Analysis of Steam Explosions and its Consequences in Nordic BWR Cavity with MELCOR-TEXAS Coupling

PSAM 18 : July 19-24, 2026
Pittsburgh, Pennsylvania

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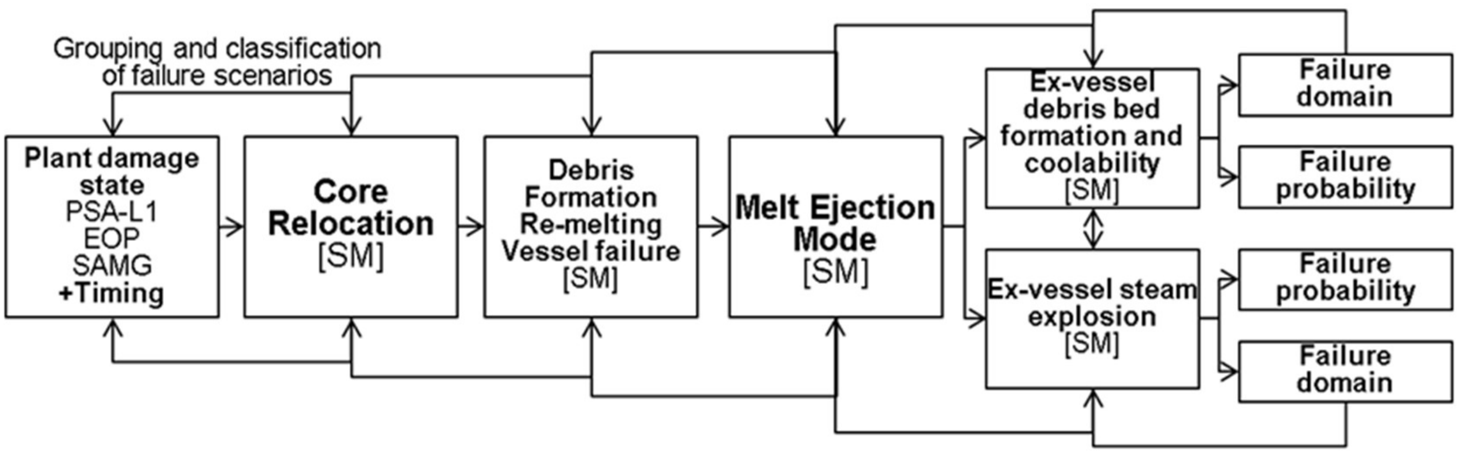
Risk Oriented Accident Analysis Methodology+

- 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.

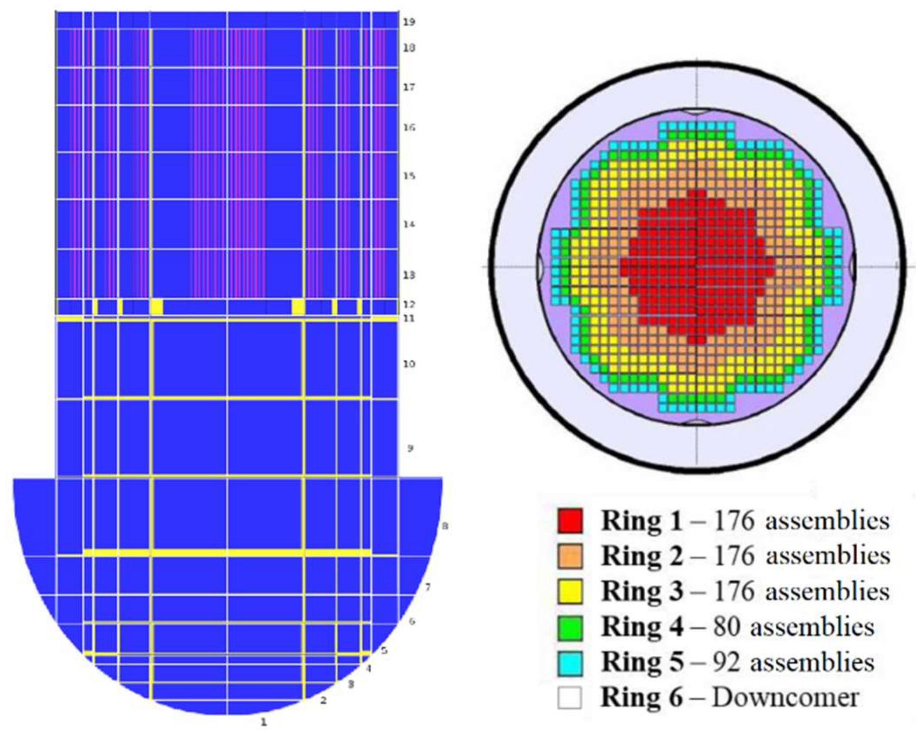


Motivation and Goals

- 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.
  - Extension of the domain of applicability for ROAAM+ to problems requiring treatment of timing of the events and dynamics of the phenomena.
  - **Develop coupling scheme to estimate risk of steam explosion on source term.**
  - **Insights into the effect of interactions between timing of the steam explosions and dynamics of the accident progression on the risk assessment results in ROAAM+.**

Reactor and Accident Scenarios of Interest

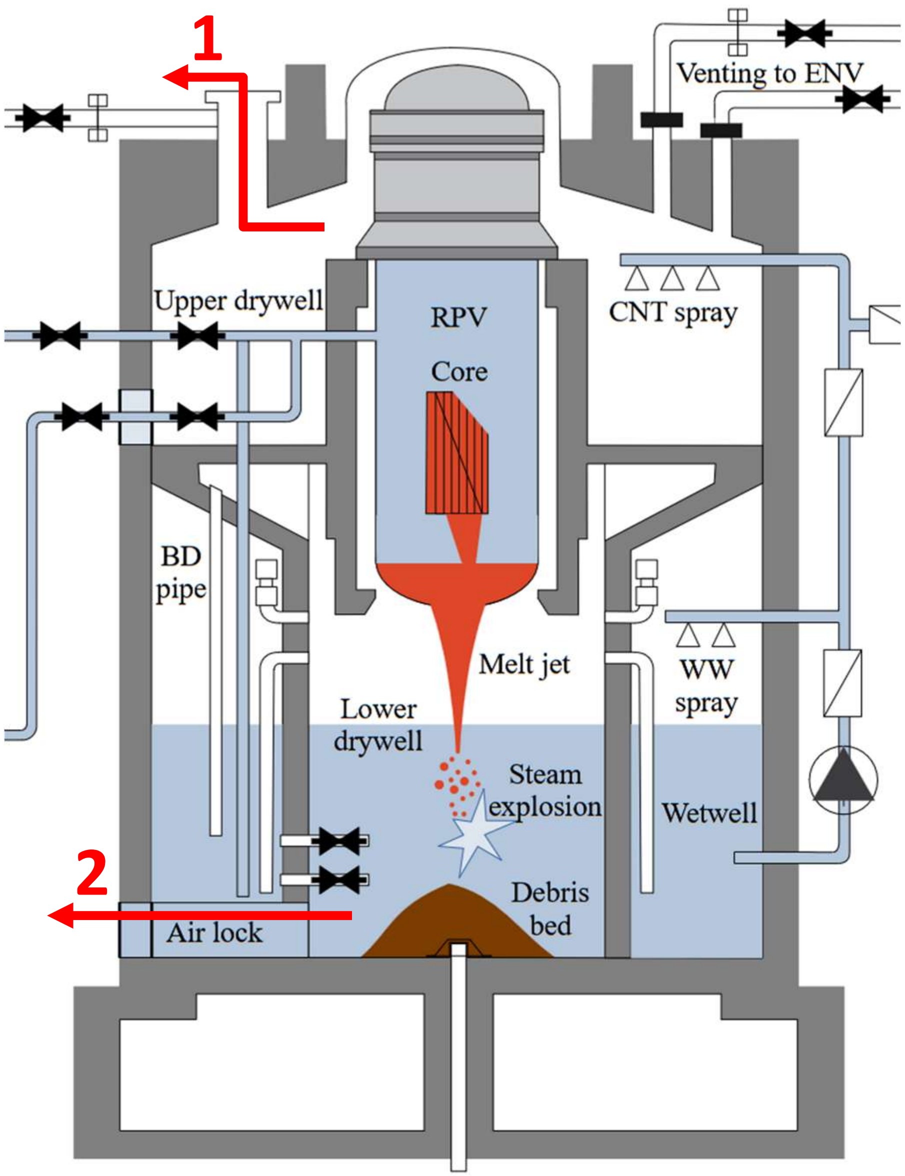
- Nordic BWR
  - ASEA/ABB Atom based on Westinghouse BWR75.
  - 3900MWth power.
  - 700 fuel elements.
    - 6 radial rings.
    - 19 axial levels.

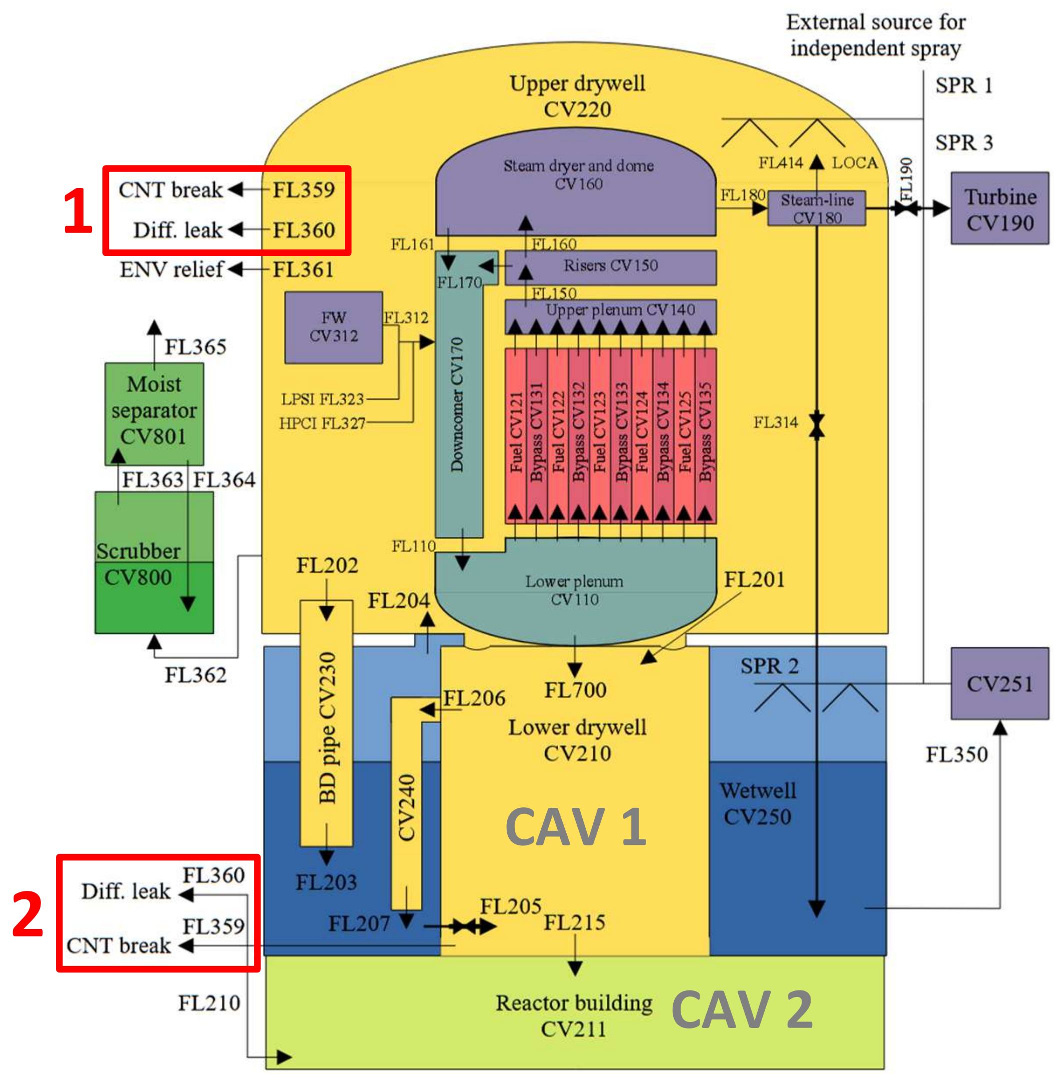


MELCOR COR nodalization

- 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



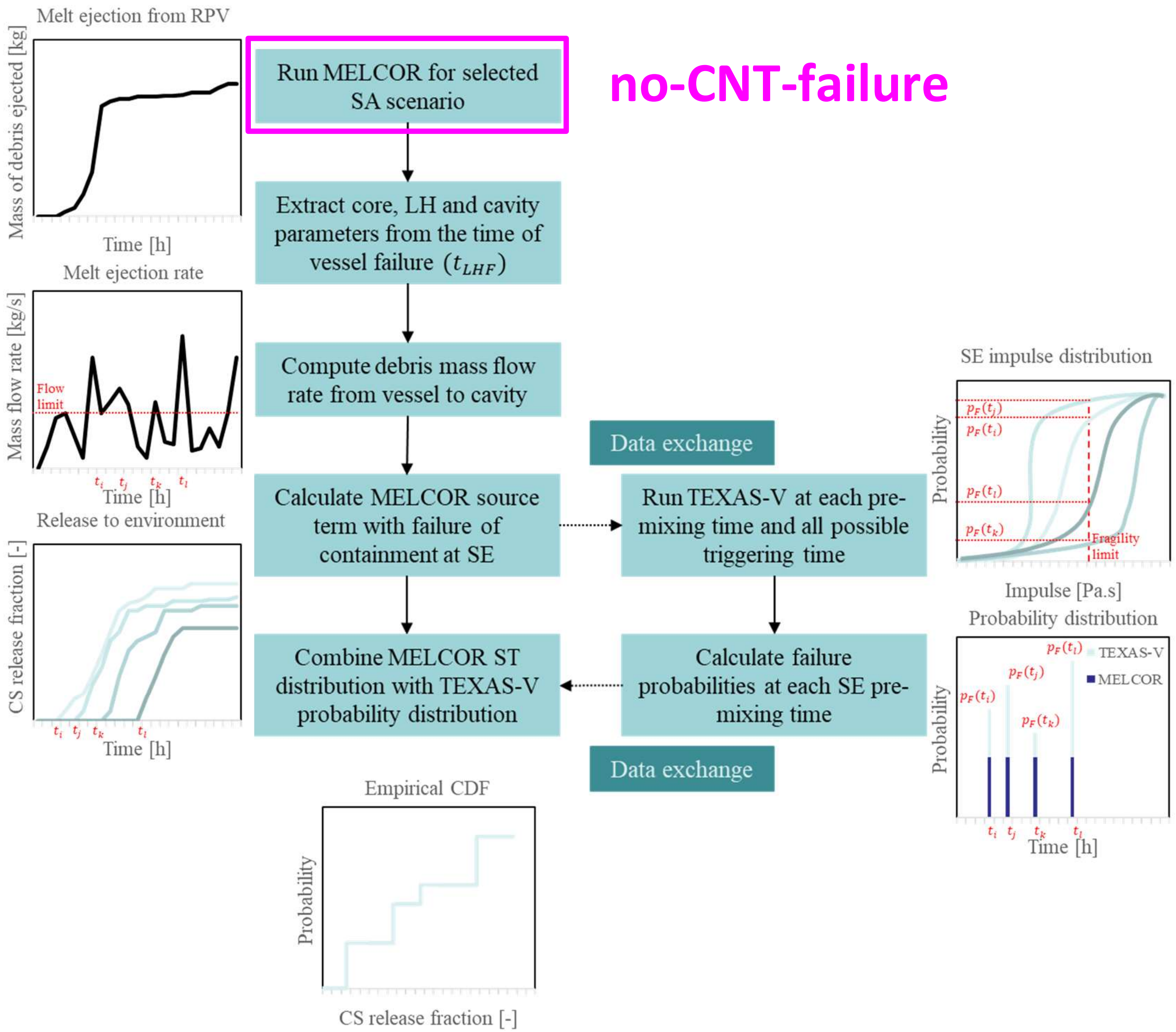


MELCOR CVH nodalization

MELCOR-TEXASV Coupling Scheme

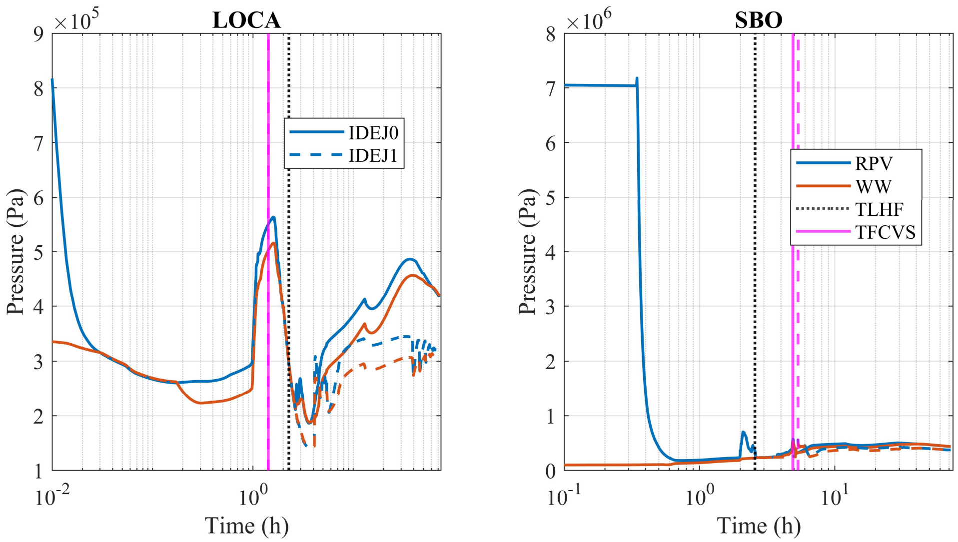
MELCOR

TEXAS

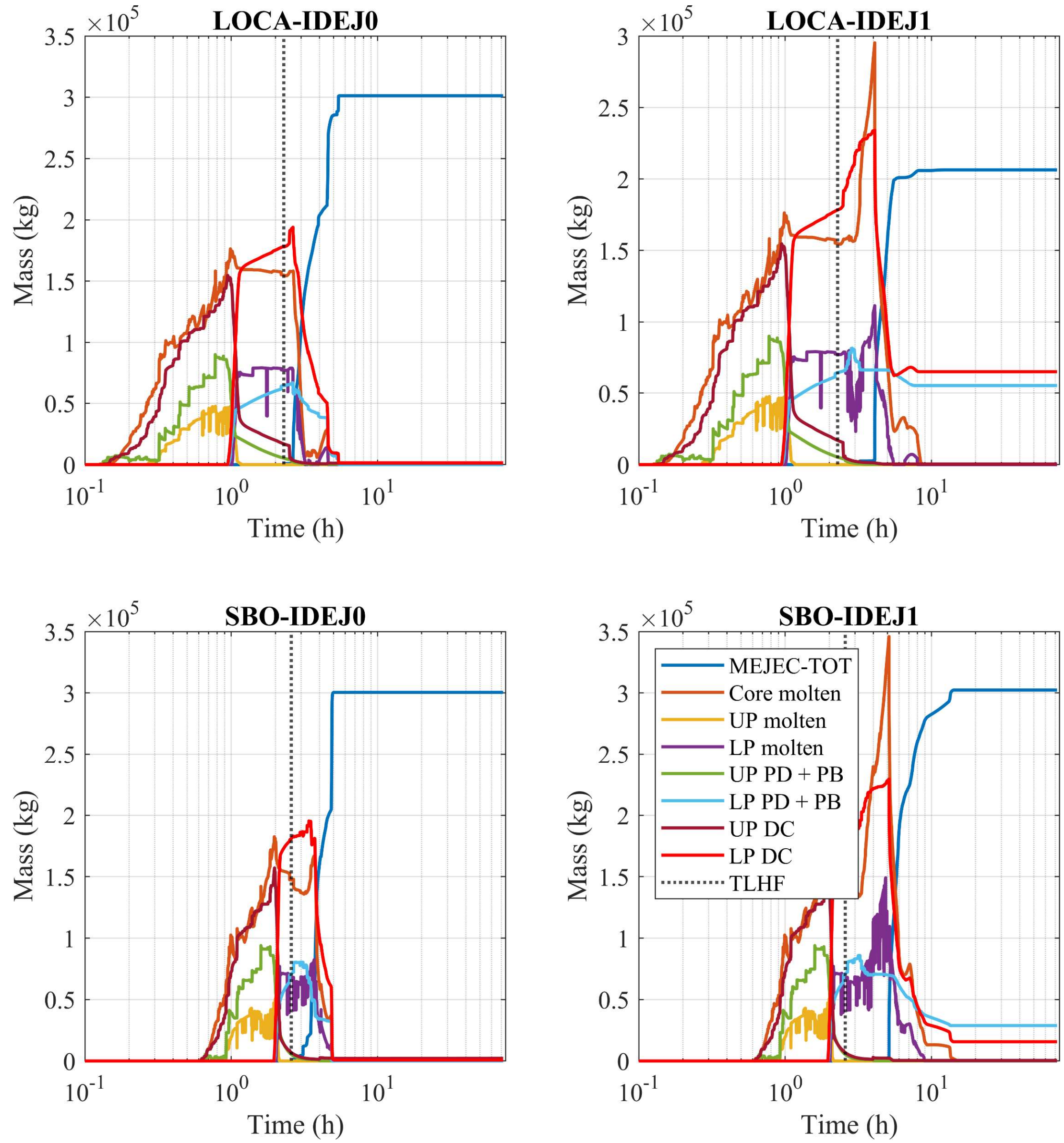


no-CNT-failure In-Vessel Results

Pressure in RPV and WW



Debris masses in RPV



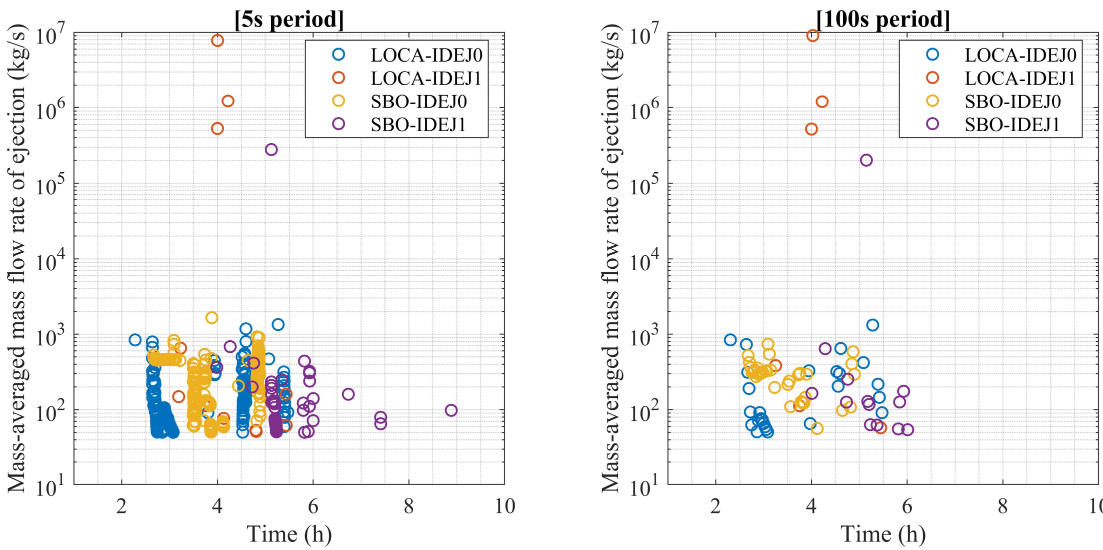
- v2.2.r2024 – Pathway 2
- COR_EUT - TUO2ZRO2
  - 2800K

no-CNT-failure Timing of Events

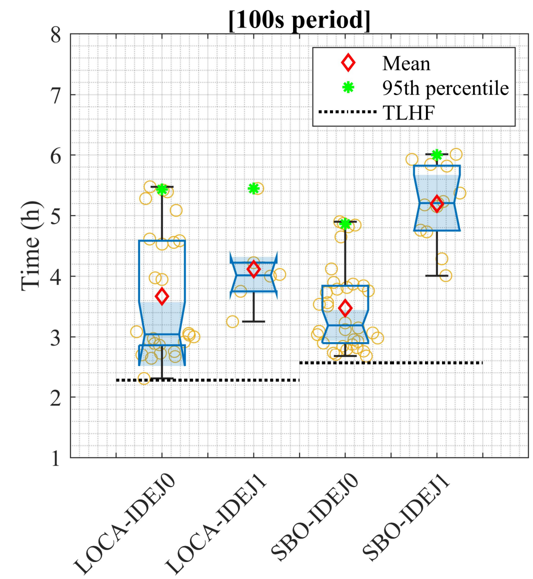
Timing [s] of key events during 4 no-CNT-failure scenarios.								
Key event	**LOCA-IDEJ0**		**LOCA-IDEJ1**		**SBO-IDEJ0**		**SBO-IDEJ1**	
	r2024	**v18019**	**r2024**	**v18019**	**r2024**	**v18019**	**r2024**	**v18019**
L4 (0.5m above TAF)	9	9	9	9	7	7	7	7
Core uncovery	9	9	9	9	838	838	838	838
L6 (1m below TAF)	27	27	27	27	1111	1111	1111	1111
ADS ON	-	-	-	-	1235	1235	1235	1235
Gap release	220	220	220	220	2008	2008	2008	2008
Particulate debris formation	477	477	477	477	2229	2236	2229	2236
Cavity flood	625	625	625	625	1950	1950	1950	1950
Fuel element degradation	866	866	866	866	2916	2916	2916	2916
Relocation to lowerhead	3302	4606	3302	4606	6938	7238	6938	7238
RPV failure	8205	6246	8205	6246	9235	9841	9235	9841
MVSS vent	5130	5130	5130	5130	17602	20280	19250	25920
MEJEC >70tons	10240	9529	15058	17825	13432	10978	18741	20034
LDW at saturation	14155	12510	20280	18859	16418	14340	23618	25555
WW at saturation	-	-	-	-	253218	-	241612	243159
MVSS dryout	-	-	222194	220972	-	-	-	-

no-CNT-failure Debris Ejection Results

Mass-averaged mass flow rates for 5s and 100s



Time instances where mass flow rate >50kg/s



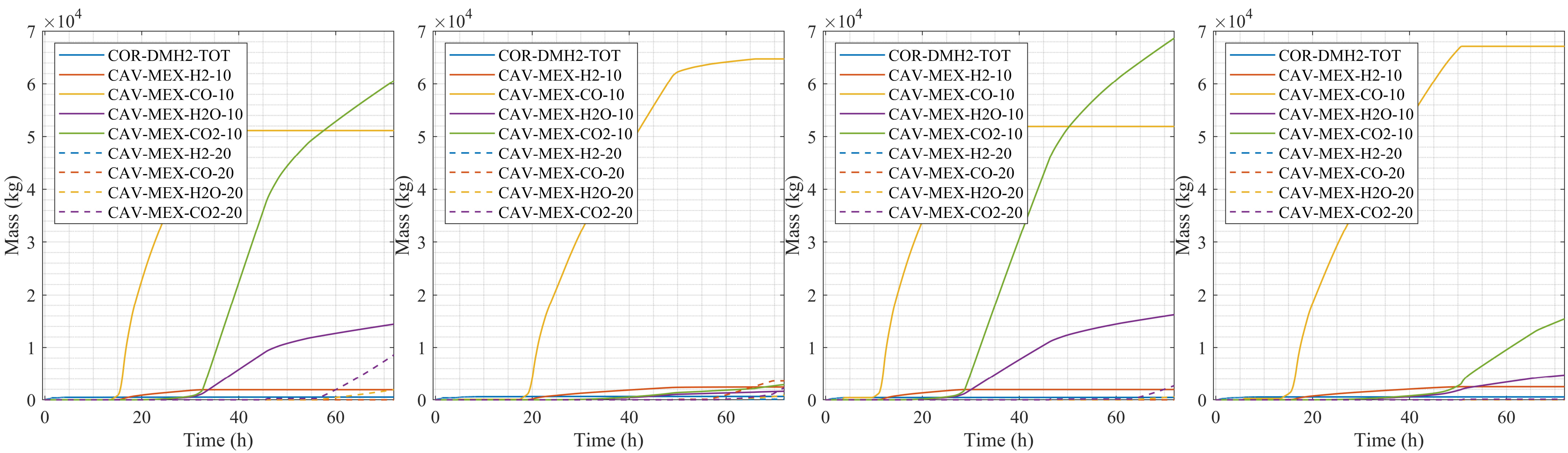
- For IDEJ0 scenarios, ejection rate is large immediately after LHF (~3*h*).
- For IDEJ1 scenarios, comparatively fewer instances of large ejection is observed immediately after LHF. Only after solid debris melts (~4h) are such instances observed.
- All filtered instances are computed to account for 26, 6, 34 and 13 of LOCA-IDEJ0, LOCA-IDEJ1, SBO-IDEJ0 and SBO-IDEJ1 scenarios respectively.

CNT-failure Cavity Dryout and MCCI

Timing [s] of key events during 4 reference CNT-failure scenarios (r2024).				
Key event	**LOCA-IDEJ0**	**LOCA-IDEJ1**	**SBO-IDEJ0**	**SBO-IDEJ1**
LDW dryout	39560	41860	20430	28140
MCCI commencement	59601	64400	14820	18130
LDW failure	191402	218000	177600	227000

- In the reference cases, SE is assumed to cause hatch door failure (or penetration failure) exactly when LH fails > rapid loss of coolant from cavity.
- For LOCA scenario cavity is dry within 39560-41860s, and for SBO within 20430-28140.

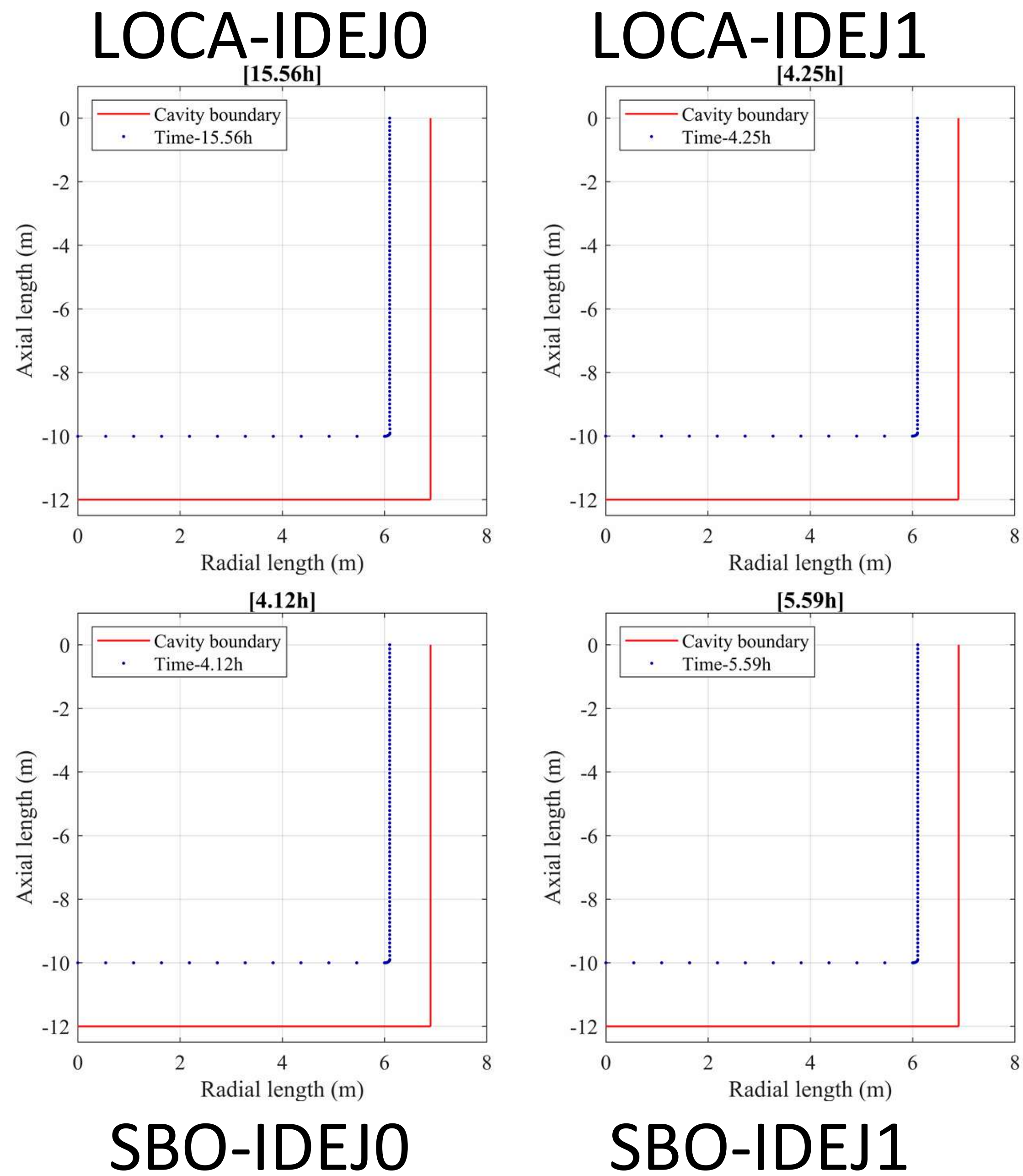
Mass of gases produced by MCCI in the cavity



LOCA-IDEJ0 LOCA-IDEJ1 SBO-IDEJ0 SBO-IDEJ1

CNT-failure Debris Spreading in Cavity

- MELCOR assumes that all the debris in the cavity is spread instantaneously and evenly throughout the floor.
- The initial radius of the debris bed can be
  - user defined (with control functions)
  - internally calculated
  - RPV breach area as initial radius
  - zero as initial radius
- A parametric study is performed by activating the default internal debris spreading model and varying the maximum debris bed radius to be {2.03, 3.05, 4.06, 5.08, 6.1}m.



CNT-failure Debris Spreading Parametric Study

Timing [s] of LDW failure for varying debris bed radius.				
Maximum radius [m]	**LOCA-IDEJ0**	**LOCA-IDEJ1**	**SBO-IDEJ0**	**SBO-IDEJ1**
2.03	24855	32774	35524	38525
3.05	65640	67229	51736	74407
4.06	95587	113904	66011	100952
5.08	97342	160312	78628	115470
6.01	191402	218000	177600	227000

- With very small debris bed radius (2.03*m*), the rate of MCCI ablation of concrete basemat is exceedingly high.
- Increasing the radius also increases the time of cavity failure.
- Despite variations in the time of LDW failure, the final release of FPs to the ENV as well as hydrogen generation by MCCI reactions were observed to be about the same.

TEXAS-V Calculations of SE Impulse Loads

- Total premixing calculations:

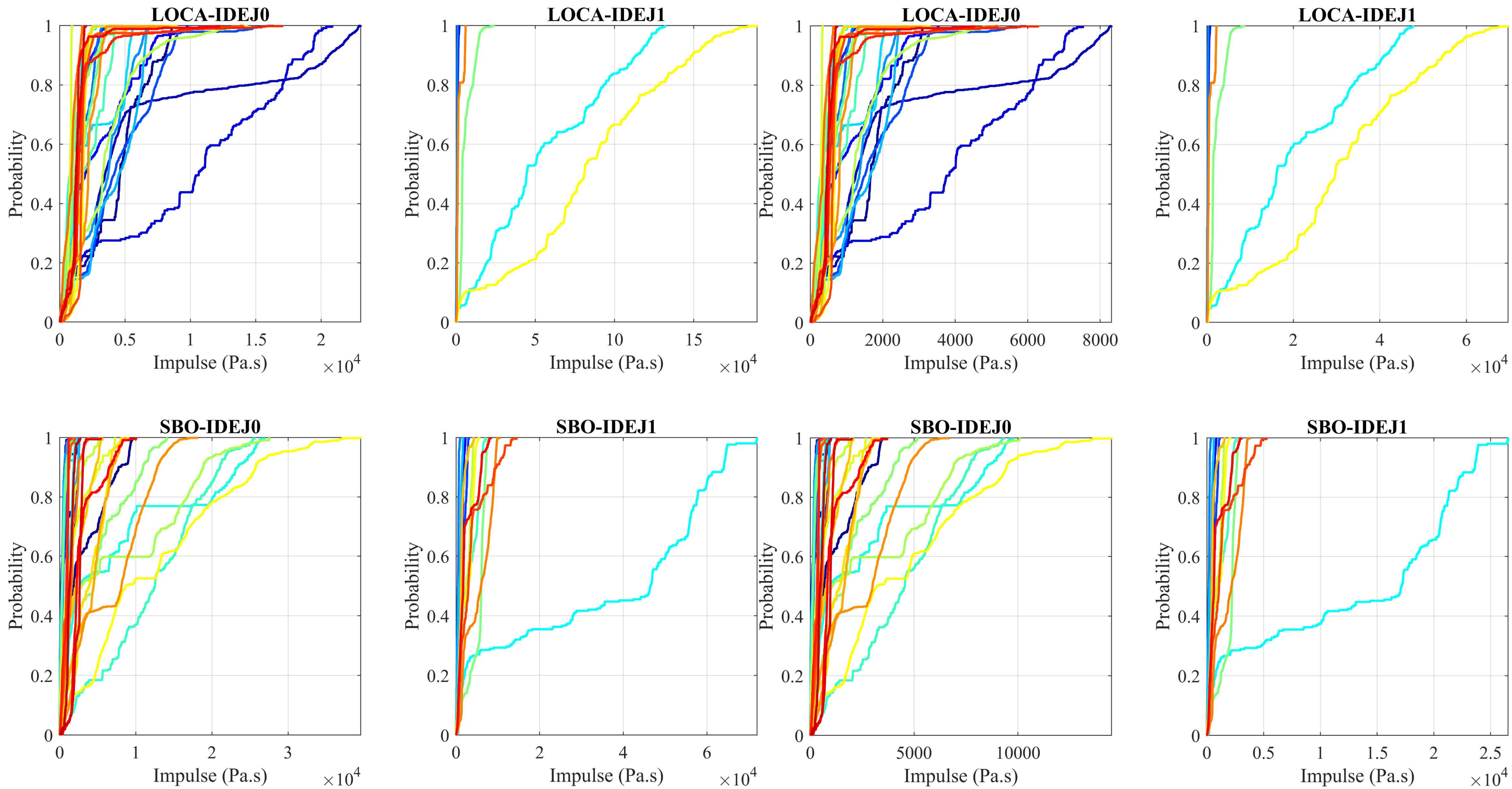
Period	LOCA-IDEJ0	LOCA-IDEJ1	SBO-IDEJ0	SBO-IDEJ1	Total
Filtered (MA) Pathway 1					
5s	358	194	465	105	1,122
100s	28	12	43	9	92
Filtered (MA) Pathway 2		Current			
5s	311	17	242	98	668
100s	26	6	34	13	79

- Out of 160 parameters, 13 most sensitive are explicitly defined in TEXAS.

D. Grishchenko, et al., (2016)

- 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.

SE Loads on the Hatch Door

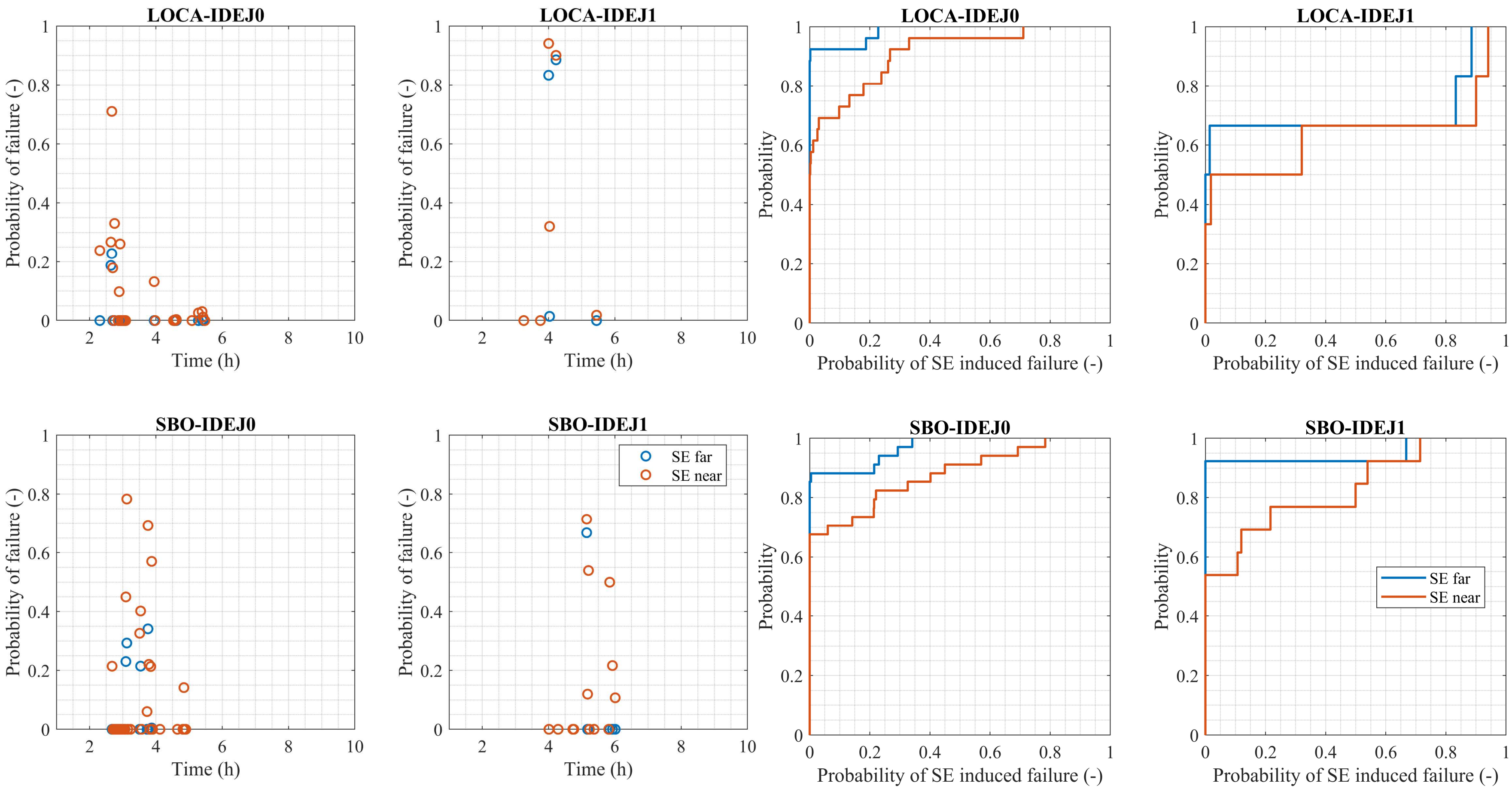


SE near (close to hatch door)

SE far (top of pool)

Probability of Failure of Hatch Door

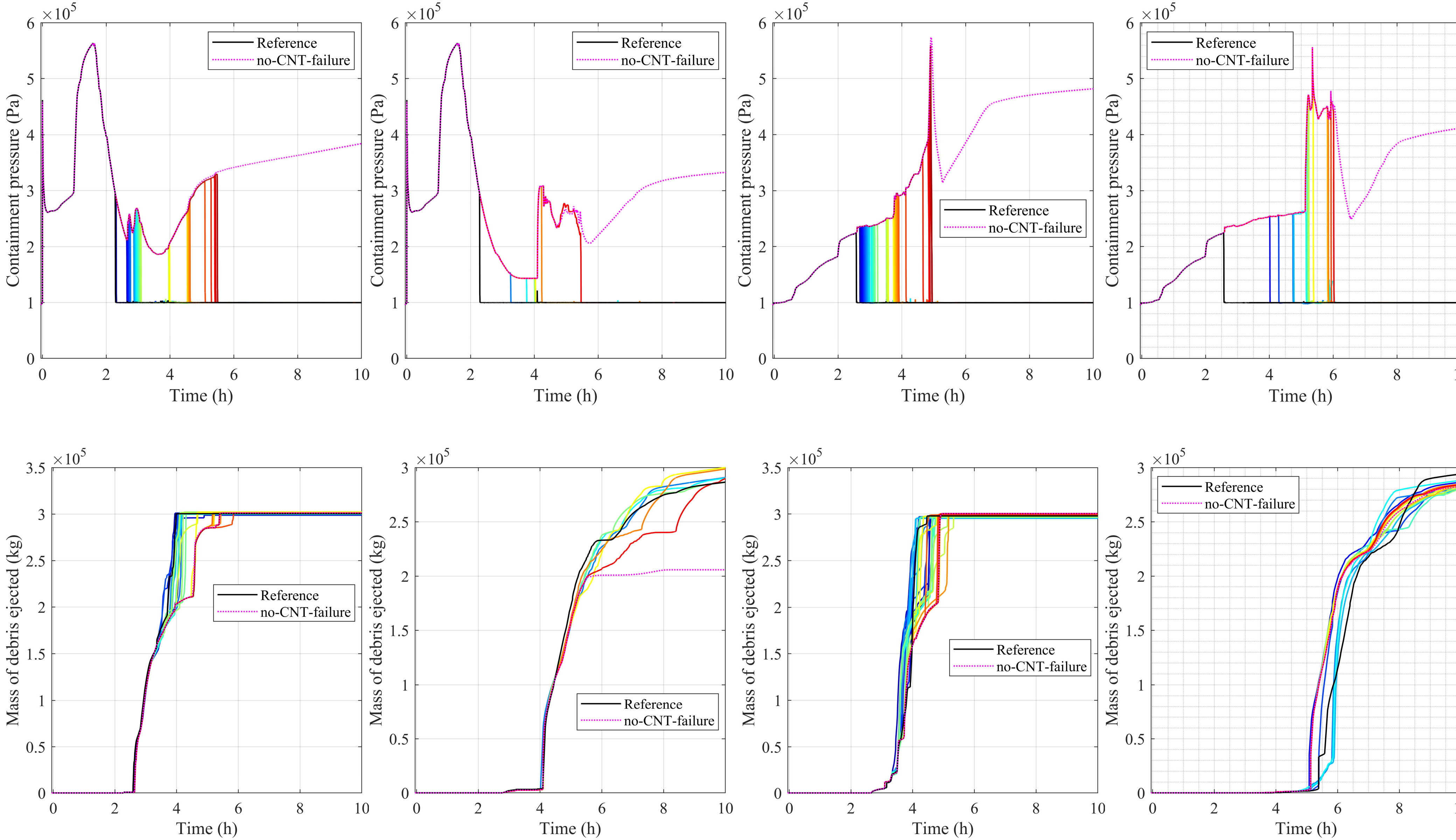
- Fragility limit of non-reinforced hatch door 6kPa.s.



Absolute

eCDF

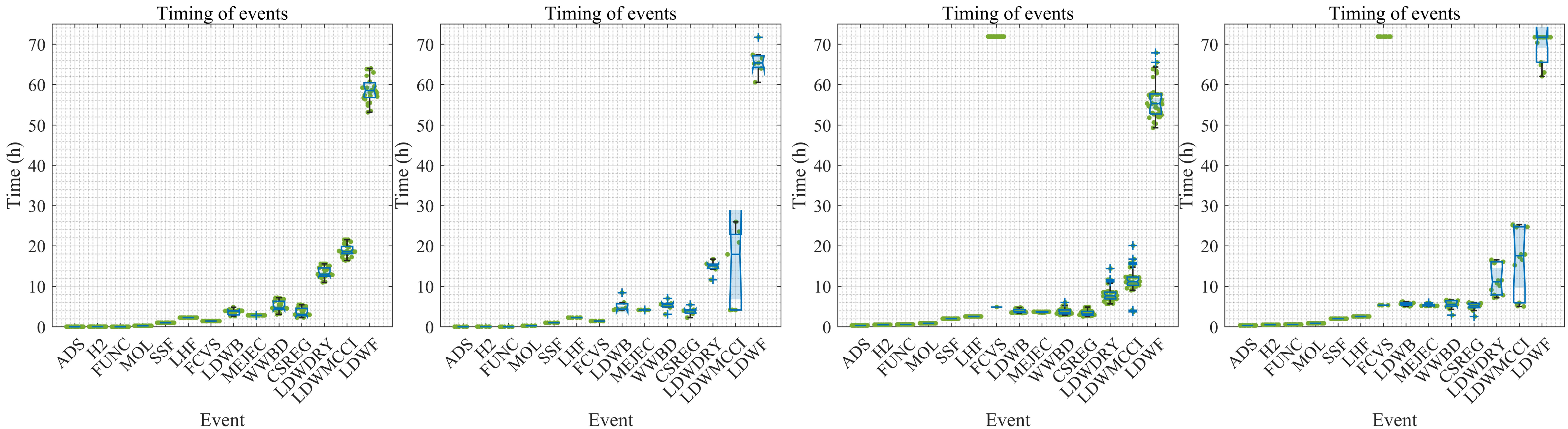
MELCOR Results for Dynamic Cases



LOCA-IDEJ0 LOCA-IDEJ1 SBO-IDEJ0 SBO-IDEJ1

MELCOR Results for Dynamic Cases

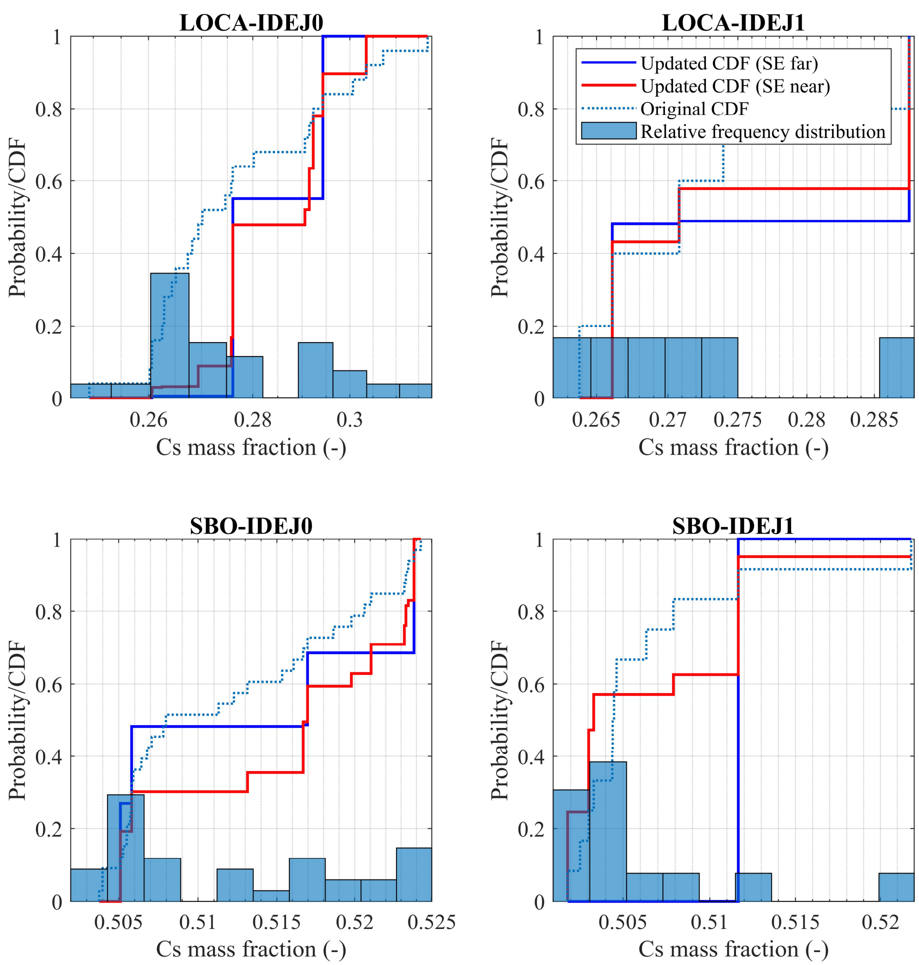
LOCA-IDEJ0 | LOCA-IDEJ1 | SBO-IDEJ0 | SBO-IDEJ1



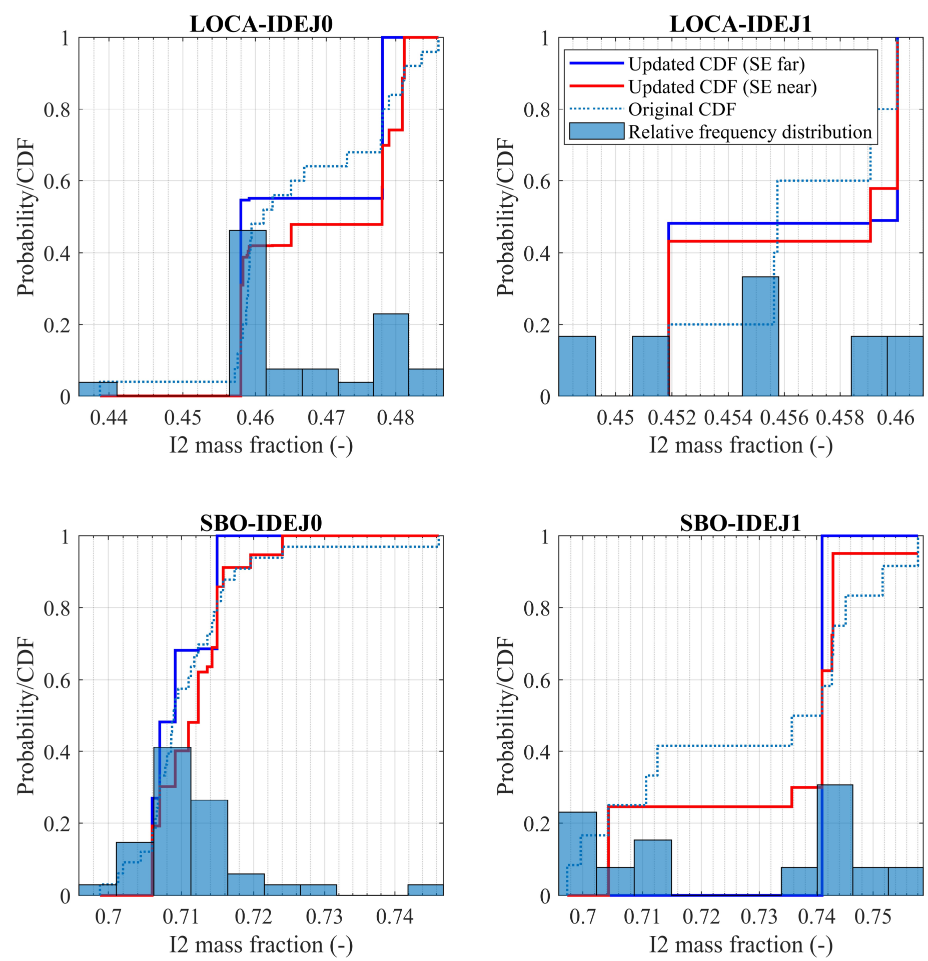
- Effect of IDEJ on MCCI is evident in the fact that time of MCCI commencement has larger range in IDEJ1 than in IDEJ0.
- In most of the cases considered, the LDW fails by 72h due to MCCI ablation.

ADS: time of ADS activation, H2: time of hydrogen generation/gap release, FUNC: time of full core uncovery, MOL: time of fuel degradation and molten debris formation, SSF: time of failure of support plate, FCVS: time of FCVS activation (t=72*h* if no activation), LDWB: time of LDW pool boiling, MEJEC: time of large debris mass ejection (>70*tons*), WWBD: time of WW pool boiling, CSREG: time of cesium release mass fraction > 0.001, LDWDRY: time of LDW dryout, LDWMCCI: time of commencement of MCCI, LDWF: time of failure of LDW.

Updated CDFs: CS and I2 Release Fractions



Cesium fraction



Iodine fraction

Conclusions

- The scheme for dynamic modelling approach within ROAAM+ framework was expanded.
  - 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 (with more instances) for SE in IDEJ0 than IDEJ1.
- The validation of the method by determining source term eCDFs for debris ejection during other accident scenarios will be performed in the future – study on the effect of manual FCVS activation is in progress.
- In the future minor discrepancies in model definitions would be corrected and a thorough parametric and sensitivity studies will be performed.

Thank you for your attention.

For questions or clarifications please email me: govatsa@kth.se.

This work is supported by the Nordic Nuclear Safety Research (NKS), under the NKS-R STATUS activity (Contract: AFT/NKS-R(21)133/5) and by the SSM ROAAM+ project at the KTH, Sweden.

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