or stochastic) and epistemic (or state-of-knowledge) uncertainty. The aleatory uncertainty arises from many stochastic events or phenomena that probabilistic models are adopted to describe their occurrences. This aspect of uncertainty is built into the structure of the PRA model itself. The epistemic uncertainty is attributed to uncertainty arising from how well the PRA model represents the actual system being modeled. The key distinction between these two types of uncertainty is that the aleatory uncertainty is by definition irreducible. The epistemic uncertainty, on the other hand, can be reduced by further study.

There are two classes of epistemic uncertainty that impact the results of PRAs: parameter uncertainty and model uncertainty. Parameter uncertainties are those associated with the values of the fundamental parameters of the PRA model, such as equipment failure rates that are used in quantifying the accident sequence frequencies. Most of the PRA codes have the capability to propagate the distribution representing uncertainty on the basic parameter values to generate a probability distribution on the results of PRA. Reference [7] provides guidance on methods for estimating the parameters used in PRA models and for quantifying the uncertainties in the estimates.

Model uncertainty reflects the limited ability to model accurately the specific events and phenomena used in the development of the PRA model. Examples include approaches to

* The views expressed in this paper are solely those of the author and do not necessarily represent those of either the ACRS or NRC.

modeling human performance during accidents and models used for evaluating severe accident phenomena in level 2 PRAs.

Various approaches for treating model uncertainty range from the mathematical to the expert judgment. Mathematical approaches, for example, include introducing a knowledge-based model uncertainty parameter into the model and treating this parameter in the same way as other uncertain parameters in PRA. The use of expert judgment may become necessary when there is a lack of complete understanding of the underlying fundamental mechanisms. This may include the structure of the model as well as uncertainty concerning the quantification of the variables involved. For a discussion on the approaches for treating model uncertainties and their merits, see for example References [8, 9].

Completeness can also be considered as one aspect of model uncertainty. Completeness uncertainty arises from the fact that not all contributors to risk are addressed in PRA models. Some contributors are not addressed because methodology for their analyses has not yet been developed. For example, the influences of organizational performance cannot now be explicitly modeled in PRAs.

Model uncertainty is the major source of uncertainty in the results of PRAs. However, much less attention is generally directed toward this kind of uncertainty, compared for instance, with parameter uncertainty. This issue was addressed in a 2003 Advisory Committee on Reactor Safeguards (ACRS) report on improvement of the quality of risk information for regulatory decision-making [10]. The ACRS stated, "The assessment of uncertainties should address model uncertainties" and "guidance for the quantitative evaluation of model uncertainties should be developed." The ACRS further noted, "More guidance regarding sensitivity and uncertainty analyses would contribute greatly to confidence in risk-informed regulatory decisionmaking." Such guidance "should address not only how uncertainties should be treated in the PRA, but also, how they impact decisionmaking with examples to show the pitfalls if uncertainties are inadequately addressed."

While a formal propagation of the uncertainty is the best way to account for model uncertainties, under certain circumstances, it can be demonstrated that the model uncertainties associated with many phenomenological issues do not affect the outcome of the decisionmaking process. Insights on severe accident phenomenological issues and their associated state-of-knowledge uncertainties may be used to develop a systematic methodology for assessing the plant specific importance of individual phenomenological issues and their model uncertainties to the overall uncertainty. This paper explores the feasibility and options for developing such assessment methodology and its use in regulatory decisions involving PRA results. Development of such assessment methodology can greatly reduce the effort necessary for formal propagation of the uncertainty to account for model uncertainty.

This paper also discusses assigning some ranking of "risk importance" among the various phenomenological issues that are considered in a plant PRA model. Such risk importance measures for phenomenological issues can be helpful for directing any needed sensitivity analysis (in the absence of any formal propagation of model uncertainty), as well as for developing research priorities to reduce the overall model uncertainty.

II. SYSTEMATIC ASSESSMENT METHODOLOGY

The proposed assessment methodology provides a systematic framework for examining the uncertainty in the context of a decision, focusing on model uncertainties that affect the outcome of decisionmaking process. Figure 1 displays schematically the major elements of the assessment methodology.

The first step of the assessment process is to specify the nature of decision to be made for which risk information is required. The details of subsequent assessment may vary depending on the specific decision and the measure of risk (risk metrics) which is required for evaluating the decision. Examples of risk metrics are core damage frequency (CDF) and large early release frequency (LERF), used as bases for acceptance guidelines in Regulatory Guide 1.174, "An Approach for Using Probabilistic Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis" [11].

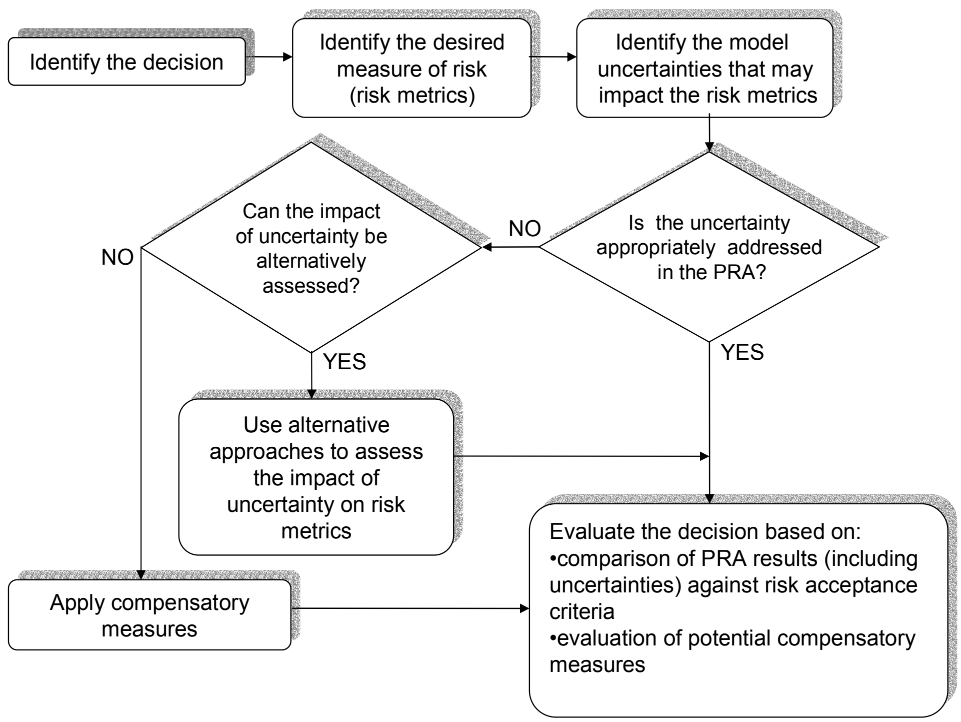

Fig. 1. Assessment of model uncertainties in the context of a decision

II.A. Identifying Model Uncertainties

Identifying the model uncertainties that may affect the results of the PRA (i.e., risk metrics) is an essential step en route to an useful assessment. All relevant model uncertainties, whether they are quantified or excluded from PRA, including completeness uncertainties should be considered.

The NUREG-1150 study [12] provides valuable insights on severe accident phenomenological issues and associated state-of-knowledge uncertainties, which are very useful to the study of plants with similar nuclear steam supply system (NSSS) and containment design. This study was a major effort to put into a risk perspective the insights into system behavior and phenomenological aspects of severe accidents. An important characteristic of this study was the inclusion of the uncertainties in the calculations of core damage frequency and risk that exist because of incomplete understanding of reactor systems and severe accident phenomena. For a discussion on sources of model uncertainty in PRAs, see also References [2, 13-14].

The effect of the model uncertainties that are appropriately addressed in the PRA are reflected in the PRA results (i.e. risk metrics). As indicated in Fig 1, those model uncertainties that are not adequately addressed may fall into two categories, depending whether their impact on the risk metrics can be alternatively assessed, or not. Use of alternative approaches, such as bounding and sensitivity analyses, for assessing the impact of uncertainties on risk metrics is discussed in Section II.B.

For those model uncertainties (including completeness uncertainties) that are not addressed in the PRA and their impact on risk metrics cannot be assessed by alternative approaches, then compensatory measures may be proposed to counter their impact.

II.B. Alternative Approaches for Assessing the Impact of Model Uncertainties on Risk Metrics

For some model uncertainties that are not adequately accounted in the PRA, alternative approaches may be used to assess their impact on the risk metrics. The primary objective of this assessment is to determine whether such uncertainties have any impact on the outcome of decision-making process.

There is not a single approach suitable for every situation and assessment. Sometimes a simple scoping analysis may suffice, while other situations may call for a more sophisticated approach. A multi-level approaches somewhat similar to the levels of uncertainty treatment proposed by Patė-Cornell [15] may be used for such assessments within the PRA framework. These approaches include:

- worst-case (very conservative) approach,
- plausible bounding estimate, and
- probabilistic approach and mean value

The worst-case approach is based on the worst-case assumptions in treating a model uncertainty. This approach is reasonable if the worst-case assumptions do not affect the outcome of decisionmaking process. For example in AP1000 PRA [16], the uncertainty about the adequacy of long – term containment cooling by airflow for some accidents was addressed by such worst-case approach. Late containment failure, and subsequent loss of core cooling, cannot be ruled out for sequences involving the release of steam inside the containment and the unavailability of water cooling mode of passive containment system (PCS). To assess the impact of such model uncertainty on the results of PRA, it was assumed that all sequences requiring containment cooling would lead to core damage, if the water-cooling mode of PCS is unavailable. This resulted in a rather small increase (about 30 percent) in the plant CDF [17]. This finding indicates that the model uncertainties associated with the long - term containment cooling by airflow does not have any significant impact on the result (i.e. CDF) of AP1000 baseline PRA.

The plausible bounding estimate involves an attempt to evaluate the bounding conditions that can be reasonably expected. For example the contribution of out-of-scope portions of the PRA model (completeness uncertainty) to the changes in risk metrics may be addressed by such bounding analyses [11]. A similar approach was also used in AP600 PRA [18] to address the issue of model uncertainty associated with the success criteria that define the event tree paths that do not result in core damage. Success criteria specify the minimum sets of equipment needed to prevent core damage under various conditions. The issue of model uncertainty is based on a concern that uncertainties in thermal hydraulic analyses, performed in order to determine system success criteria, may affect the PRA results. A process to evaluate the impact of thermal-hydraulic uncertainty on the PRA results was developed as a part of AP600 PRA [19]. This process included the analysis of low thermal-hydraulic margin risk-important accident scenarios with the design basis accident analysis computer codes to bound the thermal-hydraulic uncertainty.

Assessment of some model uncertainties by worst-case approach or plausible bounding estimates may not be conclusive (i.e., they result in exceeding the risk acceptance criteria). Therefore, a more detailed probabilistic assessment of these uncertainties is needed. An example of a probabilistic approach to address the model uncertainty is the methodology used for the resolution of the direct containment heating (DCH) in pressurized water reactors (PWRs) [21-22].

Since the mean values of risk metrics has been adopted in many risk acceptance guidelines (see Section II.C), a probabilistic framework and use of the mean value of the outcome distribution (without propagating the uncertainty) may provide another alternative approach to assess the impact of uncertainties if it can be demonstrated that the state-of-knowledge correlation is unimportant [11]. Reference [2] provides examples of situations where the bulk of contributing scenarios (cutsets or accident sequences) involve multiple events that rely on the same parameter for their quantification and thus the state-of-knowledge independence assumption cannot be supported.

It should be noted that assessing the impact of uncertainties one at a time by using any of the alternative approaches discussed above cannot account for synergistic effects where the impact of an individual uncertainty depend on the values assumed by the remaining uncertain parameters. Therefore the model uncertainties associated with such phenomena and events should be assessed together. For example, if the reactor coolant system (RCS) remains at high pressure (i.e., transients and small break LOCAs) during a core meltdown accident in PWRs, then the uncertainty associated with the thermally induced steam generator tube rupture (SGTR) should be evaluated. However, various accident management strategies have been proposed to depressurize the RCS for those accidents that would otherwise be characterized as high RCS pressure sequences. Depressurization can potentially be achieved by heat removal through the steam generators or by direct pressure relief of the RCS. Uncertainty associated with the ability of these systems to adequately depressurize the RCS (including modeling human performance) during severe accidents needs to be evaluated as a part of evaluating the impact of uncertainties associated with the modeling of the temperature-induced creep rupture of the steam generator tubes.

II.C. Using Risk Information in the Decision Process

Regulatory acceptance guidelines are generally based on a discrete summary measure (e.g., the mean, the median or various percentile values) of the risk distribution. The NRC has adopted the use of mean estimates for the purpose of implementing the quantitative objectives of its safety goal policy [20]. Regulatory Guide 1.174 [11] refers to the mean values as the appropriate numerical measure for comparing the PRA results to the acceptance guidelines in risk-informed decisions.

The effect of the model uncertainties that are appropriately addressed in the PRA are reflected in the PRA results including the mean values of the probability distribution for the risk metrics. For some model uncertainties that are not adequately accounted in the PRA, alternative approaches (discussed in Section II.B) can be used to assess their impact on the mean values of risk metrics. The results of such assessments provide useful inputs to the decision process. For example, if these assessments result in exceeding the risk acceptance guidelines and criteria, then compensatory measures may be proposed to counter the impact of uncertainties. Even if the results of such assessments do not change the final decision, presenting such information would enhance the credibility of the decision process [3]. As the philosopher Arthur Schopenhauer stated "the value of what one knows is doubled if one confesses to not knowing what one does not know."

III. RISK IMPORTANCE MEASURES FOR PHENOMENOLOGICAL ISSUES

It may also be desirable to assign some ranking of "risk importance" among the various phenomenological issues that are considered in a plant PRA model For example, a risk importance measure of "Risk Significance Worth", somewhat similar to Risk Achievement Worth (RAW) used for risk importance ranking of various plant components, can be defined as:

$$\text{Risk Significance Worth} = R\ (\text{issue } 1)^{+}/R_0$$

Where R (issue $1)^{+}$ is the calculated risk, using the bounding (conservative) assumptions in quantifying the phenomenological issue -1, and R_0 is the base-case risk. Other risk importance measures somewhat similar to Fussel-Vessly (F-V) or Risk Reduction Worth (RRW) can also be defined. It should be noted that various risk metrics could be used for defining these risk importance measures. For example, Figure 2 shows the large release frequency (LRF) importance measures for occurrence of severe accident phenomena that has been addressed in the containment event tree (CET) used in AP1000 PRA [16].

Risk importance measures for phenomenological issues can be useful for directing any needed sensitivity analysis (in the absence of any formal model uncertainty analysis), as well as for developing research priorities to reduce the overall model uncertainty.

IV. SUMMARY AND CONCLUSIONS

In this paper, a systematic framework for examining the uncertainty in the context of a decision was proposed. For those model uncertainties that are not adequately accounted in the PRA, the feasibility and options for using alternative approaches to assess their impact on the risk metrics were discussed. Although the assessment methodology has been presented with an emphasis on model uncertainties, it is sufficiently general for addressing also parameter uncertainties.

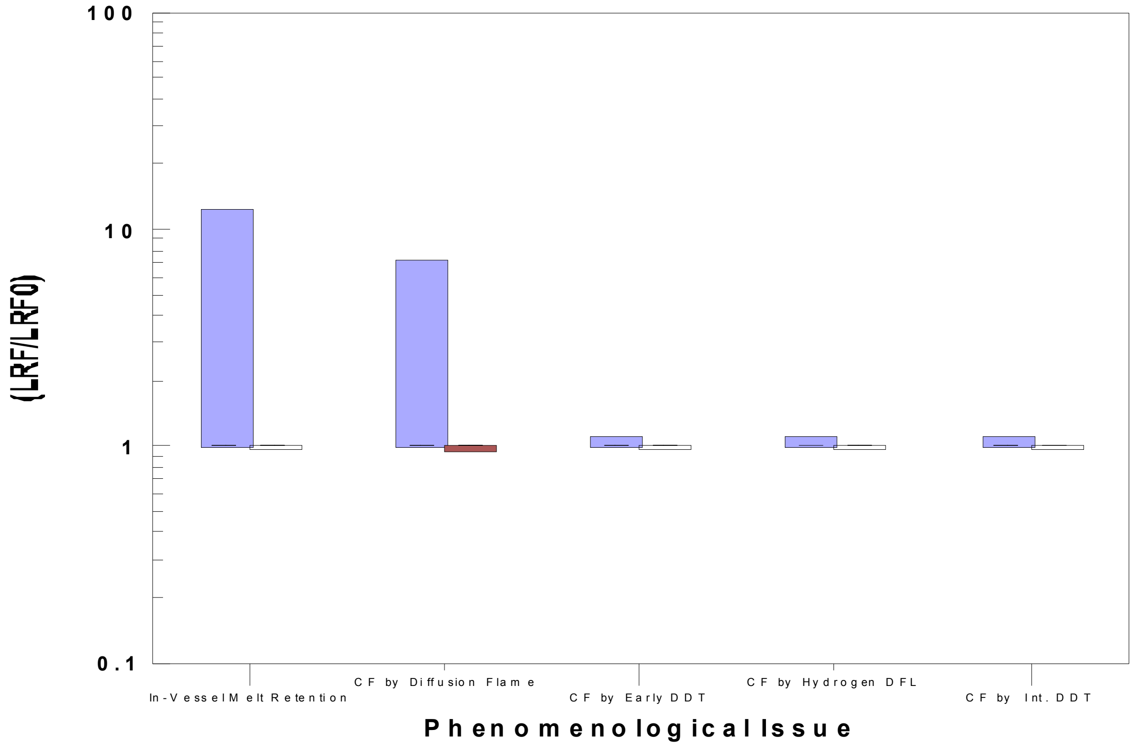

Fig. 2. Risk (LRF) importance measures for occurrence of severe accident phenomena in AP1000 design

Ranking of "risk importance" among the various phenomenological issues that are considered in a plant PRA model were also discussed. Such risk importance measures for phenomenological issues can be very helpful for directing any sensitivity analysis as well as for developing research priorities to reduce the overall model uncertainty.

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Background

- PRA is being used increasingly as an important element in regulatory decision-making
  - NRC is moving toward an expanded use of PRAs in what is termed risk-informed regulatory approach.
  - In 1995, the NRC adopted a policy that promotes increased use of PRA in all regulatory matters to the extent supported by the state-of-the-art to complement the deterministic approach.

Dealing with Uncertainties

- The safety decisions, whether risk-informed or not, are made in the face of uncertainties and within the boundaries of the state of knowledge of nuclear power plants and how they behave under both normal and accident conditions.
  - Both deterministic and probabilistic safety evaluations must deal with uncertainties.
- The uncertainty should be examined in the context of a decision, focusing on the uncertainties that have impact on the outcome of the decision-making process.

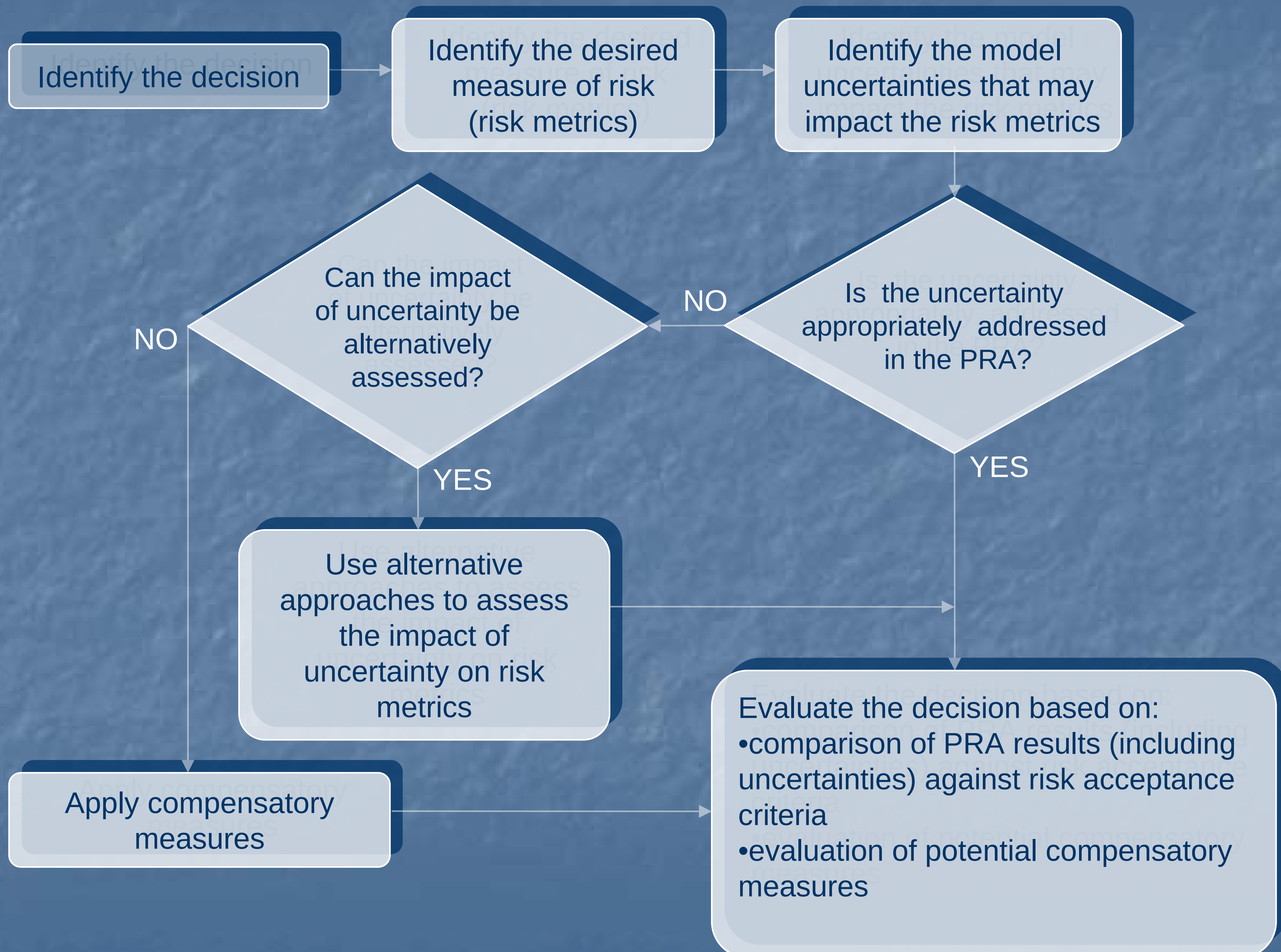
Objective

- To explore the feasibility and options for developing a systematic methodology for assessing the plant specific importance of model uncertainties and its use in regulatory decisions involving PRA results.

Sources of Uncertainty

- Aleatory (or stochastic) uncertainty
- Epistemic (or state-of-knowledge) uncertainty
  - Parameter uncertainty
  - Model Uncertainty
- Completeness can also be considered as one aspect of model uncertainty

Assessment of Model Uncertainties in the Context of a Decision



Alternative Approaches for Assessing the Impact of Model Uncertainties

- There is not a single approach suitable for every situation and assessment.
- A multi-level approaches may be used for such assessments.
  - Worst-case (very conservative) approach
  - Plausible bounding estimate, and
  - Probabilistic approach and mean value

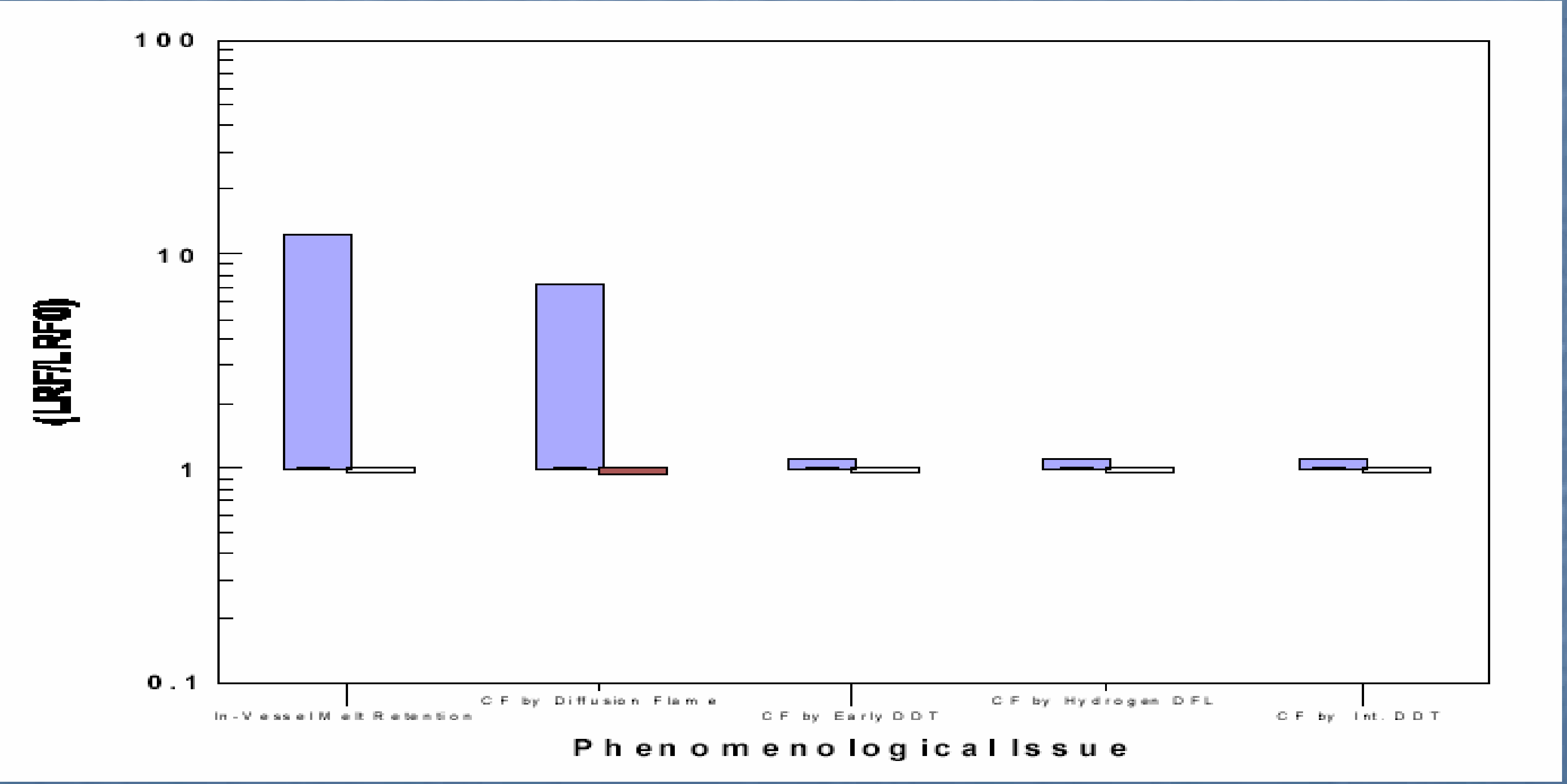
Using Risk Information in the Decision Process

- Regulatory acceptance guidelines are generally based on a discrete summary measure (e.g., the mean, the median or various percentile values) of the risk distribution.
  - Regulatory Guide 1.174 refers to the mean values as the appropriate numerical measure for comparing the PRA results to the acceptance guidelines in risk-informed decisions.
- Alternative approaches can be used to assess the impact of uncertainties on the mean values of risk metrics.

Risk Importance measures for Phenomenological Issues

- It may also be desirable to assign some ranking of "risk importance" among various phenomenological issues that are considered in a plant PRA model
  - For example , a risk importance measure of "risk significance worth", somewhat similar to RAW used for risk importance ranking of various plant components , can be defined.
- Risk importance measures for phenomenological issues can be useful for developing research priorities to reduce the overall uncertainty

Risk (LRF) Importance Measures of Severe Accident Phenomena in AP 1000 Design



Summary

- A systematic framework for assessing the uncertainty in the context of a decision was proposed
- Even if the results of such assessment do not change the final decision, presenting such information would enhance the credibility of the decision process.

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