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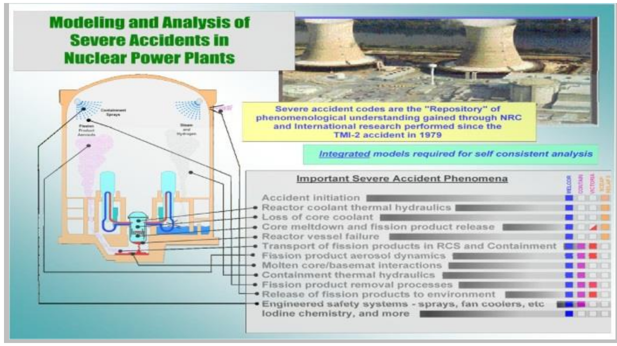

A Review of Recent SNL MELCOR Fukushima Accident Analyses

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U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration · U.S.NRC

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Topics for discussion

- MAAP-MELCOR Crosswalk
  - compare Fukushima Daiichi Unit 1 (1F1) MAAP and MELCOR results to identify areas where the codes differ in their treatment of accident phenomena
- Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF)
  - OEDC project (France, Germany, Japan, Republic of Korea, Spain, Switzerland, United States)
  - conduct full-scope analyses of the Fukushima Daiichi NPP Units 1, 2, and 3 using currently available severe accident codes
- 1F1 Uncertainty Analysis
  - evaluate the impact of core damage progression input parameter uncertainty on key figures-of-merit (e.g., H_2 production)
- Conclusions

MAAP-MELCOR Crosswalk

MAAP-MELCOR Crosswalk

- Compare MAAP and MELCOR results to identify areas where the codes differ in their treatment of accident phenomena
  - Impetus for the work was differences found between MAAP and MELCOR ex-vessel materials results from the initial SNL and EPRI Fukushima analyses
- Use 1F1 models to create results for comparison
- Focus on core damage progression
- Use comparison of results to identify where phenomena are treated/modeled differently

MAAP-MELCOR Crosswalk (CY13)

- Initial comparisons (October 2013) identified that the models and accident sequences were not consistent
  - Isolation condenser operation, feedwater coastdown, water and component inventories, SRV failure vice MSL failure
- Differences in the models and codes result in differences outputs between the codes, making comparisons difficult
- Regardless, preliminary differences were identified
  - In MELCOR, solid debris cannot completely block a core flowpath; in MAAP solid debris can completely block a core flowpath
  - MAAP calculates the formation of an in-core molten pool over top a crust, with the molten pool eventually failing into the downcomer/jet pumps; MELCOR calculates solid debris relocating to the lower core plate; eventually failing the plate and allowing debris then relocate into the lower plenum

MAAP-MELCOR Crosswalk (CY14)

- Updated models to reflect latest available plant data and BSAF boundary conditions
- Modified models to minimize water and component inventory differences
- Ran models with a “mo’ better” common accident sequence
  - IC operation, FW coastdown, decay heat
  - Turned off MSL failure in MELCOR model; forced SRV failure (stuck-open) at 7 hr in both models
- Developed a set of common results figures
- Documented latest results, comparison, conclusions, and recommendations for Phase 2 work in an EPRI report

Summary of Sequence Results

	MAAP	MELCOR
initial core degradation	core degrades to form a crust with an overlying molten pool within the active core region	core degrades mainly in the form of solid particulate debris that relocates to the lower core plate; some small fraction of molten material relocates into the lower plenum before lower core plate failure
blockage	the crust/molten pool completely block axial flow through the core.	axial flow through the core is never completely blocked by debris
relocation to lower plenum	the molten pool melts through the core shroud, allowing molten material to relocate to the lower plenum via the downcomer/jet pumps.	a small fraction of molten material relocates into the lower plenum before lower core plate failure; once the lower core plate fails debris relocates into the lower plenum; degradation and failure of the control rod guide tubes results in further fuel failures
lower plenum	relocated material forms crust with an overlying molten pool within the lower plenum.	the majority of the relocated material remains solid particulate debris
after lower head failure	material ejected to the cavity is molten	material ejected to the cavity is solid particulate

Summary of Key Results (1/2)

- Differences in code physics models and inputs, along with a paucity of plant data, makes creating "apples-to-apples" plant models and outputs for comparison difficult
- Up to the point of core degradation the code results match relatively well. Difference seen in boil down is due the partitioning of water between RPV volumes in the two codes

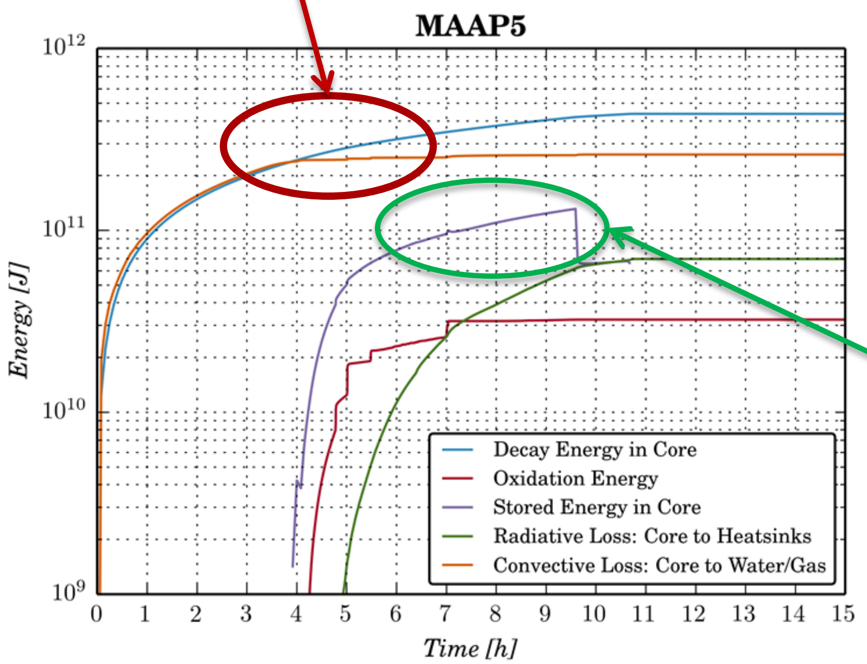
Summary of Key Results (2/2)

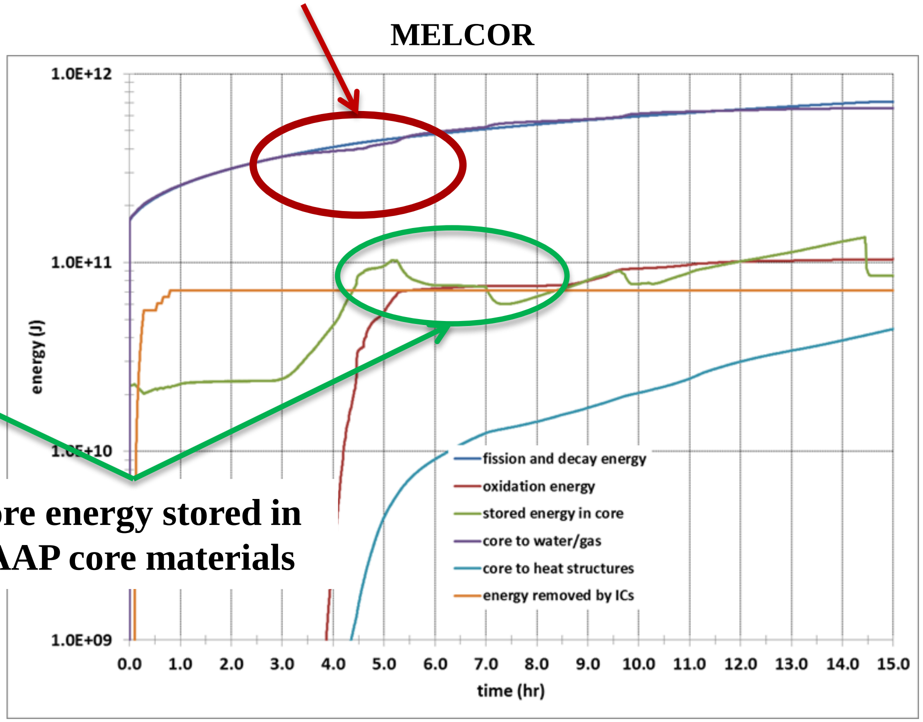
- MAAP predicts complete blockage of axial flowpaths; MELCOR has a minimum porosity (code default = 5%)
- MAAP has submodels that the treat formation of molten pools from solid debris; MELCOR performs a series of calculations over its nodalized domain to determine material movement and energy transfer, which determine if materials remain solid or melt
- MAAP models the heat transfer (area and hx-fer coef.) from particulate debris as decreasing with decreasing debris bed porosity; MELCOR models heat transfer surface area as increasing with the volume of particulate as its effective hydraulic diameter does not vary with porosity
- **MELCOR calculates a much larger amount of energy transferred from core materials to RPV water/gases than MAAP**

System Energy Balance

Decay energy > energy rejected from core materials to water/gases

Decay energy ~ energy rejected from core materials to water/gases

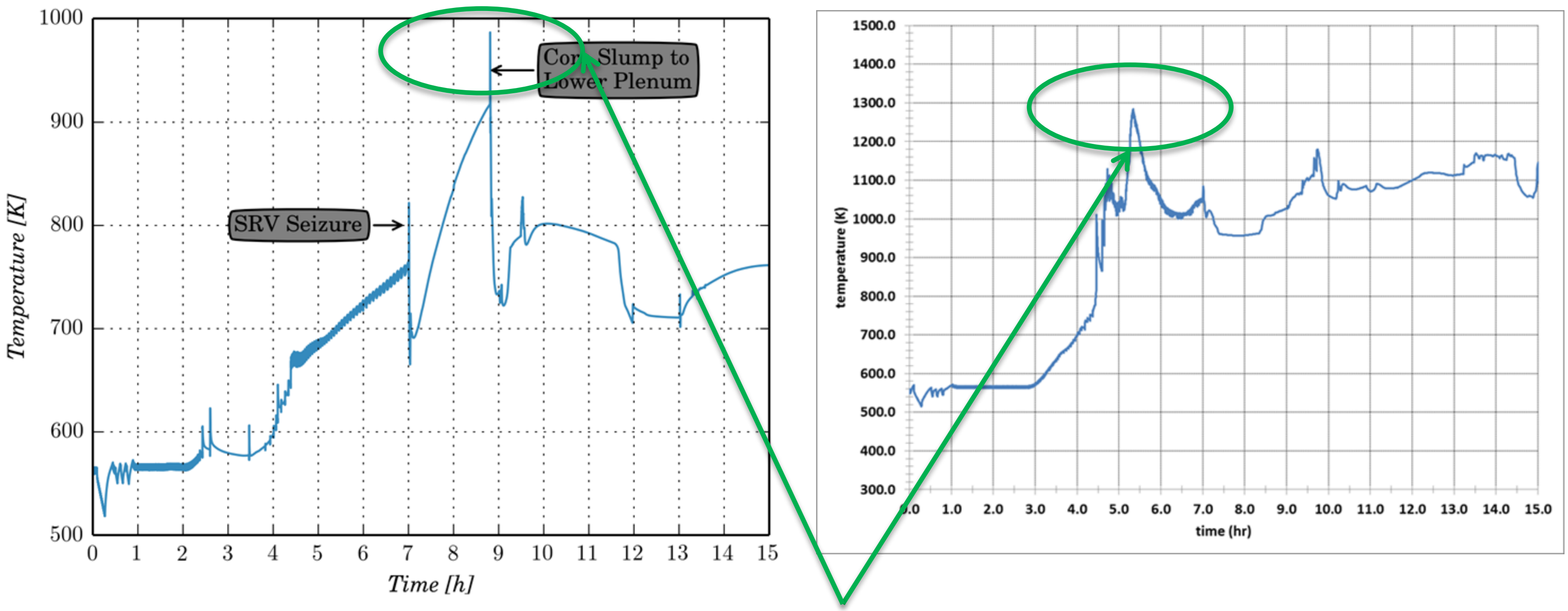




More energy stored in MAAP core materials

- MELCOR calculates a much larger amount of energy transferred from core materials to RPV water/gases than MAAP

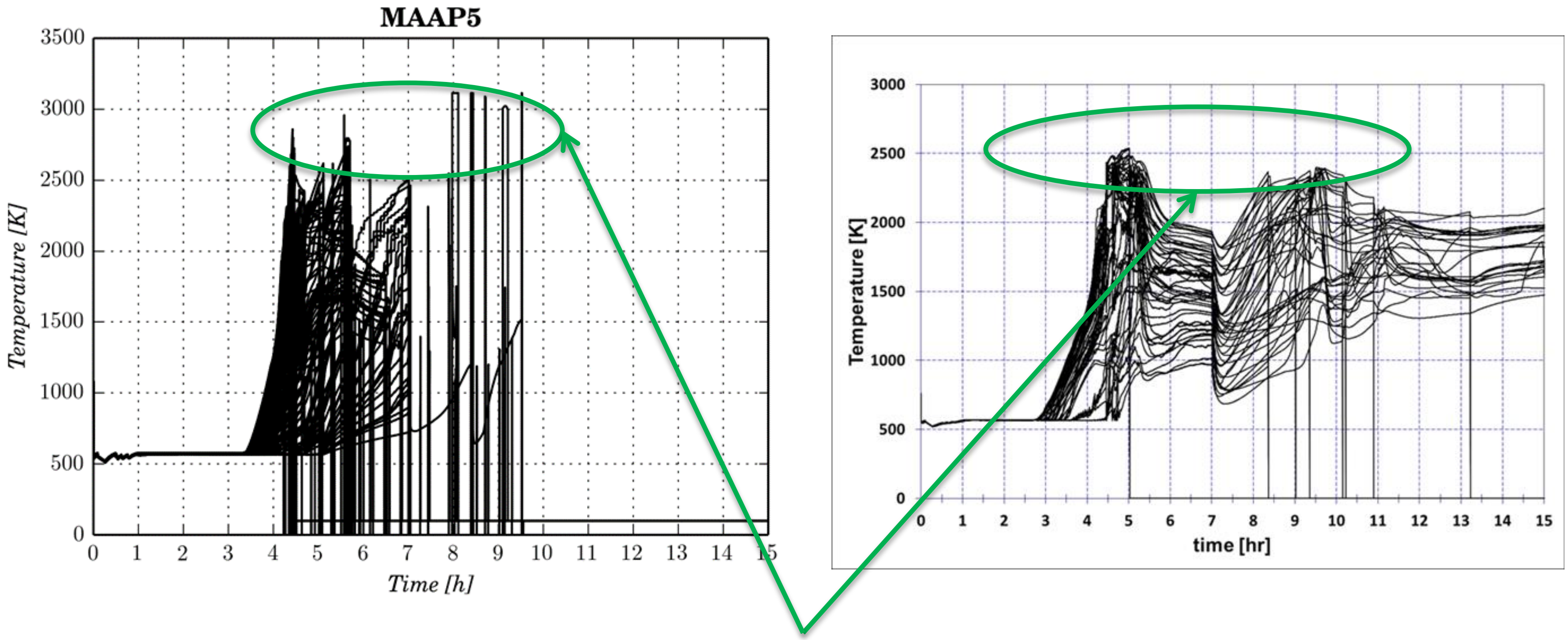
Steam Dome Temperature



MAAP ~ 1000 K (no MSL failure)
MELCOR ~ 1300 K (potential MSL failure)

- More energy in water/gas results in MELCOR predicting higher steam dome temperatures than MAAP

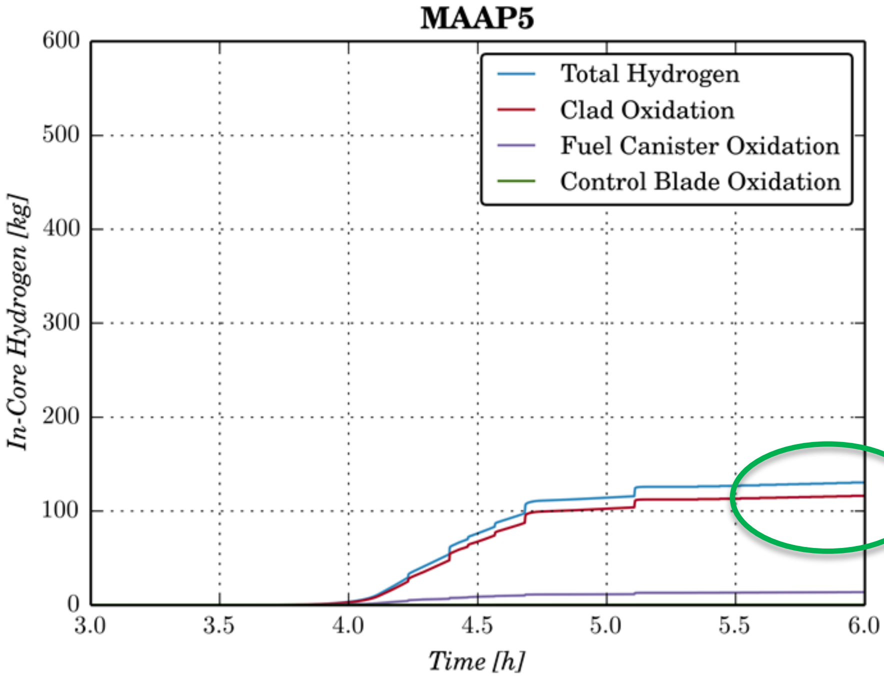
Fuel Temperature

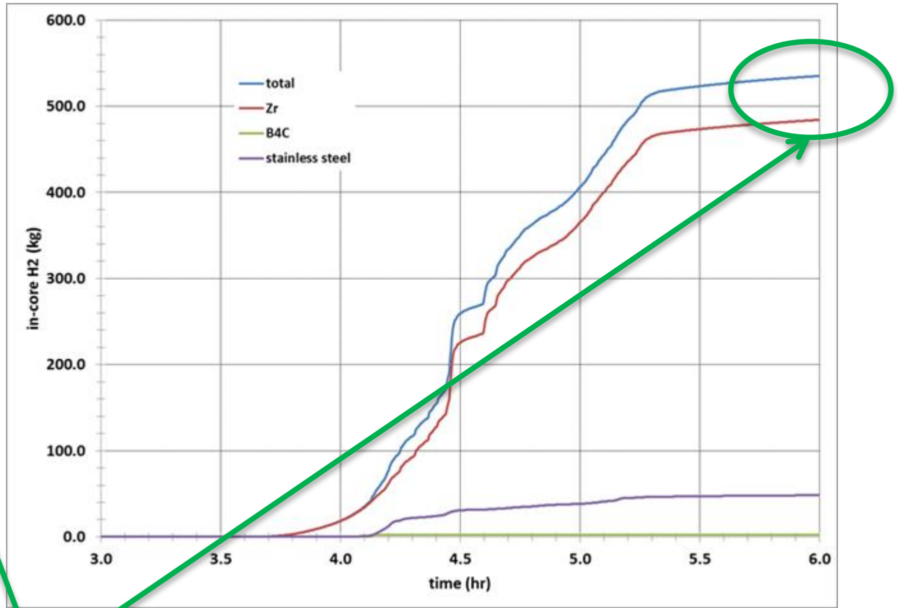


MAAP ~ 2800-3000 K (temperatures high enough to melt fuel)
MELCOR ~ 2300-2500 K (temperatures not high enough to melt fuel)

- More energy in water/gas results in MELCOR not melting fuel/debris, while MAAP does melt fuel/debris

Hydrogen Generation





MAAP ~ 140 kg H_2
MELCOR ~ 550 kg H_2

- In MAAP, complete core blockage prevents steam from reaching hot Zr. In MELCOR incomplete core blockage allows more steam to reach hot Zr.

What does this mean? (1/2)

- Due to differences in how core damage progression is modeled, MAAP and MELCOR predict different core damage progressions.
- This is “interesting”, given that each code development team has used the same set of experimental tests in their respective model development efforts. And both codes do ok at matching separate effects tests.
- There are no full-scale experiments from which to develop core damage progression models. What is in each code is each team’s “guess” at an abstraction for core damage progression, bases on the (limited) set of small-scale tests.

What does this mean? (2/2)

- Which abstraction is correct?
  - DAK: Neither. Both. It depends.
- Are there other valid abstractions “in between”?
  - DAK: Most likely.
- Does any of this matter?
  - DAK: **It depends on the purpose of the analysis. Not so much for PRA. It becomes important as the analyses look more “design” or DBA-like (e.g., SAMGs, predictions against accidents)**

Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF)

BSAF

- Executive Summary
- Brief Model Background
- 1F1 best estimate case results
  - pressure signatures
  - combustible gas generation
  - energy balance
- 1F3 best estimate case results
  - pressure signatures
  - H_2 generation
- Impact of uncertainty on results
  - Why is this important
  - 1F1 and 1F3 example results
- Summary

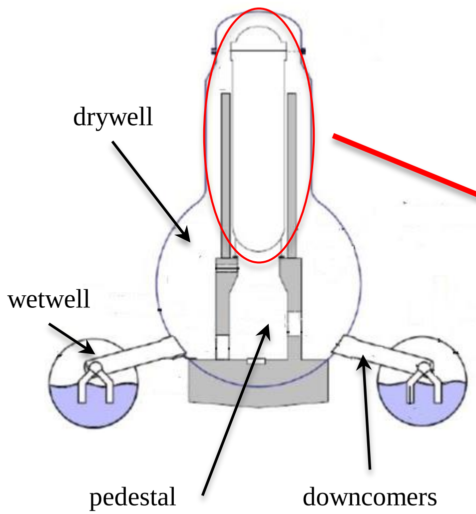
BSAF – Executive Summary

- SNL originally developed 1F1, 1F2, 1F3, and 1F1 SFP models as part of a joint DOE/NRC project (2011-2012)
- BSAF modeling and analysis used the previous work as a starting point. Due to staffing limitations, only 1F1 and 1F3 were evaluated.
- 1F1 and 1F3 BSAF cases completed
  - accident signatures look similar to previous results; those of other BSAF participants (with exceptions); and to most of the TEPCO data
  - event timings and values are different, but not markedly so
  - ready to move forward to Phase II source term analyses
- **Accounting for uncertainty is important in forensic analyses (locus of inputs) and predictive analyses (locus of solutions)**

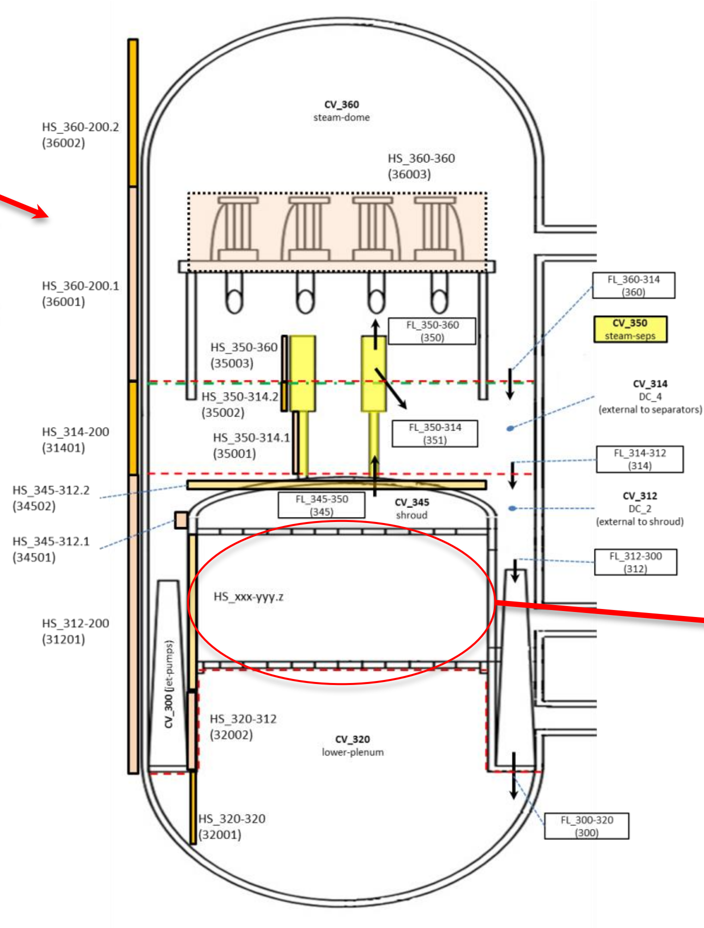
BSAF – Brief Model Background

- SNL MELCOR Fukushima models are based the Peach Bottom SOARCA model; reflects current MELCOR BWR Mk-I best practices
- Models have been updated with the best-available Fukushima inputs (e.g., TEPCO December 2011 data set, IEA November 2013 data set, BSAF BCs); fabricated surrogate inputs where necessary

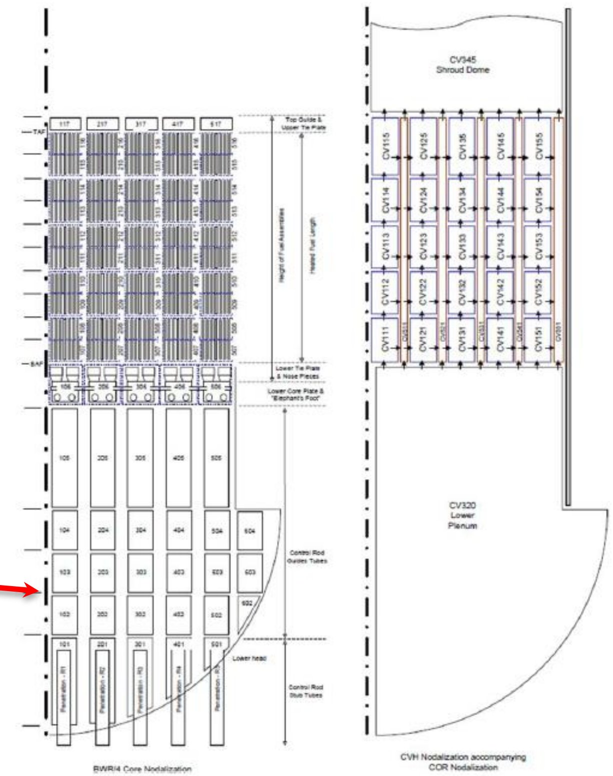
BSAF – Brief Model Background



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 – RPV/DW/WW Pressure

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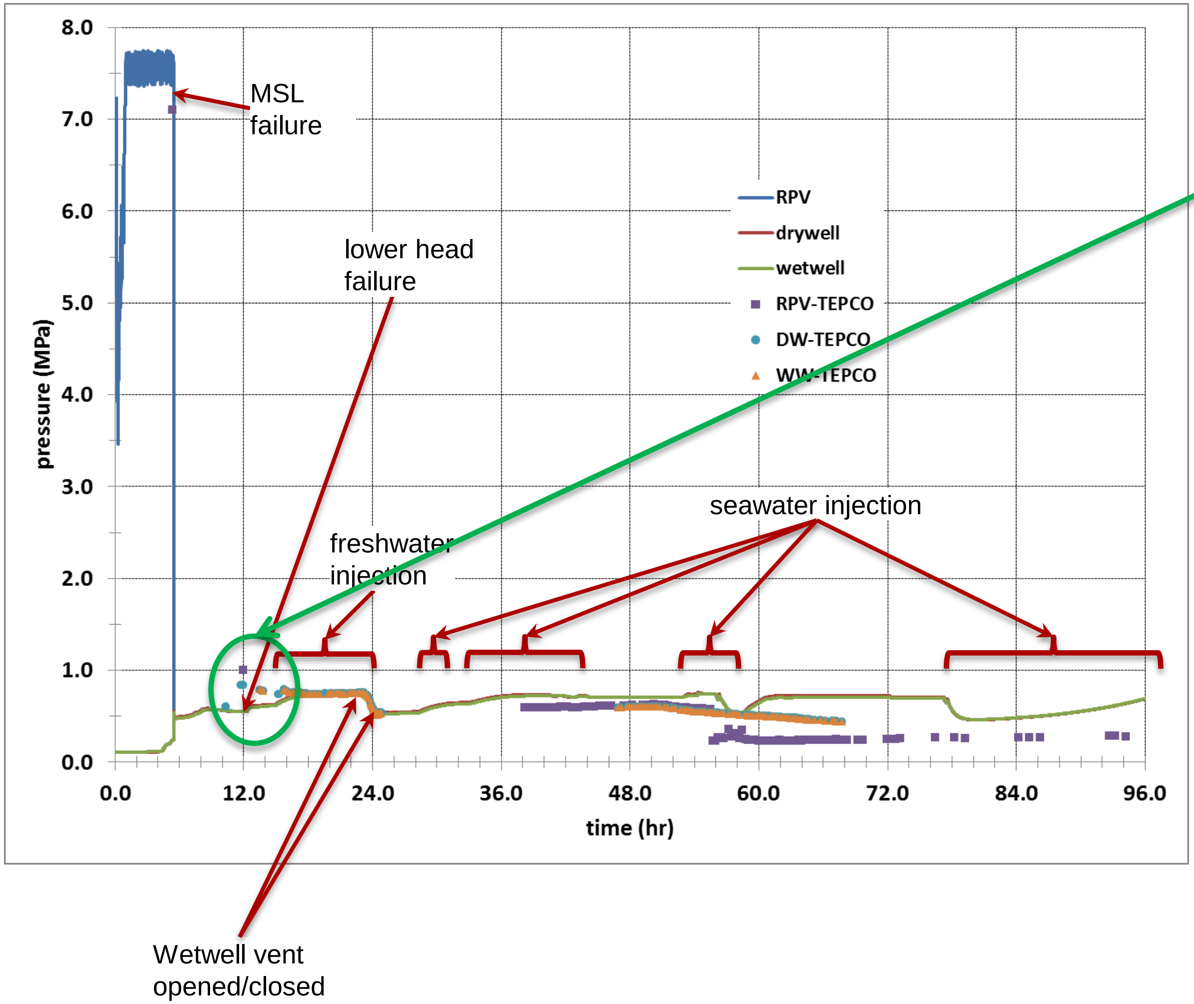
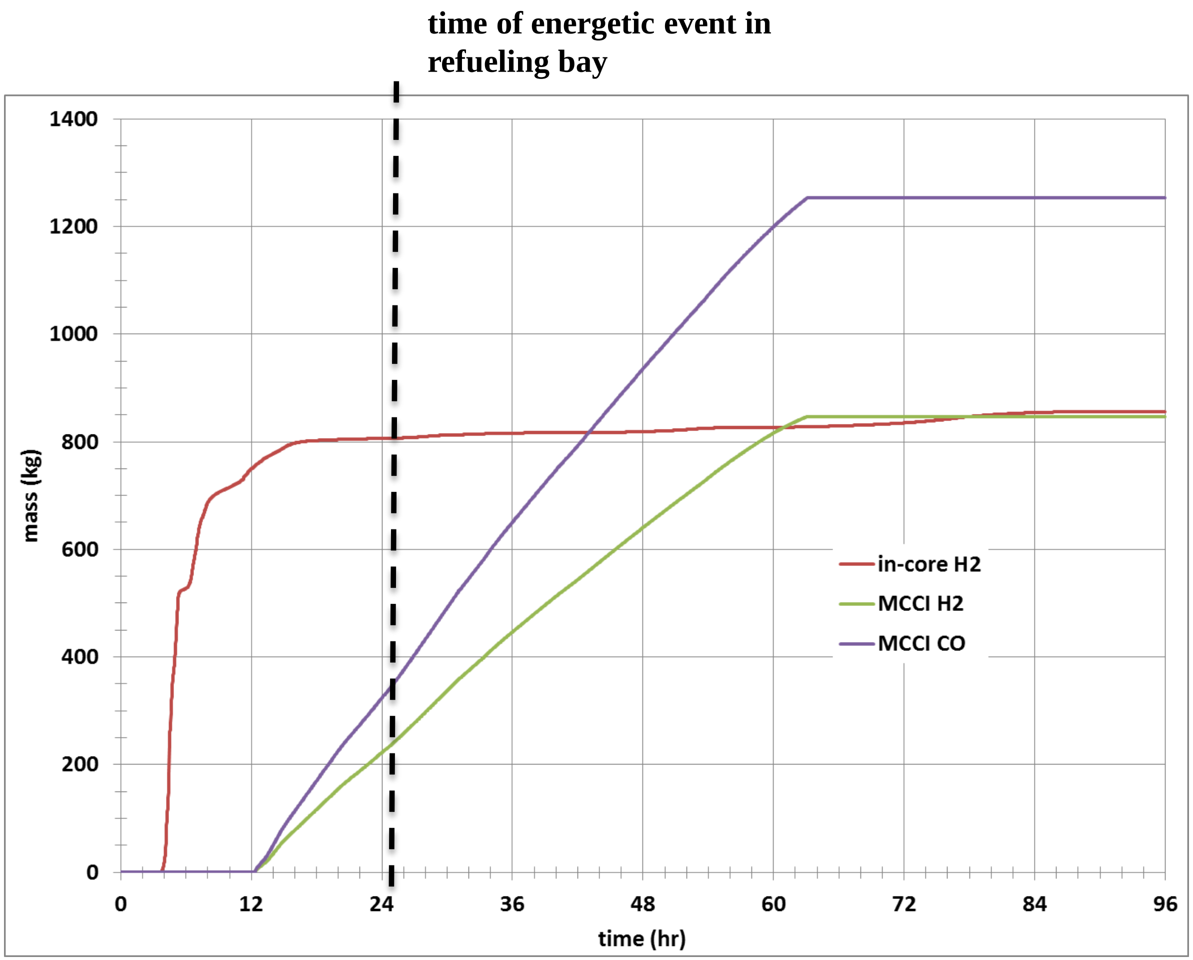


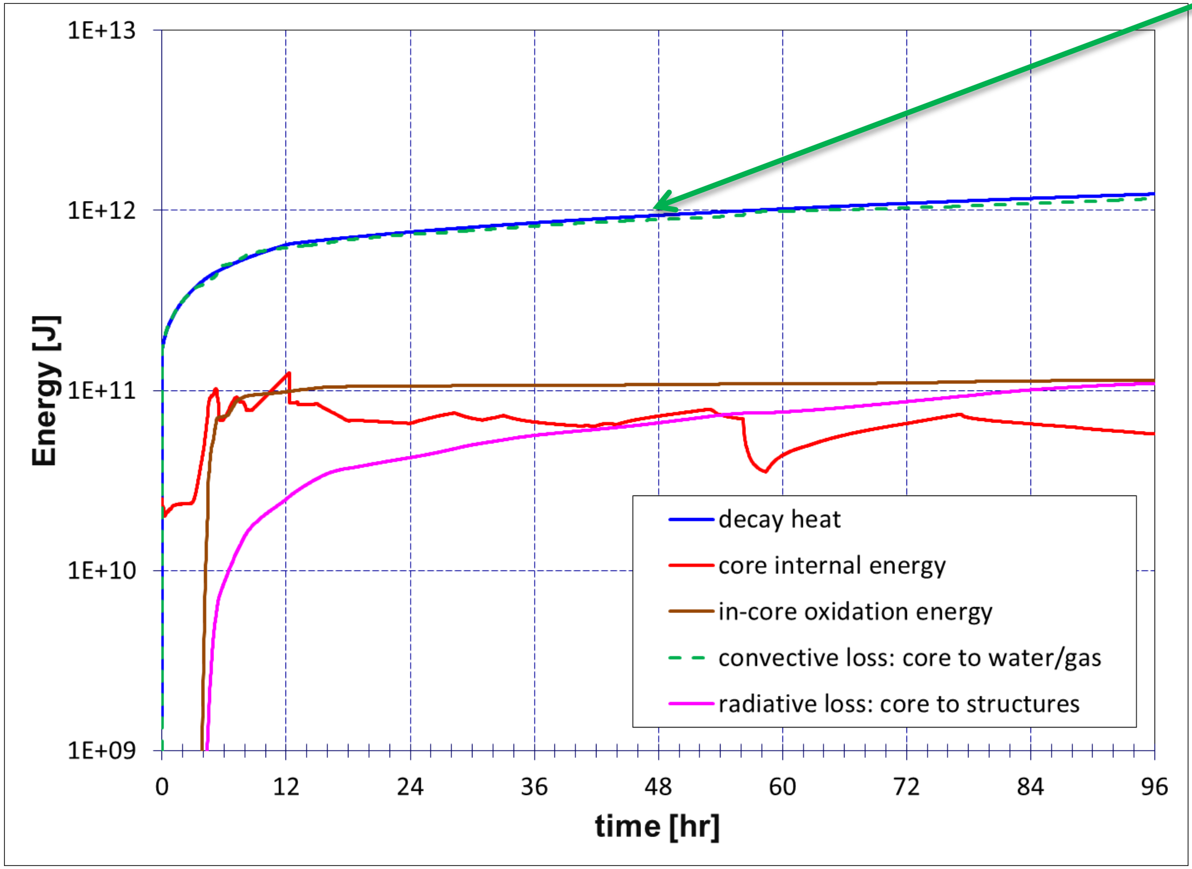
- MSL failure at ~6 hr
- LH failure at ~12 hr
- **Containment pressure increase at ~12 hr not captured; likely due to relatively "cold" particulate debris (rather than "hot" molten pool) ejection**
- late-time pressure changes are related to changes in water injection
- ad hoc leakage model will need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

1F1 – Combustible Gases



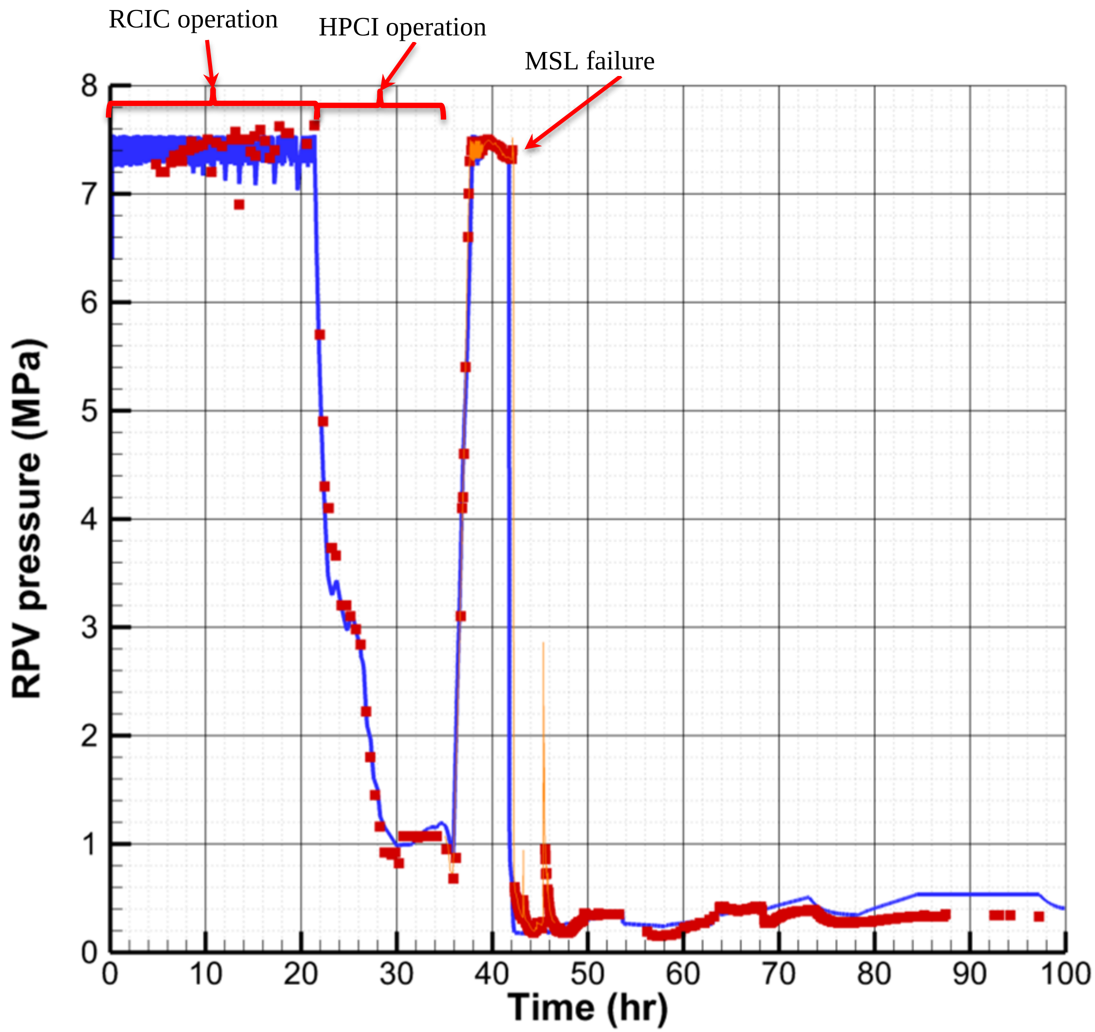
- **sufficient mass of combustible gases (H2, CO) produced to support an energetic event in the refueling bay at ~25 hr**
- lumped-parameter codes operate at too high a granularity to really predict gas composition time evolution; requires detailed analysis (i.e., CFD) to quantify
  - concentrations
  - buoyancy effects
  - steam condensation
  - leakage to/from environment
  - building heat transfer

1F1 – Energy Balance



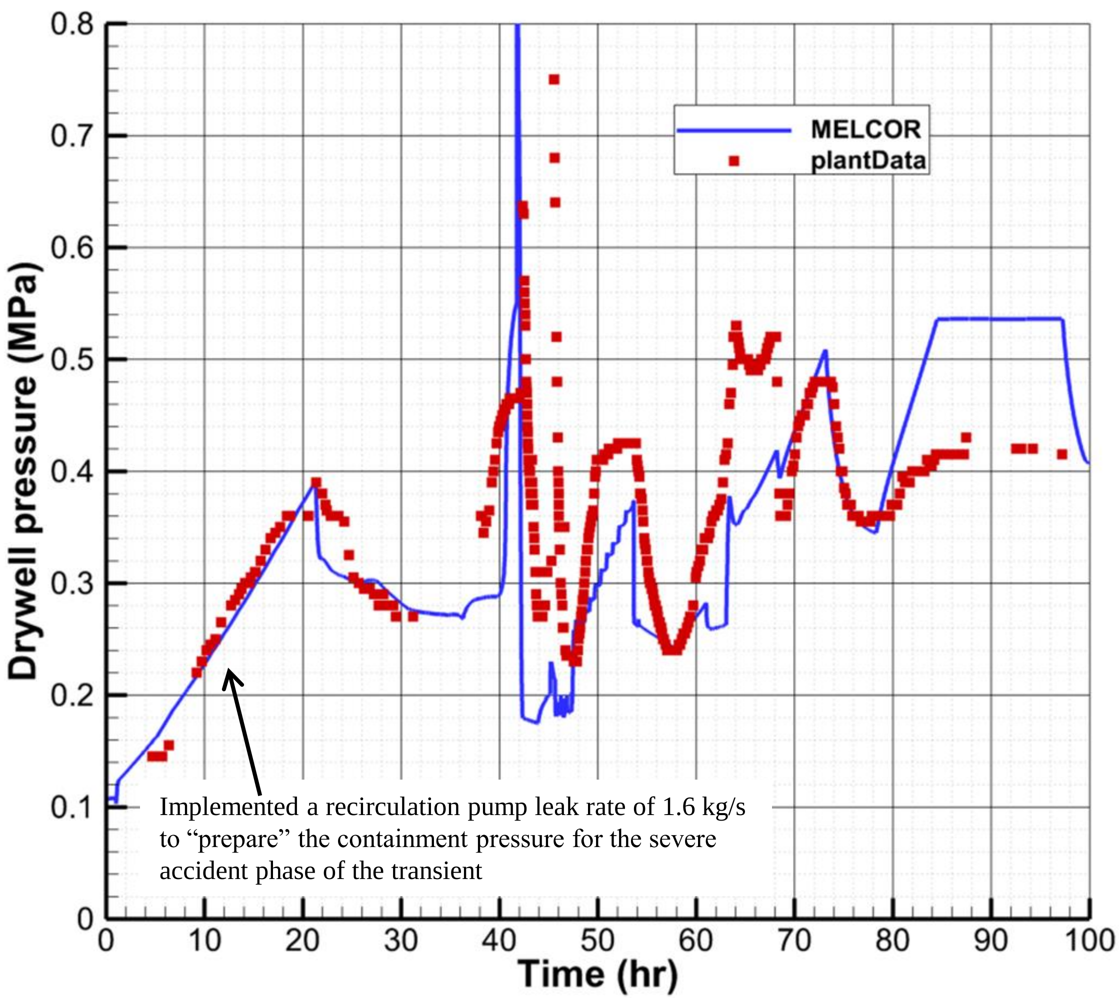
- Majority of core energy input rejected by convection to gas/water (green dashed line = blue line)
- Leads to "cold" particulate debris (instead of "hot" molten pool)
- **Likely cause of lack of pressure spike at time of LH failure and need for 20x BSAF water injection to lift drywell head**
- This was identified in the MAAP/MELCOR Crosswalk study; path forward yet to be determined

1F3 – RPV Pressure



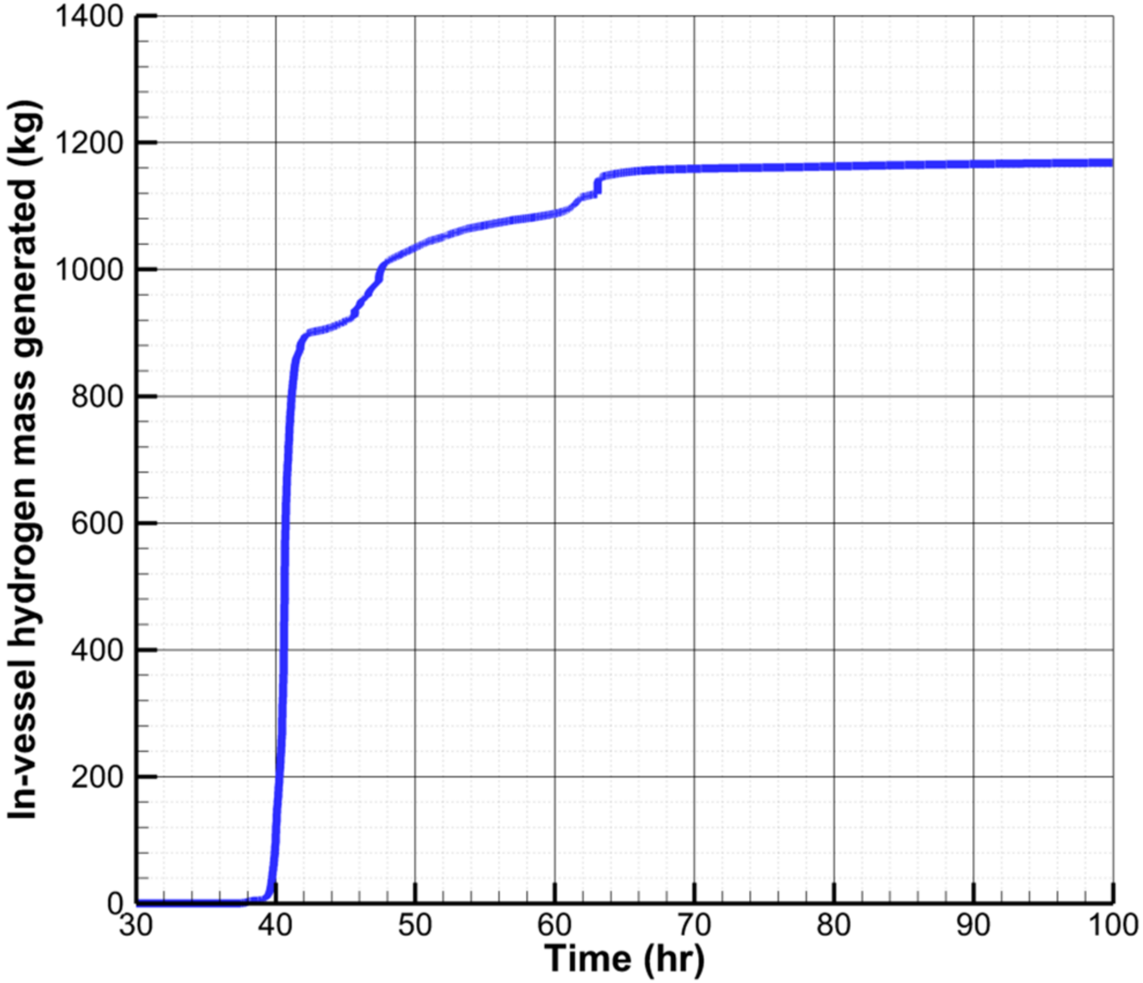
- RCIC and HPCI B.C.s based on initial BSAF information; allowed for **general agreement with plant data**
- Sets up the severe accident portion of the sequence
- MSL failure calculated to occur around 42 hr

1F3 – DW Pressure



- **general agreement with plant data**
- The largest containment pressure peak (near 45 hours after the initial RPV depressurization and first major containment peak) may be caused by core slumping into the lower plenum
- This peak and subsequent peaks are strongly dependent on the assumed WW venting behavior,
- seawater injection magnitudes
- core/RPV degradation progression
- **too much injection (subcooling) AND too little injection (no water to boil) can suppress containment pressure during certain time periods**
- the flatline after 80 hours is an assumed WW gas leak that levels out around 0.53 MPa (based on the plateau around 65-68 hours in the plant data)
- some sort of leak assumption is necessary to transport combustible gas to the Rx building

1F3 – H_2 Generation

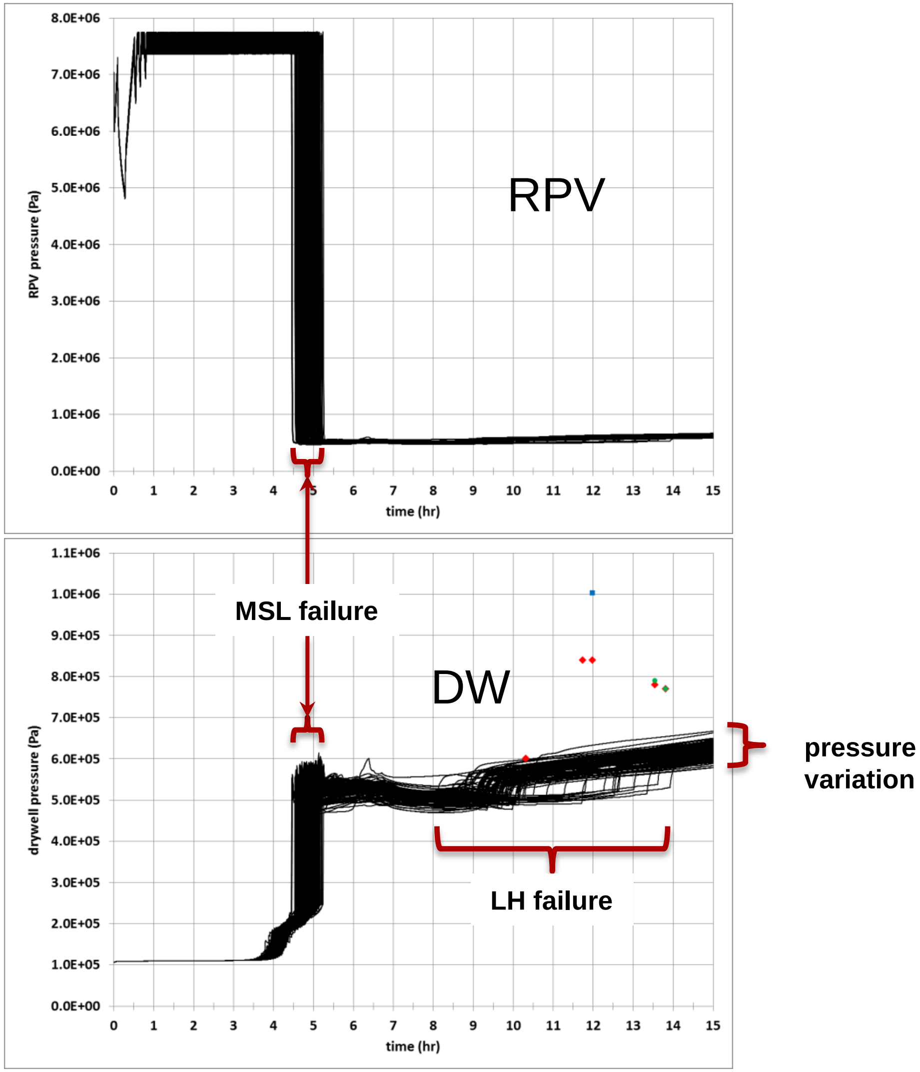


- rapid oxidation begins about 5 hr after water level drops below TAF
- **sufficient H2 generated to support the energetic event that occurred at 1F3**

But what about uncertainty?

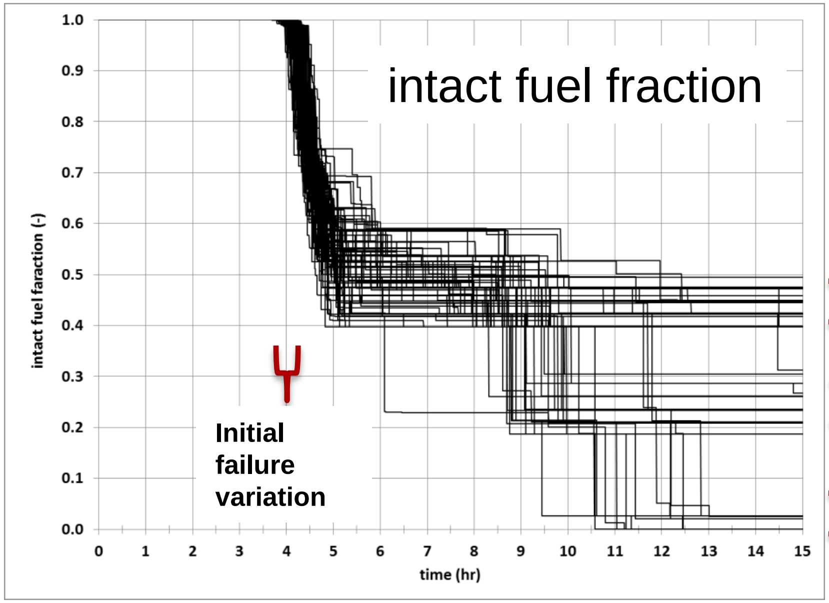
- All of our best-estimate/best-practices cases are but one of a locus of potential inputs and their results are but one of a locus of potential solutions
- Uncertainty (in input parameters and models) will produce significant variations the accident sequences
- **The impact of this is that…**
  - **“tweaks” 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 – RPV and DW pressures

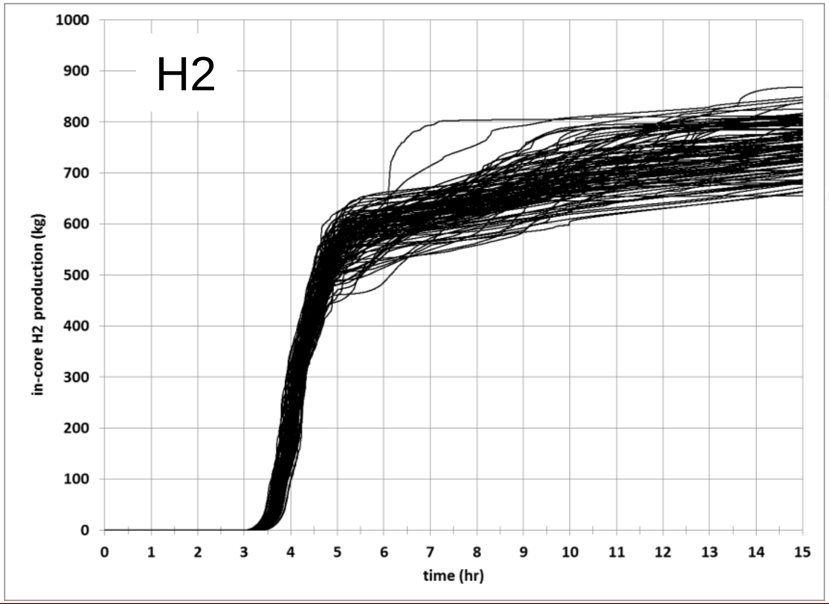


- 100 realizations with random sampling from the distribution of decay heat curves
- decay heat characterized by combining the ANS-5.1 decay heat uncertainties on primary fissile nuclides with SCALE best-estimate calculations
- Yields variation in
  - MSL failure time
  - LH failure time
  - RPV/containment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

1F1 – Intact Fuel Fraction and H_2 Generation



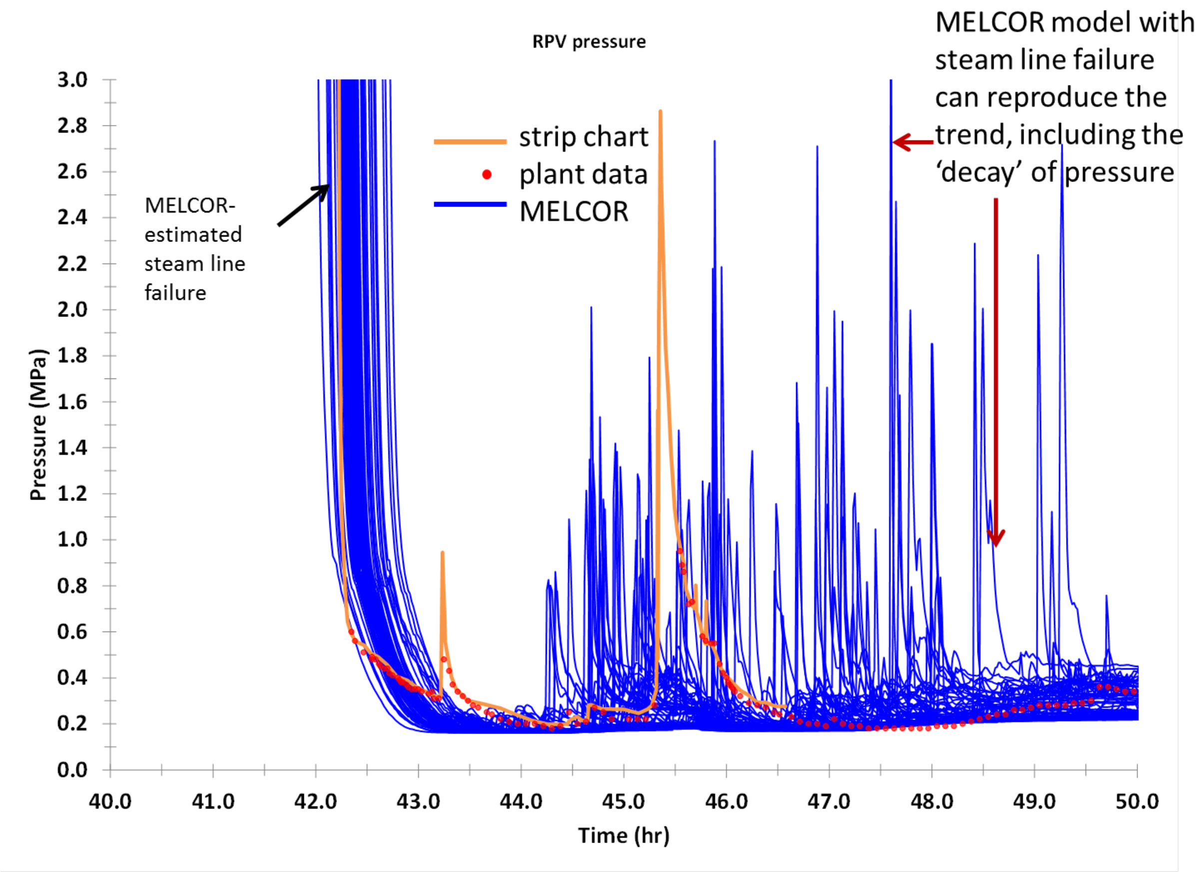
different possible final core degradation states



enough H2 to support an energetic event (650 to 850 kg)

- Intact fuel fraction results have variation in initial failure time and late-time values
- These results and those for RPV and containment pressure (previous slide) are due to variation in core damage progress

1F3 – Containment Pressure



- 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**

…and what does this mean?

- "Tweaked" deterministic analyses are useful for identifying/handling ill-defined phenomena that are postulated to influence forensic results (e.g., 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

1F1 Uncertainty Analysis

1F1 Uncertainty Analysis

- Perform a focused evaluation of uncertainty on core damage progression behavior
  - evaluate the effects of uncertain parameters on key figures-of-merit (e.g., hydrogen production, fraction of intact fuel, vessel lower head failure)
  - address the impact of very small changes in model inputs on the key FoMs (quantify and document anecdotal behavior)

1F1 UA – model and parameters

- 1F1 BSAF model used for the analysis
- uncertain parameter selection and characterization leveraged previous/current MELCOR studies
  - "Hydrogen Analysis" (2003)
  - Peach Bottom UA (2012)
  - Dynamic SAMGs Analysis (2013)
  - Surry UA (2015)
- final set of uncertain parameters
  - some from previous studies
  - additional parameters included due to focus on core damage progression
  - mainly COR package sensitivity coefficients
  - some parameter characterizations are difference from previous/current studies due to differences in technical opinions/perspectives

1F1 UA – parameters

- time constants for radial (solid) debris relocation
- time constants for radial (liquid) debris relocation
- dT/dz model, time constant for averaging flows
- dT/dz model, characteristic time for coupling dT/dz temperatures to average CVH volume temperature when dT/dz model is active
- dT/dz model, maximum relative weight of old flow in smoothing algorithm involving time constant for averaging flows
- molten zircaloy melt break-through temperature
- molten cladding (pool) drainage rate
- fraction of strain at which lower head failure occurs
- fraction of un-oxidized cladding thickness at which thermal-mechanical weakening of oxidized cladding begins
- debris quenching heat transfer coefficient to pool
- debris falling velocity
- minimum debris porosity
- fuel time-at-temperature
- total core decay heat

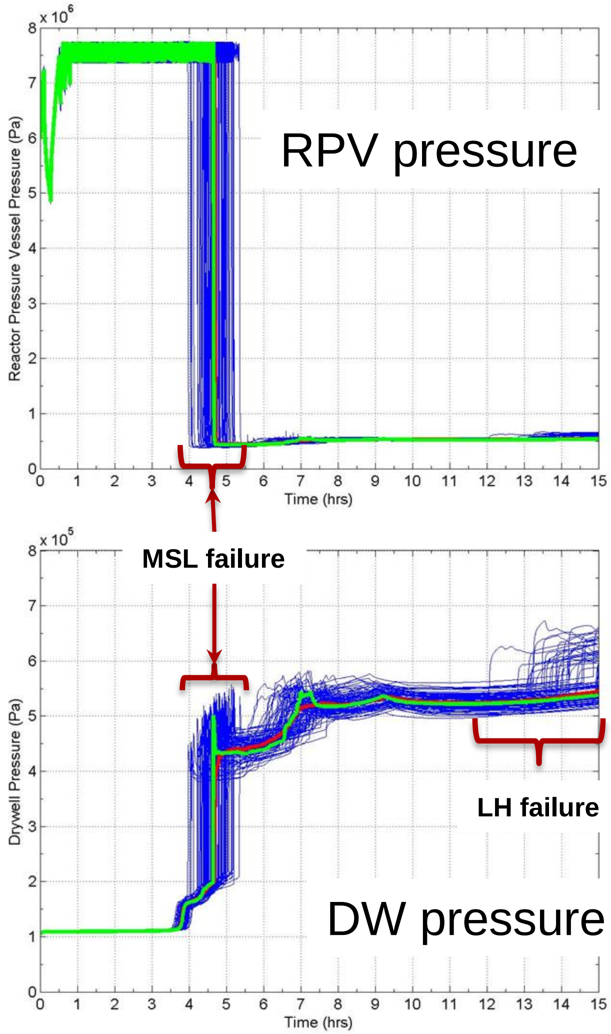
1F1 UA – MELCOR Cases

case type	id	# rlz*	description
Replicates	w-1f1-rep1	100	Replicate 1; base case for statistical analysis
	w-1f1-rep2	100	Replicate 2
	w-1f1-rep3	100	Replicate 3
	w-1f1-rep1u	100	Replicate 1; rerun with uniform distributions
perturbations	w-1f1-p01	100	"median-like" realization rerun with small perturbations (+/-0.5%) of its sampled values
	w-1f1-p02	100	"median-like" realization rerun with with DTMAX sampled from a log-uniform distribution (LB = 0.01 s, UB = 0.1 s)
	w-1f1-p03	100	"median-like" realization rerun with the model's flowpath input randomly reordered

*** number of simple Monte Carlo samples**

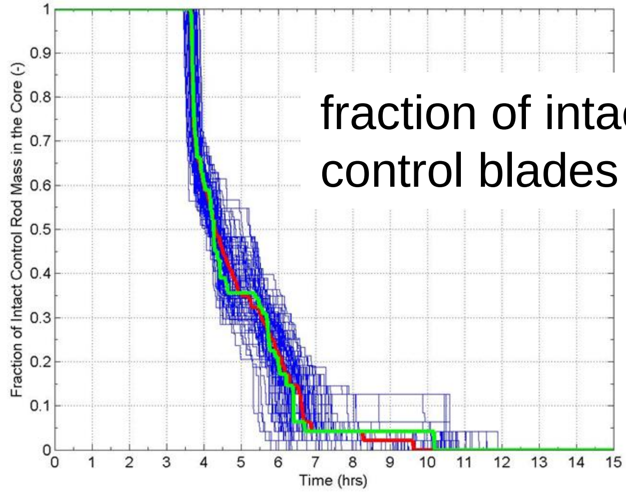
- Replicate 1 is the base case for statistical analysis
- Replicates 2, 3, and 1U are used to verify statistical convergence and to test regressions from Replicate 1
- Perturbation cases used to address the impact of very small changes in model inputs on the key FoMs

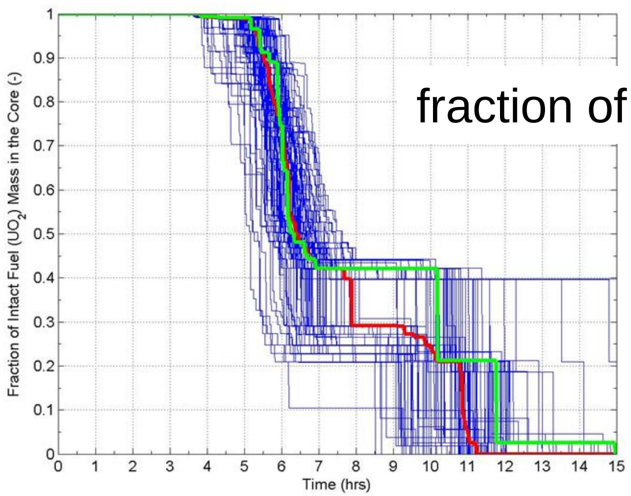
1F1 UA – Replicate 1 Results (1/3)



- Results (except for lower head failure) are similar to previous deterministic analyses (e.g., initial DOE analysis, BSAF, MAAP-MELCOR crosswalk)

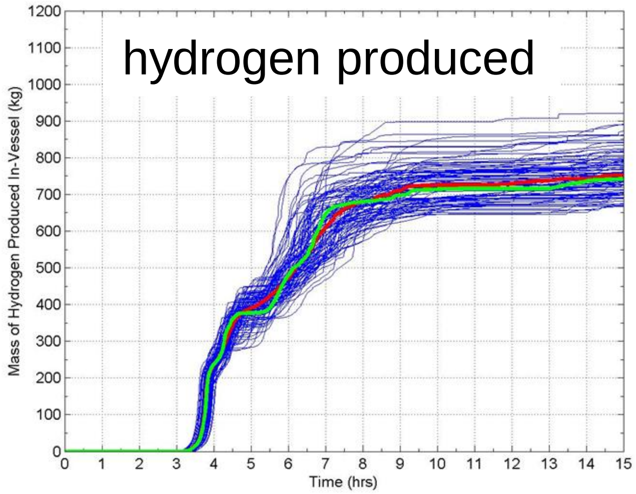
1F1 UA – Replicate 1 Results (2/3)

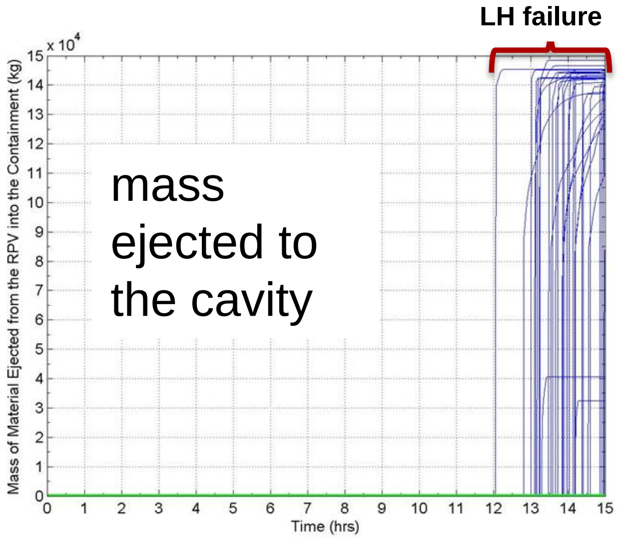




- all of the control blades eventually fail
- almost all of the fuel eventually fails between 8 and 14 hr
- similar to previous deterministic analyses

1F1 UA – Replicate 1 Results (3/3)



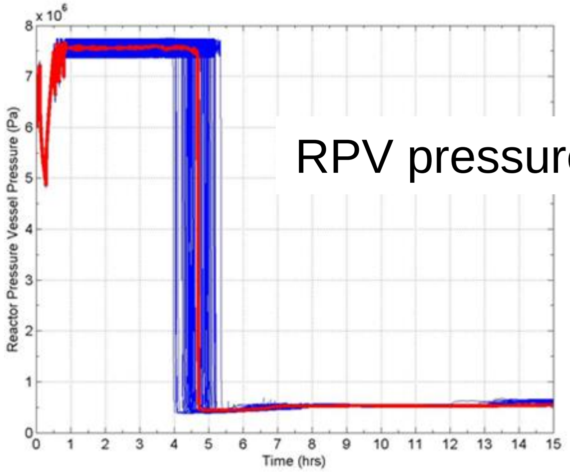


- make lots of hydrogen (700 to 900 kg); enough to support the energetic event that occurred at 1F1; similar to previous deterministic analyses
- less than 50% of the realizations have LH failure before start of freshwater injection (at 15 hr); not similar to previous deterministic analyses

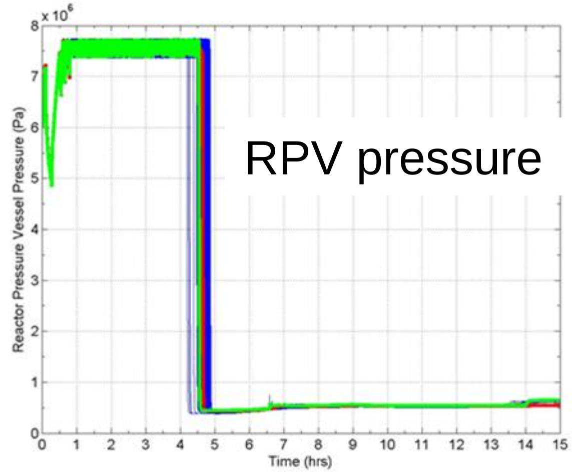
1F1 UA – perturbation analyses

- anecdotal experience suggests that small changes in model inputs can yield large changes in outputs
- performed three analyses (using a median-like realization (Rlz13) from Replicate 1)
  - small perturbations (+/-0.5% uniform samples around the Rlz13 values)
  - vary dtmax (log-uniform distribution; LB=0.01 s, UB=0.1 s)
  - shuffle flowpaths (randomly reordered flowpath input records)

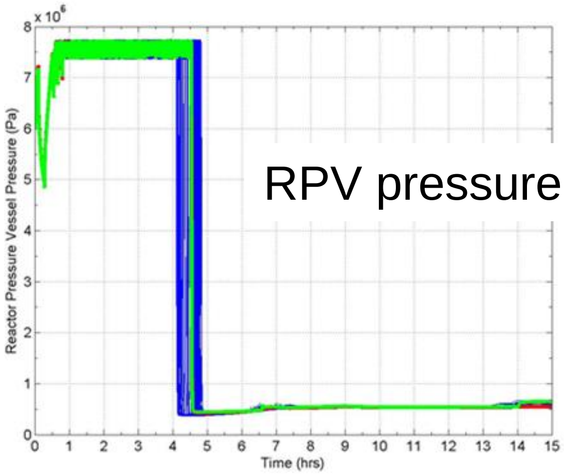
1F1 UA – perturbation Results (1/4)



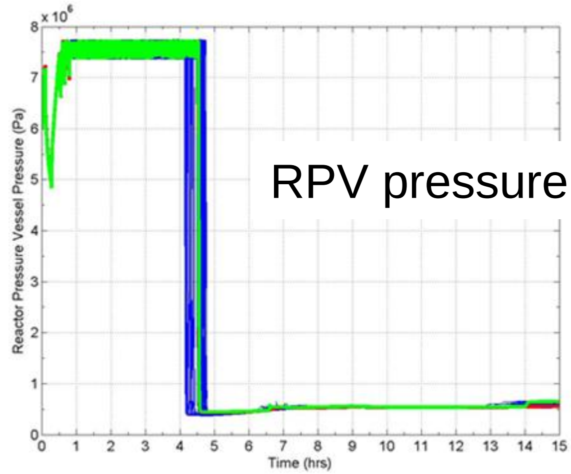
Replicate 1



Small Perturbation



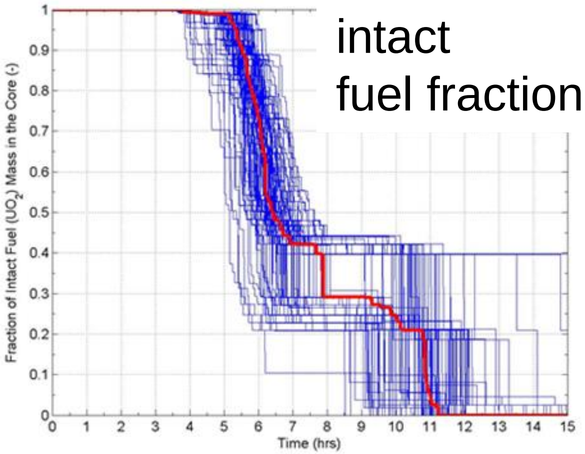
dt_{max}



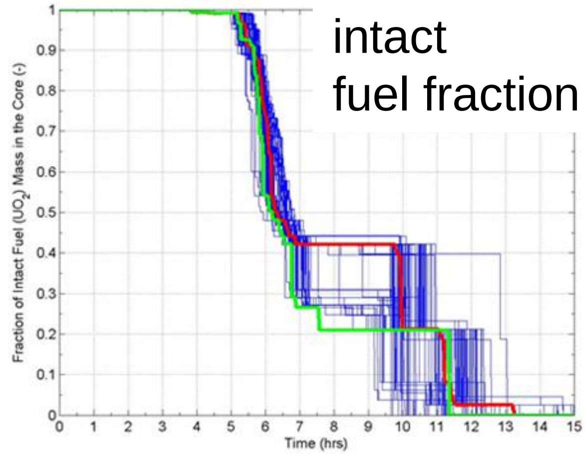
Flowpath Shuffle

- signatures are consistent
- MSL failure timings are narrower, but not as narrow as would be expected
- red = median
- green = Rlz13

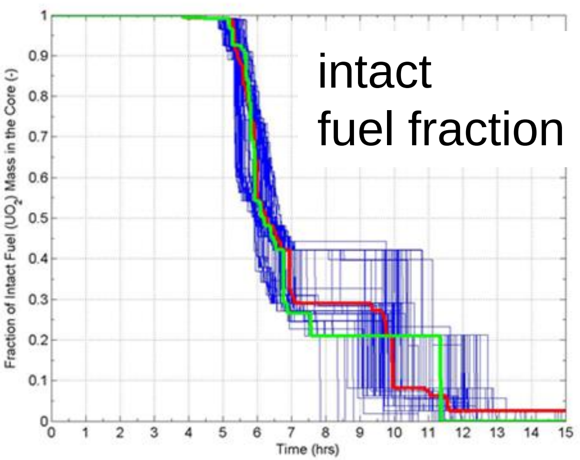
1F1 UA – perturbation Results (2/4)



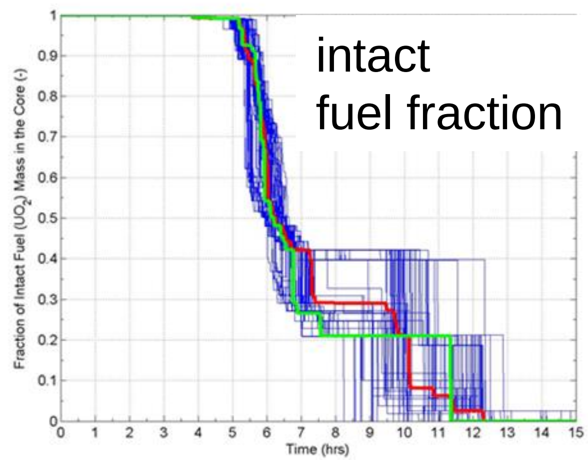
Replicate 1



Small Perturbation



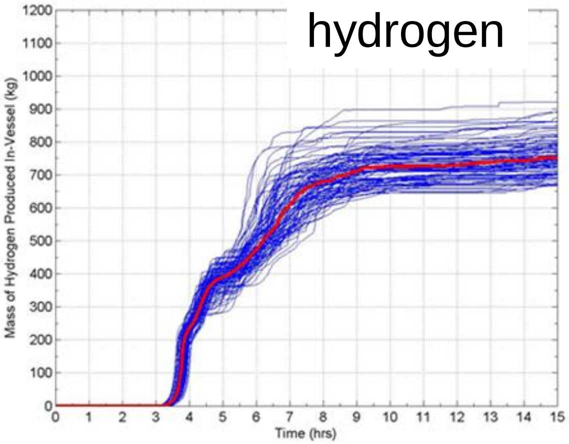
dt_{max}



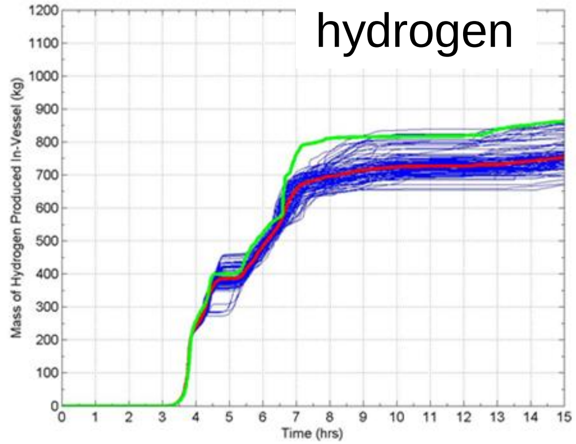
Flowpath Shuffle

- signatures are consistent
- variations are narrower, but not as narrow as would be expected
- red = median
- green = Rlz13

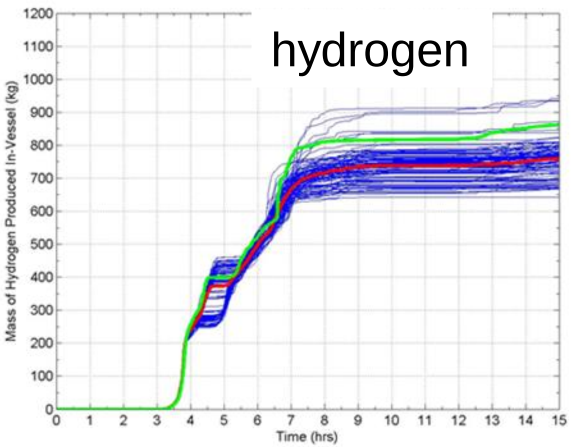
1F1 UA – perturbation Results (3/4)



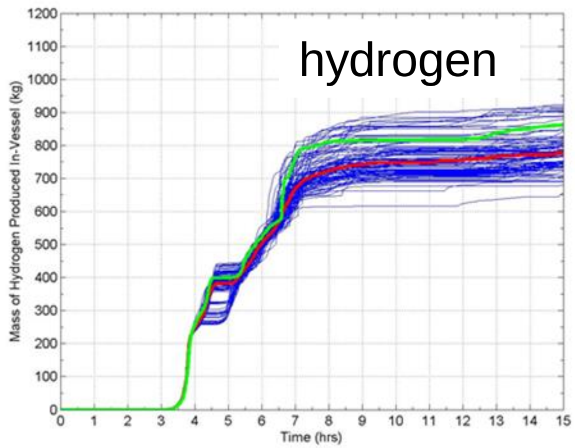
Replicate 1



Small Perturbation



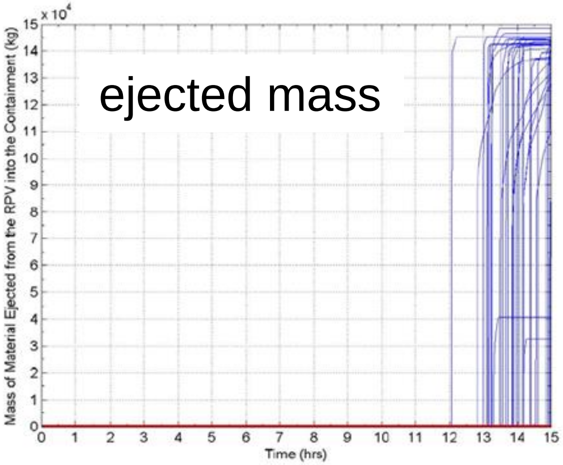
dt_{max}



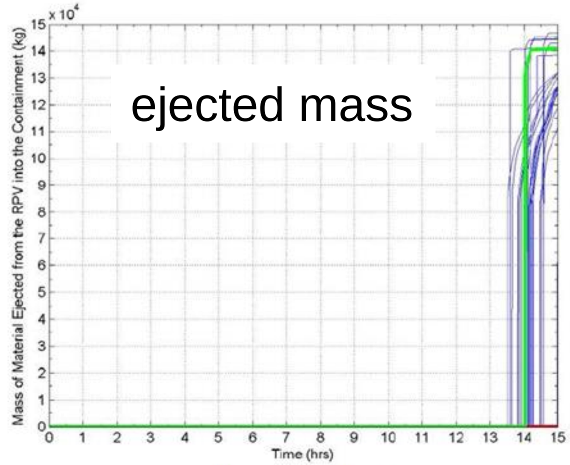
Flowpath Shuffle

- signatures are consistent
- variations are narrower, but not as narrow as would be expected
- red = median
- green = Rlz13

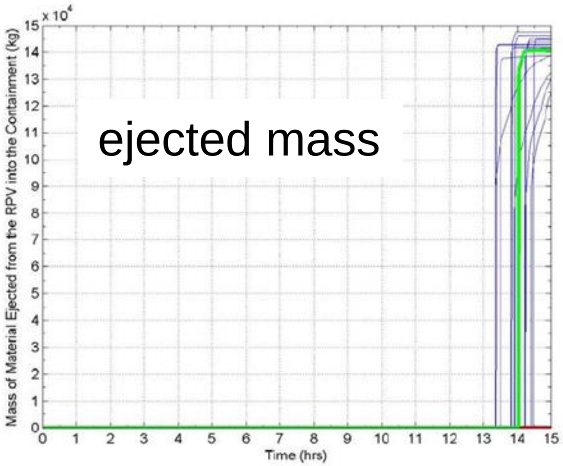
1F1 UA – Perturbation Results (4/4)



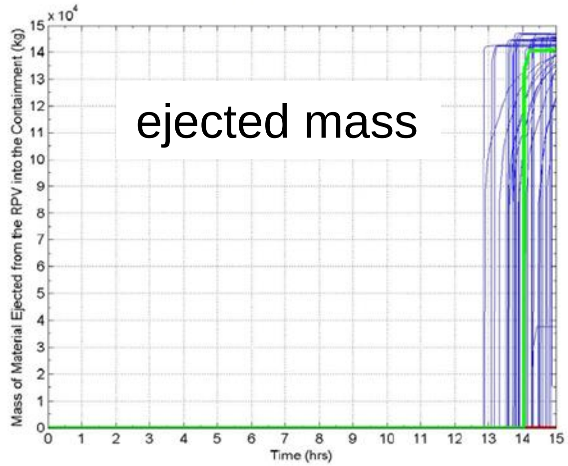
replicate 1



small perturbation



DTMAX



flowpath shuffle

- signatures are consistent
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1F1 UA – Statistical Analyses

- Convergence tests
  - tests found 100 realizations were sufficient for convergence
- Scatter plots
  - examined to find visual trends in the data
- Cumulative Distribution Functions
  - examined to find visual trends in the data
- Stepwise Linear Regression Analyses
  - concern that due to the noisy nature of core degradation-influenced MELCOR outputs, regressions may be susceptible to fitting noise instead of the signal derived from input variability.
  - only simple linear regressions are employed across various event times to determine if trends hold throughout the accident
  - these regressions are validated across multiple samples to determine if either the regression results are applicable to the entire population of 1F1 MELCOR outputs or simply to fitting noise within a given sample

1F1 UA – Statistical Analyses Results

- Perturbation cases show MELCOR results can be very noisy and only output variables which have strong influences (or signals) can easily be identified in sensitivity studies
- Regressions for **mass ejected from the lower head** have low predictive values and are subject to regressing noise
- Replicate 1 predicted a consistent influence of **molten zirconium breakthrough temperature** on **hydrogen production** throughout the accident progression
- Replicate 1 predicted a consistent influence on **molten zirconium breakthrough temperature** and **effective fuel failure temperature** on **intact fuel mass fraction** throughout the accident sequence.

1F1 UA – Conclusions

- The phenomenological uncertainties associated with severe accident modeling and the computational difficulties associated with core degradation modeling state of practice should be appreciated and considered when developing the technical basis for regulatory decision making or accident management strategy development.
- The input uncertainty analyses (Replicates 1, 2, and 3) as well as the perturbation analyses demonstrate that the key FoMs can have non-trivial variation.
- It is important that this variation is considered when using MELCOR (or any other systems level severe accident analysis code) to perform single deterministic analyses or trade-off studies.
- Using techniques like the uncertainty analysis and the statistical methods (discussed herein) can greatly strengthen the technical basis used to inform regulatory decision making activities of such trade studies

Conclusions

Conclusions

- Core damage progression modeling is not “settled science”/is uncertain
- Forensic results can be duplicated by “tweaking” models
- Multiple sets of “tweaks” can yield the same result
- Very small changes in a “tweaked” model can yield very different results
- Only inputs which have strong influences (signals) can easily be identified in sensitivity studies
- DAK: **It is important that all of the above is considered when using MELCOR (or any other systems level severe accident analysis code) to perform single deterministic analyses or trade-off studies**

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