Risk Analysis Framework for Decision Support for Severe Accident Mitigation Strategy in Nordic BWR

Sergey Galushin, Dmitry Grishchenko, Pavel Kudinov
Royal Institute of Technology
Roslagstullsbacken 21, SE-106 91, Stockholm, Sweden
galushin@kth.se, dmitrygr@kth.se, pkudinov@kth.se

Abstract: Severe accident management (SAM) in Nordic boiling water reactors (BWRs) employ ex-vessel debris cooling in a deep water pool. The success of the strategy requires formation of a coolable porous debris bed; no energetic steam explosion that can threaten containment integrity. Both scenario (aleatory) and modeling (epistemic) uncertainties are important in the assessment of the failure risks. A consistent approach is necessary for the decision making on whether the strategy is sufficiently effective, or modification of the SAM is necessary.

Risk Oriented Accident Analysis Methodology (ROAAM+) is a tool for assessment of failure probability to enable robust decision making, insensitive to remaining uncertainty. The challenge for a decision maker is to distinguish the cases when collecting more knowledge and reduction of uncertainty in risk assessment, or modification of risk management strategy would be the most adequate approach given the safety goals and criteria. When either decision is made, ROAAM+ can provide data for selection of the most efficient implementation of the decision by selecting research priorities or modifying design elements that contribute most to the risk.

In this work we discuss different approaches for communication of ROAAM+ framework analysis results and decision support. We focus on connection and integration of ROAAM+ results into risk-informed decision making models used in nuclear industry. The results of risk analysis are used in order to provide necessary insights on conditions when suggested changes in the safety design can be justified, taking into account different aspects of risk.

Keywords: ROAAM, Decision Support, Uncertainty Quantification

1. INTRODUCTION

Severe accident management (SAM) in Nordic boiling water reactors (BWRs) relies on ex-vessel core debris coolability. In the case of core meltdown and vessel failure, melt is poured into a deep pool of water located under the reactor. The melt is expected to fragment, quench, and form a debris bed that is coolable by natural circulation of water. Success of the strategy is contingent upon melt release conditions from the vessel which determine (i) properties of the debris bed and thus debris bed coolability, and (ii) potential for energetic interactions between superheated melt and volatile coolant (steam explosion). Both non-coolable debris bed and steam explosion pose credible threats to containment integrity (see Figure 1).

Both scenario (aleatory) and modeling (epistemic) uncertainties are important in the assessment of the failure risks. A consistent approach is necessary for the decision support on whether the strategy is sufficiently effective, or a modification of the SAM is necessary.

The Risk Oriented Accident Analysis Methodology (ROAAM) [1,5] can be considered as a tool for robust decision making, i.e. a decision insensitive to remaining uncertainty. Conditional containment failure probability is considered in this work as an indicator of severe accident management effectiveness for Nordic BWR. The ultimate goal of ROAAM+ application for Nordic BWR is to provide a scrutable background in order to achieve convergence of experts' opinions in decision making [1,3,4].

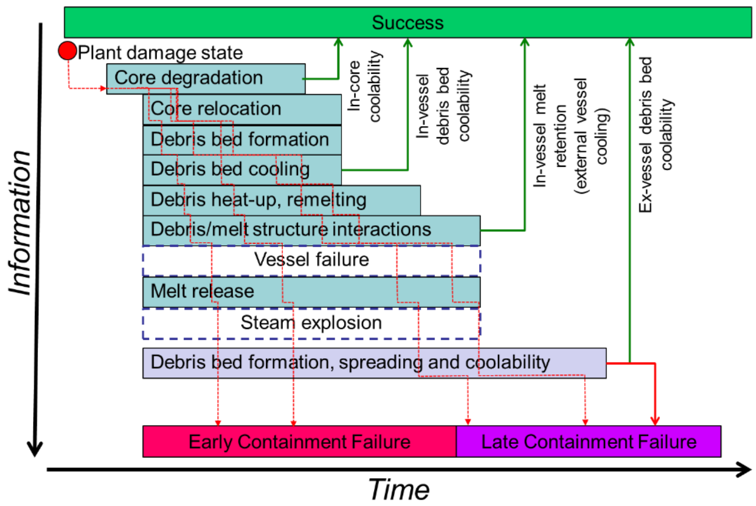

Figure 1. Severe accident progression in Nordic BWR [1].

2. APPROACH

2.1. Risk Analysis and Decision Making

According to Kaplan and Garrik's definition of risk ("risk triplet idea" see [2]), which has become a cornerstone of modern risk analysis, the risk R_i associated with specific scenario s_i (what can happen) can be characterized by its frequency f_i (how likely) and consequences c_i (if it happen, what are the consequences). Consequences are obtained from assessments which are subject to uncertainty due to incomplete knowledge (epistemic uncertainty, degree of confidence), which can be quantified as probability P_i (likelihood) of c_i [1].

$$R_i = \{s_i, f_i, P_i(c_i)\} \tag{1}$$

It was emphasized by Kaplan and Garrik that "the purpose of risk analysis and risk quantification is always to provide input to an underlying decision problem, which involves not just risks but also other forms of costs and benefits. Risk must thus be considered always within a decision theory context." (see [2]).

Decision making is an important part of nuclear power plant operation, it involves decisions that may have significant safety and economic consequences. Nuclear power plants have large capital costs and significant operational costs, thus making the decision making process more efficient can result in potentially large economical benefits [21].

In formal decision making theory, utility theory is used to evaluate decision alternatives with numeric scores, taking into account different attributes (e.g. economics, stakeholders, safety, etc.). Utility theory and associated decision making can be subdivided into the following scale of knowledge situations:

- Decision making under risk – complete probabilistic knowledge.
    - The dominating approach to decision making under risk is expected utility (EU). Expected Utility Theory states that the decision maker chooses between different decision alternatives by comparing their expected utility values, i.e., the weighted sums obtained by adding the utility values of outcomes multiplied by their respective probabilities [22].
- Decision making under uncertainty – partial probabilistic knowledge.
    - Decision making under uncertainty usually make use of some quantitative expression of partial probability information "measures of uncertainty". It can be binary measures – dividing the set of possible probability values into subsets of possible and impossible values; multivalued measures – that generally take form of a function to each probability values between 0 and 1. This value presents the degree of plausibility of each particular probability value (e.g. second order probabilities, fuzzy set membership, etc.). There are several decision criteria for decision making under uncertainty, which, in general make use of expected utility theory (e.g. maximin EU – maximize the minimal expected utility, reliability-weighted expected utility, etc.) [22].

There are several decision making approaches and methods that are capable of taking into account risk-related aspects and, at the same time, some other important factors like economics and regulatory requirements [6,7,21,23,24].

2.2. Risk-Informed Decision Making

The integrated decision making process (sometimes referred to as a risk informed decision making process, see Figure 2) is a structured process in which all the insights and requirements which relating to a safety or regulatory issue that needs to be dealt with by a regulatory body are considered in reaching a decision. It includes the recognition of any mandatory requirements, the insights from the deterministic analysis, the insights from the probabilistic analysis and any other applicable insights (see [6,7]). The aim of a structured decision making process is to ensure that a balanced decision is made that has identified and taken into account all the factors that are relevant to the decision [6].

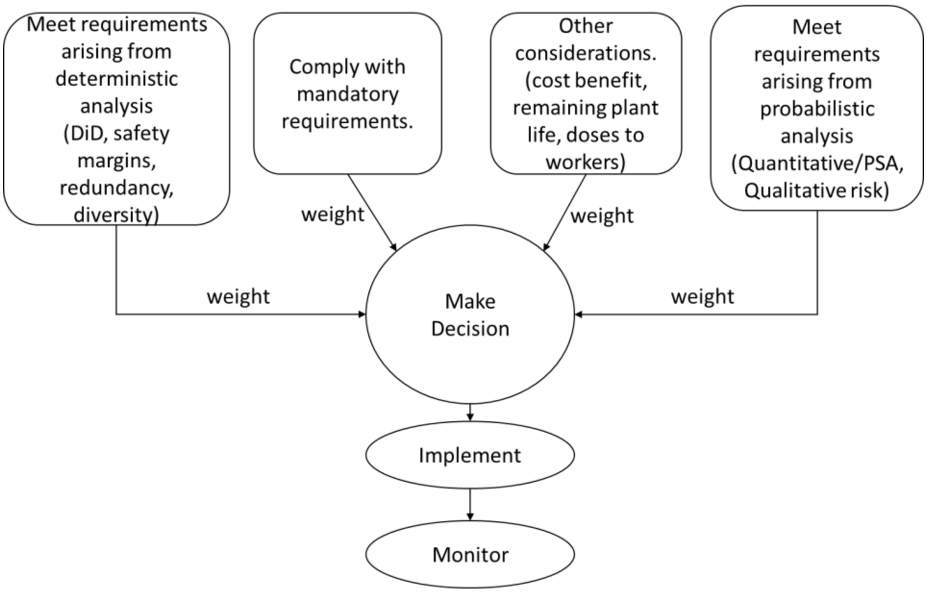

Figure 2. Risk-Informed Decision Making Process [6].

2.3. Risk Oriented Accident Analysis Methodology (ROAAM+) for Nordic BWR

ROAAM+ framework for Nordic BWR [1] represent a set of coupled modular frameworks (see Figure 3), it is designed to connect initial plant damage states with respective containment failure modes. Deterministic processes are treated using surrogate models based on the data obtained from the fine-resolution (full) models.

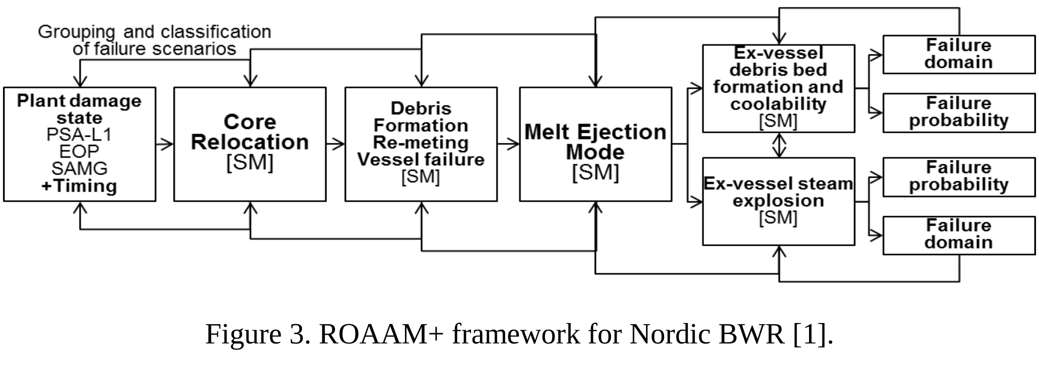

Figure 3. ROAAM+ framework for Nordic BWR [1].

The surrogate models are computationally efficient and preserve the importance of scenario and timing. Systematic statistical analysis carried out with the complete frameworks helps to identify risk significant and unimportant regimes and scenarios, as well as ranges of the uncertain parameters where fine-resolution data is missing. This information is used in the next iteration of the analysis with fine-resolution models, and then refinement of (i) overall structure of the frameworks, (ii) surrogate models, and (iii) their interconnections. Such iterative approach helps identify areas where additional data may significantly reduce uncertainty in the fine- and coarse-resolution methods, and increase confidence and transparency in the risk assessment results. The overall modular structure of the frameworks and the refinement process are discussed in the paper [1] in detail.

The ultimate goal of ROAAM process is to provide a scrutable background in order to achieve convergence of experts' opinions in decision making on the question: is containment failure physically unreasonable, given existing SAM and current state-of-the-art knowledge? This question is driven by "concerns". If inherent safety margins are large, then the answer to the question is positive and can be demonstrated through consistent conservative treatment of uncertainties in risk assessment by improving necessary knowledge and data. Otherwise, improvement of the state-of-the-art knowledge is ineffective. Appropriate modifications of the system (e.g. safety design, SAMGs, etc.) should be undertaken in order to achieve the safety goal.

The challenge for a decision maker is to distinguish when collecting more knowledge and reduction of uncertainty in risk assessment or application of risk management with SAM modifications would be the most effective and efficient approach.

The central theme of this paper is to demonstrate a conceptual approach for communication of ROAAM+ framework analysis results and provide an example of a decision support model. The results of the risk analysis are used in order to provide necessary insights on the conditions when suggested changes in the safety design are justified. In decision support model we aim to include cost benefit analysis, if, for example, a potential cost of improving the current state of knowledge are higher than the decision to change the system in order to reduce its complexity would be the most reasonable.

2.4. Second Order Probabilities in ROAAM+ Framework for Nordic BWR

In ROAAM+ framework for Nordic BWR we use the concept of second-order probability in quantification of conditional containment failure probability. The need for the second-order probabilities comes from the realization of the nature of epistemic uncertainties in prediction of failure probability (i.e. partial probabilistic knowledge). Epistemic uncertain parameters in ROAAM+ framework are separated into two groups:

- Model deterministic parameters – complete probabilistic information (i.e. range and probability distribution).
- Model intangible parameters – incomplete or no probabilistic knowledge, one can only speculate regarding possible ranges.

Since probabilities are designed to handle uncertainty, it would be logical to consider representing uncertain probabilities with probabilities. Thus, in order to assess the importance of the missing information about the distributions of intangible parameters we consider distributions as uncertain parameters. A space of possible probability distributions of the intangible parameters can be introduced. Each randomly selected set of distributions for the intangible parameters will result in a single value of failure probability P_f. Sampling in the space of the distributions for model intangible parameters will result in calculation of different possible values of P_f, including the bounding ones. A cumulative distribution function of $cdf(P_f)$ can be used to characterize confidence in prediction of P_f (see Figure 4).

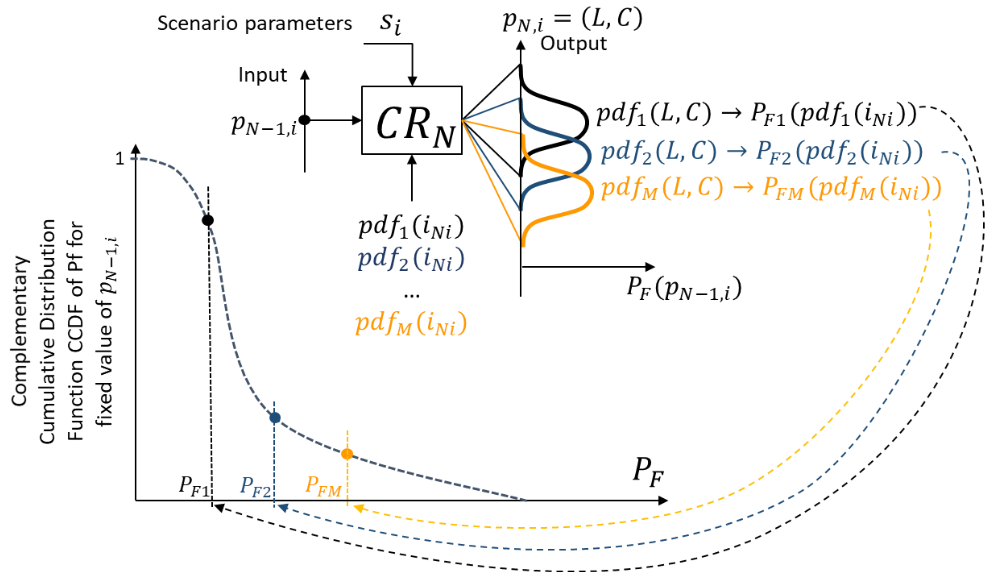

Figure 4. Treatment of model intangible parameters in ROAAM+ framework [1].

2.5. Decision Analysis with ROAAM+

The aim of the ROAAM+ framework is to provide an assessment in support of the decision whether or not the risk associated with current SAM strategy is acceptable. The risk in each scenarios is presented as a triplet $R_i = \{s_i, f_i, pdf(P_{Fi})\}$, where scenario s_i has frequency f_i and uncertainty in the failure is characterized by distribution probability of failure probability $pdf(P_{Fi})$. Such approach keeps separation between frequencies of scenarios (s_i, f_i) that characterize statistical data about frequencies of failures of systems and components etc. that can be obtained from PSA-L1, and confidence in prediction of the phenomena determining containment failure ($pdf(P_{Fi})$) that is obtained from the uncertainty analysis using deterministic models. As we will demonstrate, this separation is important for an adequate approach to interpretation of the risk and respective decision-making process (in contrast with classical approaches, see Figure 5).
Scenario frequencies are the inputs to ROAAM+ framework provided from PSA L1 analysis results, i.e. frequencies of correspondent plant damage states (PDSs). Conditional containment failure probability (or probability distribution of conditional containment failure probability) for each scenario is a main outcome of ROAAM+ framework analysis.

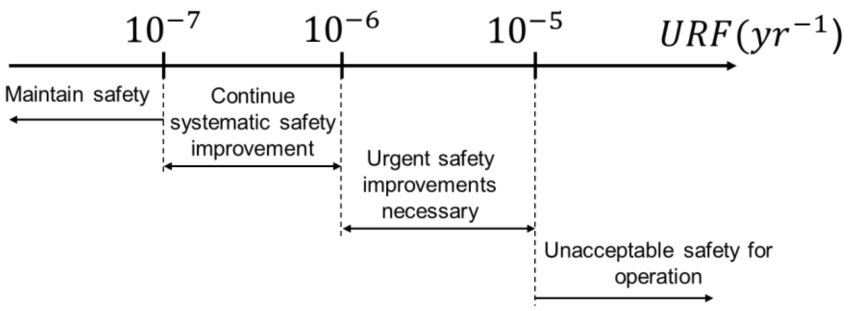

Figure 5. Unacceptable Release Frequency (URF(yr^{-1})).

Figure 5 presents the decision alternatives with respect to URF, which is an outcome of PSA Level 2 analysis. Furthermore, the results of PSA L2 analysis can be evaluated according the relative safety significance, using eq. (2), by normalizing with respect to the goal value for unacceptable release frequency - $f^U_{Nominal} = 10^{-7}(year^{-1})$ [25].

$$S^U = f^U / f^U_{Nominal} \quad (2)$$

Then, the results can be interpreted according to the Table 1.

Table 1. Probabilistic Safety Significance Decision Matrix [25].

Relative Safety Significance		Description
S ≥ 100	Unacceptable	Unacceptable Safety for Operation - Risk-reducing measures must be taken immediately. If immediate risk reduction cannot be achieved the operation should be suspended until temporary or permanent risk mitigating measures have been taken.
100 > S ≥ 10	Operation Limiting	Urgent safety improvements necessary – Temporary measures generally are necessary. Operation can continue for a limited period, depending on the medium term risk-increase. Cost-effective compensatory measures should be developed for permanent implementation.
10 > S ≥ 1	Tolerable	Continue systematic safety improvement – Continue normal operation, no additional measures are necessary. Compensating measures should be considered and planned to the extent that this is considered reasonable.
1 > S	Negligible	Maintain safety – Continue normal operation, no additional measures are necessary.

Figure 6a (see [8]) presents decision criteria as a function of accident scenario frequency (CDF – Core Damage Frequency) and Conditional Containment Failure Probability (CCFP) or Conditional Probability of Unacceptable Release (CPUR) which is used in classical ROAAM. If there is no uncertainty in CCFP, then the decision can be made directly using the correspondent values of CDF and CCFP as it demonstrated in the Figure 6a. In case of CCFP values being uncertain and represented by $pdf(P_{Fi})$ – as in Figure 6b where ROAAM+ results - $pdf(P_{Fi})$ are presented as box and whiskers plots for scenarios s_i, with respective frequencies f_i; the abovementioned approach can be used to support decision making.

Furthermore, ROAAM+ framework can be used to support decisions regarding changes to design of the plant, thus improving SAM effectiveness. ROAAM+ framework can provide material for Integrated Risk-Informed Decision Making (IRIDM) [6,7] taking into account (i) deterministic insights; (ii) probabilistic insights (e.g. probabilities of phenomena with risk significant consequences with state-of-the-art knowledge, that can additionally improve the credibility and transparency of the level 2 PSA. [19,20]). (iii) Compliance with regulatory requirements. (iv). Material for cost-benefit analysis, taking into account different stake-holders (e.g. regulatory body, society, utility) [9,21].

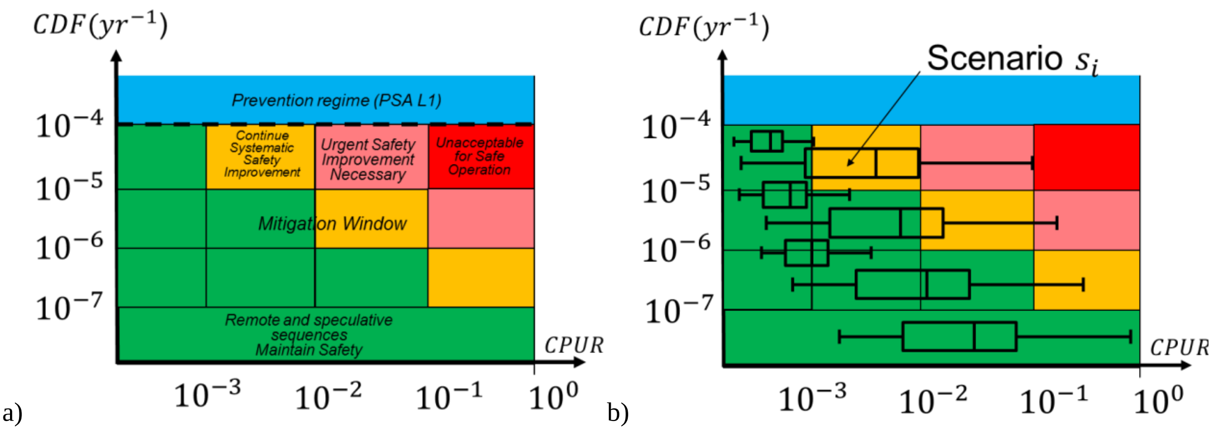

Figure 6. Conditional Probability of Unacceptable Release, (a) Decision Support in Classical ROAAM; (b) Decision support in ROAAM+.

3. RESULTS

To illustrate the approach presented in this paper we consider a severe accident initiated by the station blackout (SBO) scenario. We consider a simultaneous loss of the offsite power (LOOP) and backup diesel generators. This results in the simultaneous loss of all water injection systems, including crud purge flow through the control rod drive tubes. This kind of accident is one of the most challenging accidents scenarios for BWR's as illustrated at Fukushima-Daiichi accident [10] and is among the major contributors to the core damage frequency (CDF) for Nordic BWR according to PSA Level 1 analysis. In this work we consider HS2-TL4 plant damage state where the initiating event is a transient or a CCI, core cooling has failed and the reactor vessel pressure is low (see Figure 7).

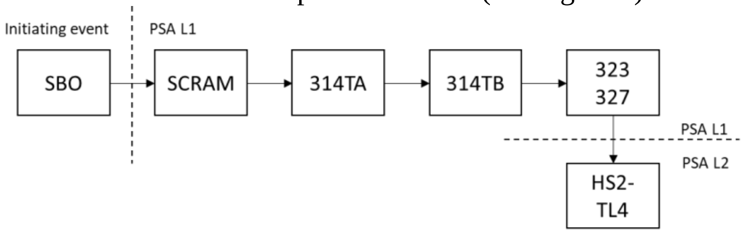

Figure 7. Block Diagram for HS2-TL4 PDS in PSA L1.

We consider 3 following scenarios:

- Unmitigated SBO – SBO1:
  - SBO with successful opening of SRV (314TA), ADS (314TB), systems 323 (LPCI/ECCS), 327 (HPCI/ECCS), 323 (Containment Sprays) considered unavailable. HS2-TL4 reference case
- Recovered SBO – SBO2:
  - SBO with successful opening of SRV (314TA), ADS (314TB), LPCI/ECCS (323) can be restored after 7200sec, Systems 327 (HPCI/ECCS), 323 (Containment Sprays) considered unavailable. HS2-TL4 + Power recovery at 7200 sec.

In SBO2 we consider that the power (external grid or diesel generators) can be recovered after time delay (7200sec) and emergency core cooling system (ECCS) system can be restarted.

We use ROAAM+ framework [1,5] (i) to perform deterministic analysis of the accident progression (from in-vessel accident progression [11,12,13], vessel failure and melt release [14,15] to ex-vessel steam explosion [16,17,18] – we use MELCOR code to perform analysis of in-vessel phase of accident progression, vessel failure and melt release and associated uncertainty; data from MELCOR code is used in SM for Ex-vessel steam explosion (SEIM) to predict corresponding loads on the containment due to ex-vessel steam explosion and associated uncertainty) and (ii) to quantify conditional containment failure probability due to ex-vessel steam explosion considering different fragility limits, i.e. 6kPa*s for containment hatch door that corresponds to original design and 50kPa*s for reinforced hatch door that represent possible design modification/improvement.
The results of ROAAM+ analysis are presented in Figure 8 and 9 (note that there is a possibility to make deterministic analysis and models more realistic regarding some of the related parameters and models. The quantitative results should therefore be seen as indicative).

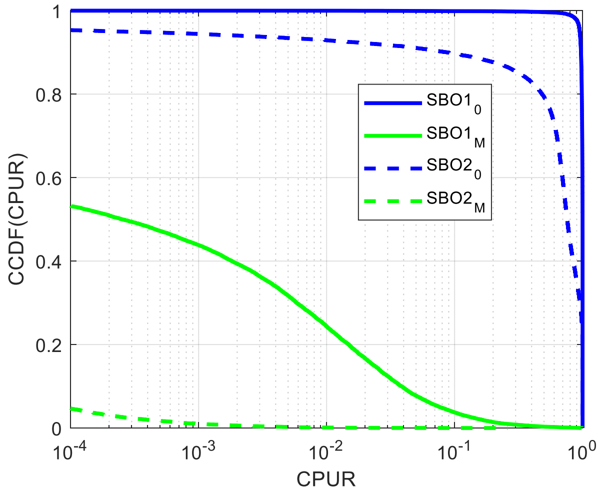

Figure 8. CCDF of Conditional Probability of Unacceptable Release due to ex-vessel steam explosion. ($SBO1_0$ – Unmitigated SBO with original design, $SBO1_M$ – unmitigated SBO with modified design, $SBO2_0$ – mitigated SBO with original design, $SBO2_M$ – mitigated SBO with modified design).

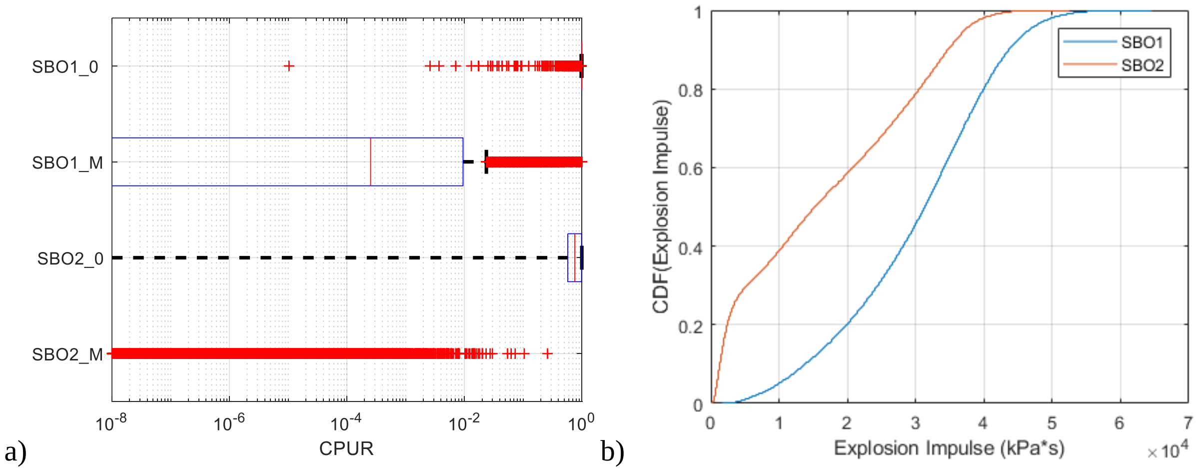

Figure 9. (a). Box and Whisker Plot[1] of Conditional Probability of Unacceptable Release due to ex-vessel steam explosion. (b). Distribution (CDF) of Ex-Vessel Steam Explosion Impulse (kPa*s).

The expected values (expected value of CPUR) can be used directly in the assessment of compliance with the regulatory requirements. Alternatively, the distributions of conditional probability of unacceptable release, obtained with ROAAM+ framework, can be interpreted as *exceedance* probabilities for different domains (risk thresholds), i.e. instead of using expected value (which is a measure of central tendency, therefore may not be desirable in ensuring the risk is below certain value) we can look into the probability of exceeding certain risk threshold (screening probability p_s).

For example, let's consider the scenario frequency to be in the range of $10^{-4} - 10^{-5}$ and screening probabilities p_s =1.e-3, 1.e-2 and 1.e-1, that corresponds to decision options: "maintain safety", "continue systematic safety improvement", "urgent safety improvements necessary", "unacceptable safety for operation" (as in figures 5 and 6), or negligible, tolerable, operation limiting and unacceptable – safety significance, according to the Table 1.

Then, in unmitigated SBO scenario (SBO1) in the original design, the exceedance probability for "maintain safety", "continue systematic safety improvement" and "urgent safety improvement is

[1] Outliers are calculated as values greater then $q_3 + w(q_3 - q_1)$ or less then $q_1 - w(q_3 - q_1)$, where w – maximum whisker length, and q_1, q_3 – are 25th and 75th percentiles of the sample data. At $w = 1.5$ should correspond to ~99.3 percent coverage if the data is normally distributed.

necessary" domains (see Figure 5 and 6) is 1, on the other hand for the modified design, exceedance probabilities are 0.438, 0.243 and 0.037, which corresponds to p_s =1.e-3, 1.e-2 and 1.e-1 correspondingly.
In mitigated scenario with water injection after 7200sec (SBO2), exceedance probabilities are 0.94, 0.92 and 0.89 for original design, and 0.01, 1.3e-3 and 1.e-6 for screening probability p_s=1.e-3, 1.e-2 and 1.e-1 correspondingly.
The results of ROAAM+ framework show the effect accident scenario and possible design modification on the CPUR. Design modification results in significant reduction of CPUR and existing SAM strategy can be considered as effective in modified design. However, depending on scenario (s_i) frequency, since p_s=1.e-3 is only met for SBO2 scenario. In SBO1 scenario with modified design, below 1.e-6 for the sequence to be considered as remote and speculative [23].
Furthermore, obtained exceedance probability values can be used to calculate expected disutility (loss, cost) of different decision options (modify vs. maintain SAM) using equation:

$$U_C = U_0 * cdf\left(P_f < 1.e-3\right) + U_R cdf\left(1.e-3 < P_f < 1.e-2\right) + \\ + U_{US}\, cdf\left(1.e-2 < P_f < 1.e-1\right) + U_{UO}\, cdf(1.e-1 < P_f < 1) \quad (3)$$

where, U_0 – cost of "Maintain Safety", which will be practically equal to zero, U_R –costs of "Continue Systematic Safety Improvement" (costs related to the research and further reduction of uncertainty), U_{US} –costs of "Urgent Safety Improvement" (costs related to urgent R&D, urgent design modification, and other economic losses related to NPP operation e.g. long shutdown; U_{UO} – costs of "Unacceptable for Safe Operation" – which include costs of reactor shutdown, long shutdown, etc. Additionally, it is possible to calculate design modification effectiveness measure, as proposed in [9], with respect to potential consequences of containment failure and large early release (in terms of disutility).

4. CONCLUSIONS

The approach presented in this paper can be used for decision support and communication of ROAAM+ framework analysis results. ROAAM+ Framework results provide both deterministic and probabilistic insights, taking into account state-of-the-art knowledge, regarding the effectiveness of the SAM strategy, the effect possible design modifications on SAM and conditions where changes in the safety design can be justified. Furthermore, ROAAM+ framework results can be used to improve the credibility and transparency of the level 2 PSA, by identifying the accident sequences where phenomena with risk significant consequences can occur and provide information regarding the probability (probability distributions) of failure due to these phenomena, which can additionally improve the credibility and transparency of the level 2 PSA.

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