Analysis of Debris Coolability and Steam Explosion Issues in Nordic BWRs

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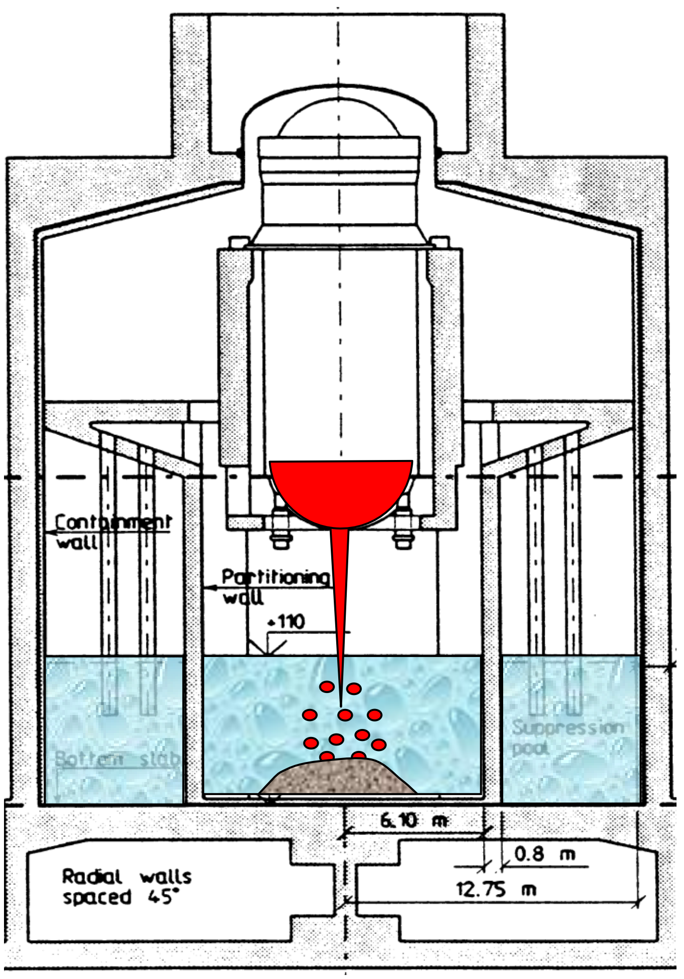
Motivation: Nordic BWR Severe Accident

- **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.
- are dependent on the ***melt release and pool state.***
- Melt release and pool state are affected by **uncertainty in the accident progression**
  - **Epistemic (phenomena)**
  - **Aleatory (scenarios)**.
- **Risk – uncertainty in effectiveness** of the strategy for preventing containment failure.

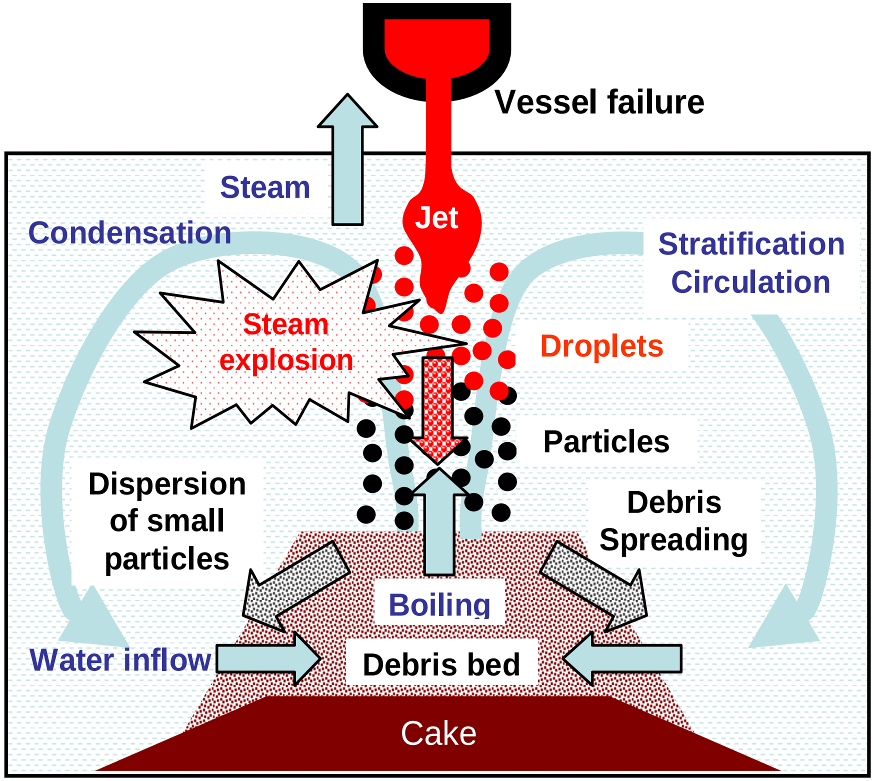
Motivation: Nordic BWR Severe Accident

- Conceptually simple mitigation strategy introduces ***complex interactions*** between:
  - **Scenarios**, and
  - **Phenomena**.

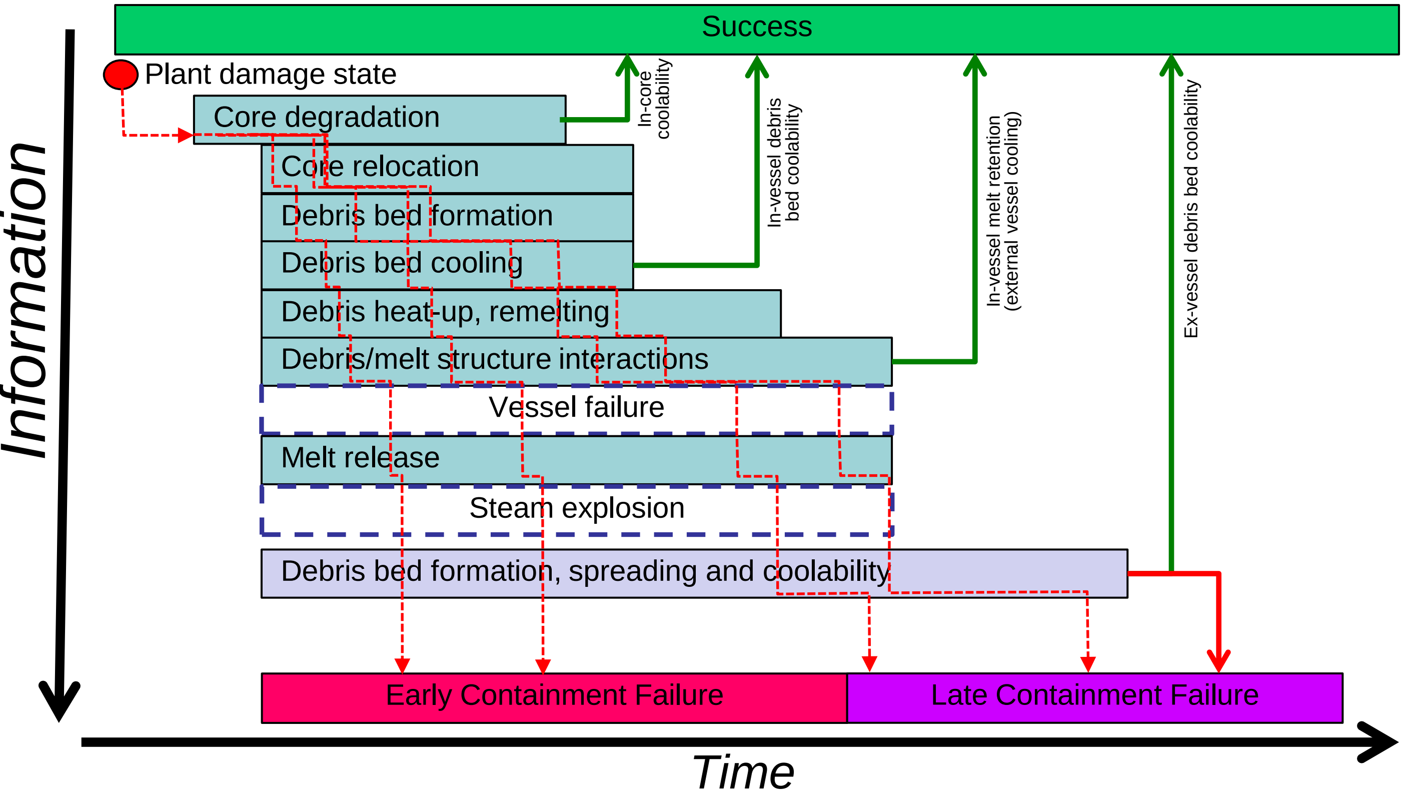
  of the accident progression.

- ***The complexity*** is a source of ***uncertainty and risk***.

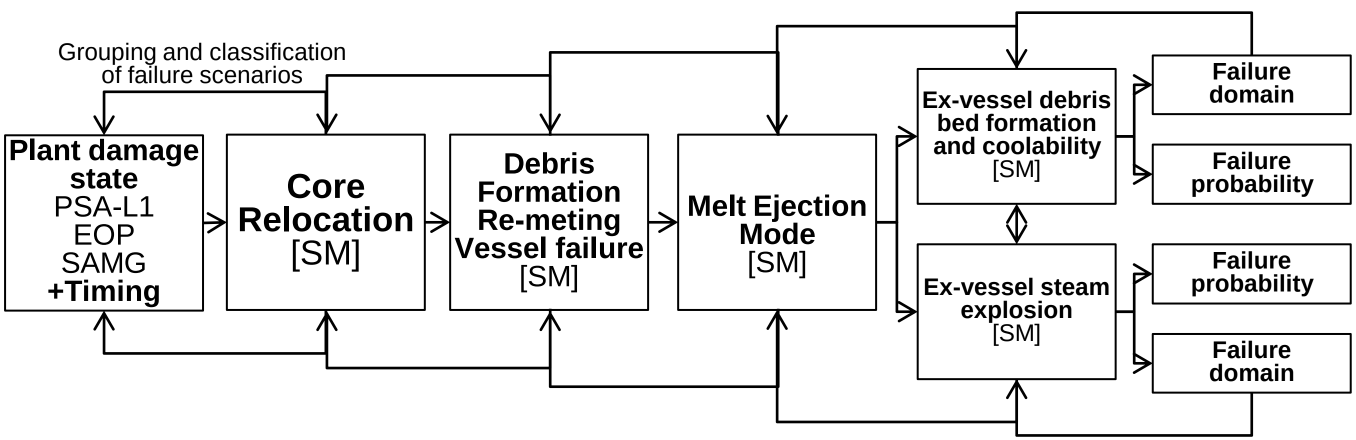
- **Risk Oriented Accident Analysis Methodology (ROAAM)**
  - marries probabilistic and deterministic approaches
  - provides guidelines for development of **frameworks for bounding** of **uncertainties**
    - **Epistemic** (phenomenological), and
    - **Aleatory** (scenario)

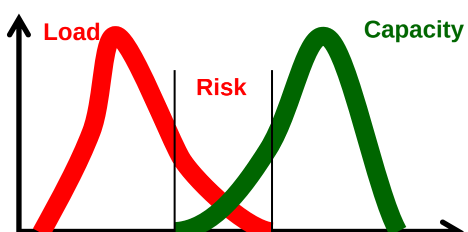


Nordic BWR Challenges for ROAAM

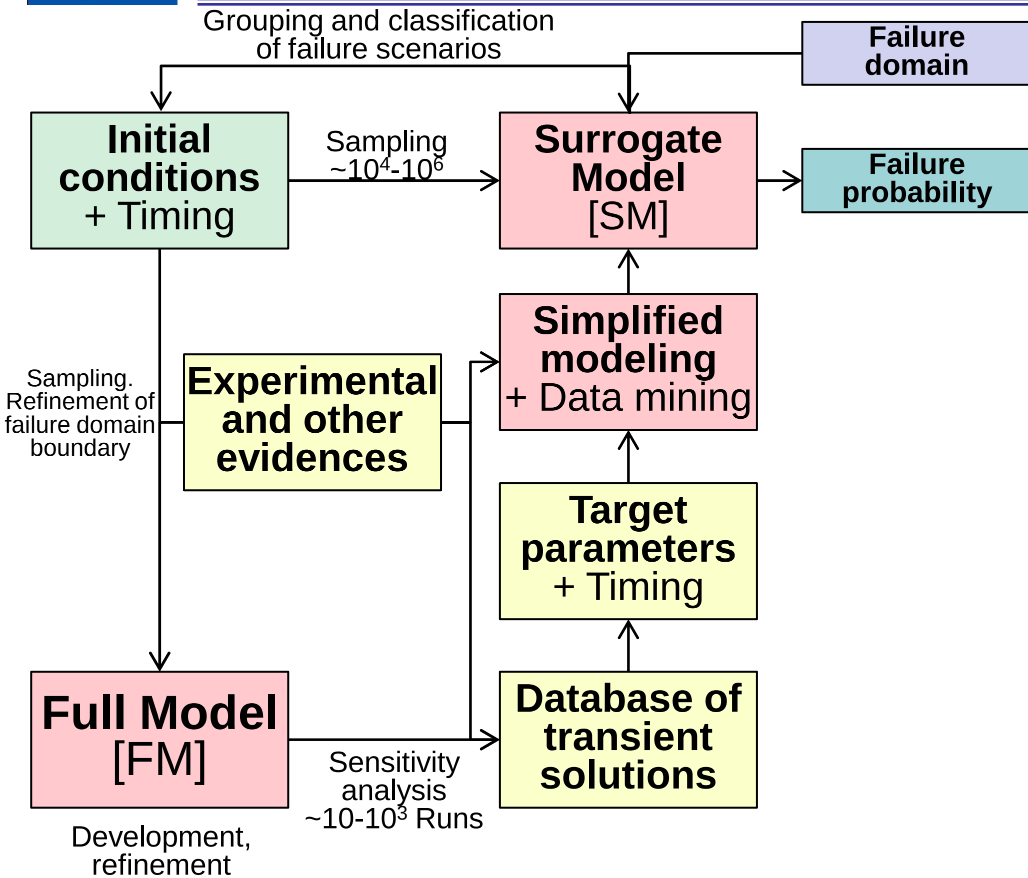


ROAAM+ framework decomposes severe accident progression into a set of causal relationships (CR) represented by respective surrogate models (SM) connected through initial conditions.





Full and Surrogate Modeling in ROAAM+ approach



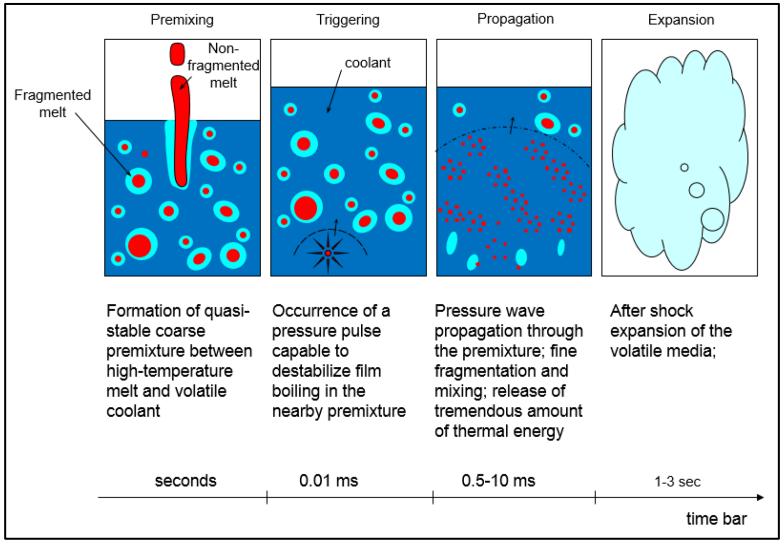
- **Initial conditions:** are the input which is created by the SM analysis at the previous stages of the framework.
- **Experimental and other evidences:** provide a knowledge base for validation of the FMs and calibration of SMs.
- **Full Model (FM):** is implemented as detailed fine resolution (computationally 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.
- **Target parameters:** are initial input conditions which are used by 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 (i)simplified (coarse resolution) physical modeling and (ii) calibratable closures.

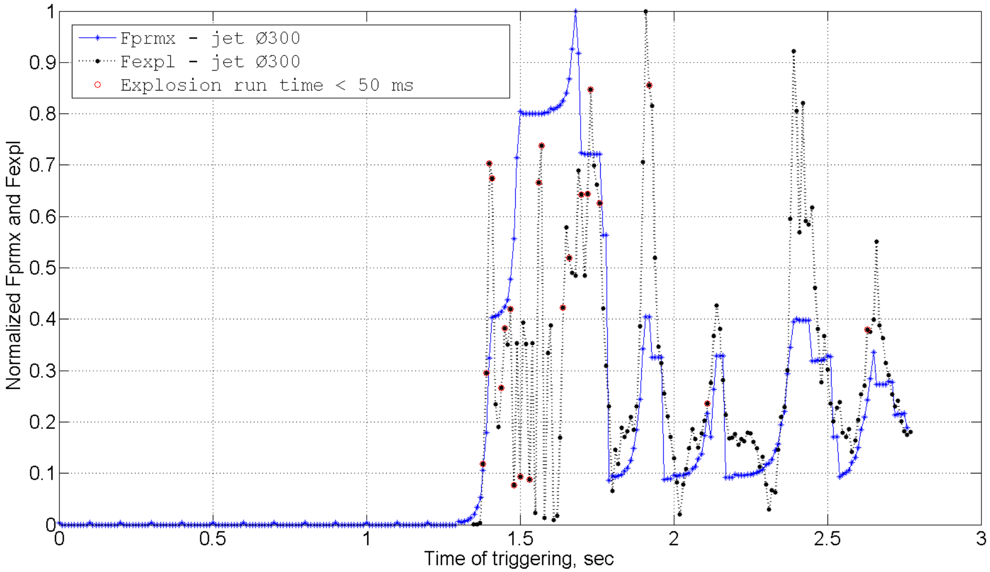
Steam Explosion Full Model: TEXAS-V

- 1D transient code
  - Eulerian for gas and liquid
  - Lagrangian for fuel particles
  - Premixing
  - Explosion

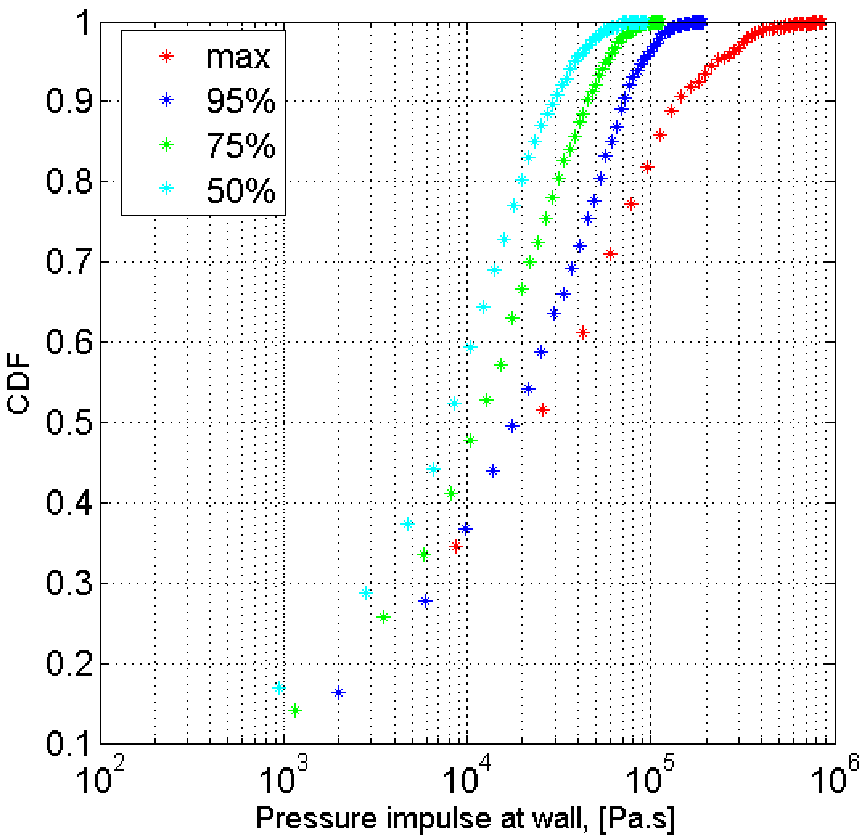
- **Small variations in the triggering time lead to large changes in the explosion energetics (*ill-posed*)**
  - Impulse variations up to 90% of the total range (0.1 to 377 kPa·s) within 100 ms time window.

- Therefore explosion impulses are characterized in probabilistic terms
  - Cumulative distributions of explosion impulses.





Database of the Full Model (FM) Solutions

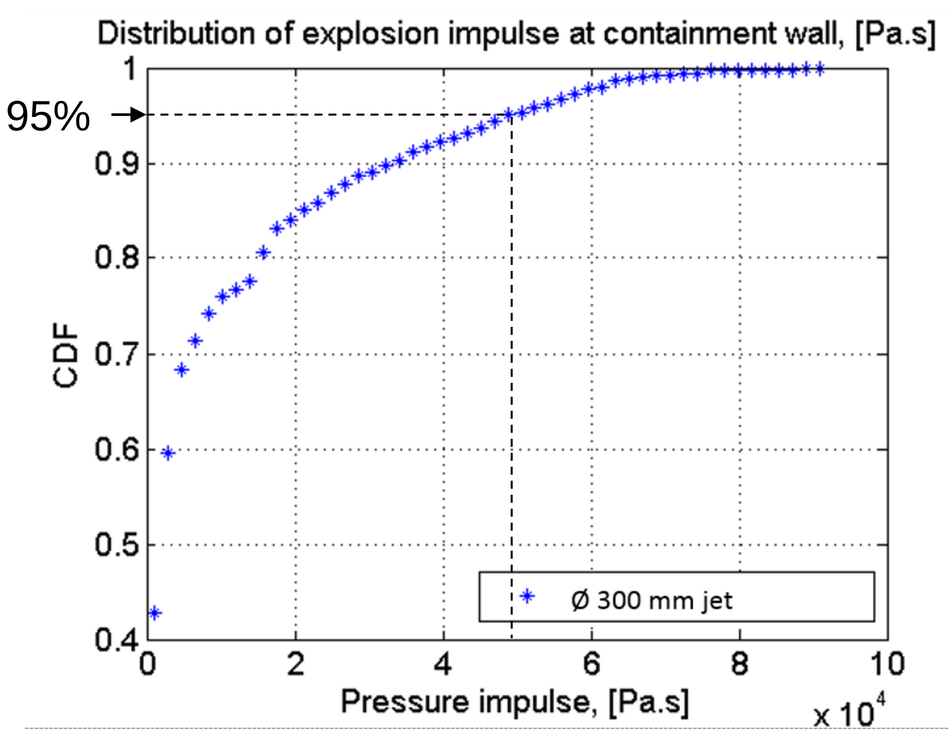


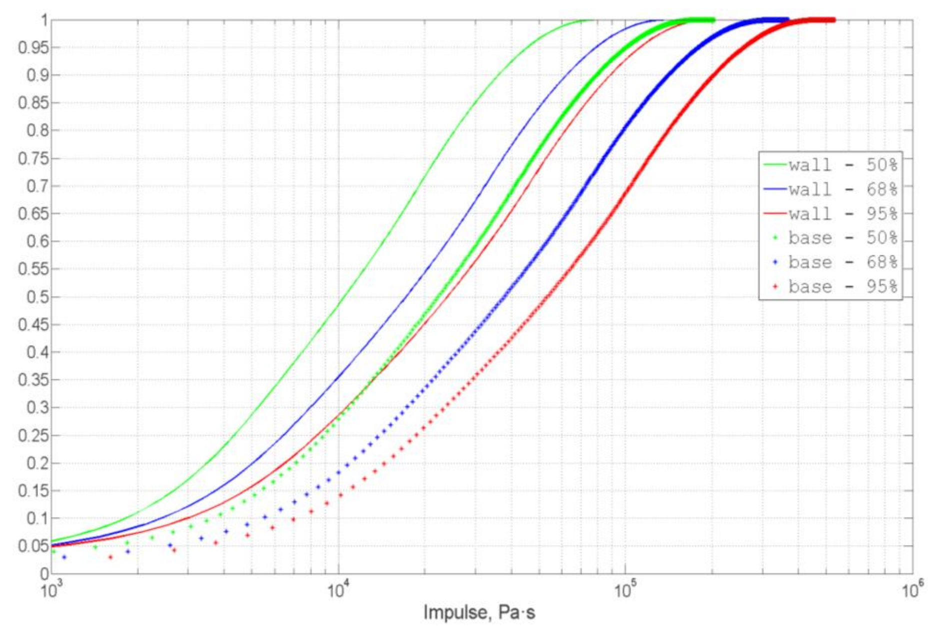
#	Parameter	Units	Range		Explanation
			min	max	
1	XPW	m	5	9	Water level
2	PO	Bar	1	4	System pressure
3	TLO	K	288	368	Water temperature
4	RPARN	m	0.035	0.3	Initial jet radius
5	CP	J/kg·K	350	650	Fuel heat capacity
6	RHOP	kg/m3	7500	8500	Fuel density
7	PHEAT	J/kg	260 000	400 000	Fuel thermal conductivity
8	TMELT	K	1600	2800	Fuel melting point
9	TPIN	K	1620	3150	Melt superheat
10	UPIN	m/s	-8	-1	Melt release velocity
11	KFUEL	W/m·K	2	42	Fuel thermal conductivity
12	CFR	-	0.002	0.0027	Proportionality constant for the rate of fuel fine fragmentation
13	TFRAGLIMT	ms	0.5	2.5	Fragmentation time

- Parameters were considered as independent.
- Halton method was used for sampling.
- Premixing/Explosion calculations with 4 ms interval.
- Total number of explosion cases: 455 386

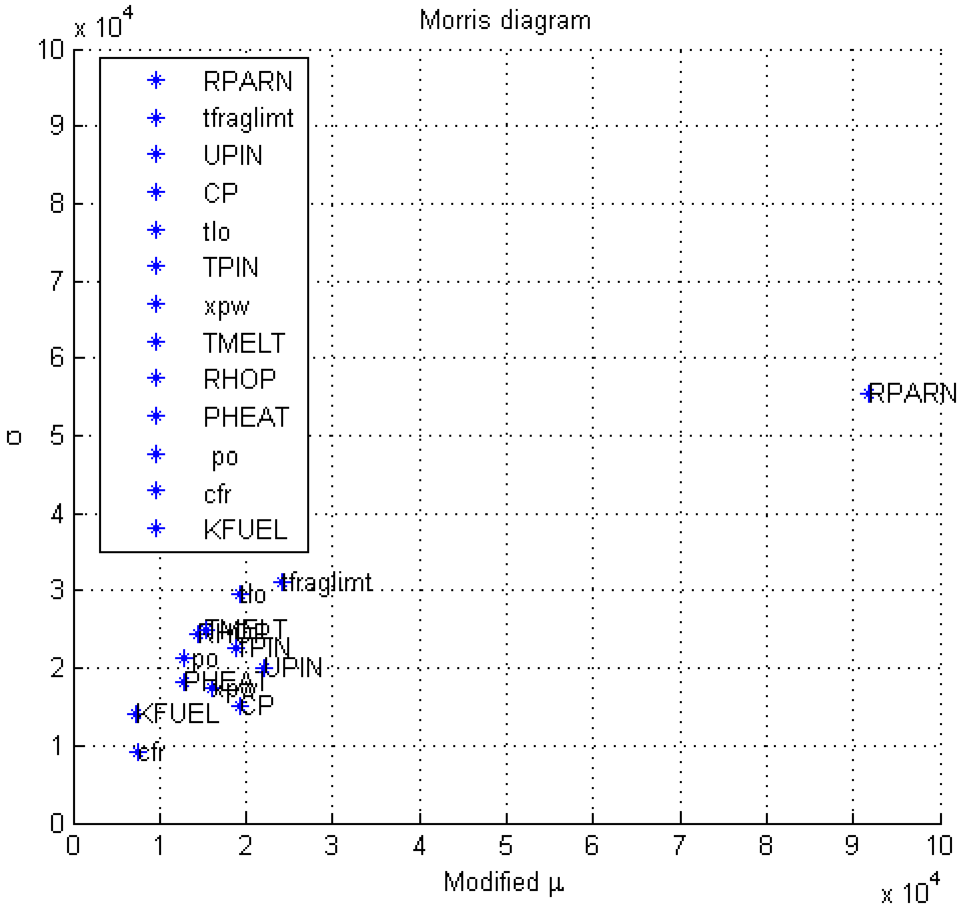
Surrogate Model (SM)

- SM is implemented using Artificial Neural Networks (ANN) to predict characteristics of CDF of explosion impulse for a given melt release scenario
  - i.e. SM predicts which value of explosion impulse will not be exceeded in 95%, 75%, 50% etc. percentile of explosion calculations



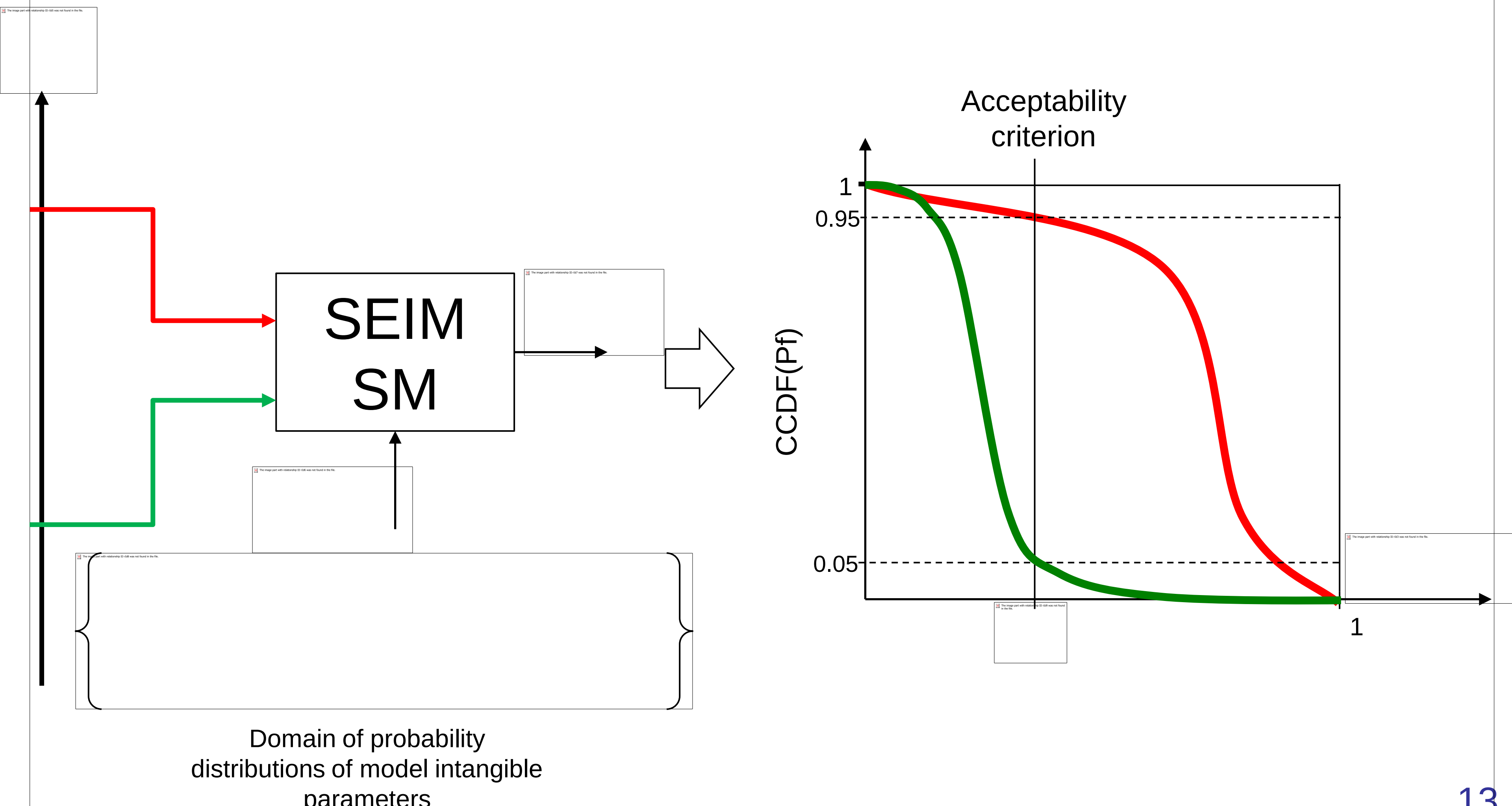


Sensitivity analsysi: Morris Diagram



- Three most influential parameters are
  - RPARN - jet radius,
  - tfraglimt - fine fragmentation time and
  - UPIN - melt release velocity.
- Note the dominating effect of the jet radius (RPARN).

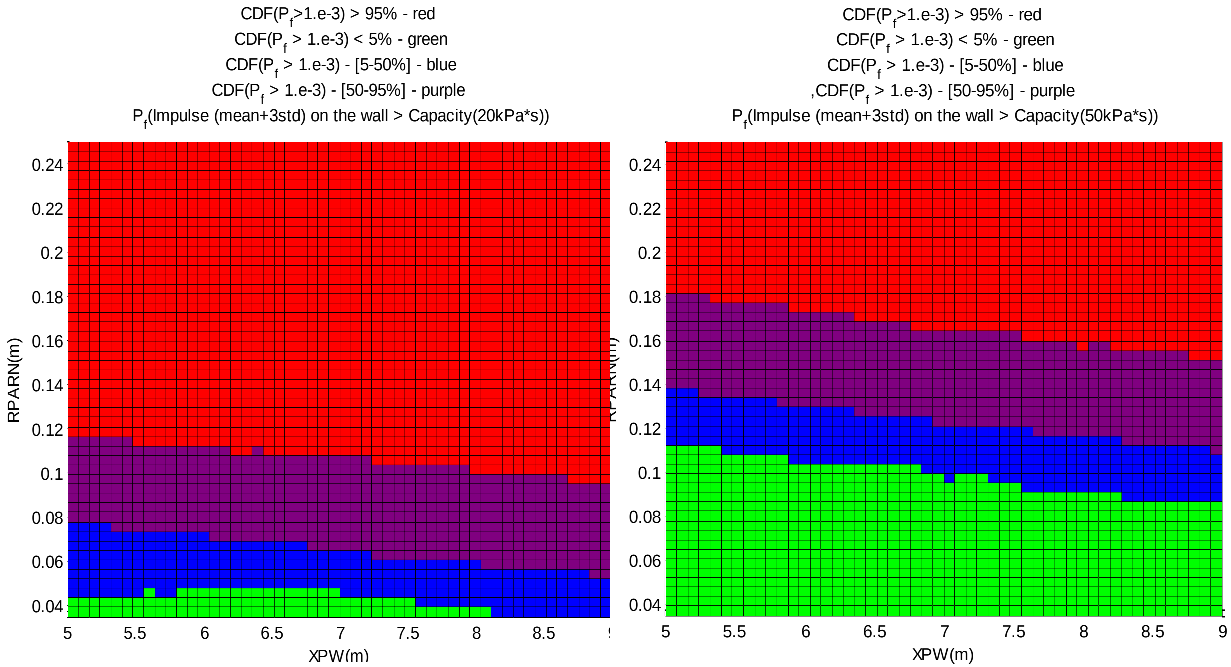
Reverse Analysis for SEIM SM with ROAAM+ framework



Failure Domain

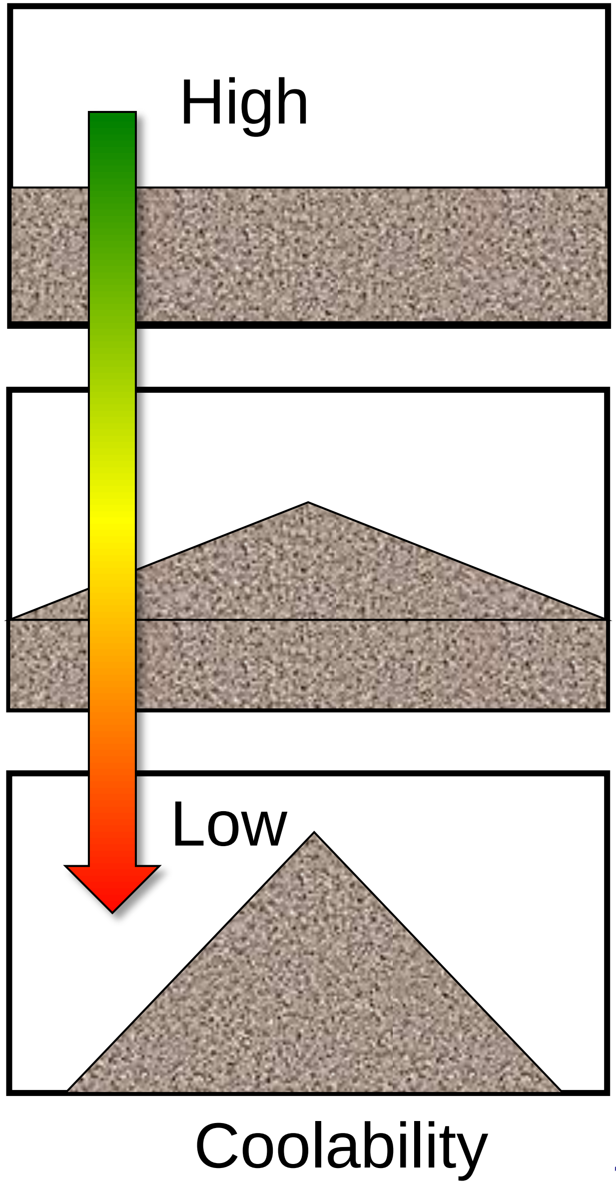
- Every possible combination of PDFs of model input parameters results in certain value of failure probability P_f
  - probability of Load(L) exceeding Capacity(C)).
- Failure domain is represented as
  - a function of most influential parameters
    - RPARN (jet radius) and XPW (LDW water pool depth) based on
  - as statistical characteristics of $CDF(P_f > P_s)$.

20 kPa*s fragility limit 50 kPa*s fragility limit



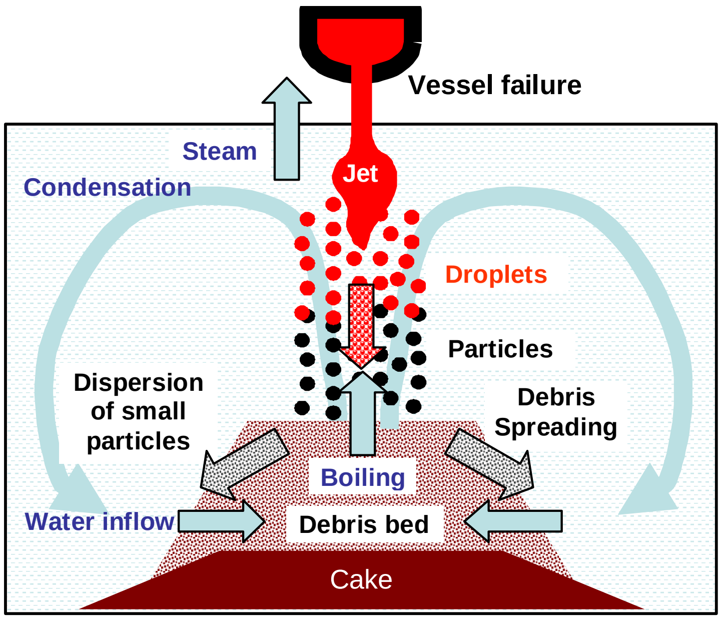
Debris Bed Coolability Problem

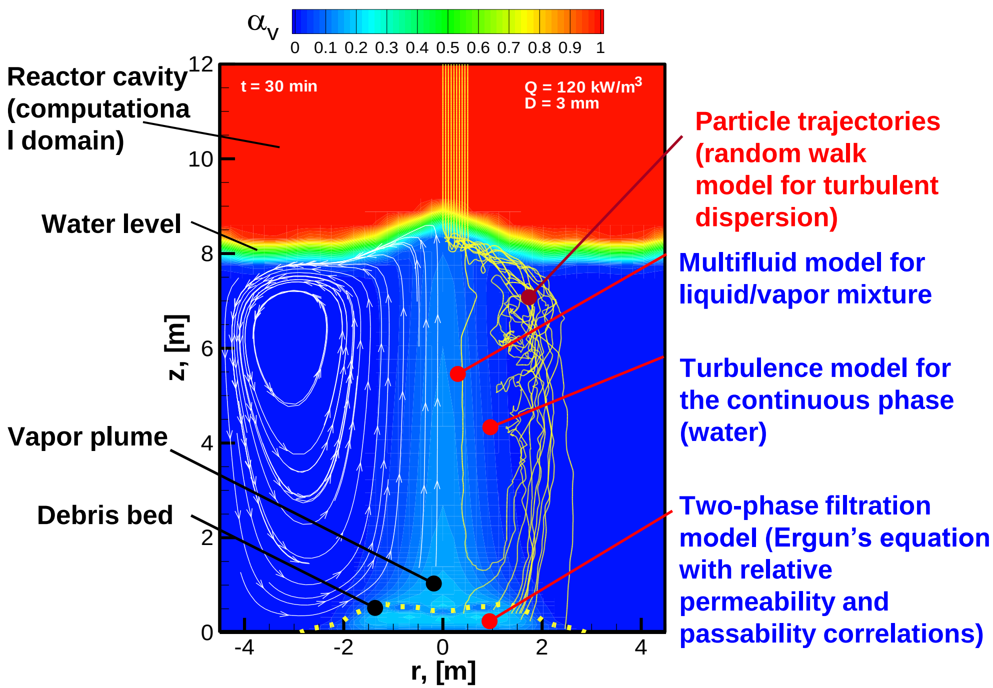
- For flat debris bed, Dryout Heat Flux (DHF) determines the coolability boundary.
- For a fixed height, 2D debris bed is more coolable due to side ingress of water.
- However, for a fixed mass, flat debris bed is more coolable because it has the lowest height.



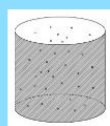
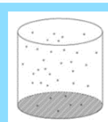
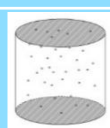
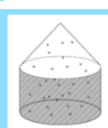
Debris Coolability: DECOSIM Development

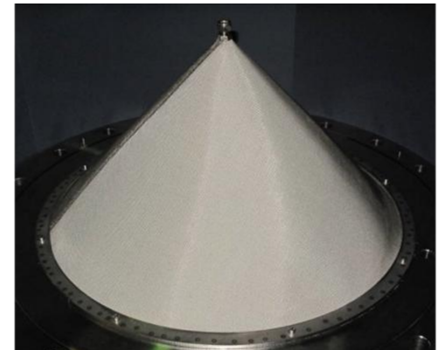
- Coolability of the bed depends on the
  - Bed shape, porous media properties, system pressure - affected by
    - fuel-coolant interaction and debris bed formation **phenomena**
    - **scenarios** of melt release and accident progression.
- <u>Goal</u>: Development of full (DECOSIM) and surrogate models for **coupled analysis** of ex-vessel debris bed **formation and coolability phenomena** in different accident **scenarios.**

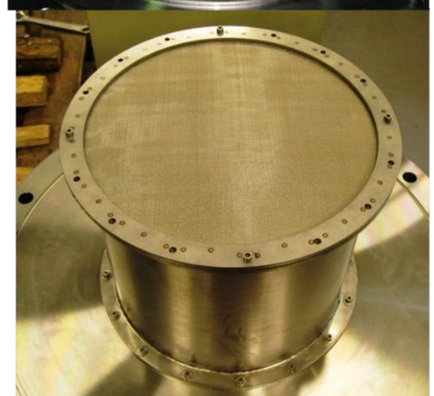




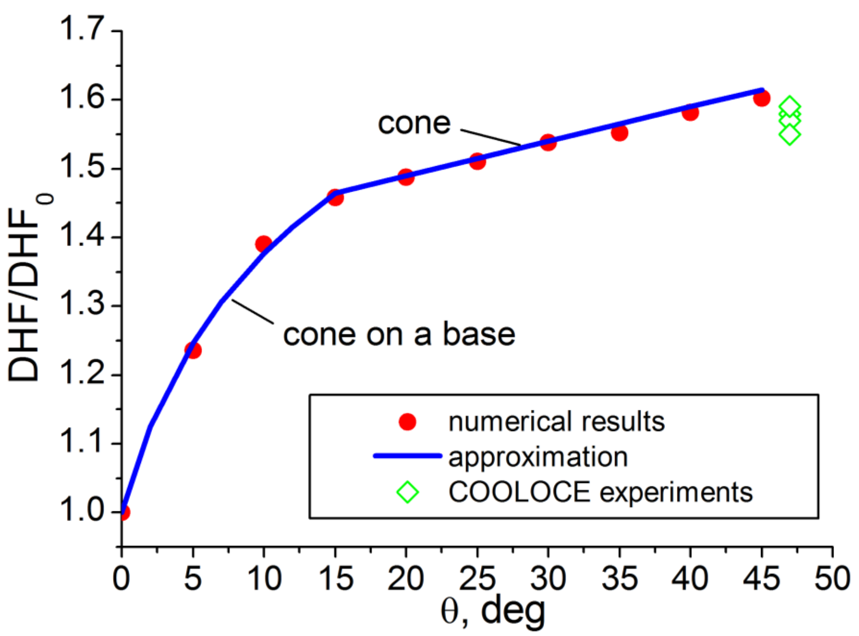
COOLOCE Tests at VTT with different bed geometries

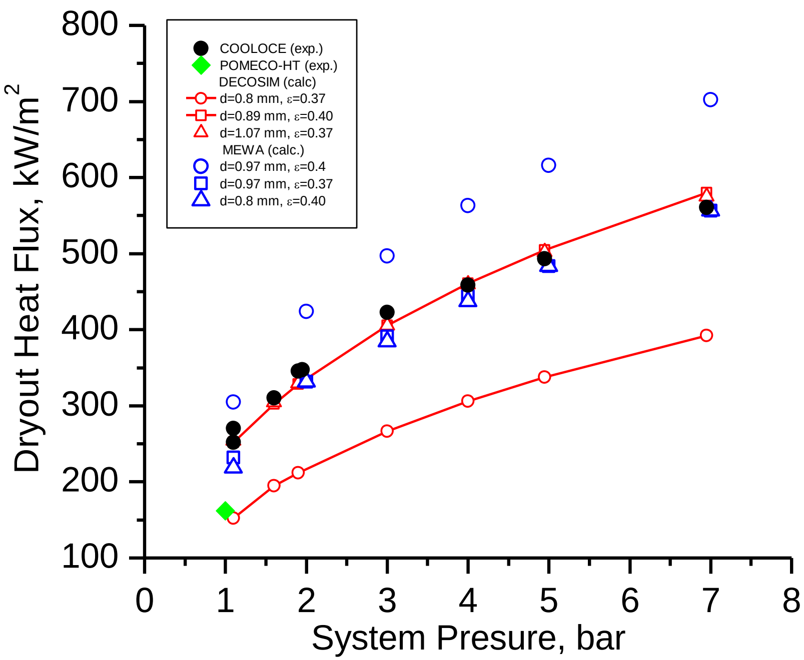
Experiment	Flow configuration	Test bed	Particle material	Pressure range [bar]
COOLOCE-1 – 2	Conical, multi-dimensional		Spherical beads	1.6-2.0
COOLOCE-3 – 5	Cylindrical, top flooding			1.0-7.0
COOLOCE-6 – 7	Conical, multi-dimensional			1.0-3.0
COOLOCE-8	Cylindrical, top flooding		Irregular gravel	1.0-7.0
COOLOCE-9	Cylindrical, top flooding*			1.0
COOLOCE-10	Cylindrical, lateral and top flooding		Spherical beads	1.3-3.0
COOLOCE-11	Cylindrical, lateral flooding			1.0-7.0
COOLOCE-12	Cone on a cylindrical base, flooding through conical part		Spherical beads	1.0-4.0





Shape Factor: Dependence of DHF (Conical Bed)

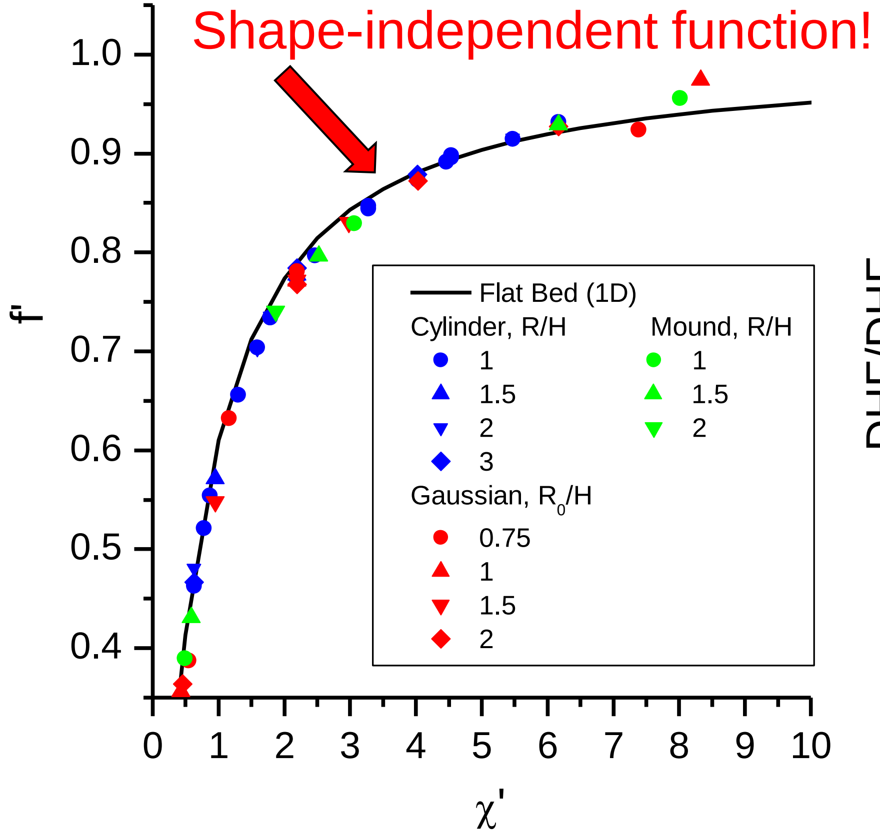




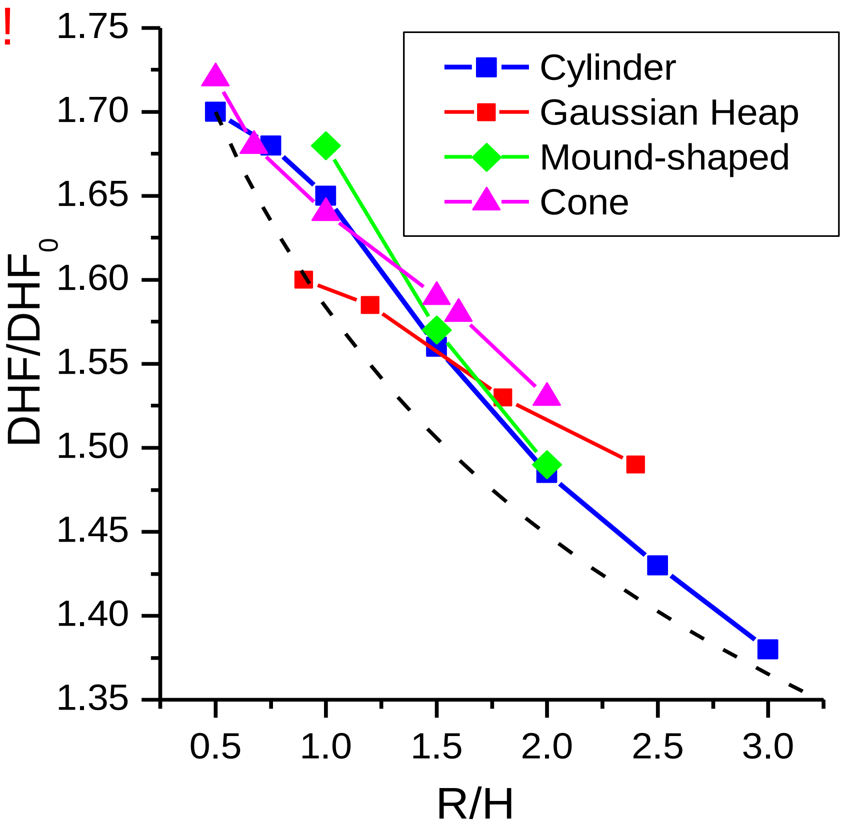
- Good agreement with COOLOCE experiments for conical bed (left) and cylinder with impermeable walls (right)

SM for Dryout Occurrence

- DHF data for different shapes (Cylinder, Gaussian, Mound) plotted together, solid line is solution for 1D flat bed



Function f' describes dependence of DHF on debris bed properties and system pressure in non-dimensional variables.

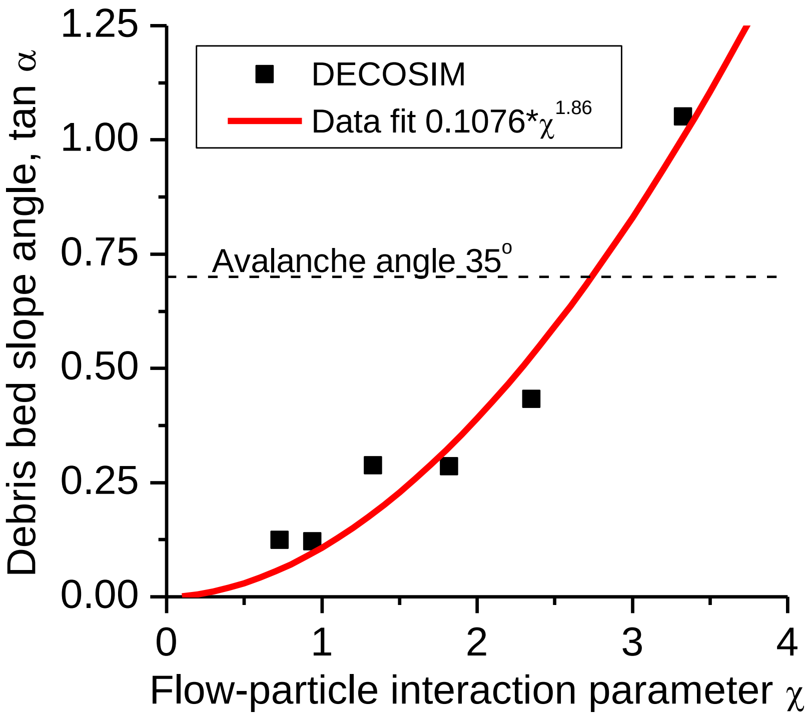


Dependence of DHF on debris bed geometry is factored out.

$$F(\text{shape}) = \text{DHF}/\text{DHF}_0 = 1.7\left(R/H + 0.5\right)^{0.175}$$

Effect of Debris Spreading in the Pool

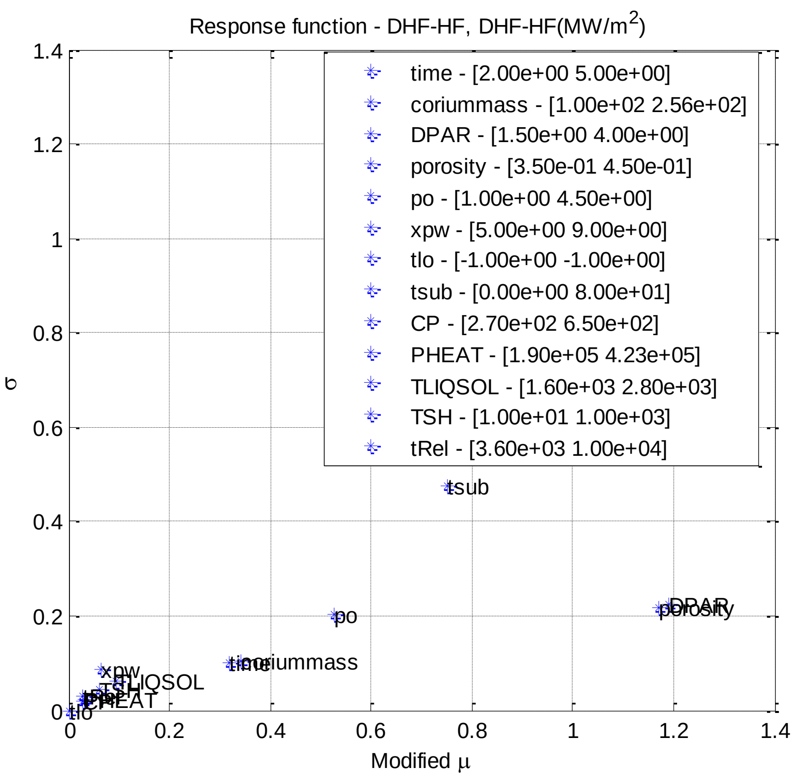
- For gradual melt release, debris bed formation is affected by convective flows in the pool which spread melt particles over the pool base mat, reducing debris bed height.
- A surrogate model for debris bed formation in the gradual melt release mode was developed and validated against DECOSIM simulations.

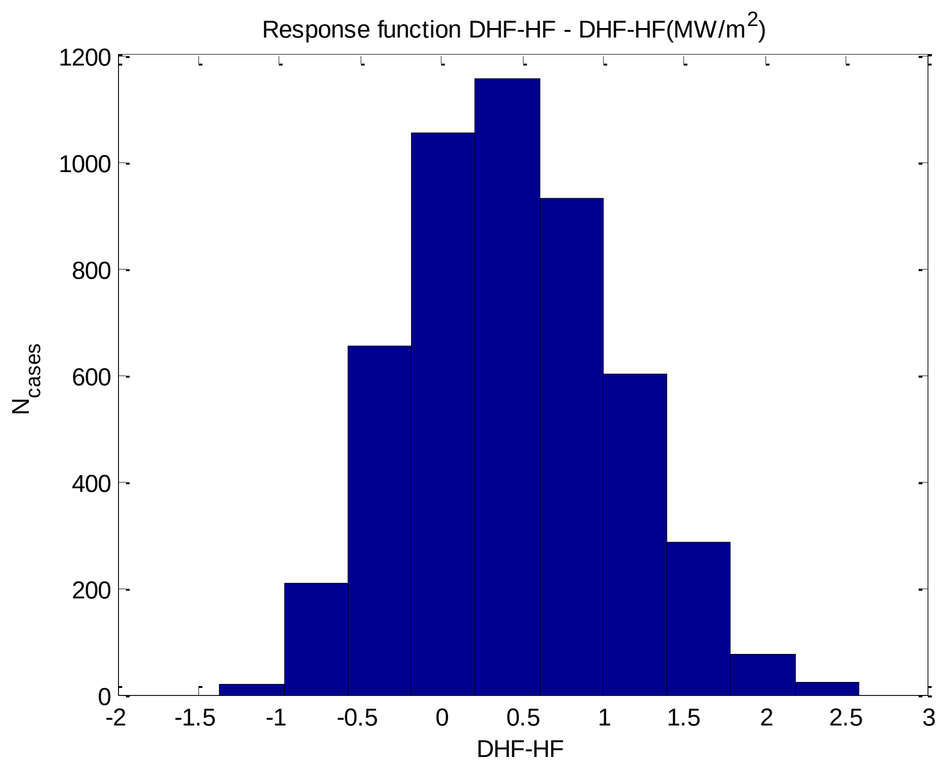


- Flow-particle interaction is described by parameter χ which depends on
  - Particle diameter and density.
  - Pool depth.
  - System pressure.
  - Decay heat power.
- For saturated pool, dependence of slope angle on χ is found.
- A correction is introduced in order to take into account initial transient time before onset of pool boiling.

Sensitivity analysis

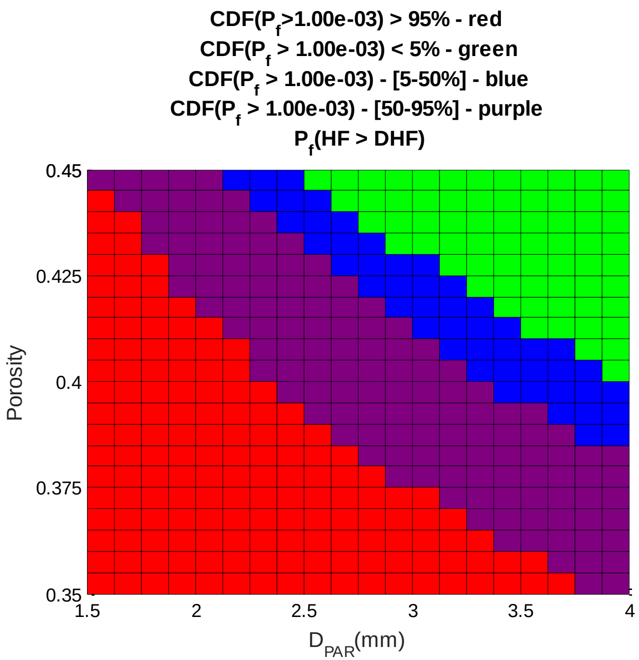
- Base Case:
  - Input parameters are sampled within possible ranges.
  - Most important are
    - Particle size (DPAR).
    - Porosity.
    - Pool subcooling.

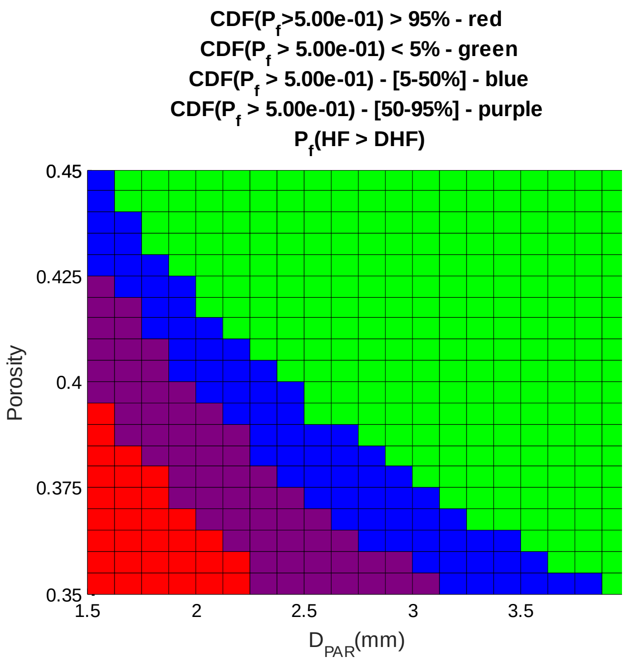


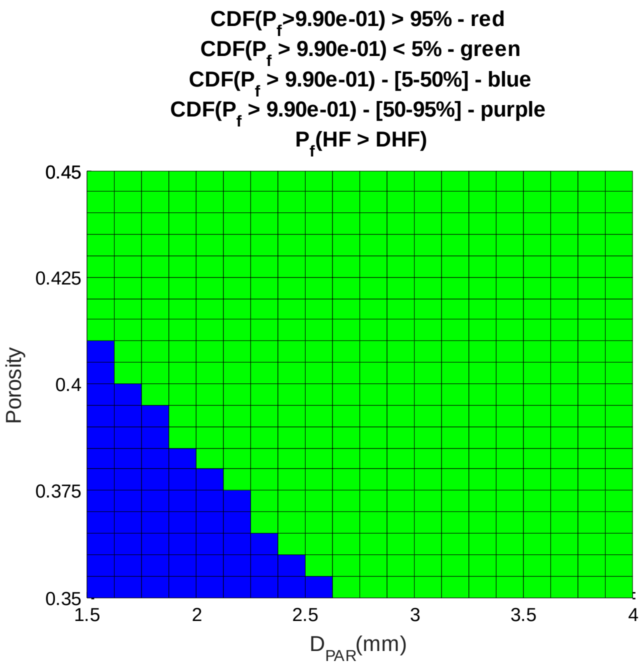


Failure domain analysis

- Base Case failure domain.
- $P_f < P_s$ in ~5% cases
  - For large particle diameters (>2.5mm) and high porosity (>0.4)
- $P_f \sim 0.5$ in half of all the cases
- There is a region with $P_f > 0.99$ in 5-50% cases.







Summary

- ROAAM+ Helps to understand importance of different factors based on simultaneous consideration of
  - Scenario (aleatory), and
  - Modeling (epistemic) uncertainty.
- Improved prediction of the size of the jet and superheat are crucial for reduction of uncertainty in steam explosion risk
  - Further work is necessary on the vessel failure modeling.
- Debris spreading in the pool is crucial for resolution of the debris bed coolability issue
  - Further combined consideration is necessary for coolability and
    - Spreading in the pool.
    - Self-levelling.
    - Agglomeration.