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Core Damage Progression Uncertainty Analysis: Fukushima Daiichi Unit 1

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Severe Accident Analysis – Where are we?

- Current integral severe accident modeling capabilities allow users to model the full scope of severe accident progression, from the initiating event to the release of radioactive materials to the environment
- The general progression of accidents in water cooled reactors are well understood
- A degree of uncertainty persists due to the complex, non-linear behavior of severe accident phenomena and their models
- Calibrated, single case analyses have been a prominent tool used successfully in many studies
- Multi-case uncertainty studies, often 100's or even 1000's of cases can evaluated, providing analysts and decision-makers with a more complete range of potential progression-end-state combinations

Severe Accident Analysis – Why?

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- The goal: severe accident analysis is to develop a robust, risk-informed decision making framework in light of irreducible uncertainties
- The challenge: capturing and quantifying the uncertainty in the "unknown" unknowns.

- This study is a proof-of-concept that basic uncertainty analysis techniques can be used to develop insights into the core damage progression, key event timings, and plant end-state configurations for the accidents at Fukushima Daiichi Nuclear Power Station

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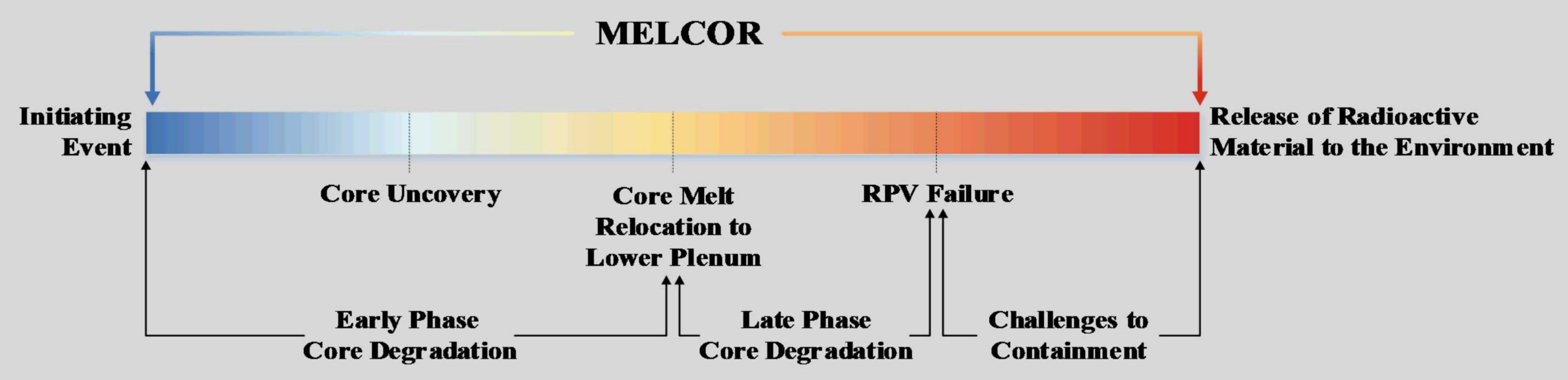
MELCOR V2.2



- MELCOR has a flexible, modular design that uses the control volume approach to model severe accidents
  - Thermal hydraulic response
  - Core heat-up, degradation, and relocation
  - Molten corium-concrete interactions
  - Hydrogen production, transport and combustion
  - Fission product release and transport

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Degraded Core Components

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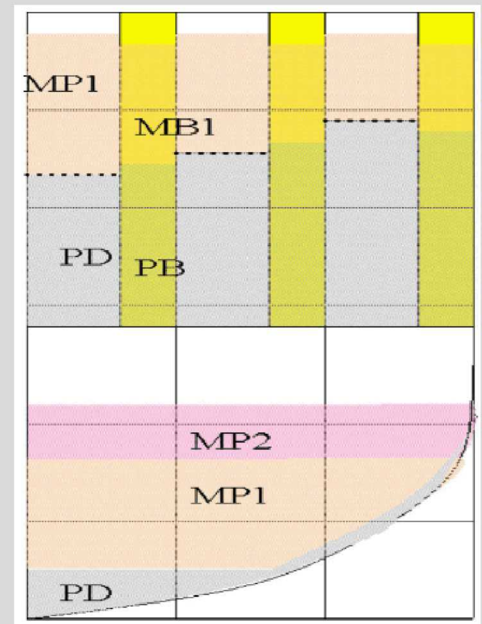
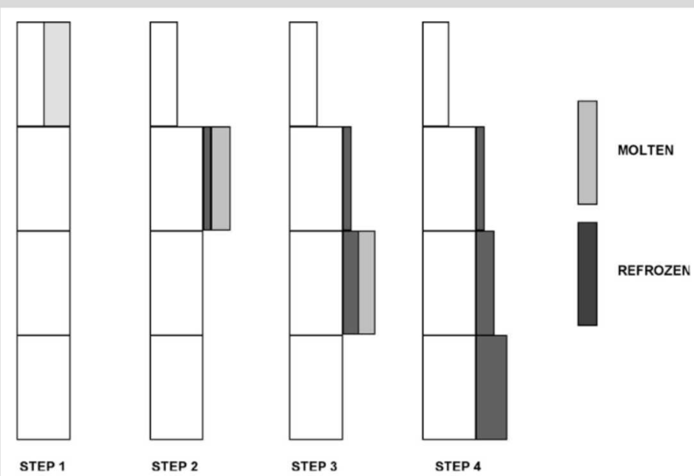
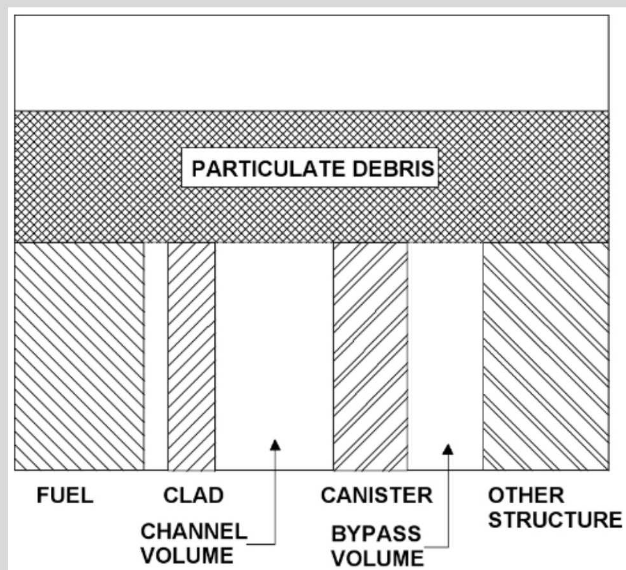
- Location
  - Channel/Bypass
  - Lower Plenum
- Conglomerate debris
  - Refrozen candled materials
  - Previously molten materials
- Particulate debris
  - Failure of a support structure
- Molten pool
  - Liquefaction and blockage
  - Oxidic
  - Metallic







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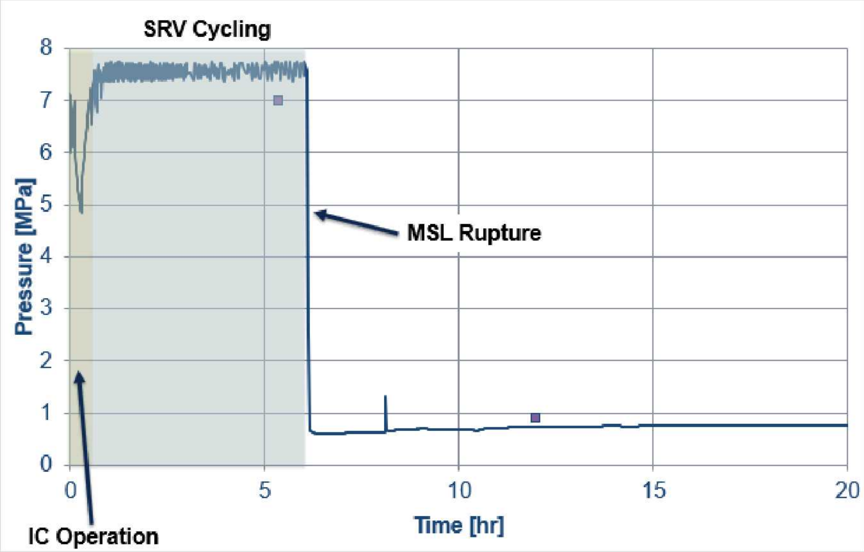
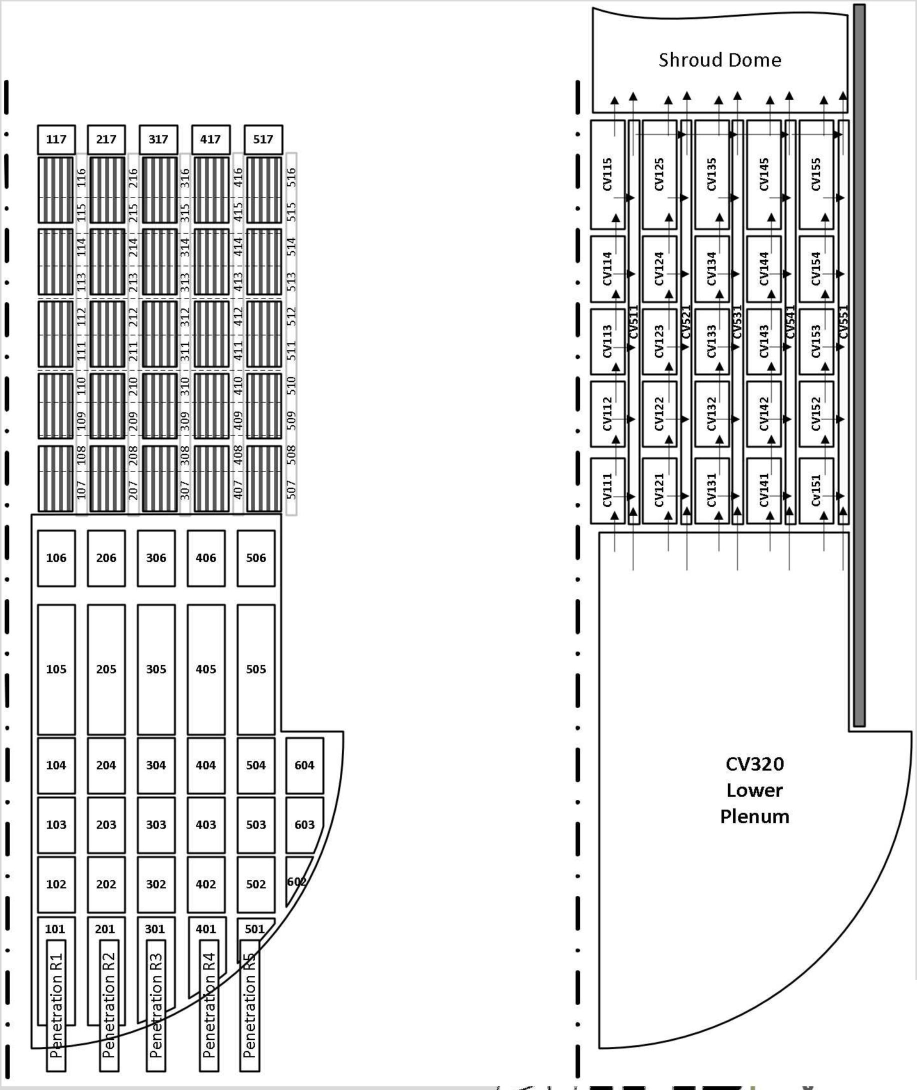
1F1 Model and Simulation Overview

- Input deck based on BSAF Phase II Analysis
- Simulation length – 25 hours





1F1 Model Boundary Conditions

Event	Time [hours]
Safety Relief Valve (SRV) Stuck Open	Never
Main Steam Line Isolation Valve (MSIV) Closure	0.0
Feedwater System Ceases Operation	0.0
IC Train A Operation	0.1-0.28 0.52-0.55 0.63-0.67 0.77-0.8
IC Train B Operation	0.1-0.28
Wetwell Venting	23.7
Reactor Building Explosion	24.8

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- Analysis
  - Event timings
  - Core damage progression
- Summary Future Work
  - Other Units
  - Expanded study

UA Summary

- Focus only on core degradation until the point of lower head failure
  - COR and MP packages
- Number of realizations
  - N = 400
- Total factors varied
  - Factors = 11
- Parameters of interest
  - Material relocation conditions
  - Eutectic treatment
  - Material transport behavior
  - Heat transport in debris
- Metrics of interest
  - Changes in debris morphology
  - Debris endstate and location

Uncertain Parameters

Package	ID	Description	Distribution	Min	Max	Other
COR	SC1131(2)	Molten Material Holdup Parameters	Scaled Beta	2100	2540	alpha: 3.83 beta: 3
COR	SC 1132(1)	Core Component Failure Parameters	UO2_INT/ZRO2_INT MP_PRC			
COR	SC 1141(2)	Core Melt Breakthrough Candling Parameters	Log Triangle	0.1	2.0	Mode: 0.2
COR	SC 1244 (3)	Debris Dryout Heat Flux Correlation: Minimum Debris Porosity	Log Triangle	0.015	1.5	Mode: 0.15
COR	SC 1250 (1)	Conduction Enhancement for Molten Components: Temperature above which enhancement is employed	UO2_INT/ZRO2_INT MP_PRC			
COR	SC 1250 (2)	Conduction Enhancement for Molten Components: Coefficient in enhancement	Log Triangle	0.001	0.1	Mode: 0.01
COR	COR_CCT	Component Critical Minimum Thicknesses	Log Triangle	1E-06	1E-04	Mode: 1E-05
COR	COR_CMT	Candling Secondary Material Transport Parameters	Uniform	0.1	1	-
COR	COR_ROD	Rod Collapse Model	-	-	-	Disabled
COR	COR_LP	Velocity of falling debris	Log Triangle	0.1	5	Mode: 1.6
MP	UO2_INT: MP_PRC	Interactive Material Melting Point	Normal	-	-	Mean: 2479 σ: 83
MP	ZRO2_INT: MP_PRC	Interactive Material Melting Point	Normal	-	-	Mean: 2479 σ: 83

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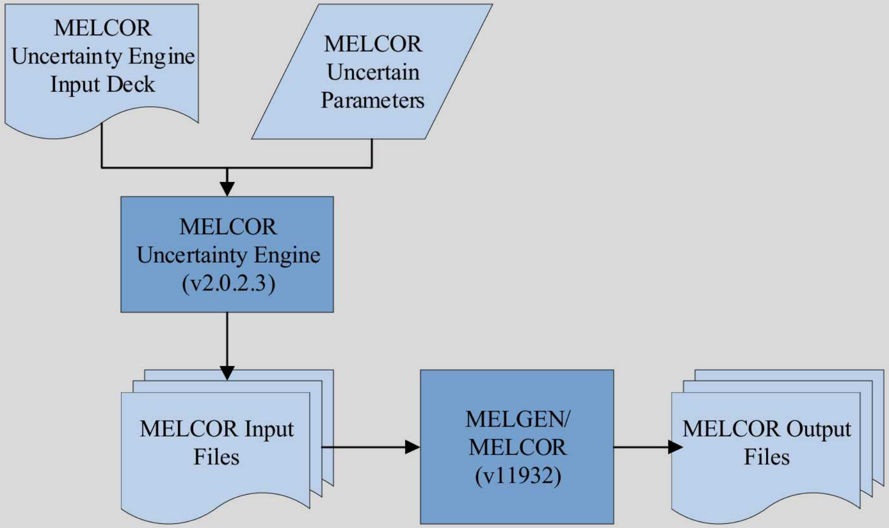
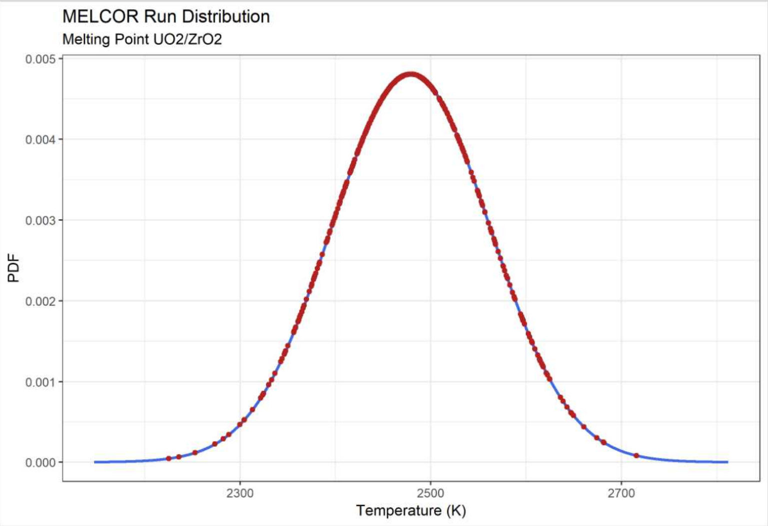
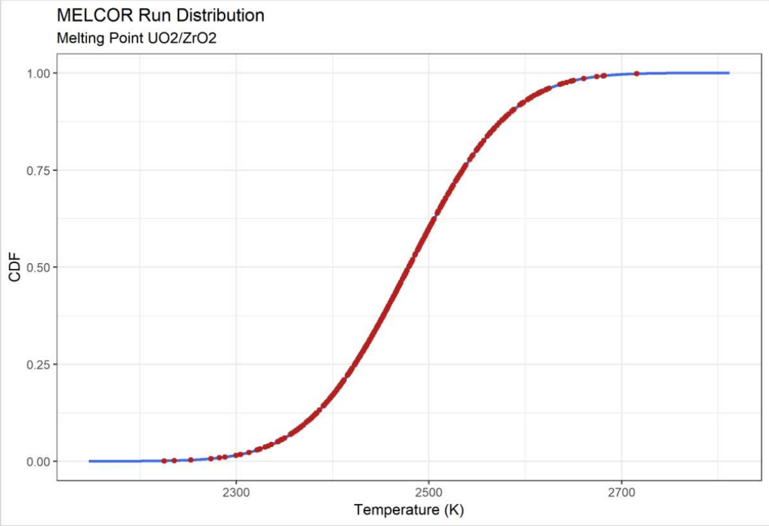
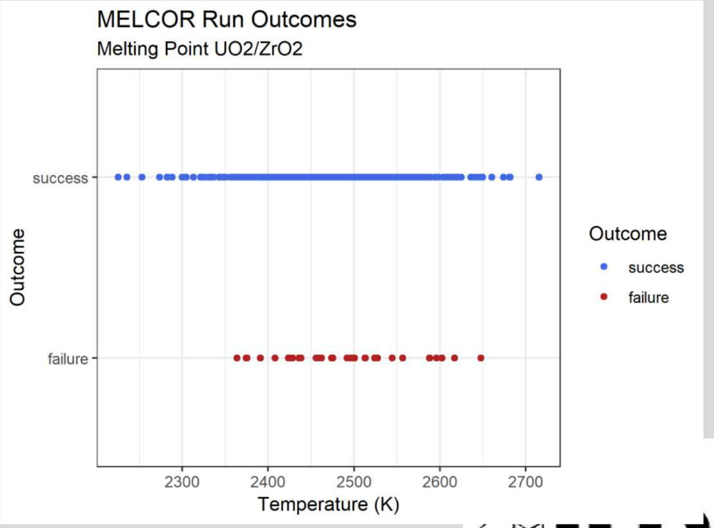
Uncertainty Analysis Overview









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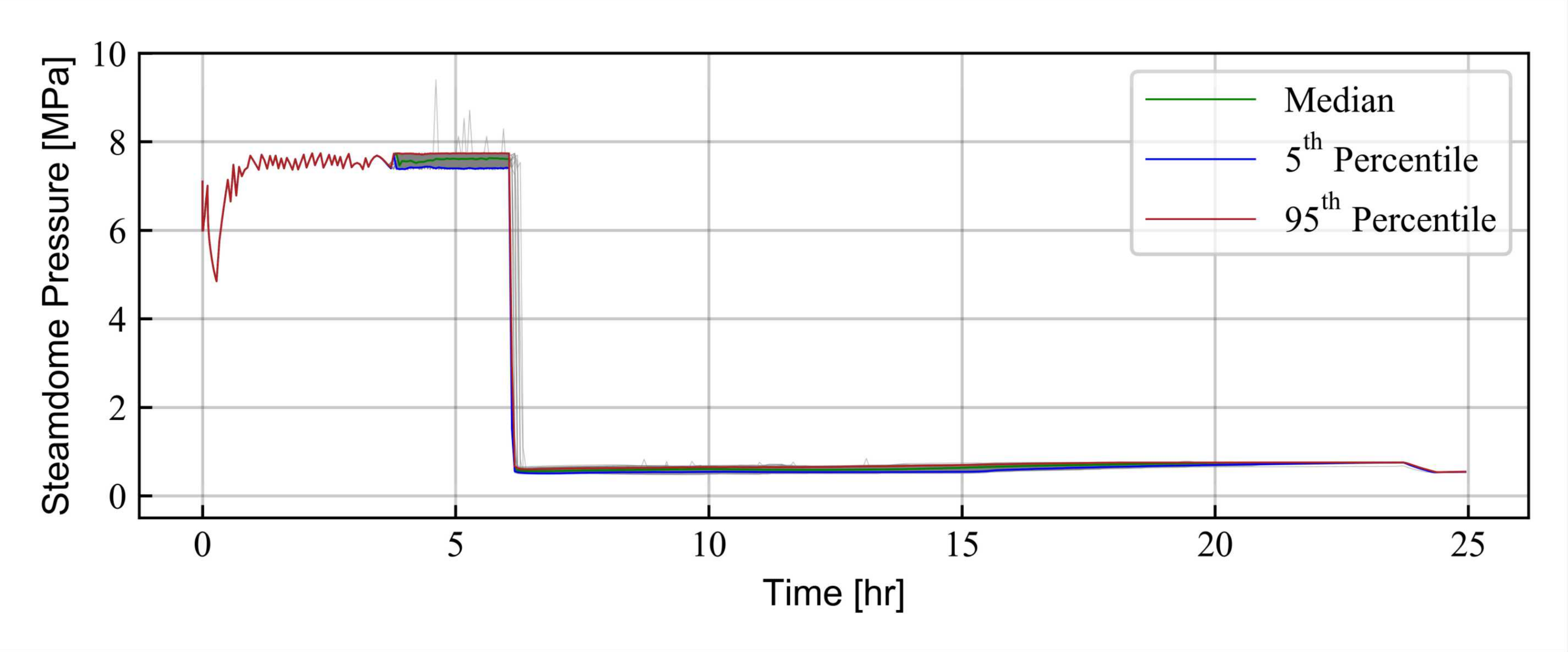
Primary Pressure



Containment Pressure

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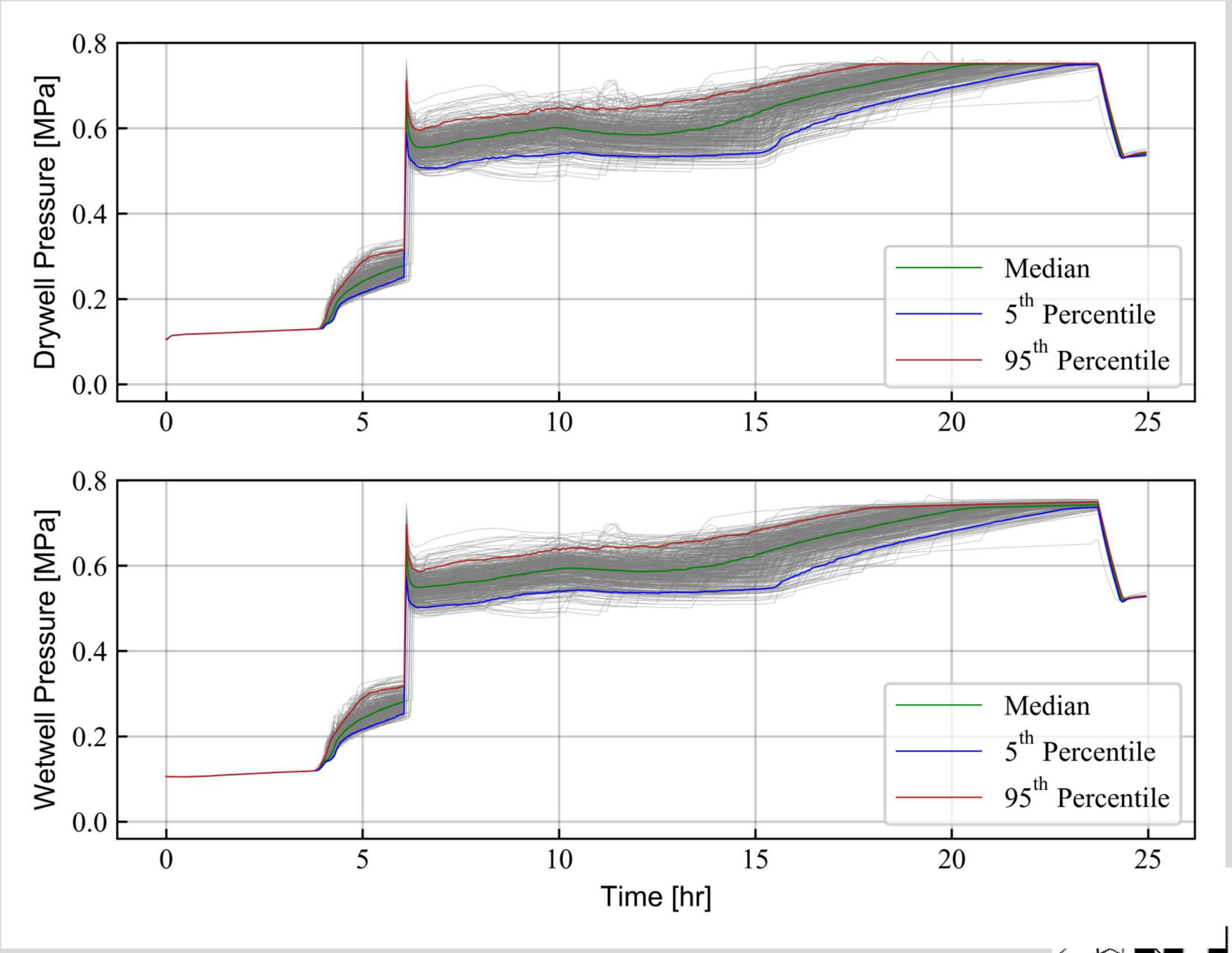

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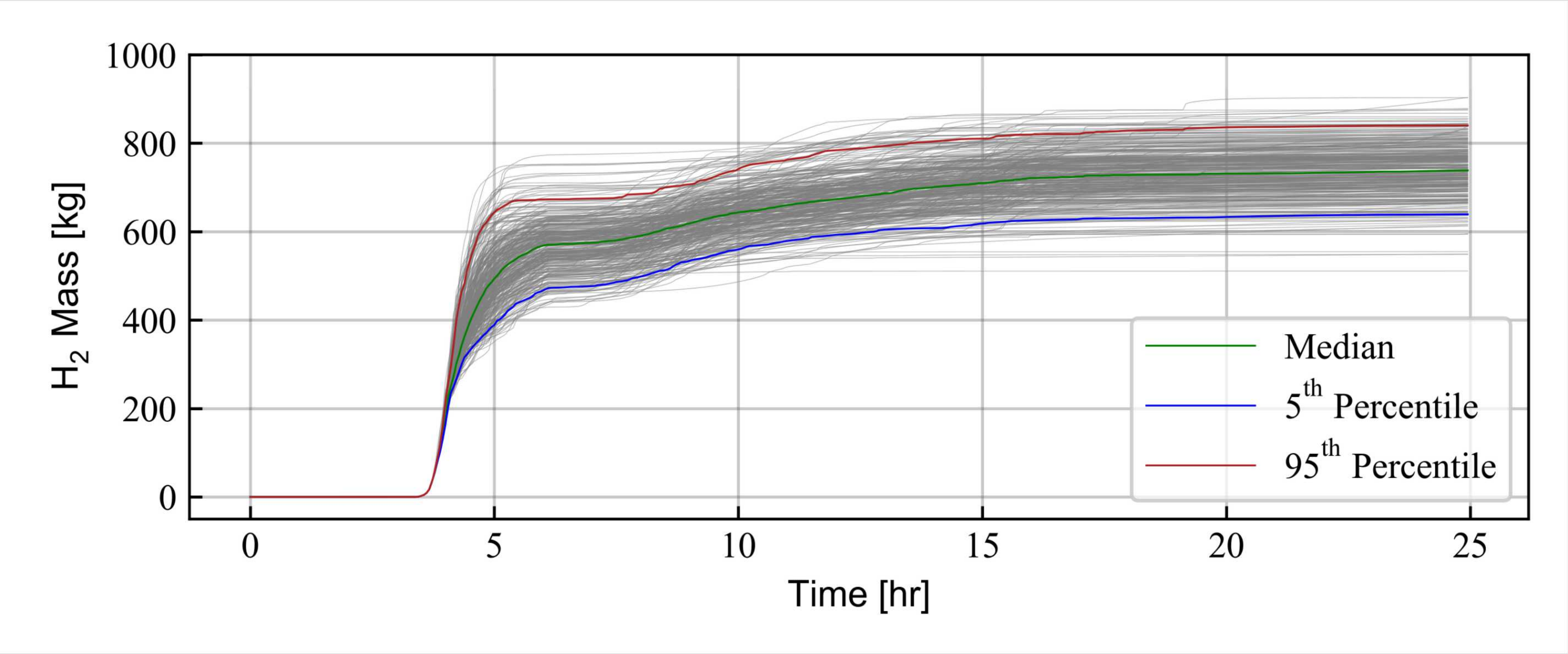
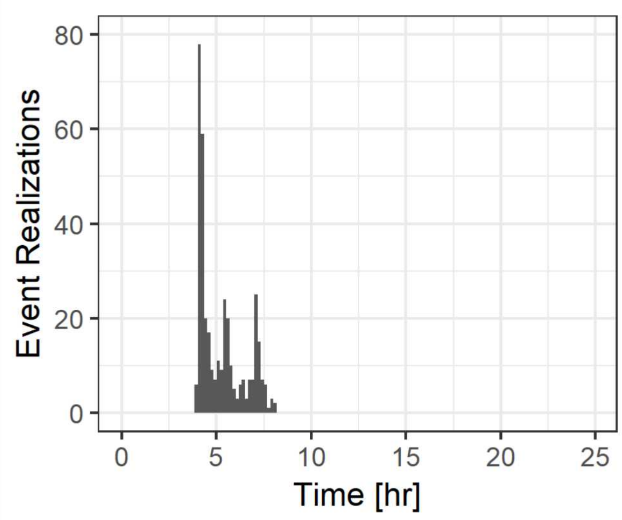
Hydrogen Production

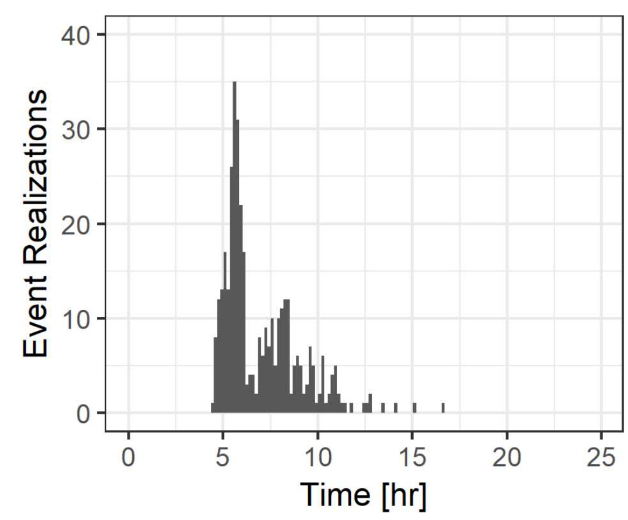


Event Timings

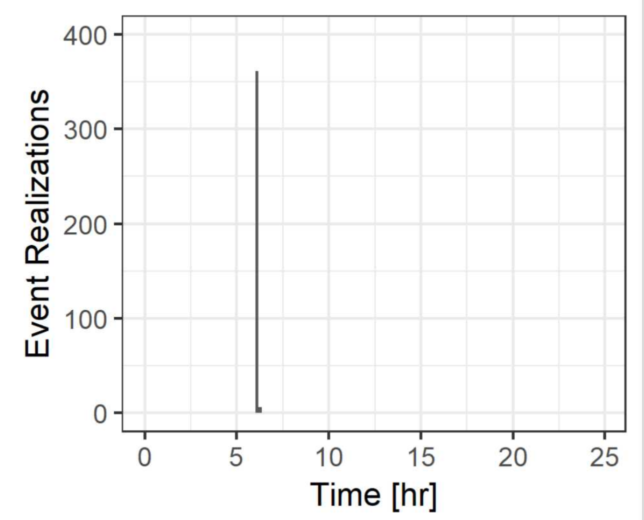
(a) >5% Fuel Damage Failure



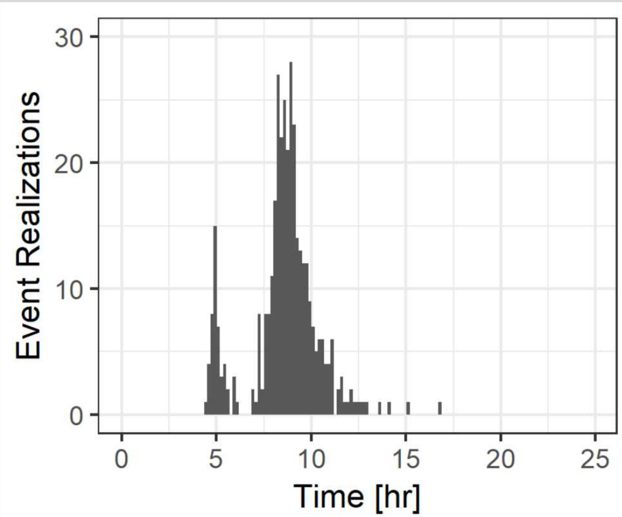
(b) Core Plate Failure



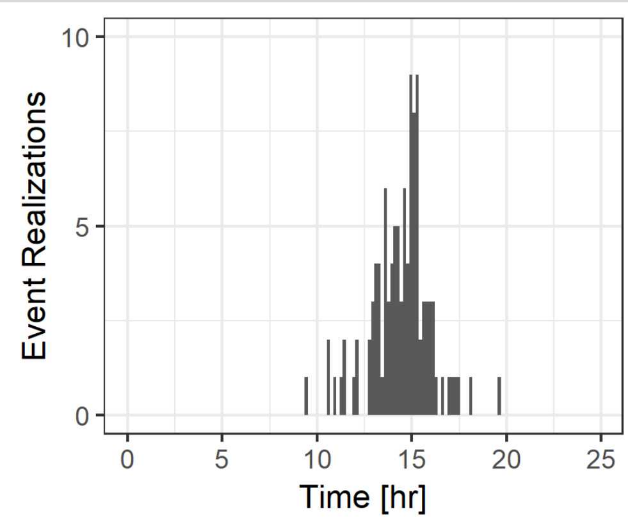
(c) Steam Line Failure



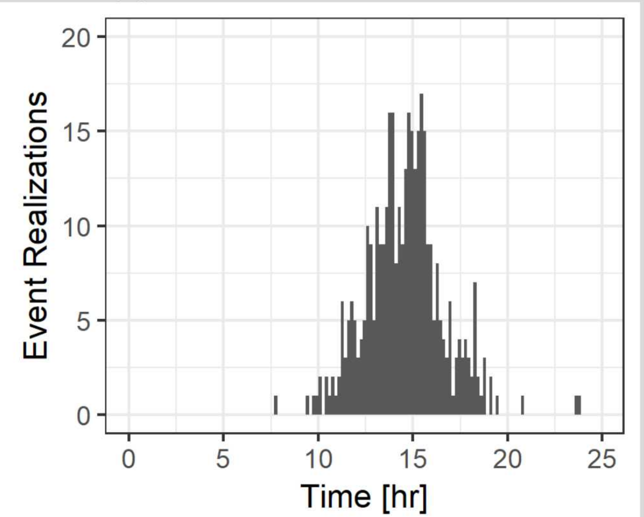
(d) Core Slump



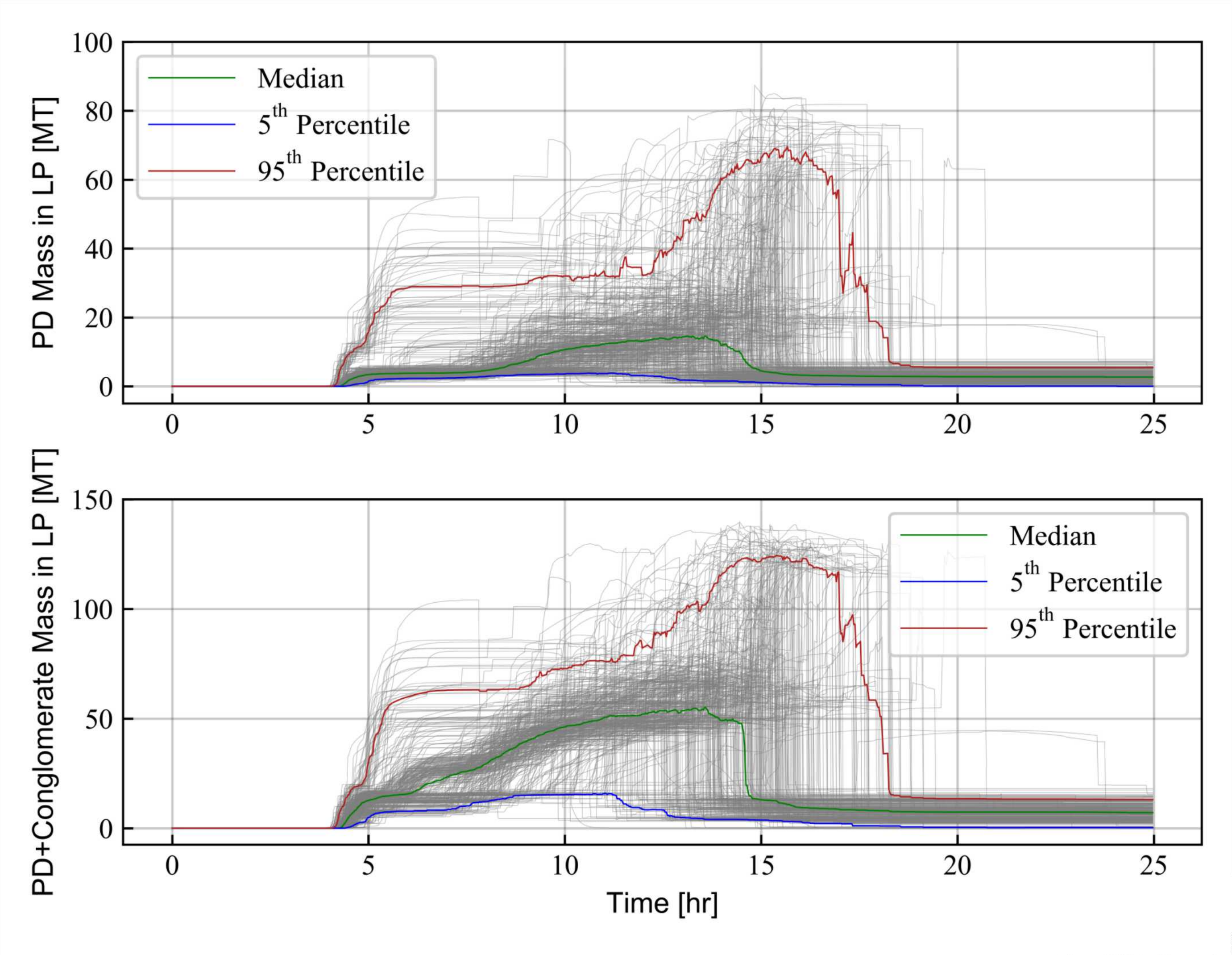
(e) >90% Fuel Damage



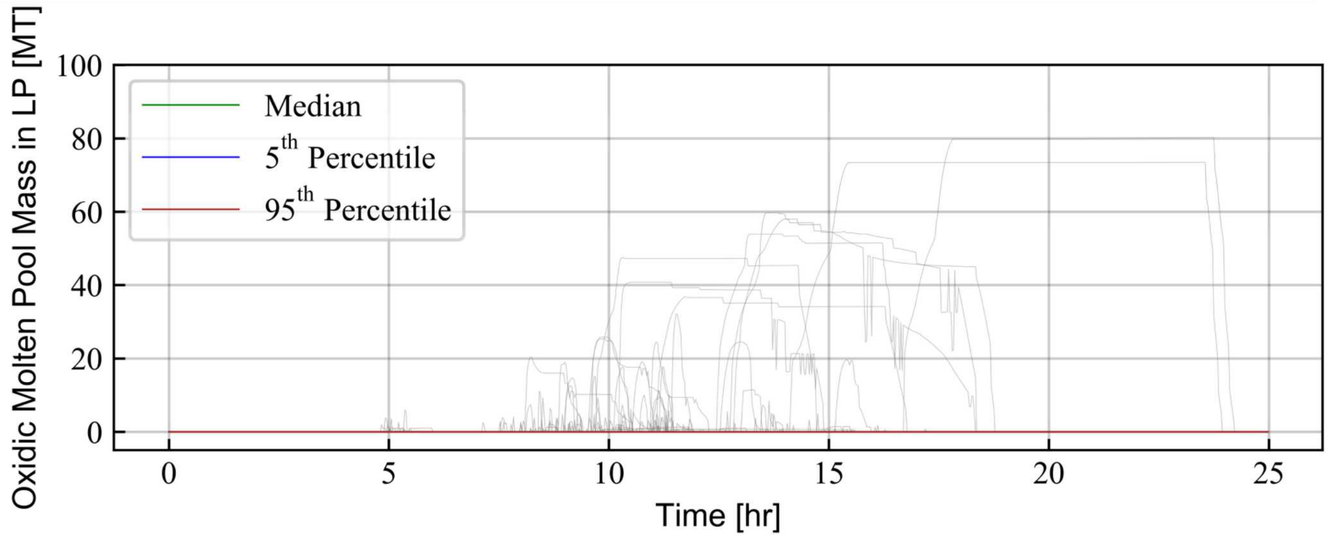
(f) Lower Head Failure

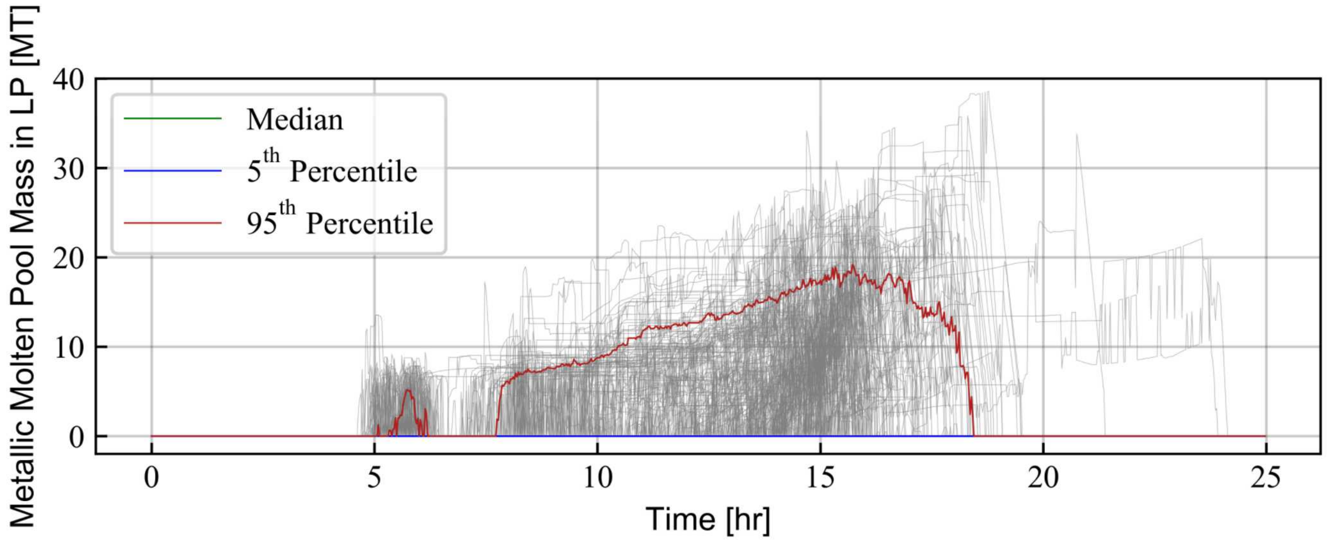


Lower Plenum Debris

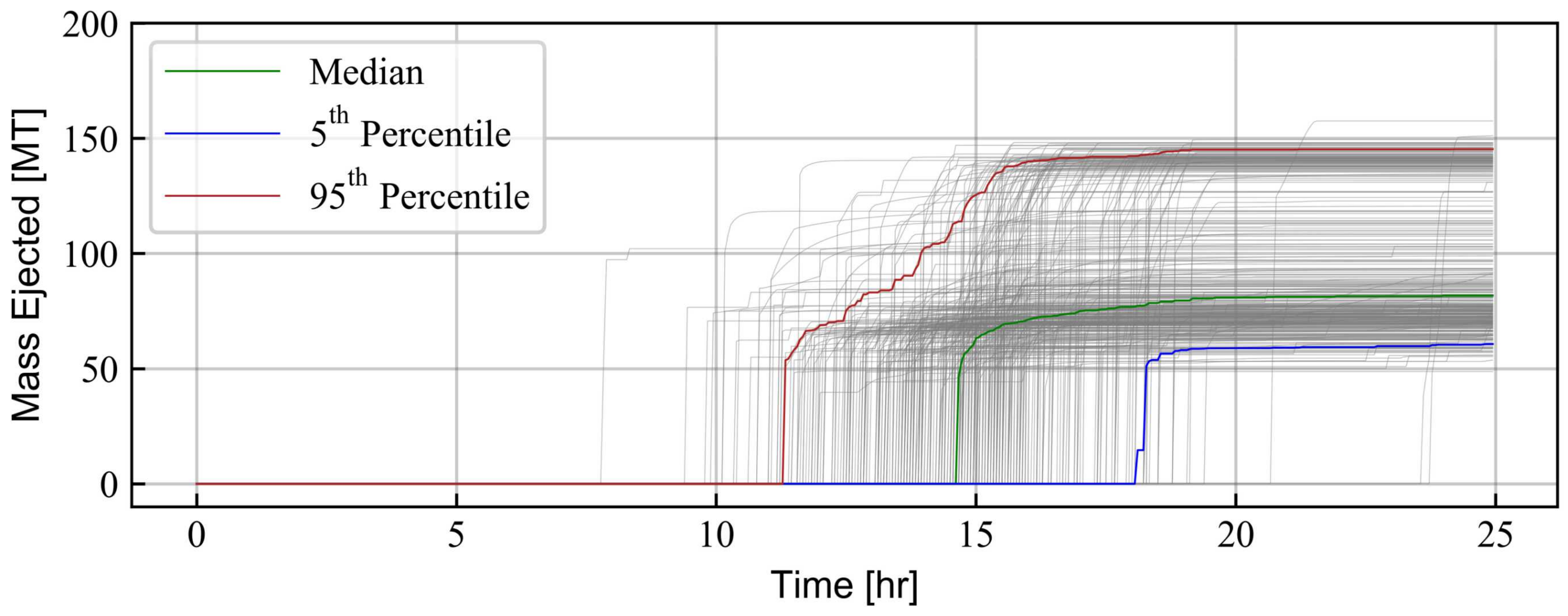


Lower Plenum Molten Debris





Ejected Debris



Summary of Key Events and 1F1 End-State: 25 Hours After Accident Initiation

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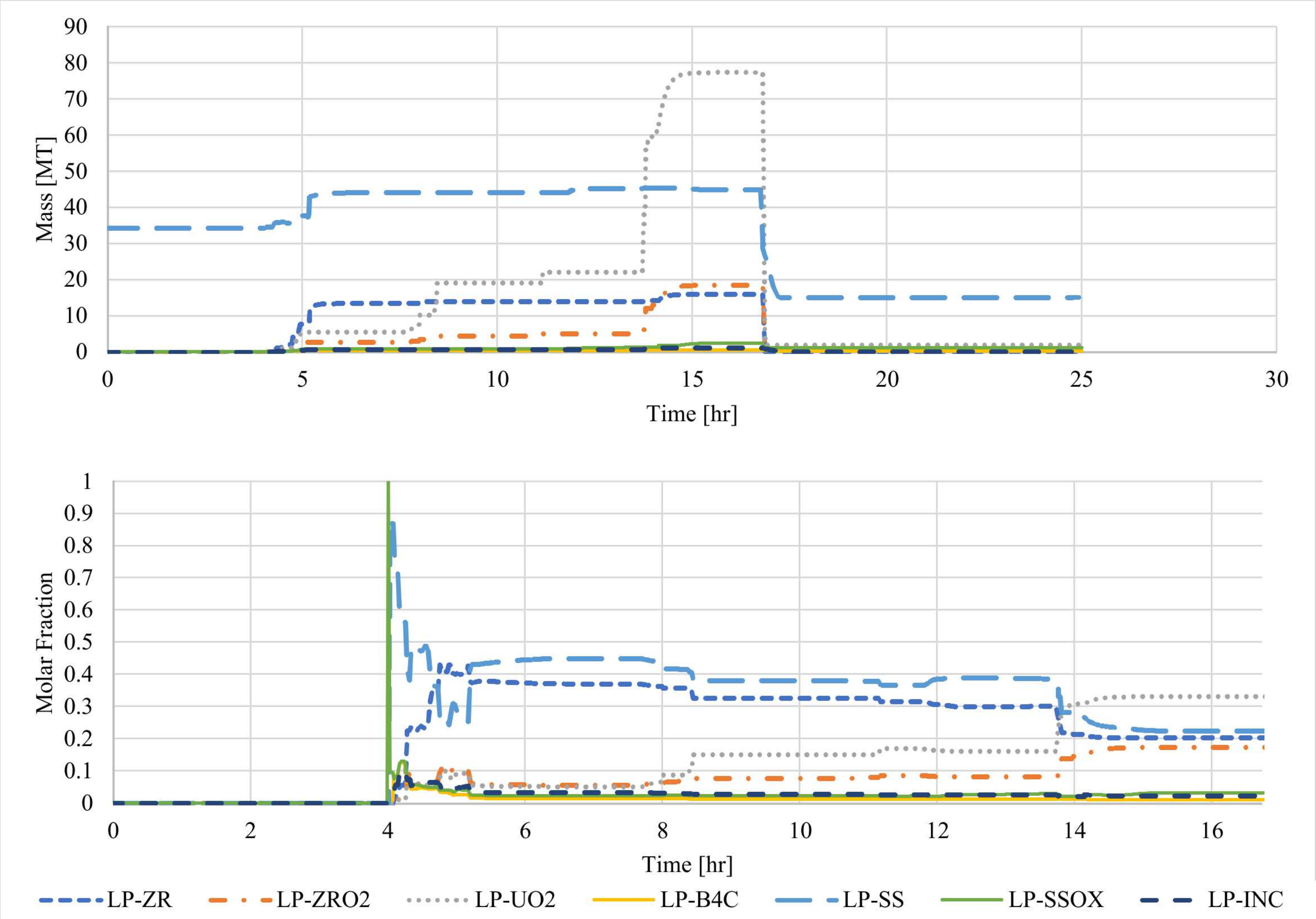
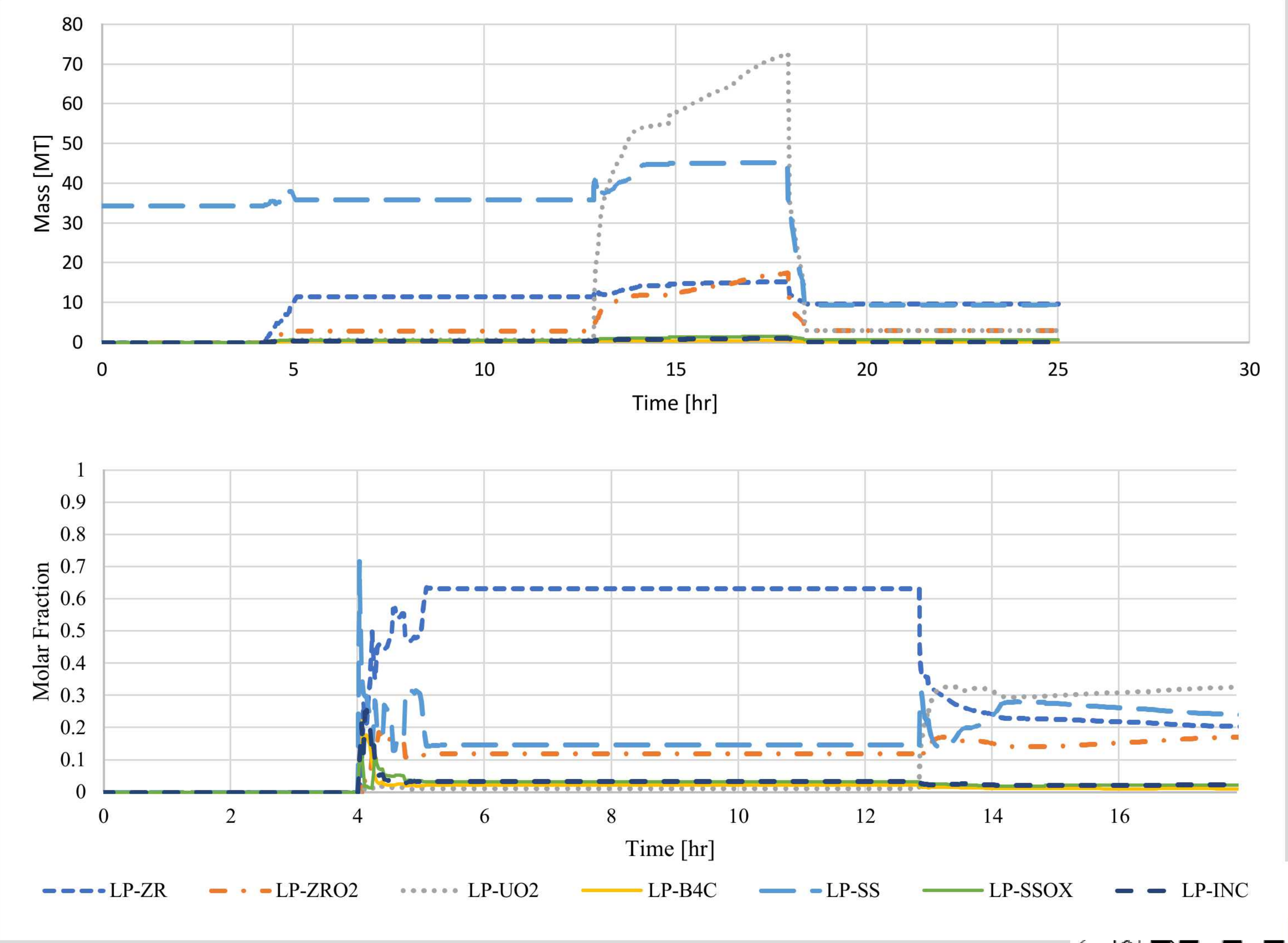
Figure of Merit	Median	5th Percentile	95th Percentile
Steamdome Pressure [MPa]	0.542	0.537	0.544
Drywell Pressure [MPa]	0.542	0.538	0.544
Wetwell Pressure [MPa]	0.528	0.527	0.529
Integral Hydrogen Production [kg]	738.6	639.1	840.1
Mass of Particulate Debris in the Lower Plenum [MT]	2. 7	0.02	5.5
Mass of Particulate Debris and Associated Conglomerate in the Lower Plenum [MT]	7.1	0.3	13.1
Mass of Oxidic Molten Pool in the Lower Plenum [MT]	0.0	0.0	0.0
Mass of Metallic Molten Pool in the Lower Plenum [MT]	0.0	0.0	0.0
Mass Ejected [MT]	81.7	60.7	145.3
Time of >5% Fuel Damage [hr]	4.7	4.0	7.3
Time of core plate Failure [hr]	6.0	4.8	10.7
Time of Main Steamline Rupture [hr]	6.1	6.1	6.1
Time of Core Slump [hr]	8.7	4.9	11.2
Time of >90% Fuel Damage [hr]	14.7	11.4	16.8
Time of Lower Head Failure [hr]	14.6	11.3	18.2

Realization 1: Lower Plenum Materials



Realization 2: Lower Plenum Materials



Realization 3: Lower Plenum Materials

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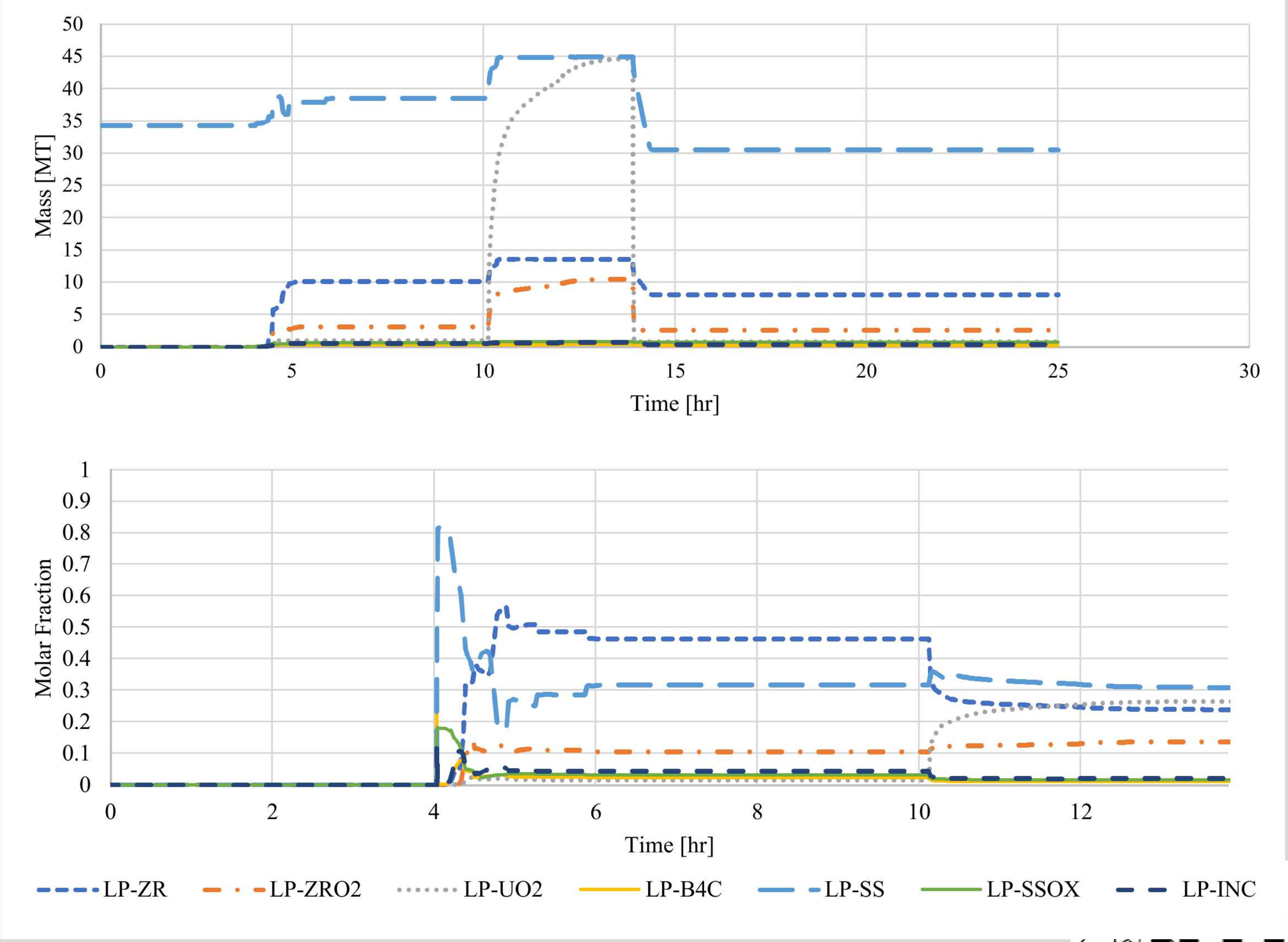

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Summary

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- Little variability in observed cases up to the onset of core degradation
- Increased variability in time after core degradation begins while still retaining the same accident signatures and general progression
- Results agree with past best estimate predictions of key event timings for the severe accident at 1F1
- Results indicate that most of the material relocated to the lower plenum is solid particulate debris and refrozen conglomerate
- Short molten pool lifetimes and smaller molten pool masses relative to solid debris, especially for oxidic molten pools
- The molar composition of debris in the lower plenum at the time of lower head failure through analyzing several individual realizations is found to be: SS 0.22 – 0.31; Zr 0.20 – 0.24; ZrO_2 0.14 – 0.17; UO_2 0.27 – 0.33; INC, B_4C, and SSOX account for ~0.05 of the debris combined

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Future Work

- Refinement and expansion of uncertain parameters
  - Include system response
    - Water injection
    - Leakages
    - Event Timings
  - Potential inclusion of other uncertain parameters
    - Focus on heat transfer models
- Comparison with similar study performed using the eutectics model
- In-depth characterization of the lower plenum debris composition
- Increased population size and simulation length
  - 1000s, not 100s of runs
  - 150 - 500 hours after accident initiation
- Similar analyses will be performed for 1F2 and 1F3

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Thank you for your attention

1F1 Plant Parameters

Plant Parameter	Value
Rated Core Power [MW_{th}]	1380
Total RPV water inventory [kg]	147634
Number of fuel assemblies [#]	400
Number of control blades [#]	97
Total Mass of UO_2 [kg]	77,403
Total Zircaloy Mass [kg]	30,431
Total Mass of Stainless Steel [kg]	47,767
Total Mass of B_4C [kg]	540
Mass of active region Zircaloy cladding [kg]	16779
Mass of upper core, non-active region Zircaloy cladding [kg]	2202
Mass of lower core, non-active region Zircaloy cladding [kg]	0
Mass of Zircaloy in fuel canister [kg]	11,451
Mass of stainless steel in control blades [kg]	9,000
Mass of stainless steel in top guide tube and upper tie plate [kg]	4,420
Mass of stainless steel in core support plate and "elephant's foot" [kg]	8,880
Mass of lower plenum structures [kg]	25,467