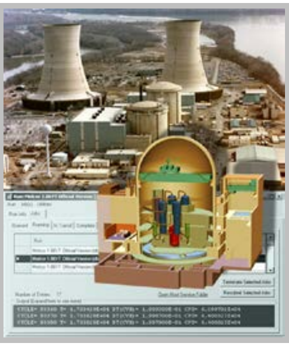
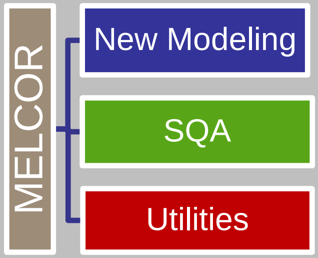
Exceptional service in the national interest

SAND2017-11530PE





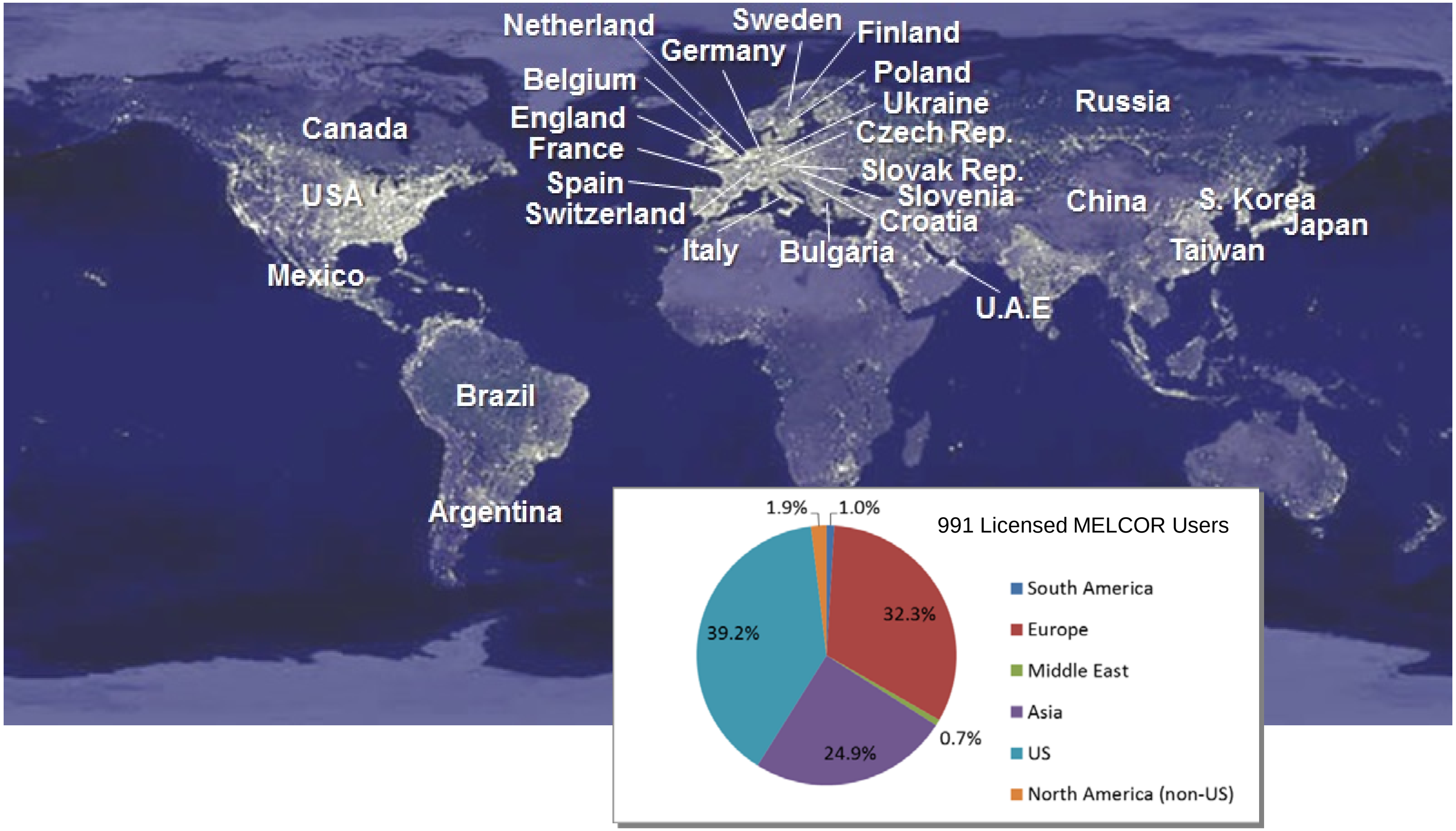
MELCOR Code Development Status

MCAP 2017

Presented by Larry Humphries

llhumph@sandia.gov

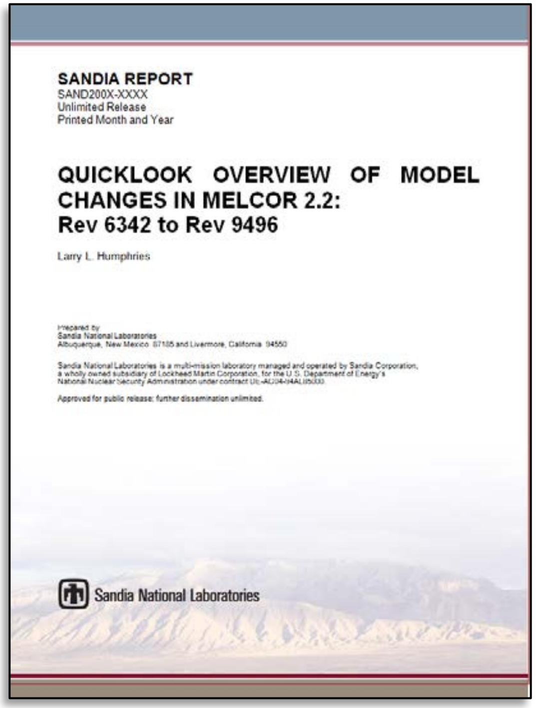
International Use of MELCOR



MELCOR Workshops & Meetings

- 2016 Asian MELCOR User Group (AMUG)
  - Hosted by SPICRI & NRSC (Beijing)
  - October 17 – 21, 2016
  - MELCOR/MACCS Workshop
- 2017 European MELCOR User Group (EMUG)
  - Hosted by CIEMAT
  - April 6-7, 2017
- KHNP Workshop
  - August 2017
  - Week long beginners' workshop (MELCOR)
  - Week long beginners' workshop (MACCS)
- 2017 CSARP/MCAP/MELCOR Workshop
  - September, 2017
  - Bethesda, MD
  - Focus will be on new models
- 2017 Asian MELCOR User Group (AMUG)
  - Hosted by KAERI (S Korea)
  - November 6– 8, 2017 (tentative)
  - MELCOR/MACCS Topics

MELCOR 2.2 Code Release



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SAND200X-XXXX
Unlimited Release
Printed Month and Year

QUICKLOOK OVERVIEW OF MODEL CHANGES IN MELCOR 2.2:
Rev 6342 to Rev 9496

Larry L. Humphries

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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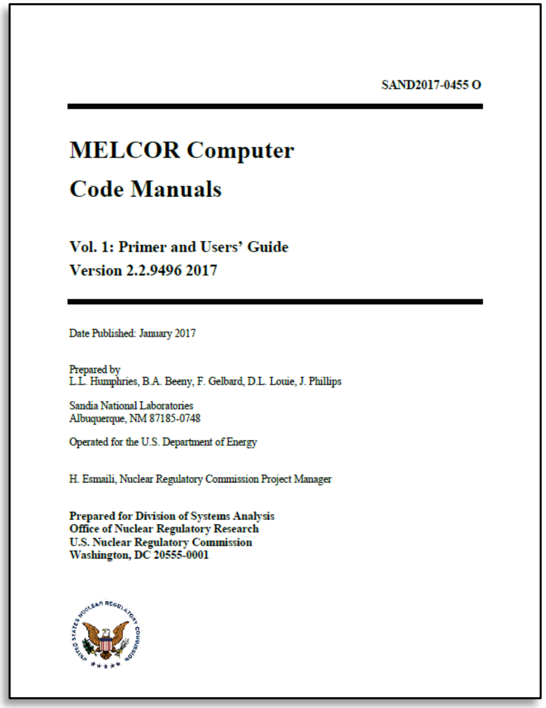


SAND2017-0455 O

MELCOR Computer
Code Manuals

Vol. 1: Primer and Users' Guide
Version 2.2.9496 2017

Date Published: January 2017

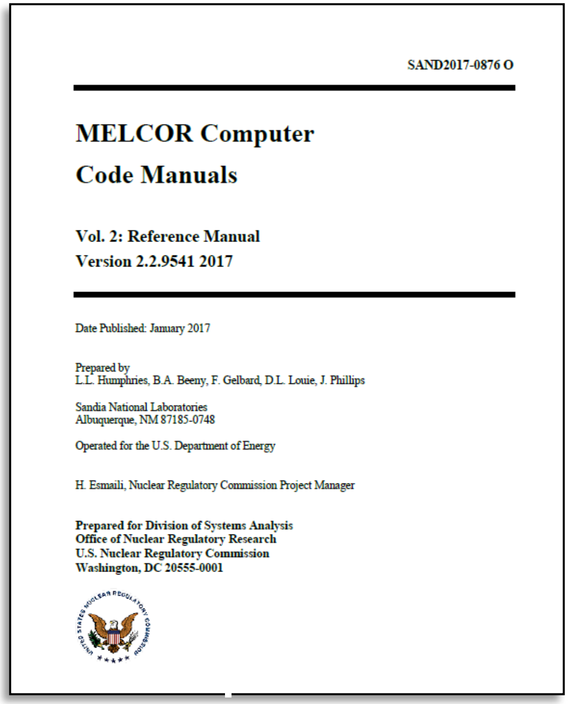
Prepared by
L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips

Sandia National Laboratories
Albuquerque, NM 87185-0748

Operated for the U.S. Department of Energy

H. Esmaili, Nuclear Regulatory Commission Project Manager

Prepared for Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001



SAND2017-0876 O

MELCOR Computer
Code Manuals

Vol. 2: Reference Manual
Version 2.2.9541 2017

Date Published: January 2017

Prepared by
L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips

Sandia National Laboratories
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MELCOR 2.2 Quicklook Overview of Model Changes in MELCOR 2.2

Volume I: User Guide

R&A Complete
SAND2017-0445 O

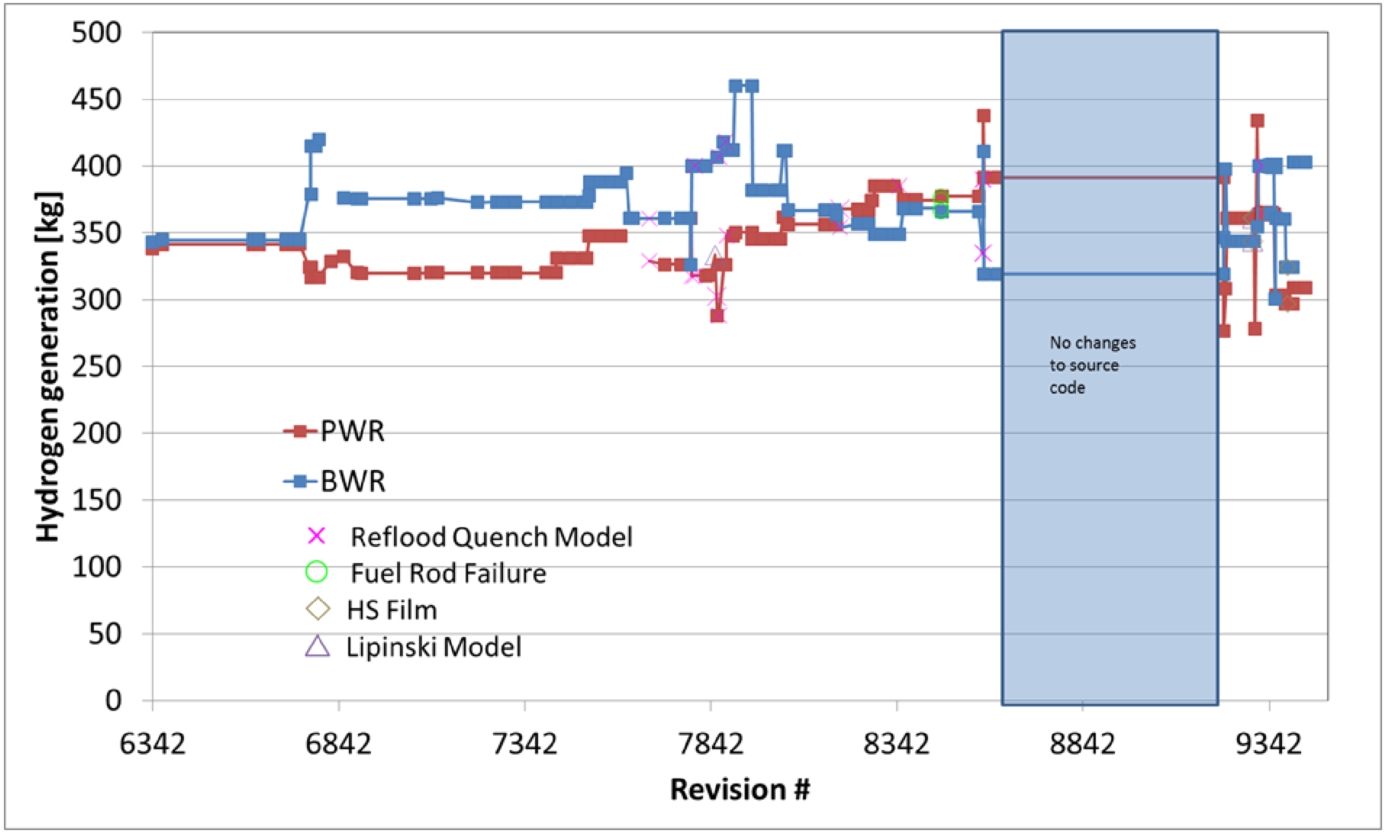
Volume II: Reference Manual

R&A Complete
SAND2017- 0876 O

M2.2 Significant Code Changes

- New defaults
  - Fuel Rod Collapse Model
  - Melt Spreading Model
- Code corrections
  - Mass error with flashing model when hygroscopic model is enabled [r8612]
  - Corrections to reflood quench model [multiple revisions]
  - Lipinski dryout model not used above the core support plate [r7874]
    - Improvements toTMI-2 Assessments
  - Revised candling model for canisters [r7864 but not active until 9387]
  - Decay heat transfer to small fluid volumes [r8274]
  - Correction to fuel rod collapse modeling (temperature failure criteria) [r8574]
- Many new models

Changes in H2 Generation from Oxidation

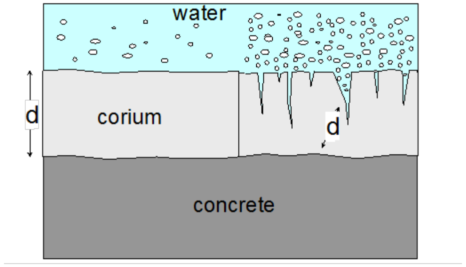


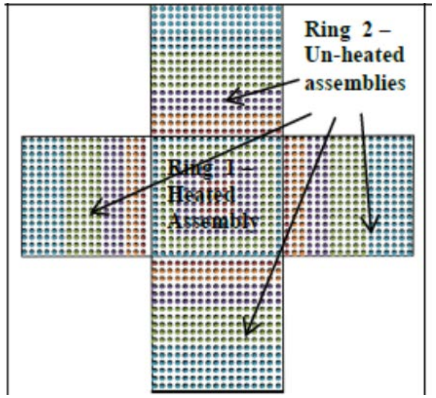
MELCOR Runtime and Robustness

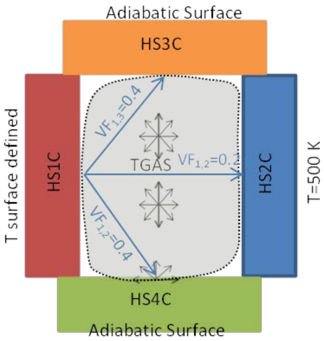
- Code Corrections & Modeling Improvements
  - Corrections to reported bugs
  - Model reviews
  - Targeted efforts to improve code performance
    - Examination of calculations showing time step reduction scenarios.
- Code Performance Improvements
  - Improvement of runtime (for 100 hours) Rev. 5864 → Now
    - 1F1 – 4 day calc. = 4 day CPU → 500 hours calc. = 50 hours CPU
    - 1F3 - 4 day calc. = 8 days CPU → 500 hours calc. = ~150 hours CPU
  - Enabled extension of Fukushima simulation time
    - 100 hours => 500 hours
- Robustness Improvements
  - 2013 – 75% success rate
  - 2015 - 84% success rate
  - 2017 (Recent Sequoyah UA) – 95% success rate

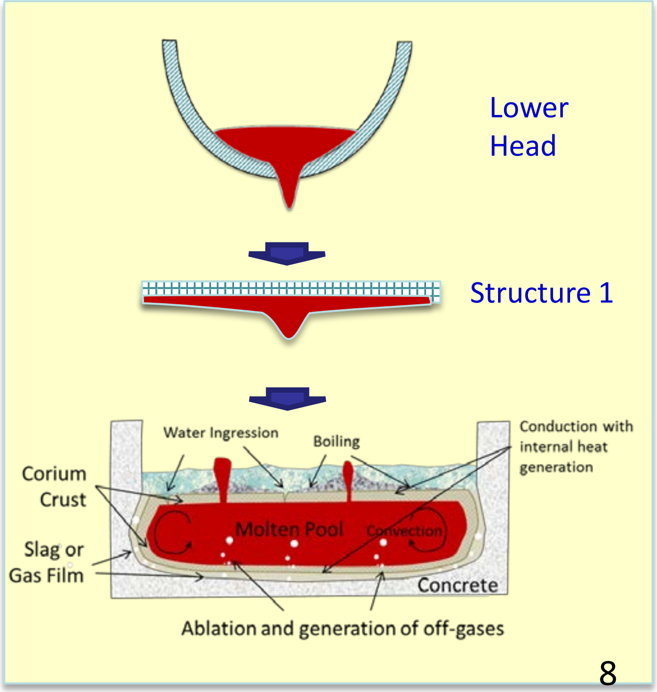
New Model Development Tasks (2014-2016)

- Completed
  - Fuel Rod Collapse Model (NRC)
  - Homologous pump model (NRC)
  - Multi-HS radiation enclosure model
  - Aerosol re-suspension model
  - Zukauskas heat transfer coefficient (external cross-flow across a tube bundle)
  - Core Catcher (multiple containment vessels)
  - Multiple fuel rod types in a COR cell (NRC)
  - Generalized Fission Product Release Model
  - New debris cooling models added to CAV package (NRC)
    - Water-ingression
    - Melt eruption through crust
  - Spreading model implemented into CAV package (NRC)
  - Miscellaneous models and code improvements (NRC)
    - COR_HTR extended to heat structures
    - LAG CF
    - MACCS Multi-Ring Release
    - Valve Flow Coefficient
    - MACCS release types
- In Progress or future
  - Vectorized Control Functions (NRC)
  - Eutectics model
  - CONTAIN/LMR models for liquid metal reactors
  - CVH/FL Numerics (NRC)
  - RCIC Terry Turbine model (NRC)

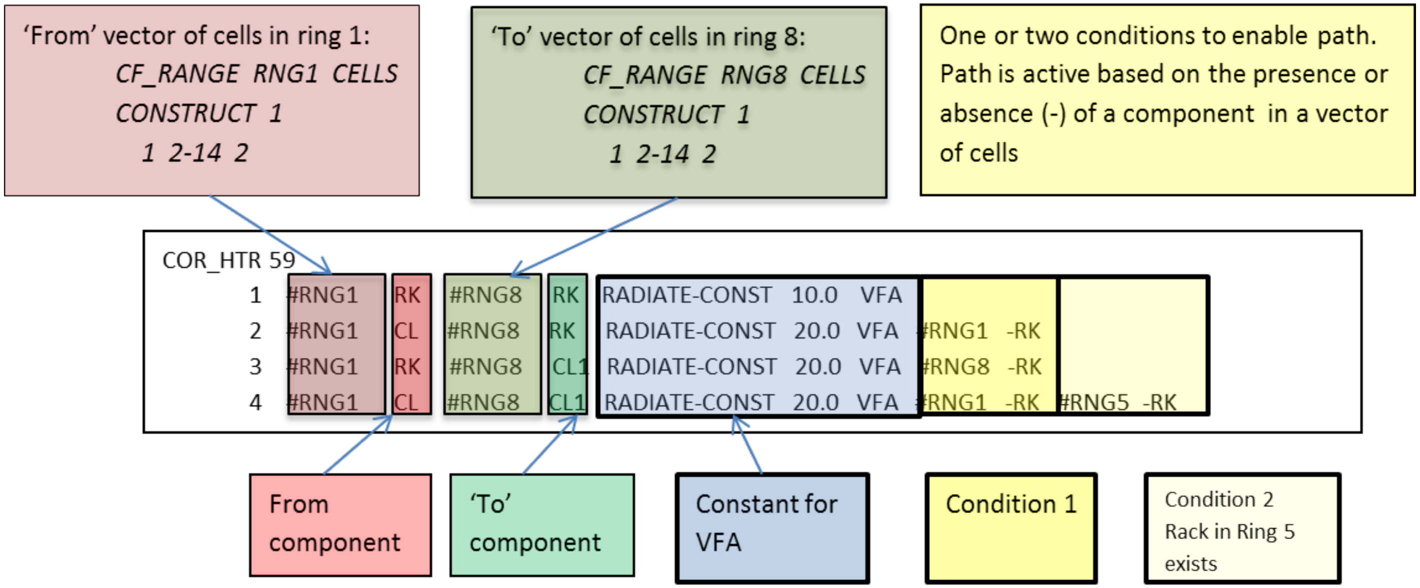








Vectorized COR_HTR Input



'From' vector of cells in ring 1:

```
CF_RANGE  RNG1  CELLS
CONSTRUCT  1
  1  2-14  2
```

'To' vector of cells in ring 8:

```
CF_RANGE  RNG8  CELLS
CONSTRUCT  1
  1  2-14  2
```

One or two conditions to enable path. Path is active based on the presence or absence (-) of a component in a vector of cells

```
COR_HTR 59
        1   #RNG1  RK   #RNG8  RK   RADIATE-CONST  10.0  VFA
        2   #RNG1  CL   #RNG8  RK   RADIATE-CONST  20.0  VFA  #RNG1  -RK
        3   #RNG1  RK   #RNG8  CL1  RADIATE-CONST  20.0  VFA  #RNG8  -RK
        4   #RNG1  CL   #RNG8  CL1  RADIATE-CONST  20.0  VFA  #RNG1  -RK  #RNG5  -RK
```

From component

'To' component

Constant for VFA

Condition 1

Condition 2 Rack in Ring 5 exists

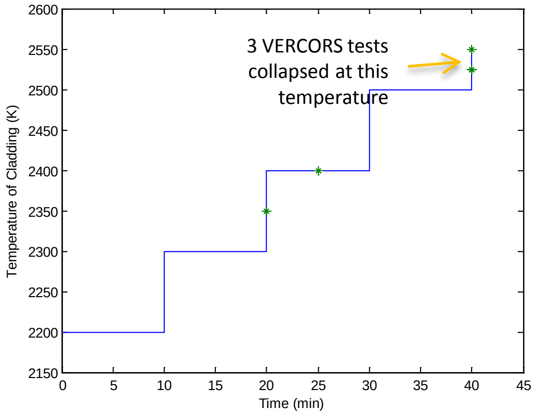
- Reduces number of input records significantly.
  - Otherwise input is required cell by cell.
  - Unnecessary CF logic required to determine existence of components.
  - Difficult to read (QA)
    - Input for a cell is scattered among COR_HTR records and multiple CF records
  - One example reduced number of records from over 7000 records to under 100

Fuel Rod Collapse Model

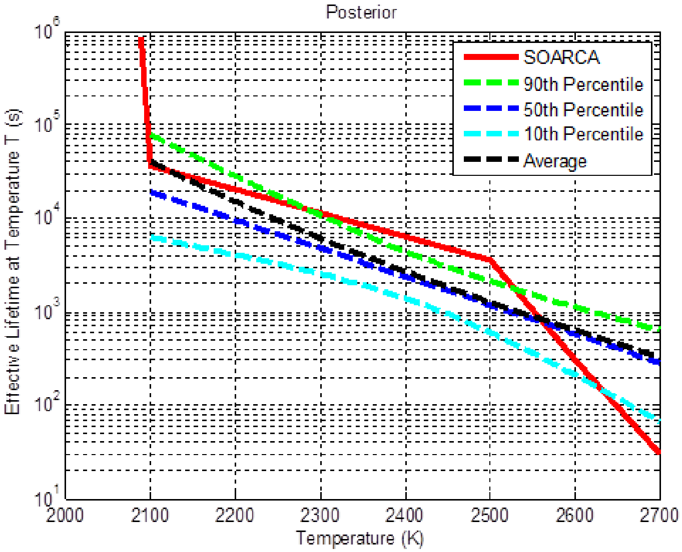
- Time-at-temperature model
  - Available in M186 but not default until now
  - Characteristics had to be provided by user
  - Eliminates temperature threshold effect from failure temperature model
- Updated based on VERCORS experiments and SOARCA models
  - Damage function used in SOARCA analyses

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

  - Coefficients A & B fit using Bayesian statistical analysis of VERCORS fuel collapse data
    - 6 Data points



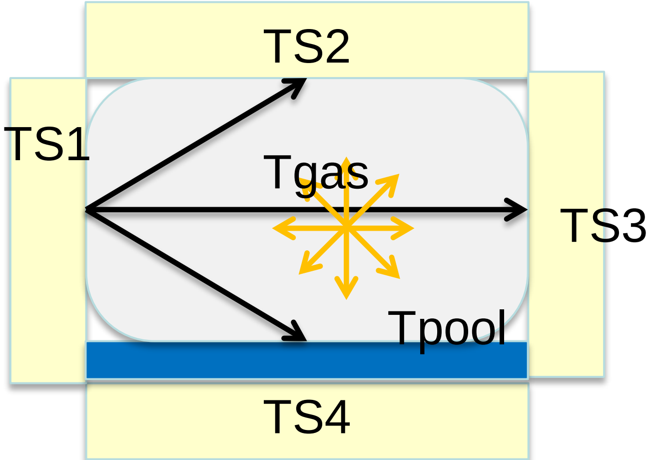
Time at Temperature Histories from the VERCORS Experiments . All tests underwent identical temperature ramps, stars indicate fuel collapse times.



“Development of the SharkFin Distribution for Fuel Lifetime Estimates in Severe Accident Codes”, 2016 ANS Winter Meeting**.**
M. R. Denman

Multi HS Radiation Enclosure Model

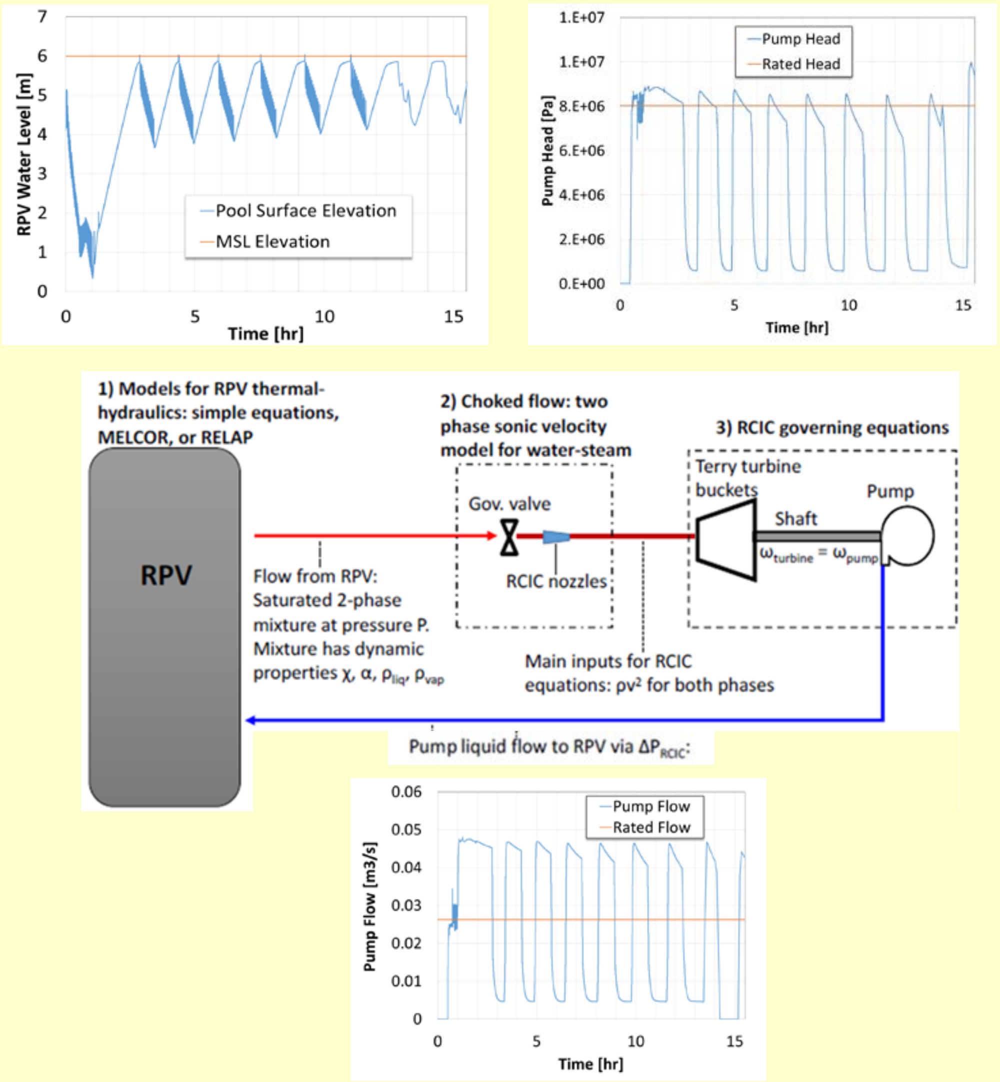
- Recent model improvements
  - Continuation of view factor records onto new line
  - View factors can now be specified by control functions.
    - Sum of view factors for a surface cannot exceed 1.0
  - Radiation to pool surface
    - When pool covers a participating surface on a HS, the pool surface replaces that HS surface in the enclosure network.



```
HS_Rad 4  NET3       !EM      BeamL    VF
   1   HS1C      RIGHT  EM1     0.5        0.0   0.2   0.4    &
                                  'MyLongNamedCF'
   2   HS2C      LEFT    EM2      0.5       0.2  0.0  0.3  0.5
   3   HS3C      LEFT        -       0.5       0.4  0.3  0.2  0.1
   4   HS4C      RIGHT     -       0.5       0.4   0.5  0.1  0.0
```

MELCOR Terry Turbine Model(s) Overview

- Terry turbine pressure-stage model (rapid steam expansion across nozzles)
  - Isentropic steam expansion or analytical Wilson point approach to capture phase non-equilibrium effects
  - Back-pressure effects for either under-expanded or over-expanded flow
- Terry turbine compound velocity-stage model (impulse of steam on turbine rotor)
  - Interfaces to pressure-stage model
  - Predicts rotor torque from initial impingement of steam plus subsequent stages (reversing chambers)
- Turbo-shaft model
  - Rigid coupling of the turbine to the homologous pump model
  - Solves a torque-inertia equation to govern turbo-shaft speed



1) Models for RPV thermal-hydraulics: simple equations, MELCOR, or RELAP

2) Choked flow: two phase sonic velocity model for water-steam

3) RCIC governing equations

Flow from RPV: Saturated 2-phase mixture at pressure P. Mixture has dynamic properties χ, α, ρ_{liq}, ρ_{vap}

Main inputs for RCIC equations: ρv^2 for both phases

Pump liquid flow to RPV via ΔP_{RCIC}:

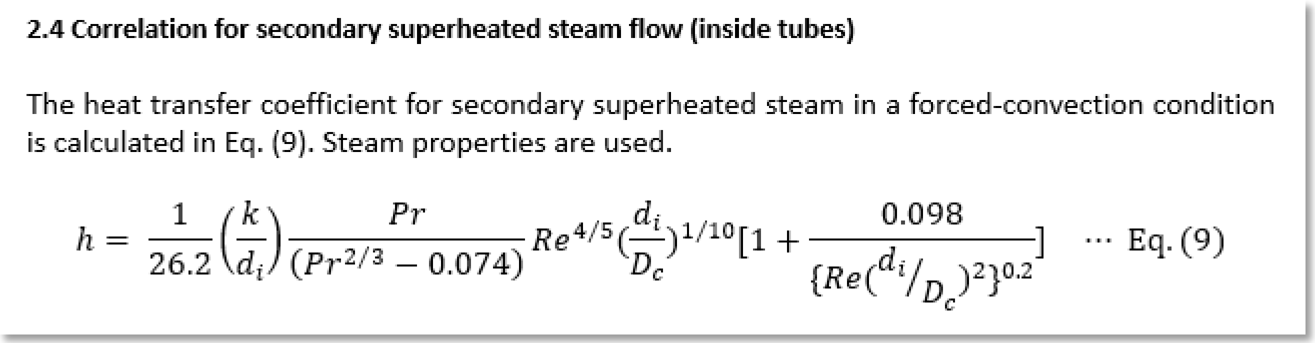
New models exercised on a pseudo-Fukushima RCIC.

Helical SG HTC in MELCOR 2.2

Helical Steam Generator (HSG) Heat Transfer Coefficients were implemented in MELCOR 2.2

Subroutines added for calculations of HSG heat transfer coefficients

- Subroutine HSGhtcSubcool for subcooled boiling
- Subroutine HSGhtcbl for two-phase flow
- Subroutine HSGhtcat for super-heated steam [Eq. (9)]



2.4 Correlation for secondary superheated steam flow (inside tubes)

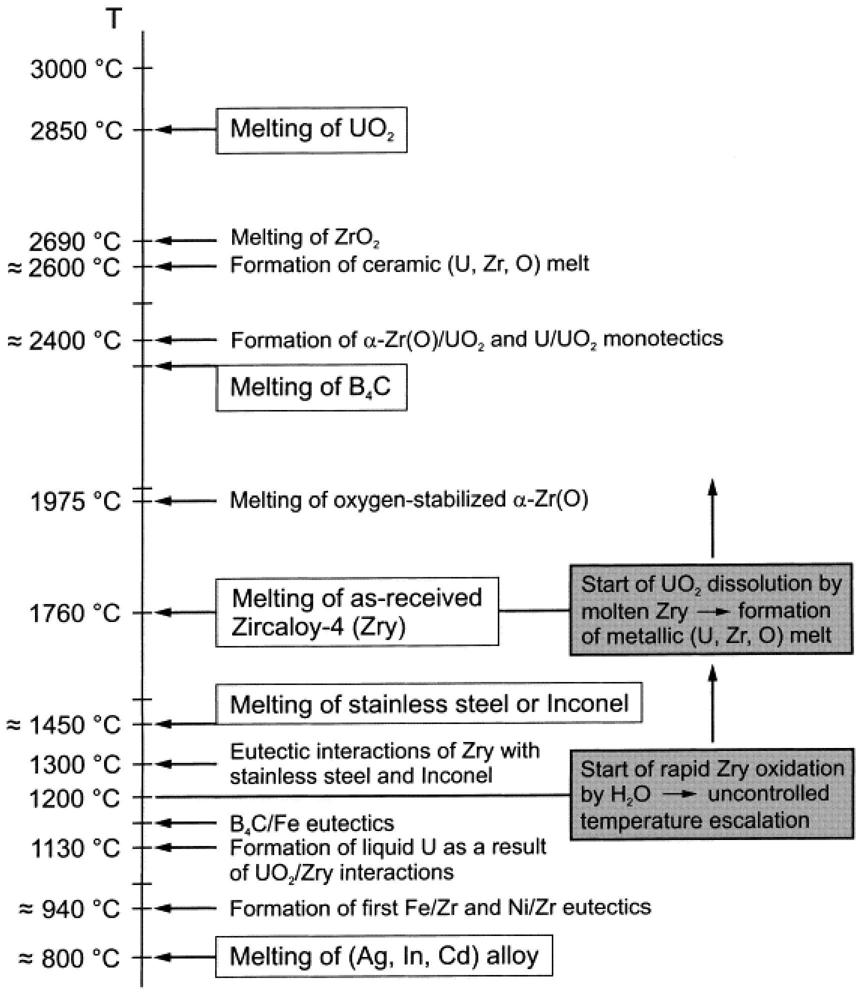
The heat transfer coefficient for secondary superheated steam in a forced-convection condition is calculated in Eq. (9). Steam properties are used.

$$h = \frac{1}{26.2}\left(\frac{k}{d_i}\right)\frac{Pr}{(Pr^{2/3}-0.074)}Re^{4/5}\left(\frac{d_i}{D_c}\right)^{1/10}\left[1+\frac{0.098}{\{Re({}^{d_i}/_{D_c})^2\}^{0.2}}\right] \quad \cdots \text{Eq. (9)}$$

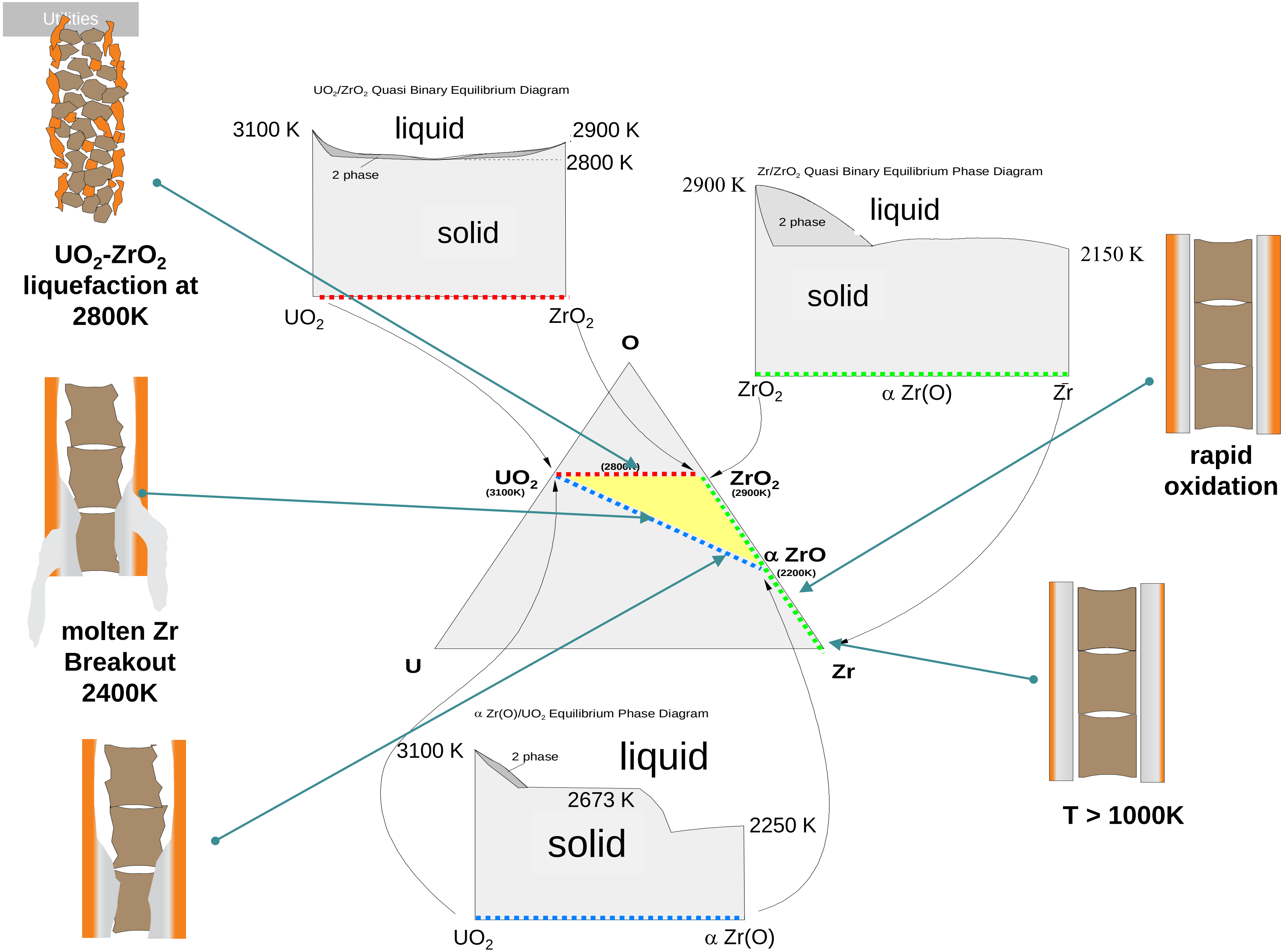
Sensitivity Coefficients added for the user to adjust code calculation

MELCOR Eutectic Model Overview

- Eutectics model has been in the code since M1.8.2
  - Eutectic model was not functioning since <u>at least </u>M1.8.5
    - UO2-INT and ZRO2-INT have been used to reduce melt temperature and modify enthalpy curves as an alternate approach
    - Applied globally to intact and conglomerate fields
- Recent work was done to revive eutectic model.
  - Only applies to conglomerate
    - Liquefaction of solids in contact using calculated rates
  - Two candling routines were used depending on whether eutectics active
    - Routines were recently unified
  - Numerous calls to mixture enthalpy routines were reviewed and corrected.
  - Eutectics model almost ready for beta testing
    - Passes all mass energy conservation tests



U/Zr/O Ternary Phase Diagrams



UO$_2$-ZrO$_2$ liquefaction at 2800K

molten Zr Breakout 2400K

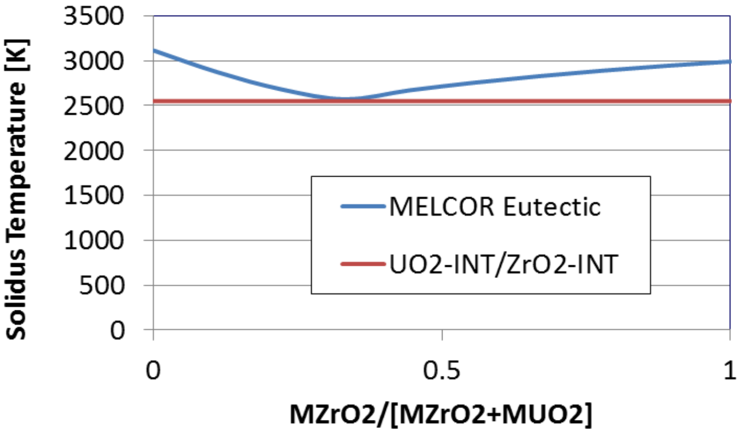
rapid oxidation

T > 1000K

MELCOR Eutectic Temperature

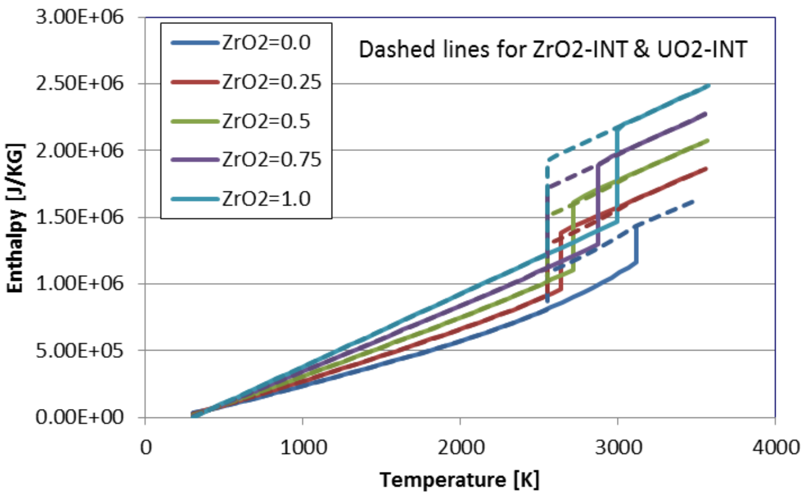
UO2-INT/ZRO2-INT

- Melt temperature for UO2 & Z
  materials as it is for conglomer
- Does not depend on compositi



Eutectic Model

- Melt temperature of intact ma
  points while conglomerate use
  - Liquefaction of solids in contact f
- Melt temperature dependent (



The existing MELCOR eutectics model provides a framework from which a new MELCOR model may be constructed

Eutectic Model Input

- New Input for the Eutectic model

```
   COR_EUT  1  !  PairMelt        T              f1
                1   'UO2/ZRO2'   2550.0      0.5
```

COR_EUT   0   enables the model w/o additional
                        records & uses defaults

PairMelt can be one of the following:

ZR/SS (or 1), ZR/INC (or 2), UO2/ZRO2 (or 3)

TM is the Solidus temperature for the eutectic pair

F1 is the molar ratio of the first member in the pair at the eutectic temperature

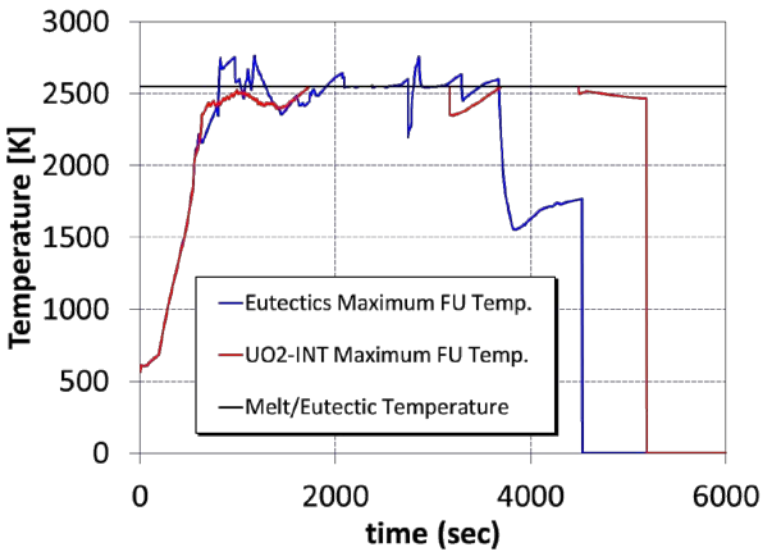
- Obsolete input for activating eutectic model
  - COR_MS   IEUMOD
    - Message will indicate new input method.
      - ERROR: The Eutectics model is enabled on COR_EUT
- Interactive materials should not be used with the eutectic model

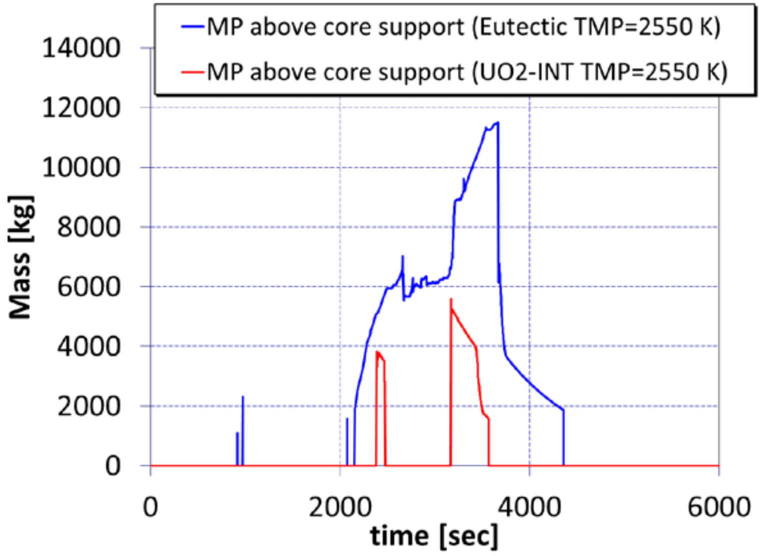
```
MP_INPUT
          MP_ID 'ZRO2-INT’
                    MP_PRC 5600.0 2502.0 707000.0 ! density, melt temp, latent heat
          MP_ID 'UO2-INT'
                    MP_PRC 10960.0 2502.0 274000.0! density, melt temp, latent heat
COR_INPUT
          COR_MAT 2   !          CORMAT        MATNAM
                    1          UO2     'UO2-INT'
                    2          ZRO2  'ZRO2-INT'
```

These cards should be removed from deck

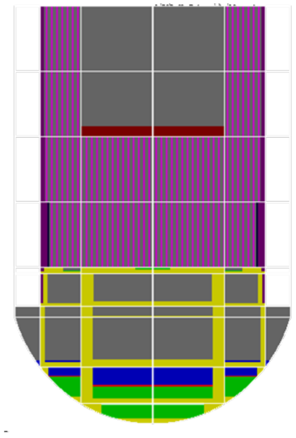
Eutectic Model - Simple BWR

- BWR test case
  - Eutectics point = 2550 K
  - UO2-INT/ZRO2-INT MP = 2550 K
- FU temperature exceeds eutectic temperature
- FU always less than UO2-INT melt temperature
- More molten material relocates early to lower head for UO2-INT
- Molten pool in upper core is larger for eutectics case



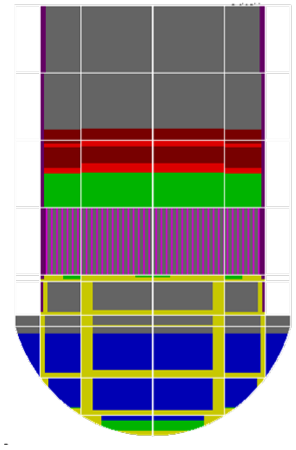


UO2-INT



3040 (sec)

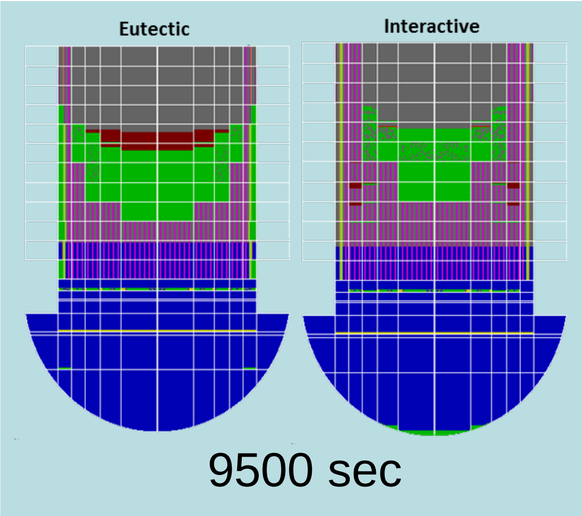
Eutectic

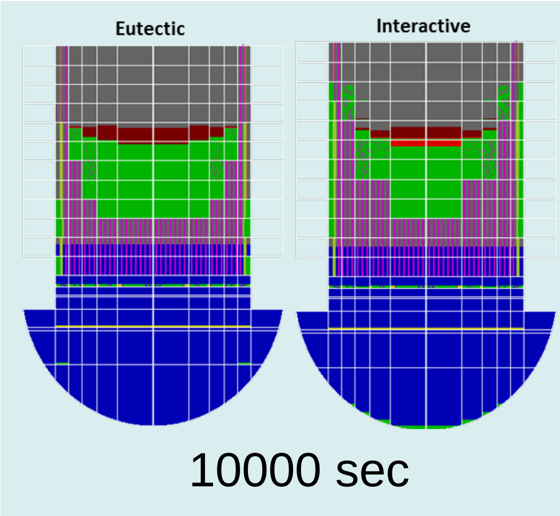


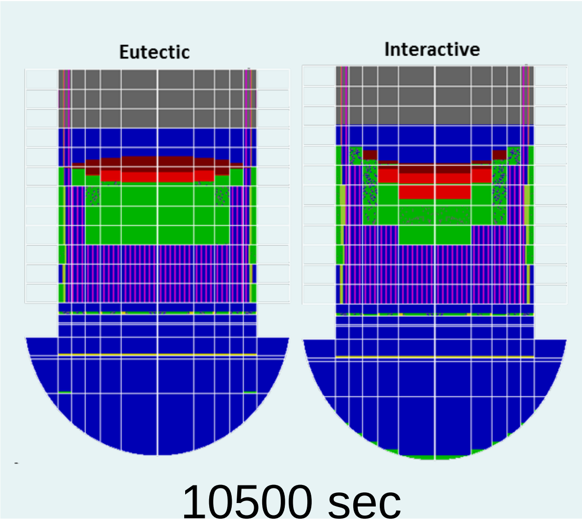
3040 (sec)

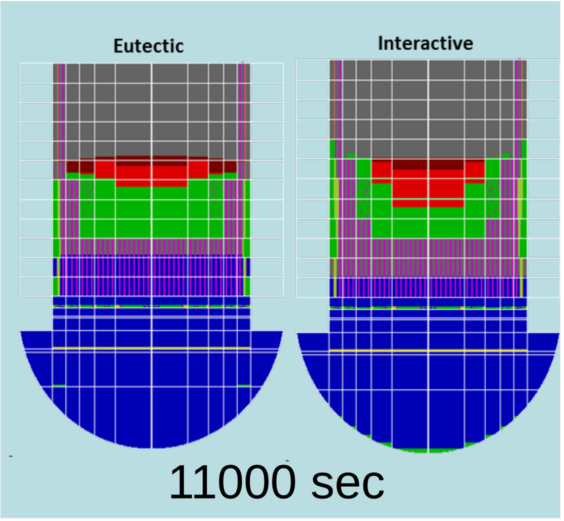
TMI Melt Progression – Preliminary Results

- Compare two TMI-2 test cases
  - Eutectics point = 2550 K
  - Interactive UO2-INT/ZRO2-INT 2550 K
- Similarities but notable differences
  - Core damage
    - Greater for eutectics
  - Size of Molten pool
    - Greater for interactive
  - Material relocating to lower plenum
    - Greater for interactive
- Interactive case appears slightly more representative of TMI
  - Results are preliminary



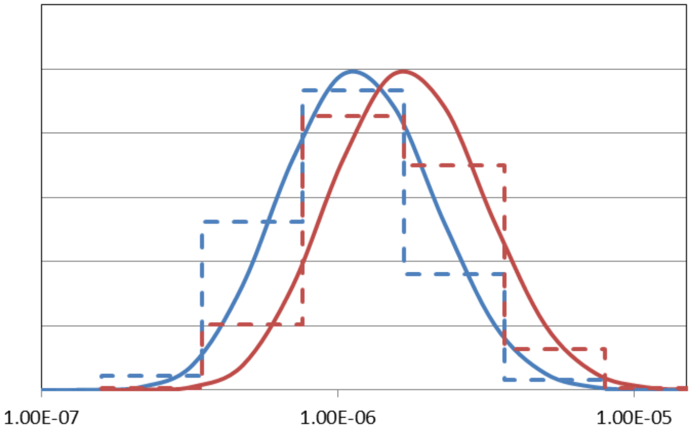




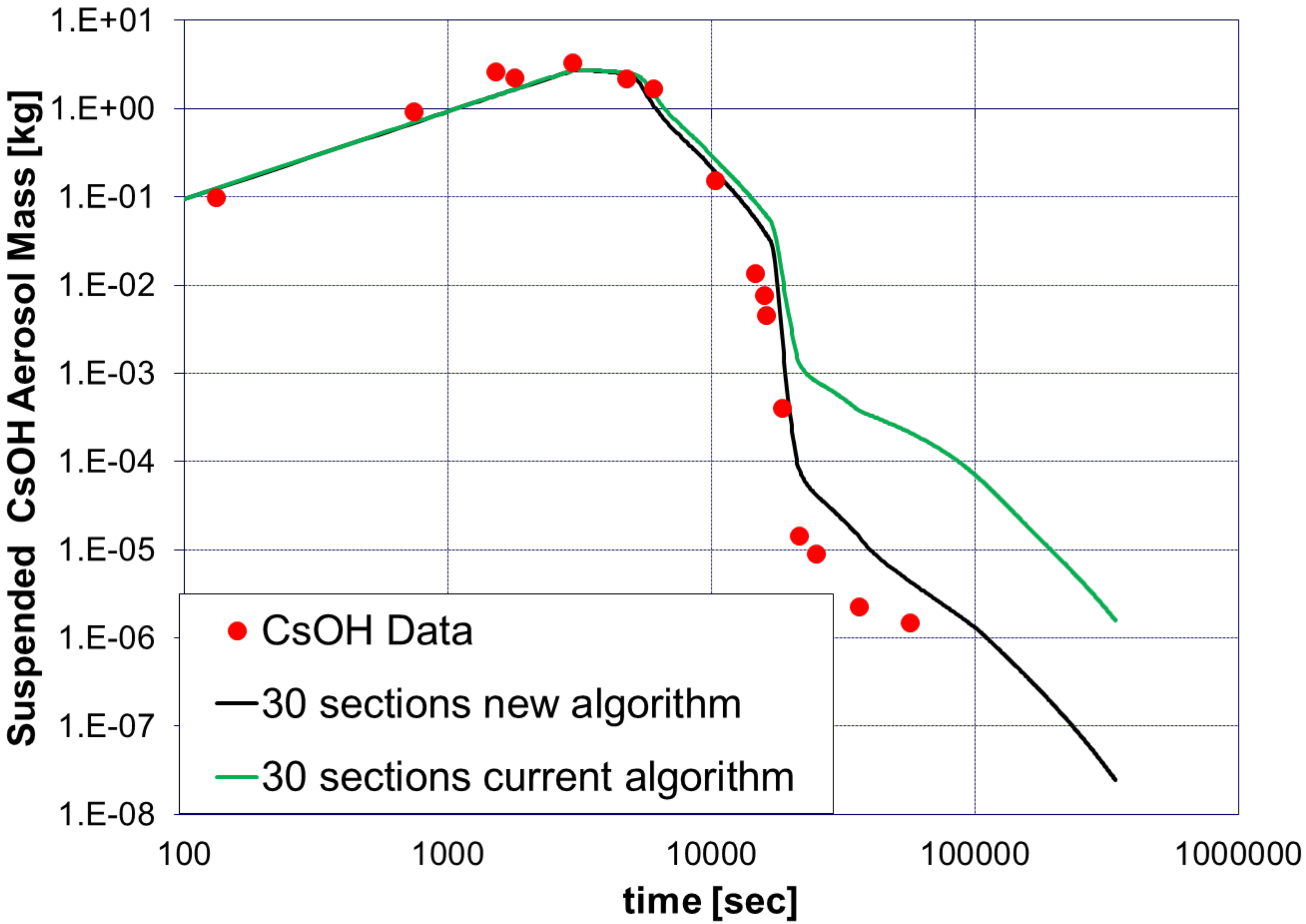


Vapor Condensation/Hygroscopic Model (in progress)

- Multiple aerosol components (i.e. chemicals or materials) can condense or vaporize instead of just one component which is typically water.
- New condensation/evaporation algorithm significantly reduces numerical diffusion of aerosol growth
  - Better resolution of aerosol mass within a section (particle size bin).
    - Number mean particle mass tracked in addition to total mass
  - Previously aerosol particles growing into a section were automatically uniformly spread across size bin, but now higher order resolution within a bin to be used.



Improved Condensation Algorithm Results (LA4)



Upcoming Aerosol Modeling

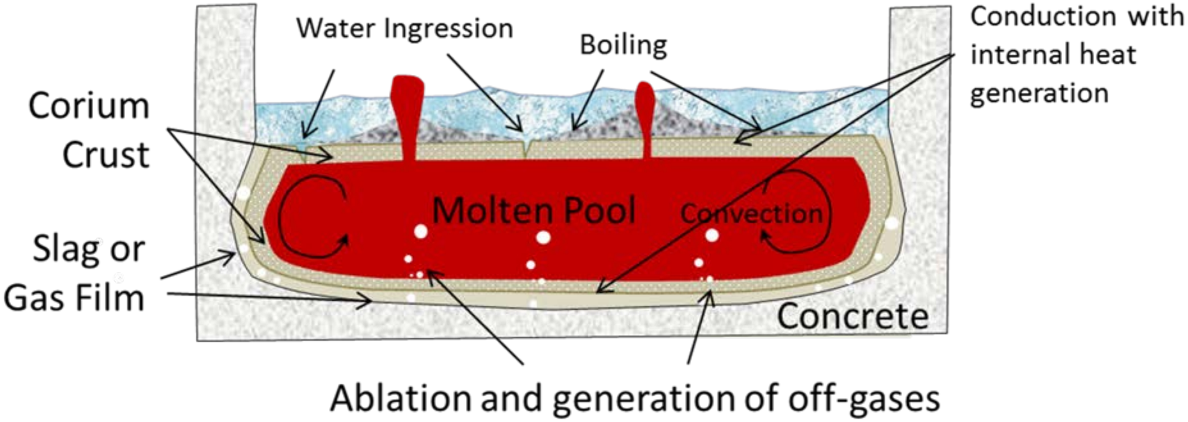
- **Current Status**: all aerosol components (chemicals) have the same material density, typically 1000 kg/m^3 corresponding to water.

- **Upcoming**: MELCOR will allow for each aerosol component to have user specified material density from a set of material densities.
  - This will significantly affect gravitational settling removal of different aerosol components with different material densities.
  - Algorithm already developed. Testing, **incorporation into MELCOR,** and documentation remain.

Upcoming Code Development

- Fix CORQUENCH models (water ingression)
- Heat Structure surface area and axial lengths variations
- User-Defined COR Materials
- In-vessel Retention Modeling
- Advanced Technology Fuels (ATF)
- Non-LWR Reactors
  - HTGR
  - Sodium
  - Molten Salts

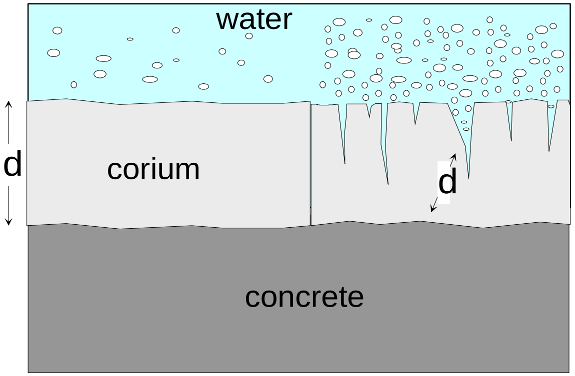
New Modeling for Top-Quenched Debris in Cavity



- Quenching of the upper crust at the top of the corium debris can lead to a considerable density change (~18%volume) leading to cracking and formation of voids
  - Water ingression reduces conduction path to molten pool and increases surface area of contact
- Molten corium extruded through crust by entrainment from decomposition gases as they escape through fissures and defects in the crust.
  - Enhance the coolability of the molten corium
    - by relocating enthalpy from the internal melt through the crust
    - more coolable geometry that is more porous and permeable to water

Pre 2015 MELCOR Best Practice

- Water ingression will increase the contact surface area between water and the corium
- Decrease the conduction path length through the corium, both of which will enhance the heat transfer through the crust



$$Q = -A \cdot k \frac{dT}{dz} \sim -\frac{\boldsymbol{A}}{\boldsymbol{d}} k\Delta T \sim -\frac{A}{d} \boldsymbol{k} \Delta T$$

- MELCOR best practice attempted to account for this effect by applying a thermal conductivity multiplier
  - Based on benchmarking against MACE tests
- MELCOR model development is focusing on improvements in the CAV package to capture water ingression and melt eruptions
  - New porous layer for debris relocating above crust
  - New porous crust layer
  - Dense crust layer

CORCON/CORQUENCH Model

Enhanced Conductivity

(2010)

```
CAV_U   9
   …
  5 BOILING   value  10.0
  6 COND.OX    mult 5.0
  7 COND.MET   mult 5.0
  8 HTRINT  multip 1.0
  9 HTRSIDE multip 1.0
```

Modified Enhanced Conductivity

(2012)

```
CAV_U   10
   …
5 BOILING   value  10.0
6 COND.OX    mult 1.0
7 COND.MET   mult 1.0
8 HTRINT  multip 5.0
9 HTRSIDE STAND
10 COND.CRUST   3.0
```

Still current best practice

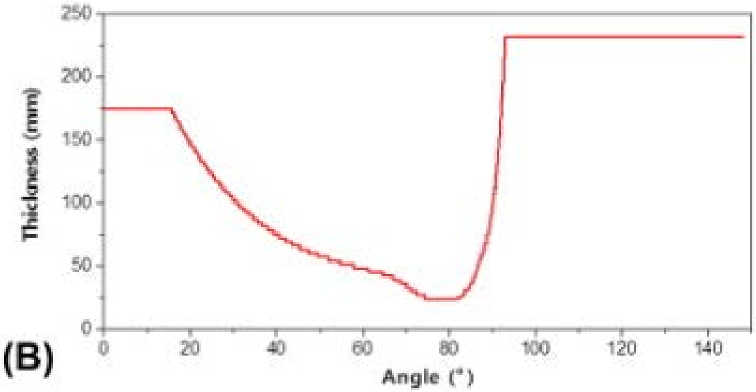
Water Ingression

(2015)

```
CAV_U   10
   …
  5 BOILING    VALUE 10.0
  6 COND.OX    MULT 1.0
  7 COND.MET   MULT 1.0
  8 COND.CRUST 1.0
  9 WATINGR    ON
  10 ERUPT  ON
```

Future In-Vessel Retention Code Improvements

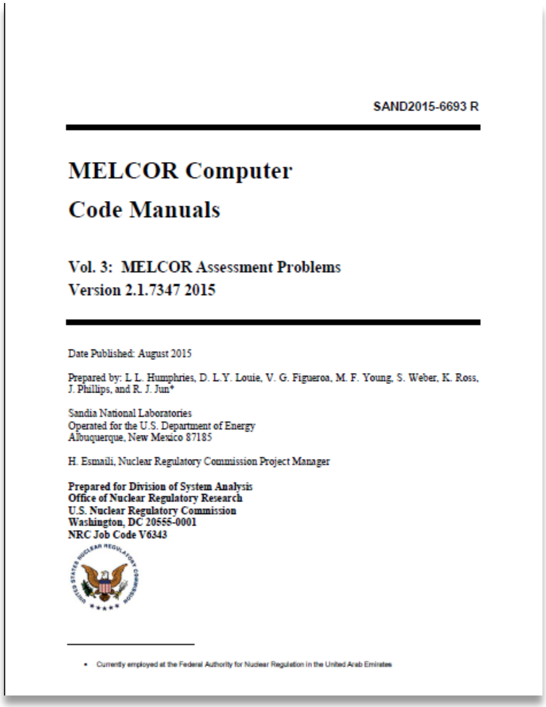
- Melting Lower Head
  - Addition of molten steel to debris
    - Similar to HS degassing model
    - Impact on focusing effect
    - Steel relocates to CAV for MCCI
  - Modify lower head thermal model for moving melt boundary
    - Adaptive vs fixed grid
    - Thinning of vessel wall
    - Effect on local stress
  - Improved diagnostics
- Control Rod Guide Tubes
  - Cooling effects
  - Penetration Failure Model
    - Review of LHF experiments and add strain-based model
  - Heavy Metal Layer?



Thickness of the reactor vessel wall SBO

Evaluation of heat-flux distribution at the inner and outer reactor vessel walls under the in-vessel retention through external reactor vessel cooling condition
Jaehoon Jung, KAERI, January 2015

Future MELCOR Manual Updates



SAND2015-6693 R

MELCOR Computer
Code Manuals

Vol. 3: MELCOR Assessment Problems
Version 2.1.7347 2015

Date Published: August 2015

Prepared by: L. L. Humphries, D. L.Y. Louie, V. G. Figueroa, M. F. Young, S. Weber, K. Ross, J. Phillips, and R. J. Jun*

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Volume III: Assessments

R&A Complete
SAND2015-6693 R

By December 2017
- Demo PWR plant deck
- Demo BWR plant deck
- COR/CVH Nodalization
- Containment DBA
- Numerical Variance
- Steady State Initialization

By December 2018
- FL/CVH Modeling
- Uncertainty Analysis
- Spent Fuel Pool Modeling
- Radionuclide Class Modeling
- MELCOR/MACCS Integration
- Troubleshooting MELCOR runtime issues
- Lower Head Modeling
- Heat Structure Modeling
- Cavity Related Modeling

Volume IV: Modeling Guide

Objectives for Modeling Guide

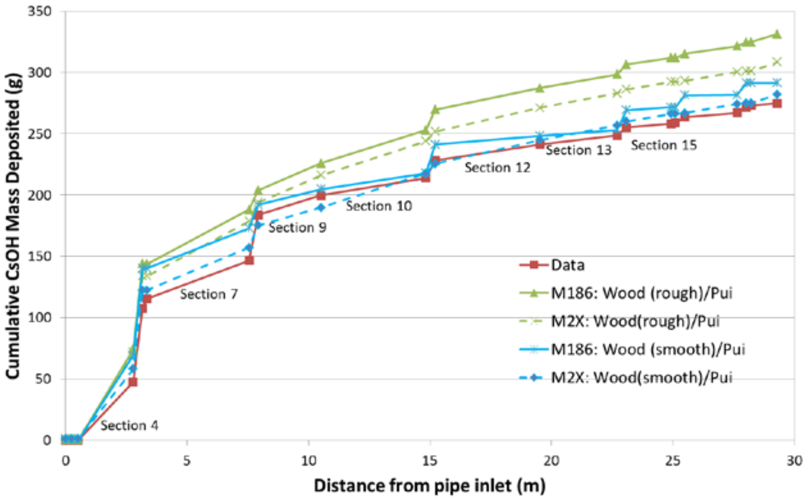
- User Guidance
  - MELCOR has a steep learning curve and guidance is needed to help new users learn how to develop input decks.
    - Generate non-proprietary plant decks
      - BWR, PWR, SFP
    - Volume IV references these sample plant decks
  - Provide meaningful insights, recommendations, demonstrations of modeling methodology in a formal report for many commonly asked questions across much of the model space
  - Describe pitfalls and methods for troubleshooting and assessing results.
    - How to address code execution problems
    - How to review results to know the code is giving reasonable results
- Best Practices
  - Provide guidelines for appropriate use of the code in modeling severe accidents.
    - Recommended models and model options

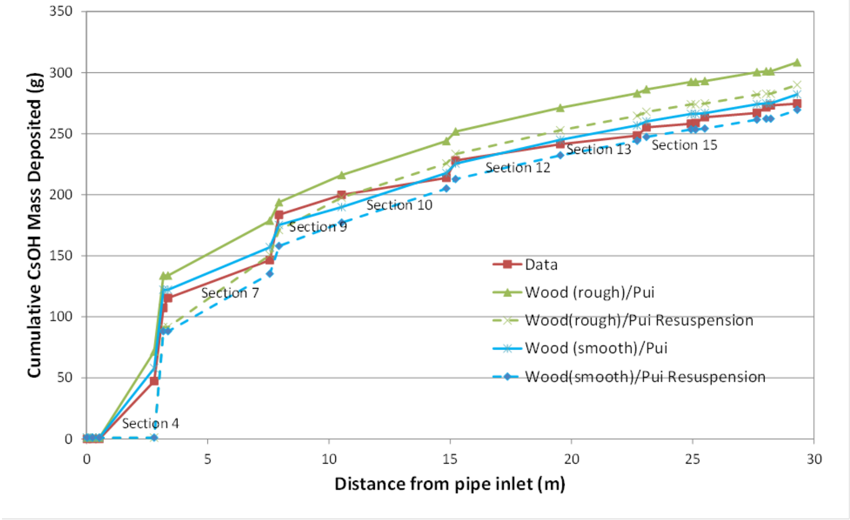
Cases in MELCOR Assessment Report - SAND2015-6693 R

- **MELCOR ANALYTIC ASSESSMENT**
  - Saturated Liquid Depressurization
  - Adiabatic Expansion of Hydrogen
  - Transient Heat Flow in a Semi-Infinite Heat Slab
  - Cooling of Heat Structures in a Fluid
  - Radial Heat Conduction in Annular Structures
  - Establishment of Flow
- **MELCOR ASSESSMENTS AGAINST EXPERIMENTS**
  - Analysis of ABCOVE AB5 and AB6 Aerosol Experiments
  - Analysis of ACE Pool Scrubbing Experiments
  - Analysis of AHMED 1993 NaOH Experiments
  - Analysis of the Bethsy 6.9c Experiment (ISP-38)
  - Analysis of Containment System Experiment for Spray –A9 Test
  - Analysis of the Cora 13 (ISP 31) Experiment
  - Analysis of Aerosol Behavior from the Demona-B3 Experiment
  - Analysis of Level Swell from the General Electric Large Vessel Blowdown and Level Swell Experiment – 5801-13
  - Containment Analysis from the JAERI Spray Experiments
  - Analysis of LACE LA-4 Experiment
  - Analysis of LOFT LP-FP-2 Experiment
  - Analysis of Critical Flow from the Marviken CFT-21 and JIT-1 Experiments
  - Analysis of Marviken-V Aerosol Transport Test (ATT-4)
  - Analysis of NTS Hydrogen Burn Combustion Tests
  - Analysis of the Nuclear Power Engineering Corporation (NUPEC) Mixing Tests
  - Analysis of the PHEBUS FPT-1 Experiment
  - Analysis of the PHEBUS FPT-3 Experiment
  - Analysis of the POSEIDON Integral Experiments under Hot Pool Conditions
  - Analysis of STORM Aerosol Mechanical Deposition Tests
  - Melt Coolability and Concrete Interaction Experiments
    - CCI-1, CCI-2, and CCI-3
- **ASSESSMENTS IN NEXT REVISION**
  - LACE LA3 (Turbulent Deposition)
  - TMI-2 Accident
  - STORM (resuspension phase)

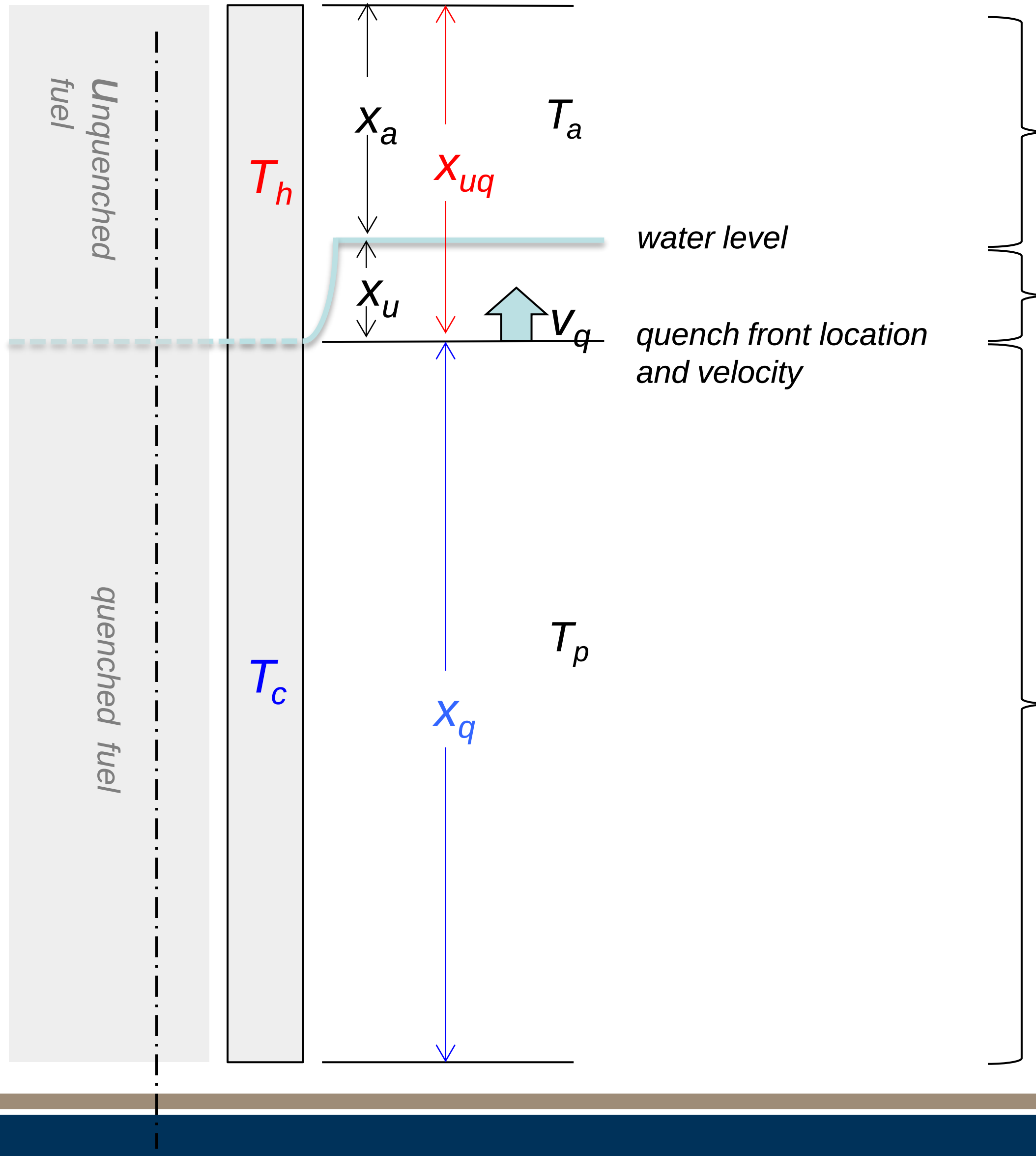
LACE LA3 Assessment of Turbulent Deposition

- MELCOR 2.1 assessment of turbulent deposition model shows excellent agreement with test data
  - Minor modeling improvements/corrections were made since the M186 implementation
  - Input for turbulent deposition model was recently improved
    - Workshop exercise
    - Updated in recent manuals
- New resuspension model was also assessed against this test
  - Predicted resuspension may be too large at entrance
  - May not correctly account for sticking of aerosols





Reflood Quench Model (1)



HTCATM, QCNVA

HTCPR, QCNVS*, QCNVIN

* includes "quenching" heat transfer as location moves

HTCPOL, QCNVP

Reflood Quench Model (2)

- MELCOR computes a quench velocity, distinct from pool water level
  - The quench velocity correlation implemented is that of Dua and Tien[1]

$$Pe = \left[\bar{B} \left(1 + 0.4 \bar{B} \right) \right]^{1/2}$$

    - Where
      - Pe is the dimensionless quench velocity or Peclet number

$$\mathrm{Pe} = u^* = \frac{u\delta}{\alpha}$$

      - $\bar{B}$ is a dimensionless Biot number

$$\bar{B} = \mathrm{Bi}(1-\Theta)^2/\Theta \qquad \mathrm{Bi} = \frac{h^*\delta}{k} \qquad \Theta = \frac{T_h - T_{sat}}{T_{max} - T_{sat}}$$

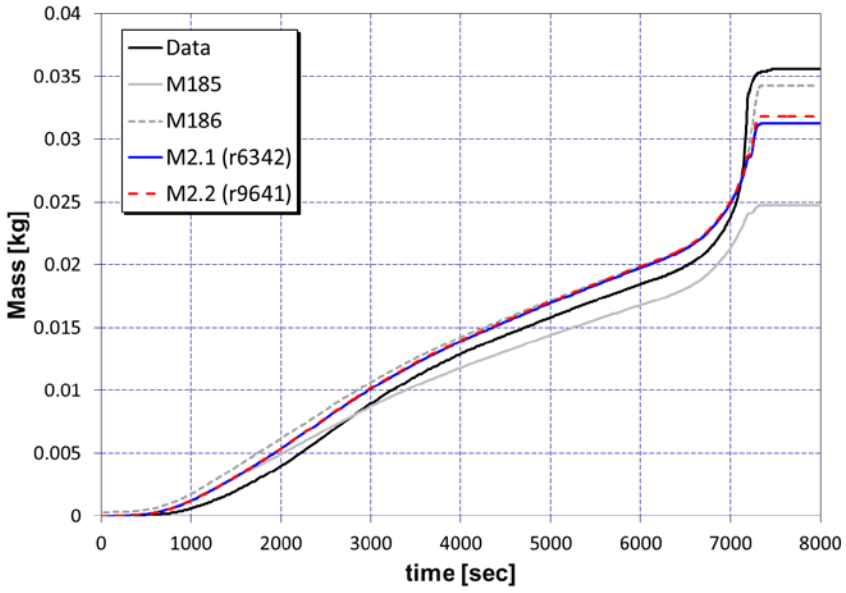
  - May be thought of as an interpolation between a result based on one-dimensional conduction in thin surfaces (small Bi), and one based on two-dimensional conduction in thick surfaces (large Bi).

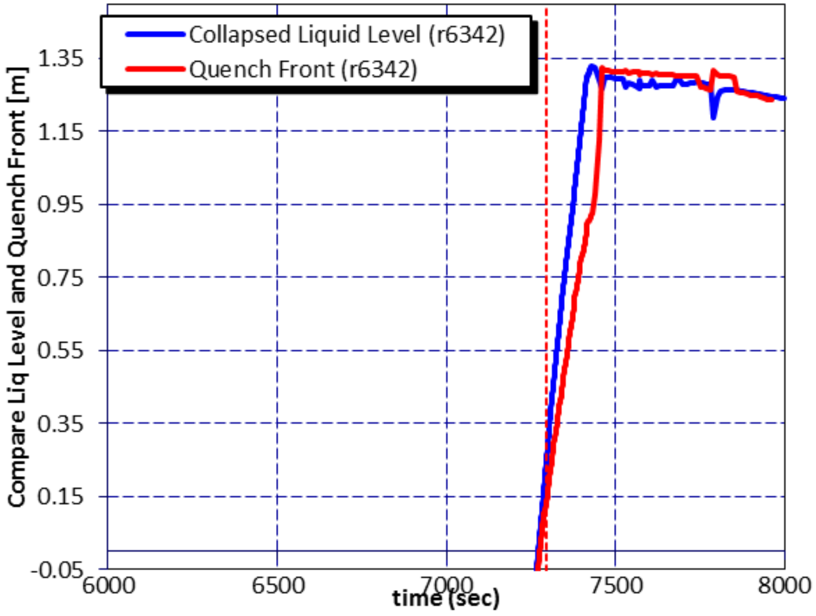
---

[1] *S. S. Dua and C. L. Tien, Intl. J. Heat and Mass Transfer 20, pp.174-176 (1977).*

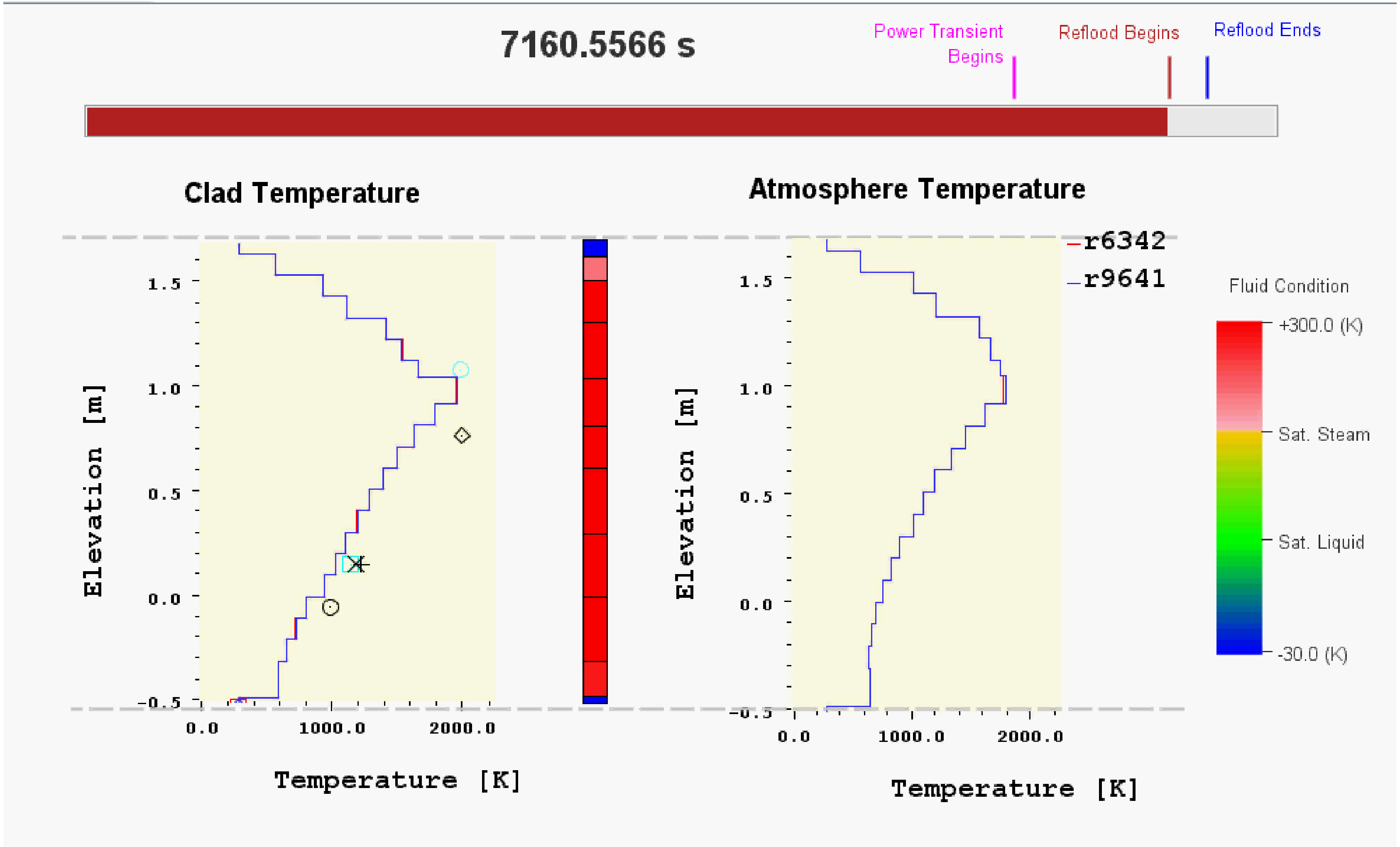
ISP-45 (Quench-06 experiment) MELCOR Simulation

- Quench model effects oxidation
  - Changes component temperatures
  - Oxidation of submerged components
  - Little change in total oxidation since last release (r6342)

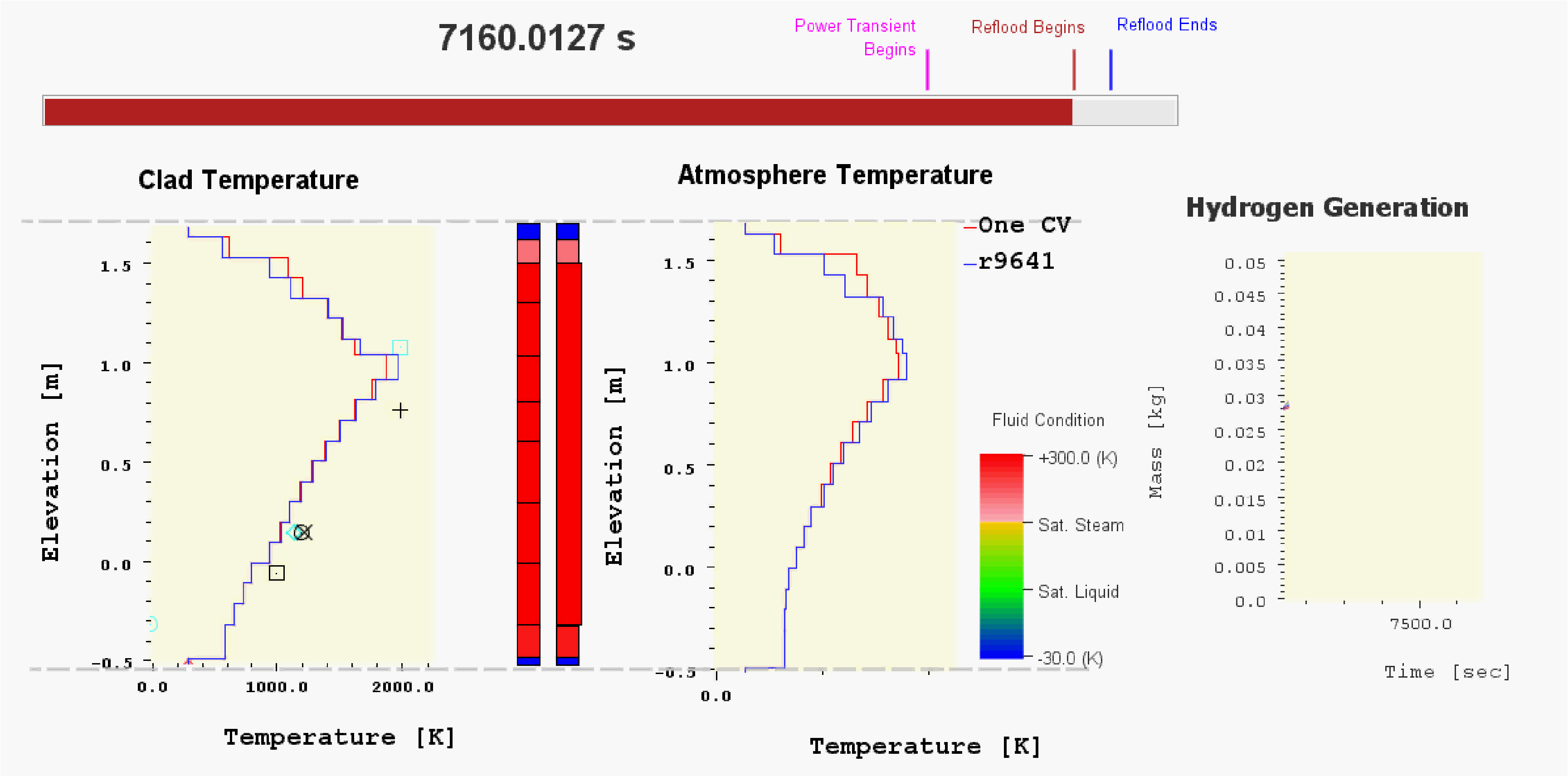




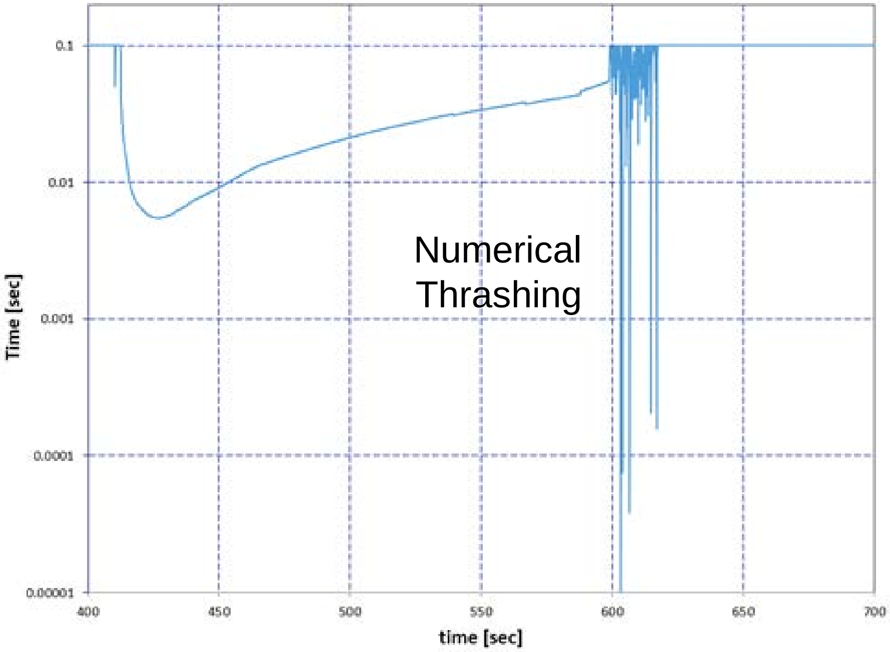
ISP-45 (Quench-06 experiment) MELCOR Simulation



Nodalization – Compare Single CV to CV stack (Preliminary Results)

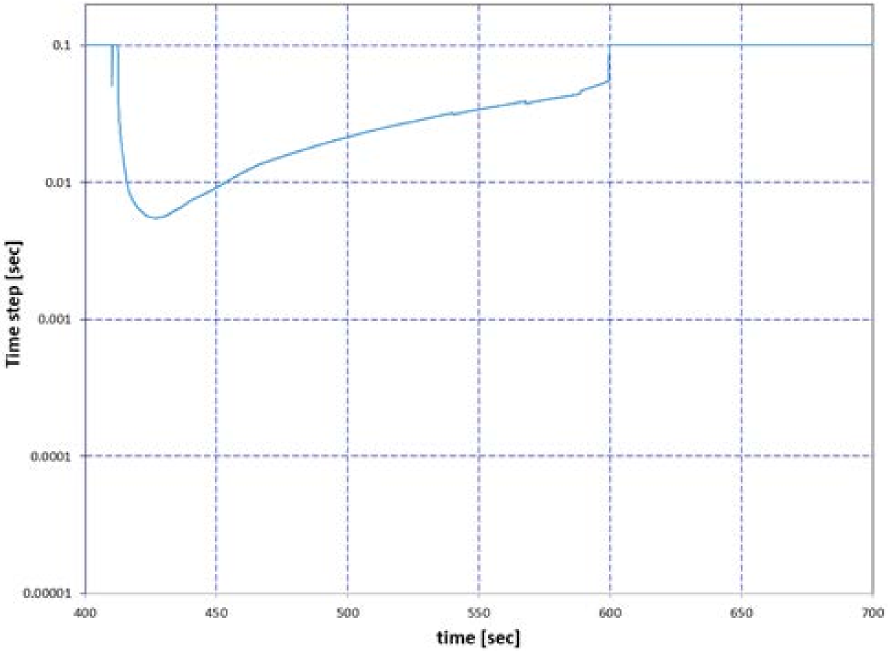


Time-step size vs. simulation time



Numerical Thrashing

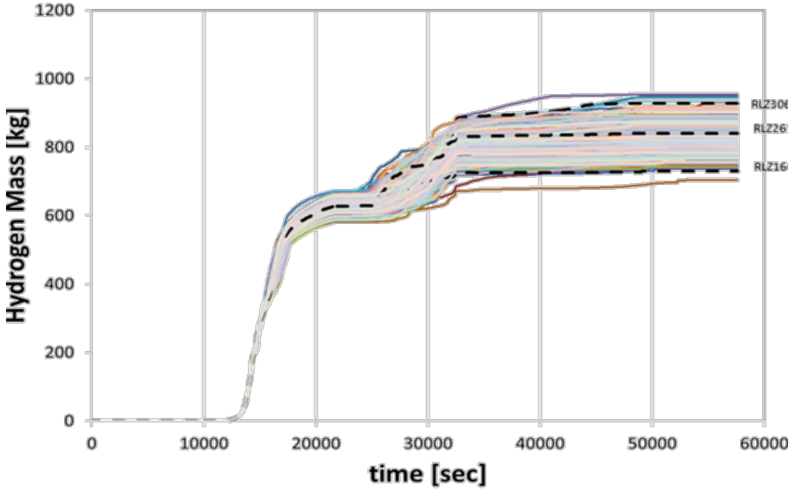
Modeling changes inactive

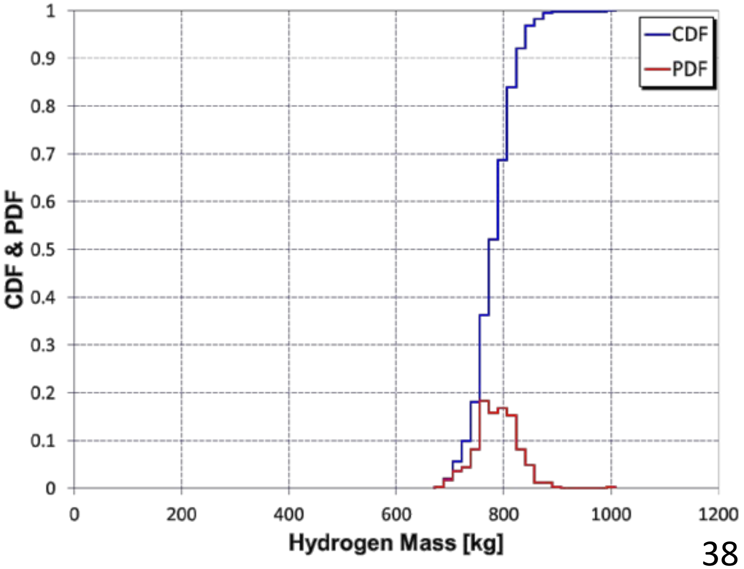


Modeling changes active

Numerical Variance

- Two calculations with the same geometric definition, identical boundary conditions, and identical code versions giving different results.
  - Numerical noise sources
    - Roundoff
      - Matrix solves
        - direct, iterative
    - Convergence criteria
  - Numerical amplifiers
    - Numerical instabilities
      - cause exponential growth and unless controlled will cause the code to crash.
    - Numerical oscillations
      - these take a smooth solution with a very high entropy and add oscillation structure. These are most dangerous when the oscillation “triggers” a set point in the calculation and start the transient on a new path like a pressure relief valve.
    - Discontinuous physics models
      - Such threshold effects may be due to a model in the code or can even result from ‘user models’ based on control functions.
  - Variance initiators
    - Flow path shuffling
    - Time step history
    - Computer systems



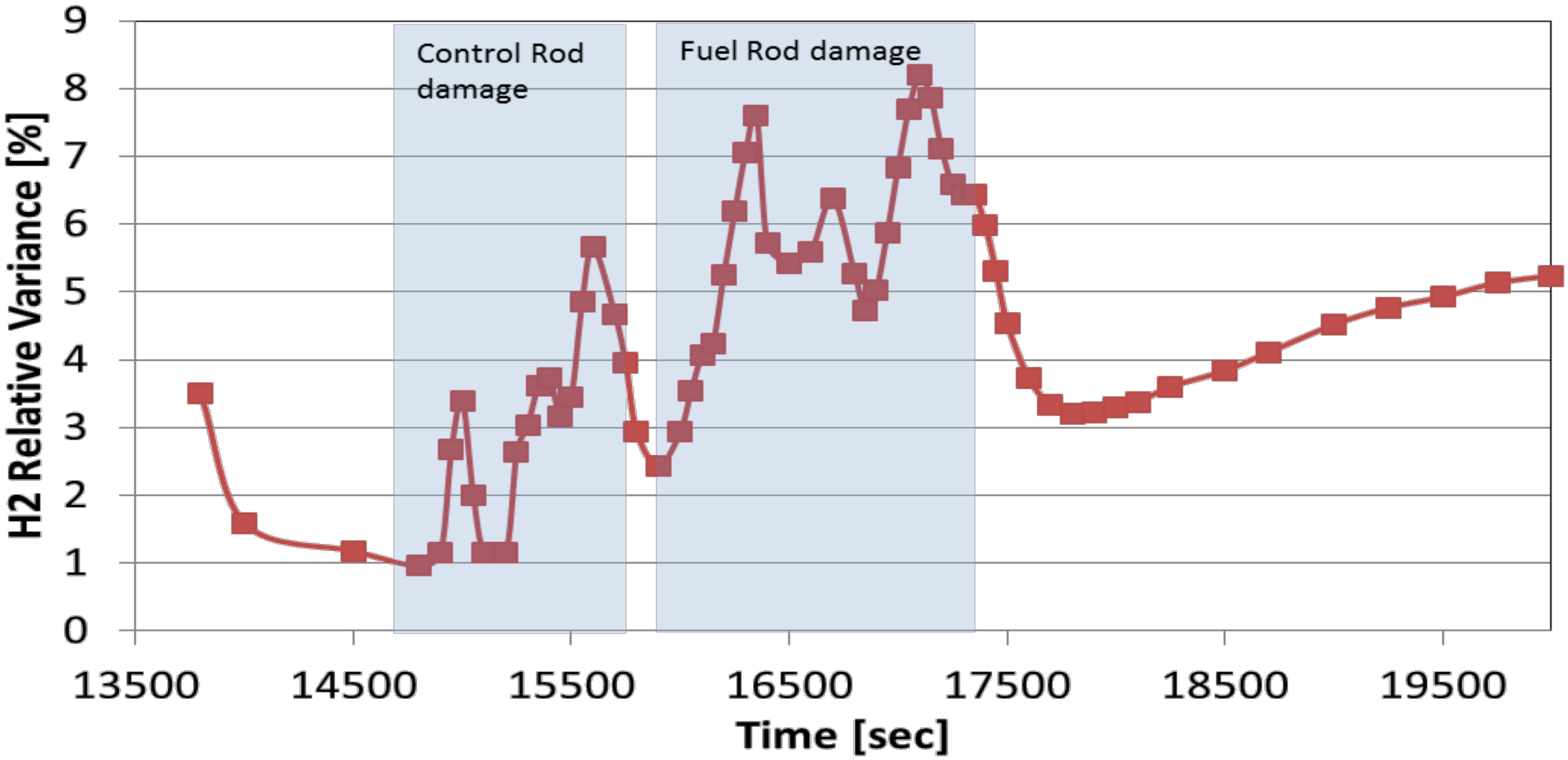


Numerical Variance

- Characterization of Numerical Variance
  - Background code variance
    - Sources of variance
    - Amplifiers
  - Effect of COR Nodalization on Numerical Variance
    - COR cell nodalization
    - CVH nodalization
  - Assess the sensitivity of the variance to COR degradation models
  - Time step variations & time step convergence
  - Application to UA variations
    - Discriminating parameter variance from background variance
      - Signal to noise ratio
- Reduction of Numerical Variance
  - Reduction of tolerances
  - Hysteresis effects (Relief Valves)
  - Others

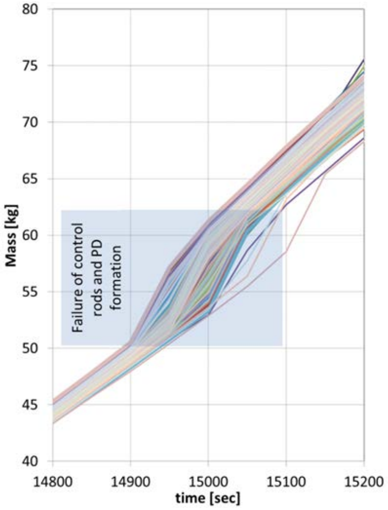
Propagation of Variance

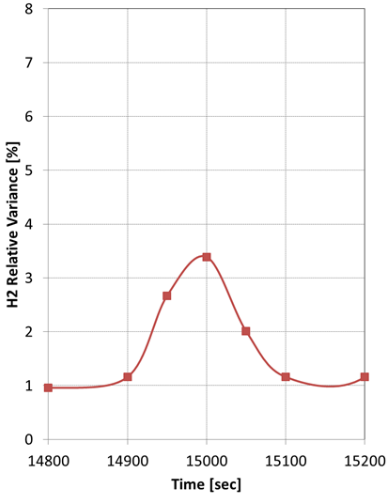
- Monitor code variance during accident sequence
- Identify events leading to increased variance.



Events with full recovery of variance

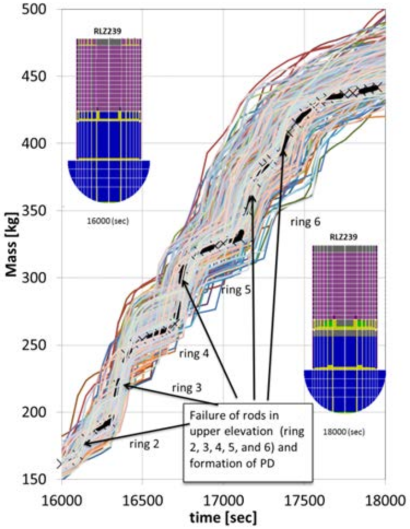
Failure of control rods in ring 1

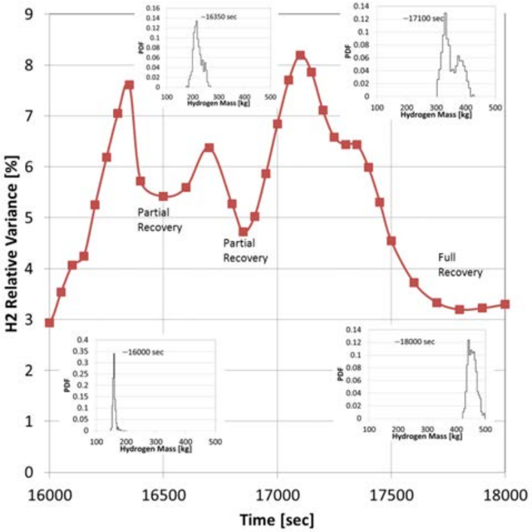




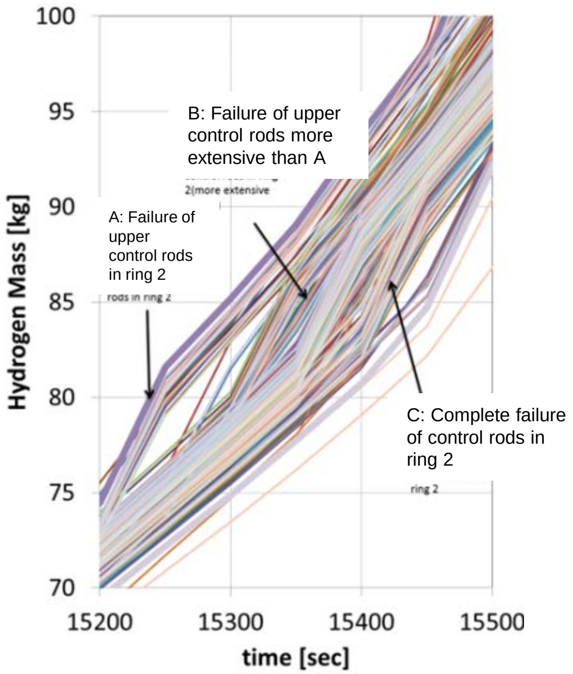
Full recovery (time offset event)

Failure of Upper Level





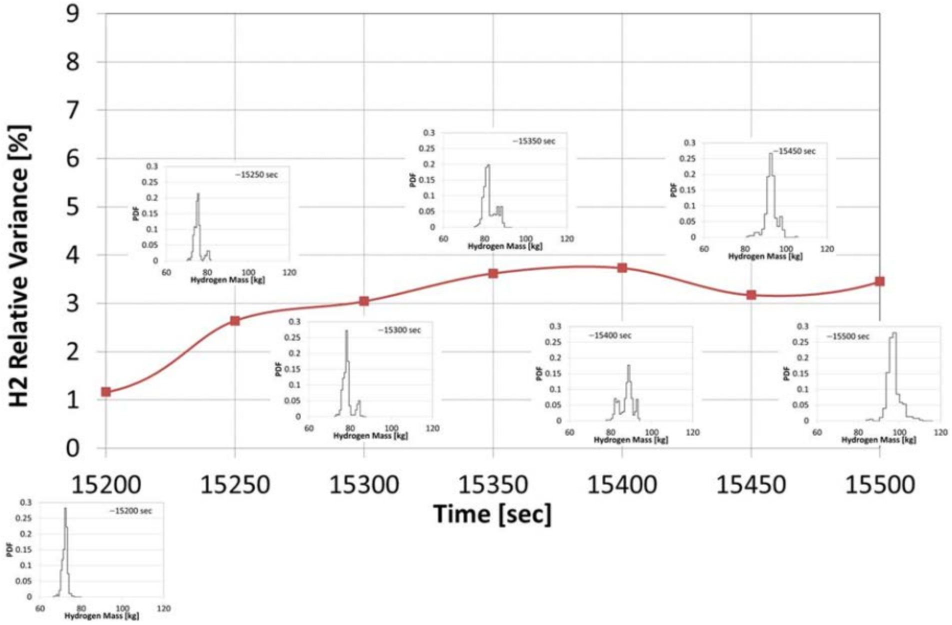
Events without recovery in variance



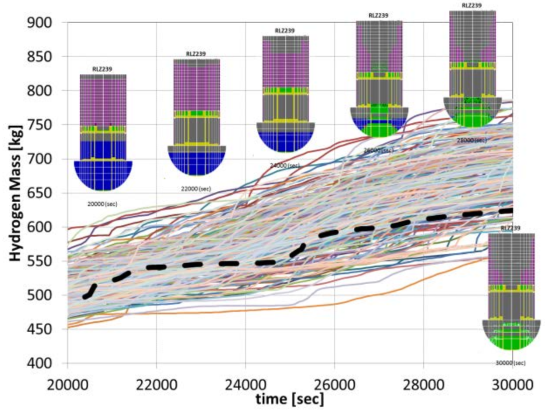
B: Failure of upper control rods more extensive than A

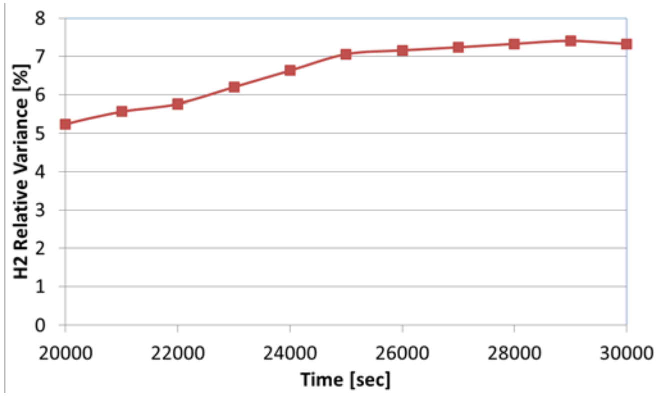
A: Failure of upper control rods in ring 2

C: Complete failure of control rods in ring 2



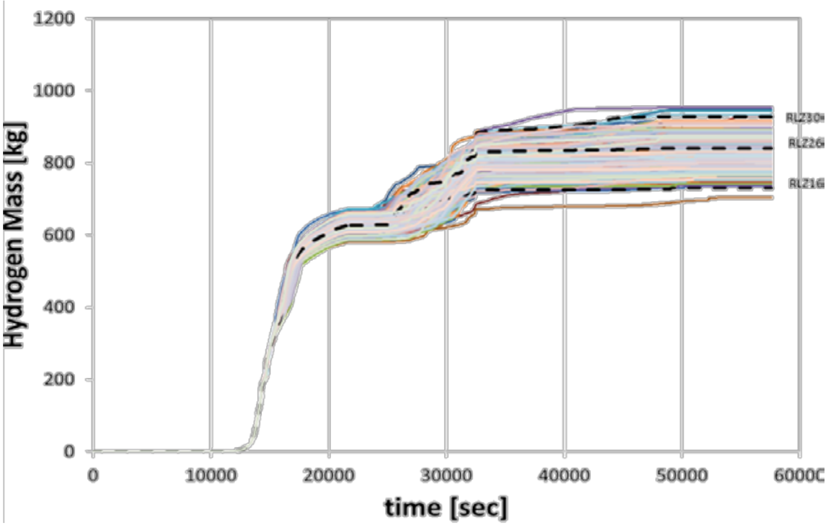
Failure of Active Core



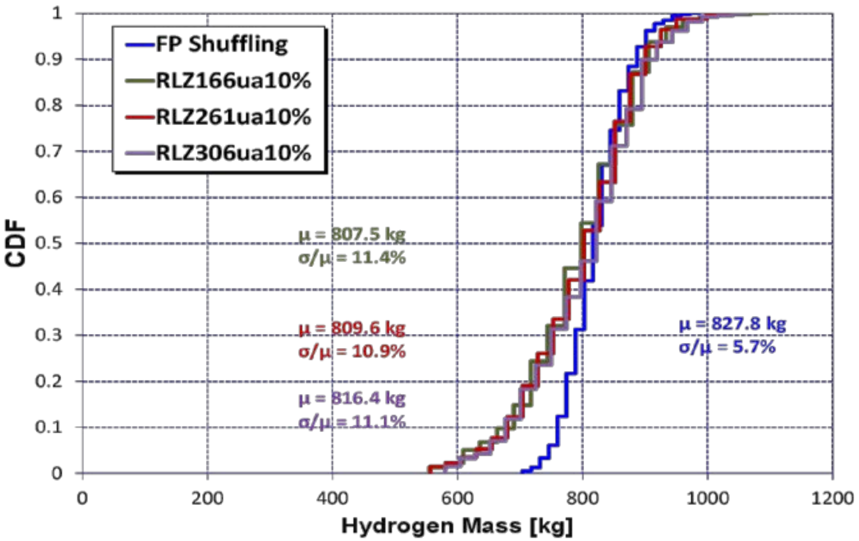


Representative Extremes of “shuffle” used as seed for 10% UA variations

- FU1 deck was perturbed via flow path shuffling
- Representative realizations were selected at average and extremes
- Realizations were perturbed via flow path shuffling.

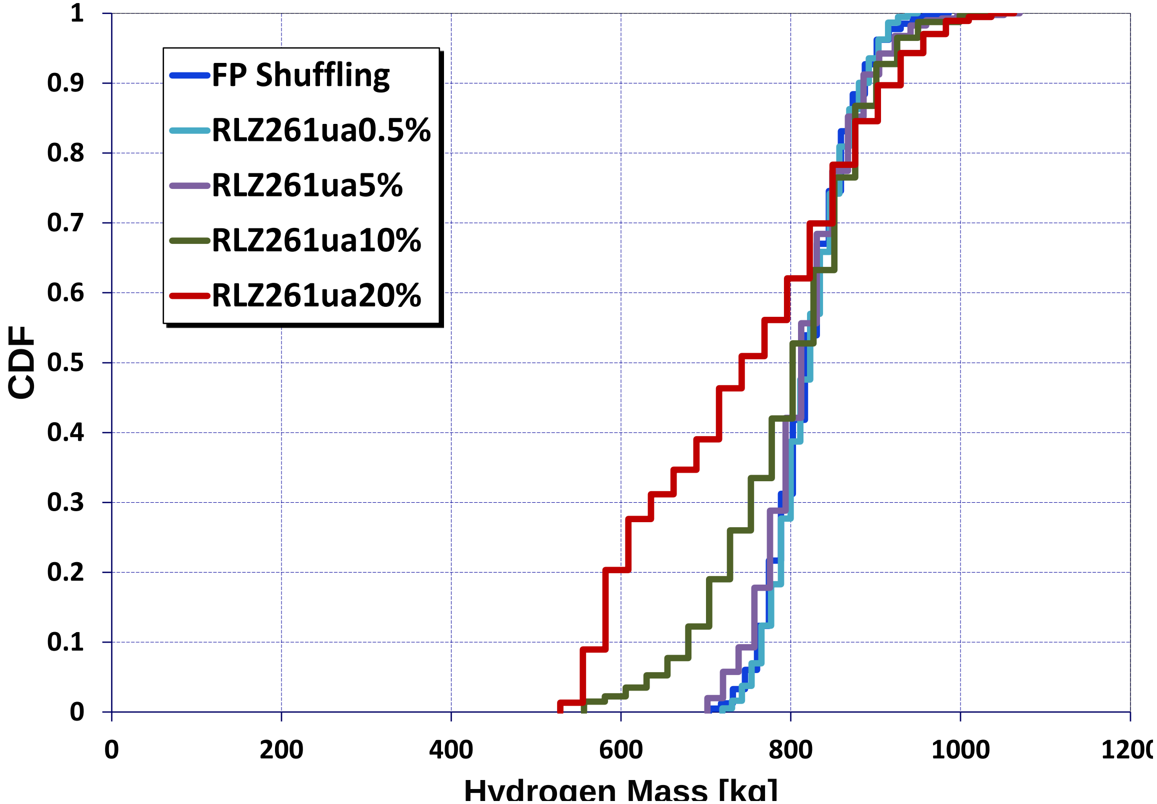


Each representative member of the “shuffle” ensemble returns the same resultant distribution when UA parameters are varied



UA Variation Explored to Characterize Signal to Noise Ratio

- Uncertainty analysis was performed for 'average' realization
- All uncertainty parameters were varied uniformly over a defined range
- Variance distribution functions were compared to numerical variance case (FP shuffling)

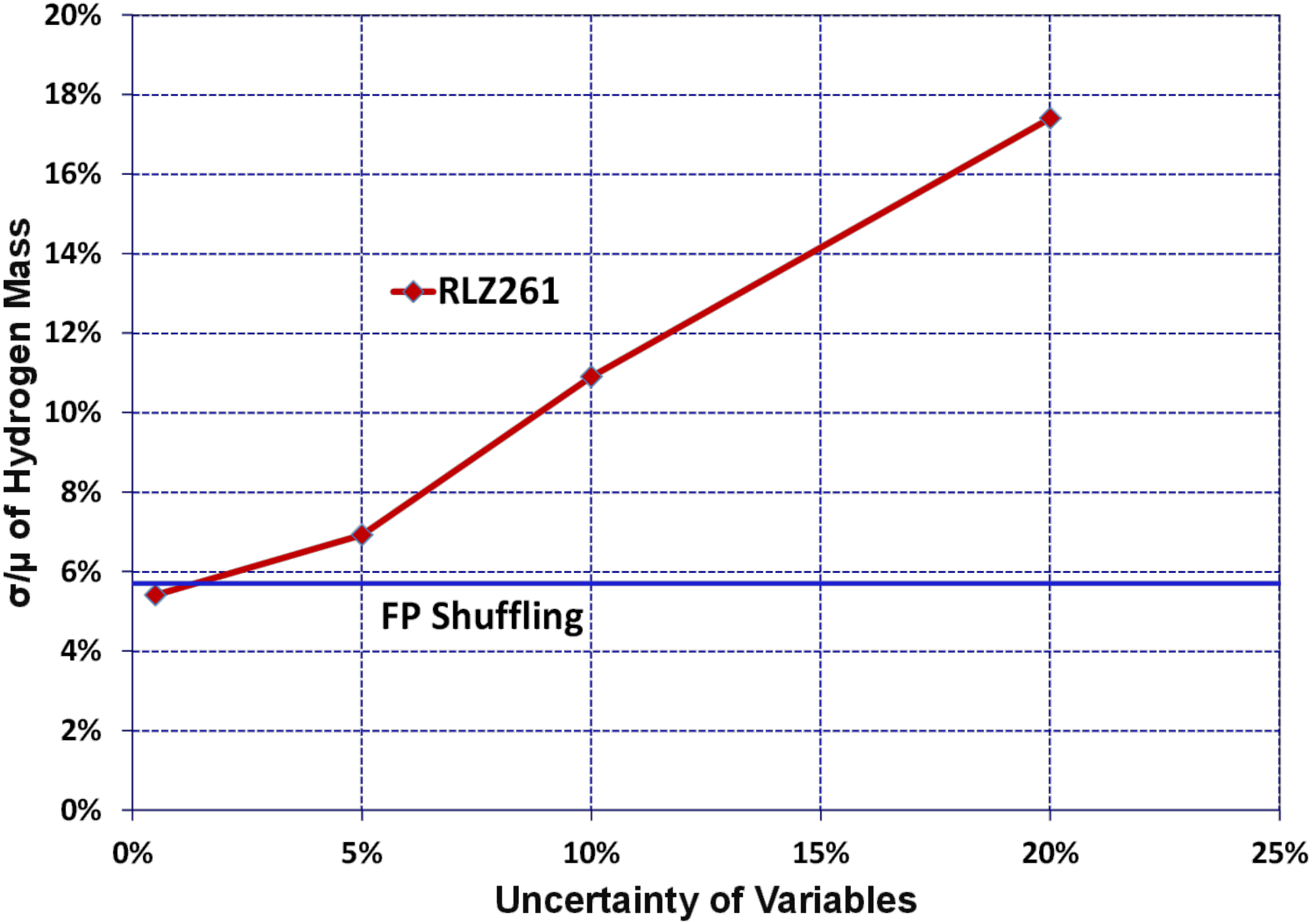


0.5% and 5% UA variations nearly same as background numerical noise

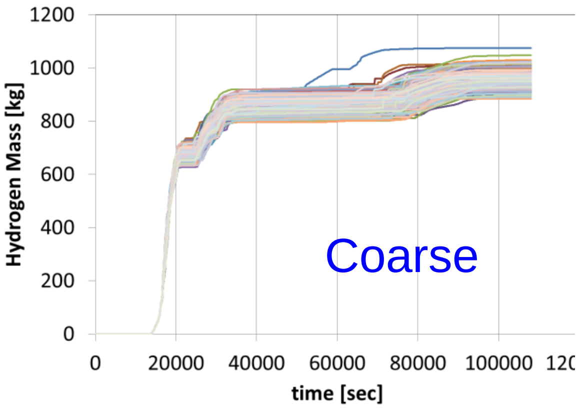
10% and higher variation clearly distinguishable from background noise

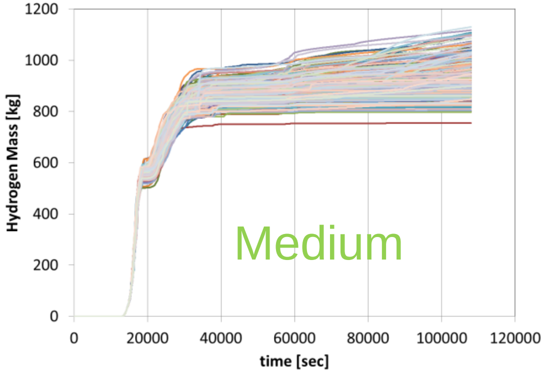
]

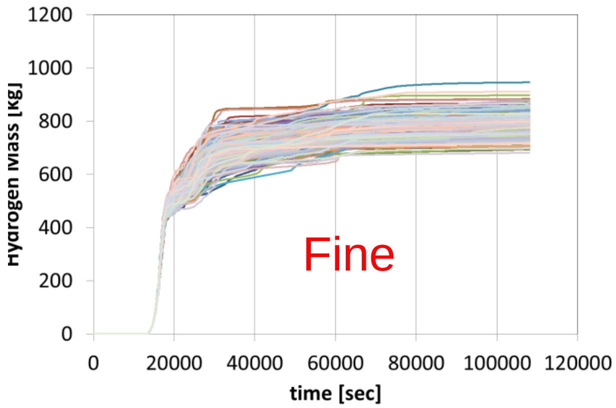
Signal to Noise versus % Variation for Hydrogen



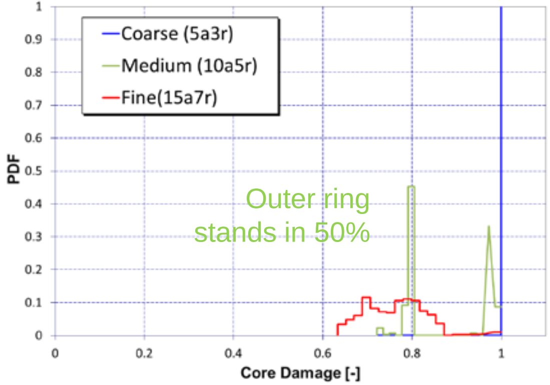
Numerical variance associated with nodalization



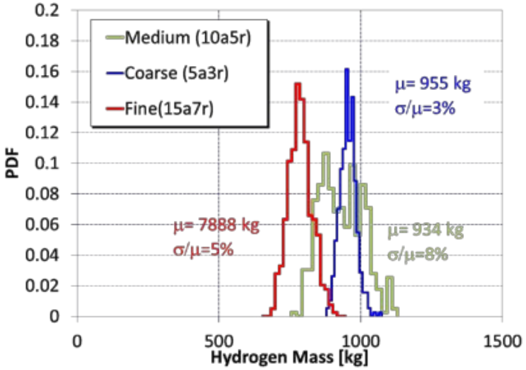




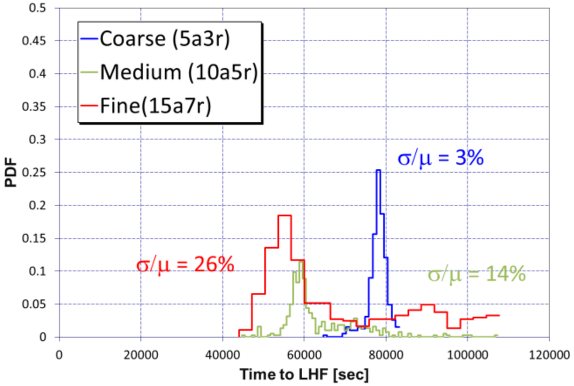
Core Damage



Hydrogen Mass



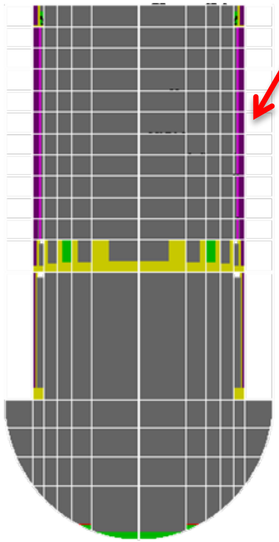
Time to LHF

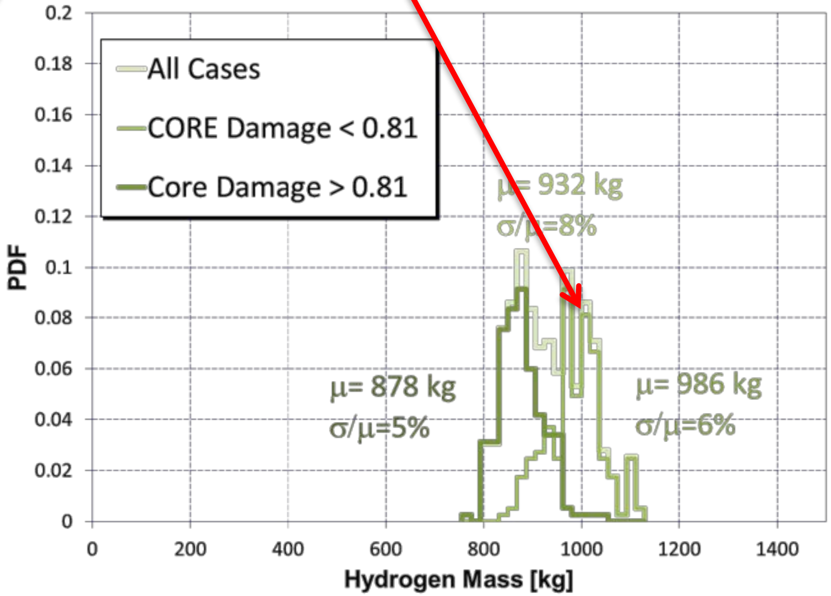


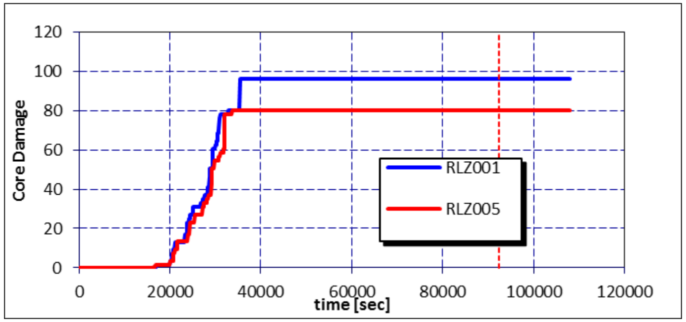
Hydrogen variance in medium nodalization Case

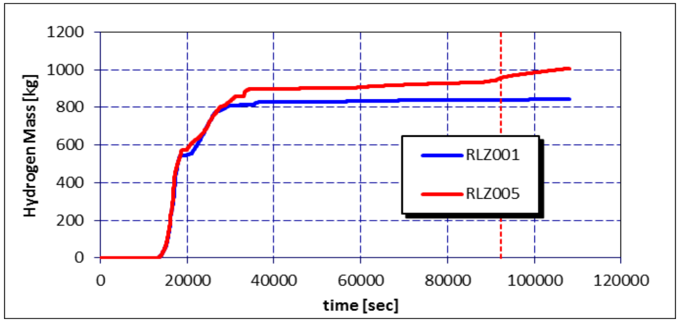
- Hydrogen variance strongly dependent on failure of outer ring.
  - Hydrogen distribution and core damage are highly correlated.
  - Cases where outer rod survives results in more overall hydrogen generation in core after vessel failure
  - **Note: Equal area nodalization was used!**
- Future: Multi-rod model in outer rings?

Fuel Rods in Outer Ring

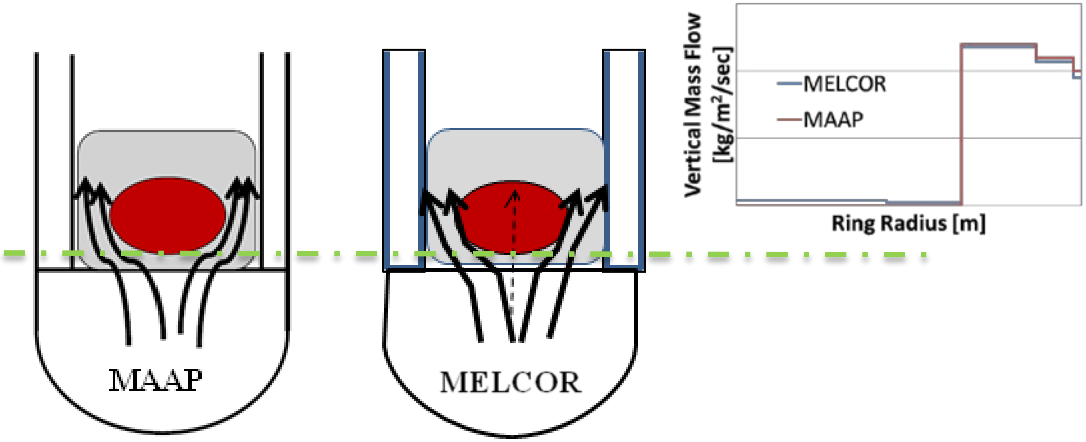






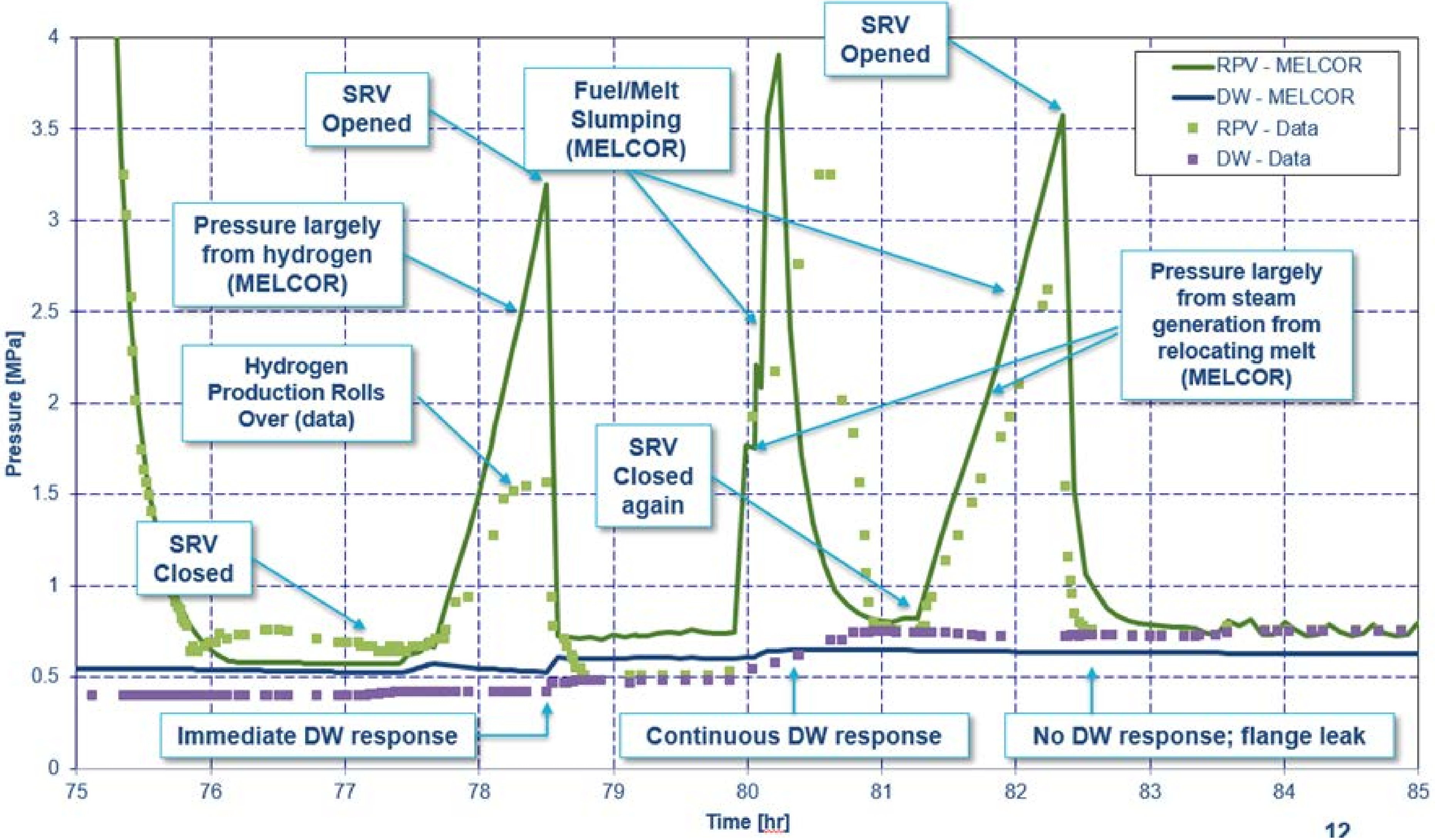


MELCOR- MAAP Cross-Walk Conclusion



- MELCOR does not completely block fluid flow where MAAP does
  - Originally intended to prevent numerical problems with blocked volumes
  - Difficult to envision complete blockage in a large COR ring.
  - MELCOR assumes minimum porosity for flow
    - Large pressure drop and low flow result
    - May not be as big a difference as some suggest
- Current approach is to allow flow for small porosity
  - SC1505(1) - Minimum porosity to be used in calculating the flow resistance (flow blockage model)
  - SC1505(2) - Minimum porosity to be used in calculating the area for heat transfer to fluid.
  - SC1505(3) – Fraction of volume reserved for CVH
  - SC4414(1) Minimum Hydrodynamic Volume Fraction

1F2 “Three Peaks” Results



SRV Opened

Fuel/Melt Slumping (MELCOR)

SRV Opened

Pressure largely from hydrogen (MELCOR)

Pressure largely from steam generation from relocating melt (MELCOR)

Hydrogen Production Rolls Over (data)

SRV Closed again

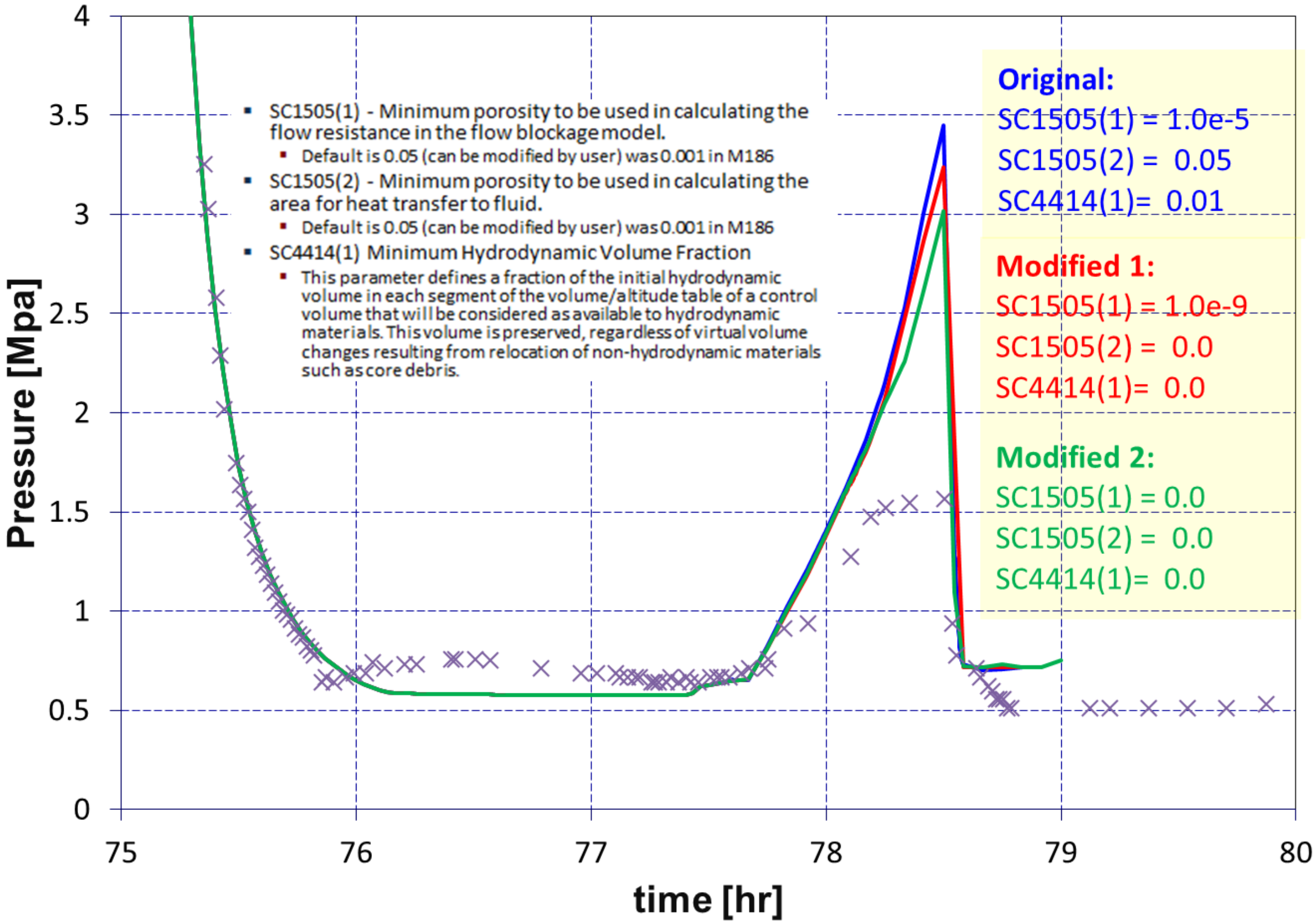
SRV Closed

Immediate DW response

Continuous DW response

No DW response; flange leak

Reduce Minimum Porosities



Revision 7783

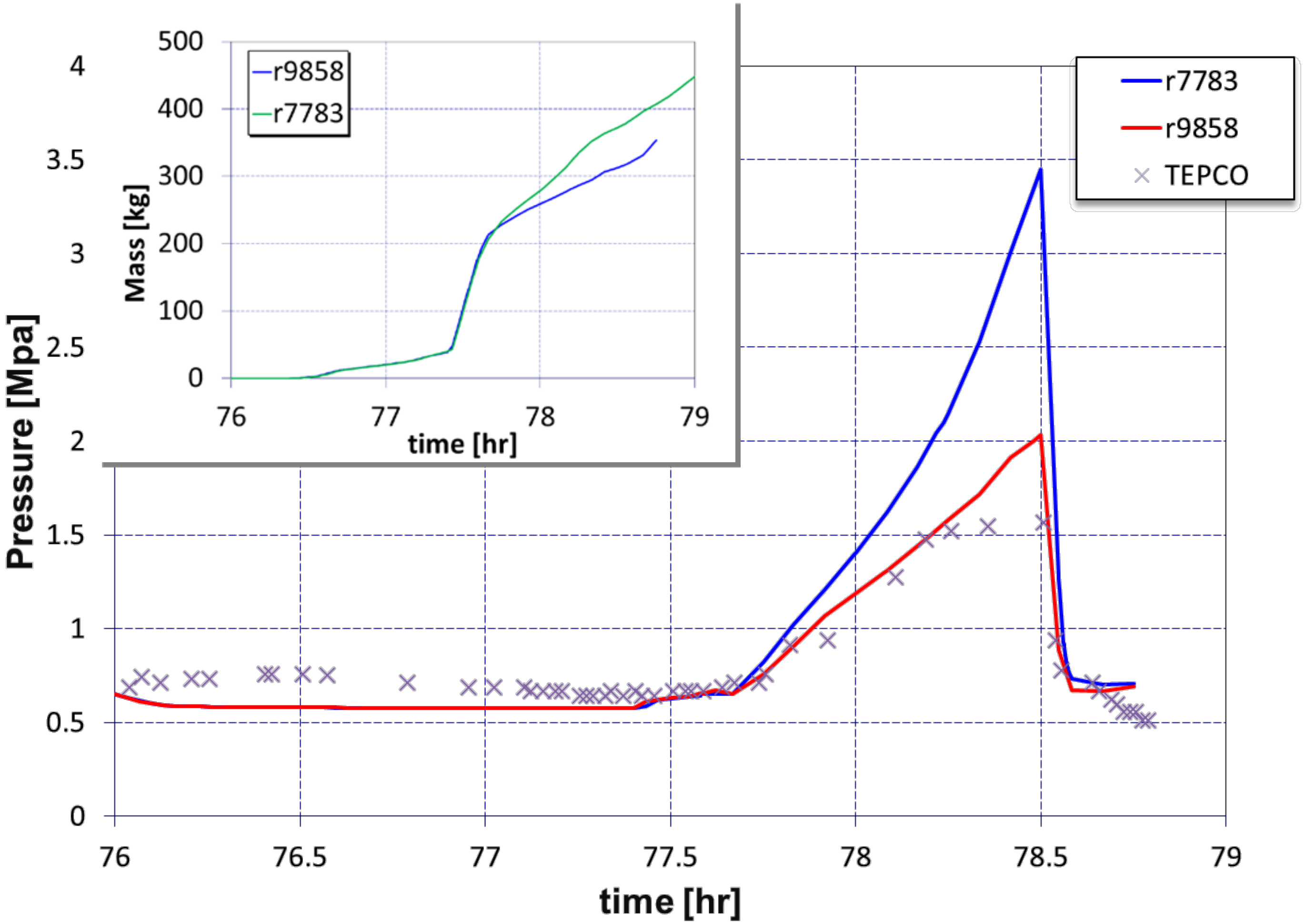
- SC1505(1) - Minimum porosity to be used in calculating the flow resistance in the flow blockage model.
  - Default is 0.05 (can be modified by user) was 0.001 in M186
- SC1505(2) - Minimum porosity to be used in calculating the area for heat transfer to fluid.
  - Default is 0.05 (can be modified by user) was 0.001 in M186
- SC4414(1) Minimum Hydrodynamic Volume Fraction
  - This parameter defines a fraction of the initial hydrodynamic volume in each segment of the volume/altitude table of a control volume that will be considered as available to hydrodynamic materials. This volume is preserved, regardless of virtual volume changes resulting from relocation of non-hydrodynamic materials such as core debris.

Original:
SC1505(1) = 1.0e-5
SC1505(2) = 0.05
SC4414(1)= 0.01

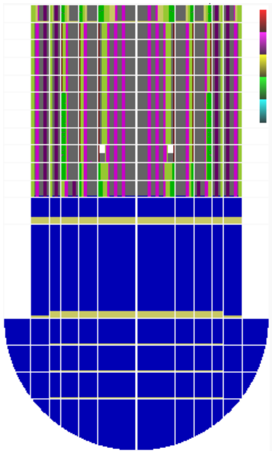
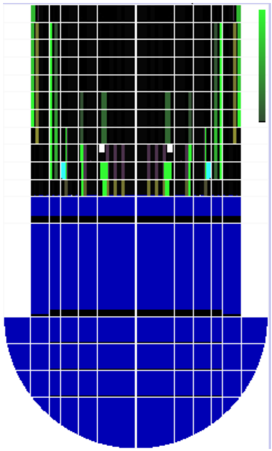
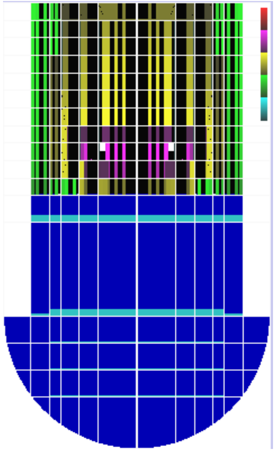
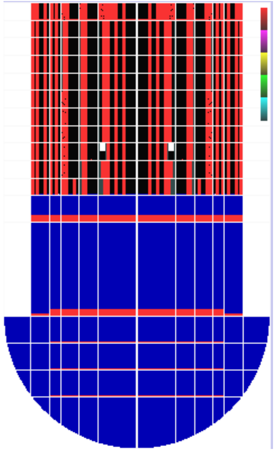
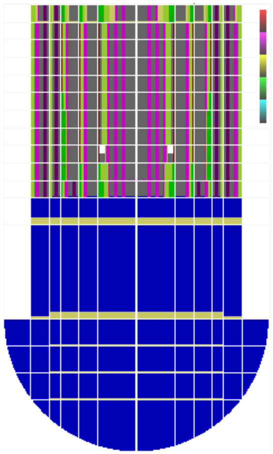
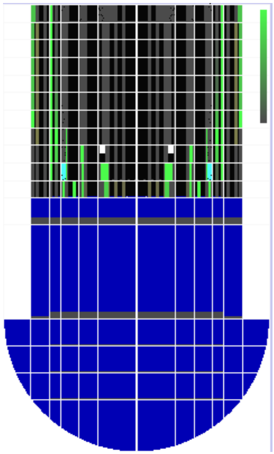
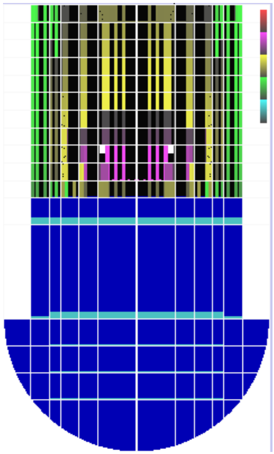
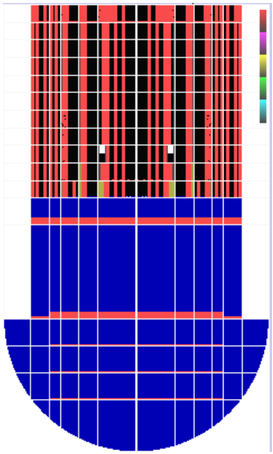
Modified 1:
SC1505(1) = 1.0e-9
SC1505(2) = 0.0
SC4414(1)= 0.0

Modified 2:
SC1505(1) = 0.0
SC1505(2) = 0.0
SC4414(1)= 0.0

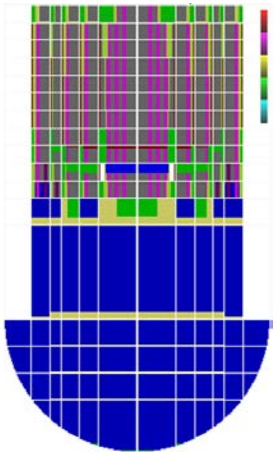
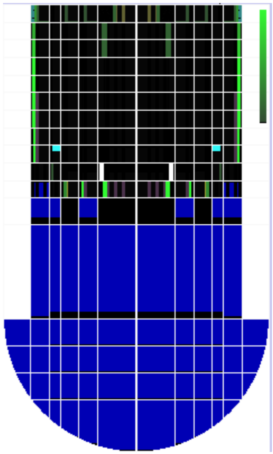
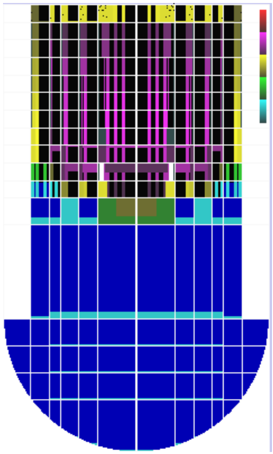
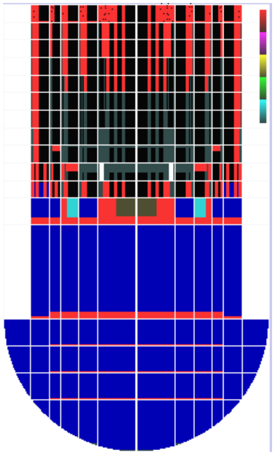
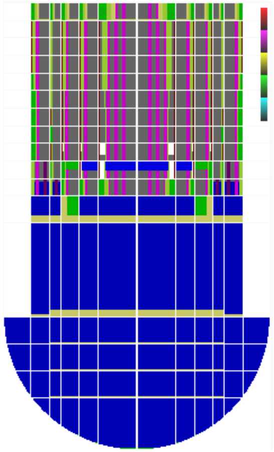
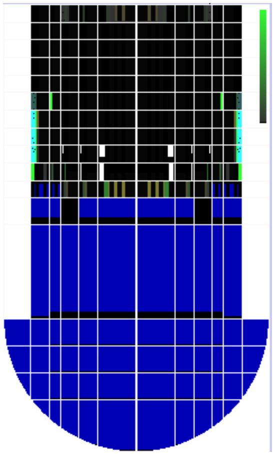
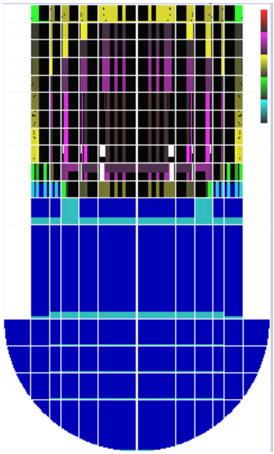
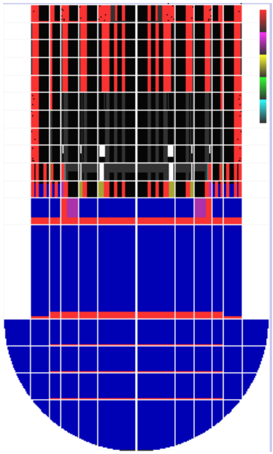
Recalculate with latest code version



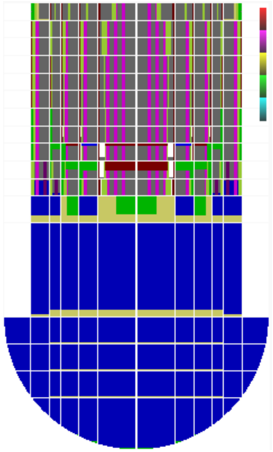
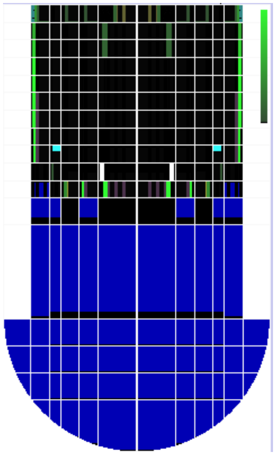
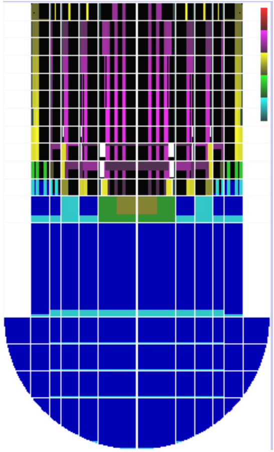
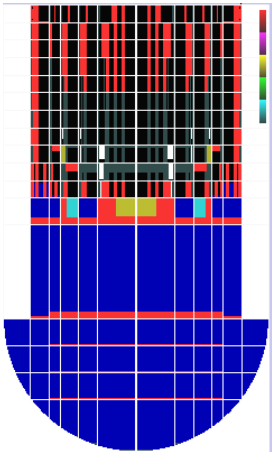
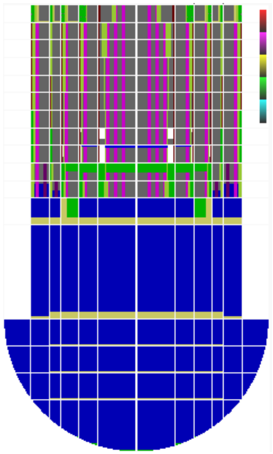
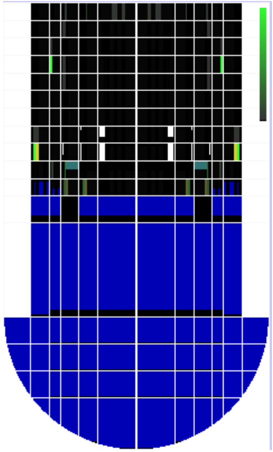
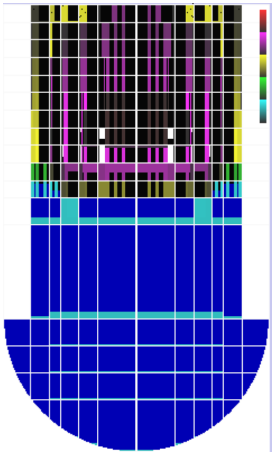
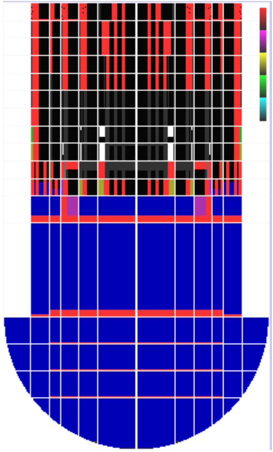
Compare at 77.5 hours

REV	Degradation	Oxidation Rate	Temperature	Area Ox
r7783				
r9858				

Compare at 78 hours

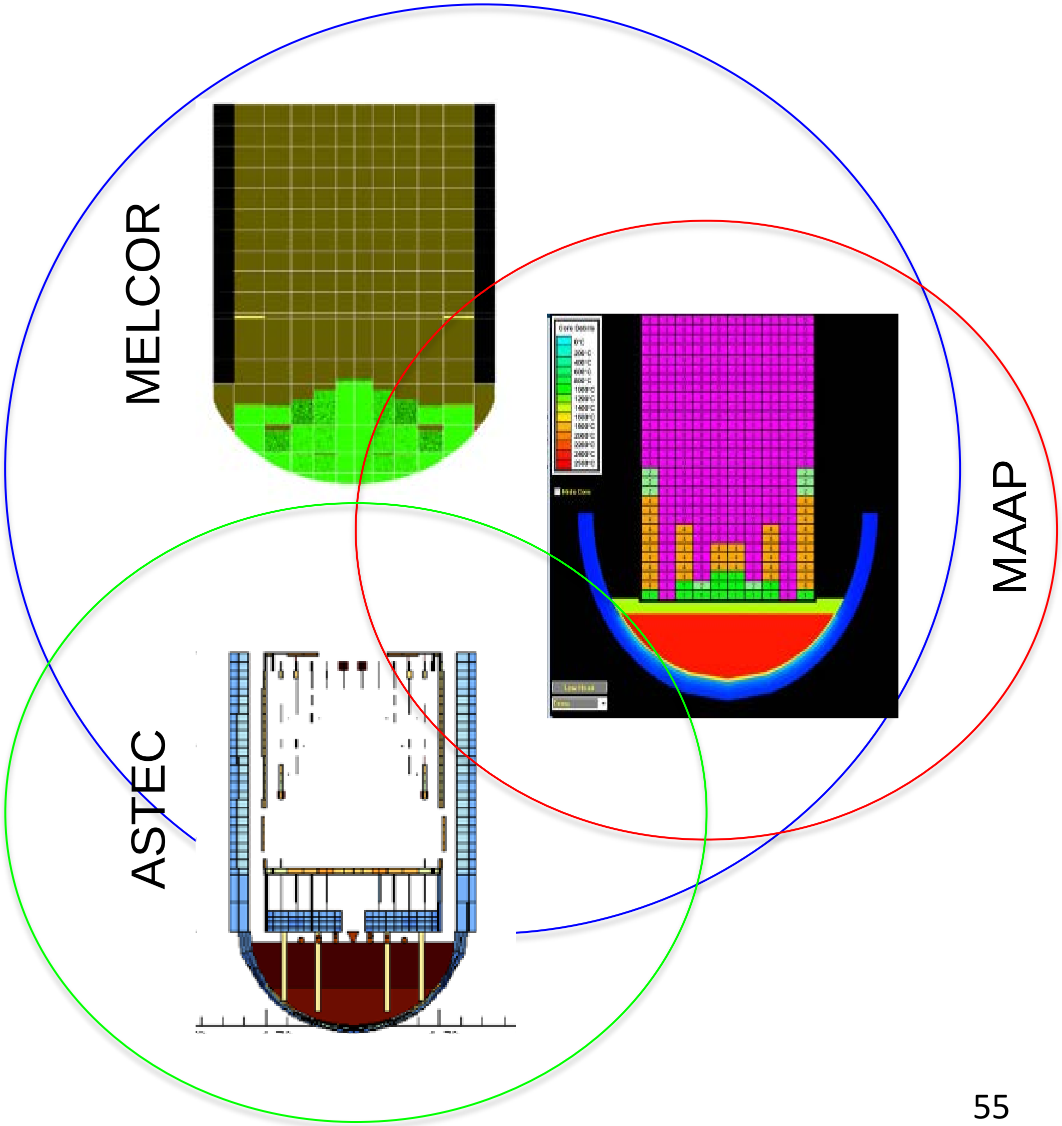
REV	Degradation	Oxidation Rate	Temperature	Area Ox
r7783				
r9858				

Compare at 78.3 hours

REV	Degradation	Oxidation Rate	Temperature	Area Ox
r7783				
r9858				

Cross-walk and Model Uncertainty

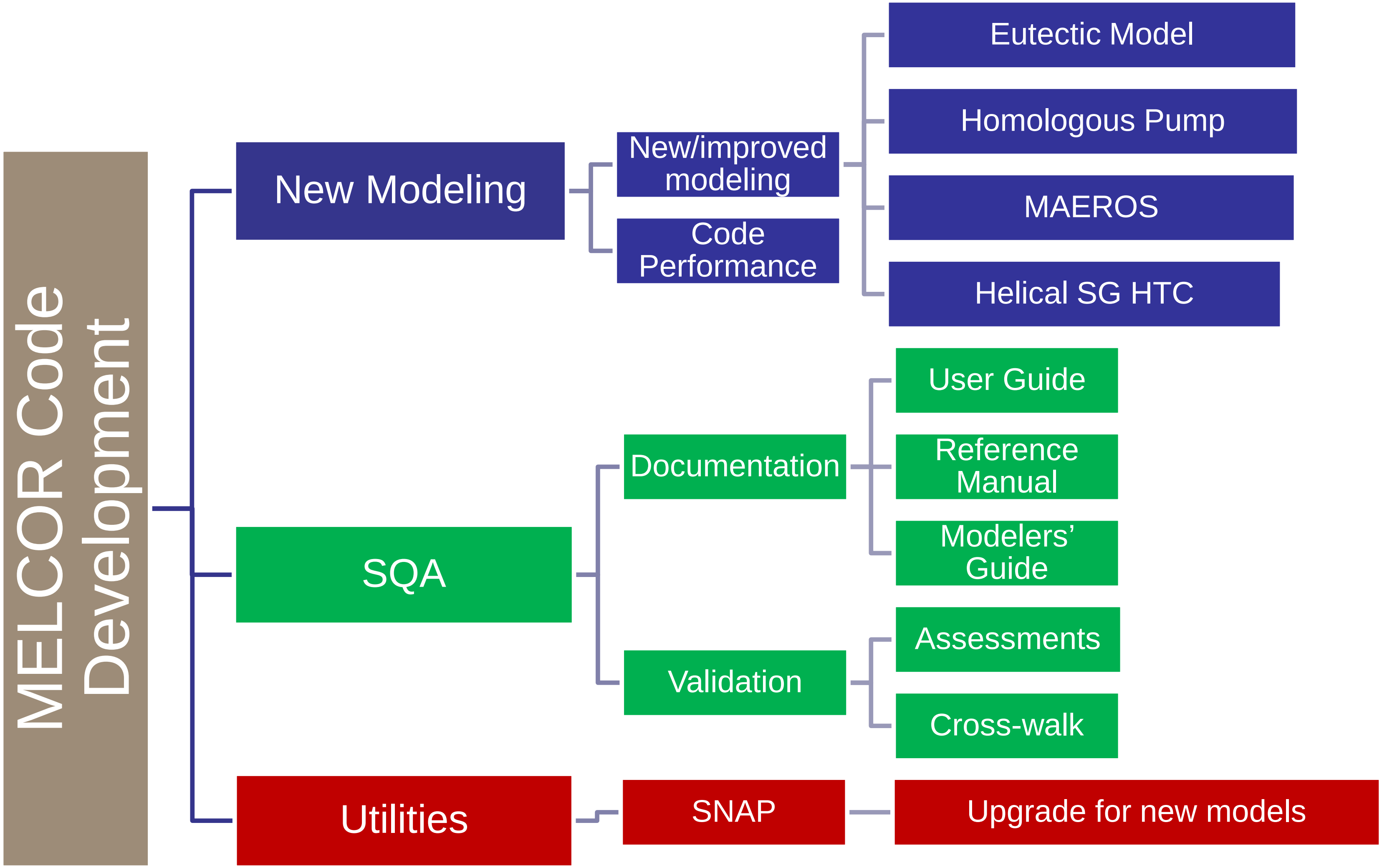
- Where validation data exists, codes give reasonable agreement
- During core degradation, codes diverge
  - Distinct core degradation models
    - ASTEC – Melting only
    - MELCOR – minimum porosity
    - MAAP – molten-pool crust
- Uncertainty analyses capture the uncertainty of a particular code model but do not capture the uncertainty from the possible core degradation paradigms
  - Extend the domain of MELCOR to capture other code model paradigms
  - Evidence from BSAF may be used to reduce this domain



SNAP Upgrade (Upcoming)

- Input Processing
  - Support input for new models
    - Recent update to UG would be a good start but we should review again for missing input
    - Some features may be difficult to implement – vector CFs
  - Review nomenclature used
  - Possible reorganization of interface
    - COR package input is inefficient
- Post-processing
  - Remove idiosyncrasies -
    - Requirement to load a med file in order to inherent COR dimensions
  - Improve interface
    - Adding a profile plot is extremely laborious
  - Extending graphical output
    - Update COR bean to show more than just component degradation
      - temperature, oxidation rate, Zr mass, flow, etc.
    - Update MELCOR & PTFREAD for BWR first
- Accumulate feedback from users

Questions?



MELCOR Code Development

New Modeling

New/improved modeling

Code Performance

Eutectic Model

Homologous Pump

MAEROS

Helical SG HTC

SQA

Documentation

User Guide

Reference Manual

Modelers' Guide

Validation

Assessments

Cross-walk

Utilities

SNAP

Upgrade for new models