A FRAMEWORK FOR ASSESSMENT OF SEVERE ACCIDENT MANAGEMENT EFFECTIVENESS IN NORDIC BWR PLANTS

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Abstract: In the case of severe accident in Nordic boiling water reactors (BWR), core melt is poured into a deep pool of water located under the reactor. The severe accident management (SAM) strategy involves complex and coupled physical phenomena of melt-coolant-structure interactions sensitive to the transient accident scenarios. Success of the strategy is contingent upon melt release conditions from the vessel which determine (i) if corium debris bed is coolable, and (ii) potential for energetic steam explosion. The goal of this work is to develop a risk-oriented accident analysis framework for quantifying conditional threats to containment integrity for a Nordic-type BWR. The focus is on the process of refining the treatment and components of the framework to achieve (i) completeness, (ii) consistency, and (iii) transparency in the review of the analysis and its results. A two-level coarse-fine iterative refinement process is proposed. First, fine-resolution but computationally expensive methods are used in order to develop computationally efficient surrogate models. Second, coupled modular framework is developed connecting initial plant damage states with respective containment failure modes. Systematic statistical analysis is carried out to identify the needs for refinement of detailed methods, surrogate models, data and structure of the framework to reduce the uncertainty, and increase confidence and transparency in the risk assessment results.

Keywords: Severe accident, Risk oriented, Debris coolability, Steam explosion, Nordic BWR.

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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 if the bed is coolable or not, and (ii) potential for energetic interactions (steam explosion) between hot liquid melt and volatile coolant. Both non-coolable debris bed and steam explosion pose credible threats to containment integrity.

While conceptually simple, this strategy (i) involves extremely complex and often tightly coupled physical phenomena and processes, which are also (ii) sensitive to the conditions of transient accident scenarios. For instance, late recovery actions might affect core degradation and relocation processes, which can change formation of the in-vessel debris bed, reheating and re-melting of multi-component corium debris, thermo-mechanical interactions between melt and vessel structures and penetrations, vessel failure, melt release and jet fragmentation, debris solidification, energetic melt-coolant interactions, two-phase flow in porous media, spreading of debris in the pool, spreading of particulate debris bed, etc. (Figure 1). These phenomena have been a subject of extensive investigations in a

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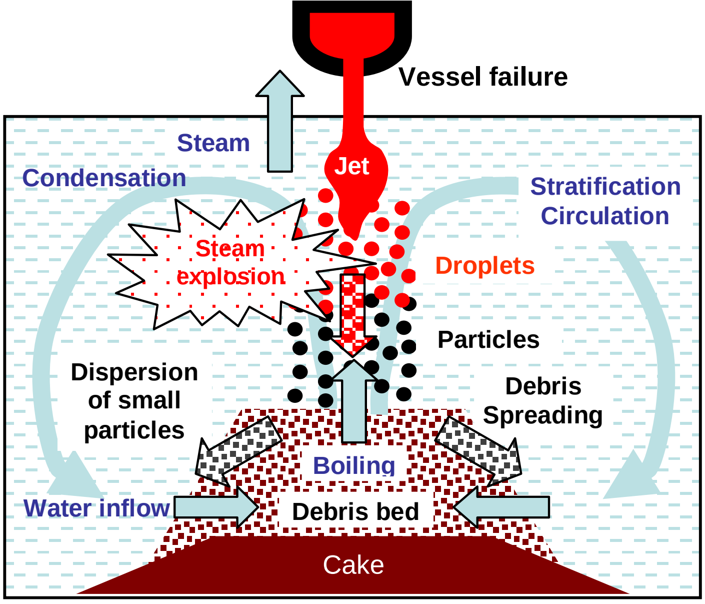
large-scale research program on Melt-Structure-Water Interactions (MSWI) at the Royal Institute of Technology (KTH) over the past few decades.

Figure 1. Severe accident phenomena in Nordic BWR.



While a significant progress has been made in understanding and predicting MSWI physical phenomena, complex interactions and feedbacks between (i) scenarios of accident progression, and (ii) phenomenological processes, have hampered a comprehensive assessment of SAM in the Nordic BWRs. Presently, the issues of ex-vessel debris coolability and steam explosion are considered as intractable by only probabilistic or only deterministic approaches.

Enter the Risk Oriented Accident Analysis Methodology (ROAAM) that marries probabilistic and deterministic approaches. This methodology developed by Professor Theofanous [1] has been applied to successfully resolve different severe accident issues in LWR plants, and severe accident treatments in ALWR designs e.g., [2]. When applied to the Nordic BWR plants, tight coupling between severe accident threats (steam explosion and basemat melt-through due to debris un-coolability) and high sensitivity of the SAM effectiveness to timing of event (e.g., vessel failure) and characteristics (e.g., melt release conditions) present new challenges in decomposition, analysis, and integration.

The goal of this work is to develop a risk oriented accident analysis framework for quantifying conditional threats to containment integrity for a Nordic type BWR. The focus of this work is on the process of refining the treatment and components of the framework. The aim of the process is to achieve (i) completeness, (ii) consistency, and (iii) transparency in the review of the analysis and its results.

A two-level coarse-fine iterative analysis is employed. First, fine-resolution but computationally expensive methods are used in order (i) to provide better understanding of key phenomena and their interdependencies, (ii) to identify transitions between qualitatively different regimes and failure modes, and (iii) to generate reference data. The fine-resolution codes are run independently, assuming wider possible ranges of the input parameters. Second, a set of coupled modular frameworks is developed connecting 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 models. 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 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 in detail.

2. NORDIC BWR CHALLENGES FOR RISK ORIENTED APPROACH

4.1. Background: Quantitative Definition of Risk and ROAAM Basics

According to quantitative definition of risk, proposed by Kaplan and Garrick [3], the risk R_i associated with specific scenario s_i can be characterized by its frequency f_i and consequences c_i. Consequences are obtained from assessments which are subject to uncertainty due to incomplete knowledge. Such epistemic uncertainty (or degree of confidence) can be quantified as probability P_i (likelihood) of c_i

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

Consequences c_i of scenario s_i can be presented as joint probability density function $\mathrm{pdf}_{C_iL_i}(L_i, C_i)$, which accounts for the epistemic uncertainty and possible dependencies between the loads (L_i) on the system in question and its capacity (C_i) to withstand such loads. Thus, failure probability P_{Fi} for scenario s_i can be evaluated as

$$P_{Fi} = P(L_i \geq C_i) = P(C_i - L_i = Z_i \leq 0) = \iint_{Z_i \leq 0} \mathrm{pdf}_{C_iL_i}(c, l)dcdl \tag{2}$$

Or, in case when load and capacity are independent

$$P_{Fi} = P(L_i \geq C_i) = \int_{-\infty}^{\infty} \int_{-\infty}^{l \geq c} \mathrm{pdf}_{L_i}(l)\, \mathrm{pdf}_{C_i}(c) dc\, dl = \int_{-\infty}^{\infty} \mathrm{CDF}_{C_i}(l)\, \mathrm{pdf}_{L_i}(l) dl \tag{3}$$

where CDF_{C_i} is the cumulative probability density function for the capacity. Unacceptability of containment failure is equivalent to conditions that all P_{Fi} should be at a “physically unreasonable” level P_s.

The idea of characterizing risk as a set of triplets (scenario, its frequency, and probability of consequences) was further developed and practically applied to assessment of severe accident risks in ROAAM [1]. According to ROAAM, the use of Risk for effective management and regulation of rare, high-consequence hazards requires the simultaneous (coherent) consideration of (i) safety goal, (ii) assessment methodology, and (iii) application specifics. ROAAM provides guidelines for development of frameworks for bounding the epistemic (modeling), and aleatory (scenario) uncertainties in a transparent and verifiable manner that should enable convergence of experts’ opinions in the review process.

Important premise of ROAMM is that safety goals can be defined only qualitatively when epistemic uncertainty is significant. The goal should effectively communicate the idea that the perceived hazard is “physically unreasonable” under “any circumstances” leading up to it in a “physically meaningful” context. More specifically, for severe accident analysis the safety goal can be defined as: “containment failure is a physically unreasonable event for any accident sequence that is not remote and speculative” [1].

In order to achieve the transparency and verifiability, ROAAM employs its principal ingredients: (i) identification, separate treatment, and maintenance of separation (to the end results) of aleatory and epistemic uncertainties; (ii) identification and bounding/conservative treatment of uncertainties (in parameters and scenarios, respectively) that are beyond the reach of any reasonably verifiable quantification; and (iii) the use of external experts in a review, rather than in a primary quantification capacity.

The degree of uncertainty (or confidence) in prediction of the future course of events based on currently available evidences (data and experience with similar courses of action in the past) is often expressed using such terms as "possibility", "likelihood", or "probability". In this work, we use "probability" to characterize epistemic uncertainty, i.e. confidence in prediction of outcomes of a physical process, or that a value of a physical parameter belongs to certain interval. Such probability is evaluated by an expert, but it is determined by the evidence in hand. Therefore, two rational beings given the identical evidence must assess the probability identically [3]. "Frequency" is the outcome of an experiment involving repeated trials. Aleatory uncertainty is expressed in terms of frequency.

Separation of epistemic and aleatory uncertainties stems from the work of Kaplan and Garrick [3]. Separate treatment of screening frequency for aleatory, and the physically unreasonable concept for epistemic uncertainties is a must for clarity and consistency of the ROAAM result.

An arbitrary scale for probability is introduced which defines a physically unreasonable process as one involving the independent combination of an end-of-spectrum with one expected to be outside but cannot be positively excluded [1]:
1/10 Behavior is within known trends but obtainable only at the edge-of-spectrum parameters.
1/100 Behavior cannot be positively excluded, but it is outside the spectrum of reason.
1/1000 Behavior is physically unreasonable and violates well-known reality. Its occurrence can be argued against positively.

The starting point of ROAAM is an interest in the "likelihood" (L_i) of different containment failure modes (hazards H_k) given a set of initial plant damage states ($\{D_i\}$)

$$L_i(H_k) = G(p_1, p_2, \dots, p_l), \quad \text{given } \{D_i\} \tag{4}$$

where damage states have frequency higher than selected screening frequency f_s and lower than target frequency f_t achieved as the prevention goal, that is, $f_s < f_i(D_i) < f_t$.

The approach employed in ROAAM is not to realize a defensible approximation to function G, and seeking the likelihood L_i, but to establish that it is (or can be made by appropriate decisions) low enough as to regard the hazard H_k as physically unreasonable, avoiding excess conservatism while still remaining convincing [1].

A separation must be made between the aspects of systems response that can be stated as well-posed physical problems or "causal relations", and other aspects which are subject to inherently variable behavior and called "intangibles". The structure of separation synthesis is called "probabilistic framework". Each framework refers to a particular "scenario" s_j. The art in the decomposition is to envelop the behavior through the coherent use of "intangibles" and respective "scenarios" such that it will be understandable (and scrutable). Each "causal relation" requires an in-depth and demonstrable understanding of the controlling physics; "scenarios" and "intangibles" are to fill in the gaps whenever this is not possible. Uncertainty in causal relations can be reduced. Uncertainty in intangibles can only be qualitatively approached, but it can always be bounded. The adequacy of scenarios can be determined according to the completeness of the logical structures used in deriving them. The process of integration through the probabilistic framework is effected by introducing a scale for the temporary quantification of intangibles, and the results are rendered in qualitative terms by applying this scale in reverse.

The problem is decomposed into framework and stochastic scenarios $\{s_{ij}\}$, such that:

$$L_i(H_k) < P_{ij}(H_k), \quad P_{ij}(H_k) = F(d_1, d_2, \dots, i_1, i_2, \dots) \tag{5}$$

where $\{d_i\}$ is a set of "deterministic" parameters, $\{i_i\}$ is a set of "intangible" parameters, $P_{ij}(H_k)$ is based on arbitrary probability scale. The goal of analysis is to show that

$$P_{ij}(H_k) < P_s \text{ given } \{D_i\} \text{ for all } \{s_{ij}\} \tag{6}$$

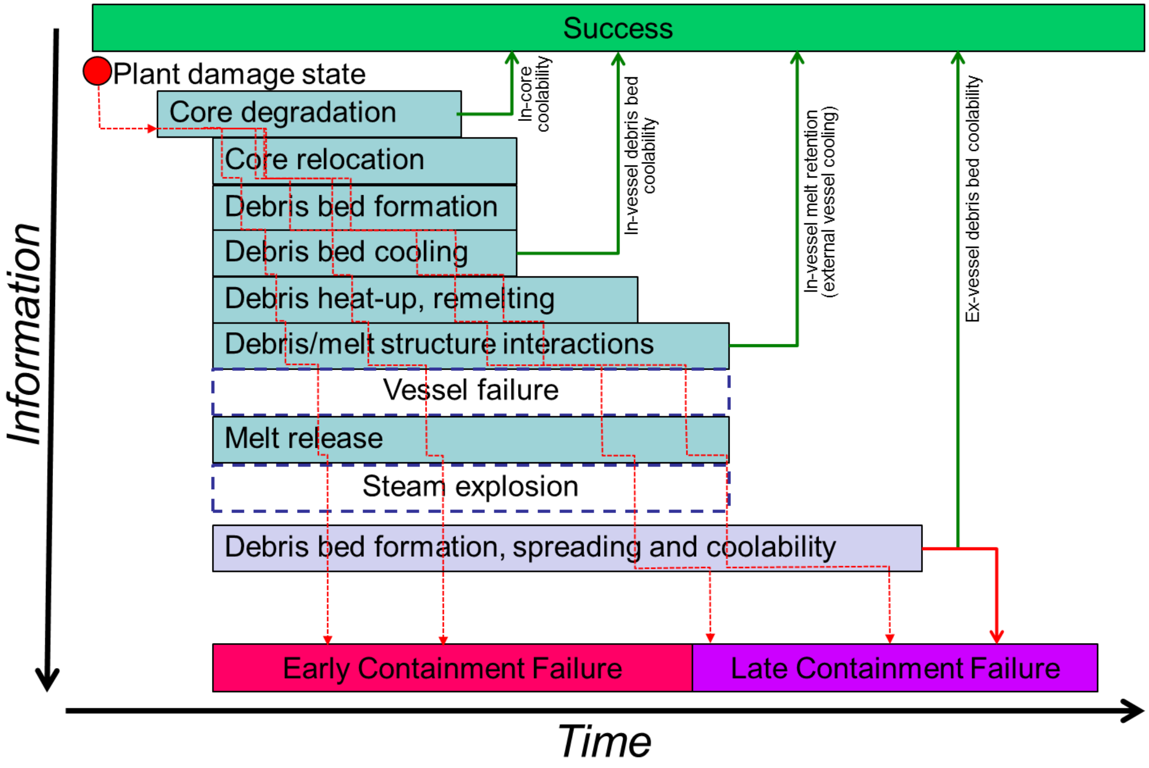
where P_s is the "physically unreasonable" level. The above structure separates out epistemic from aleatory uncertainty which is also motivated by the distinct approaches to judge residual risk: with screening frequency for aleatory, and with physically unreasonable concept for epistemic. Any stochastic behaviour not already included in the definition of the severe accident window (the plant damage states to be considered) can be taken up in the definition of scenarios and intangibles, since they would be expected to dominate the uncertainty in any case. If necessary, however, stochastic parameters, or even processes, can appear explicitly in (5). A similar separation can be effected in this case, too, by simply finding the total probability in each frequency range, and applying the same criteria for judging the results – but now these frequencies should be combined with the respective plant damage state frequencies [1].

4.1. Nordic BWR challenges for ROAAM

Phenomenology and Scenarios

While ROAAM is logically sound and has been successfully applied in several practical cases to resolve severe accident issues, there are some challenges for application of ROAAM to Nordic BWR case. Typical phenomenological stages of severe accident progression in Nordic BWR are shown in Figure **1**.

Figure 2. Severe accident progression in Nordic BWR.



The multistage path from the initial plant damage state to the containment threats is an important source of complexity and uncertainty. Phenomena and scenarios including operator actions are tightly coupled in their mutual interactions and eventual impact on the possibility of different containment failure modes. Conditions created at the earlier stages can significantly affect configurations and problem statements at later stages. For instance, if there is no activation of lower drywell flooding, then steam explosion risk is eliminated, but hot corium melt will attack cable penetrations in the containment floor leading to almost immediate containment failure.

Timing of transition between different stages is also important. Different time-dependent trajectories of the accident scenarios with the same logical sequence of the stages can result in different outcomes. For instance, decay heat is decreasing with time providing much better chances for coolability of the debris bed if melt is released from the vessel later [4]. However, if melt is released from the vessel later, it will have higher temperature, which could increase the risk of debris agglomeration [5], [6], [7] and eventually hinder coolability of the debris bed [8] and create a potential for an energetic steam explosion which can threaten containment integrity.

Combination of (at least) two threats (non-coolable debris and steam explosion) is another source of uncertainty. For instance, even a mild steam explosion might lead to degradation of debris bed cooling function, e.g. by destroying protective covers for cable penetrations in the containment floor and exposing them to hot debris, or by creating a leak of coolant from the lower drywell, or by activating filtered containment venting, releasing fraction of nitrogen which can potentially lead to drop of containment pressure below atmospheric level, etc.

Apparent major challenge for application of ROAAM to Nordic BWR is complexity of tightly coupled transient phenomena and scenarios which limit effectiveness of heuristic approaches in (i) problem decomposition and (ii) a priori judgment about importance and impact of coupled in time phenomena and scenarios on the accident progression and outcome.

Decision Making Context

Conditional containment failure probability is considered in this work as an indicator of severe accident management effectiveness for Nordic BWR. It is instructive to note that different modes of failure (assumed to be equivalent to loss of containment integrity) can potentially lead to quite different consequences in terms of radioactivity release. At this point we consider any failure mode as unacceptable for the sake of conservatism.

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.

However, it is not always obvious that existing system cannot meet the safety goal even if further investments in development of new knowledge will be continued. Especially for complex systems, such as SAM of Nordic BWR, uncertainty can create a space for decision makers' "hope" that the system is safe due to some incompletely understood phenomena or interactions, and thus acquiring further knowledge about the system is justified. As such proposition is driven by the "hope", it is clear that conservative treatment of uncertainty would not be very helpful. For clarifying if such hope is reasonable, the assessment should be focused on the possibility that containment doesn't fail using "optimistic" treatment of uncertainty.

Thus, to be truly useful for decision making on the Nordic BWR SAM case, the risk assessment framework should be capable of providing assessments in support for both possible decisions: (i) current strategy is sufficiently reliable and no changes are necessary; (ii) strategy is not sufficiently reliable and changes are necessary.

A difficulty arises when neither can be demonstrated with sufficient confidence. For instance, bounding ("conservative" or "optimistic") approaches fail to characterize system risks when failure or success domains are positioned in the middle of the uncertainty space. In other words, only an "optimal" course of events can lead to success or failure. This is often the case when there are competing and interacting phenomena or threats, when positive or negative effect on the failure possibility of some parameter or event changes depending on other parameters or events. For instance, in case of successful attempt of in-vessel debris cooling using control rode guide tube (CRGT) flow, melt release from the vessel can be prevented. However, if corium retention is not successful, CRGT cooling can lead to delay of vessel failure, formation of a larger melt pool with higher superheat. Melt release from the vessel with such conditions can significantly increase potential energetics of steam explosion and the risk of formation of agglomerated, non-coolable debris bed. Feasibility of using "best estimate" or "risk informed" approaches for decision making in this case is contingent on the system, data and knowledge. If dependencies are strong, risk quantification can be polluted with uncertainty to the point where "everything is possible" due to "combinatorial explosion of possibilities". Using "risk informed" approach in such case can be at best inconclusive, and in the worst case misleading. If "everything is possible", it is a clear sign that the system is complex. In other words, understanding and control of the system is beyond our reach.

Eventually decision has to include cost benefit analysis. If potential costs of improving the current state of knowledge are high then the decision to change the system in order to reduce its complexity would be the most reasonable. If the costs are acceptable, then extensive sensitivity and uncertainty analysis can be quite useful for identification of priorities on collection of data and defining research priorities. However, quantitative uncertainty is high in estimations of risks related to potential losses vs cost of necessary research.

Thus a structured process is needed for coherent (i) development of risk assessment framework, (ii) collection of necessary data, and (iii) development of new knowledge. This process should be guided by extensive sensitivity and uncertainty analysis and eventually result in a robust and scrutable assessment of either "possibility" or "necessity" of containment failure in order to support decision making. In the next section we discuss some important aspects of development of such process for Nordic BWR SAM.

4. ROAAM+ PROBABILISTIC FRAMEWORK FOR NORDIC BWR

It is clear that key ingredients of ROAAM such as:

- Separation of aleatory and epistemic uncertainties through
    - Consideration of risk as a set of the triplets (scenario, its frequency, and probability of consequences),
    - Decomposition of the problem into stochastic "scenarios" and deterministic "frameworks",
- Arbitrary scale of probability for epistemic uncertainty,
- Qualitative definition of safety goal,

are critical for consistency of assessment and transparency of review and must be preserved. However, the challenges presented by Nordic BWR SAM strategy require further development of the approach. In this section we discuss the basic ideas and examples of development of such an approach which we call ROAAM+.

The goal of the ROAAM+ approach is to provide sufficient information for a decision to:

I. Keep SAM strategy: "Possibility" of containment failure is low even with "conservative" treatment of uncertainty, thus current strategy is reliable.
II. Modify SAM strategy: "Necessity" of containment failure in the course of accident is high (i.e. "possibility" that containment doesn't fail is low) even with "optimistic" treatment of uncertainty, thus the current strategy is unreliable and changes should be considered.

In order to achieve the goal, ROAAM+ process is developed for construction and adaptive refinement of the risk assessment framework, models, and data. The process is aiming to refine the resolution of the framework in order to bound the influence of the largest contributors to the uncertainty in risk assessment.

4.1. Iterative Adaptive Refinement Process for Development of Risk Assessment Framework: Two-Level "Coarse-Fine", "Forward" and "Reverse" Analysis.

System complexity can limit effectiveness of heuristic approach (based on expert judgment) to identification of the key physics which drive system behavior. Therefore, there is a need for an iterative research process which can help in identifying and evaluating importance of different factors for the ultimate risk assessment. This implies that at each stage of the process, a framework for risk assessment should exist, providing a means for sensitivity and uncertainty analysis of "possibility" and "necessity" of containment failure with respect to the uncertain elements of the framework. Such analysis should, in turn, results in activity on improvement of the framework and data to assess the impact of such improvements in the next iteration.

Therefore, in the proposed framework we implement three different types of analysis (i) Conservative assessment of containment failure possibility; (ii) Optimistic assessment of containment failure necessity; and (iii) Sensitivity and uncertainty analysis as an instrument for guiding construction and refinement of the risk assessment framework itself. In practice, different analysis types are implemented through consistent use of assumptions on uncertainty in (i) scenarios and (ii) ranges and probability distributions of the uncertain parameters. Sensitivity and uncertainty analysis is employed for both (i) optimal refinement of the data, knowledge and risk analysis framework, and (ii) optimization and assessment of effectiveness of potential system modifications.

Complex phenomena and feedbacks require adequate complexity of the models. These "full models" (FMs) are usually implemented for each stage of accident progressing in respective multidimensional severe accident, thermal hydraulic, and structural analysis codes. Direct application of such fine-resolution models for extensive sensitivity and especially uncertainty analysis is often unaffordable due to extreme computational costs and difficulties in establishing direct coupling between the codes. Therefore, we employ a two-level coarse-fine modeling approach. At the first (bottom) level we use loosely coupled FMs and available experimental evidences in order to generate relevant data and develop understanding of key physics. The data and knowledge are used to develop and validate coarse-resolution "surrogate models" (SMs). The SMs provide computationally efficient approximations for the most important parameters of the FM solutions. The SMs are used at the second (top) level of the framework for sensitivity, uncertainty analysis and risk quantification. We call this process "forward" analysis.

When complexity is high, it is difficult to identify a priori what is more important and what is missing from our knowledge of each individual stage of the accident progression. Such information can be obtained when all stages are coupled and a connection between uncertainties at each individual stage and resulting uncertainty in containment failure probability can be established. Until such connection is established, it is not possible to assess if FMs provide sufficient resolution for all important phenomena. In fact, some of the FMs might not be available yet. In such case FMs should be designed according to the requirements which can be inferred from the results of the reverse analysis. Accuracy of the FM should be sufficiently qualified through scaling, calibration, verification, validation and uncertainty quantification process using relevant experimental data. The need for new data stems from the model validation needs. Therefore there is a need for iterative refinement process of the FMs, SMs, experimental data and structure of the framework. Criteria for the need of refinement can be established based on consideration of the failure domain. Failure domain (FD) is a domain in the space of the uncertain parameters where probability of containment failure is larger than a "physically unreasonable" threshold. The main criteria for the need of the refinement are (i) how large is the uncertainty in resolving the boundaries of the failure domain with existing FM and SM implemented in the framework, and (ii) are there any physical phenomena or scenarios which are not taken into account yet, but can significantly change FD boundary. Naturally, the FD identification and necessary refinement starts from the last stages of the accident progression analysis and propagates "upstream" to the earlier stages. We call this process "reverse" analysis.

The two-level coarse-fine approach to development and iterative adaptive refinement of the risk assessment frameworks is summarized below:

1) *Development and refinement:* of models, frameworks and data based on the results of the forward and reverse analyses in order to reduce uncertainty in the failure probability and resolution of failure domain boundary.

Experimental evidences and fine-resolution but computationally expensive methods (FMs) are used in order to:

   i. Develop hypothesis about key phenomena and provide better understanding of their possible interdependencies,
   ii. Identify transitions between qualitatively different regimes and failure modes, and
   iii. Generate reference databases for development calibration and verification of coarse-resolution but computationally efficient surrogate models (SMs).

FMs are run in "exploratory" mode, loosely coupled or independently from each other, assuming bounding ranges for model input parameters. Preliminary scaling analysis is carried out for the experimental evidences.

2) *Forward analysis:* quantification of major contributors to the uncertainty in the failure probability at each stage of the modeling of accident progression.

A probabilistic framework is developed based on coupled SMs in order to connect the initial plant damage states with respective containment failure modes.

   i. Deterministic processes are treated using the developed and verified SMs preserving importance of scenarios and timing.
   ii. Sensitivity and uncertainty analysis is carried out using the framework to:
      a. Identify significant and unimportant parameters, regimes and scenarios.
      b. Quantify the risk and contribution to the overall uncertainty for the most influencing factors.

3) *Reverse analysis:* identification of failure domains and their boundaries at each stage of the modeling of accident progression.

Failure domains and their boundaries are identified in the spaces of uncertain input parameters for each SM (representing different stages of the accident progression) in order to identify the needs for improvement of:

   i. Experimental data and scaling.
   ii. FMs and their validation matrices.
   iii. SMs, calibration and verification databases (based on FMs and experimental data), interconnections and databases of solutions.
   iv. Overall structure of the problem decomposition into scenarios and frameworks.

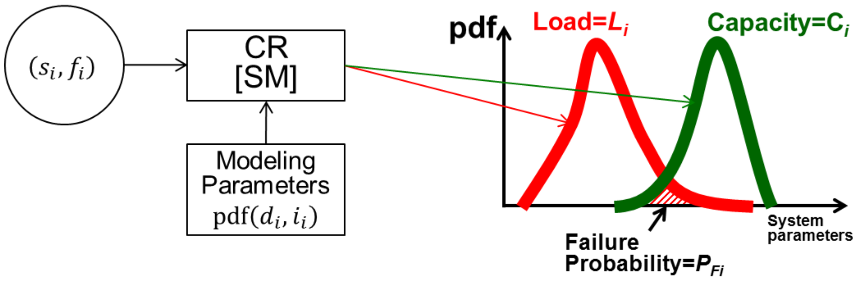
Such iterative process is designed to develop state of the art knowledge, confidence and transparency in the risk assessment results, to the point when convergence of experts' opinion on the possibility or necessity of containment failure can be achieved. Possibility of such convergence is a stopping criterion for the refinement process.

Adaptive decomposition (into scenarios and phenomena) depends largely on the knowledge base (relevant data, code capability, etc.). Employment of the fine resolution FMs in the process of risk quantification and uncertainty reduction is justified when appropriate evidences of the models' validation are provided. Failure domain (reverse) analysis points to the domains of parameters and scenarios where evidences of detailed validation are most needed and improvement of the validation database has the largest impact on the uncertainty reduction. Proper scaling of experimental data is important for establishing consistency between modeling and experimentation in the iterative process of uncertainty reduction. In this light, a list of phenomena and corresponding experiments that can be used for validation of FMs and calibration of SMs should be provided along with the assessment of the data quality (relevance, scaling, and uncertainty). Such information is a basis for the decisions on decomposition and the needs for improvements of the evidence database.

4.3. Failure Probability

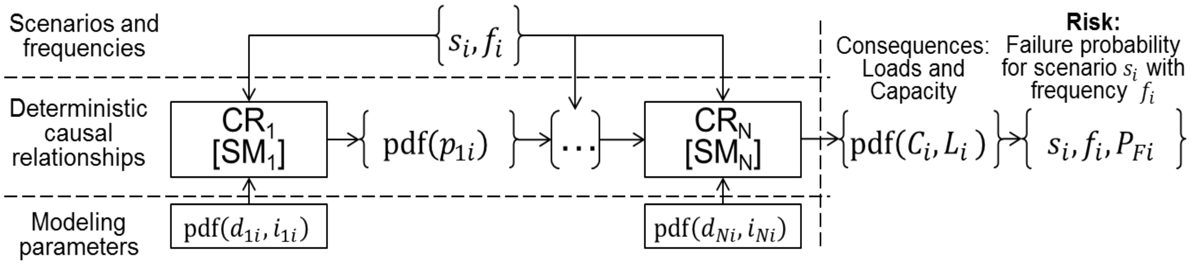
Quantification of failure probability is the ultimate goal of the analysis. Illustration of the failure probability quantification determined by forward propagation of the uncertainties through a single stage framework is illustrated in Figure 3.

Figure 3. Failure probability in a single stage framework.



For each plant damage state $\{D_i\}$ there is a set of respective scenarios $\{s_{ij}\}$, are characterized by frequencies (f_{ij}). For the sake of brevity, in the future we will omit second index when referring to scenarios (s_i) and their probabilities (f_i) considering them as a whole set of all scenarios relevant to all initial damage states. Scenarios (s_i) introduce specific combinations of initial and boundary conditions for causal relationships (CR) and structure of the probabilistic framework. The CR provides "bounding" assessment of the load and the capacity which can provide optimistic and conservative estimates. If bounding assumptions in modeling approaches are not obvious "a priori", sensitivity analysis is required. A set of surrogate models (SM) is used to approximate the CR. Epistemic uncertainty in prediction of the failure probability is introduced by multidimensional probability density function $(\text{pdf}(d_i, i_i))$ of intangible (i_i) and deterministic (d_i) modeling parameters. These distributions determine the probability of the consequences $(P_i(c_i))$ or, more specifically, probability of containment failure (P_{Fi}) of scenario (s_i). It is instructive to note that Figure 3 provides a simplified view on the problem, where space of system parameters is generally multidimensional and different types of loads and capacities correspond to different threats and failure modes.

Figure 4. Failure probability in a multistage framework.



Similarly to the single stage process, the probability of failure (P_{Fi}) in scenario (s_i) can be introduced for a multistage framework where CR is a set of N models connected through initial conditions, as illustrated in Figure 4. Simulations are carried out for each individual scenario s_i separately, which enables maintaining of transparent separation of aleatory (characterized by frequency f_i of scenario s_i) and epistemic uncertainties. Note that scenario parameters can affect modeling at any intermediate stage. Respective timing should also be provided as a part of scenario s_i, e.g. timing of activation, failure or recovery of specific safety systems. Different scenarios might require different chains of CRs, or "phenomenological event trees". Splinters should be used to ensure consistent bounding approaches in addressing intangible characteristics of the scenarios. Output of CR_k is determined as multidimensional probability density function $\{\text{pdf}(p_{ki})\}$ and provides an initial input conditions for model CR_{k+1}. Timing is explicitly included as one of the p_{ki} parameters.

In the conservative assessment we are seeking for a confirmation that $P_{Fi} < P_S$, or, in other words, that containment failure in scenario s_i can be positively excluded as physically unreasonable according to current state of knowledge. This conclusion would support the proposition that current SAM is reliable and no changes are necessary.

In the optimistic assessment we are looking for confirmation that $P_{Fi} > P_S$ which can be interpreted as: containment failure cannot be excluded as physically unreasonable even with optimistic bounding assumptions and state of the art knowledge. In other words "necessity" of containment failure is unacceptably high and the SAM has to be changed through modifications of the SAMGs or design.

The state of knowledge is expressed in terms of the ranges and probability distributions for the uncertain input parameters. Selection of the models, ranges and distributions is based on evidences (experimental data, scaling, synthesis of fine resolution simulation results, etc.).

Failure probability is used not only as the final results of the assessment, but also as a research instrument in the adaptive process. Sensitivity analysis of P_{Fi} to ranges and distributions of the uncertain parameters is used to identify (i) major sources of the uncertainty and possible unreasonable conservatism in the risk assessment, (ii) the needs for refinement of the evidence database.

Joint consideration of sensitivity of failure probability P_{Fi} to (i) possible improvement of knowledge necessary to reduce conservatism in the framework, and (ii) possible changes in the accident management strategy necessary to decrease failure probability with given state of knowledge, and associated costs for both options can provide a quantitative measure for selection of the most efficient approaches in both (a) risk assessment, and (b) risk management.

In the forward analysis, information is propagated from the initial plant damage state through the sequences of phenomena, determined by specific scenarios, towards the failure probability for each scenario, estimated at the very end. Such process provides limited information for inferring about adequacy of selected framework structure and generated data for the assessment of the failure possibility. Forward propagation of the uncertainties, especially in the multistage modeling framework, often amplifies uncertainties at each stage, unless there are clear limiting physical mechanisms. As a result of such amplification, there is a risk of "phenomenological explosion" (analogous to combinatorial explosion) when epistemic uncertainty becomes so large that success and failures become equally possible and nothing can be positively excluded as physically unreasonable. Therefore, there is a need for another kind of analysis where adequacy and consistency of the modeling framework and data can be evaluated.

4.4. Failure Domain

The primary goal of failure domain analysis is to identify the conditions and explain the reasons of failure in terms of key physics and scenarios. Identification of the failure domain is a product of the "reverse" analysis which propagates information "backwards" from the end state where failure is determined through the CR to the spaces of input (scenario and modeling) parameters (Figure 5). By identifying and grouping scenarios and conditions which lead to failure, we can determine and explain the reasons of failure using compact representation of information, amenable for scrutiny. "Failure Domain" (FD) in the space of scenario parameters $\{s_i\ \}$ is a subdomain where probability of failure P_F is larger than a "physically unreasonable" level (P_S) of probability ($P_{Fi} \geq P_S$) (Figure 5).

$$\{s_i^F | \mathrm{pdf}(d_i\ , i_i\ )\}\colon P_F(s_i^F) \geq P_S \tag{7}$$

"Failure Domain" (FD) in the space of deterministic modeling parameters $\{d_i\ , i_i\ \}$ is a subdomain where load (L_i) exceeds Capacity (C_i) (Figure 5).

$$\{(d_i^F, i_i^F) | s_i\ \}\colon Z_i(d_i^F, i_i^F) = C_i - L_i \leq 0 \tag{8}$$

Figure 5. Failure probability in a single stage framework.

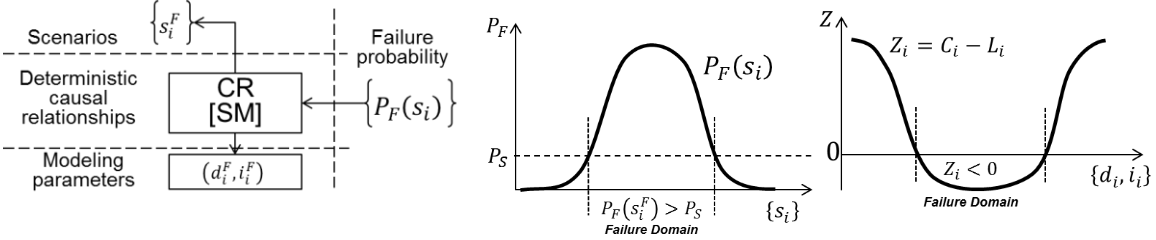
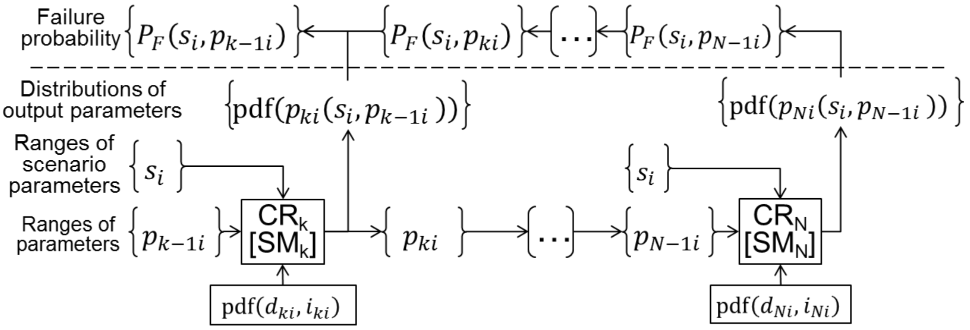


Figure 6. Failure probability in a multistage framework.



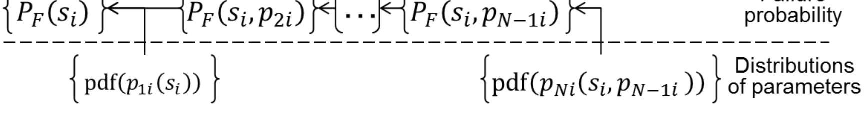
Failure domain can also be used when CR is presented as a set of models connected through initial conditions. “Reverse” analysis starts from the last stage where information about failure possibility is available and is propagated “upstream” through the previous stages. In this case, the output p_{ki} of any intermediate stage CR_k depends on the input parameters from the previous stage p_{k-1i}, in addition to scenario and modeling parameters, as shown in Figure 6. Therefore, characteristics of the failure domain at each stage (k) also include p_{ki} and p_{k-1i}. For instance, failure probability as a function of the output from the previous $(k-1)$ stage $P_F(s_i, p_{k-1i})$ can be calculated according to (9), (10) if $P_F(s_i, p_{ki})$ and distribution $\mathrm{pdf}\big(p_{ki}(s_i, p_{k-1i})\big)$ at the current stage (k) are provided.

$$P_F(s_i, p_{N-1i}) = \iint_{Z_i \leq 0} \mathrm{pdf}_{Z_i}\Big(p_{Ni}\big(s_i, p_{N-1i}\big)\Big)\, dp_{Ni} \tag{9}$$

$$P_F(s_i, p_{k-1i}) = \int_{-\infty}^{\infty} P_F(s_i, p_{ki})\mathrm{pdf}\Big(p_{ki}\big(s_i, p_{k-1i}\big)\Big)\, dp_{ki} \tag{10}$$

These formulas can be applied recursively as shown in Figure 7 from the very end to the very beginning. The goal of such recursive calculations is to obtain failure characteristics at all intermediate stages.

Figure 7. Recursive calculations of failure probability in a multistage framework.



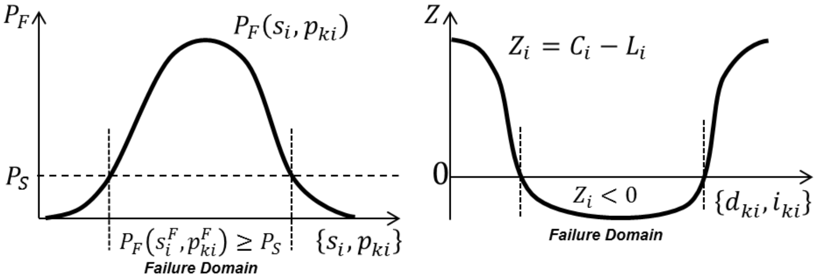
At each stage, similarly to the single-stage case, we can determine failure domains in the space of scenarios and model input parameters $\big(s_i\ , p_{ki}\big)$, and in the space of uncertain modeling parameters $\big(d_{ki}, i_{ki}\big)$:

$$\big\{\big(s_i^F, p_{ki}^F\big)\big|\mathrm{pdf}\big(d_{ki}, i_{ki}\big)\big\}\colon P_F\big(s_i^F, p_{ki}^F\big) \geq P_S \tag{11}$$

$$\big\{\big(d_{ki}^F, i_{ki}^F\big)\big|\big(s_i\ , p_{ki}\big)\big\}\colon\ Z_i\big(d_{ki}^F, i_{ki}^F\big) = C_i - L_i \leq 0 \tag{12}$$

Note that $(s_i \ , p_{ki})$ in formula (12) is not a distribution but a point selected within the ranges of respective parameters. It is instructive to note that identification of failure domain (s_i^F, p_{ki}^F) can be done even if model CR_k doesn't exist yet. In fact, reverse analysis is an efficient tool for development of requirements (e.g., to resolve boundary of the failure domain (s_i^F, p_{ki}^F)) for the models and new experiments which should be designed and incorporated in the framework.

Figure 8. Failure domains in a multi-stage framework.



Failure domain boundary (index FB) can be determined in the space of scenario (s_i^{FB}, p_{ki}^{FB}) and modeling parameters $(d_{ki}^{FB}, i_{ki}^{FB})$ using provided formulas (11), (12) with equality sign. For computationally efficient identification of the failure domain boundaries application of some sort of optimization approach (e.g. such as genetic algorithm) is usually required. Grouping of different scenarios is necessary to present information in a compact form, especially when different failure modes correspond to multiple failure domains.

Analysis of the failure domain boundary can tell a lot about what is important for transition from "safe" to "failure" to occur. Sensitivity analysis of failure domain boundary is a powerful instrument for identification of the needs for refinement of the data and structure of the risk assessment framework. It points to the key phenomena and data affecting failure probability. Adequacy and consistency between: (i) scenarios, (ii) structure of the framework, (iii) individual physical models, (iv) ranges and distributions of the uncertain modeling parameters, and (v) available experimental data and other evidences, should be carefully evaluated to increase confidence in prediction of the failure domain boundary.

4.5. Characterization of evidence for integrated assessment and FM validation

Each FM represents a complex, often multi-physics and multi-scale phenomenon/processes. Multiple models are then brought together. To reduce uncertainty in model forms and model parameters, e.g., narrowing their distributions (pdf or applicability intervals), models and simulation codes are benchmarked and calibrated against relevant experiments. This requires identification, processing, qualification, and appropriate integration of a necessarily substantial and large body of heterogeneous data. Generally, effectiveness of model calibration depends on (a) availability (quantity, reproducibility) of applicable experiments; (b) degree of applicability of experiments (material scaling, geometric similarity, physics scaling); (c) quality of experimentation: characterization of uncertainty in experimental (initial, boundary) conditions; (d) diversity of diagnostics, number of measuring channels, temporal and spatial resolutions; and (e) characterization of uncertainty of measured data [20].

Subject to a broad range of above-listed characteristics, data sets obtained in experimental programs vary greatly by their format and validation and uncertainty quantification (VUQ) quality. In order to evaluate the impact of the uncertainty on predicted quantity of interest (QOI), it requires that the uncertainty be quantified, integrated and propagated toward QOIs. In an assessment framework such as one developed in this study, characterization and harmonization of evidence are ever more instrumental for the integration. For example, information value (weight) of evidence (dataset) can be computed through a function of global accuracy (relevance/applicability/scaling): Reactor Prototypicality Parameter, and local precision e.g. Experimental Measurement Uncertainty [20].

5. DEVELOPMENT OF THE FRAMEWORK AND MODELS

5.1. Approach to Development and Refinement of the ROAAM+ Framework, Models and Data for Nordic BWRs

The top layer of the ROAAM+ framework for Nordic BWR (Figure 9) decomposes severe accident progression (Figure 1) into a set of causal relationships (CR) represented by respective surrogate models (SM) connected through initial conditions. While decomposed, the framework SMs still can be used for an end-to-end transient analysis if necessary.

Computational efficiency of the top layer of the framework allows for extensive sensitivity and uncertainty analysis in the forward and reverse analyses. Forward analysis defines conditional containment failure probability for each scenario $\{s_j\}$. Reverse analysis identifies failure domains in the space of scenarios $\{s_i\}$, and “deterministic” $\{d_i\}$ and “intangible” $\{i_i\}$ parameters specific to each model. Grouping and classification of failure scenarios corresponding to specific initial plant damage states helps to identify plant vulnerabilities and provides insights into possible efficient mitigation actions by operator. Failure domain in the space of deterministic and intangible modeling parameters $\{d_{ki}, i_{ki}\}$ identifies the need for improvement of knowledge, modeling and data.

Figure 9. ROAAM+ framework for Nordic BWR.

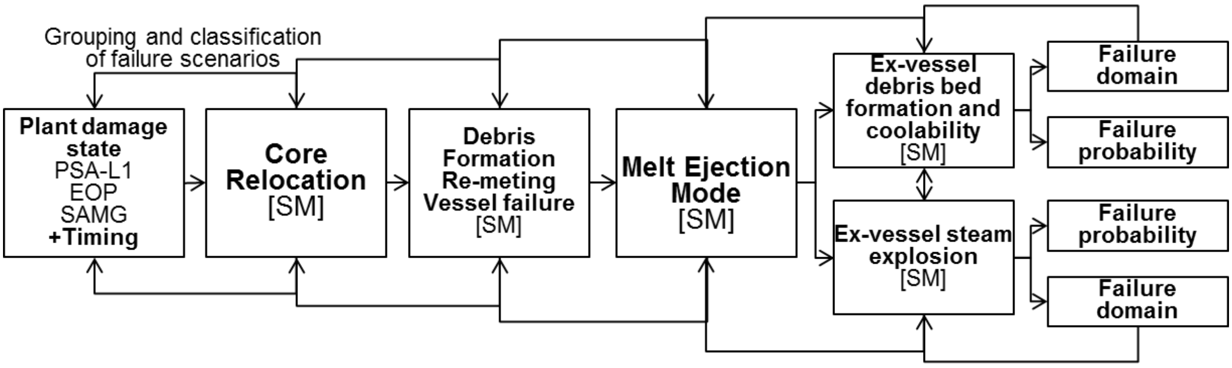
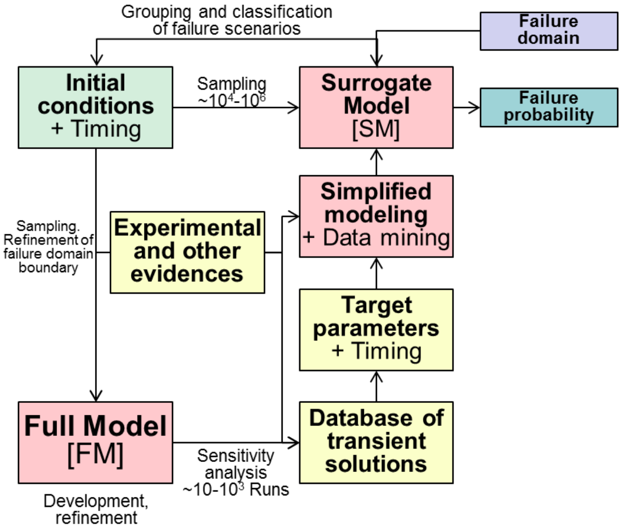


Figure 10. Full and Surrogate model development, integration with evidences, refinement, prediction of failure probability and failure domain identification.

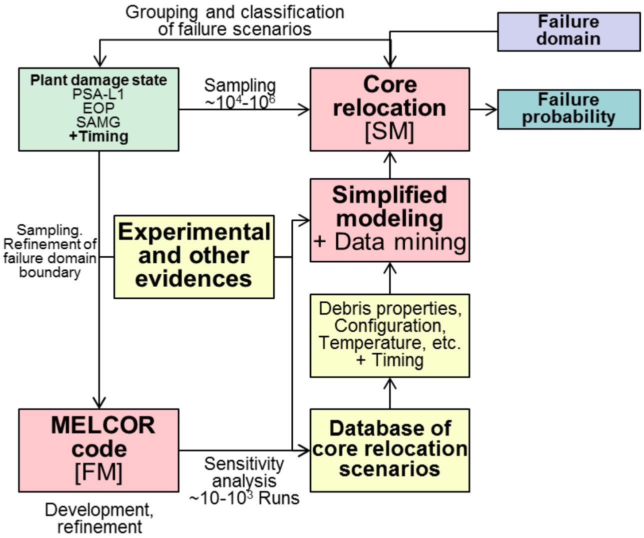


However, the process of development and validation of the individual surrogate models is most important for completeness, consistency, and transparency of the results. General ideas of the process are illustrated in Figure 10. Initial conditions come from the SM analysis at the previous stages of the framework. Experimental and other evidences provide a knowledge base for validation of the FMs and calibration of SMs. Full Model (FM) is implemented as detailed fine resolution (computationally expensive) simulation approach. Database of the FM transient solutions is developed in order to provide better understanding of basic physical processes and typical behavior of the target parameters. The target parameters are the input conditions for the next model in the framework. Simplified modeling approaches and data mining techniques are used in order to develop a surrogate model. Surrogate model (SM) is an approximation of the FM model prediction of the target parameters which employ simplified (coarse resolution) physical modeling, calibratable closures, or approximations to the response surface of FM.

5.2. Core Relocation SM

Core relocation determines the initial conditions for corium-structure interactions, vessel failure and melt release analyses. Core relocation SM can be constructed based on quite representative database of MELCOR simulations. Timing determines initial level of decay heat for the analysis of the debris reheating and remelting. Properties of the relocated debris determine timing and mode of the vessel failure.

Figure 11. Core relocation surrogate model.



5.3. Vessel Failure SM

DECOSIM [8] and PECM [9] codes are complementary approaches which describe two different classes of scenarios with initially (i) porous debris bed and (ii) “solid cake” bed. The goal of the vessel failure SM is to predict mode (IGT, CRGT, vessel wall), timing, amount, properties and superheat of the melt available for release.

5.4. Melt Ejection SM

Quantification of breaching, ablation and plugging of the vessel opening phenomena can potentially help to reduce uncertainty in the melt release mode. Filtration of liquid melt through solid porous debris can slow down the release, limiting the effective size of the melt jet. Moreover, in the case of IGT failure, melt interaction with control rod (CR) drive motors can help to destroy coherent melt jet, at least for some initial period of time. In case of a CR guide tube (CRGT) failure and ejection, such interactions and jet breakup might be quite limited. Currently, melt release mode is the least investigated element of the framework. Adequate experimental work is necessary in order to collect the relevant evidences.

Figure 12. Debris re-melting Vessel failure surrogate model.

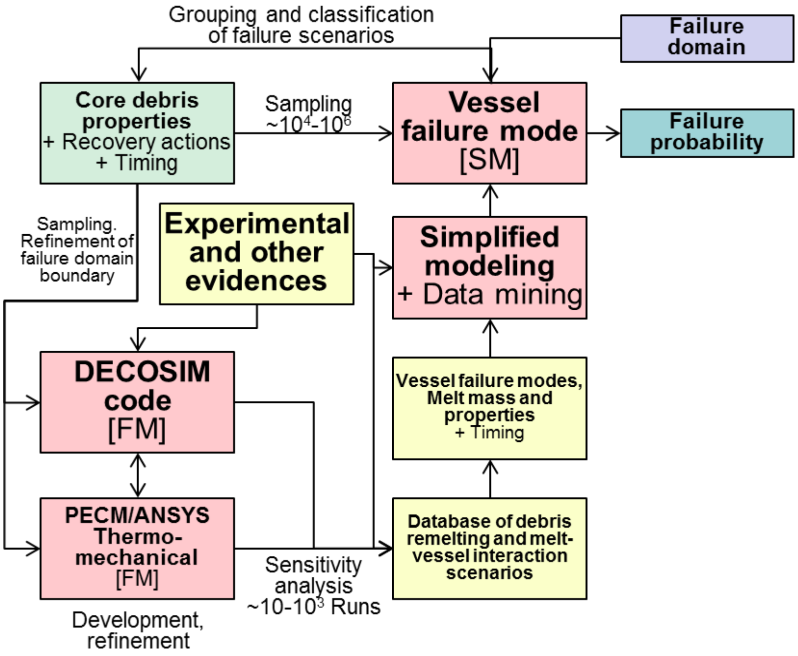
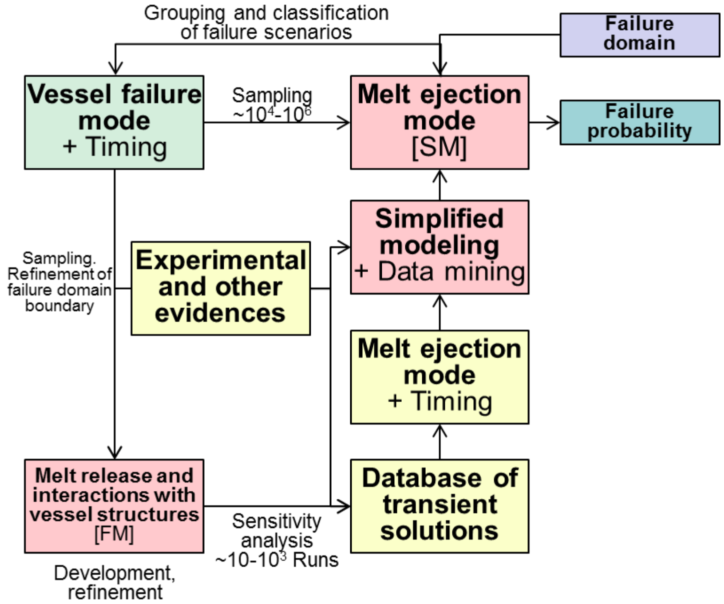


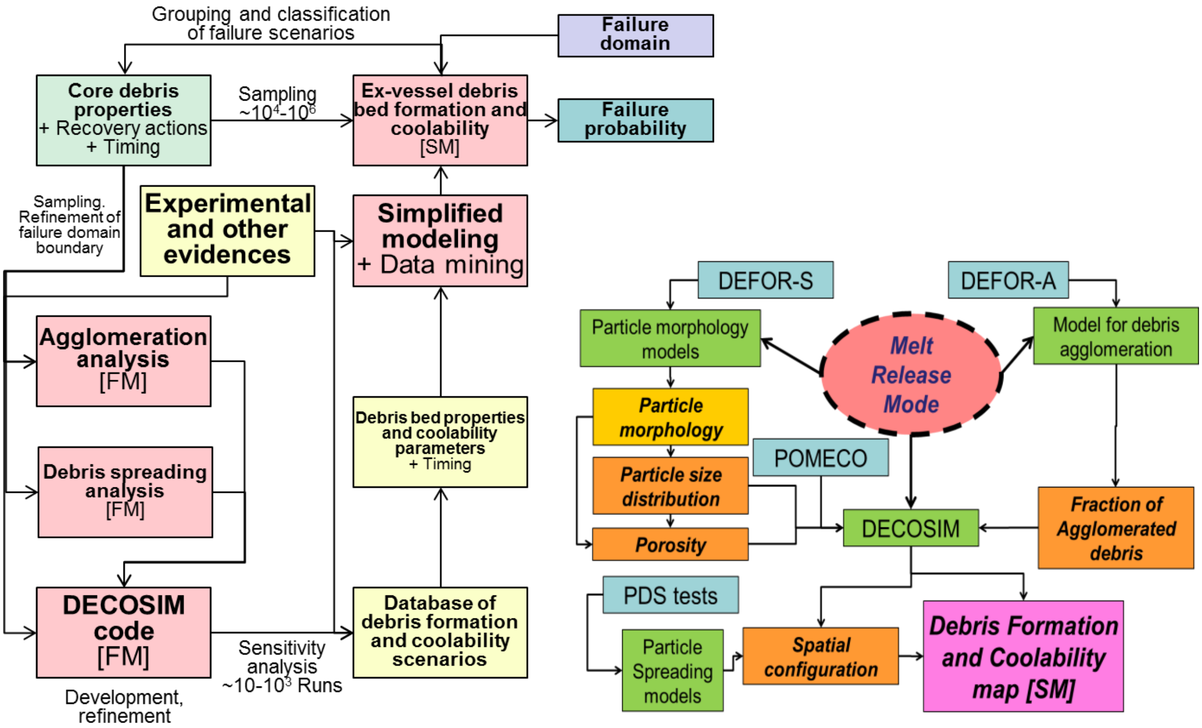
Figure 13. Melt ejection mode surrogate model.



5.5. Ex-vessel Debris Coolability SM

Phenomenology of debris bed formation and coolability is quite complex, which includes (i) jet breakup, (ii) melt droplet sedimentation and interaction with water pool; (iii) debris agglomeration; (iv) particle spreading by pool flows; (v) debris bed self-levelling by vapor flows; (vi) debris bed coolability; (vii) post-dryout behavior with possible remelting, etc. Relevant phenomena have been extensively studied in the past. Experiments (Figure 14) on debris bed and particle properties (DEFOR-S) [10], debris agglomeration (DEFOR-A) [11], porous media coolability (POMECO) [12], particulate debris spreading (PDS) [13] have been carried out. A set of full and surrogate model has been developed and validated against produced experimental data for the debris formation [14], agglomeration ([15], [16]), coolability ([17], [18]) and spreading [19] of the debris (Figure 14).

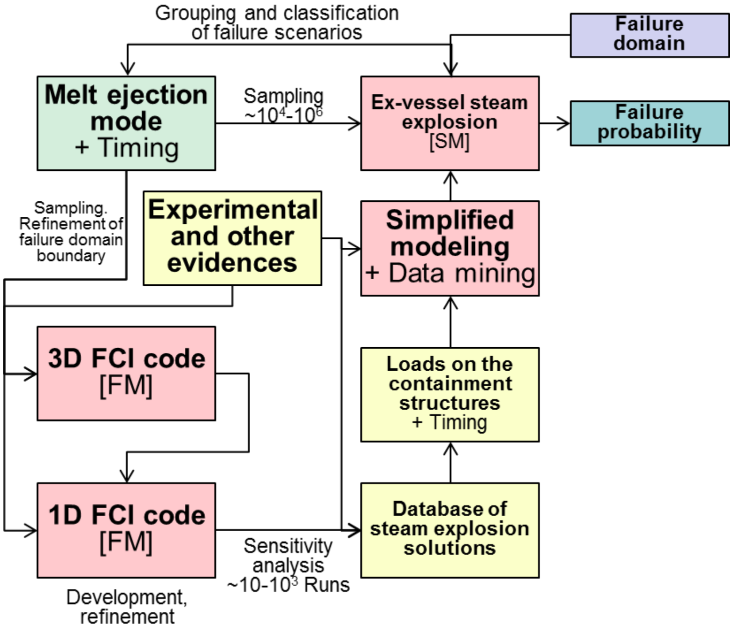
Figure 14. Ex-vessel debris bed formation and coolability surrogate model.



5.6. Ex-vessel Steam Explosion SM

The ex-vessel steam explosion framework connects melt ejection mode with steam explosion loads on the containment structures to estimate containment failure probability. Development of the SM relies on a database of solutions generated by a 1D FCI code.

Figure 15. Ex-vessel steam explosion surrogate model.



Multidimensional fuel-coolant-interaction (FCI) codes can help to identify information which is missing in 1D FCI codes. However, 2D/3D FCI codes are too computationally expensive to provide even sensitivity analysis, given large number of uncertain scenario and modeling parameters. Application of 1D code requires an additional method for calculating loads on containment structures. There is a need to resolve the link between ex-vessel coolability and steam explosion. Even a mild steam explosion might lead to degradation of debris bed cooling function. However, small size particles generated in steam explosion have little chance to settle on the bed as long as there is intensive coolant circulation in the pool.

6. CONCLUSION

Nordic BWR severe accident management case presents a fundamental challenge for ROAAM approach due to multistage process of accident progression, importance of timing in transition between different stages, coupling of threats, large uncertainty with respect to safety margins, complexity of physics and needs for computational efficiency, a-priori unknown relative importance of different factors coupled in time. In meeting the challenge, a new ROAAM+ approach is proposed. The ROAAM+ approach is designed to enable a decision on either: (i) maintaining or (ii) modifying the current SAM strategy. Respectively, in option (i), "possibility" of containment failure is low even with "conservative" treatment of uncertainty, thus the current strategy is reliable; while option (ii) entails high "necessity" of containment failure in the course of accident. The framework is based on the classical ROAAM philosophy of consistent and transparent treatment of different sources of uncertainties (aleatory and epistemic). The key ingredient of ROAAM+ approach is the process of iterative, adaptive refinement of two-level (coarse-fine resolution) framework, which integrates experimental and other evidences, full and surrogate models, and scenarios. The framework is used for guiding "forward" and "reverse" analyses in an iterative manner. Forward analysis is used to quantify failure probability and major contributors to the uncertainty in the risk assessment. Reverse analysis is used to identify failure domains in the space of uncertain parameters and respective needs for improvements of the data, models, scenarios and overall structure of the framework.

Acknowledgements

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