Analyzing Ex-Vessel Steam Explosions During Severe Accidents in Nordic BWRs

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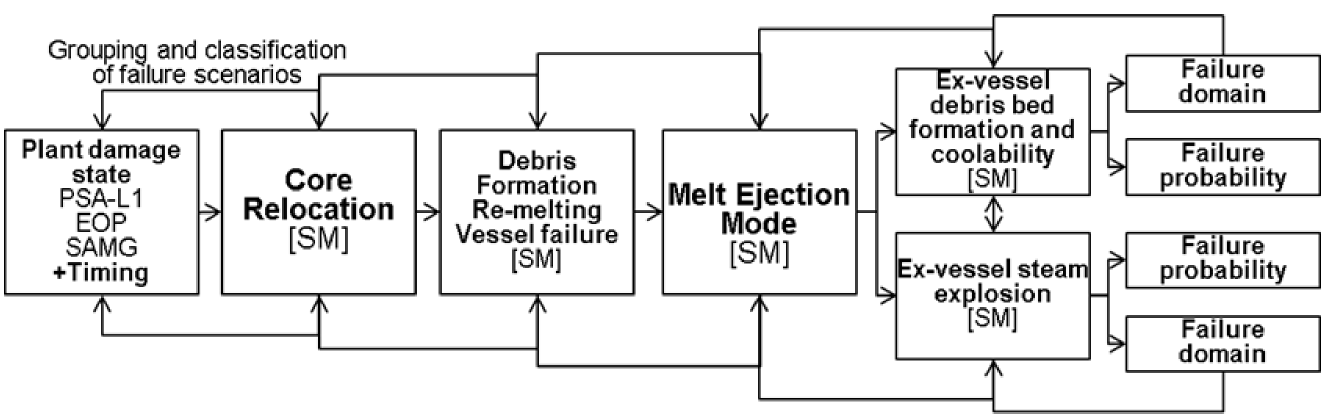
Risk Oriented Accident Analysis Methodology+

- ROAAM+ framework is being developed at KTH to address uncertainties in:
  - Scenarios – aleatory.
  - Phenomena – epistemic.
- ROAAM+ comprises of:
  - Detailed full models (FMs) – for key information about physics.
  - Fast-running surrogate models (SMs) – for sensitivity, uncertainty and failure domain analysis.
- ROAAM+ has highlighted:
  - Debris bed coolability – needs deep pool of water in cavity.
  - Steam explosion risks – necessitates reinforcement of hatch doors in the cavity.

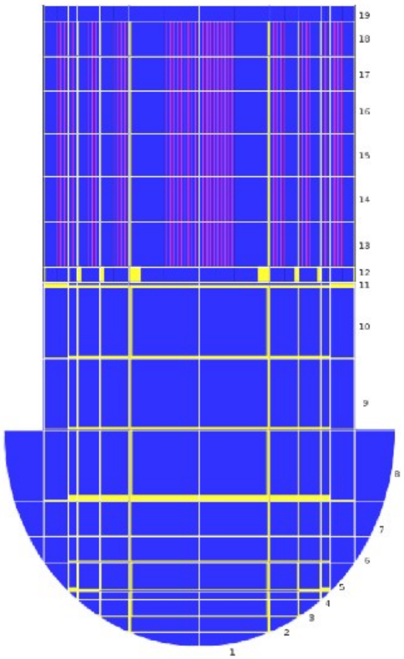


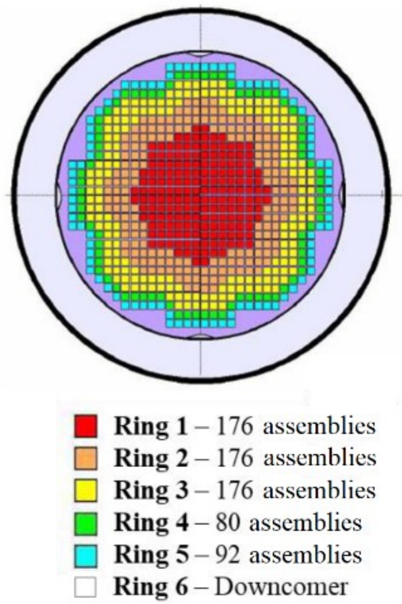
Motivation and Goals

- SMs based on time-independent variables obtained from FMs.
  - Average melt release rate.
  - Maximal loads on containment.
  - Maximum temperature of debris bed.
- Loss of potential information during averaging.
  - Transient nature of phenomena cannot be “averaged”.
  - Operator interventions, containment phenomena are time dependent.
- ROAAM+ needs dynamic SMs for effective treatment of transients.
  - …
  - Develop coupling scheme to estimate risk of steam explosion on source term.
  - …

Reactor and Accident Scenarios of Interest

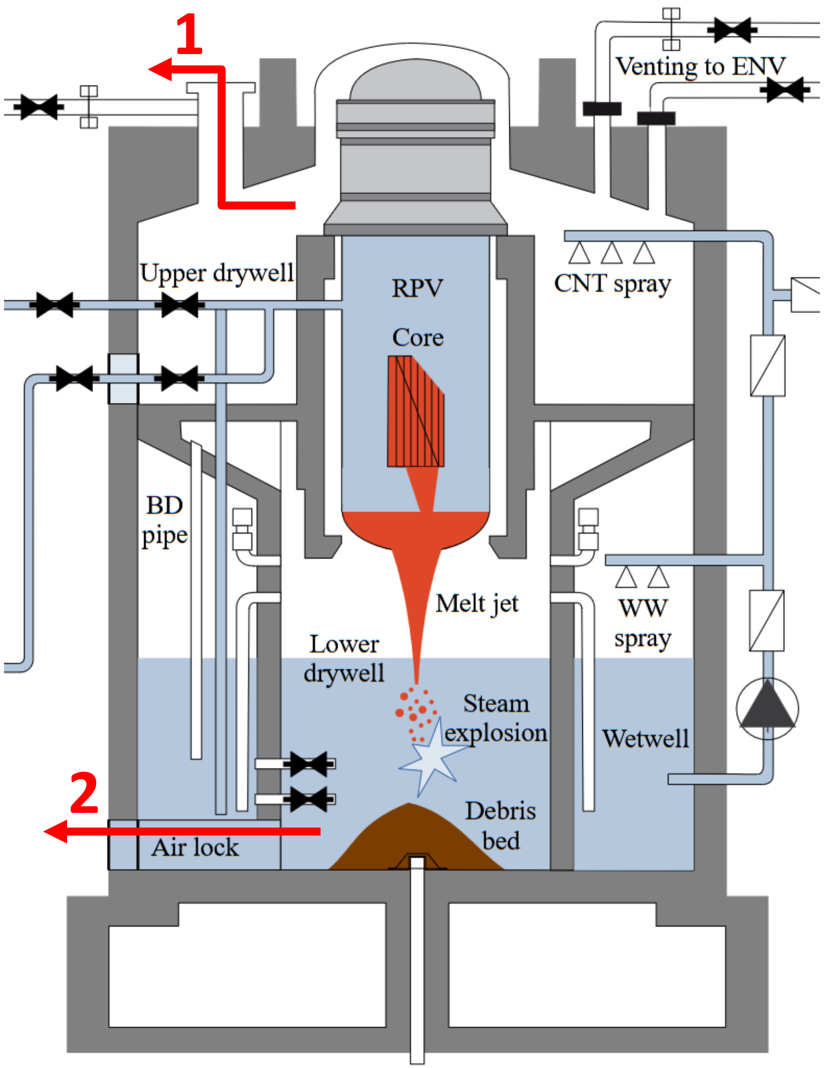
- Nordic BWR
  - ASEA/ABB Atom based on Westinghouse BWR75.
  - 3900MWth power.
  - 700 fuel elements.
    - 6 radial rings.
    - 19 axial levels.

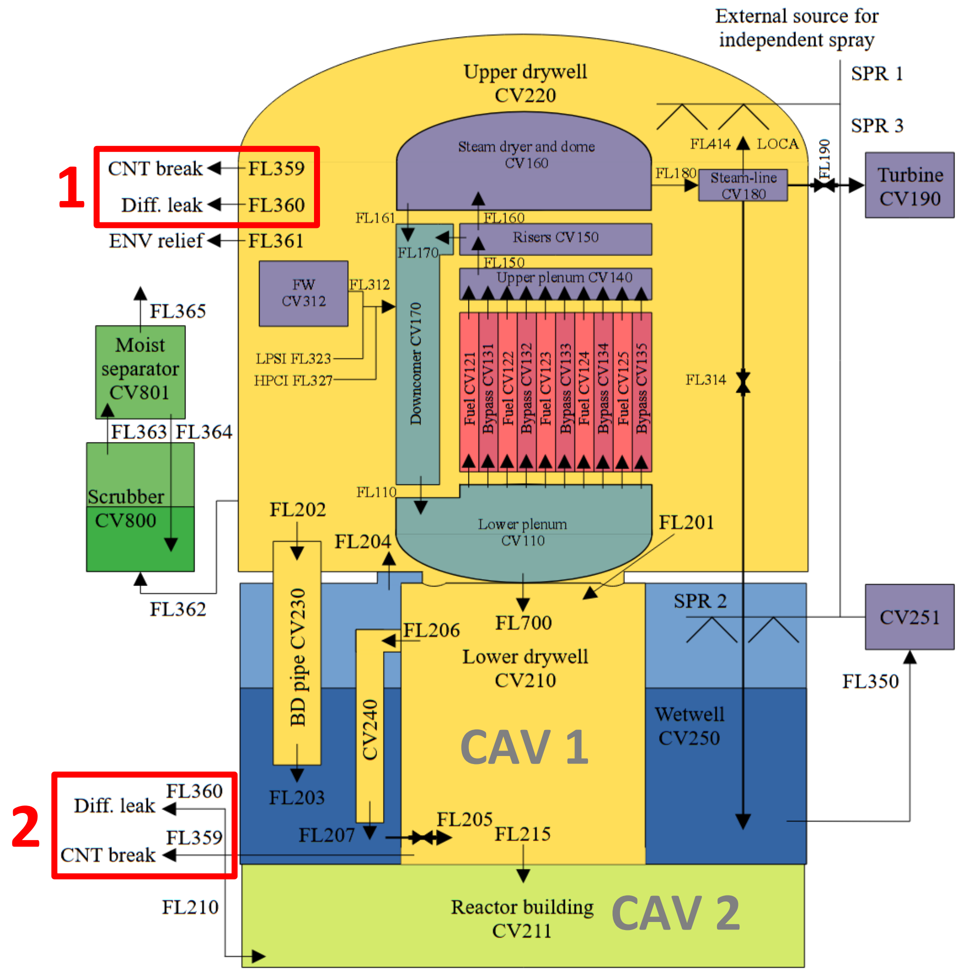




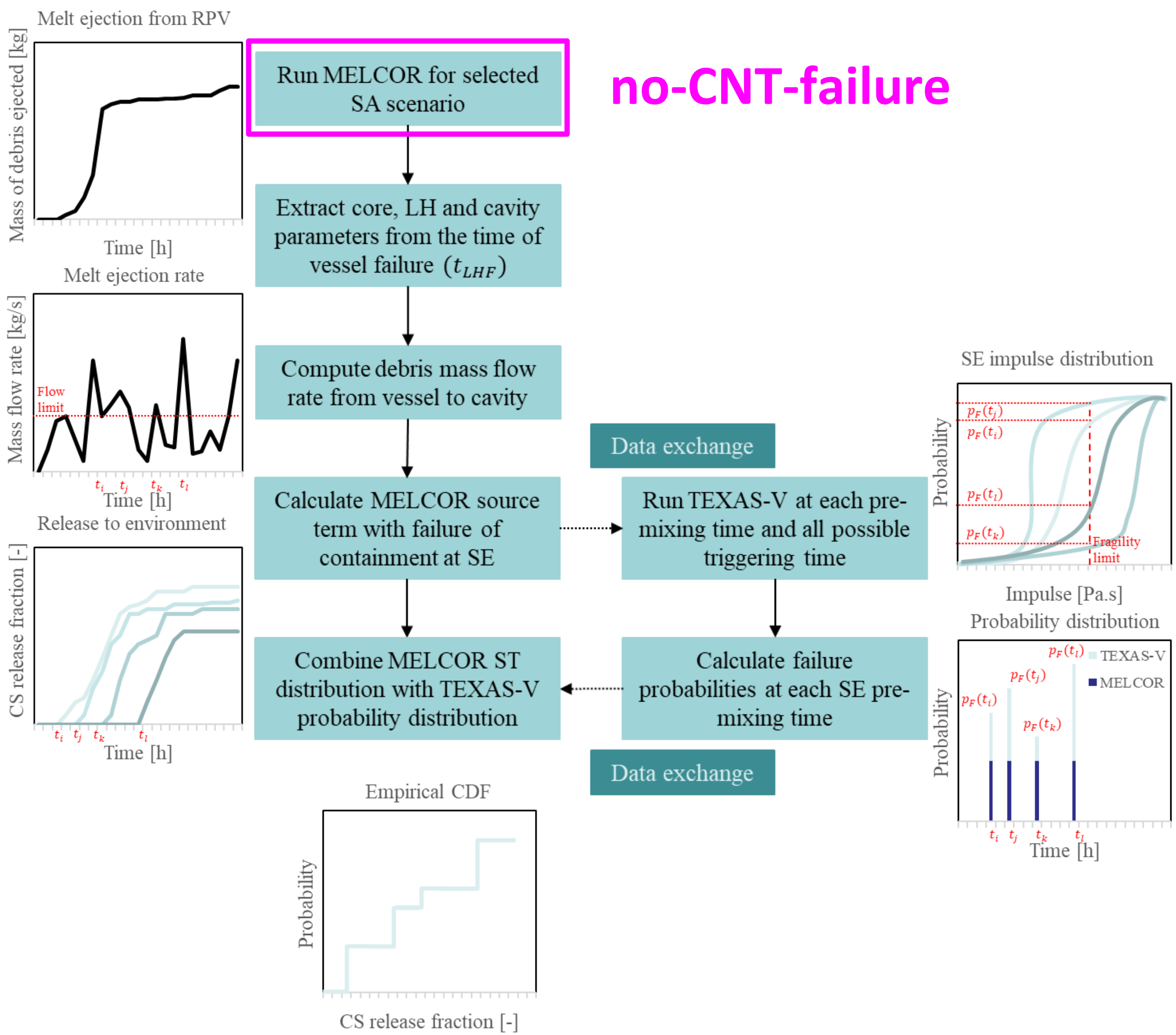
- RC4 – Severe accident initiated by a transient or LOCA with containment failure due to containment phenomena (FCI/basemat melt through)
  - RC4A – LOCA: unmitigated
  - RC4B – SBO: unmitigated

MELCOR Model Nodalisation



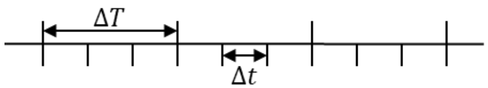


MELCOR-TEXASV Coupling Scheme

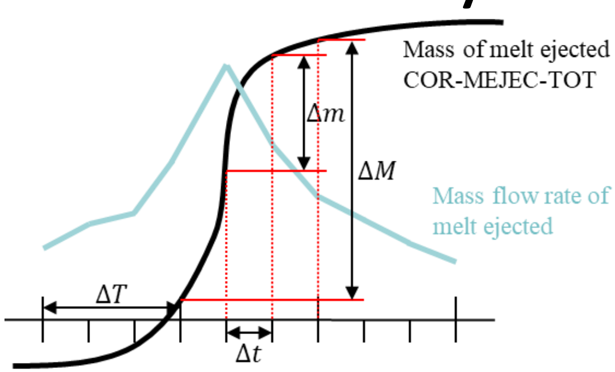


MELCOR Data Extraction and Post-Processing

- `EDF WRITE` to write melt ejection and cavity characteristics for every 0.1s.
- Coarse time-steps considered:
  - 5s period, and 100s period.



- Mass-averaged mass flow rate and velocity:



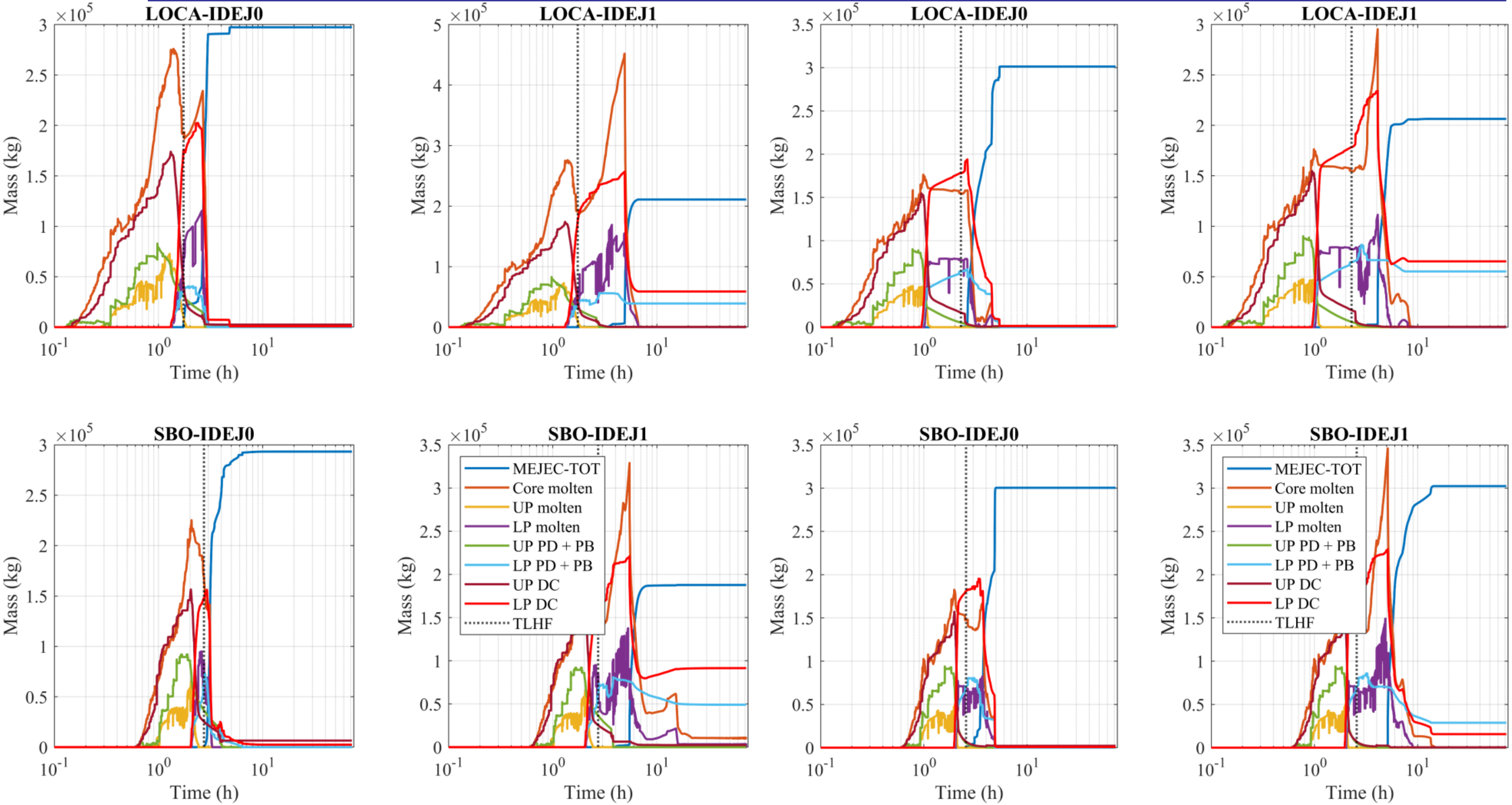
MELCOR variable	Definition	Unit
EXEC-TIME	Absolute time in MELCOR simulation	s
EXEC-DT	Time step value	s
CAV-RHO(CAVITY, HMX)	Density of melt layer in cavity	$kg.m^{-3}$
COR-ABRCH	Vessel breach area	m^2
COR-MEJEC-TOT	Cumulative mass of melt ejected to cavity	kg
COR-T-LP(OXI, CH)	Temperature of oxidic pool in lower plenum	K
COR-T-LP(MET, CH)	Temperature of metallic pool in lower plenum	K
CVH-CLIQLEV('LDW')	Collapsed liquid level of water in cavity	m
CVH-P('LDW')	Pressure in the cavity	Pa
CVH-VOID('LDW', POOL)	Void fraction of the water phase in the cavity	-
CVH-TVAP('LDW')	Temperature of the vapour phase in the cavity	K
CVH-TLIQ('LDW')	Temperature of the water phase in the cavity	K

$$\bar{\dot{M}}_i = \left(\frac{1}{\Delta M_i}\right)\sum_{j=1}^{N}\frac{\Delta m_j^2}{\Delta t_i} \qquad v_i = \frac{\Delta M_i}{\Delta T_i \rho_i A_{breach}}$$

MELCOR Data Extraction and Post-Processing

- Instances of $\bar{\dot{M}}_i$ < 50kg/s is filtered out.
- Composition of melt ejected is assumed to be constant and temperature to be 3000K.
- Debris ejection mode:
    - IDEJ0 – default, solid and molten debris is ejected.
    - IDEJ1 – only molten debris is ejected.
  - LOCA-IDEJ0, LOCA-IDEJ1, SBO-IDEJ0 and SBO-IDEJ1.
- MELCOR version used:
  - Pathway 1 – MELCOR 2.2.18019 – no CAV 2.
  - Pathway 2 – MELCOR 2.2.r2024.0.3 – with CAV 2.
  - Run for 72h from IE.

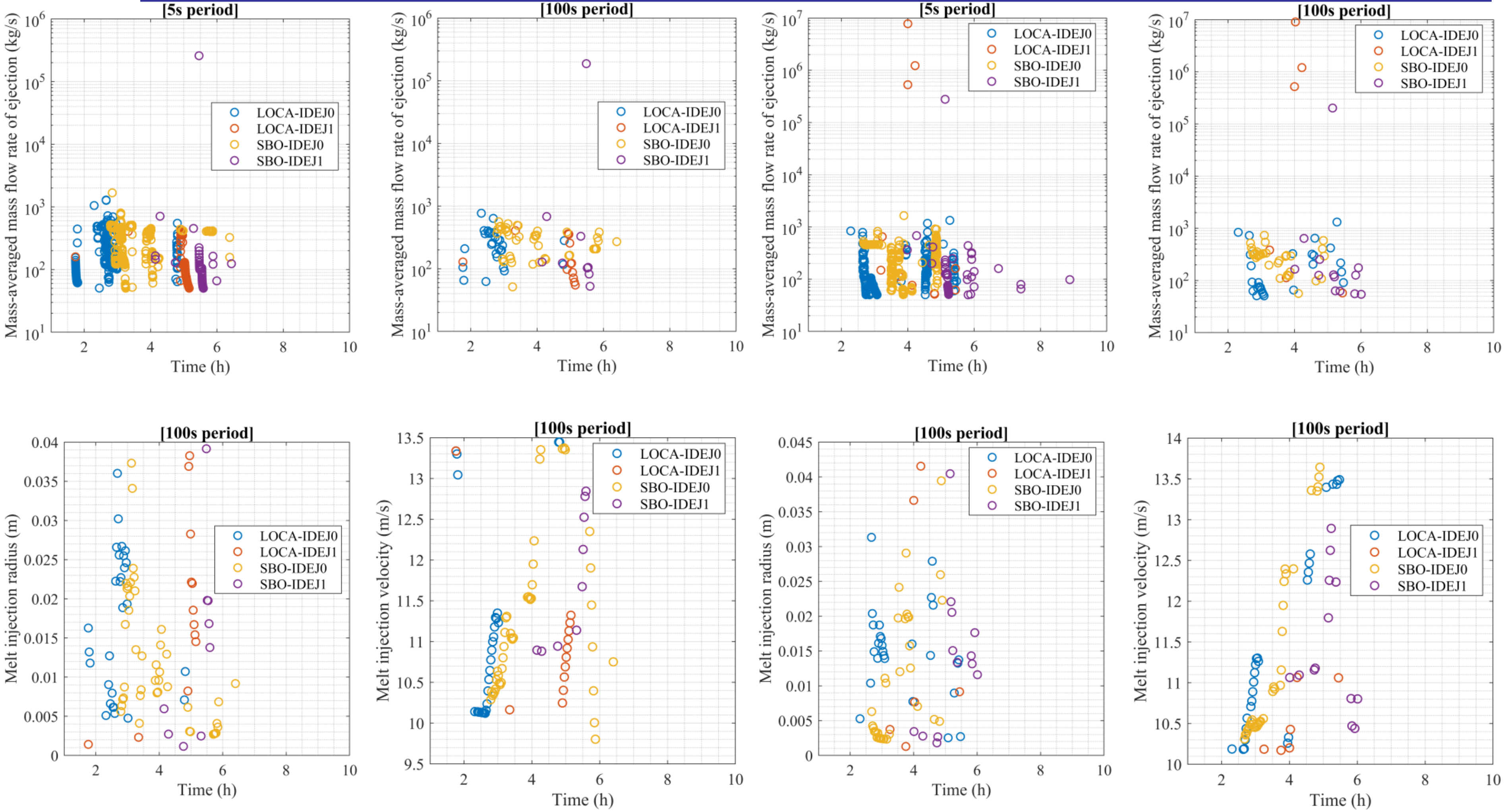
no-CNT-failure Results



- v2.2.18019 – Pathway 1
- COR_EUT - TUO2ZRO2
  - 2450K

- v2.2.r2024.0.3 – Pathway 2
- COR_EUT - TUO2ZRO2
  - 2800K

no-CNT-failure Results



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  - 2800K

TEXAS-V Calculations

- Total premixing calculations:

Period	LOCA-IDEJ0	LOCA-IDEJ1	SBO-IDEJ0	SBO-IDEJ1	Total
Filtered (MA) Pathway 1		Done			
5s	358	194	465	105	1,122
100s	28	12	43	9	92
Filtered (MA) Pathway 2		Ongoing			
5s	311	17	242	98	668
100s	26	6	34	13	79

- SE impulse is sensitive to triggering time.
- Premixing is calculated for entire time melt takes to reach bottom of domain.
  - Configurations were saved at each 1ms time-step.
  - SE calculations were done for each of these instances.
- Therefore, SE energetics are treated statistically with 1000’s of instances for each premixing time.
- Impulse is calculated for each of these instances to derive empirical CDFs.

Propagation of SE Impulse onto CNT

- TNT equivalence method to calculate impulse generated at scaled distance.
- SE assumed to be represented by underwater TNT explosion: Melt thermal energy > charge of TNT.
  - SE energy = total energy of melt – total internal energy of water
  - $E_{SE} = \Delta E_{melt} - \Delta e_{water}$ $[J]$
  - $W_{TNT} = \frac{E_{SE}}{4200000}$ $[kg]$

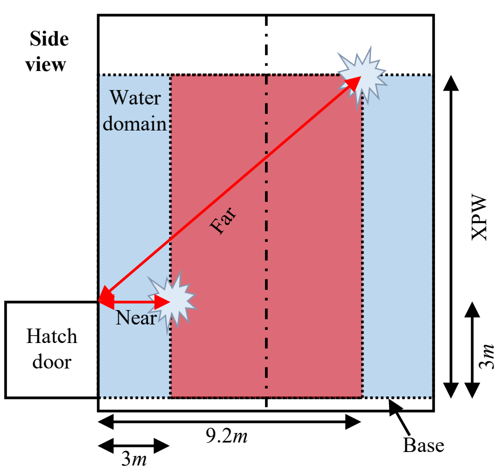
$$P_m = K_1 \left(\frac{W_{TNT}^{1/3}}{r}\right)^{\alpha}$$

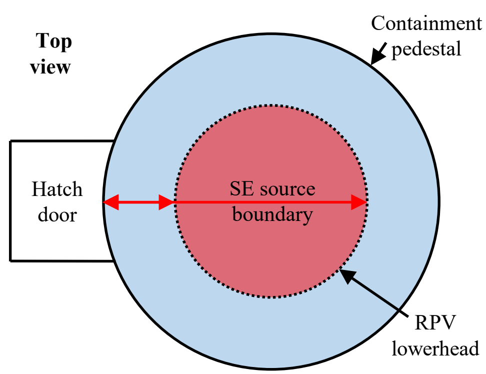
$$e = K_2\, W_{TNT}^{1/3} \left(\frac{W_{TNT}^{1/3}}{r}\right)^{\beta}$$

$$I = K_3\, W_{TNT}^{1/3} \left(\frac{W_{TNT}^{1/3}}{r}\right)^{\gamma}$$

$$\theta = K_4\, W_{TNT}^{1/3} \left(\frac{W_{TNT}^{1/3}}{r}\right)^{\delta}$$

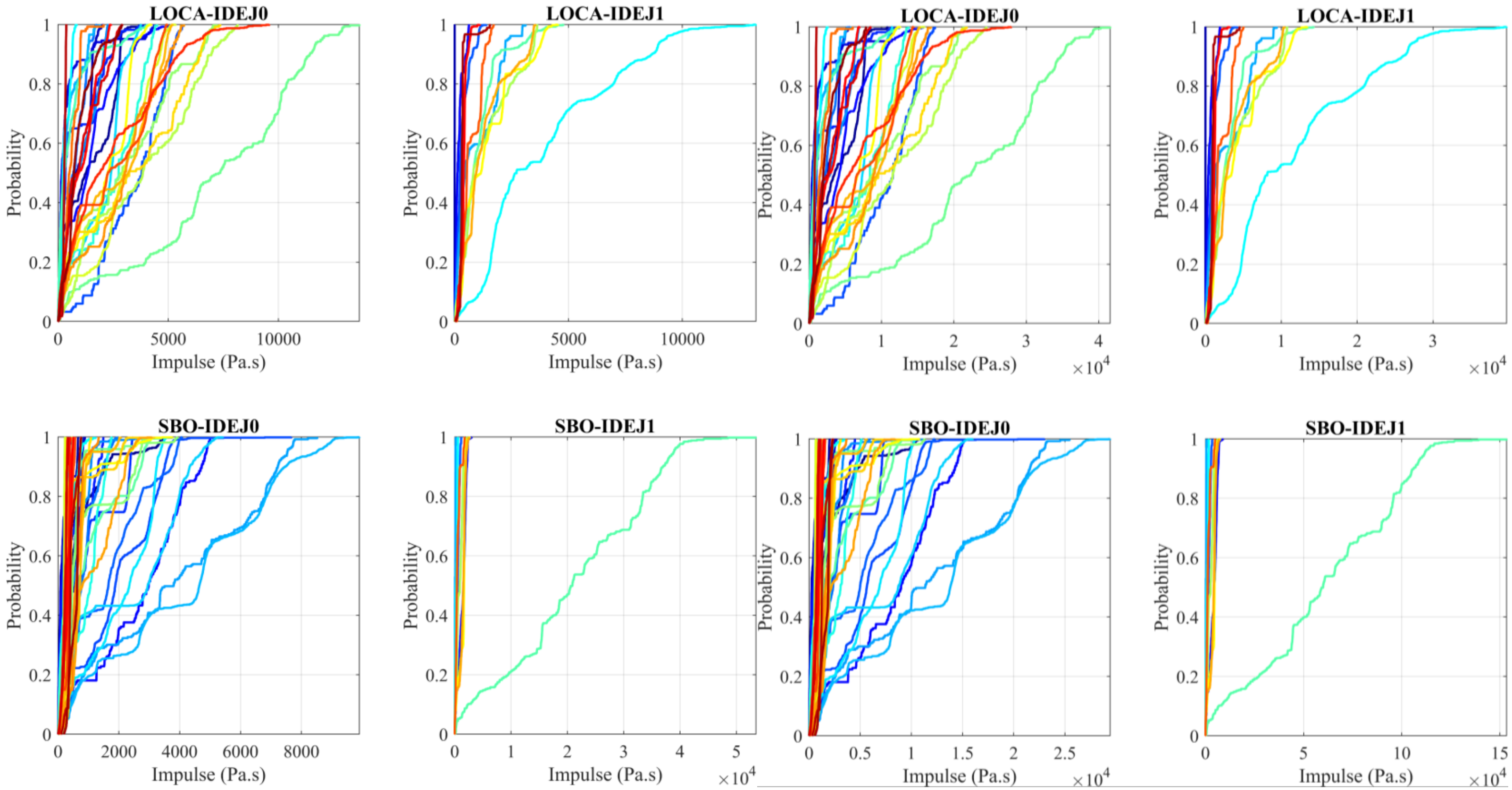
- SE source is assumed to be within bounded region:





Target	Maximum distance [m]	Minimum distance [m]
Hatch door	$\sqrt{((XPW-3)^2+9.2^2)}$	3

SE Loads on the Hatch Door

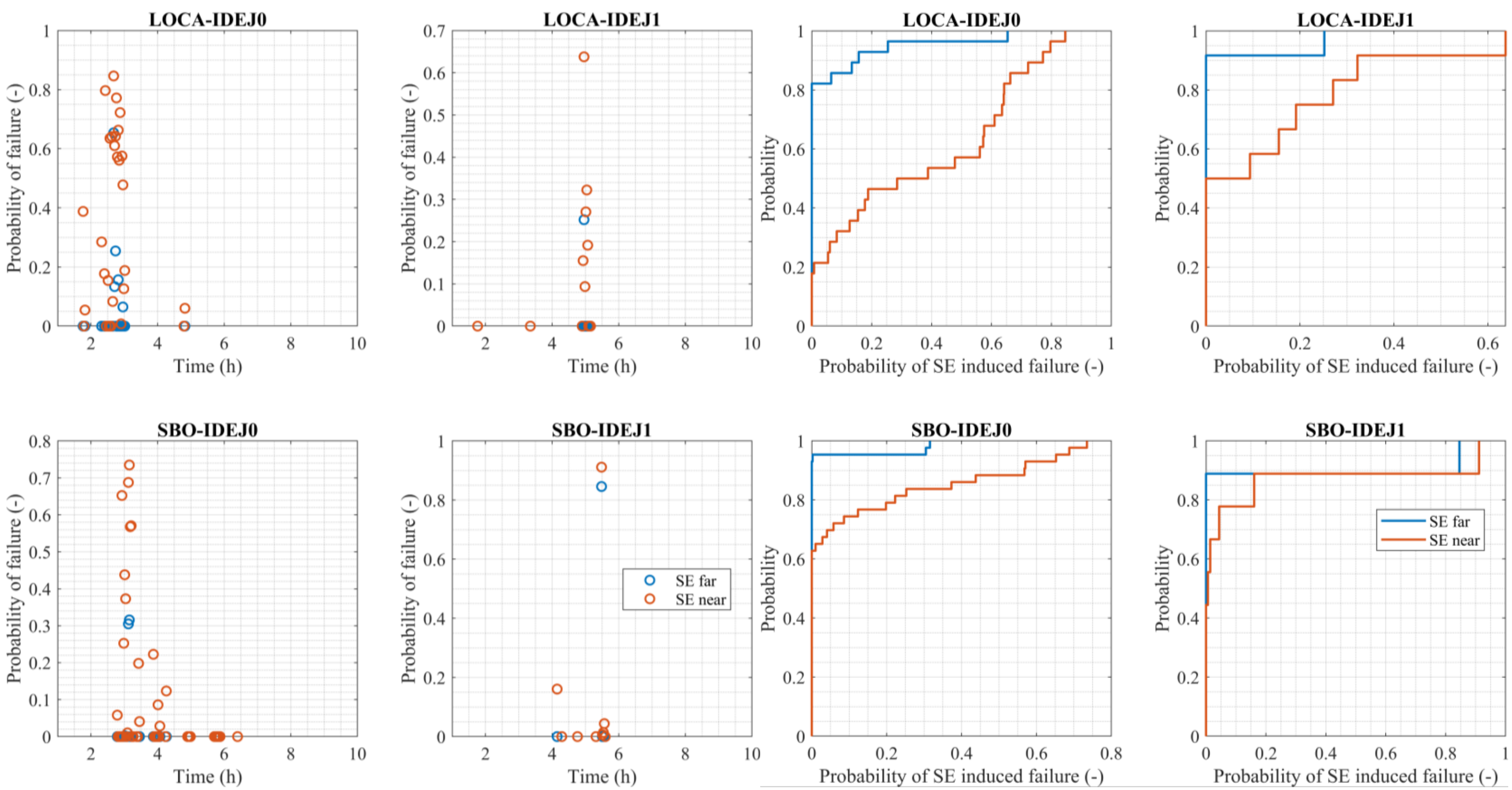


SE near

SE far

Probability of Failure of Hatch Door

- Fragility limit of non-reinforced hatch door 6kPa.s.



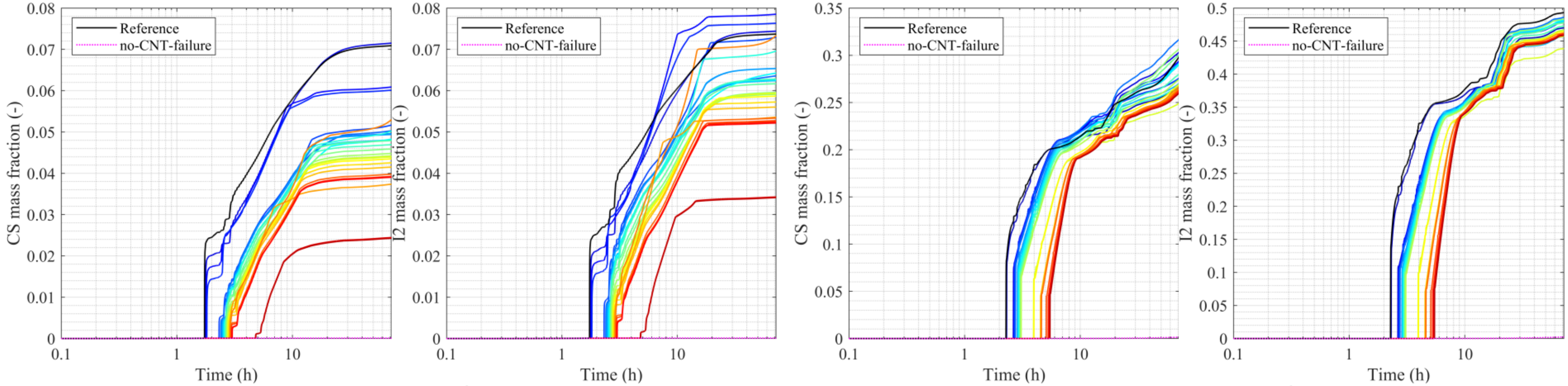
Absolute

CDF

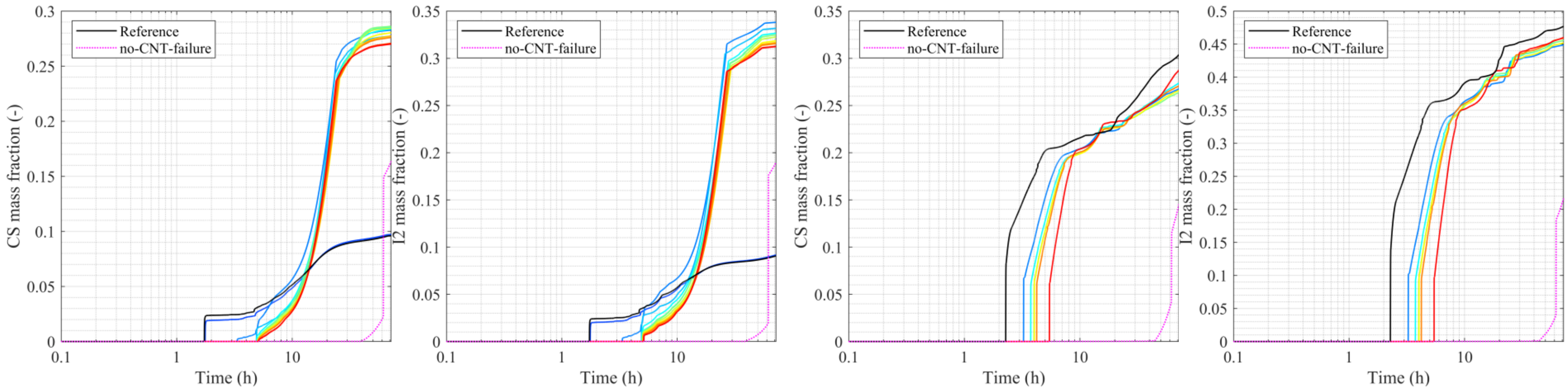
MELCOR Source Term Calculations

- CS and I2 release fractions during LOCA

IDEJ0 IDEJ0



IDEJ1 IDEJ1

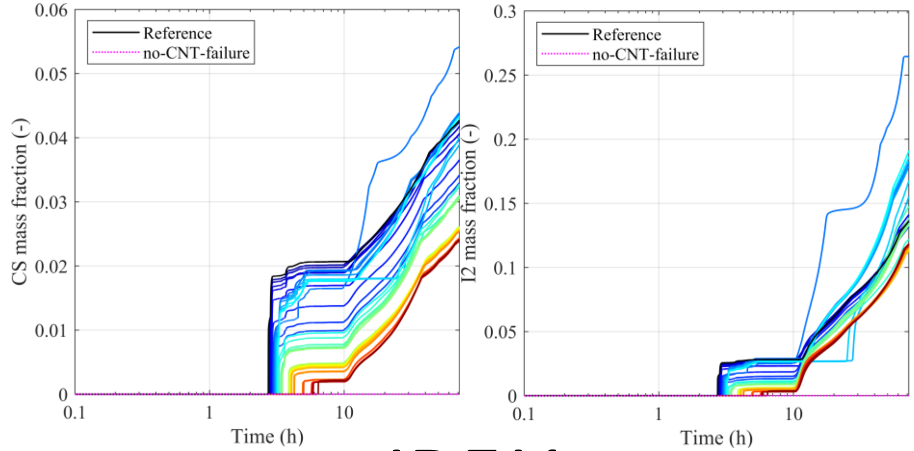


v2.2.18019 – Pathway 1 v2.2.r2024.0.3 – Pathway 2

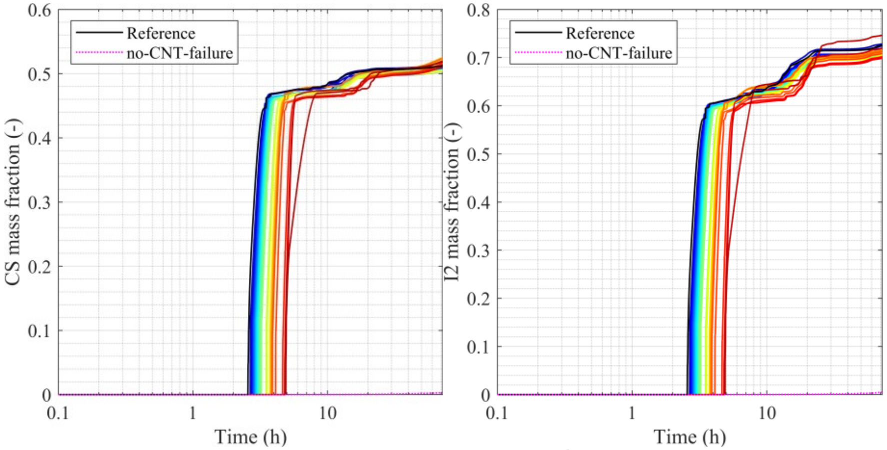
MELCOR Source Term Calculations

- CS and I2 release fractions during SBO

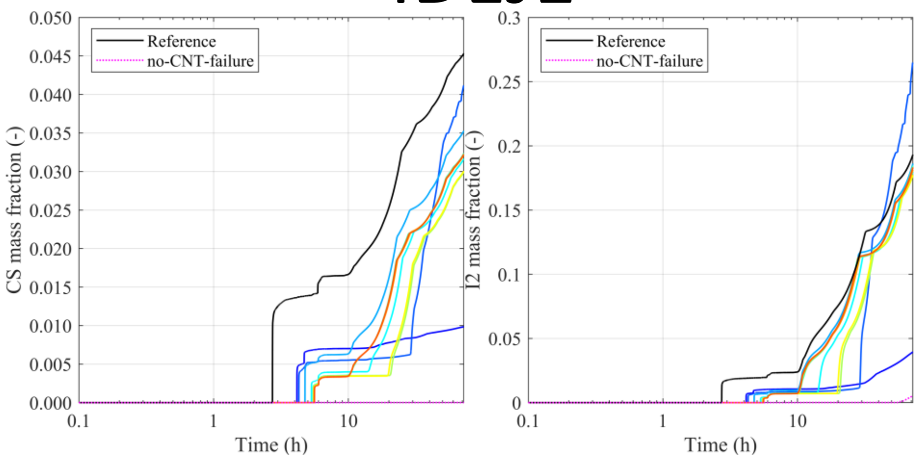
IDEJ0



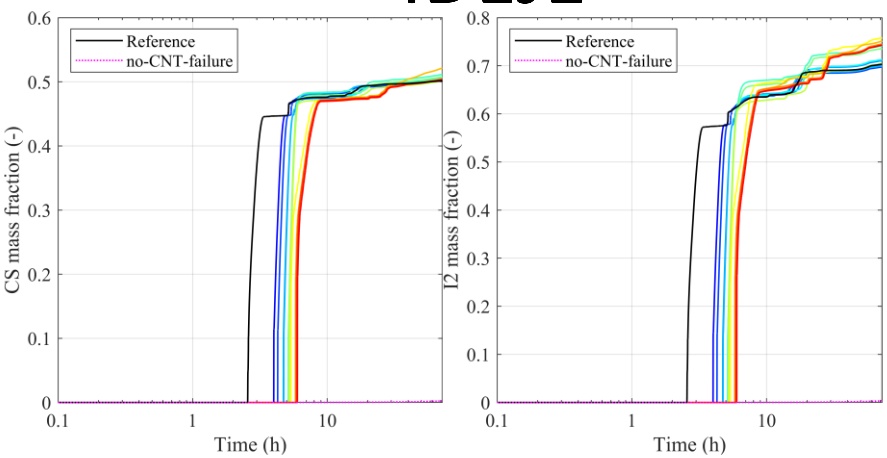
IDEJ0



IDEJ1



IDEJ1

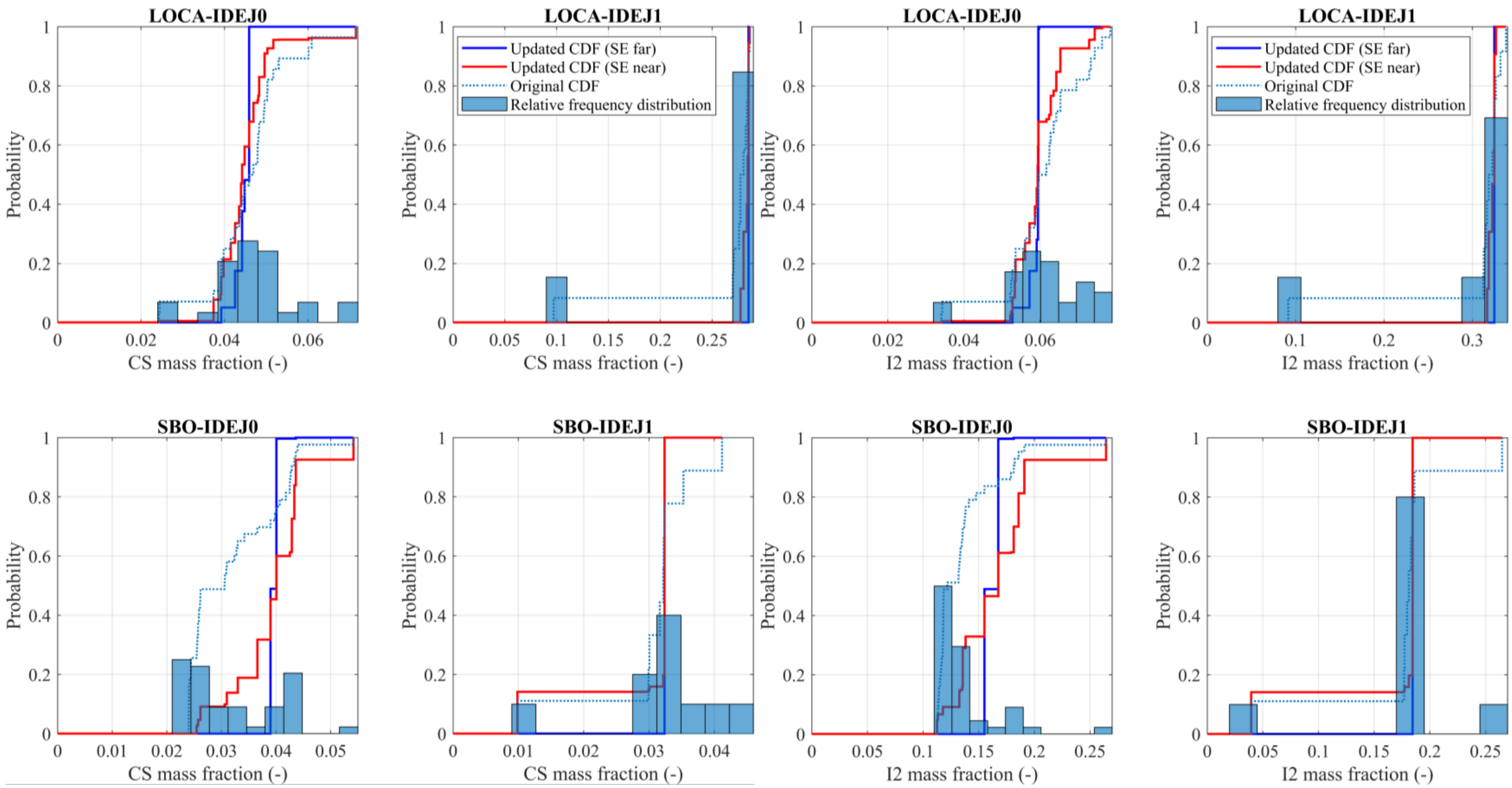


v2.2.18019 – Pathway 1

v2.2.r2024.0.3 – Pathway 2

Updated CDFs

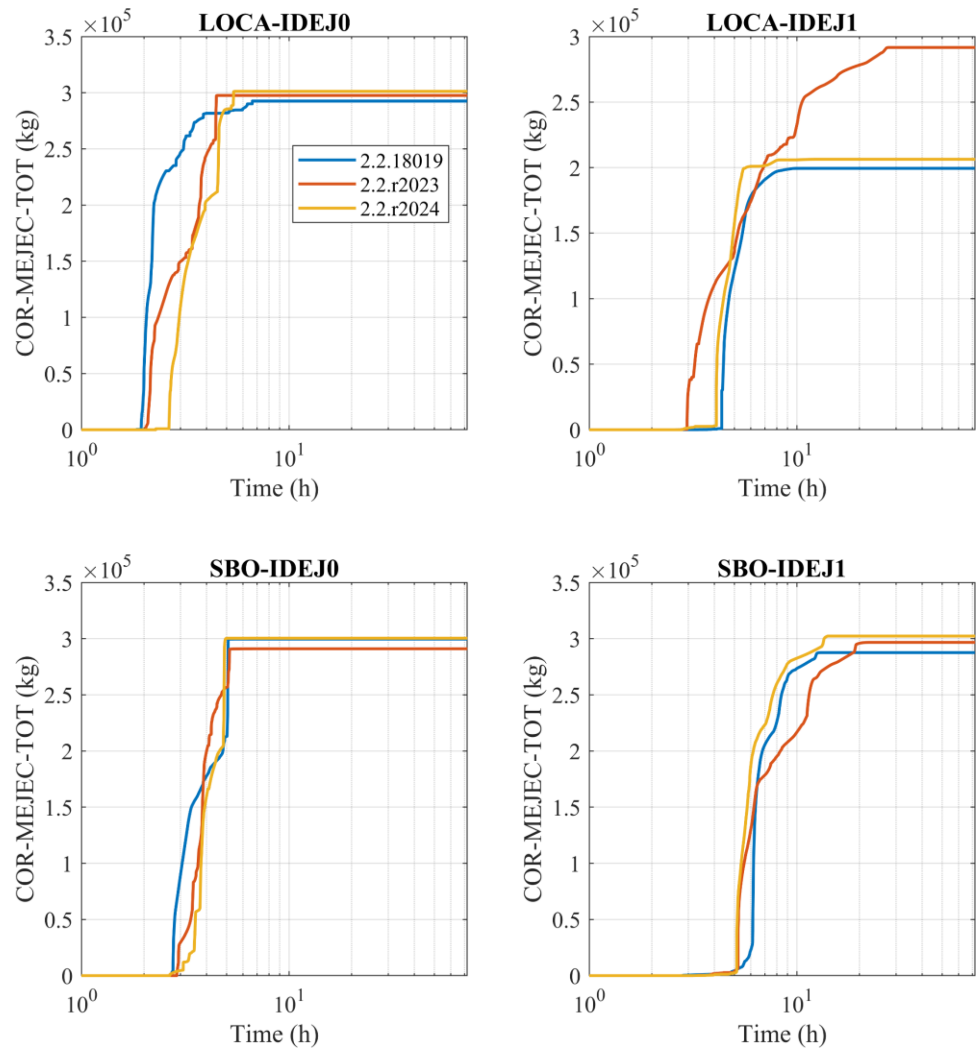
- CS and I2 release fractions at 72h



v2.2.18019 – Pathway 1

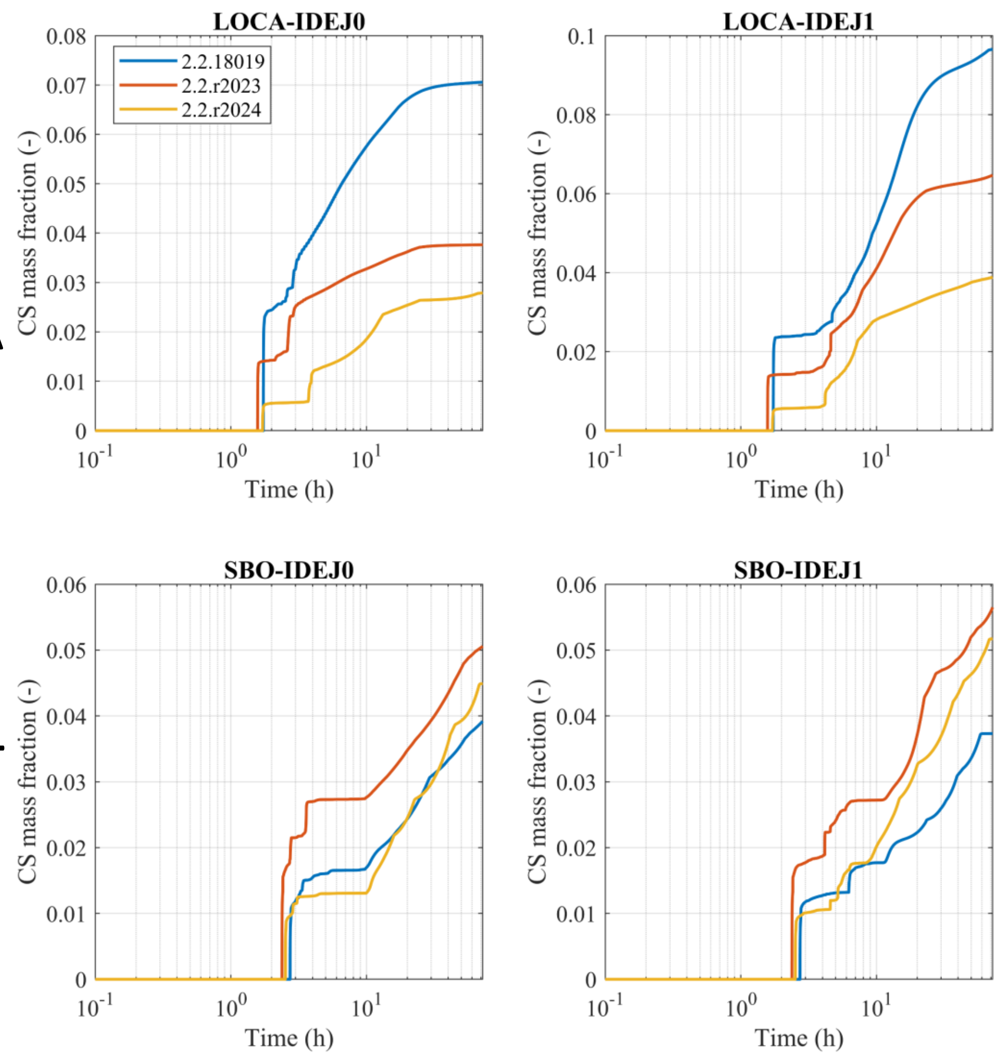
MELCOR Experience

- MELCOR v2.2.18019 – Frequent crashes post cavity dryout.
- Modified COR_EUT TUO2ZRO2 temperature from 2450K to 2800K – same results > crashes when CNT fails at different time.
- Later version v2.2.r2023 and v2.2.r2024
  - TUO2ZRO2 – 2800K.
  - Run to termination without frequent crashes.
  - Used for Pathway 2 with 2 cavities →
  - Further analysis underway.



MELCOR Experience

- Pathway 1 → different versions with TUO2ZRO2 2450K.
- CS release during LOCA is larger in 18019 than 2023 and 2024, and smaller during SBO.
  - CORSOR-Booth (ICRLSE-5) model used.



Conclusions

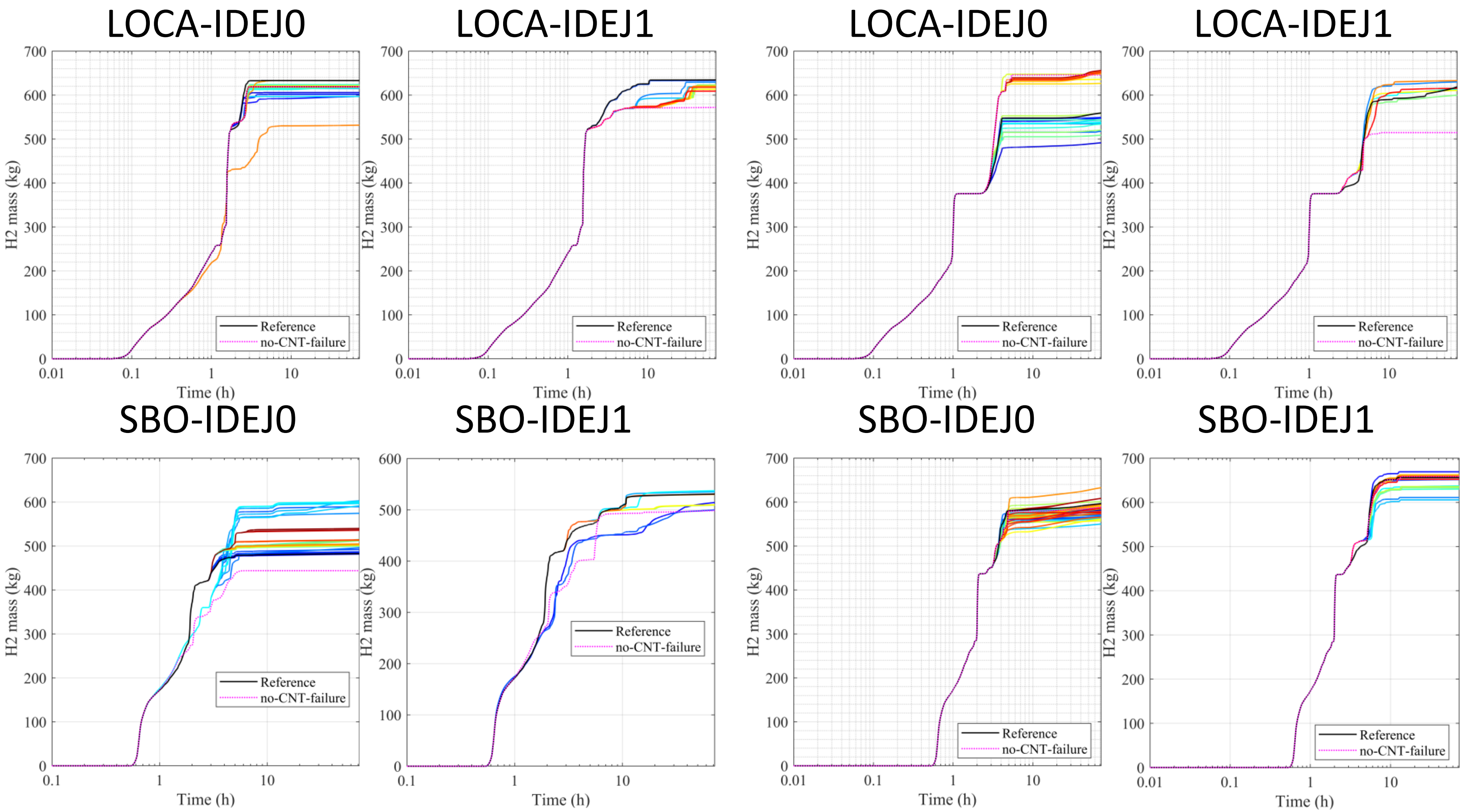
- A scheme for dynamic modelling approach within ROAAM+ framework was developed.
  - Data to be used in developing dynamic SM generated.
- Non-trivial release can be observed in certain accident scenarios.
- Feedback of probabilities of SE loads on the debris coolability.
  - Higher probability of SE induced failure of non-reinforced hatch door.
  - Larger potential for SE in IDEJ0 than IDEJ1.
- MELCOR version can impact final CDFs.
  - Analysis of Pathway 2 underway.

Thank you.

1. L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips, R.C. Schmidt and N.E. Bixler, "MELCOR Computer Code Manuals Vol. 1: Primer and Users' Guide Version 2.2.19018", SAND2021-0252 O, Sandia National Laboratories, Albuquerque, NM, 2021.
2. L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips, R.C. Schmidt and N.E. Bixler, "MELCOR Computer Code Manuals Vol. 2: Reference Manual Version 2.2.18019", SAND2021-0241 O, Sandia National Laboratories, Albuquerque, NM, 2021.
3. Corradini, M.L., et al., "Users' manual for Texas-V: One dimensional transient fluid model for fuel-coolant interaction analysis", University of Wisconsin-Madison: Madison WI 53706, 2002.
4. R.H. Cole, Underwater explosion, Princeton University Press, Princeton, NJ, 1948.
5. L. Bjørnø, P. Levin, "Underwater explosion research using small amounts of chemical explosives", Ultrasonics, 14(6), pp. 263-267, 1976.

MELCOR Calculations

- H2 generated



v2.2.18019 – Pathway 1 v2.2.r2024.0.3 – Pathway 2

TEXAS-V Parameters

Parameter	Range		Description	Units
	min	max		
XPW	4.111	8.423	Water level	m
PO	140891	561528	System Pressure	bar
TLO	334.405	421.966	Water temperature	K
RPARN	0.0051	0.1385	Initial jet radius	m
CP	650	650	Fuel heat capacity	J/kg.K
RHOP	5718.27	9320.57	Fuel density	kg/m^3
PHEAT	400 000	400 000	Fuel latent heat	J/kg
TMELT	2800	2800	Fuel melting point	K
TPIN	3000	3000	Melt superheat	K
UPIN	9.620	13.310	Melt release velocity	m/s
KFUEL	3.000	3.000	Fuel thermal conductivity	W/m.K
CFR	0.0027	0.0027	Proportionality constant for the rate of the fuel fragmentation	–
TFRAGLIMT	0.0025	0.0025	Fragmentation time	ms
ARIY	0.010	7.509	Cell cross sectional area	m^2