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Identification and communication of uncertainties of phenomenological models in PSA

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Abstract

This report aims at presenting a view upon uncertainty analysis of phenomenological models with an emphasis on the identification and documentation of various types of uncertainties and assumptions in the modelling of the phenomena. In an uncertainty analysis, it is essential to include and document all unclear issues, in order to obtain a maximal coverage of unresolved issues. This holds independently on their nature or type of the issues. The classification of uncertainties is needed in the decomposition of the problem and it helps in the identification of means for uncertainty reduction. Further, an enhanced documentation serves to evaluate the applicability of the results to various risk-informed applications.

Keywords

Uncertainty analysis, PSA, risk informed decision making

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1 Introduction

The aim with probabilistic safety assessment (PSA) is to identify, analyse and quantify risks of the studied object, e.g., a nuclear power plant. PSA integrates many kinds of knowledge as well as results from numerous technical analyses into a comprehensive probability model. Inevitably, PSA is based on many assumptions and modelling restrictions. Some are known and explicitly presented in the analysis, some are implicitly accepted.

Uncertainties and uncertainty analysis have been considered as a relevant topic since WASH-1400 (1975). PSA is often completed by a quantitative uncertainty analysis. Traditionally, this means the use of distributions for basic event probabilities instead of expectation values and applying Monte Carlo Simulation to propagate the uncertainties through the model. The end result of the simulation is, thus, the uncertainty distribution of the event probabilities or consequences of accident sequences. This kind of uncertainty study cannot be seen as comprehensive enough for many reasons. First, it only concentrates, by definition, on random uncertainties in the basic event data. Secondly, it does not treat modelling and identification related uncertainties. Further, as purely quantitative, it doesn't sufficiently document the causes of uncertainty and the evidence behind uncertain assumptions.

Since the views upon uncertainty differ among various participants of PSA, there is a need to improve the understanding of uncertainties, and to facilitate communication between PSA-analysts and "physicists" who analyse the phenomena. In other words, there is a need to establish more agreement between system analysts', reliability engineers' and physicists' views on uncertainty. The adoption of risk informed decision making principles also creates requirements for uncertainty analysis.

This report aims at presenting a view upon uncertainty analysis of phenomenological models with an emphasis on the identification and documentation of various types of uncertainties and assumptions in the modelling of the phenomena. In an uncertainty analysis, it is essential to include and document all unclear issues, in order to obtain a maximal coverage of unresolved issues. This holds independently on their nature or type of the issues. The classification of uncertainties is needed in the decomposition of the problem and it helps in the identification of means for uncertainty reduction. Further, an enhanced documentation serves to evaluate the applicability of the results to various risk-informed applications.

2 Views on uncertainties

2.1 Modelling and uncertainties

The correspondence between a model and reality is always incomplete to some extent. In PSA, the final initiating event classes may not include all possible events, which could lead to core damage in combination with failures of some safety systems. Similarly, the fault- or event-trees may not be detailed enough to describe the failure modes of the system. In phenomenological models, all phenomena having impact on the systems behaviour may not be included in the model. This type of uncertainty is often referred to as *incompleteness*. It can be due to intentional decisions during the analysis planning: some things have been left out of the scope of the analysis on purpose. The reason for this kind of decisions is usually lack of resources. Droguett and Mosleh (1999) refer this type of model uncertainty as application-context related issues. The difficulty with this kind of intentional incompleteness is that the decisions according to which some issues have been left out from the model are often not documented in a sufficient way.

In the worst case, the incompleteness may be due to misunderstanding or lack of knowledge about the plant features. This kind of uncertainty can only be taken into account by independent review or analysis of the model.

Incompleteness can be seen as a special form of *model uncertainty or model inadequacy.* Model uncertainties are often related to assumptions behind the model, level of detail, and scope or domain. In addition to application-context related uncertainties, Droguett and Mosleh (1999) identify conceptualisation related (phenomena exclusion, use of surrogate phenomena and conceptual approximations), and data related (data interpretation, model interpretation) model uncertainties.

As examples of conceptualisation related model uncertainties we mention uncertain physical model assumptions e.g. in determining success criteria of safety functions, approximation of time dependent physical phenomena with static models, approximation of high dimensional phenomena with two or one dimensional models, and inexact description of boundary conditions.

The definition of failure modes corresponding to a fault-tree basic event is also an issue from to the above mentioned model uncertainty category. This uncertainty is connected to the data related uncertainties. Interpretations of basic events and initiating events, are also typical representatives of this category. Especially, imprecisely defined human errors and common cause failures are important from this point of view. When the probabilities for the above mentioned events are determined from data, it may be very difficult to be sure that the data and the events to be quantified really correspond to each other.

Parameter uncertainties refer to the unknown parameter values of valid models. This uncertainty is present as well in probability models (fault-trees, and failure time distributions) as in deterministic or probabilistic phenomenological models. Parameter uncertainty has been traditionally taken into account in uncertainty propagation of PSA models.

In addition to the classification of types of uncertainties to incompleteness, model and parameter uncertainties (see e.g. IAEA, 1992), a distinction in the nature of the *phenomenological uncertainty* may be made. One cane speak about randomness - or stochastic variability - and *epistemic uncertainty* (e.g. Apostolakis 1999, Hofer 1996, Parry 1998). Stochastic or *aleatory uncertainty* is sometimes called irreducible, since it cannot be made smaller without observing the real realisation of the uncertain process (e.g. the result of a toss of a coin). The phenomenon under analysis is in this case *inherently random,* and we may speak about inherent uncertainty. Epistemic uncertainty (knowledge uncertainty) or reducible uncertainty can be decreased by obtaining additional information or by making experiments. There are differing opinions whether such distinction can be made, but often they may have useful implications for the practice of modelling, e.g. in decomposition.

Figure 1 illustrates the relationships between phenomenon, model and uncertainties. The model represents certain features of the phenomenon, but the selected abstraction level may not allow the description of all properties of the phenomenon (e.g. two dimensional model of three dimensional reality, simplifications in describing the boundary conditions, etc.). Uncertainties are left in the model also due to modelling goals and lack of data.

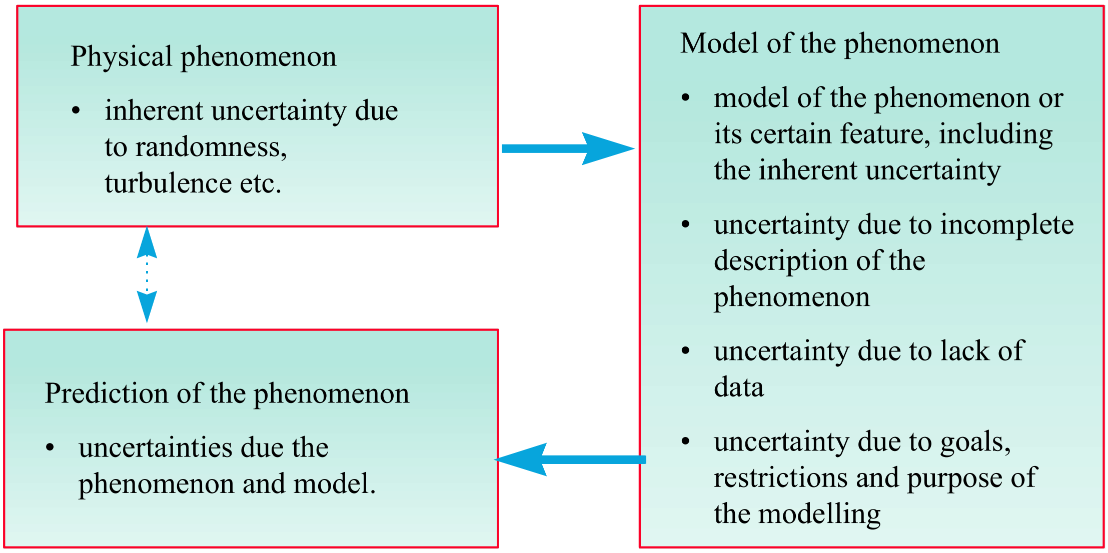

Figure 1. Relationships between uncertainties in a phenomenological PSA model.

The uncertainties are reflected to the predictions made with the model. However, measurements made from the system may decrease the uncertainties and help in updating the model. On the other hand, the controls based on the model may have impact on the behaviour of the system.

When PSA is used in decision making, results from several sub-models made by several analysts have to be taken into account. In this case the interface between models is one source of uncertainty. The decision maker must understand the uncertainty of each sub-model and the relationship between the models and their uncertainties. This creates requirements for qualitative uncertainty analyses and their documentation. Figure 2 illustrates this situation.

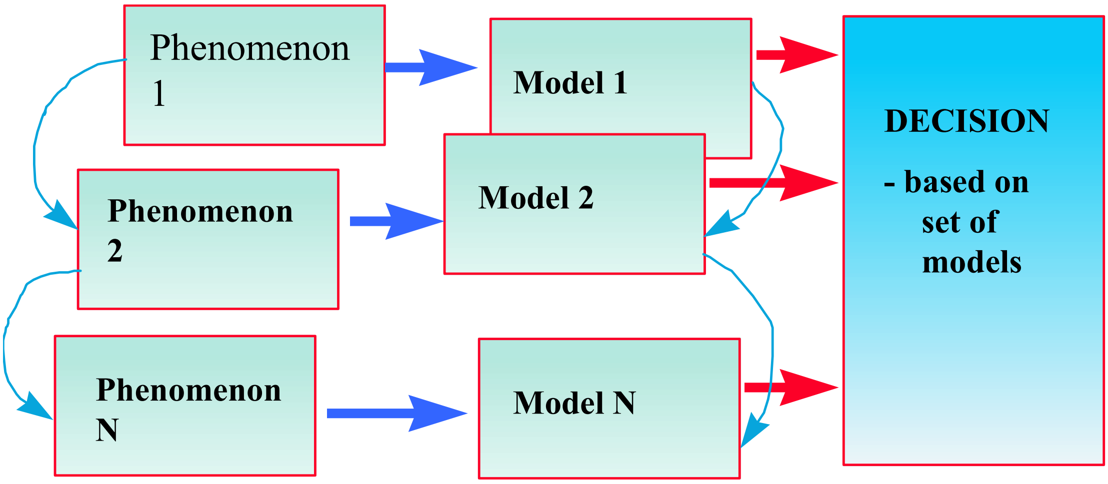

Figure 2. Decision making based on several uncertain models

2.2 PSA and uncertainties

PSA has many roles in safety related decision making. The way that uncertainties must be taken into account depends on the type of PSA application. In the following we discuss how uncertainties affect decision making, with examples related to requirements for PSA when it is used in safety verification and risk-informed applications.

2.2.1 Safety verification

The purpose of safety verification is to provide confirmation of the adequacy of the design from safety point of view. The role of PSA is, on one hand, to complement deterministic safety analyses and, on the other hand, to prove compliance with specific probabilistic safety targets.

Usually, probabilistic safety targets are related to core damage frequency and to large early release frequency. These targets are absolute measures and set requirements for the completeness of the model. For instance, if some initiating events are missing from the model, the verification of core damage frequency target is questionable. For this purpose, the use of conservative assumptions, e.g., system success criteria, can be justified.

A target can also be to verify that the design is well balanced, i.e., no hazard, system, component or manual action is clearly dominating the core damage risk. This kind of target is relative and it sets requirements for the degree of detail. In such case, the use of conservative assumptions can be a weakness in the model.

The decision making in safety verification is to make conclusions based on results from PSA. Four different decision making situations related to safety verification can be identified. In the first case, PSA shows compliance with safety targets and the result is accepted. There is no requirement to improve the design or safety analyses. In the second case PSA shows that safety targets are not met, and since the quality of PSA's results is considered good enough, it can be used for identification and comparison of alternatives for safety improvements. The third and fourth cases are more problematic. The decision-maker has to judge whether it is better to modify design or to improve quality of safety analyses. In this judgement, uncertainty analyses play an important role. In some cases, a modification in design or practices may be a cheaper option than to perform a more detailed safety analysis. (Holmberg & Pulkkinen 1999).

2.2.2 Risk informed applications

Risk informed applications aim at more rational decision making, which takes the PSA results into account together with results from other analyses. It is important to be sure that the PSA model really includes the facts that affect the decision. Sometimes, the model is not detailed enough to solve the decision problem, e.g. the components or failure modes which are relevant for the decision are not modelled in the fault-tree, or the evidence on failure probabilities is insufficient. In some other cases, phenomena (e.g. time dependent progression of the accident) are not adequately described for decision making purposes.

PSA uncertainties have an important role in the adaptation of risk informed approaches. One has to know what aspects of decisions are affected by uncertainties and what is their impact on the decisions. A well documented uncertainty analysis serves this purpose.

2.2.3 Nature of uncertainty analyses

PSA studies are often different from their scope, extent and depth. Thus, also the information provided by the studies is different and it emphasises different aspects of the plant. Since PSA attempts at evaluating unwanted consequences and, on the basis of various evidence, randomness related to them, it can be seen as an organised collection of evidence about the safety of the plant. From this point of view, the purpose of an uncertainty analysis is to document and clarify the evidence behind the PSA results. Another purpose is to identify and to document uncertain assumptions, variables or models.

An extensive uncertainty analysis evaluates critically the relationship between various pieces of evidence, assumptions, models, and results of PSA. Often, this requires quantitative modelling of uncertainties and making a distinction between random and epistemic uncertainties. An analysis of consistency in modelling and in use of data becomes an essential part of a developed uncertainty analysis. By fulfilling the purposes mentioned above, an uncertainty analysis explicates the uncertain issues and makes the PSA easier to review and use.

As an evaluation of evidence behind PSA results, an uncertainty analysis also identifies the additional evidence or analyses needed in both reviewing and clarifying PSA. In most cases, this can be done without extensive quantitative assessments.

It is important to keep in mind that the need and degree of detail of a quantitative uncertainty analysis depends on the purpose of the PSA model. A rather "simple" PSA may be used to support the assessment of plant vulnerabilities, while the requirements for a PSA are more demanding if the analysis should support risk significance evaluations or to form a basis for licensing. Correspondingly, the treatment of uncertainties may vary. The levels of uncertainty treatment are discussed e.g. in (Paté-Cornell, 1996) where the lowest level of uncertainty treatment is a simple hazard detection and failure mode identification, and the most detailed level is the full treatment of uncertainties.

PSA itself or PSA as decision making aid requires expertise from various disciplines. Many kinds of thermohydraulic calculations must be made, for example, in order to define success criteria for emergency functions, and to define consequences of failures. Similarly, qualitative reliability analyses must be interpreted in order to develop fault trees or other quantitative models. Often, the interfaces between different models or modelling phases create uncertainties. The other analysts may not understand the assumptions made in earlier phase or by other analysts in the same way. Qualitative uncertainty analyses can be seen as a communication tool between various modellers, in which the assumptions and modelling choices are made transparent.

3 General strategy for uncertainty analysis

The previously discussed decision making situations set requirements for appropriate uncertainty analysis. It is common that the decision makers, who are in position to e.g. require risk informed applications, have not usually participated in PSA themselves. They only use the results of PSA, and any unclarity of assumptions or PSA results appears to them in similar way: they do not usually know the reason of uncertainty, whether it is due to phenomenological or modelling uncertainties, or due to incompleteness or boundary conditions of the model. Thus, it is important to clearly express, which assumptions are made and why.

A full analysis and propagation of uncertainties is a difficult and costly exercise, and thus it should be done only if it is relevant to the risk management issue (Paté-Cornell 1996). However, the need for a qualitative uncertainty analysis should be emphasised, because with rather moderate expenses, the main uncertainties can be summarised, and such a summary can serve the decision maker in identification of needs for further analyses or in selecting other most cost-effective means for uncertainty reduction.

In addition to requirements originating from the scope or nature of PSA, the regulatory authorities may require evaluation of uncertainty. For example, the Finnish regulatory guide YVL-2.8 states, among other things that

- In using methods based on expert judgement, the estimation procedure shall be conservative enough and the uncertainties associated need to be studied and documented.

- Level 1 PSA includes sufficient information for the evaluation of the uncertainty and sensitivity of the results.
- Level 2: estimation of the respective probability of accident sequences with the associated uncertainties

The Finish requirements emphasise the qualitative identification, documentation of uncertainties as well as the quantification of the impacts of uncertainty.

Due to the above requirements and limitation of uncertainty analysis, an effective way to tackle with uncertainties is a hierarchic approach, in which qualitative analyses are first made in order to identify and screen uncertain issues for further analyses. In continuation, quantitative analyses, including various sensitivity studies and uncertainty propagation, are made. An important part of quantitative uncertainty analyses should be presentation and interpretation of results.

Qualitative analyses

A qualitative uncertainty analysis consists of a systematic review of a model and its sub-models, of an identification of critical assumptions and of limitations and a qualitative judgement of the importance of uncertainties.

Further, a summary of uncertainties, related to the various phases or parts of the analysis, can help decision making concerning e.g. needs for further analyses or selecting other most cost-effective means for uncertainty reduction.

In this connection, it may be useful to classify uncertainties according to their nature (see section 2), in order to facilitate the search for additional evidence for uncertainty reduction. Further, the description of existing evidence on each uncertain issue should be described explicitly, and its applicability to the analysis of current issue should be evaluated.

In PSA, the qualitative analyses of various uncertainty types are different. Incompleteness, and most problematic phenomenological uncertainties, can be treated only by describing the principles according to which the degree of model detail is selected and what is behind these modelling decisions. For other modelling uncertainties, the critical assumptions should be justified, and their significance should be analysed. In this connection, the validity of applied models should be critically evaluated. The parametric uncertainties are dealt basically in quantitative way. However, it is necessary to define the parameters exactly, and evaluate the applicability of used data (including expert judgement) with respect to the parameter definitions and the plant under analysis.

As a part of qualitative analysis, a preliminary screening according to the significance of each issue is made. This serves as a guideline for selecting the method for quantitative analysis to be made as the next phase.

Quantitative analyses

A quantitative uncertainty analysis consists of different types of sensitivity analyses, probabilistic uncertainty propagation, and determining of probability distributions for unknown parameters on the basis of existing statistical or other evidence. In many cases, quite simple but well planned sensitivity calculations help in finding out the significance of most uncertain issues. However, sensitivity analyses of multi-parameter and complicated physical models may be a difficult task. We emphasise that sensitivity studies should be made on the basis of the findings from qualitative analyses. Uncertainty propagation requires much more resources, and its results may be difficult to interpret.

An important task of quantitative uncertainty analysis is the quantification of parameter uncertainty distributions, which is needed in judgement of significance of the issue. It is essential to find out how different pieces of evidence are reflected in uncertainty distribution, and to get an idea, how large part of the uncertainty is related to subjective expert judgements. In this connection, the Bayesian statistical models and interpretations are useful.

Documentation of analyses

An uncertainty analysis, as the whole PSA, is useless without a sufficient documentation. When PSA results are used in decision making, one has to know what the region of validity of the PSA model is, how much one can rely on the results and how uncertain are the issues related to the decision task at hand. The basic requirements for the documentation are transparency and traceability. The aim of the uncertainty analysis is not only to express the confidence on results, but also to identify the needs and possibilities for uncertainty reduction. The classification of sources and types of uncertainties, and at least a rough evaluation of their importance, as discussed earlier, are needed to enable the identification of potential for uncertainty reduction. The explicit description and evaluation of the existing evidence serves for this aim, too.

We recommend that the following points should be explicitly included in the documentation:

1. description of all identified uncertainties;
2. evaluation of the significance of each uncertain issue and justification of its evaluation method;
3. description of the evidence related to each uncertain issue, and justification why this evidence is seen as applicable and
4. evaluation on how the uncertainties can be reduced.

4 An approach for identification and communication of uncertainties

4.1 Outline of the approach

Earlier we emphasised the importance of a good qualitative analysis in relation to uncertainty investigations. It is essential to have results presented in such a way that the significance of various assumptions can be determined (Parry 1998). As pointed out also by Pulkkinen & Huovinen (1996), complex mathematical formulations of the model uncertainty may hide the importance of the qualitative study that is the basis of any risk analysis. Thus we aim at a method for identifying and documenting the uncertainties.

In this chapter, we introduce a format developed for identifying, classification, and evaluation of uncertainties, and for summarising results of uncertainty and sensitivity analyses.

Advantages of a structured summary of uncertainty analysis are obvious. The interpretation of uncertainties in not straightforward and thus the understanding of uncertainties may differ between analysts, experts from different disciplines and decision makers. As the results of analyses of physical phenomena are used in safety related decision making, it is important that the understanding of uncertainties is transferred in a comprehensive and transparent way to the decision makers. A well structured summary with short description of applied modelling approach will also serve in verifying that all major assumptions, limitations, and uncertainties have been described and their importance has been evaluated.

Our approach consists of formats or uncertainty documentation tables, in which each phenomenon or issue is considered. First the phenomenon is described and its significance for PSA (or decision under consideration) is evaluated qualitatively. In this connection, the decomposition of phenomenon and related accident sequences are documented, and the decompositions are justified. The relationships to other issues and other models are discussed. Next, the models or computer tools used in the analysis, and reasons to use them are discussed. The theoretical basis and the degree of validation of the models and tools is described. Furthermore, the use and role of formal or informal expert judgement is explained, and the sensitivity and uncertainty analyses together with applied methodologies and main results made are presented.

In addition to the above-mentioned general description each possible source of uncertainty is evaluated. In this connection both qualitative characterisation and, if possible, the impact of uncertainty to the final results is evaluated in a (semi)quantitative way. In some cases it may be advantageous to evaluate whether the analysis is based on conservative, optimistic or ”best estimate” assumptions. In order to direct additional analyses, the possibilities to reduce the uncertainty are presented.

In the documentation format, the sources of uncertainties to be covered include

- the inherent and knowledge uncertainties related to the phenomenon under analysis (e.g. randomness, turbulence, material properties)
- model uncertainties, including those originating from the scope of the analysis, incompleteness
- uncertainties due to input data
- uncertainties due to boundary conditions applied in the model
- uncertainties in selection of initial states for calculations (e.g. initiating events, assumptions on the amount of certain substances in the system, the results from another model)
- uncertainties due to computational or numerical properties of the model (nodalisation, time steps).

It is important to clearly express, which assumptions are made and why. Within an analysis, for some initial values a best estimate may be used while other parameters are based on conservative assumptions.

4.2 Example: BWR reactor building hydrogen scenario

The previously described approach was applied to an analysis of hydrogen leakage from a BWR containment to the reactor building rooms and its combustion during a severe accident. The analysis was also done in NKS/SOS-2 project and it is described in details in Silde & Lindholm (2000), Saarenheimo (2000) and Silde & Redlinger (2001). We describe here only briefly the accident scenario and main assumptions in the analysis.

The BWR containment is normally inerted with nitrogen during operation and thus hydrogen combustion phenomena inside containment are prevented and hydrogen burning issues are not considered in BWR severe accident management studies. However, hydrogen leakage from the containment into the surrounding reactor-building rooms during an accident cannot be ruled out, and because the atmosphere in the reactor building is normal air, the ignition and combustion of hydrogen is possible. The safety concern is whether the hydrogen in the reactor building can detonate and jeopardise the containment integrity from outside. Earlier studies on assumed hydrogen leakage and distribution in the selected reactor building rooms in Olkiluoto BWR suggest that hydrogen accumulates closer to the ceilings of rooms (see e.g. Manninen et al 2000). The assumed accident scenario was a station black-out sequence with depressurisation of the reactor coolant system. It was assumed conservatively that all zirconium will be oxidised, leading to a hydrogen release of 1900 kg in the containment. It was assumed that the hydrogen leaks to one reactor building room, and that the location of the leakage is near penetrations. The stratification tends to be rather stable and yield very high hydrogen concentrations.

The main steps of the analysis and the models used in these steps are presented in table 1.

Table 1. Analysis steps and models in the BWR reactor building hydrogen scenario.

Analysis step	Model
1. Release of H_2	MELCOR
2. H_2 concentrations	1) MELCOR, 2) FLUENT
3. Detonation loads	1) simple 1-D model, 2) DET3D (3-D)
4. Structural integrity	ABAQUS/Explicit

The formats described in the previous chapter were sent to the analysts of the steps of the scenario, and they were asked to start to fill them. After that, a meeting with them was organised to discuss through their uncertainty evaluations. The analyses of steps 1-3 were considered together, and the same procedure was applied separately to the structural analysis (step 4).

The filled formats are presented in tables 2 and 3. It should be noticed that these answers are reflecting uniquely the uncertainty perception of the analysts. These formats could be further used in discussion with e.g. the decision maker (utility, authority) and might be updated according to new insights.

4.3 Conclusions from the case study

Both MELCOR and FLUENT calculations indicate that for the analysed leakage sizes, flammable and detonable hydrogen-steam-air mixtures can be obtained. Different combustion scenarios are possible depending on the size of the leak and the timing of hydrogen ignition. An inherent phenomenological uncertainty is related to the ignition of the hydrogen. Large uncertainties are also related to the flame acceleration and the deflagration-to-detonation-transition (DDT). Uncertainties in detonation pressure loads are due to the ignition location and room geometry. Uncertainties in structural analyses (given a pressure load) are related e.g. to material properties and reinforcement, but seem to be minor compared to uncertainties in ignition and DDT. The structural analyses aimed at simulating the structural behaviour of the wall hit by a peak type detonation transient. The slowly decreasing static pressure after the detonation peak may damage the wall more severely than the detonation itself, but this phenomenon was considered only by some simple calculations.

Analysts of the scenario felt that the approach to summarise the uncertainties is useful. It helps to structurise and decompose the uncertainties related to the analysis. Although many uncertainty evaluations and analyses are routinely conducted during the phenomenological study processes, only minor attention is often paid to their structured documentation. In this specific scenario, the expertise from several disciplines were needed, which makes it even more important to have a comprehensive understanding of the major uncertainties.

Table 2. Filled uncertainty analysis summary format for hydrogen distribution and detonation analyses in BWR reactor building.

Description of the phenomenon	Calculation of hydrogen distribution and detonation in BWR reactor building in a severe accident scenario.
Its role and importance in PSA - Decomposition of relevant accident sequences	TVO has shown interest in the assessment of possible consequences of hydrogen leakage from containment to the reactor building. Assumptions: - loss of reactor building ventilation due to loss of power; - core melt accident, 100 % of zirconium oxidised (Finnish regulatory requirement/assumption) - hydrogen is accumulating in the reactor building through a small leakage from the containment (either nominal leakage or small hole in a containment penetration)
Models used (theory behind, possible computer codes) - Validation - Why	The formation and release of hydrogen in containment are calculated with MELCOR. The distribution of hydrogen in the reactor building: rough calculations with MELCOR Detailed calculations of hydrogen distribution and estimation of hydrogen burn with FLUENT. Estimation of flame acceleration/ detonation possibility based on FLUENT analyses and semi-empirical conservative criteria. Shock pressure loads were initially assessed with a simple 1-D code in order to obtain results of the order of magnitude. More detailed best estimate detonation studies were performed with DET3D code.
Role of expert judgement in the analysis	Hydrogen ignition: definition of applicable flammability limits. Possibility for DDT: assessment based on simple rules derived from experiments. Detonation calculations: error estimation, first order pressure/impulse estimates.
Uncertainty and sensitivity analyses made, methodology, main results	2 different leakage sizes, rough calculations (MELCOR) of H_2 distribution for 3 different reactor building rooms with different volume/configuration. Even rough calculations showed very high hydrogen concentrations in the smallest room. The two less severe cases were selected for the detailed calculations (FLUENT), to check if proper modelling of stratification will result in locally higher hydrogen concentrations. This was, indeed, the case. The detonation pressure loads were calculated with DET3D code, and several sensitivity studies were made to e.g. evaluate the effect of ignition location and nodalisation.

Table 2. Cont.

Main sources of uncertainties	Description	Characterisation of impact	Possibilities/restrictions for uncertainty reduction
Phenomenon: - Inherent - Knowledge	Leak size and location, and time scale for H_2 accumulation. Probability of DDT in selected geometry and conditions. Reflection and focusing of detonation and shock waves in 3-D geometry. Influence of gas non-homogeneities.	Size of the leak has a significant impact on the time scale of H_2 accumulation. Scale and geometry have significant influences on flame acceleration and DDT, especially for lean hydrogen-air mixtures.	The aim of the study is to evaluate the probability of this scenario with many uncertainties. Mitigating measures for the management of hydrogen leakage in the reactor building are to be developed if a burn in reactor building could jeopardize the integrity of containment penetrations.
Model uncertainties - Incompleteness	Rough calculations: assumption of homogeneous and instant mixing in a control volume. Turbulence model used in FLUENT calculations. Influence of scale on DDT mechanisms. 1-D approximation for shock pressure calculations.	MELCOR calculations gave (locally) lower H2 concentrations by a factor of 2 compared to more detailed calculations. Simple 1-D code for detonations models an adiabatic shock wave and does not consider properly the 3-D effects of reflecting waves. 3-D modelling accounting for reflections is considered much more reliable.	Specially designed experiments on hydrogen leak and accumulation would reduce these uncertainties significantly. Some prerequisite conditions for DDT can be found from literature of large scale experiments such as performed at RUT facility. Possibility for flame acceleration were studied in detail by 3-D CFD code FLUENT.
Input data for the model (experiments, generic data, own experience, expert judgement)	Opening pressure of certain doors in the investigated rooms could not be accurately defined	Presumably meaningful effect in rough calculations, minor effect in detailed H_2 distribution calculations.	
Boundary conditions	Geometric boundaries in 1-D calculations.		Uncertainties related to 1-D calculations were reduced by performing DET-3D simulations.

Selection of initial states for calculation	Definitions by TVO; location of ignition; data transfer between models (MELCOR->FLUENT-> DET3D)		Some “worst case” initial conditions are assumed intentionally (e.g. release of hydrogen) due to regulatory requirement. Detonation loads have been evaluated in different ignition locations and gas compositions.
Numerical/Computational (nodalisation, time steps...)	Number of compartments. Simplified modelling of room geometry, especially in combustion modelling. Number of computational cells.	The effect of nodalisation estimated to be small in hydrogen distribution analyses. Selection of turbulence model may have some effect on local gas distribution, no effect on the overall conclusions. Grid density may influence the combustion modelling in 3-D calculations. Nodalisation and chosen accuracy level in 3-D detonation analyses may have an impact on maximum pressure spike, but minor effect on total pressure impulses.	Several sensitivity studies have already been performed to assess the impact of nodalisation and accuracy of calculation in DET3D simulations

Table 3. Filled uncertainty analysis summary format for structural integrity analyses of BWR reactor building wall under hydrogen detonation.

Description of the phenomenon	Structural integrity of a reinforced concrete wall under hydrogen detonation conditions in a BWR reactor building.
Its role and importance in PSA - Decomposition of relevant accident sequences	The structural analysis in this case has the following (rather standard) phases: 1. description of the geometric features of the structure with the element grid (Iterative step, first a coarse model of the most important parts of the structure with simple model for other parts. In this case study, one wall of the structure was described with a grid, and the other parts, e.g. the floors were described as equivalent single elements) This step involves also the selection of time step, which is dependent on the material properties 2. transfer of the previously calculated detonation loads to the FEM analysis 3. selection of the material parameters for the reinforced concrete structure 4. calculations (iteratively) 5. interpretation of results
Models used (theory behind, possible computer codes) - Validation - Why	ABAQUS/Explicit, Finite Element Method: ABAQUS is a general purpose FEM analysis code, which is validated for several types of structural integrity analyses. Validation data does not exist for this specific case. All the non-linear material properties of the reinforced concrete are not totally known and validated. Tensile cracking and strain dependent yielding of reinforcement were modelled. ABAQUS/Explicit is more suitable for materially non-linear dynamic analyses than ABAQUS/Implicit,, but it cannot model the compression-crushing of concrete.
Role of expert judgement in the analysis	Expert judgement is needed 1) in iterative specification of the FEM mesh, modelling of boundary conditions, description of steel reinforcement, considerations about the shape of elements (as regular shapes as possible should be used), 2) in selection of the material model parameters (for most materials, some data exists), e.g. the behaviour of concrete is non-linear phenomena (concrete cracking, yielding of reinforcement), 3) especially in interpreting the results produced by the model. Modelling of the boundary conditions is selected according to the analysis purposes.
Uncertainty and sensitivity analyses made, methodology, main results	Iterative modelling, variation of geometric details, material properties and detonation load.

Table 3. Cont.

Main sources of uncertainties	Description	Characterisation of impact	Possibilities/restrictions for uncertainty reduction
Phenomenon: - Inherent - Knowledge	material properties, modelling of non-linear behaviour of concrete and reinforcement	reinforcement is important, because it often determines the strength of the structure non-linear material behaviour are important in assessing the ultimate capacity of the structure	Not considered in this limited study
Model uncertainties - Incompleteness	the assumptions in FEM grid details, boundary conditions for the model, slowly decreasing static pressure after detonation peak	Too coarse grid may overestimate the stiffness of the structure Boundary conditions affect the results, but the selection is made according to the analysis purposes The possible slowly decreasing static pressure is important	Variations in calculations to verify descriptiveness More detailed analyses of the pressure decrease after detonation, taking into account the holes and cracks in the concrete wall
Input data for the model (experiments, generic data, own experience, expert judgement)	• detonation pressure loads given by hydrogen detonation calculations • expert judgements for non-linear material behaviour	Pressure loads are assumed as given, as the aim of the structural analyses is to study the wall integrity with previously assessed detonation pressure loads	Sensitivity analyses by varying the load transient have been done.
Boundary conditions	Separate analyses for various structural details	Results are somewhat sensitive for the selection of boundary conditions	Iterative modelling of details. Has been done to some extent.
Selection of initial states for calculation	See input data and Table 2.		
Numerical/Computational (nodalisation, time steps...)	FEM grid density, selection of some material parameters	somewhat sensitive for the grid density and material parameters	Sensitivity analyses

5 Conclusions and recommendations

In this report, we have presented views upon uncertainty analyses of phenomenological models in PSA. Our starting point has been that PSA should be seen as an organised collection of evidence about the safety of the plant, and the purpose of an uncertainty analysis is to document and clarify the evidence behind the PSA results. This is important because PSA is made and used by many parties, which should understand the assumptions, limitations and uncertainties of the analyses. We emphasise the need of an extensive qualitative uncertainty analysis, which serves as a basis for determining the requirements for quantitative analyses.

Each modelling task of PSA includes uncertainties, the type of which may be task-specific. The uncertainty analysis should aim at a transparent documentation of assumptions and unclear issues of the analysis. The identification and interpretation of the nature of uncertainty is not always straightforward and may depend on the individual, e.g. the analyst, decision maker, or other observer. Thus the coverage in uncertainty analyses and transparency in documentation are important for the communication between various parties.

There are differing opinions whether various types of uncertainties can be distinguished or not. We think that categorisation may be helpful in decomposition of the problem and it may improve the transparency of the uncertainty analyses. The distinction of various types of uncertainty can be used in a decision making situation in order to identify the most suitable measures for uncertainty reduction and for determining the needs for additional evidence.

We have proposed the use of a format to summarise the major sources of uncertainties, their impact on the results of the analysis and possibilities and restrictions for uncertainty reduction. Such a summary is useful in communicating the uncertainties between various analysts representing different disciplines, and decision makers. Enhanced documentation serves to evaluate the applicability of the results to various risk-informed applications.

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Abstract	This report aims at presenting a view upon uncertainty analysis of phenomenological models with an emphasis on the identification and documentation of various types of uncertainties and assumptions in the modelling of the phenomena. In an uncertainty analysis, it is essential to include and document all unclear issues, in order to obtain a maximal coverage of unresolved issues. This holds independently on their nature or type of the issues. The classification of uncertainties is needed in the decomposition of the problem and it helps in the identification of means for uncertainty reduction. Further, an enhanced documentation serves to evaluate the applicability of the results to various risk-informed applications.
Key words	Uncertainty analysis, PSA, risk informed decision making

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