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Joint Application of Risk Oriented Accident Analysis Methodology and PSA Level 2 to Severe Accident Issues in Nordic BWR

**Sergey Galushin, Dmitry Grishchenko,
Pavel Kudinov**

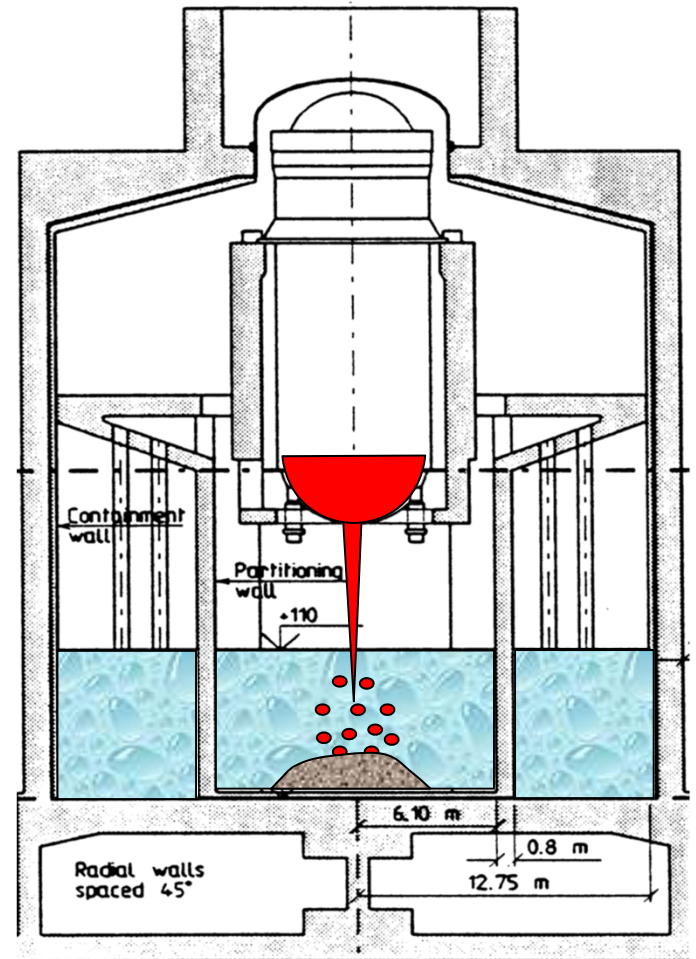
Royal Institute of Technology (KTH), Stockholm, Sweden

**Ola Bäckström, Anders Riber Marklund,
Lisa Ranlöf, Yvonne Adolfsson,**

Lloyd's Register Consulting, Stockholm, Sweden

Motivation: Nordic BWR Severe Accident

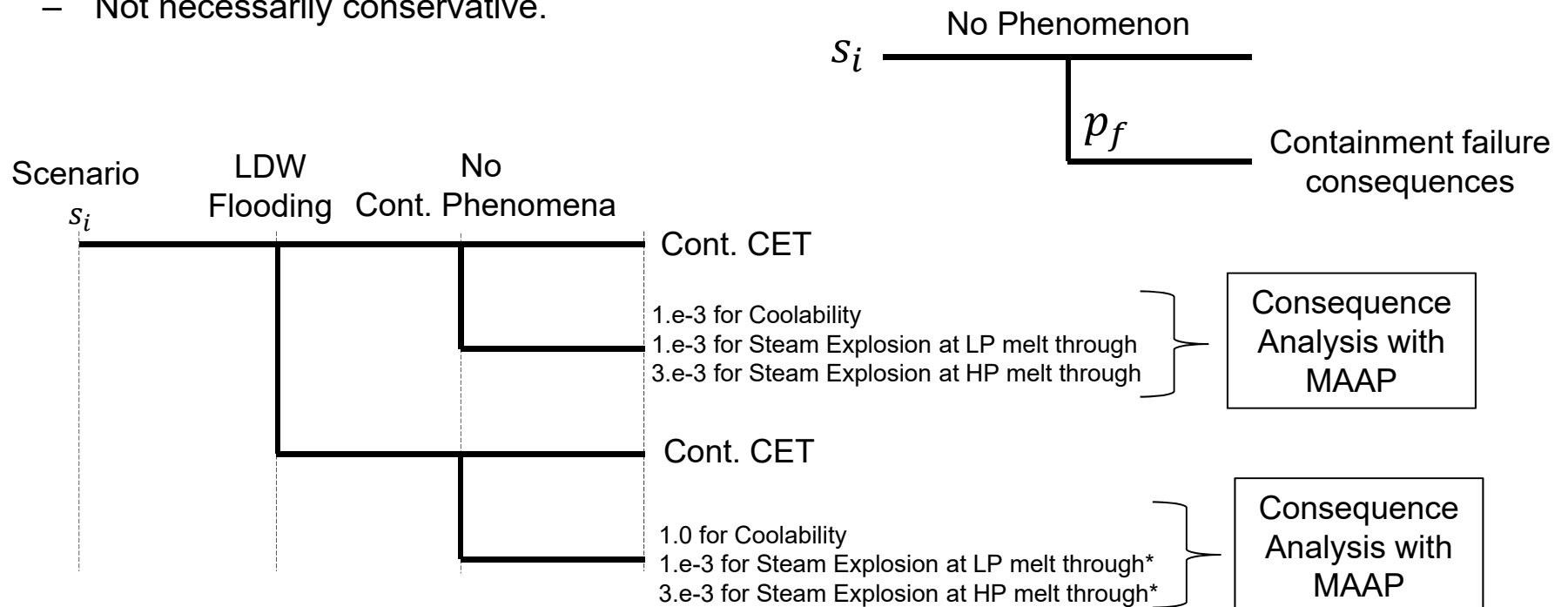
- **Severe accident mitigation strategy in Nordic BWRs:**
 - Lower drywell is flooded with water to **prevent cable penetrations failure** in the containment floor.
 - Core melt is released from the vessel into (7-12 m) deep water pool.
 - The melt is expected to fragment quench and form a **coolable 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 **the accident progression uncertainty:**
 - **Epistemic (phenomena)**
 - **Aleatory (scenarios)**.
- **Risk – uncertainty in effectiveness** of the strategy for preventing containment failure.



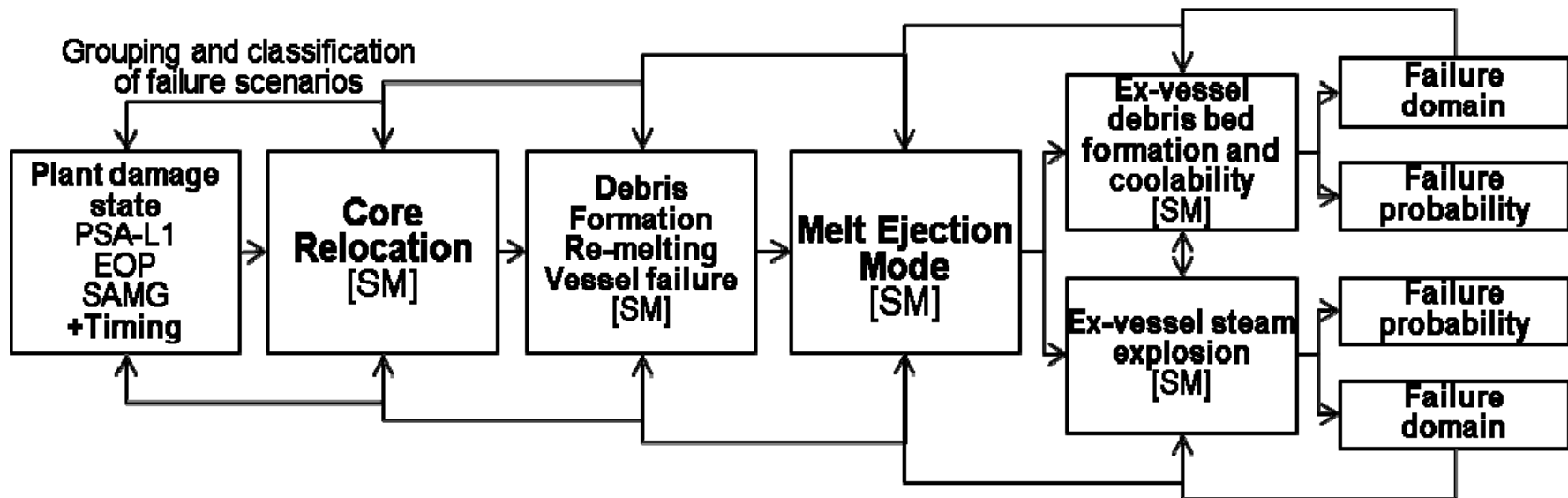


Current PSA Level 2 treatment of the containment phenomena

- In current PSA-L2 approach epistemic uncertainty in the outcomes of the phenomena is represented by a single probability number:
 - i.e. degree of confidence that containment can be damaged by ex-vessel steam explosion, or by non-coolable debris.
 - The number can be based on expert judgment combined with uncertainty quantification.
 - This epistemic uncertainty can be reduced by gaining knowledge.
- Consequences of containment damage are often point estimates (single MAAP calculation) for given scenarios.
 - No comprehensive quantification of modeling uncertainty in the magnitude of the release.
 - Not necessarily conservative.



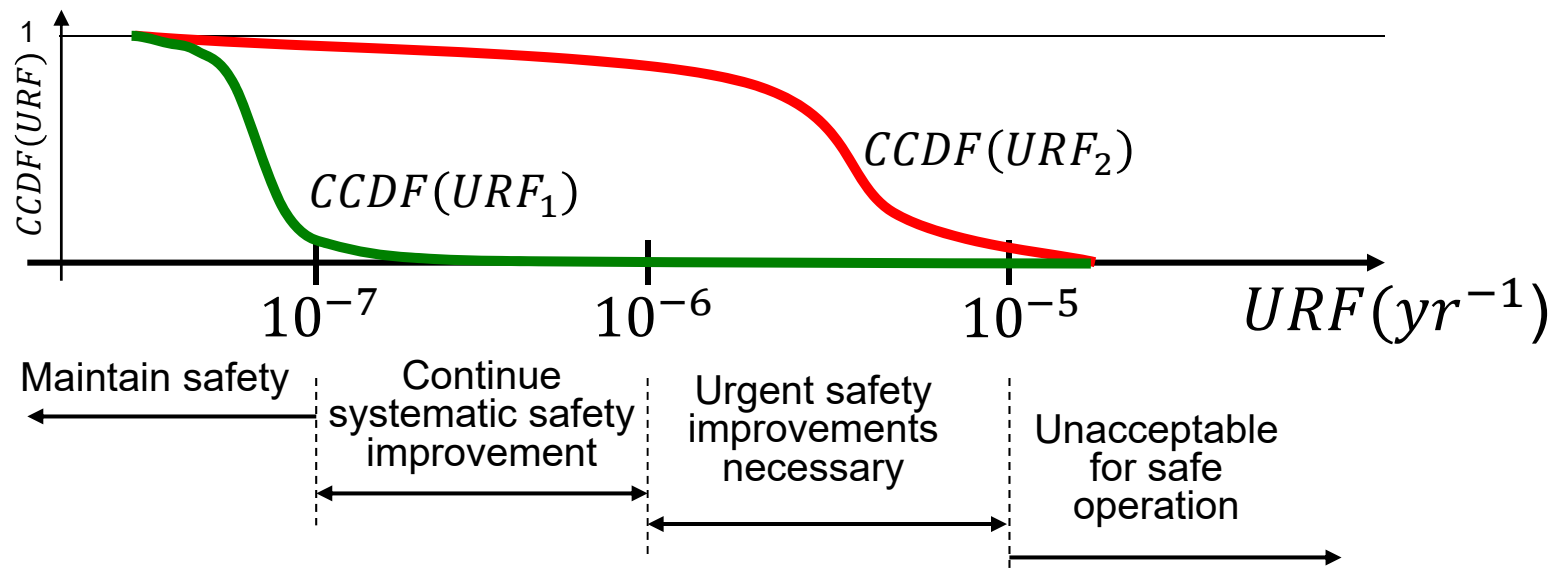
* These values are applied even if LDW fails, since no positive credit should be taken for systems failures.



- **ROAAM+** framework is currently under development in KTH, for quantification of the conditional threats to containment integrity
- The ROAAM+ framework for Nordic BWR decomposes severe accident progression into a
 - set of connected causal relationships (CR)
 - Each CR is represented by respective surrogate model (SM)
 - Computational efficiency of the framework is necessary for extensive sensitivity and uncertainty analysis in forward (**failure probability**) and reverse (**failure domain**) analyses:

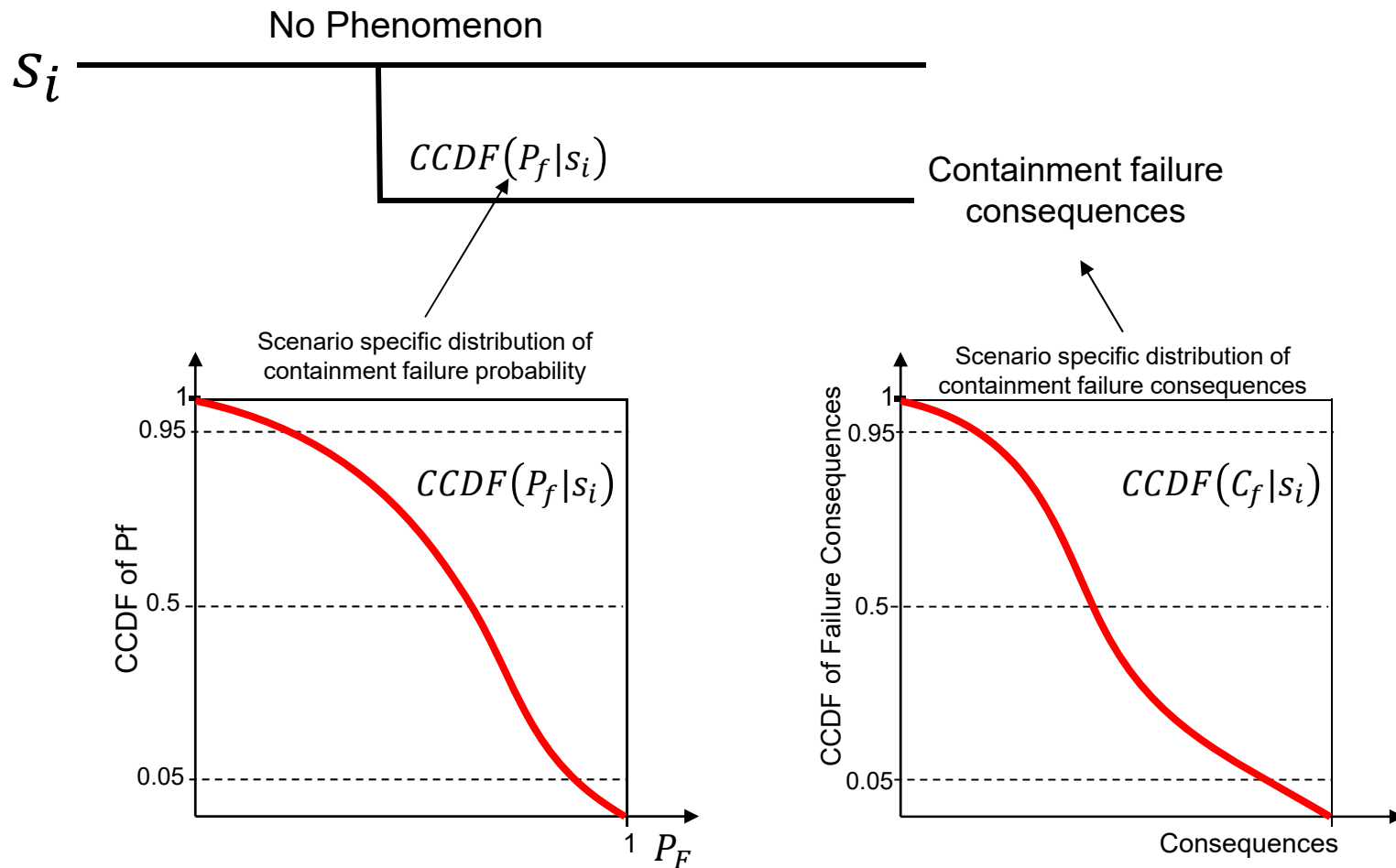
ROAAM+ and decision support

- ROAAM+ is a decision oriented approach that provides
 - means for systematic and comprehensive quantification of uncertainty.
- The data on uncertainty can be directly utilized in PSA
 - Extending and making PSA representation of the uncertainty more adequate for the decision makers.



Improvements in PSA modelling

- Uncertainty quantification:
 - Already implemented in some PSA software
 - (e.g. Risk Spectrum)





Improvements in PSA by integration with ROAAM+ Framework

- ROAAM+ analysis shows that the probabilities of containment failure due to the phenomena are highly sensitive to the:
 - The mass flow of core melt from the reactor vessel.
 - The depth of the water pool under the reactor vessel.
 - The temperature of the water pool.
- The influence of these parameters can be taken into account in the PSA.
- The information from the deterministic analysis is used to create an enhanced PSA model:
 - improve definition of the sequences (PDS, APB)
 - estimation of probabilities of containment failure due to phenomena.

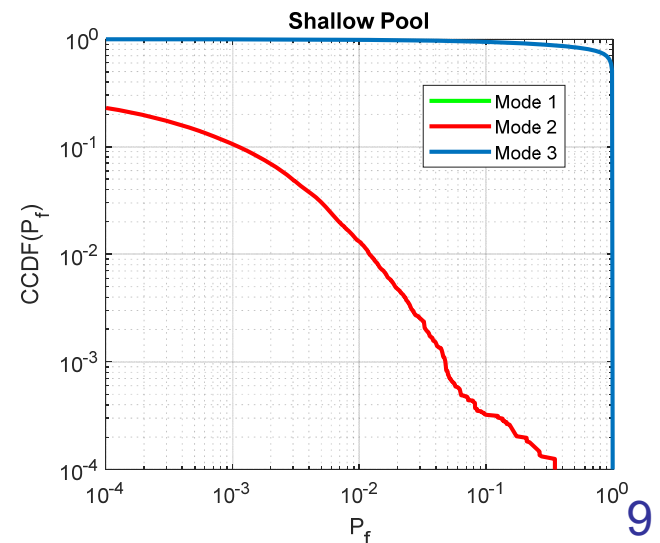
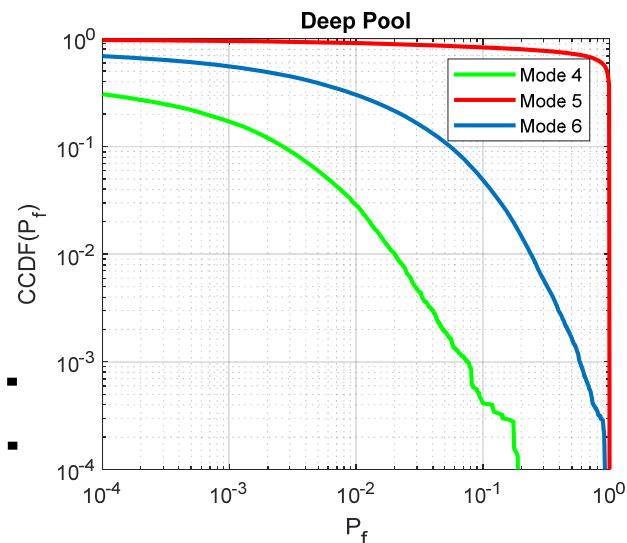
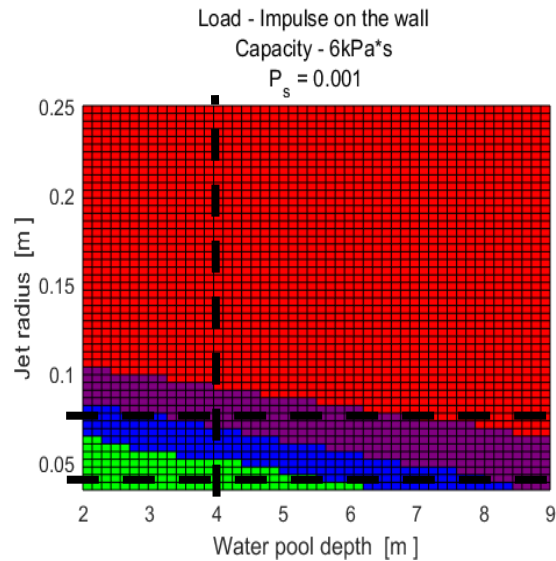
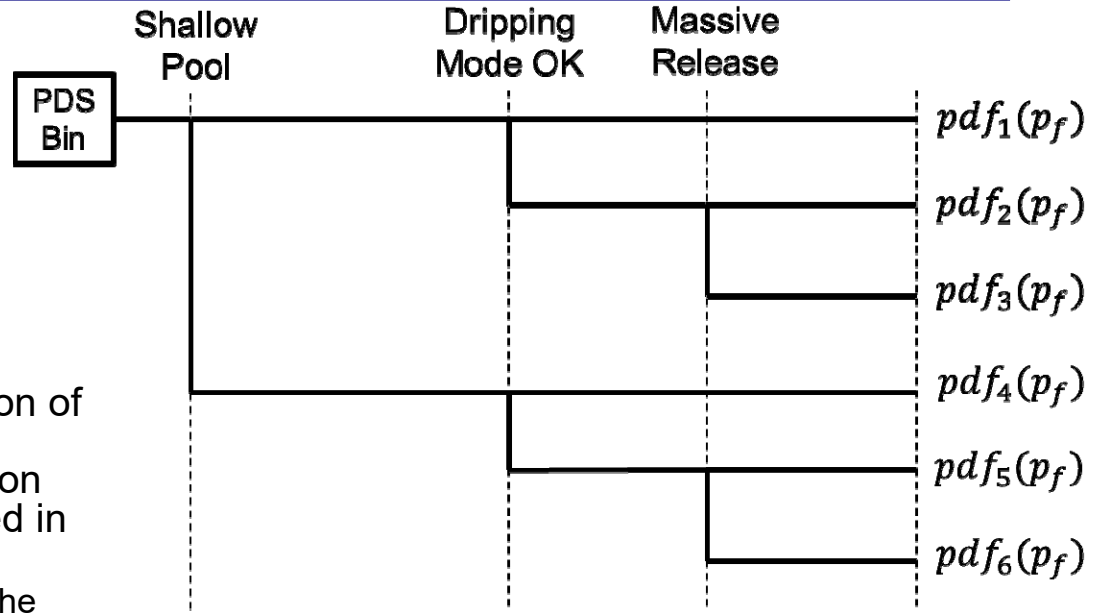


Example of a Dynamic Approach in a Large Scale PSA Model

- The dynamic approach to PSA can be used to enhance the PSA in several aspects. A feasibility study is performed as an example of how a dynamic approach can be used in a large scale PSA.
 - The feasibility study is aiming at studying, in a greater level of detail, the attributes that are of interest for the core relocation, melt through of the reactor pressure vessel (RPV) and the following effects on phenomena.
- A generic PSA for Nordic BWR is used as a reference case. In the reference model each phenomenon, for example steam explosion and debris bed coolability, is modelled with fixed probabilities independent of the accident progression sequence in which they are used.
 - The reference case provides information to the deterministic analysis about which phenomena and parameters that are currently analyzed and used in the binning of sequences and consequences.
- Two important phenomena at reactor vessel melt through are steam explosion and debris bed coolability.
 - To be able to study how these phenomena are dependent of different parameters a dynamic approach is used.
 - The parameters that may influence the phenomena are physical parameters such as pressure, temperature and water depth in different parts of the plant, scenario specific parameters such as size of the melt through as well as intangible parameters.

Refined CET with Uncertainties

- LDW Water depth scenarios :
 - Deep pool 7.8m.
 - Shallow pool 3.9 m.
 - No water.
- Melt flow scenarios:
 - Dripping (djet < 0.075 m).
 - Medium (0.075 < djet < 0.150 m).
 - Large (djet > 0.150 m).
- For each scenario given by a combination of water depth and melt flow there is a probability distribution for steam explosion and formation of non-coolable debris bed in LDW.
 - This distribution is explicitly modeled in the CET.



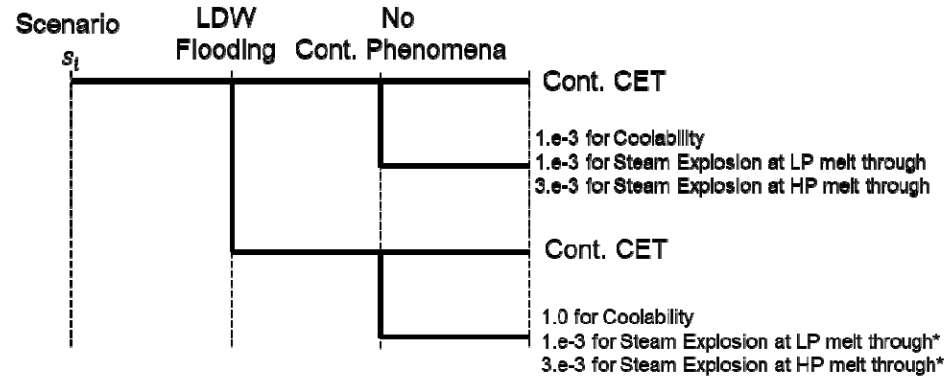


Improvements in PSA by integration with ROAAM+ Framework

- Reference large scale PSA model is modified to consider the depth of the water pool and the mass flow of corium at vessel melt through.
 - The model is updated with regards to the containment event trees (CET) and scenario specific probabilities for the failure due to the containment phenomena.
 - The study aims at indicating the effect of taking the enhanced information about phenomena into account when calculating the large early release frequency for transients and CCI leading for these PDS.
- The analysis is performed for a few specific the plant damage states (PDS) corresponding to (HS2) core damage due to inadequate core cooling (initiating event is a transient or a CCI) at:
 - High pressure (HS2-TH1)
 - Low pressure (HS2-TL4)

Improvements in PSA modelling to integrate dynamic features - 1

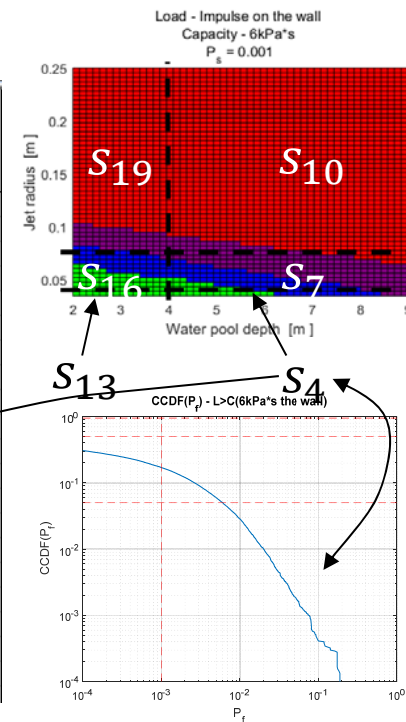
- Reference PSA L2



* These values are applied even if LDW fails, since no positive credit should be taken for systems failures.

- Enhanced PSA L2

Recovery core cooling	LDW water filled (358)	Late LDW Fill	Melt - Drip/ med/ large	No Stm expl	Coolable in LDW	No.
RSPM	N	N2	FLOW	STEX	COOL	1
			1			2
			2			3
			3			4
		2	1			5
			2			6
			3			7
						8
						9
		2	1			10
			2			11
			3			12
						13
						14
						15
						16
						17
						18
						19
		2				20





Probabilities of failure due to phenomena

- The probability that steam explosion or non-coolability will lead to containment failure is calculated as
 - the average value of different melt flows in each size respectively,
 - given the depth and the temperature of the water pool.
- This results in the following average probabilities for containment failure due to steam explosion and non coolable debris bed in LDW.

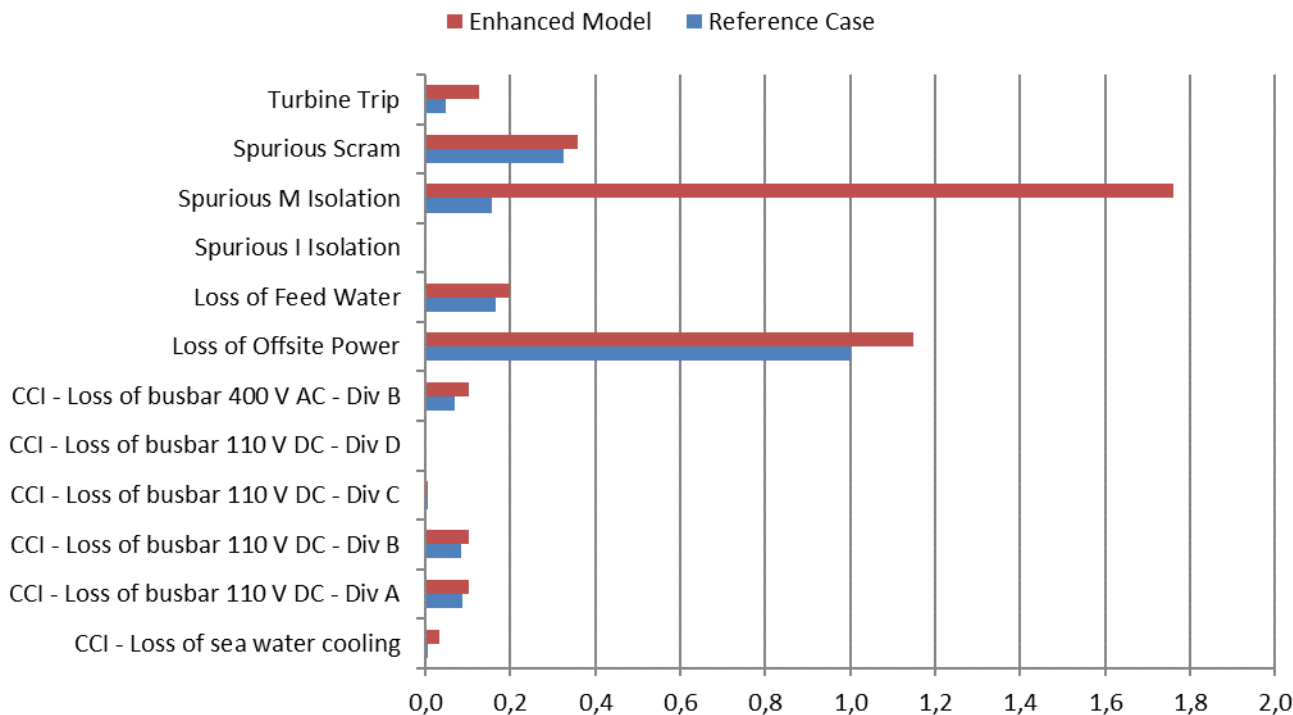
Failure of containment due to	Steam Expl.	Non. Coolable
Deep pool, dripping flow	0	3.61E-02
Deep pool, medium flow	1.55E-02	2.83E-01
Deep pool, large flow	6.36E-01	8.52E-01
Shallow pool, dripping flow	0	1.0
Shallow pool, medium flow	3.60E-04	1.0
Shallow pool, large flow	3.78E-01	1.0

- In the PSA model it is not the average values that are used, instead there are probability distributions for each scenario.



Analysis and Comparison between Reference Case Model and Enhanced Model

- All transients and CCIs leading to the plant damage states HS2-TH1 and HS2-TL4 are analyzed for all analyzed level 2 release categories.
 - Releases over 0.1% of the core inventory of an 1800 MW BWR are grouped as non-acceptable.
- The result are normalized for non-acceptable release per type of initiating event.
 - The result for Loss of offsite power and non-acceptable release is set to 1.0 for the reference case and all the other results are divided by the same scaling factor.





Analysis and Comparison between Reference Case Model and Enhanced Model

- Comparison between the reference case and the modified model for containment failure due to phenomena (always early and no DW spray is credited)
 - normalized
- The frequency approximately increases with a factor of 4 due to the increased probability for steam explosion.
 - The release frequency related to the release category “Filtered release, Early opening, No DW spray” decreases to 50 % of the reference case.
 - The release frequency related to the remaining release categories changes only slightly between the reference model and the enhanced model.

Initiating event	Reference Case	Enhanced Model	Difference
CCI - Loss of sea water cooling	4.8E-03	3.2E-02	561%
CCI - Loss of busbar 110 V DC - Div A	4.1E-03	2.1E-02	406%
CCI - Loss of busbar 110 V DC - Div B	1.8E-03	1.8E-02	873%
CCI - Loss of busbar 110 V DC - Div C	3.2E-03	3.2E-03	0%
CCI - Loss of busbar 110 V DC - Div D	2.4E-04	1.2E-4	-100%
CCI - Loss of busbar 400 V AC - Div B	1.5E-03	3.4E-02	2240%
Loss of Offsite Power	2.7E-01	4.2E-01	56%
Loss of Feed Water	6.6E-04	3.5E-02	5180%
Spurious I Isolation	6.6E-04	1.7E-03	150%
Spurious M Isolation	1.6E-01	1.8E+00	1035%
Spurious Scram	5.6E-02	8.8E-02	56%
Turbine Trip	4.4E-02	1.2E-01	178%
Total result	5.4E-01	2.5E+00	370%



Analysis and Comparison between Reference Case Model and Enhanced Model

- Comparison between the reference case and the modified model for non-acceptable release.
 - Normalized
- The analysis shows that the non-acceptable release frequency is doubled in the enhanced model.

Initiating event	Reference Case	Enhanced Model	Difference
CCI - Loss of sea water cooling	5.0E-03	3.2E-02	541%
CCI - Loss of busbar 110 V DC - Div A	8.7E-02	1.0E-01	19%
CCI - Loss of busbar 110 V DC - Div B	8.5E-02	1.0E-01	18%
CCI - Loss of busbar 110 V DC - Div C	4.7E-03	4.7E-03	0%
CCI - Loss of busbar 110 V DC - Div D	1.4E-03	1.2E-03	-16%
CCI - Loss of busbar 400 V AC - Div B	7.0E-02	1.0E-01	47%
Loss of Offsite Power	1.0E+00	1.2E+00	15%
Loss of Feed Water	1.7E-01	2.0E-01	21%
Spurious I Isolation	7.9E-04	1.7E-03	118%
Spurious M Isolation	1.6E-01	1.8E+00	1014%
Spurious Scram	3.3E-01	3.6E-01	9%
Turbine Trip	4.9E-02	1.3E-01	158%
Total result	2.0E+00	3.9E+00	102%

Uncertainty analysis

- The results of the uncertainty analysis for non-acceptable release.
 - The results show that the uncertainty ranges from roughly half the point estimate frequency up to about 1.5 of the point estimate frequency.
 - This is a reasonably narrow interval, which is positive – as the uncertainty is an important factor in PSA-L2.
 - It could be relevant to further study the cases where the uncertainty range is greater – to understand if the uncertainty can be reduced.

Initiating event	5%	median	95%
CCI - Loss of sea water cooling	56%	100%	158%
CCI - Loss of busbar 110 V DC - Div A	91%	100%	112%
CCI - Loss of busbar 110 V DC - Div B	91%	100%	112%
CCI - Loss of busbar 110 V DC - Div C	95%	100%	107%
CCI - Loss of busbar 110 V DC - Div D	100%	100%	100%
CCI - Loss of busbar 400 V AC - Div B	84%	100%	123%
Loss of Offsite Power	93%	100%	109%
Loss of Feed Water	91%	100%	112%
Spurious I Isolation	58%	100%	163%
Spurious M Isolation	54%	100%	161%
Spurious Scram	95%	100%	107%
Turbine Trip	66%	100%	147%



Discussion.

- The initiating event group “Spurious M-isolation” (feed water lines) is much more affected by the enhanced modelling than the other initiating event types studied.
 - The group of non-acceptable releases, for a Nordic BWR, to a relatively large extent contains so-called bypass sequences, in which closure (isolation) of the containment fails and the release path occurs through e.g. open steam lines.
 - Such sequences will not be affected by the ROAAM+ approach since they are not created by the studied containment rupture phenomena.
 - M-isolation refers to a specific function of the reactor protection system, which initiates closing of isolation valves in the feed water lines.
 - In the generic Nordic BWR plant design represented by the PSA model used in this study, M-isolation automatically activates closure of the steam lines.
 - This implies that for sequences starting with spurious M-isolation, bypass sequences through open steam lines are directly excluded (apart from cases with mechanical errors in the MSIVs) and this category of initiating events becomes the only category where the ROAAM+ methodology will influence all the resulting accident sequences.
- On the other hand, a part of the sequences initiated by other initiating event groups (e.g. Loss of offsite power, Loss of feed water) will end up in bypass sequences and, thus, will have relatively low impact from ROAAM+ results.



Conclusions and Outlook.

- Pilot application of the ROAAM+ generated data for improvement of a large scale PSA model provided following insights.
 - The feasibility study has shown an example of coupling PSA with ROAAM+.
 - The results from the deterministic analysis are used in the PSA to improve sequence definition as well as improve the estimation of frequency of unacceptable release due to phenomena depending on the sequence.
- ROAAM+ results can be used to refine and improve the PSA in several ways.
 - The integrated approach requires improvement in scenario definition, which practically leads to larger number of plant damage states (PDS).
 - The PDS should consider all necessary scenario parameters, that may affect the calculation of phenomena and hence consider also the system availability normally represented within containment event trees (CETs).
- The pilot application showed that the integration of the ROAAM+ results and the PSA model is not only feasible, but could potentially lead to a considerable change of the frequency for non-acceptable release.



Influence of Limitations in Enhanced PSA model

- There are a number of assumptions and limitations in the implementation in the enhanced PSA model that influence the result. Some comments regarding the importance of different parameters and modeling aspects are:
 - Melt jet diameter - dripping, medium, large:
 - An assumed probability of 1/3 for each size is used in the analysis.
 - This parameter is crucial for the results since steam explosion at dripping melt flow has a probability of zero.
 - A more realistic modeling is needed when determining the probabilities of the melt jet diameter.
 - Failure criteria:
 - The data from ROAM+ for steam explosion and debris bed non-coolability are obtained according to different failure criteria. For both parameters the criteria yielding the highest probabilities were chosen.
 - For steam explosion this is realistic since the doors are not yet reinforced.
 - Conservatism of the assumption about 0.9 agglomeration as failure criterion for coolability to be clarified.
 - Water depth for deep/shallow pool:
 - The water depth at “deep pool” is related to system functionality and can be calculated with MAAP or even with simple hand calculations.
 - If the LDW flooding system works, there will always be about 8 m of water in LDW.
 - The water depth for shallow pool is much more uncertain since this completely depends on the sequence.
 - A more realistic modeling could take different water depth for shallow pool in different sequences.
 - Water temp in LDW at vessel melt through:
 - The temperature is assumed to be 322 K for all cases (This is according to MAAP calculations of HS2-TH1 and HS2-TL4 sequences.)
 - It is also seen in the data from ROAM+ that the LDW water temperature has a small effect on the phenomena studied here.
- There is a need to make the feasibility study more realistic regarding some of the related parameters discussed above. The quantitative results should therefore be seen as indicative.

Structure of Failure Domain Using Different CCDF $\{P_F\}$ Thresholds

- For the same screening frequency we can introduce different ranges for the CCDF $\{P_F\}$ thresholds
 - i.e. ranges of the percentiles of the distributions $pdf_j(i_{Ni})$ which can result in $P_F > P_S$.
- For instance, we can consider domains where
 - CCDF $\{P_F(p_{N-1,i}) \geq P_S\} \leq 0.05$ – Safe domain (Green)
 - CCDF $\{P_F(p_{N-1,i}) \geq P_S\} \in (0.05 - 0.5]$ – “Blue” subdomain – failure in less then half cases
 - CCDF $\{P_F(p_{N-1,i}) \geq P_S\} \in (0.5 - 0.95]$ – “Purple” subdomain – failure in more then half cases
 - CCDF $\{P_F(p_{N-1,i}) \geq P_S\} > 0.95$ – Failure domain (Red)

