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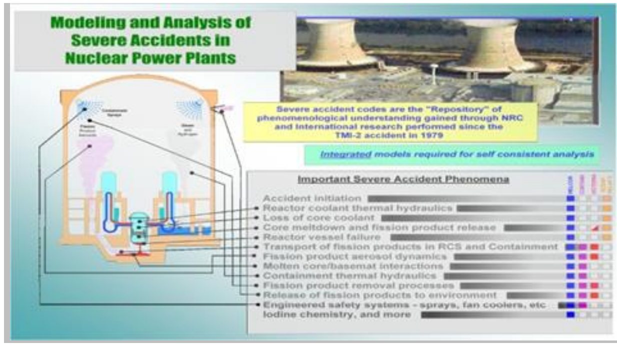

Fukushima Uncertainty Analysis

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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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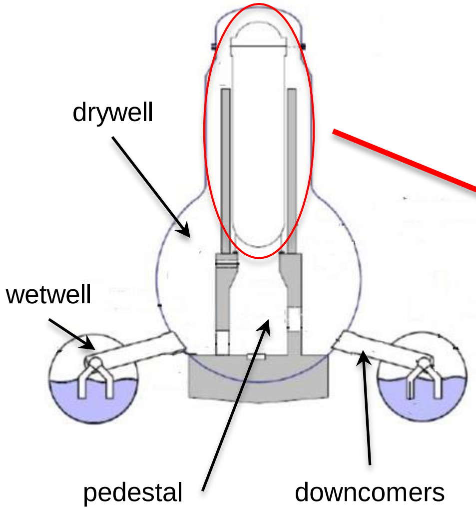
Topics for discussion

- Brief 1F1 Model Background
- Uncertain Parameters
- Results
  - Horsetails
  - Scatter Plots
  - CDFs
  - Regressions
- Perturbations
  - Max Time Step Variations
  - Walkthrough
- Summary

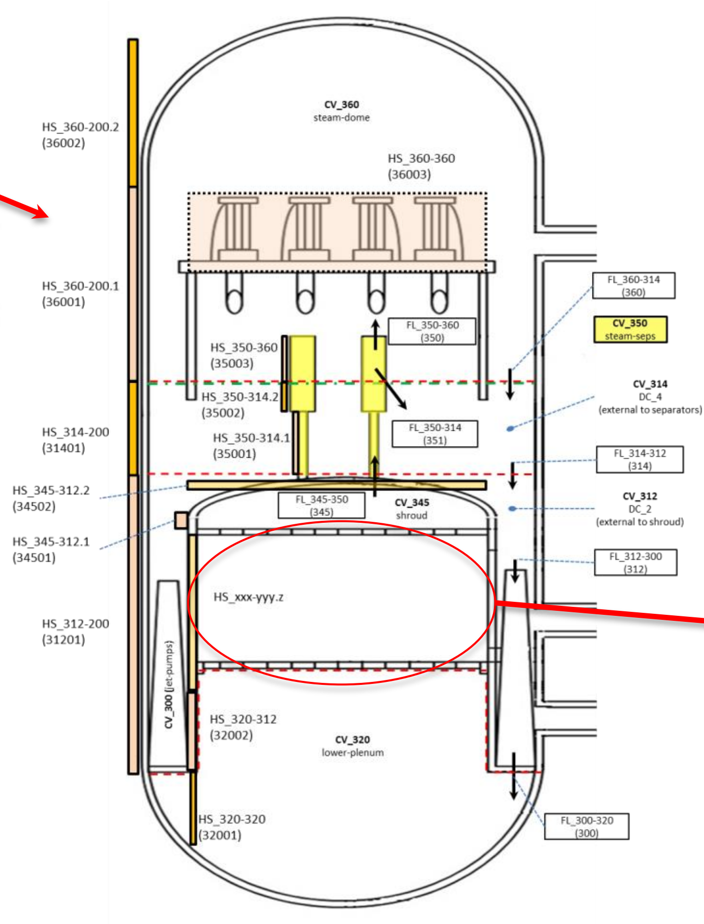
Brief 1F1 Model Background

- SNL MELCOR Fukushima models are based on the Peach Bottom SOARCA model; reflects current MELCOR BWR Mk-I best practices
- Models have been updated with the best-available Fukushima inputs developed surrogate inputs where necessary

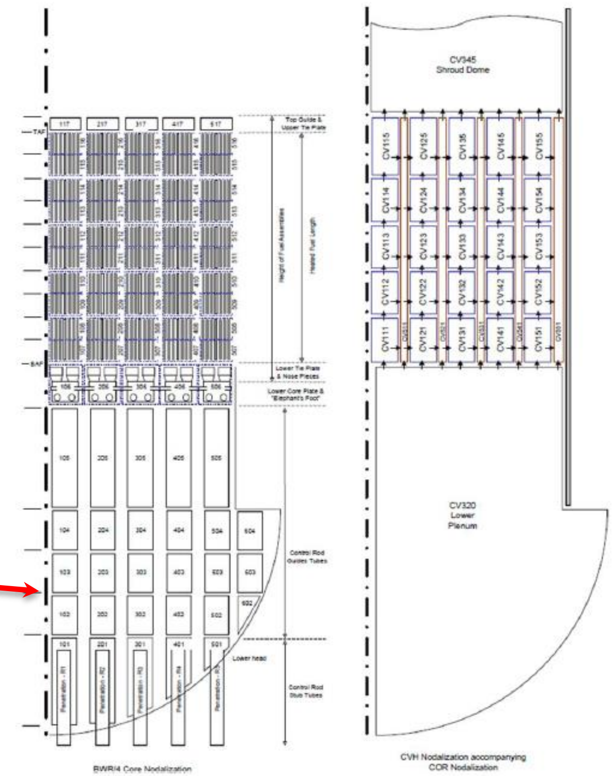
Brief 1F1 Model Background



containment CVH nodalization (4 CVs)



RPV CVH nodalization (7 CVs)



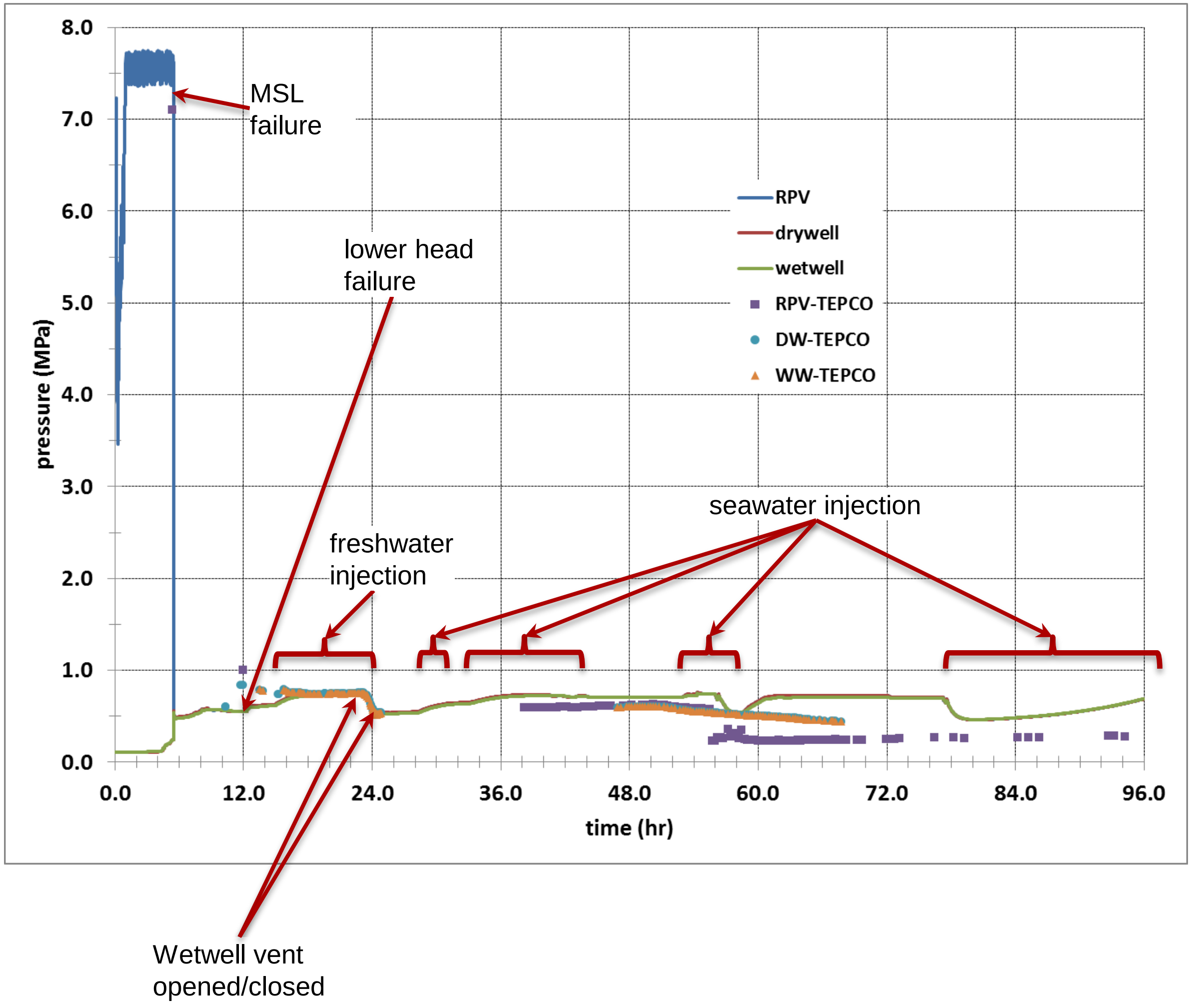
Lower RPV COR/CVH nodalization

- 5 active fuel rings, 10 active fuel axial levels
- 5 rings, 1 axial level above the active fuel
- 6 LP rings (lvls 2-4), 6 axial levels
- 5 ch x 5 byp CVs or 5 ch x 1 byp CVs

1F1 Best Estimate (BE) Case Overview

- Revised decay heat/RN inventory input with results from SNL SCALE6 analyses
- IC implementation includes efficiency as a function of RPV pressure; carry-over from previous 1F1 analyses
- SRV gasket failure not implemented; MSL failure model activated
- Did not implement wetwell stratification; not amenable MELCOR lumped-parameter conceptual model nor with the SPARC90 scrubbing model

1F1 BE– RPV/DW/WW pressure



- MSL failure at ~6 hr
- LH failure at ~12 hr
- Containment pressure increase at ~12 hr not captured; likely due to relatively "cold" particulate debris (rather than "hot" molten pool) ejection
- late-time pressure changes are related to changes in water injection
- ad hoc leakage model will need to be implemented to capture late-time leakage

1F1 UA Purpose

- Evaluate the impact of key uncertain parameters on core melt progression
  - Failure timings
    - First control blade
    - Frist channel box
    - First fuel
    - Lower core plate
    - Lower head
  - Intact fuel fraction
  - H2 produced
  - Debris mass ejected to drywell

Uncertain Parameter Selection

- Started with distributions from the Peach Bottom and Surry UAs
- Focus on core damage progression parameters
  - Sequence uncertainties are removed (e.g., battery life, SRV failure, …)
  - Core degradation parameters introduced (e.g., debris falling velocity, dT/dz model assumption)
- Most distributions were converted to beta distributions
  - Beta's are more diffuse - Triangular distributions provide too much certainty on the mode (ACRS comment from Peach Bottom)
  - Uniform distributions were transformed to Beta distributions, then softened (shape factors were set to 1.1, not 1.0) to de-emphasize the extreme values
- Fuel failure treatment is shown later.

Parameters

parameter	nomenclature	uniform distribution	beta distribution (mode/mean)	beta distribution (BMLE)
time constants for radial (solid) debris relocation	SC1020_1	LB = 180 s UB = 720 s	LB = 180 s UB = 720 s α = 1.33 β = 1.67	LB = 180 s UB = 720 s α = 2.08 β = 2.56
time constants for radial (liquid) debris relocation	SC1020_2	LB = 30 s UB = 120 s	LB = 30 s UB = 120 s α = 1.33 β = 1.67	LB = 30 s UB = 120 s α = 2.08 β = 2.59
dT/dz model, time constant for averaging flows	SC1030_2	LB = 0.09 s UB = 0.11 s	LB = 0.09 s UB = 0.11 s α = 1.1 β = 1.1	LB = 0.09 s UB = 0.11 s α = 1 β = 1
dT/dz model, characteristic time for coupling dT/dz temperatures to average CVH volume temperature when dT/dz model is active	SC1030_4	LB = 8 s UB = 12 s	LB = 8 s UB = 12 s α = 1.1 β = 1.1	LB = 8 s UB = 12 s α = 1 β = 1
dT/dz model, maximum relative weight of old flow in smoothing algorithm involving time constant for averaging flows	SC1030_5	LB = 0.5 s UB = 0.7 s	LB = 0.5 s UB = 0.7 s α = 1.1 β = 1.1	LB = 0.5 s UB = 0.7 s α = 1 β = 1
molten zircaloy melt break-through temperature	SC1131_2	LB = 2100 K UB = 2540 K	LB = 2100 K UB = 2540 K α = 2.77 β = 2.33	LB = 2100 K UB = 2540 K α = 2.58 β = 2.05
molten cladding (pool) drainage rate	SC1141_2	LB = 0.1 kg/m-s UB = 2.0 kg/m-s	LB = 0.1 kg/m-s UB = 2.0 kg/m-s α = 1.11111 β = 1.8889	LB = 0.1 kg/m-s UB = 2.0 kg/m-s α = 1.24 β = 2.26
fraction of strain at which lower head failure occurs	SC1601_4	LB = 0.16 UB = 0.20	LB = 0.16 UB = 0.20 α = 1.1 β = 1.1	LB = 0.16 UB = 0.20 α = 1 β = 1

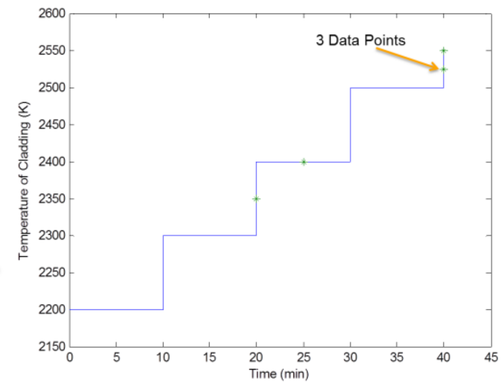
Parameters

parameter	nomenclature	uniform distribution	beta distribution (mode/mean)	beta distribution (BMLE)
scaling factor for candling heat transfer coefficients	cor_cht_hfzrXX	LB = 0.9 UB = 1.1	LB = 0.9 UB = 1.1 α = 1.1 β = 1.1	LB = 0.9 UB = 1.1 α = 1 β = 1
fraction of un-oxidized cladding thickness at which thermal-mechanical weakening of oxidized cladding begins	cor_rod_2	LB = 0.0005 m UB = 0.0015 m	LB = 0.0005 m UB = 0.0015 m α = 1.1 β = 1.1	LB = 0.0005 m UB = 0.0015 m α = 1 β = 1
debris quenching heat transfer coefficient to pool	cor_lp_2	LB = 100.0 W/m^2 K UB = 2000.0 W/m^2 K	LB = 100.0 W/m^2 K UB = 2000.0 W/m^2 K α = 1.1 β = 1.1	LB = 100.0 W/m^2 K UB = 2000.0 W/m^2 K α = 1 β = 1
debris falling velocity	cor_lp_4	log-uniform dist. LB = 0.01 m/s UB = 1.0 m/s	LB = 0.01 m/s UB = 1.0 m/s α = 0.0587 β = 0.4763	LB = 0.01 m/s UB = 1.0 m/s α = 0.85 β = 1.14
minimum debris porosity (Lipinski dryout model); SC1244(1) min. porosity used in flow blockage Ergun pressure drop equation; SC4413(5) min. hydrodynamic volume fraction; SC4414(1) minimum porosity to be used in calculating the flow resistance in the flow blockage model; SC1505(1) minimum porosity to be used in calculating the area for heat transfer to fluid; SC1505(2)	minpordp	LB = 0.01 UB = 0.2	LB = 0.01 UB = 0.2 α = 1.1 β = 1.1	LB = 0.01 UB = 0.2 α = 1 β = 1
fuel time-at-temperature	TaT	(1)	(1)	(1)
total core decay heat	dch	(2)	(2)	(2)

Parameters

- Time-at-Temperature uncertainty
  - A simplified time at temperature curve whose parameters have been fit with a Bayesian regression analyses.
- Decay Heat uncertainty
  - Considers aleatory variability from a combination of ANS 5.1 Decay Heat Standard and SCALE calculations

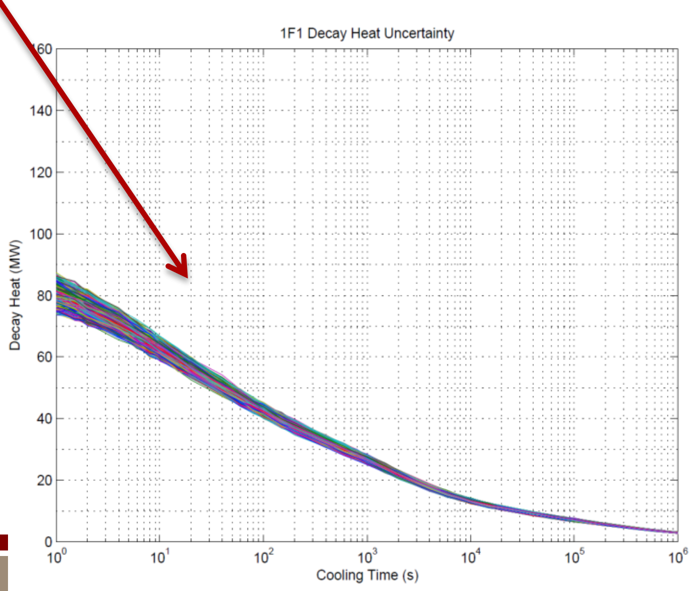
High Burnup VERCORS tests
Time at Temperature histories

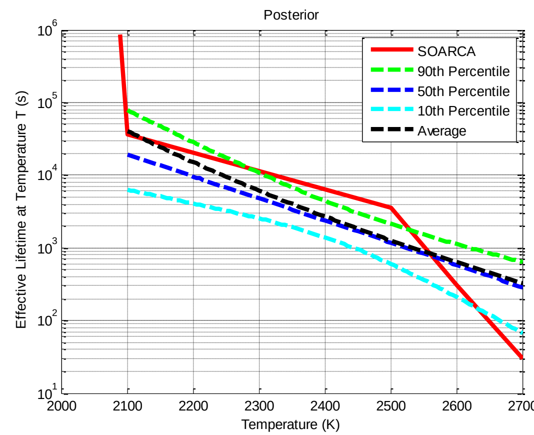


$$\frac{1}{t(T)} = A * \exp(BT), \quad D(t) = \sum\left(\frac{1}{t(T)} * \Delta t\right)$$

$$L(E|A,B,\sigma,E,M) = \prod_{i=1}^{N}\left[\frac{1}{D_i * \sigma * \sqrt{2\pi}} * \exp\left(-\frac{\ln(D_i) - \mu}{2\sigma^2}\right)\right]$$

$$\pi(A,B,\sigma|M,E) = \frac{L(E|A,B,\sigma,M) * \pi(A,B|M)dAdB * \pi(\sigma|E,M^*)d\sigma}{\{\int\int\int L(E|A,B,\sigma,M) * \pi(A,B|M)dAdB * \pi(\sigma|E,M^*)d\sigma\}}$$





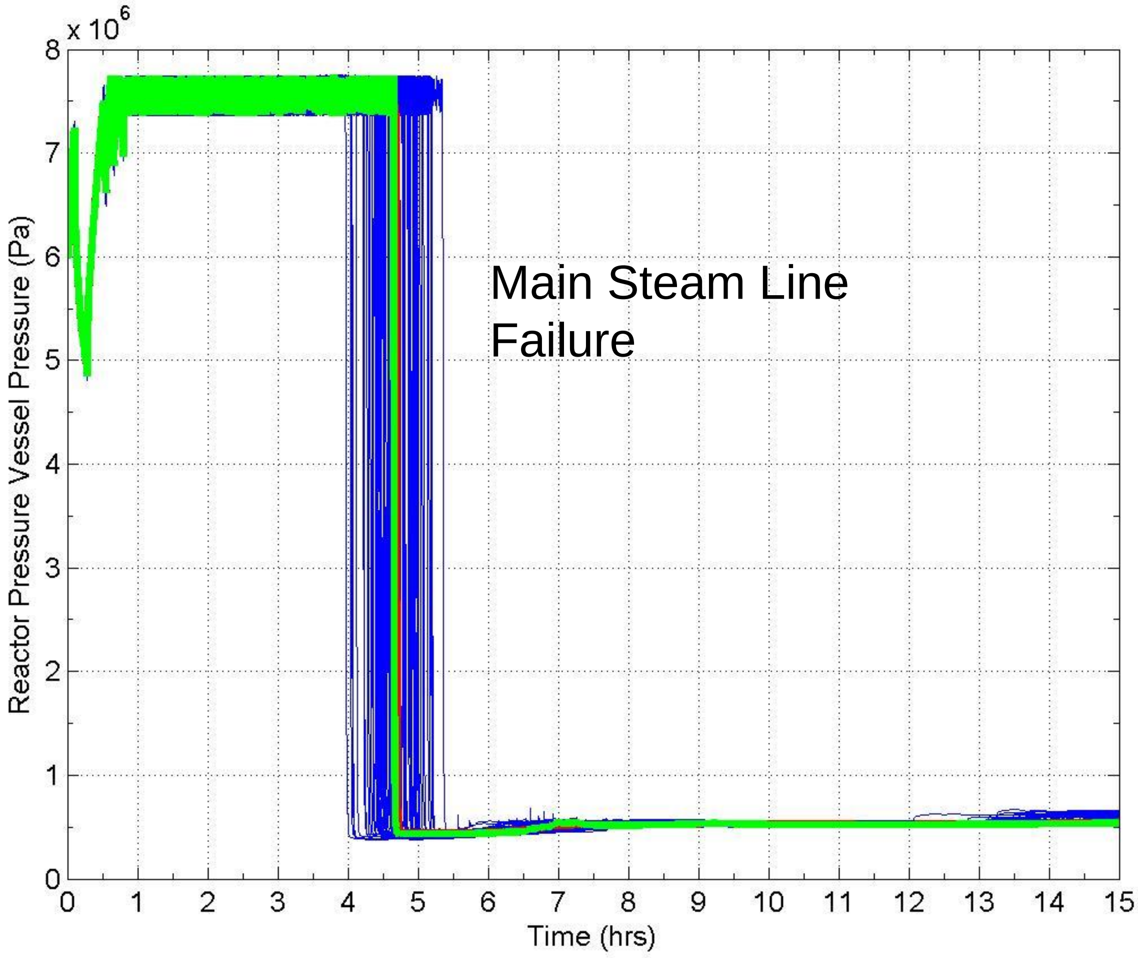
MELCOR Cases

- 3 replicates (100 rlz) with the beta uncertain parameters
  - Replicate 1 is the "base case" for statistical analyses
- Rerun of replicate 1 (100 rlz) with uniform uncertain parameters parameters
  - Does shape of distributions at their bounds impact the results
- Reruns of "median-like" replicate 1 realization (100 rlz) with
  - Small perturbation (Uniform -> +/-0.5%) of median-like realization's scalar uncertain parameters
  - Log-uniform [0.1 s,0.01 s] variation of median-like realization's DTMAX
  - Reordering flowpath inputs
  - Provide heuristic measures of irreducible MELCOR code uncertainty/degree of MELCOR code convergence

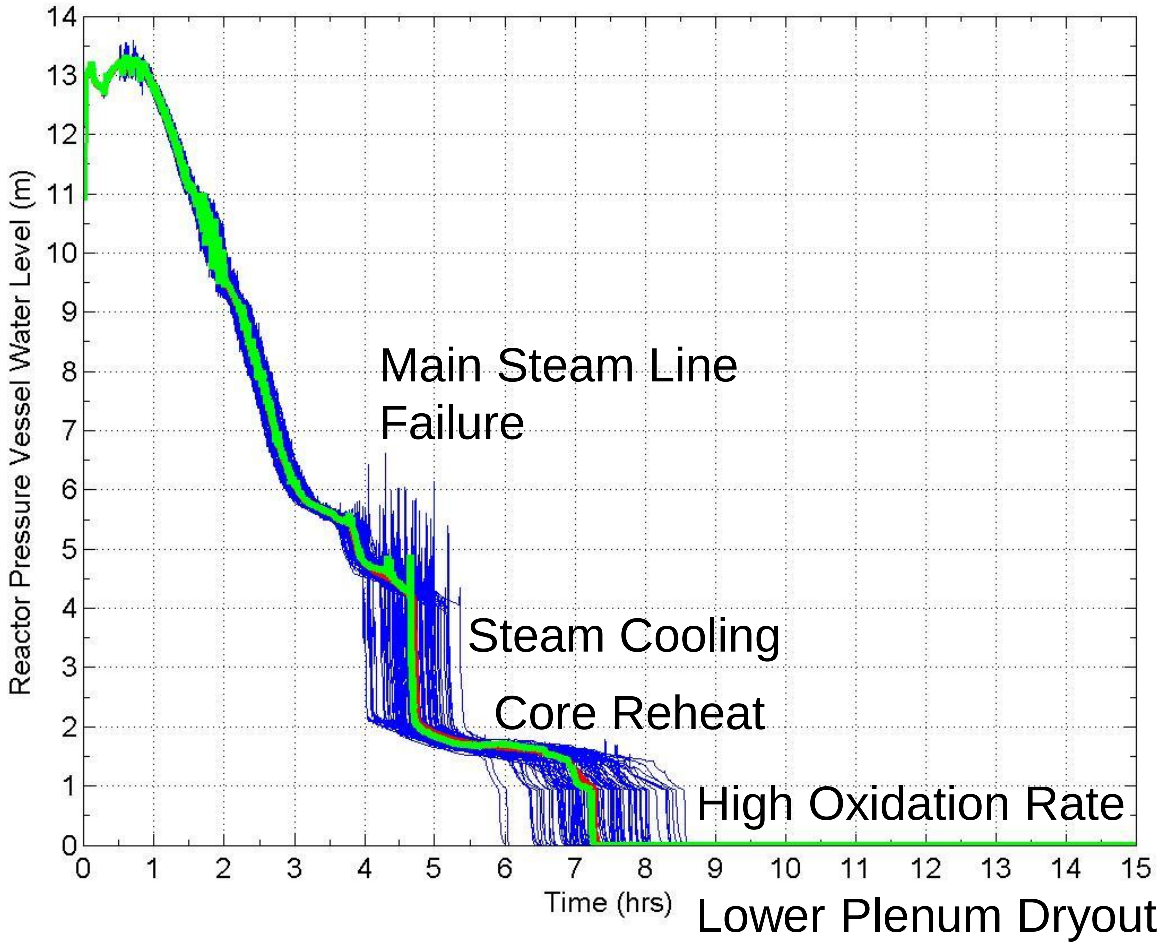
UA Results

- Horsetails – Provide a high level examination of uncertainty results
- Scatterplots – Visual examination of the unprocessed data
- Cumulative Distribution Functions – What do the distributions of results look like?
- Regressions – What parameters seem to influence the distribution of results?

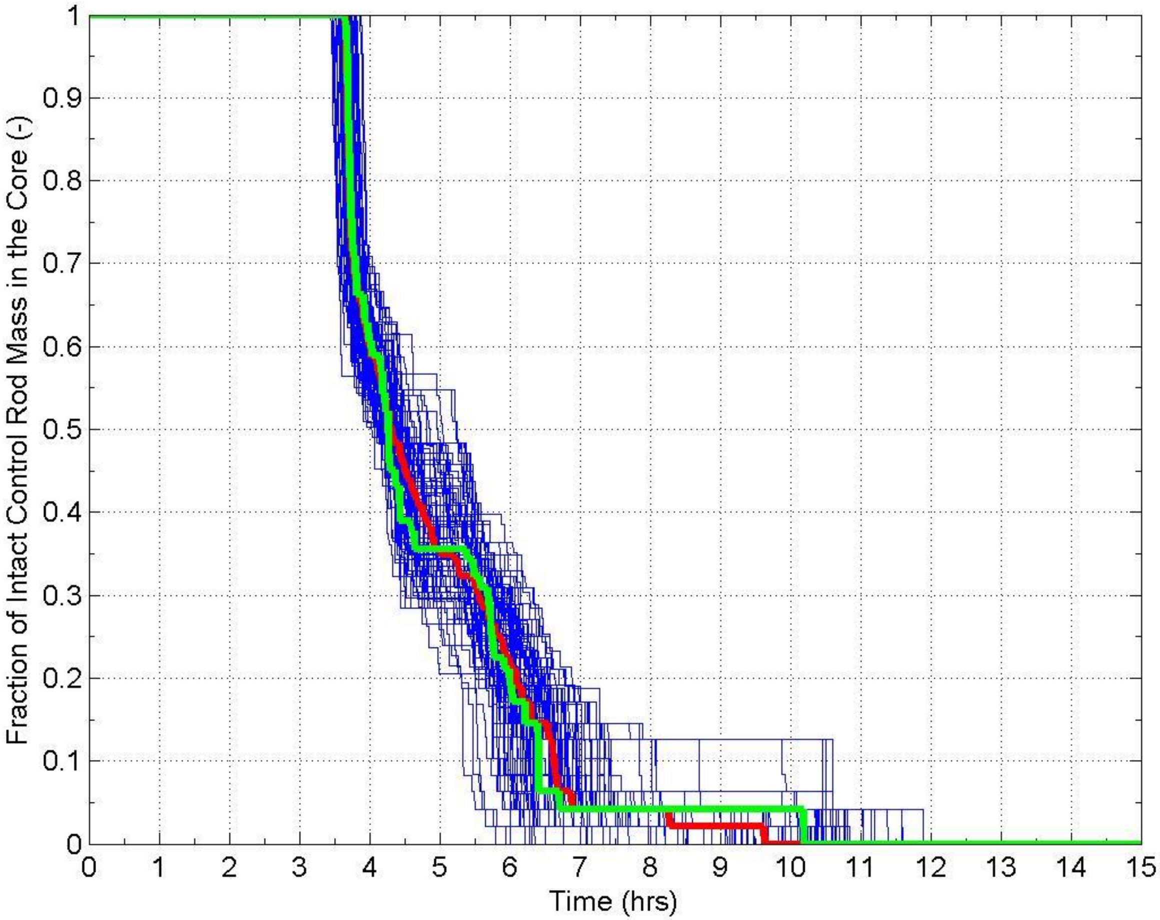
Horsetails – RPV Pressure



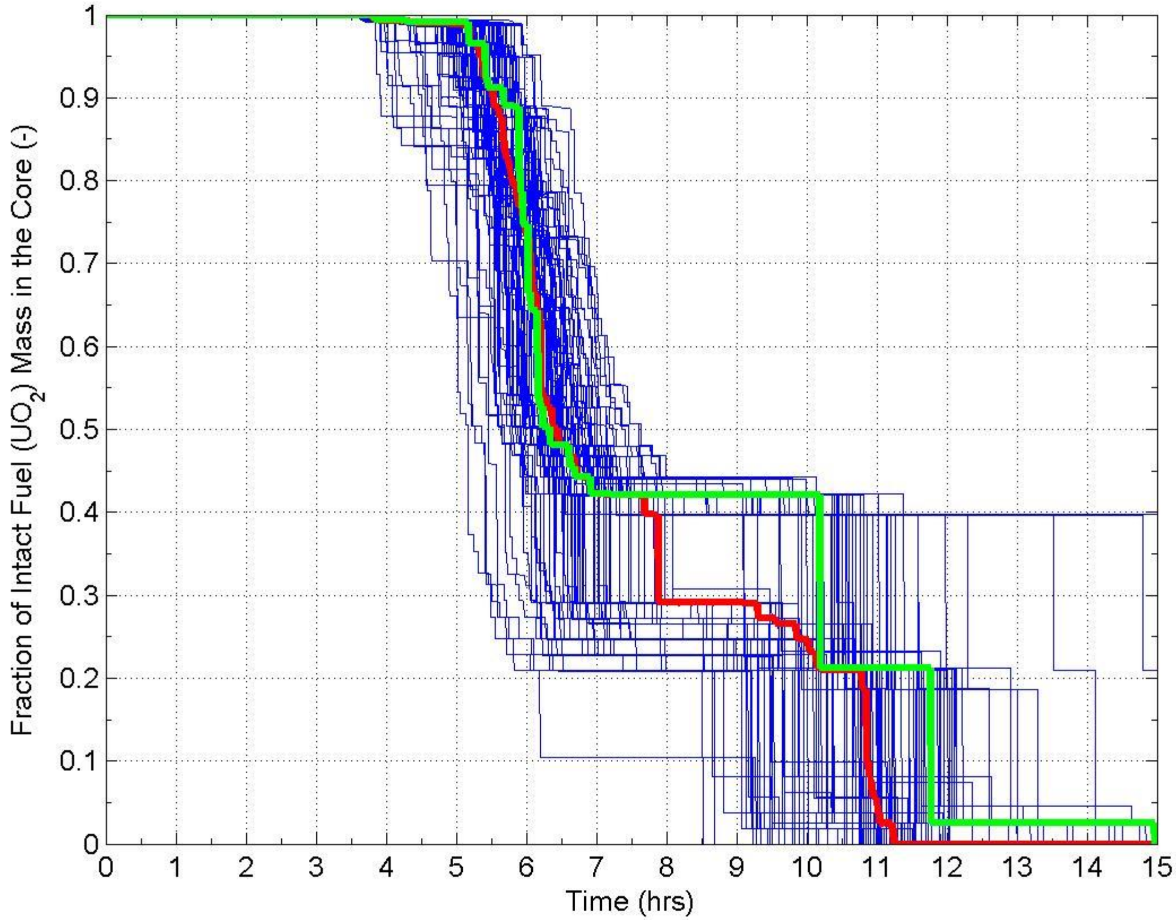
Horsetails – RPV Water Level



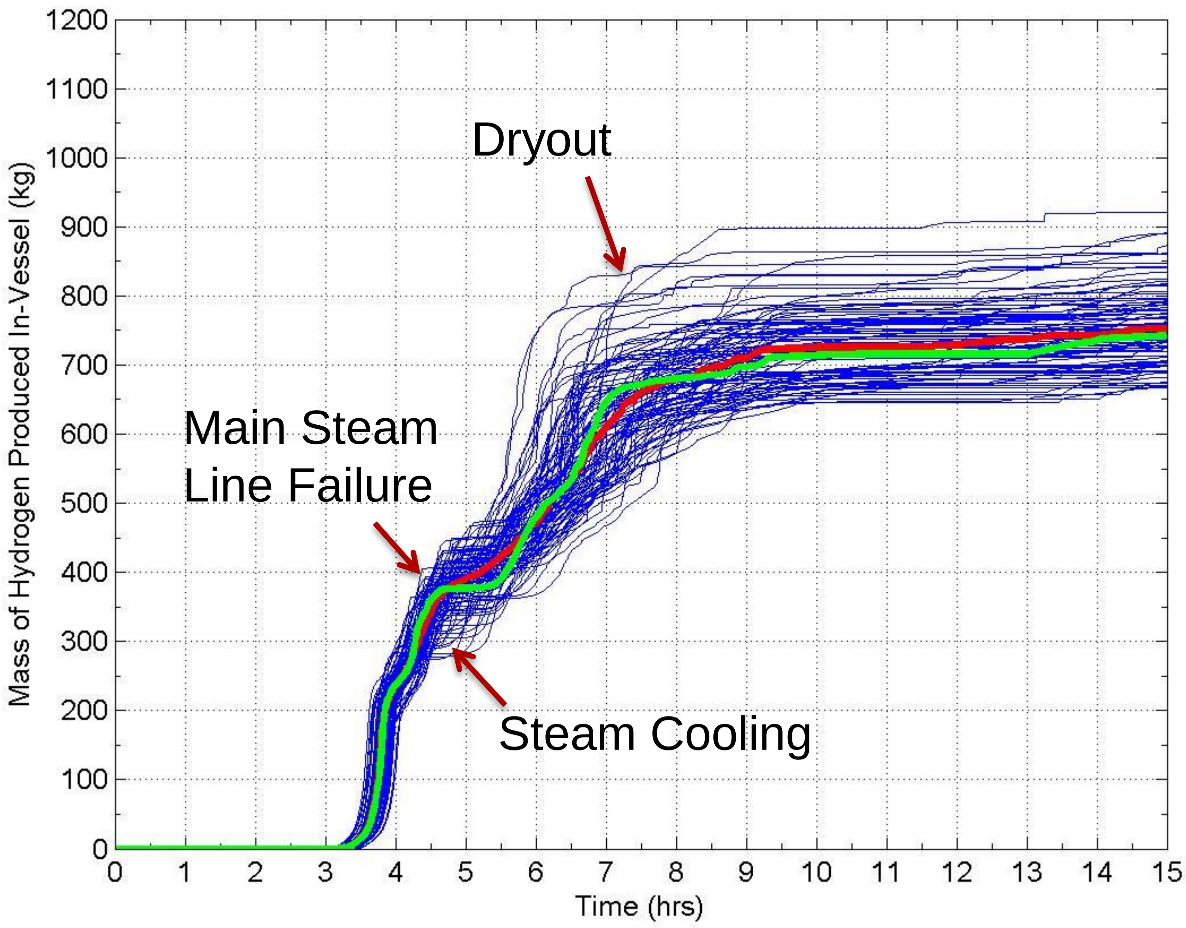
Horsetails – Intact Control Rod Mass



Horsetails – Intact Fuel Mass



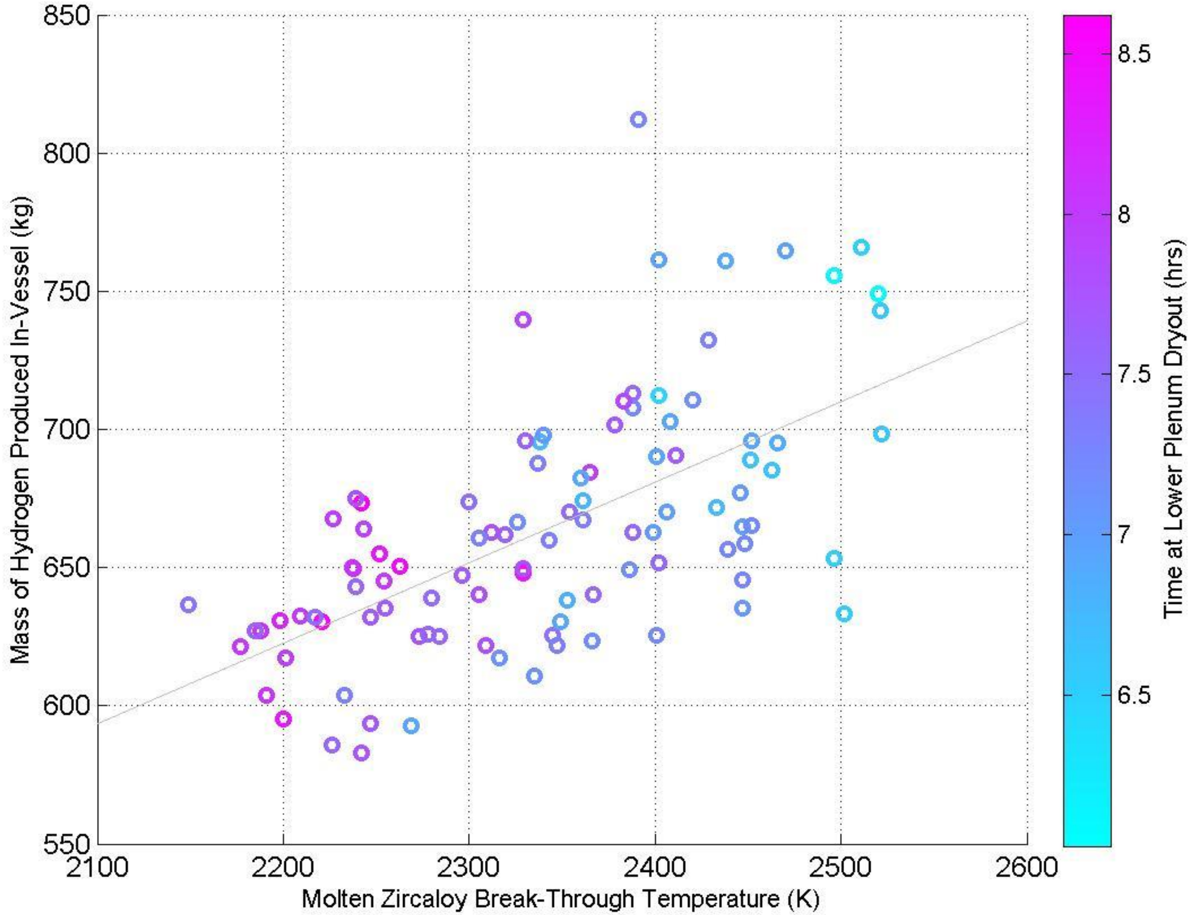
Horsetails – Intact Fuel Mass



Scatter Plots

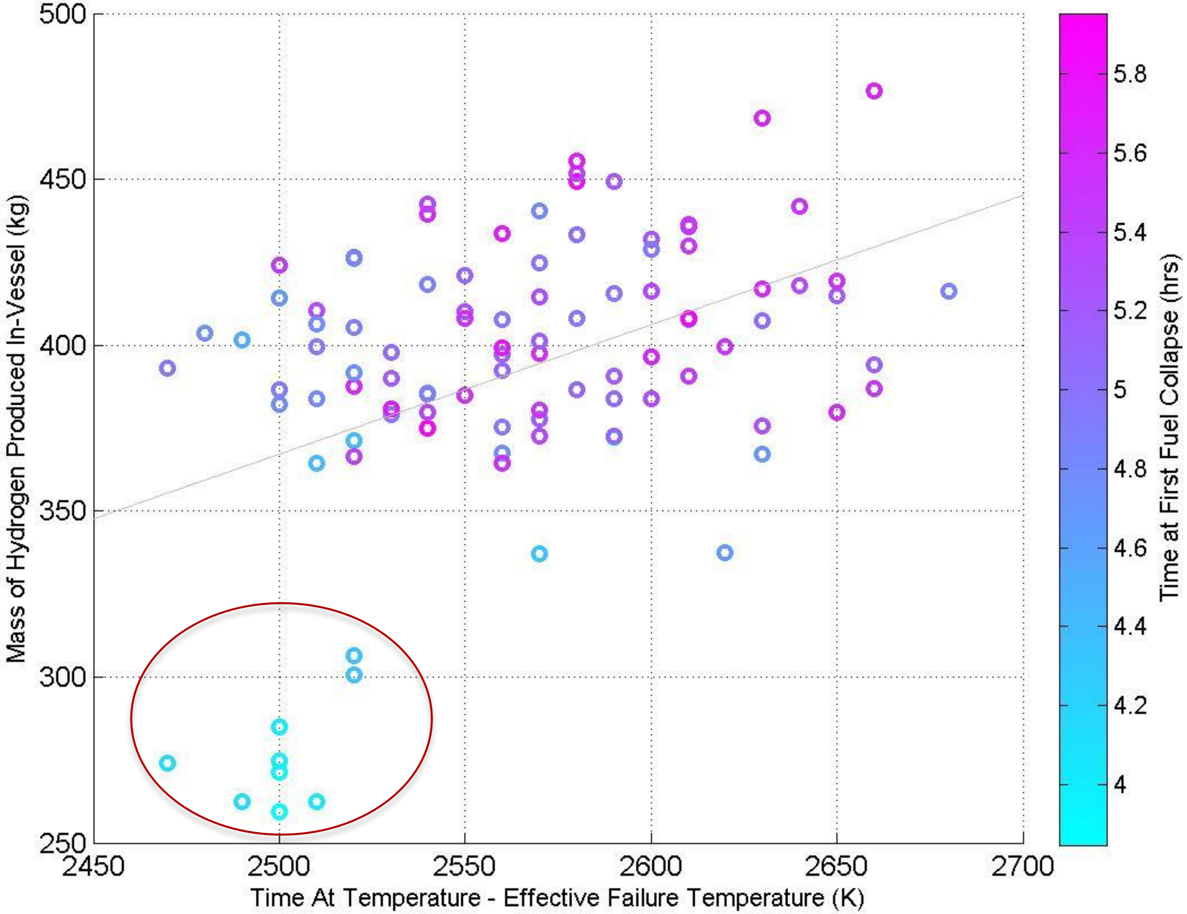
- Hydrogen and Fraction of Intact Fuel Mass
  - Molten Zirconium Breakthrough Temperature
  - Fuel Failure Temperature
- Hydrogen Early vs Hydrogen Late

MZBT

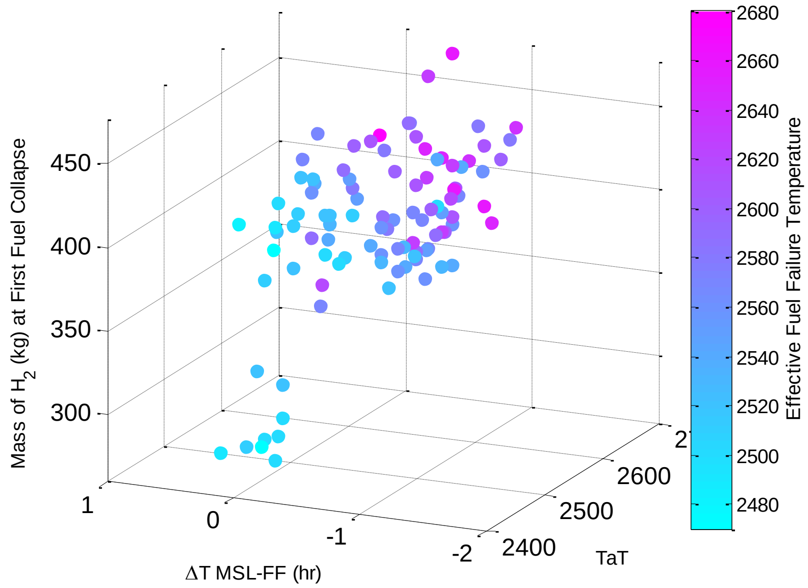


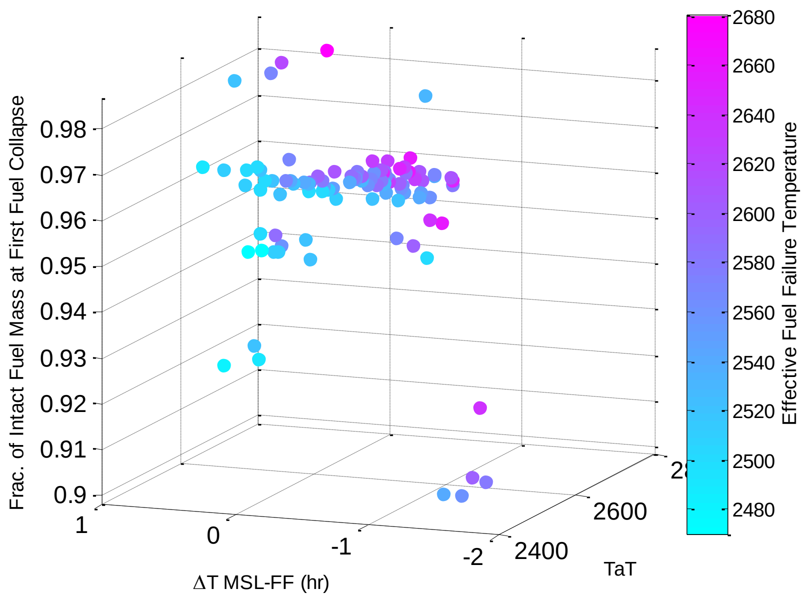
850
800
750
700
650
600
550
2100
2200
2300
2400
2500
2600
Molten Zircaloy Break-Through Temperature (K)
Mass of Hydrogen Produced In-Vessel (kg)
8.5
8
7.5
7
6.5
Time at Lower Plenum Dryout (hrs)

Fuel Failure Temperature

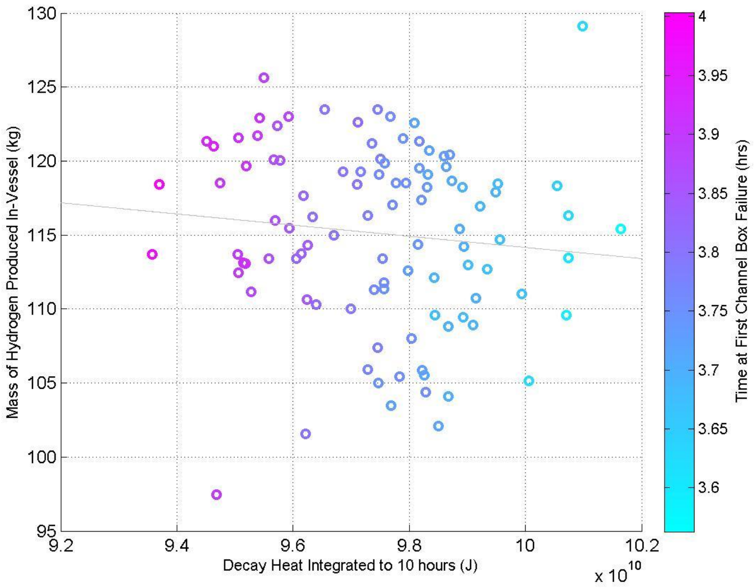


Fuel Failure Temperature (2)

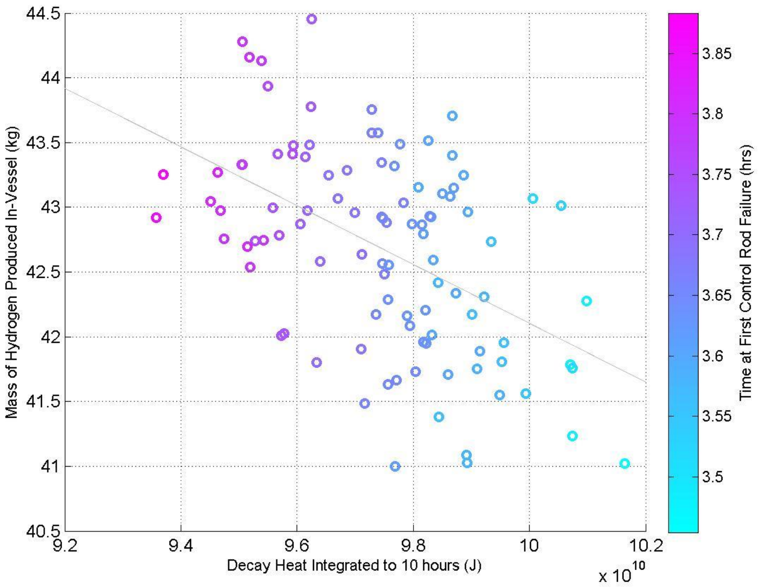




Decay Heat

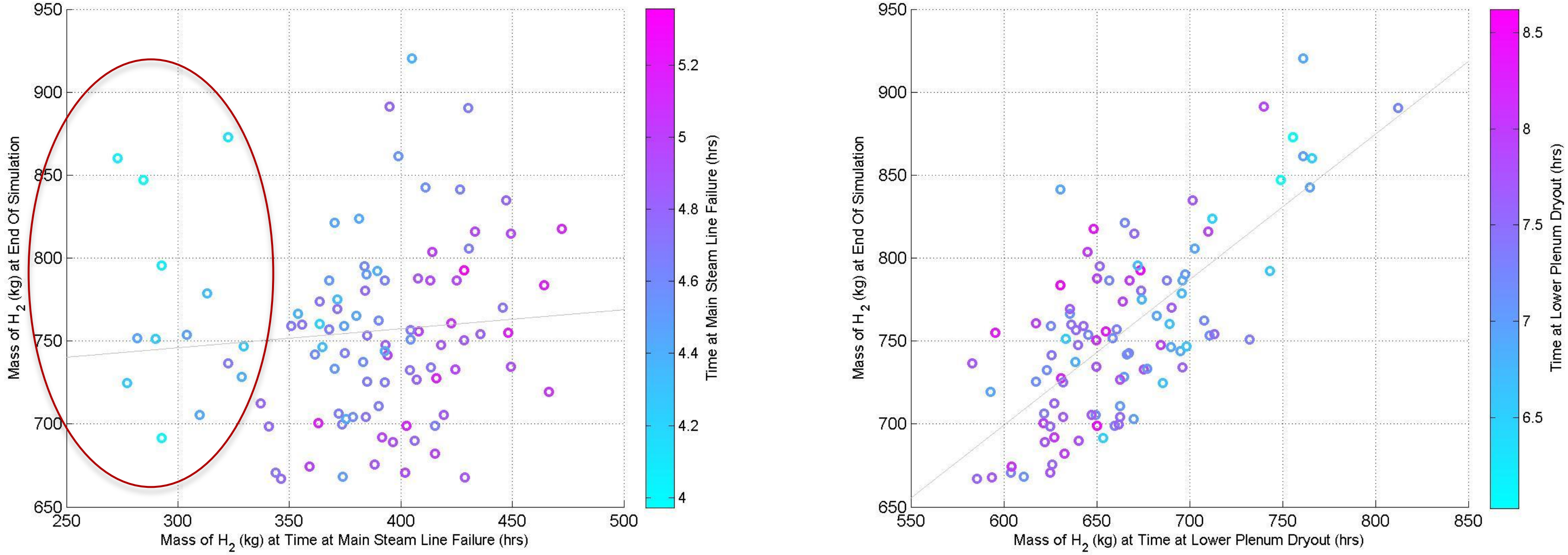


Mass of Hydrogen Produced In-Vessel (kg)
130
125
120
115
110
105
100
95
9.2
9.4
9.6
9.8
10
10.2
Decay Heat Integrated to 10 hours (J)
x 10^10
Time at First Channel Box Failure (hrs)
4
3.95
3.9
3.85
3.8
3.75
3.7
3.65
3.6

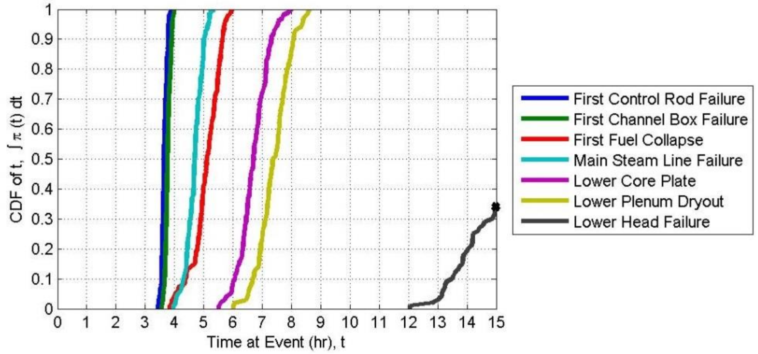


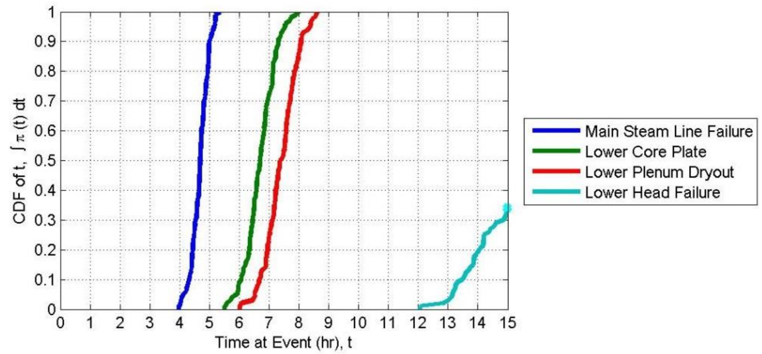
Mass of Hydrogen Produced In-Vessel (kg)
44.5
44
43.5
43
42.5
42
41.5
41
40.5
9.2
9.4
9.6
9.8
10
10.2
Decay Heat Integrated to 10 hours (J)
x 10^10
Time at First Control Rod Failure (hrs)
3.85
3.8
3.75
3.7
3.65
3.6
3.55
3.5

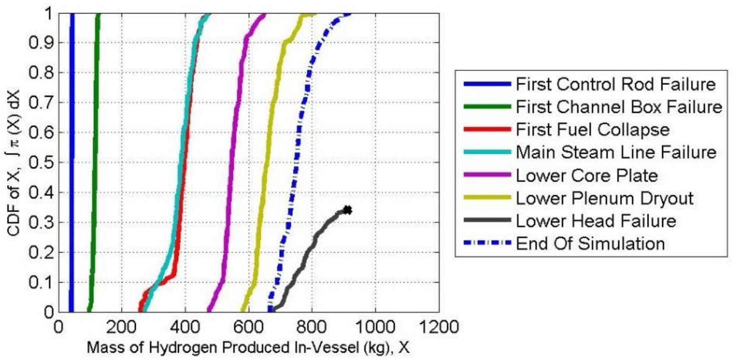
Hydrogen Early vs Hydrogen Late

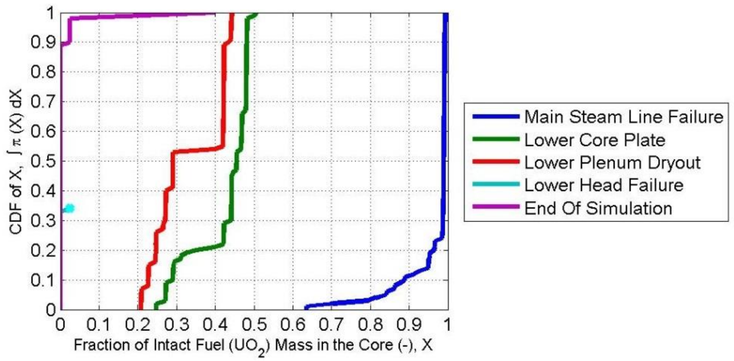


Cumulative Distribution Functions









Regression Results

Regression insights are correlative, not necessarily causal, and are comingled with the timing of the event.

- For example, reduced H_2 at fuel failure with higher decay heat may be caused by higher decay heat bringing down fuel earlier, thus reducing the available time to produce hydrogen.
- Thus, higher decay heat levels should not be interpreted to produce less H_2 during a severe accident.

Regressions should be tested against new data to demonstrate the worth of the regression results

Interpreting Dependency Tables

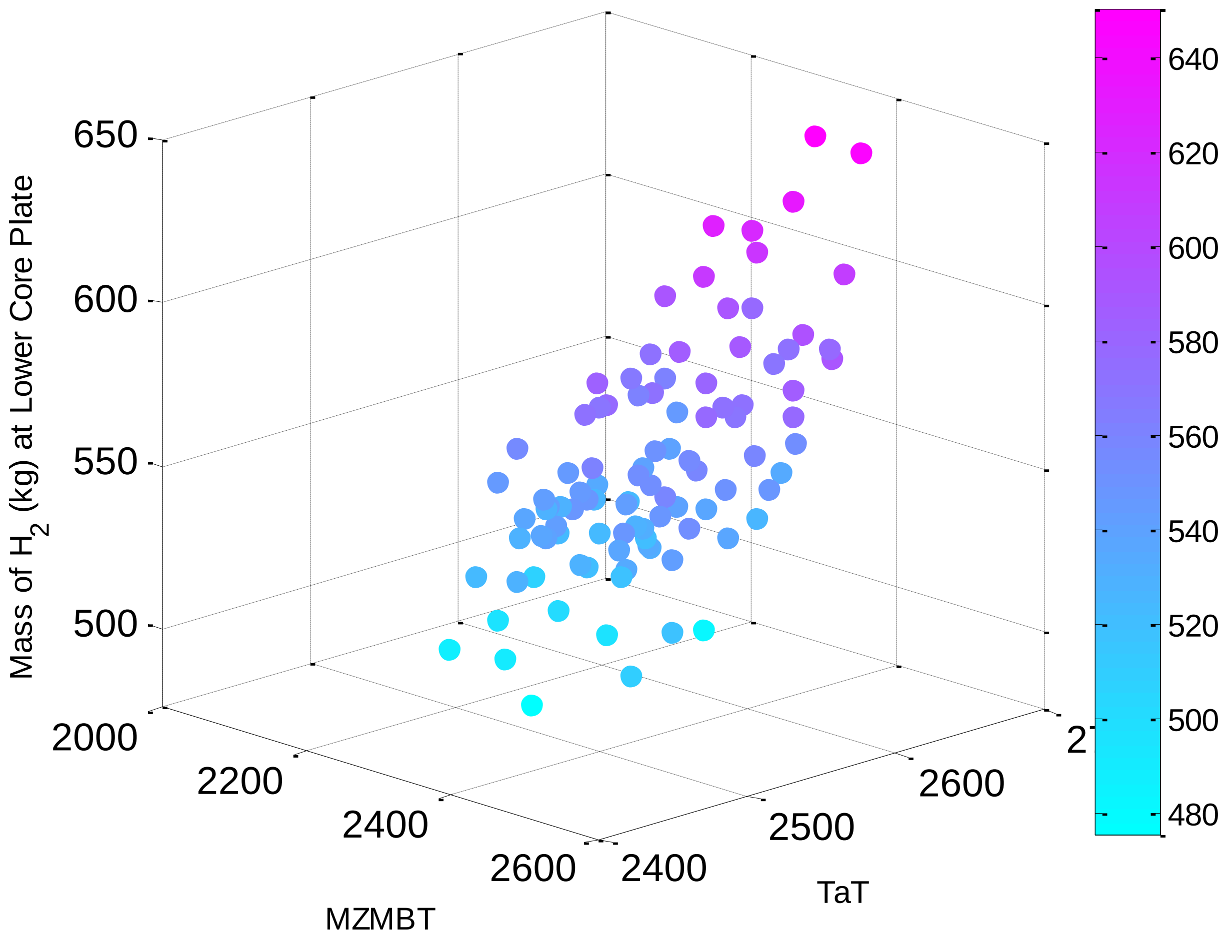
	1st Control Rod Failure	1st Channel Box	1st Fuel Failure	Main Steam Line	Lower Core Plate	Lower Plenum Dry-out	Lower Head Failure	End of Simulation
R^2 / R^2_{adj} / F-stat vs. Const./ p-val	.28 / .26 / 18.7 / 0	.06 / .05 / 5.9 / 0.017	.26 / .24 / 11.3 / 0	.33 / .31 / 11.9 / 0	.58 / .55 / 21.1 / 0	.485 / .463 / 22.3 / 0	.66 / .6 / 10.7 / 0	.194 / .177 / 11.7 / 0
Intercept	65 kg	144 kg	155 kg	757 kg	8288 kg	158.44 kg	-126.73 kg	242.09 kg
Time Constants for Radial (solid) Debris Relocation (s) [1]				[33, 81, 128] [-184, -117, -48][4] [-56, -36, -15]	[-34, -22,-9]		[35, 84, 132]	
Time Constants for Radial (liquid) Debris Relocation (s)								
dT/dz Model, Time Constant for Averaging Flows (s)		[-32, -29,-26]						
dT/dz Model, Characteristic Coupling Time (s)								
dT/dz Model, Relative Weight of Historical Flow (s)								
Molten Zircaloy Break-Through Temperature (K) [2]			[-217, -202, -185]	[-470, -437,-400]	[-9221, -8570, -7857] [8248, 8996, 9679][6] [391, 426, 459]	[665, 725, 780]	[632, 689, 742]	[491, 535, 576]
Molten Cladding (pool) Drainage Rate (kg/(m*s))								
Fraction of Strain at Which Lower Head Failure Occurs					[73, 83, 91]			
Scaling Factor for Candling Heat Transfer Coefficients								
Fraction of Un-oxidized Cladding Thickness Initiating T. M. Weakening (m)[3]							[97, 177, 282] [-151, -95, -52][5] [45, 82, 131]	
Debris Quenching Heat Transfer Coefficient to Pool (W/(m*m*K)) [4]				[9, 95, 162] [-200, -117, -11][1] [-38, -22, -2]		[-1314, -772, -74] [73, 757, 1290][6] [-25, -14, -1]		[-37, -22, -2]
Debris Falling Velocity (m/s)[5]	[-0.511, -0.187, -0.007]						[2, 62, 169] [-258, -95, -4][3] [-89, -33, -1]	
Minimum Debris Porosity					[-19, -10, -1]			
Time At Temperature - Effective Failure Temperature (K)[6]			[887, 979, 962]		[-8597, -8212, -7924] [8680, 8996, 9418][2] [756, 784, 821]	[-215, -205, -198] [731, 757, 793][4] [533, 552, 578]		
Decay Heat Integrated to 10 hours (J)	[-23, -22, -21]		[-502, -482, -462]					

$$[\Delta Y_{\min}, \Delta Y_{median}, \Delta Y_{\max}] | X_i \sim \{\min(\widehat{\beta}_i [X_{\min,i}, X_{median,i}, X_{\max,i}]),$$
$$median\ (\hat{\beta}[X_{\min,i}, X_{median,i}, X_{\max,i}]), \max(\hat{\beta}[X_{min,i}, X_{median,i}, X_{max,i}])\}$$

In-Vessel Hydrogen Produced

	1st Control Rod Failure	1st Channel Box	1st Fuel Failure	Main Steam Line	Lower Core Plate	Lower Plenum Dry-out	Lower Head Failure	End of Simulation
R^2 / R^2_{adj} / F-stat vs. Const./ p-val	.28 / .26 / 18.7 / 0	.06 / .05 / 5.9 / 0.017	.26 / .24 / 11.3 / 0	.33 / .31 / 11.9 / 0	.58 / .55 / 21.1 / 0	.485 / .463 / 22.3 / 0	.66 / .6 / 10.7 / 0	.194 / .177 / 11.7 / 0
Intercept	65 kg	144 kg	155 kg	757 kg	8288 kg	158.44 kg	-126.73 kg	242.09 kg
Time Constants for Radial (solid) Debris Relocation (s) [1]				[33, 81, 128] [-184, -117, -48][4] [-56, -36, -15]	[-34, -22,-9]		[35, 84, 132]	
Time Constants for Radial (liquid) Debris Relocation (s)								
dT|dz Model, Time Constant for Averaging Flows (s)		[-32, -29,-26]						
dT|dz Model, Characteristic Coupling Time (s)								
dT|dz Model, Relative Weight of Historical Flow (s)								
Molten Zircaloy Break-Through Temperature (K) [2]			[-217, -202, -185]	[-470, -437,-400]	[-9221, -8570, -7857] [8248, 8996, 9679][6] [391, 426, 459]	[665, 725, 780]	[632, 689, 742]	[491, 535, 576]
Molten Cladding (pool) Drainage Rate (kg/(m*s))								
Fraction of Strain at Which Lower Head Failure Occurs					[73, 83, 91]			
Scaling Factor for Candling Heat Transfer Coefficients								
Fraction of Un-oxidized Cladding Thickness Initiating T. M. Weakening (m)[3]							[97, 177, 282] [-151, -95, -52][5] [45, 82, 131	
Debris Quenching Heat Transfer Coefficient to Pool (W/(m*m*K)) [4]				[9, 95, 162] [-200, -117, -11][1] [-38, -22, -2]		[-1314, -772, -74] [73, 757, 1290][6] [-25, -14, -1]		[-37, -22, -2]
Debris Falling Velocity (m/s)[5]	[-0.511, -0.187, -0.007]						[2, 62, 169] [-258, -95, -4][3] [-89, -33, -1]	
Minimum Debris Porosity					[-19, -10, -1]			
Time At Temperature - Effective Failure Temperature (K)[6]			[887, 919, 962]		[-8597, -8212, -7924] [8680, 8996, 9418][2] [756, 784, 821]	[-215, -205, -198] [731, 757, 793][4] [533, 552, 578]		
Decay Heat Integrated to 10 hours (J)	[-23, -22, -21]		[-502, -482, -462]					

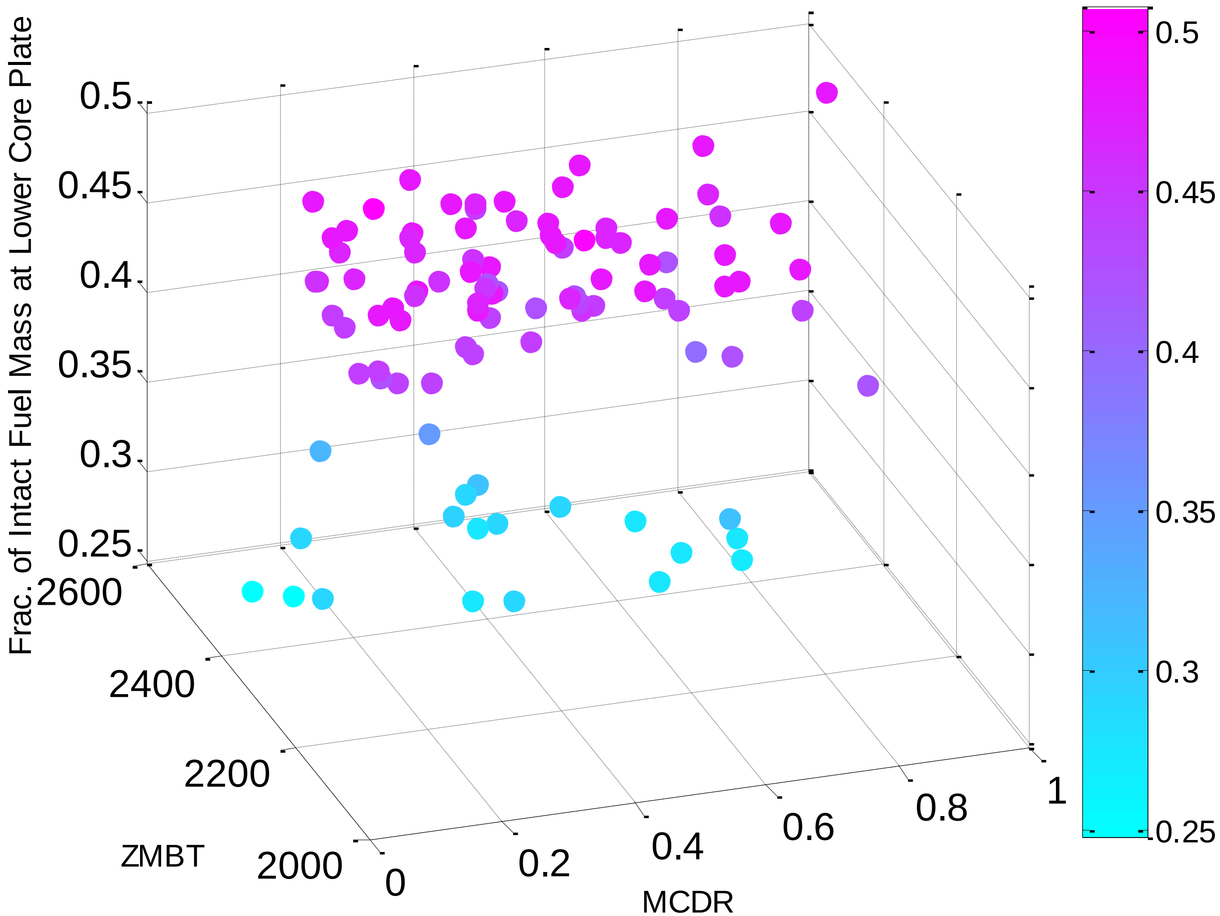
Interesting Scatter Plots from In-Vessel Hydrogen



Intact Fuel Mass

	1st Fuel Failure	Main Steam Line	Lower Core Plate	Lower Plenum Dry-out	Lower Head Failure	End of Simulation
R^2 / R^2_{adj} / F-stat vs. Const./ p-val	.12 / .102 / 6.62 / .002	.185 / .176 / 22.2 / 0	.307 / .286 / 14.2 / 0	.182 / .165 / 10.8 / 0	N/A	.238 / .215 / 10 / 0
Intercept	0.8415 kg	-0.36111 kg	16.947 kg	0.23813 kg	0.00074 kg	-0.12205 kg
Time Constants for Radial (solid) Debris Relocation (s)						
Time Constants for Radial (liquid) Debris Relocation (s)						
dT|dz Model, Time Constant for Averaging Flows (s)						
dT|dz Model, Characteristic Coupling Time (s)						
dT|dz Model, Relative Weight of Historical Flow (s)						
Molten Zircaloy Break-Through Temperature (K) [1]	[-0.1005, -0.1097, -0.11979]		[-19, -18, -16] [16, 17, 18] [4] [-0.79. -0.74, -0.68]	[-0.84, -0.78, -0.72]		
Molten Cladding (pool) Drainage Rate (kg/(m*s))						
Fraction of Strain at Which Lower Head Failure Occurs						
Scaling Factor for Candling Heat Transfer Coefficients						
Fraction of Un-oxidized Cladding Thickness Initiating T. M. Weakening (m) [2]						[0.08, 0.15, 0.24] [-0.192, -0.12, -0.066] [3] [0.016, 0.029, 0.046]
Debris Quenching Heat Transfer Coefficient to Pool (W/(m*m*K)) [3]						[0.01, 0.1, 0.17] [-0.2, -0.12, -0.01] [2] [-0.035, -0.021, -0.002]
Debris Falling Velocity (m/s)						
Minimum Debris Porosity						
Time At Temperature - Effective Failure Temperature (K) [4]		[1.28, 1.33, 1.39]	[-17, -16, -15] [16, 17, 18] [1] [1.14, 1.18, 1.24]	[0.85, 0.88, 0.92]		
Decay Heat Integrated to 10 hours (J)	[0.219, 0.228, 0.238]					

Interesting Scatter Plots from Intact Fuel Mass



Mass of Material Ejected

	Lower Head Failure	End of Simulation
R^2 / R^2_{adj} / F-stat vs. Const./ p-val	.56 / .516 / 12.7 / 0	N/A
Intercept	1998.7 kg	44930 kg
Time Constants for Radial (solid) Debris Relocation (s)		
Time Constants for Radial (liquid) Debris Relocation (s)		
dT|dz Model, Time Constant for Averaging Flows (s)		
dT|dz Model, Characteristic Coupling Time (s)	[66450, 81748, 99124]	
dT|dz Model, Relative Weight of Historical Flow (s)		
Molten Zircaloy Break-Through Temperature (K)		
Molten Cladding (pool) Drainage Rate (kg/(m*s))		
Fraction of Strain at Which Lower Head Failure Occurs		
Scaling Factor for Candling Heat Transfer Coefficients		
Fraction of Un-oxidized Cladding Thickness Initiating T. M. Weakening (m)		
Debris Quenching Heat Transfer Coefficient to Pool (W/(m*m*K))	[-51758, -30396, -2910]	
Debris Falling Velocity (m/s)	[482, 12511, 34129]	
Minimum Debris Porosity		
Time At Temperature - Effective Failure Temperature (K)		
Decay Heat Integrated to 10 hours (J)		

But are any of these regressions reliable?

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- Multiple different samples were taken from the underlying distributions. If the regressions can predict trends in new samples, it might be trustworthy.
- The correlation coefficient for the regressions can be used to calculate the predictive worth of the regression:

$$R^2_{training} = 1 - \frac{\frac{1}{n-k-1}\sum_{i=1}^{n}\left(y_i - y_{i|M}\right)^2}{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

$$r^2_{predict} = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - y_{i|M}\right)^2}{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

Test Study – H2 at Lower Plenum Dryout Fit to Training Data

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Set	*Type*	n	k	R^2	R^2_{adj}	F_{stat}
Rep. 1	Raw	100	4	0.49	0.46	22.3
	Rank	100	4	0.52	0.50	25.8
Rep. 2	Raw	98	2	0.40	0.39	31.6
	Rank	98	1	0.38	0.37	57.6
Rep. 3	Raw	100	2	0.34	0.33	24.9
	Rank	100	2	0.38	0.36	29.1
Rep. U	Raw	100	3	0.45	0.43	26.3
	Rank	100	2	0.41	0.40	33.6
Rep. 1&2	Raw	198	3	0.41	0.40	45.5
	Rank	198	3	0.44	0.43	51.1

Test Study – H2 at Lower Plenum Dryout Predictive Worth

Linear Regression

	Rep1	*Rep2*	*Rep3*	*RepU*	*Rep12*
Rep1	0.31	0.16	0.25	0.19	0.39
Rep2	0.25	0.53	0.32	0.32	0.39
Rep3	0.23	0.02	0.24	0.23	0.19
RepU	0.34	-1.53	0.38	0.39	0.37
$\overline{R^2_{pred}}$	0.27	-0.45	0.32	0.25	0.28
R^2_{adj}	0.29	0.50	0.23	0.38	0.37

Rank Regression

	Rep1	*Rep2*	*Rep3*	*RepU*	*Rep12*
Rep1	0.29	0.21	0.21	0.14	0.34
Rep2	0.32	0.42	0.30	0.30	0.34
Rep3	0.17	0.20	0.23	0.20	0.26
RepU	0.19	0.29	0.32	0.35	0.27
$\overline{R^2_{pred}}$	0.23	0.23	0.28	0.21	0.27
R^2_{adj}	0.26	0.39	0.22	0.34	0.33

Replicate 2 had the most consistency in terms of model fit to data and ability of other models to reduce variance in the data, but the predictive models from Replicate 2 were unreliable, especially for the raw data. The model predicted from Replicate 3 had the lowest R^2 over the training data but consistently had the best predictive merit. ZMBT and TaT were consistently resolved across the samples and were the only parameters resolved in Replicate 3.

Perturbation – dt_{max} - Horse Tails

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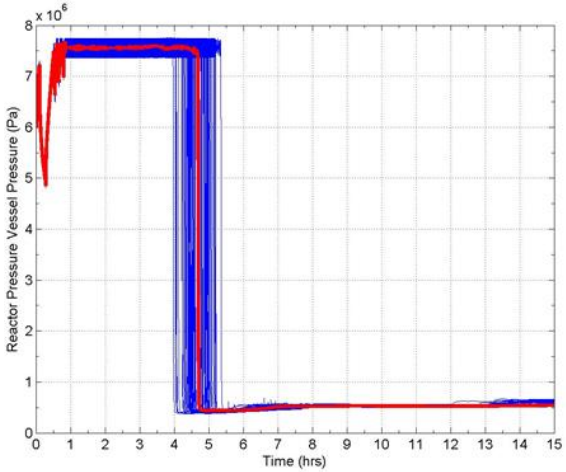
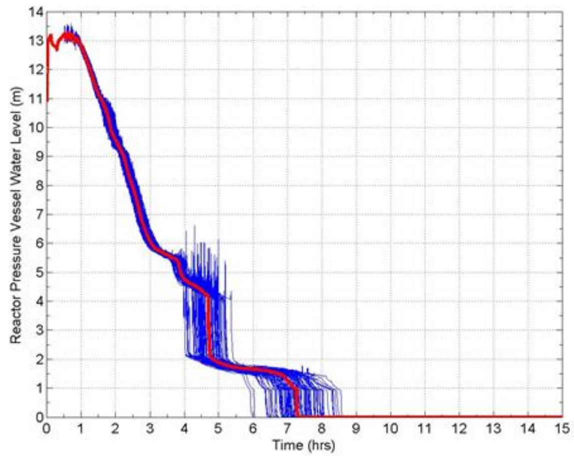
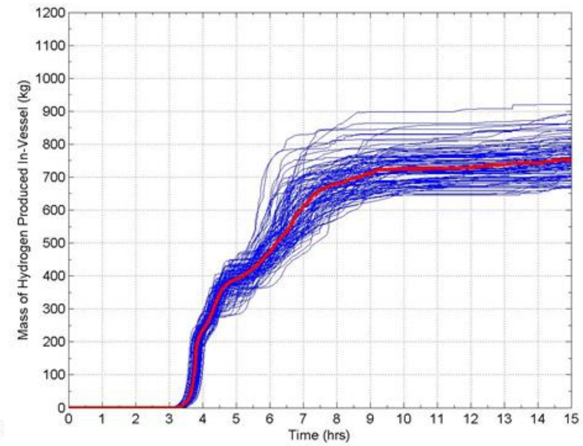


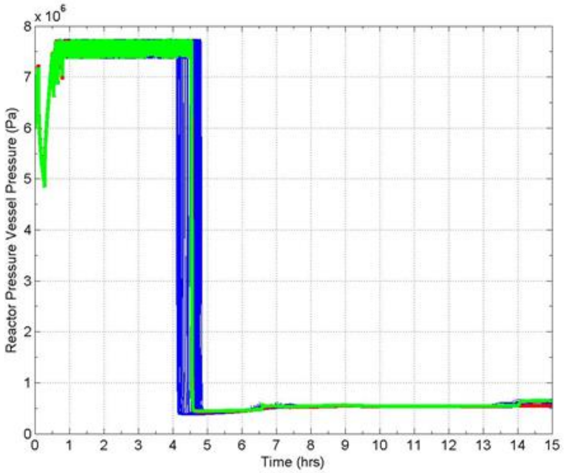
Replicate 1



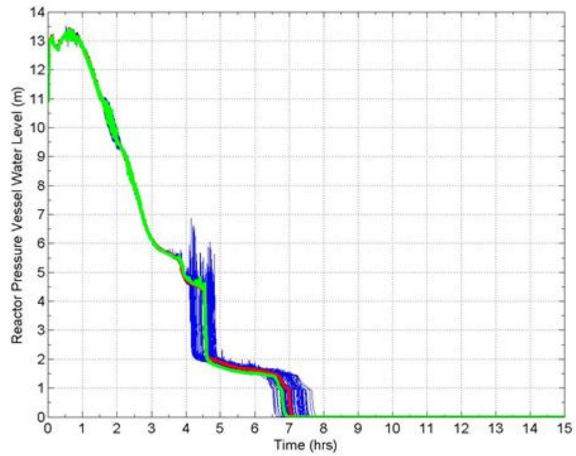
Replicate 1



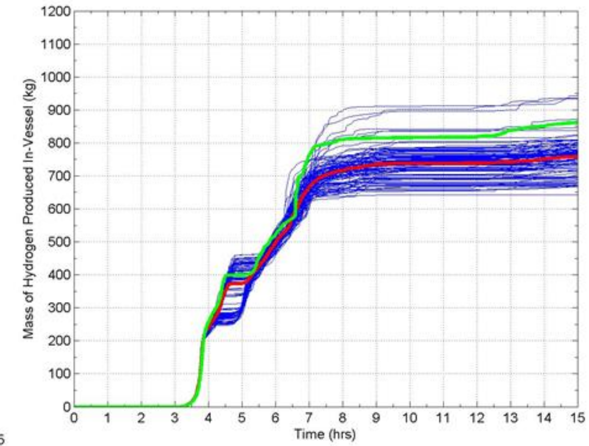
Replicate 1



dt_{max}



dt_{max}



dt_{max}

Perturbation – dt_{max} - Scatter Plots

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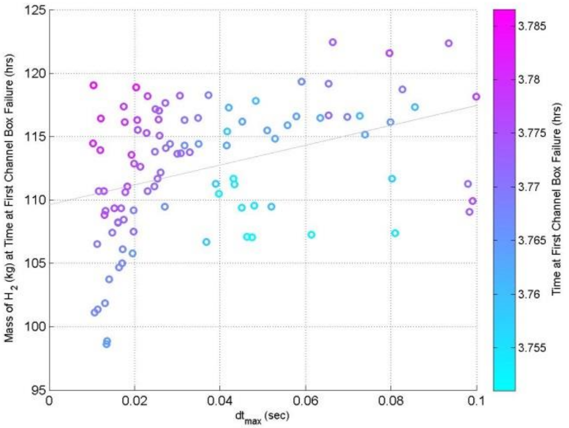
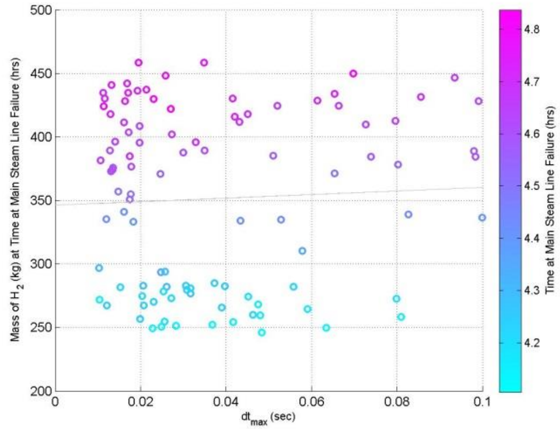
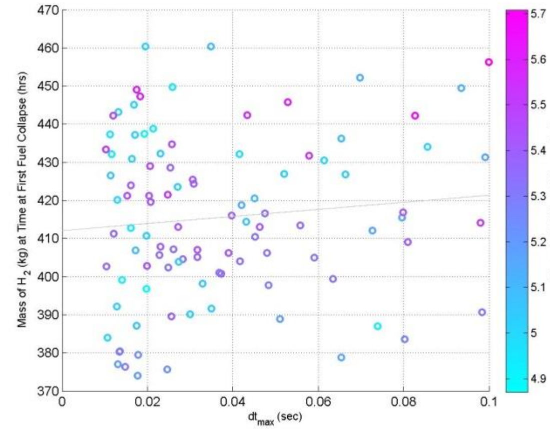
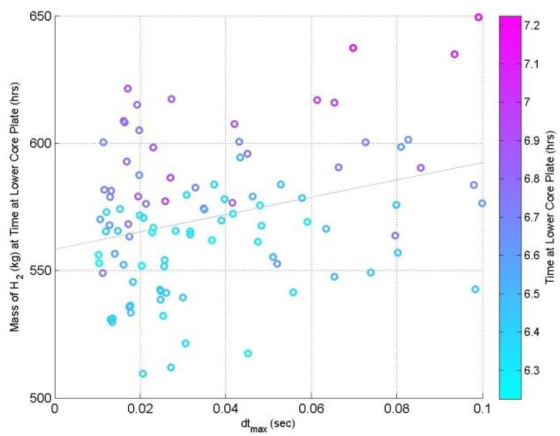
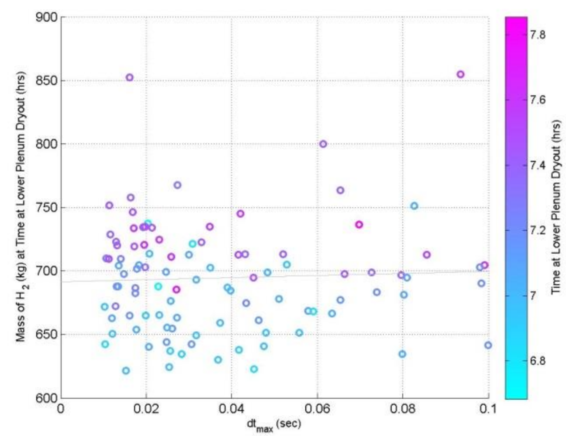






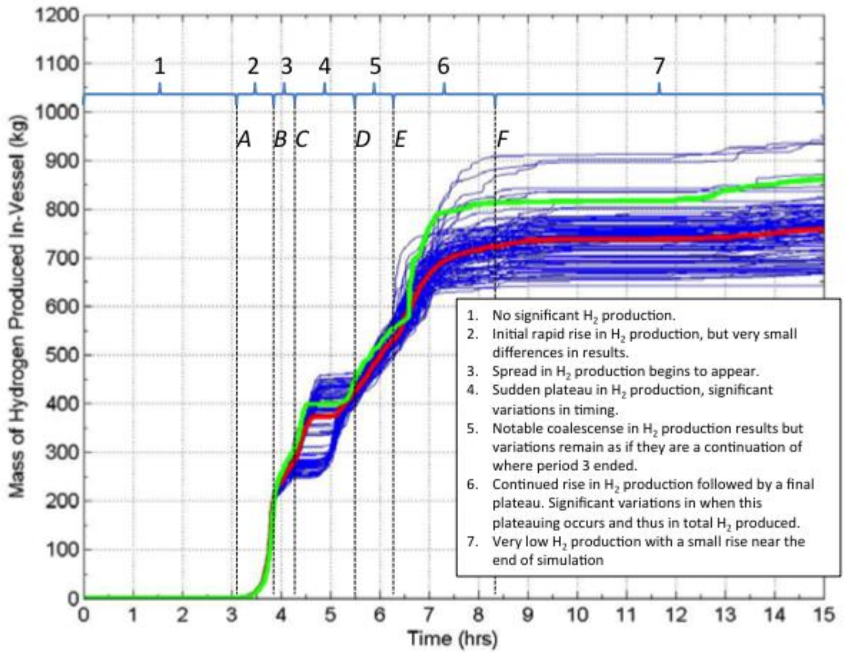




Perturbation – dt_{max} - What is going on?

- Results are internally consistent and physical

1. Notable variations in the time-pressure history begin to gradually occur from the very beginning of the simulations.
2. Strong dependence of the reaction rate equations to temperature, and also to steam availability, unavoidably cause local variations between perturbed realizations

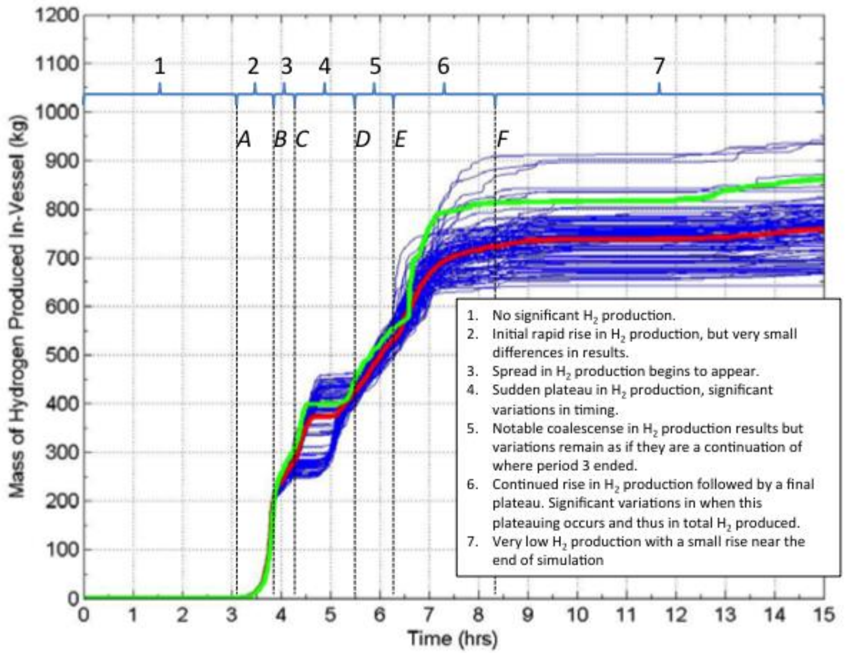


Perturbation – dt_{max} - What is going on?

Sandia National Laboratories

- Results are internally consistent and physical

3. Relatively small differences in time-integral histories can be magnified into significant differences in failure times for the main steam line.
4. Significant spatial and temporal differences in things such as local temperature, material composition, blockage formation, steam availability, oxidation rates and so forth continue to evolve between different realizations.

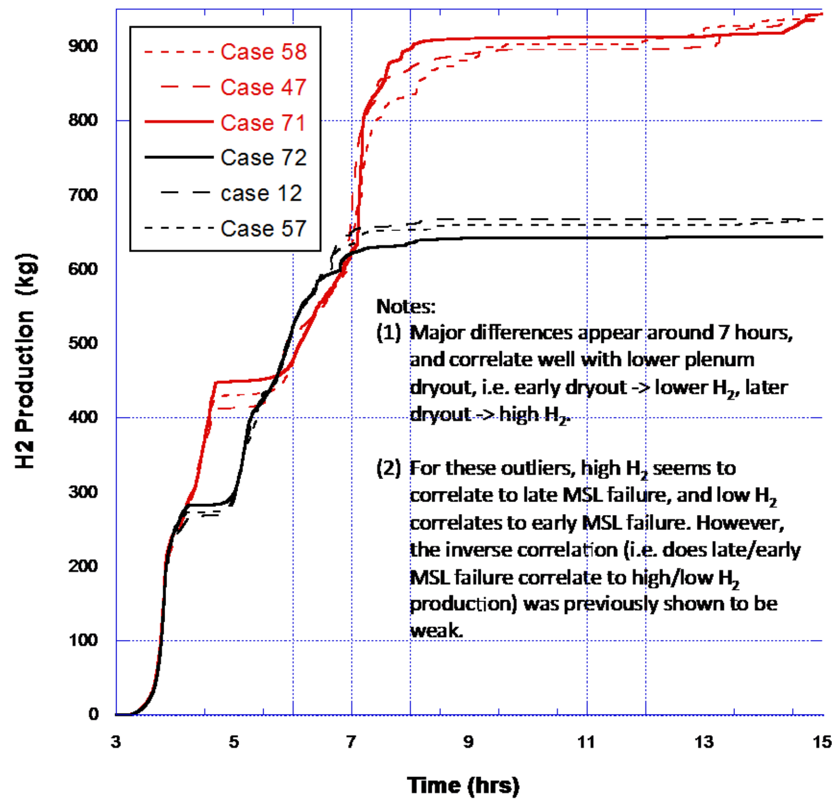


Perturbation – dt_{max} - What is going on?

Sandia National Laboratories

- Results are internally consistent and physical

5. Timing and state of lower core plate failure and lower plenum dryout effected by early perturbations
   - There exist many ways to get to the middle, but few ways to get to the tails.
6. Dryout stops further H2 production because water is removed from the system



What does this study say about:

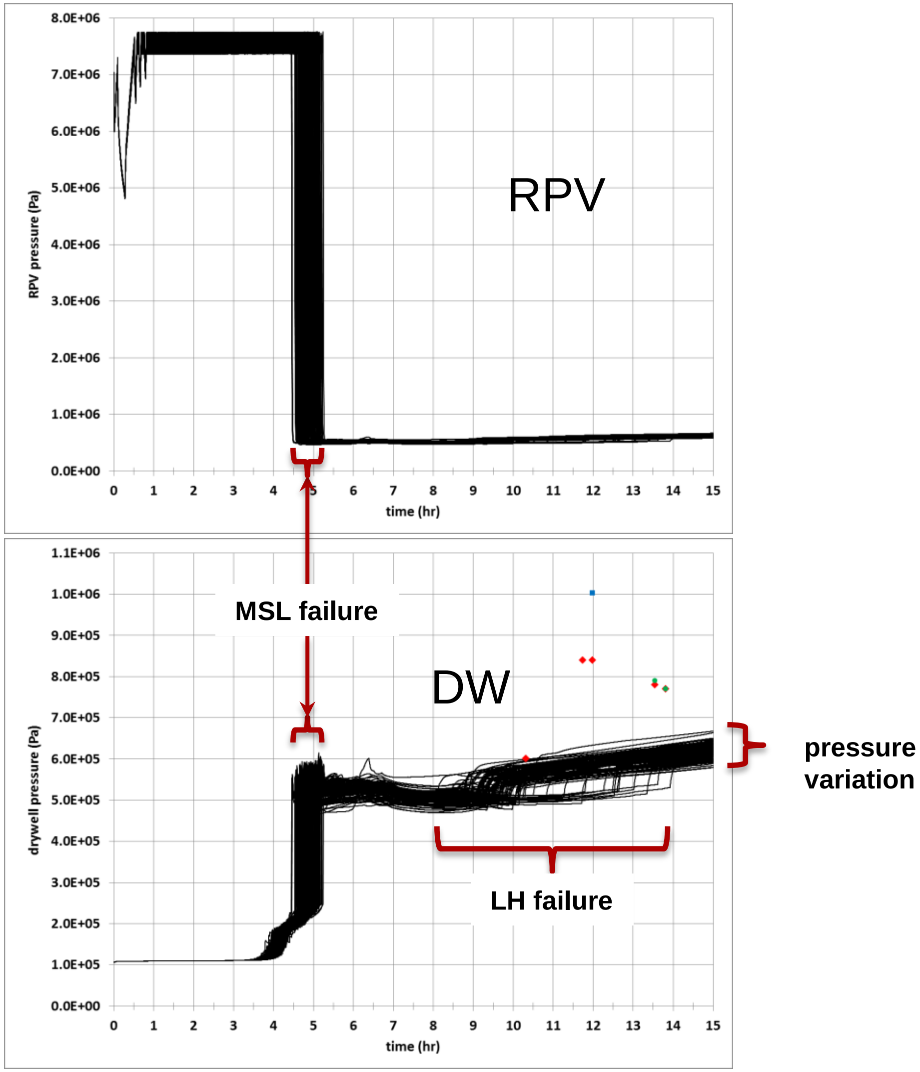
- Fukushima Decommissioning:
  - These simulations suggest that it is highly likely that the core is completely disassembled.
- Current state of severe accident knowledge:
  - A study of a 1F1 meltdown pre-Fukushima may have predicted in-vessel retention.
- Key uncertain parameters:
  - Current techniques and modeling approaches suggest strong dependencies on molten zirconium breakthrough temperature, decay heat, and debris movement.
  - Statistical techniques can easily be distorted by discrete event outputs
- Dynamic discrete event modeling:
  - Severe accident modeling is significantly different from design basis accident modeling. Care must be taken to ensure that the modeler has a proper understanding of the tool he or she is using.

Backup Slides

But what about uncertainty?

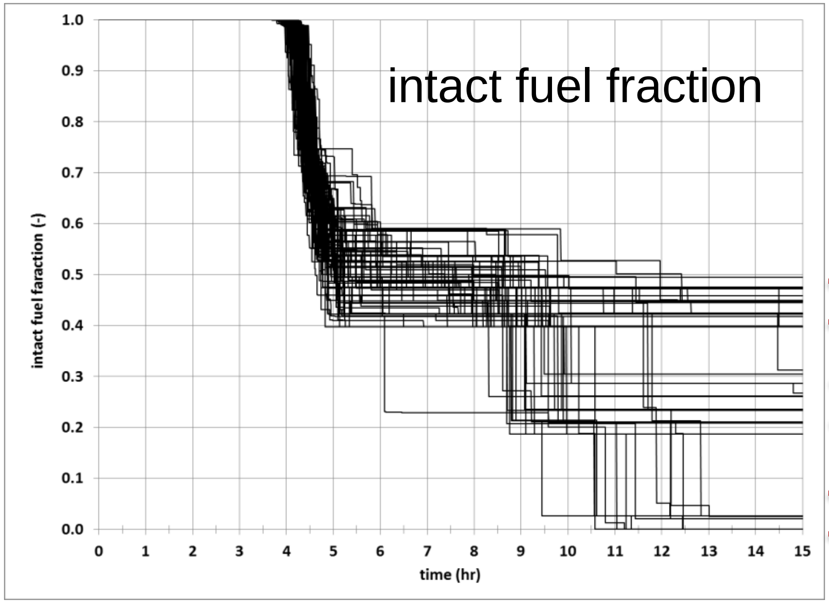
- All of our best-estimate/best-practices cases are but one of a locus of potential inputs and their results are but one of a locus of potential solutions
- Uncertainty (in input parameters and models) will produce significant variations the accident sequences
- The impact of this is that…
  - “tweaks” made to fit the forensic data may not be valid over the entire range of input parameter and model uncertainty
  - The next accident may not be within the range of validity of the “tweaks” and current “best-practices”

1F1 Example

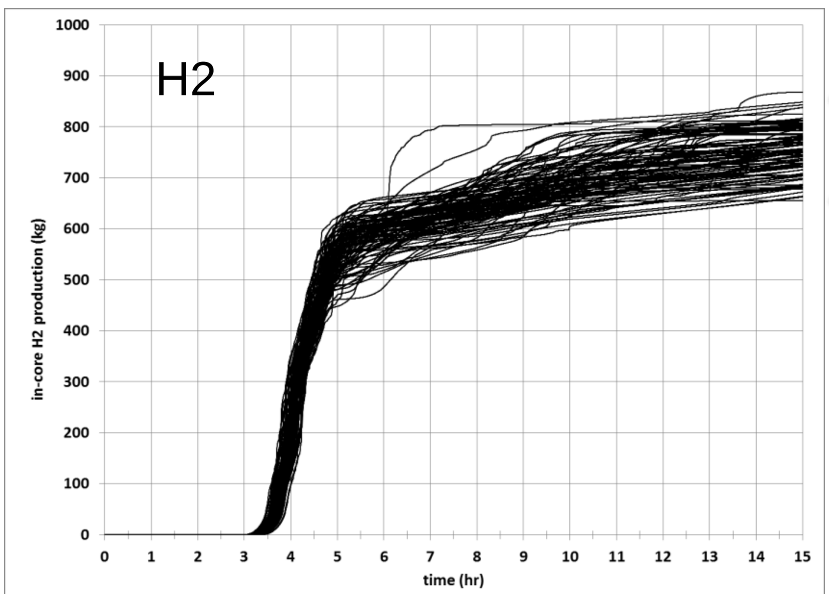


- 100 realizations with random sampling from the distribution of decay heat curves
- decay heat characterized by combining the ANS-5.1 decay heat uncertainties on primary fissile nuclides with SCALE best-estimate calculations
- Yields variation in
  - MSL failure time
  - LH failure time
  - RPV/containment pressure

1F1 Example



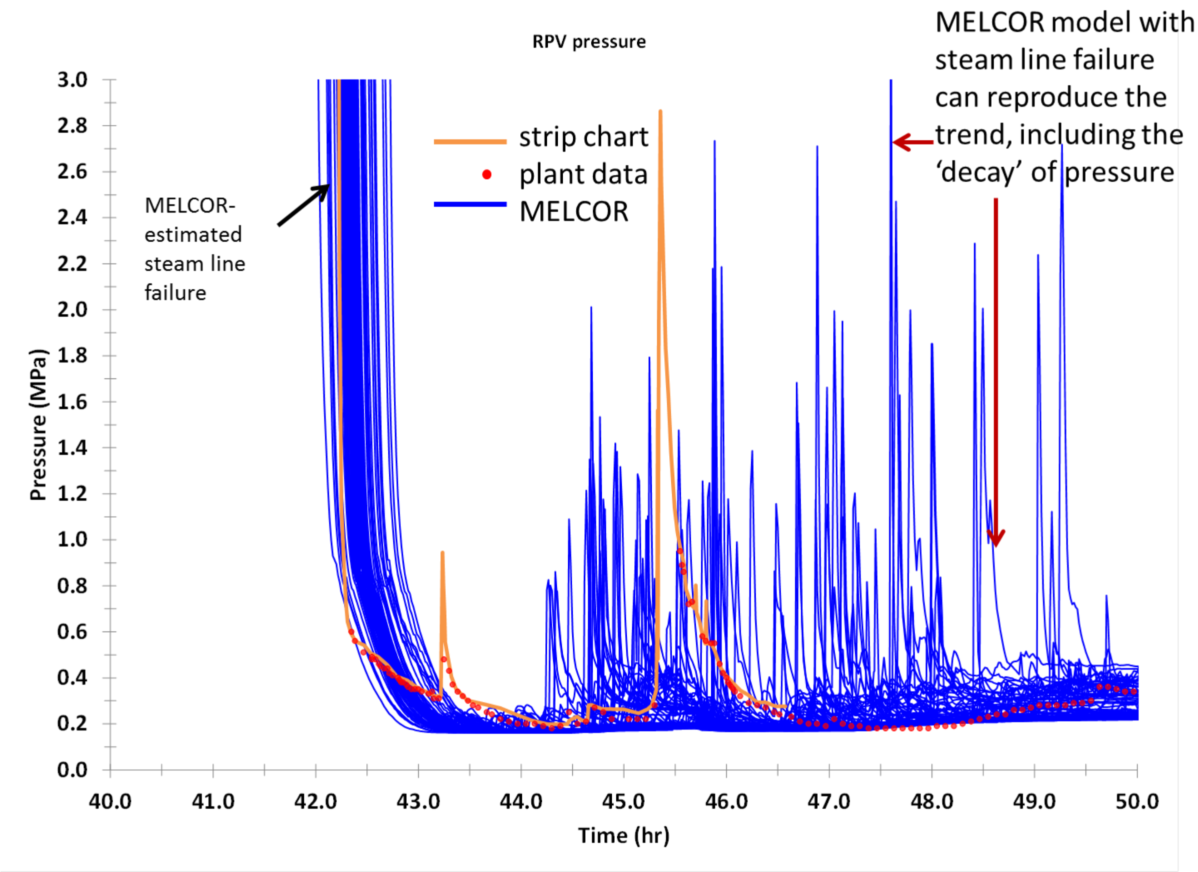
different possible final core degradation states



enough H2 to support an energetic event

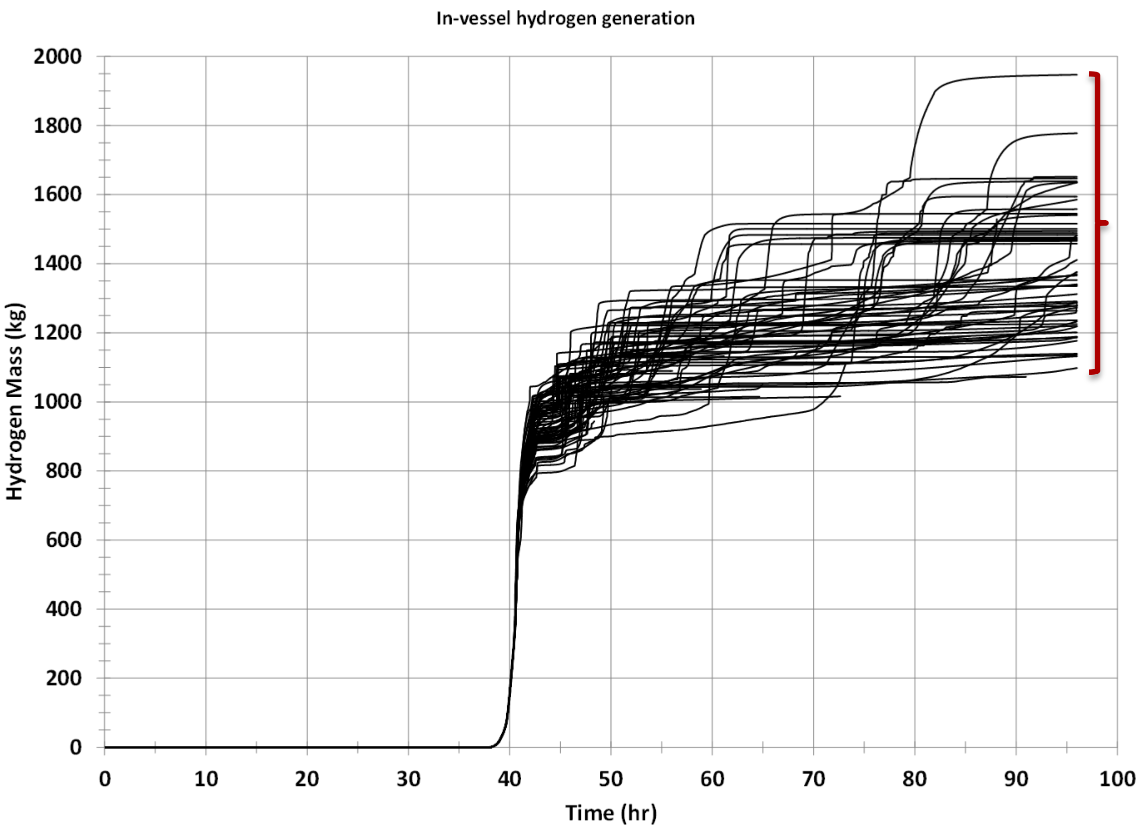
- H_2 in-core production results have variation in initiation time and late-time value
- These results and those for RPV and containment pressure (previous slide) are due to variation in core melt progress

1F3 Example



- 100 realizations that vary
  - wetwell vent opening fraction
  - water injection rate
  - quench parameters
- Some realizations capture the timing, some capture the peak
- There is not a single solution; several different combinations of uncertain variables can reproduce the data trend

1F3 Example



enough H2 to support an energetic event

- in-core H2 generation begins to deviate due to variation in core melt progression

…and what does this all mean?

- "Tweaked" deterministic analyses are useful for identifying/handling ill-defined phenomena that are postulated to influence forensic results (e.g., 1F2 torus cooling, venting, water injection)
- However, input and model uncertainty have the potential to invalidate "tweaks" tied to forensic results, which can render them invalid for predictive analyses
- Experience has shown that source term results have significant variation; this will be important to handle for BSAF Phase II analyses

Summary

- 1F1 and 1F3 best estimate accident signatures are similar to those from older models/analyses; they match well enough with the limited data
- Still looking at 1F1 initial ex-vessel behavior
- Accident signatures are very dependent on boundary conditions (e.g., water injection rate, RPV depressurizations mechanism, RCIC & HPCI operation)
- Signatures can be sensitive to uncertainty in BCs and other inputs (explicitly seen in these results and those in the results of a separate 1F1 core-damage progression uncertainty analysis)