Vysus Group

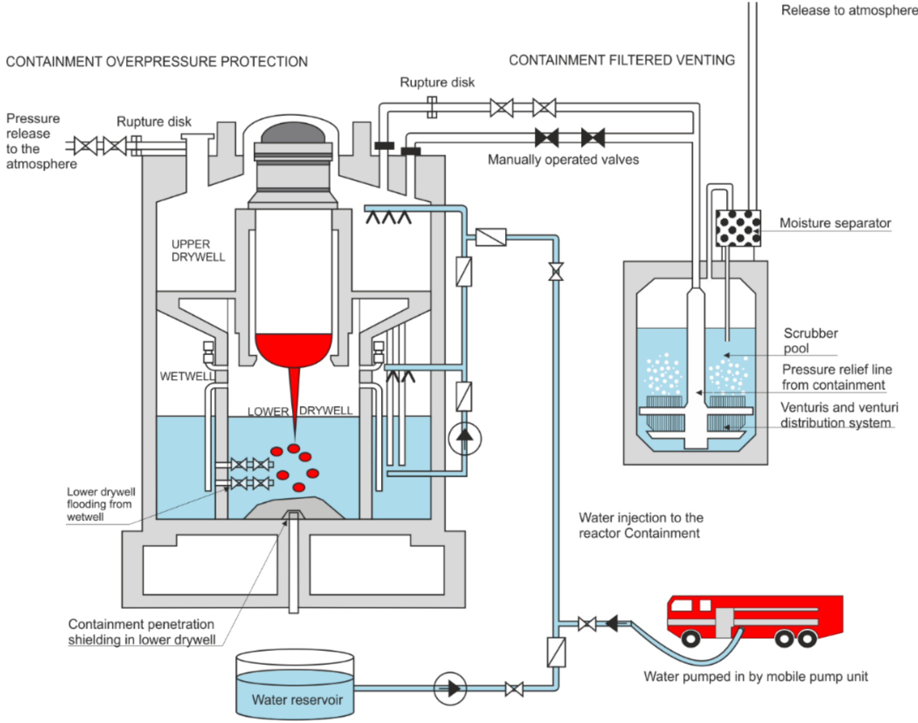
Treatment of Phenomenological Uncertainties in Level 2 PSA for Nordic BWR Using Risk Oriented Accident Analysis Methodology

Ingenuity.
Imagination.
Insight.

Sergey Galushin, Anders Riber Marklund, Anders Olsson (Vysus Group)
Ola Bäckström (Lloyd’s Register)
Dmitry Grishchenko, Pavel Kudinov (Royal Institute of Technology)

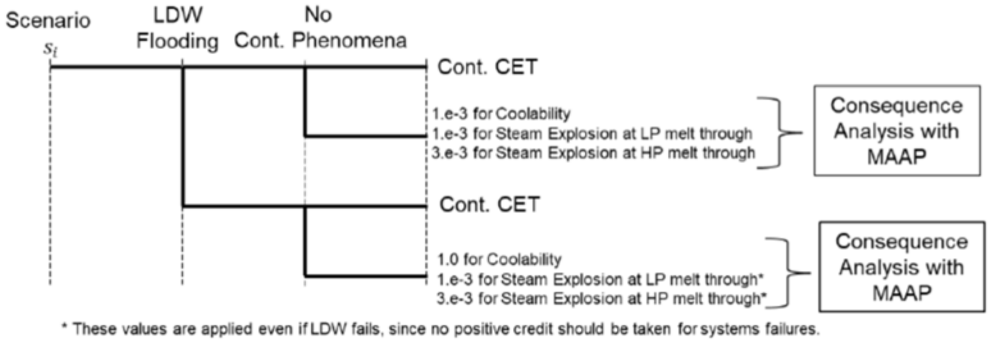
Nordic BWR Severe Accident

- **Severe accident management strategy in Nordic BWRs:**
  - Lower drywell is flooded to ***prevent cable penetrations failure*** in the containment floor.
  - Core melt is released from the vessel into (7-12 m) deep water pool.
  - The melt is expected to fragment quench and form a ***coolable debris bed.***
- **Threats to containment integrity**
  - Steam explosion.
  - Formation of non-coolable debris bed.
- depend on ***melt release and pool conditions.***
- Melt release and pool conditions are affected by uncertainty in **the accident progression:**
  - **Phenomena (epistemic)**
  - **Scenarios (aleatory)**.
- Therefore ex-vessel coolability and steam explosion are **intractable** for **standalone deterministic or probabilistic** analysis.



Current Treatment in L2 PSA for Nordic BWR

- In the reference PSA model, the accident progression for PSA level 2 is modelled in a containment event tree, CET.
  - In the CET there is no explicit modelling of phenomena. Instead, there is a function event where all the phenomena are treated in a common fault tree.
    - > *Epistemic uncertainty in the outcomes of the phenomena is represented by a single probability number (based on expert judgement).*

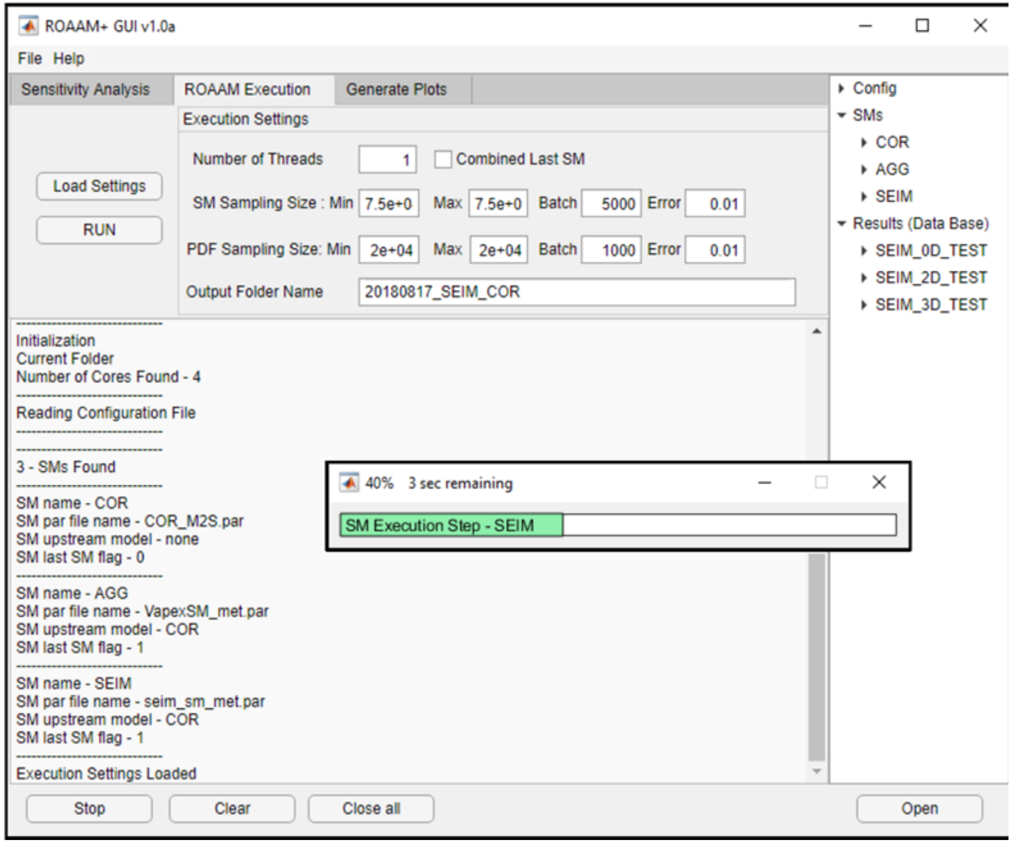


CET in reference PSA model of Nordic BWR

- The static PSA models are built on a pre-determined set of scenario parameters to describe the accident progression sequence and use a limited number of simulations in the underlying deterministic analysis to evaluate the consequences
  - Not necessarily conservative
  - No comprehensive characterization of epistemic uncertainty

ROAAM+ Probabilistic Framework

- KTH has developed the ROAAM+ probabilistic framework as a code with GUI.
  - General purpose tool for risk analysis.
- Surrogate Model (SM) coupling.
  - To perform analyses for single & coupled SMs.
- Sensitivity analysis.
- Quantification of probability of failure and failure domain analysis.
- Visualization of the results.
- Data export to external tools.
- Data export to RiskSpectrum PSA software format for UA.



Use of ROAAM to generate uncertainty data for PSA

Goals of ROAAM+ for Nordic BWR

- ROAAM+ is a risk assessment framework that can be used to provide data to support a decision:
  - Keep SAM strategy (if strategy reliable enough),
  - Modify SAM strategy (if strategy not reliable enough, changes are necessary).

Goals of PSA: Support decision making

- Check that existing safety design meet the requirements.
- Identify the weaknesses in the design and suggest improvements.

ROAAM+ Input for PSA:

- Identification of critical accident sequences.
- Estimation of probability of containment failure due to phenomena:
  - Using state of the art knowledge and deterministic models.
    - Reduced reliance on expert judgement.
- Probability of event occurrence is driven by physics (not predetermined).
  - Probability of event occurrence depends on accident scenario, which is also driven by physics (not predetermined).
- Proper quantification of epistemic uncertainty.
  - "Complete" vs. "Incomplete" probabilistic knowledge.
  - "Deterministic" vs. "Intangible" parameters in ROAAM+ formulation.

"We all work for PSA [Risk Analysis [**Decision-Making**]], we just don't realize it"
Robert Youngblood "Making Decisions About Safety", IDPSA Workshop, Stockholm, Sweden, 2012.

ROAAM+ Connection with PSA

ROAAM+ Framework connects initial plant damage states (PDSs) to respective containment failure modes:

- **MELCOR code** is used to predict in-vessel accident progression, vessel failure and melt release.
- **TEXAS V code** is used to predict the effect of melt release conditions on containment loads due to ex-vessel steam explosion.
- **VAPEX SD\DECOSIM codes** are used to predict the effect of melt release conditions on ex-vessel debris coolability.

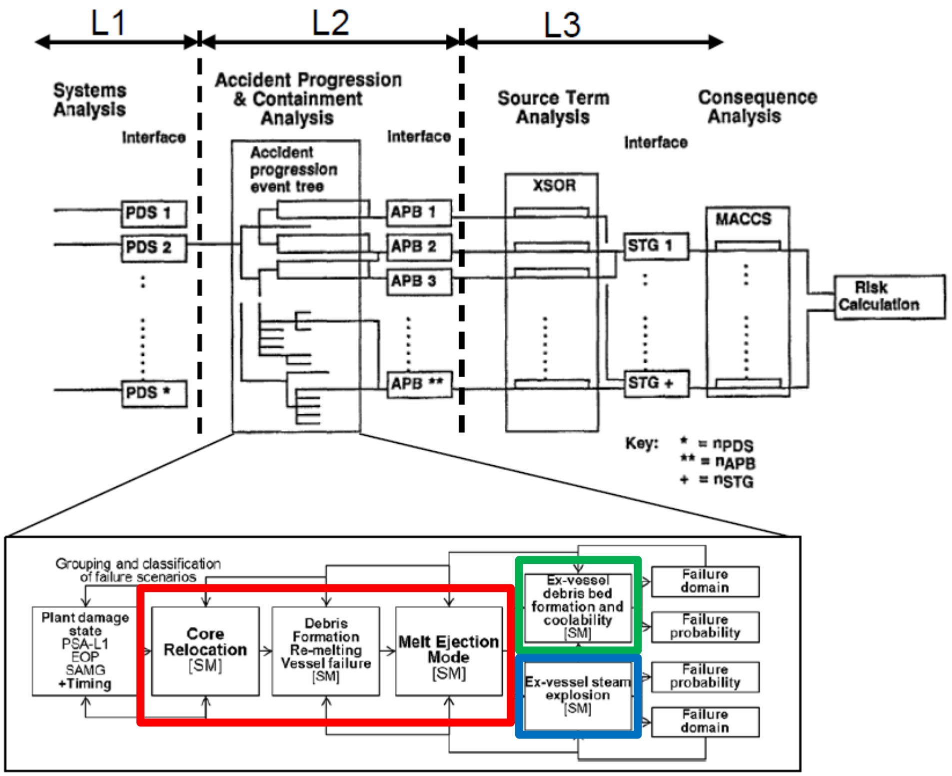
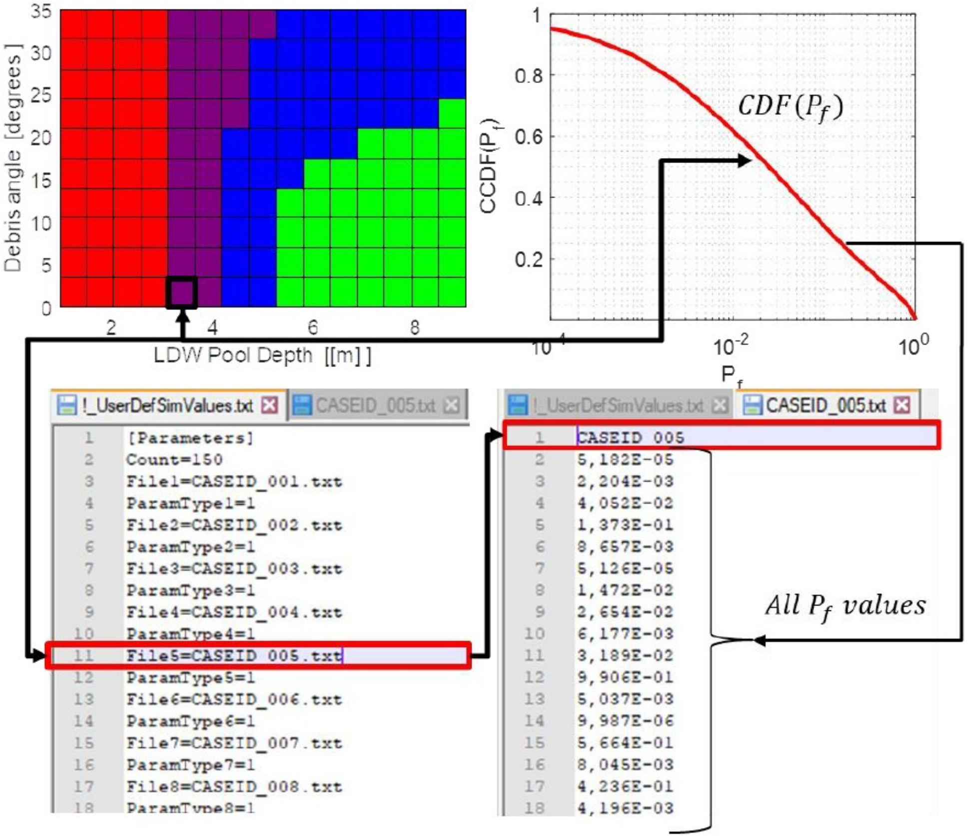


Figure: Connection between ROAAM+ and PSA L1 – L2 analyses

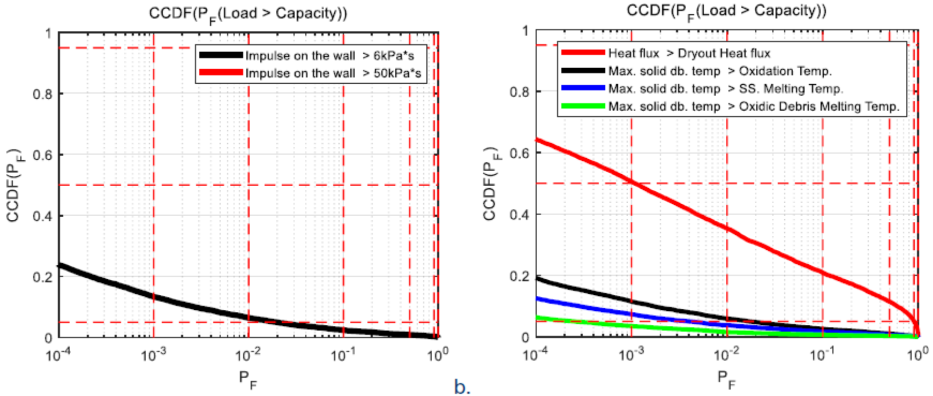
ROAAM GUI - RiskSpectrum PSA interface

- An interface connecting ROAAM GUI and RiskSpectrum PSA have been developed.
- The results of ROAAM analysis can be exported to RS PSA in form of “user defined simulation values” for uncertainty analysis.
  - Addressing **aleatory**(scenarios) and **epistemic**(phenomenology) sources of uncertainty.



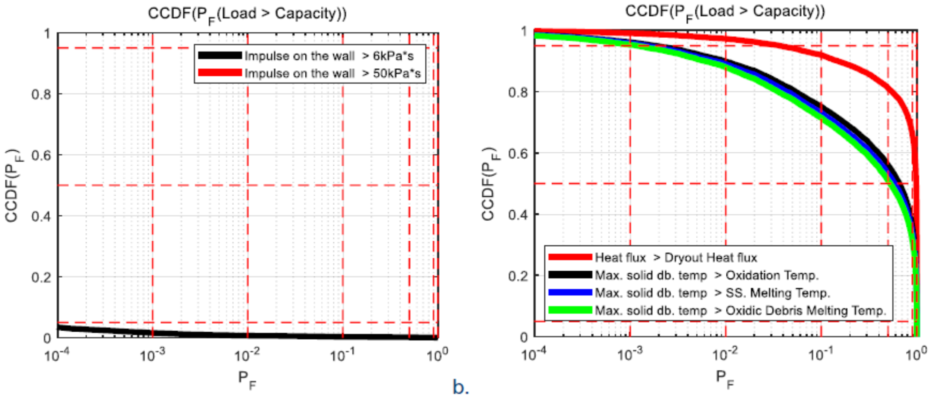
Example of ROAAM+ analysis results used as an input in RS PSA

- Unmitigated SBO scenario was analyzed using ROAAM+ framework for Nordic BWR, which resulted in the following distributions of probability of containment failure due to:
  - Ex-vessel steam explosion.
  - Ex-vessel debris non-coolability (failure of penetration in the LDW floor).
- These distribution were exported into RiskSpectrum PSA as probability distributions of basic events representing containment failure due to ex-vessel steam explosion and due to non-coolability in PSA model.



a. b.

Figure 1. CCDF of P_F for EIGT100-IDEJ0 scenario a) MEM-SEIM b) MEM-AGGDECO in case of deep pool.

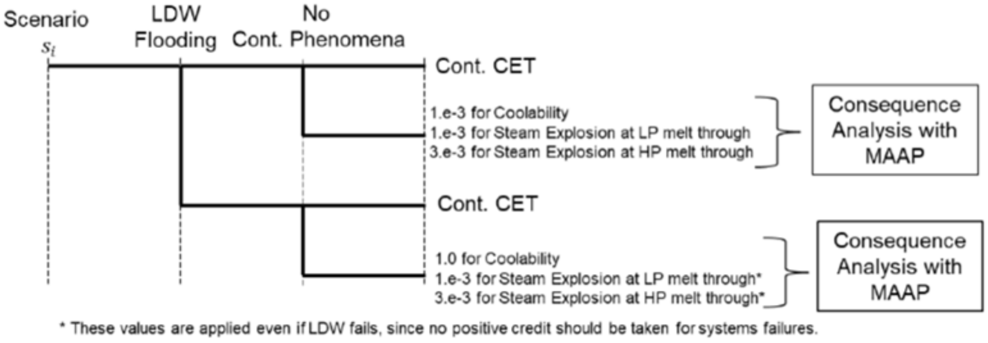


a. b.

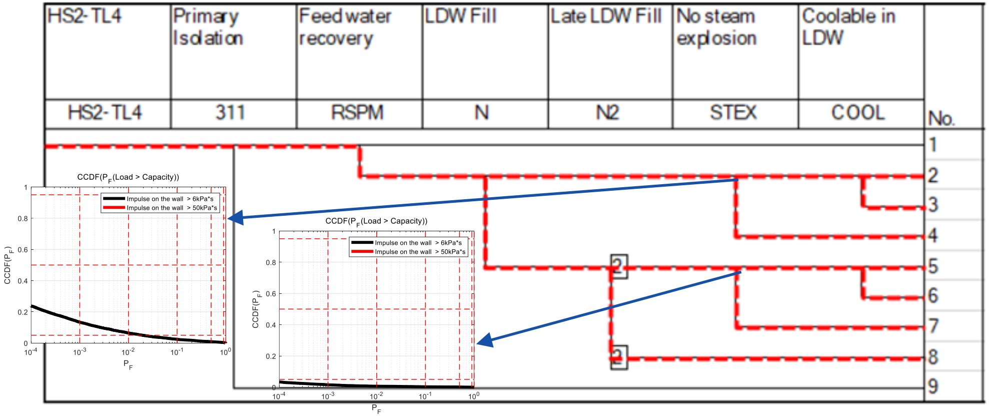
Figure 1. CCDF of P_F for EIGT100-IDEJ0 scenario a) MEM-SEIM b) MEM-AGGDECO in case of shallow pool.

ROAAM+ for Nordic BWR – Effect on PSA Model

- Based on ROAAM results the reference PSA model CETs for respective plant damage states were refined to account for:
  - Different depths of the water pool in lower drywell (LDW), since it affects probabilities of phenomena damaging the containment.
    - Deep water pool, Shallow water pool, No water in LDW.
- Mode of debris ejection from the vessel (IDEJ):
  - Currently considered as phenomenological splinter (due to lack of knowledge).
  - ROAAM uses “splintering” of the trajectory into as many as needed “independent” branches when no relative likelihoods can be introduced.



CET in reference PSA model of Nordic BWR



CET in refined PSA model of Nordic BWR

Important assumptions and Limitations

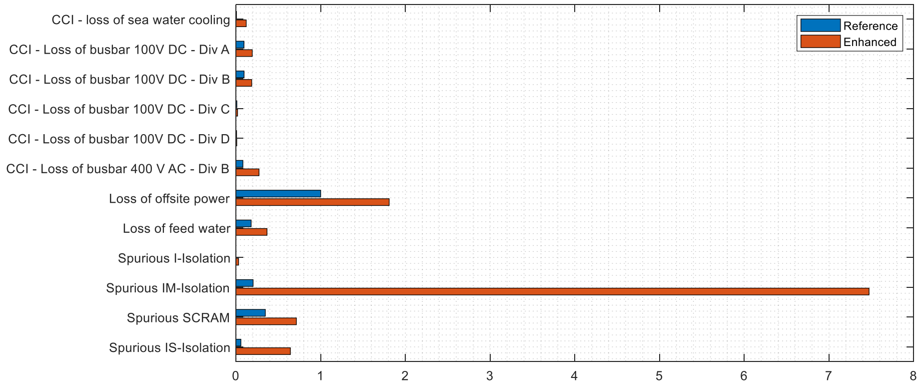
- Melt jet diameter - Predicted by MEM SM, based on MELCOR code results.
  - This parameter is crucial for the results since steam explosion energetics and probability of formation of non-coolable debris configuration strongly depend on the mode of debris ejection from the vessel (size of the jet, and ejected debris temperature in particular).
  - The uncertainty in MELCOR predictions of the size of the jet is significant and dominated by the IDEJ parameter – mode of debris ejection from the vessel (considered as splinter).
    - *In case of IDEJ=1 (solid debris ejection – OFF) – 100% cases result in creep-rupture of the lower head (typically ~1h after [*] initial failure and ejection of LH penetrations) and significant sizes of the melt jets.*
    - *In case of IDEJ=0 (solid debris ejection – ON), the sizes of the jet are limited to slightly ablated IGT sizes, and rather gradual melt and debris releases from the vessel.*

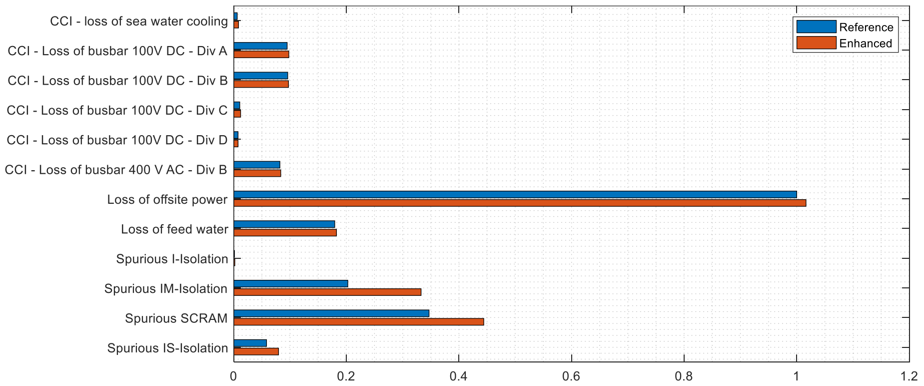
- Failure criteria:
  - Steam explosion: 2 failure criteria were considered:
    - *6kPa*s – that represent original (current) design, based on expert judgement;*
    - *50kPa*s – that represent possible design modification (hatch door reinforcement).*
  - Debris bed coolability:
    - *The onset of remelting of metallic debris.*
- Water depth for deep/shallow pool:
  - Successful activation of LDW flooding - the depth of the pool was predicted by MELCOR code.
  - In case of shallow pool conditions (late activation of LDW flooding), the pool depth was considered as an intangible parameter within a specified range, based on the failure domain analysis results.

[*] S. Galushin, P. Kudinov, Sensitivity and uncertainty analysis of the vessel lower head failure mode and melt release conditions in Nordic BWR using MELCOR code, Annals of Nuclear Energy 135 (2020) 106976

PSA Results comparison (Reference vs. Enhanced PSA models)

Normalized (against reference value for TE(loss of offsite power)) frequencies of non-contained release between the reference and the enhanced models for IDEJ0(right)/ IDEJ1(left) with non-reinforced hatch door for different initiating event groups:





PSA Results comparison (Reference vs. Enhanced PSA models)

- Current state of modelling suggest that the values used in reference PSA model significantly underestimate the values obtained with ROAAM.
  - In case of IDEJ=0 (both solid and liquid debris can be ejected –which results in gradual ejection in-vessel debris\melt) the results obtained with ROAAM data are close to the values obtained with reference PSA model.
  - In case of IDEJ=1 (only molten materials can be ejected –leads to vessel lower head wall failure and massive release) the results obtained with ROAAM data ~4.2 to 5.6 times larger the values obtained with reference PSA model.
- Quite significant phenomenological uncertainties in melt and debris ejection from the vessel that significantly affect ex-vessel consequences and PSA analysis results.
  - Refinement of underlying deterministic models (modelling of debris and melt ejection in MELCOR code) is required.
    - To find out if, current results should be considered as bounding estimates.

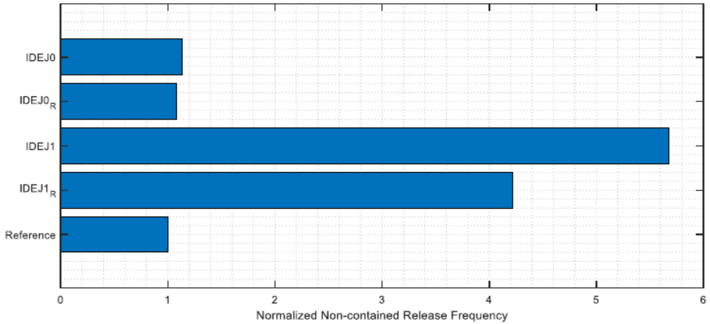


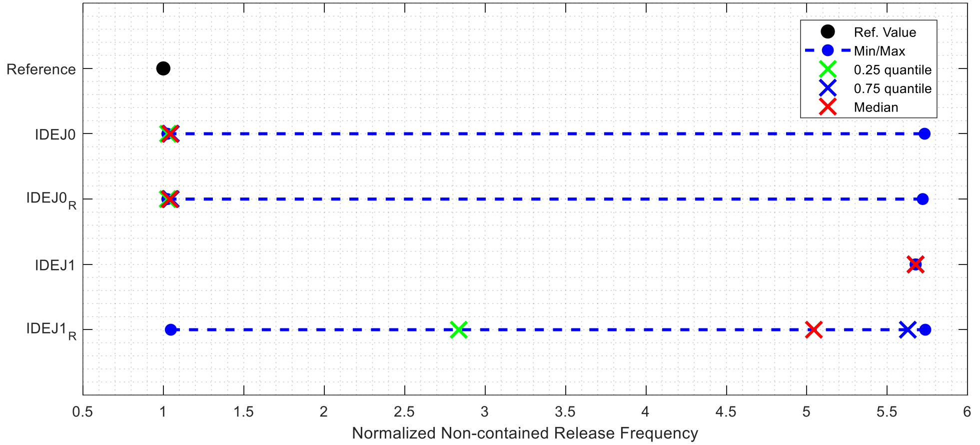
Figure 1: Expected value of Normalized Non-contained Release Frequency.

Cumulative value of non-contained release frequency for considered PDS (core damage due to inadequate coolant inventory makeup).

- **Reference PSA model,**
- **Enhanced PSA model**
  - **Original design (IDEJ1 and IDEJ0)**
  - **Modified design (IDEJ1 and $IDEJ0_R$)**

PSA Uncertainty analysis results

- The resultant distributions of non-contained release frequency have quite significant spread in most of the cases, with exception to IDEJ1.
  - The results for IDEJ0 and $IDEJ0_R$ the major part of the distribution is concentrated very close to the minimum value,
    - > *however there are parameter combinations in deterministic models that can lead significantly large sizes of the jet and large values of non-contained release frequency.*



- In case of $IDEJ1_R$ the distribution of non-contained release frequency is skewed to the right,
  - ~50% of the cases it is below 5 times the reference value,
  - and in ~25% of the cases it is below ~2.85 times the reference value,
  - and for some deterministic models parameters combinations it can be very close to the values obtained with reference model

Conclusions

- These activities have demonstrated that:
  - It is both possible, achievable and desirable to increase the interaction between the deterministic and probabilistic assessment with regard to especially PSA level 2.
  - Probabilities for phenomena can be estimated using the physical models in the deterministic codes.
  - The uncertainty can be assessed and correlation between phenomena can be managed.
  - There is room for improvement in current modelling in PSA level 2 with regards to sequence parameters.
- This work was performed under NKS-SPARC 2017-2019 and APRI projects.

Vysus Group

Sergey Galushin[a], Anders Riber Marklund[b], Anders Olsson[c], Ola Bäckström[d], Dmitry Grishchenko[e], Pavel Kudinov[f]

[a]Vysus Group, Stockholm, Sweden, sergey.galushin@vysusgroup.com

[b]Vysus Group, Stockholm, Sweden, anders.ribermarklund@vysusgroup.com

[c]Vysus Group, Stockholm, Sweden, anders.olsson@vysusgroup.com

[d]Lloyd's Register, Stockholm, Sweden, ola.backstrom@lr.org

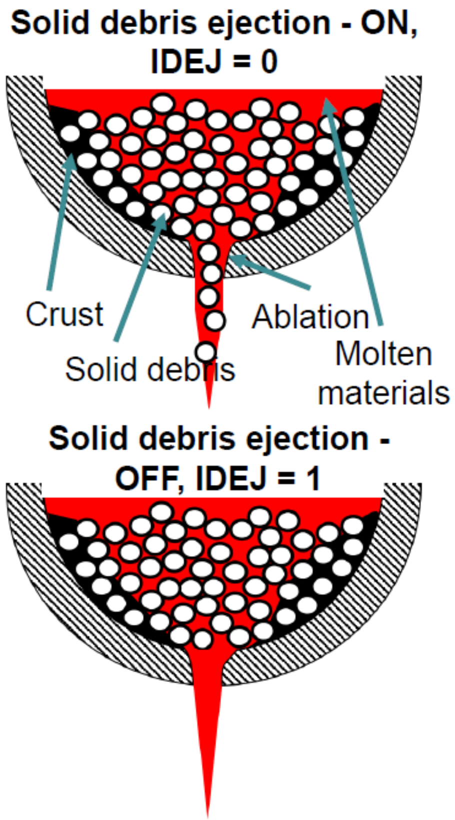
[e]Royal Institute of Technology (KTH), Stockholm, Sweden, dmitrygr@kth.se

[f]Royal Institute of Technology (KTH), Stockholm, Sweden, pkudinov@kth.se

Thank you

Debris ejection modelling in MELCOR

- Two options for debris ejection from the vessel in case of penetration failure.
  - IDEJ = 0: **Solid debris ejection –ON**
    - both solid and liquid (molten) debris can be ejected (default).
  - IDEJ = 1: **Solid debris ejection –OFF**
    - only molten debris can be ejected (plus small fraction of solids)
    - Typically leads to gross failure of the vessel lower head.
- **Gross failure of vessel wall**,
  - all debris in the bottom axial level of the corresponding ring is discharged linearly over 1s time step (no regards to IDEJ).



ROAAM: Extended Treatment of Safety Goals

- *Physically unreasonable** process that violates well-known reality
  - screening probability $P_s = 10^{-3}$.

The ROAAM+ framework aims to provide support for a robust decision making:

I. Keep SAM strategy:
   > *"Possibility" of containment failure is low* $P_f < P_s = 10^{-3}$

II. Modify SAM strategy:
   > *"Necessity" of containment failure ("possibility of non-failure") is high* $1 - P_f < P_s = 10^{-3}$ *or* $P_f > 0.999$

- Decision is considered robust if it is insensitive to remaining uncertainty.

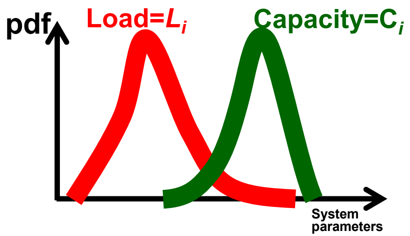
[*] T. G. Theofanous, "On Proper Formulation of Safety Goals and Assessment of Safety Margins for Rare and High-Consequence Hazards," Reliability Engineering and System Safety, 54, pp.243-257, (1996).

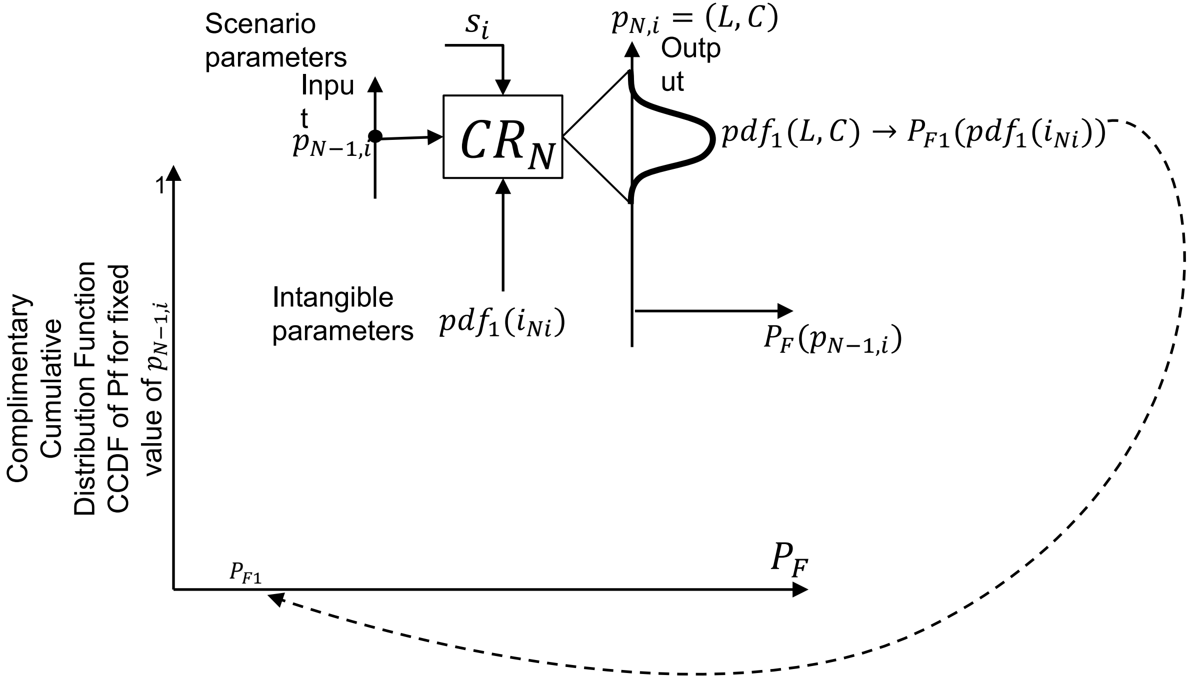
Treatment of Model Intangible Parameters

The CR provides assessment of the load (L_i) and the capacity (C_i).

- probability density function ($pdf(d_i, i_i)$) of intangible (i_i) and deterministic (d_i) modeling parameters determines the probability of failure:

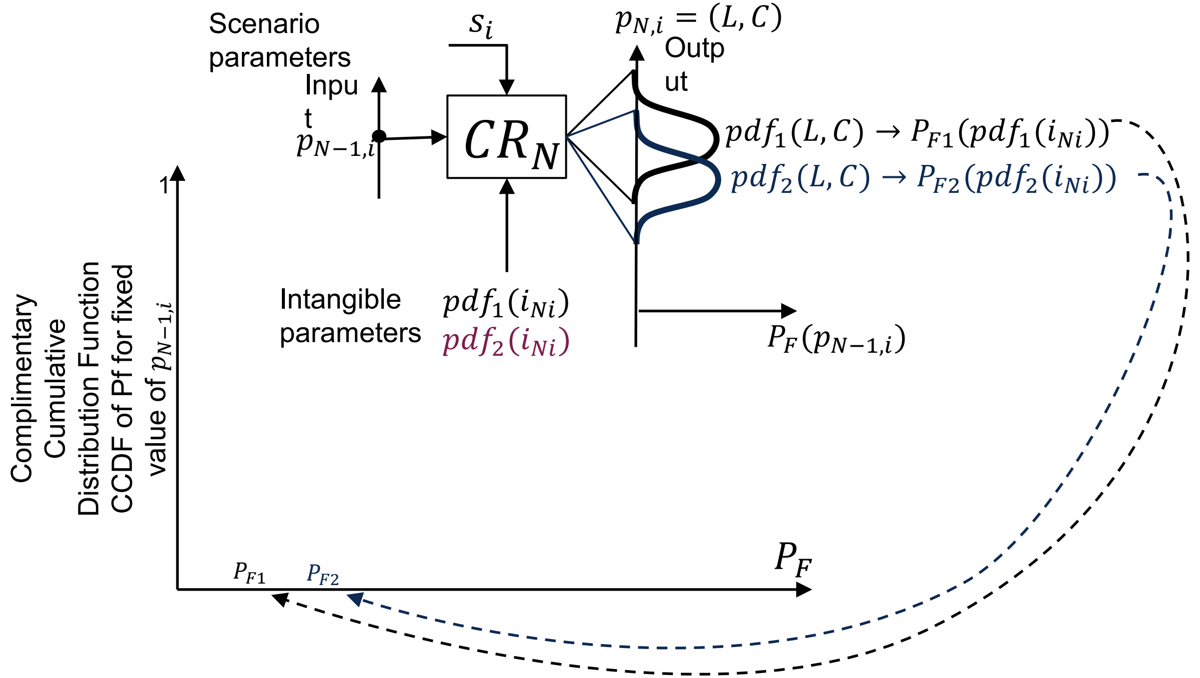
$$P_{Fi} = P(L_i \geq C_i) = \iint_{L_i \geq C_i} \mathrm{pdf}_{C_i L_i}(c, l) dcdl$$





Treatment of Model Intangible Parameters

- Different values of P_f, including the bounding ones, can be obtained by sampling in the space of the distributions $\mathrm{pdf}(i_i)$ of model intangible parameters.



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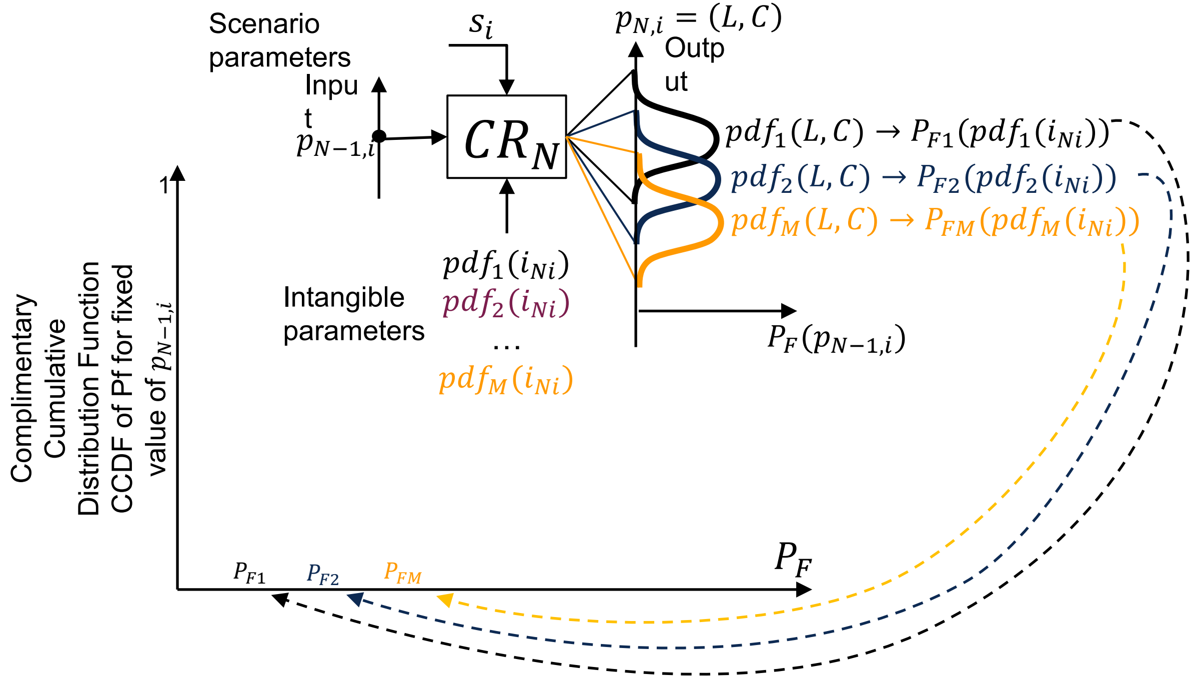
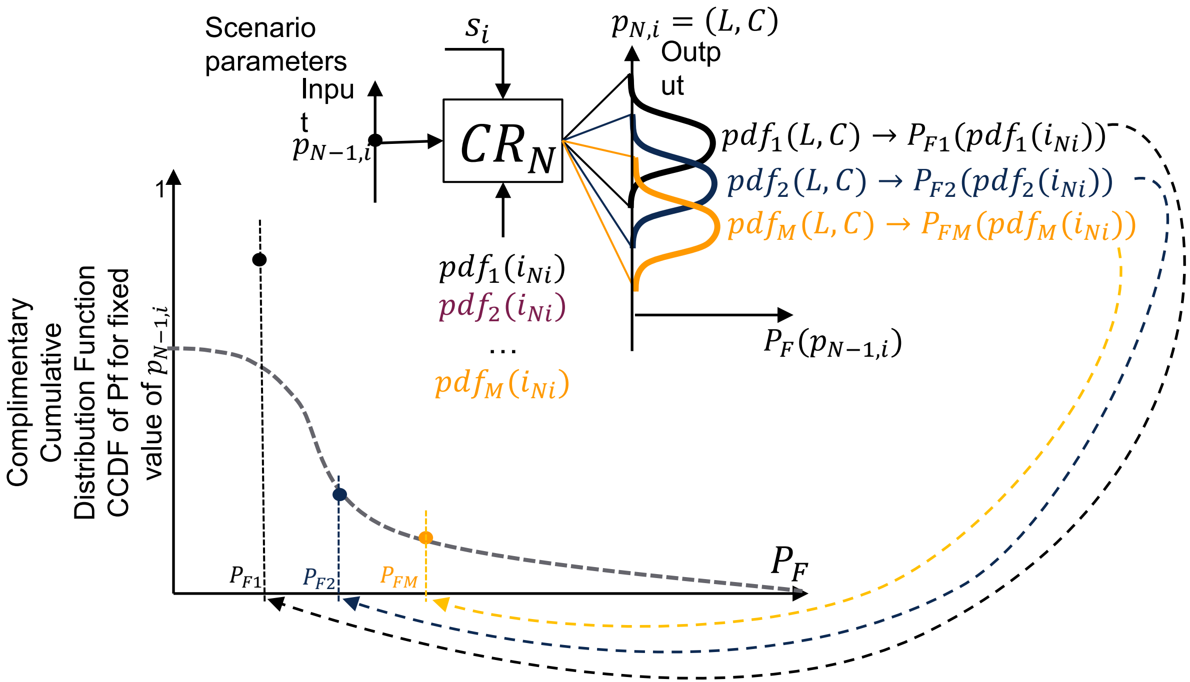


Treatment of Model Intangible Parameters

- Result of the sampling is a distribution of failure probability $CCDF(P_F)$.



Failure domains

Failure domain colour-coding: how likely that P_f exceeds screening probability P_s for a given point in the space of model input parameters.

- **Green**: at most in 5% of the cases $P_f > P_s$,
- **Red**: at least in 95% of the cases $P_f > P_s$,
- **Blue**: P_F exceeds P_s in 5-50% of the cases,
- **Purple**: P_F exceeds P_s in 50-95% of the cases.