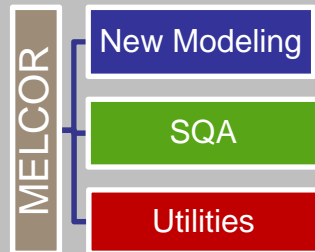
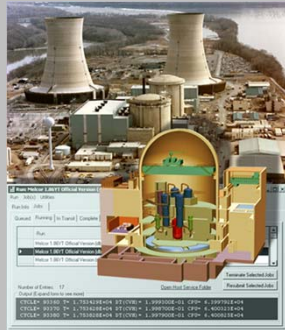


Exceptional service in the national interest



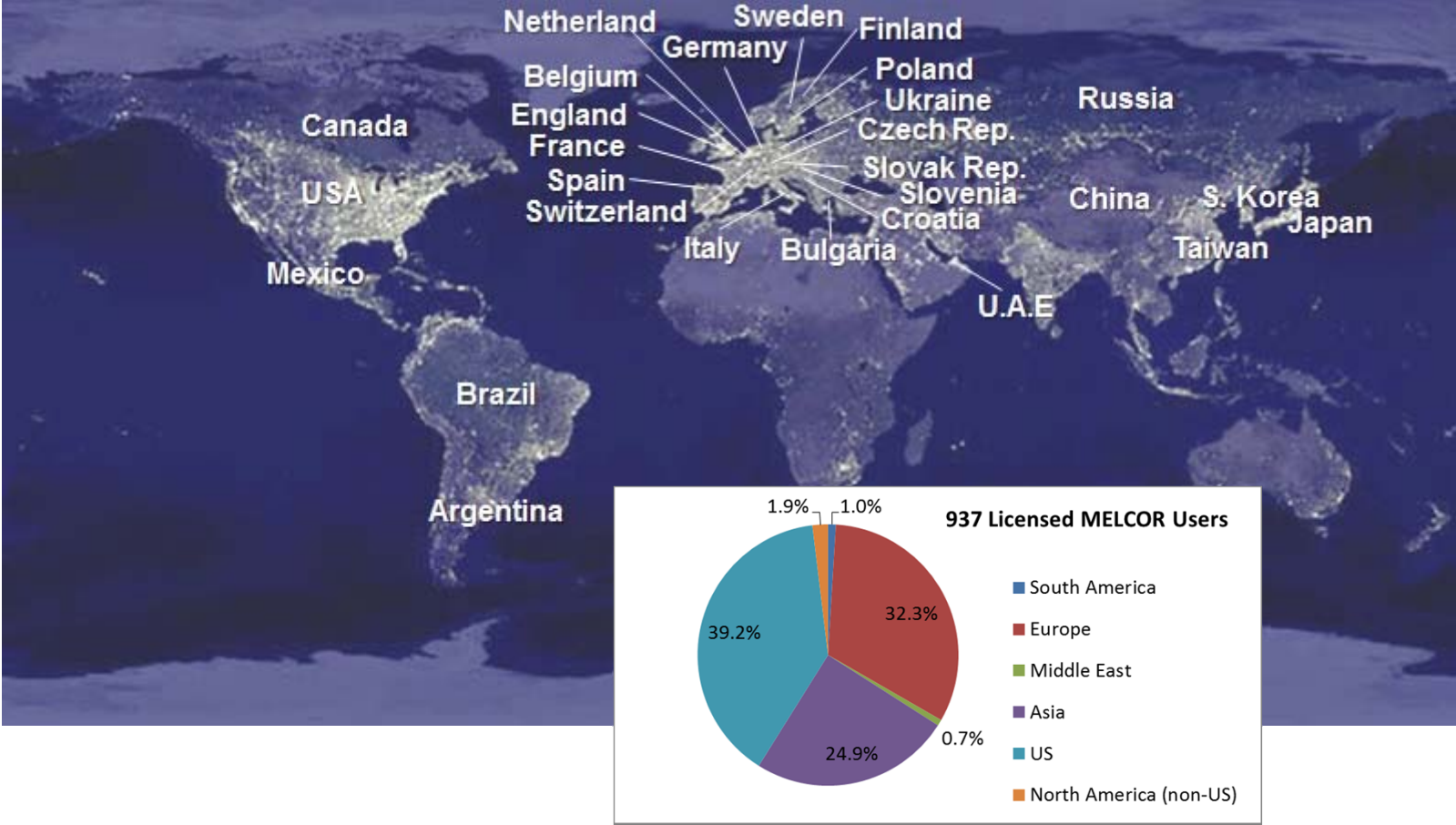
MELCOR Code Development Status EMUG 2017

Presented by Larry Humphries
llhumph@sandia.gov



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International Use of MELCOR



MELCOR Workshops & Meetings

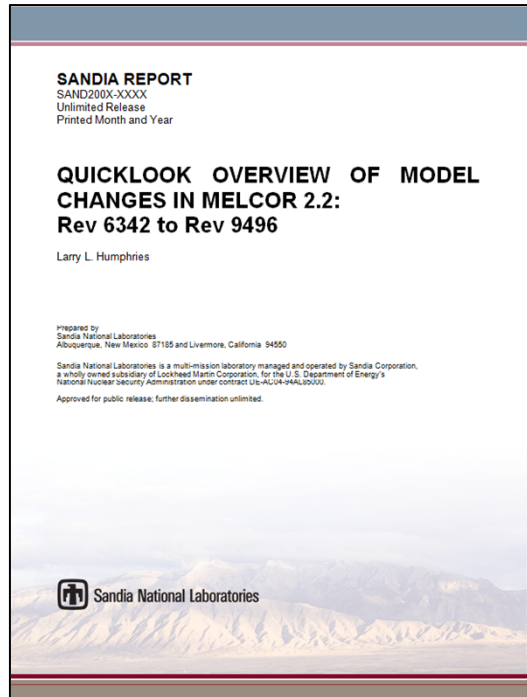
- 2016 Asian MELCOR User Group (AMUG)
 - Hosted by SPICRI & NRSC (Beijing)
 - October 17 – 21, 2016
 - MELCOR/MACCS Workshop
- 2017 European MELCOR User Group (EMUG)
 - Hosted by CIEMAT
 - April 6-7, 2017
- 2017 CSARP/MCAP/MELCOR Workshop
 - September, 2017
 - Bethesda, MD
 - Focus will be on new models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



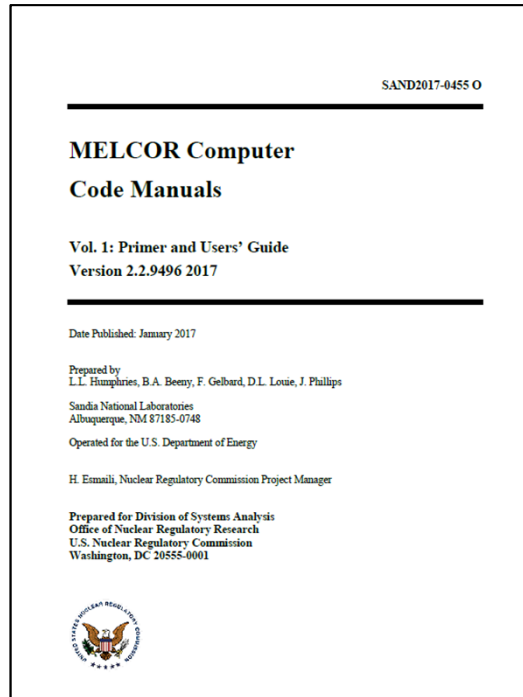
Historical Review of MELCOR Workshops (Since 2001)

- **2001 – 1 Week Beginner Workshop**
 - MELCOR 1.8.5 release
- **2002 – 1 Week Beginner Workshop**
 - Focused on MELCOR physics models (Reference Manual)
- **2005 – 1 Week Beginner Workshop**
 - MELCOR 1.8.6 release
- **2006 – 1 Week Beginner Workshop**
 - MELCOR 2.0 beta release
- **2008 – 1 Week Beginner Workshop**
 - Converting between code versions, best practices, 2.1 input
- **2009 – One Day: New or Improved Models**
 - CC flow, HTGR, 2.1 Input, Formula CFs, Smart Restart, Accumulators
- **2010 – One Day: RN Package**
 - Also highlighted HTGR modeling
- **2011 – 1 Week Beginner Workshop**
 - First use of SNAP,
 - Special Topics: SFP, Turbulent deposition, HTGR
- **2012 – One Day: COR Package**
- **2013 – One Day: Containment Modeling**
- **2014 – 1 Week beginner Workshop**
 - Special Topics: SFP and Uncertainty Analysis
- **2016 One Day: Control functions and New Models**
- **2017 One Day: New Models**

MELCOR 2.2 Code Release

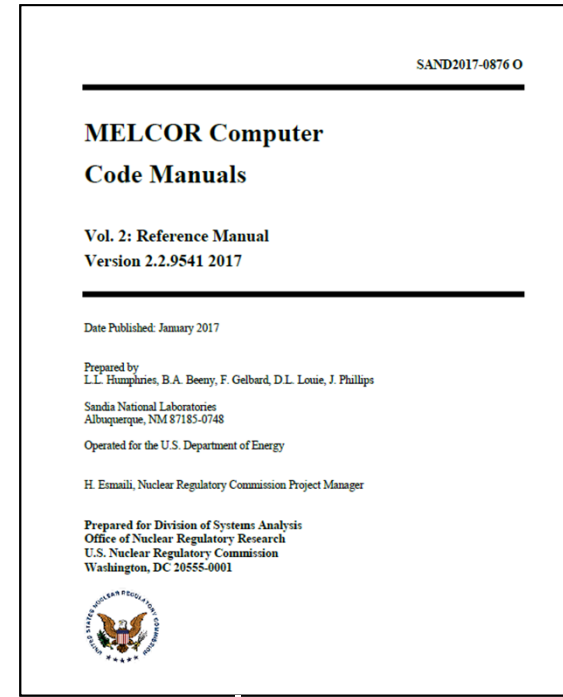


MELCOR 2.2 Quicklook Overview of Model Changes in MELCOR 2.2



Volume I: User Guide

R&A Complete
SAND2017-0445 O



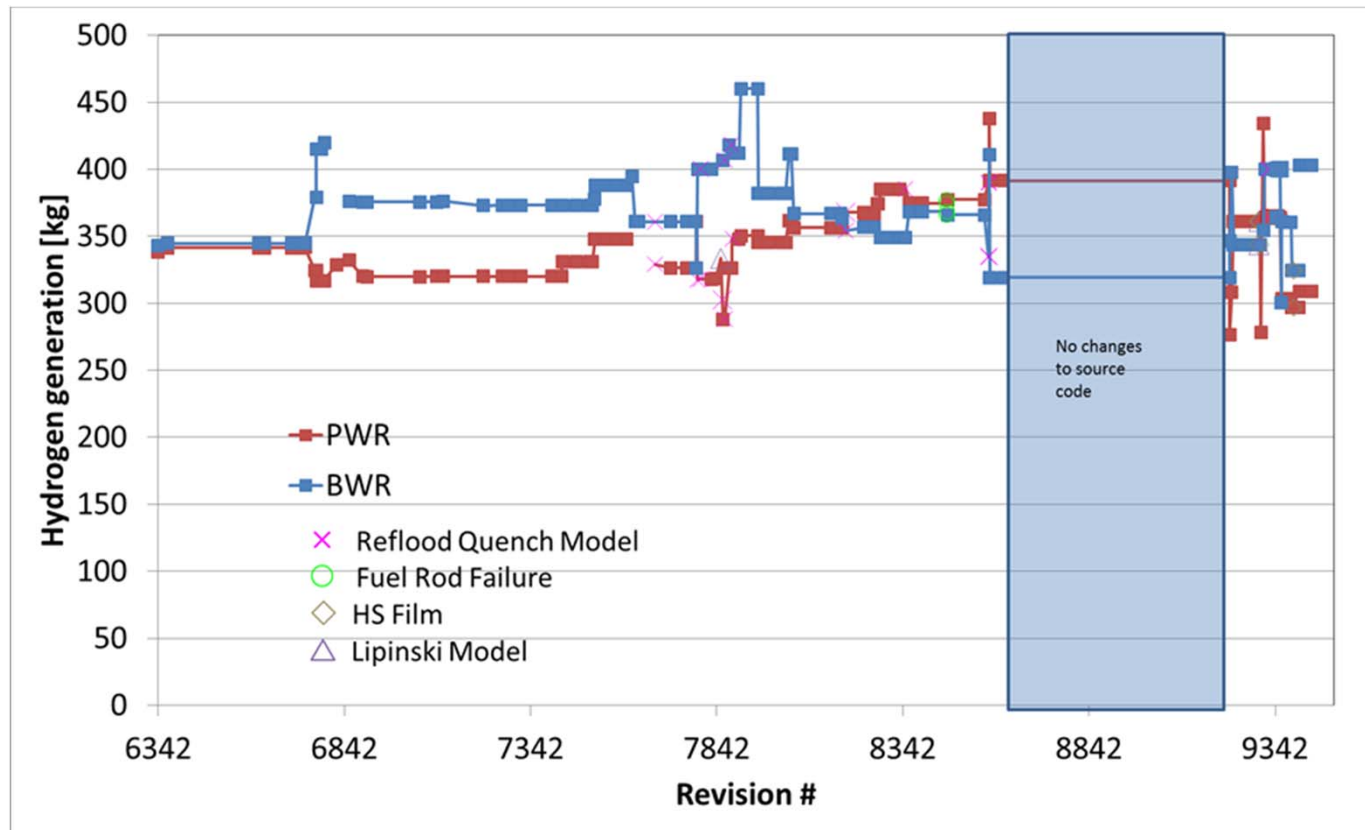
Volume II: Reference Manual

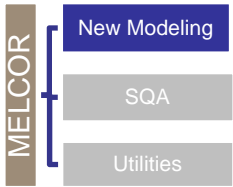
R&A Complete
SAND2017- 0876 O

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]
 - 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]

Changes in H2 Generation from Oxidation





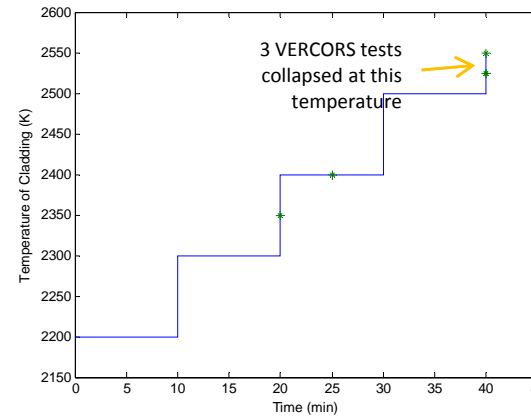
New Model Development Tasks (2014-2015)

- Completed
 - Fuel Rod Collapse Model
 - Homologous pump model
 - 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
 - Generalized Fission Product Release Model
 - New debris cooling models added to CAV package
 - Water-ingression
 - Melt eruption through crust
 - Spreading model implemented into CAV package
 - Miscellaneous models and code improvements
 - COR_HTR extended to heat structures
 - LAG CF
 - MACCS Multi-Ring Release
 - Valve Flow Coefficient
 - MACCS release types
- In Progress
 - Vectorized Control Functions
 - CONTAIN/LMR models for liquid metal reactors
 - CVH/FL Numerics

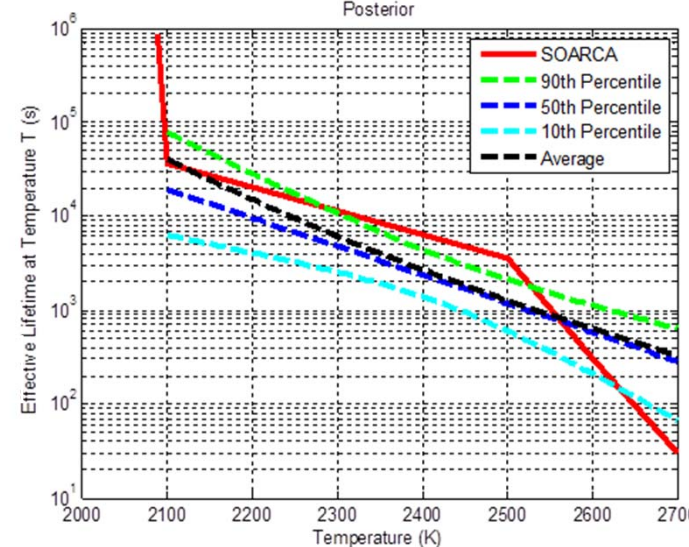
Fuel Rod Collapse Model

- 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

Homologous Pump Model

- Transient Pump operation characterized by
 - Rotational speed
 - Volumetric flow rate
 - Dynamic head
 - Hydraulic torque
- Pump characteristic curves or four quadrant curves
 - Any one of the above quantities can be expressed as a function of any other two
 - Dynamic head and hydraulic torque are expressed as functions of volumetric flow and rotational speed ratios
 - Eight curves for the dynamic head
 - Eight curves for hydraulic torque
 - Empirically characterized by manufacturer
 - Similarities to RELAP and TRACE models
- Curve Definitions
 - Built-in pump curves
 - Semi-scale
 - Loft
 - User defined curves
 - Uses tabular function (32 TFs for full coverage)
 - If user does not define all modes, error occurs when pump enters undefined domain
 - Universal correlation
 - Systematic approach for predicting pump performance where data does not exist
 - Fits to several data sets (including LOFT & Semiscale)
 - Only valid in normal operating mode
 - Lahssuny, Jedral. Universal Correlations for Predicting Complete Pump Performance Characteristics. 2004.

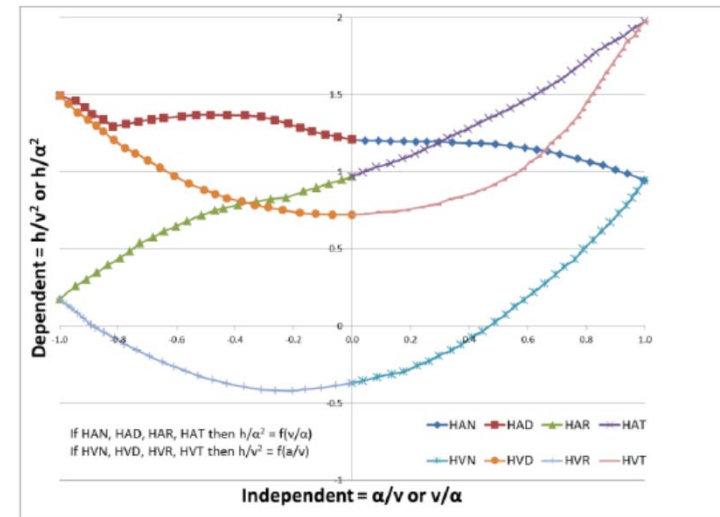


Figure 1. Semiscale single-phase head curve

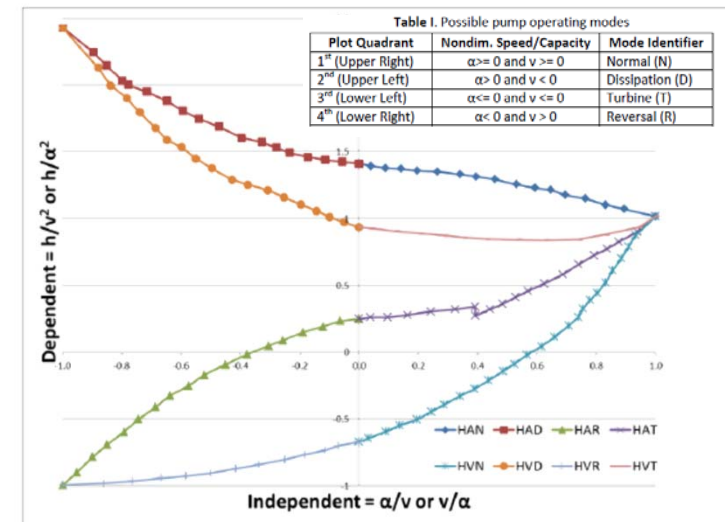


Figure 4. LOFT single-phase head curve

$$\alpha = \frac{\omega}{\omega_R} \text{ and } v = \frac{Q}{Q_R}, \text{ for rated speed and capacity } \omega_R, Q_R$$

Multi HS Radiation Enclosure Model

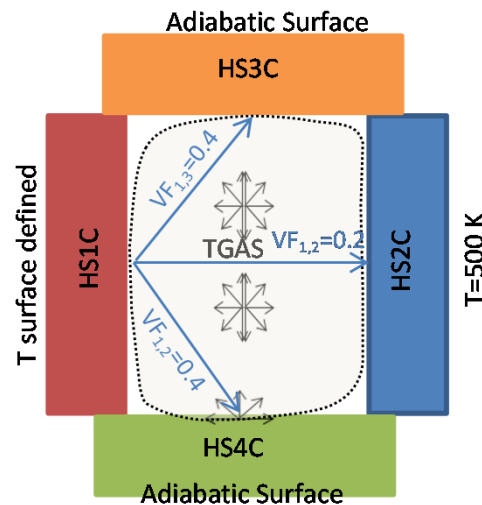
- Previous HS radiation model
 - Radiation defined only for surface pairs
 - Radiation to gas performed independently for each surface
 - Does not account for transmissivity of gas
- New enclosure model
 - Multiple enclosure networks, each with multiple heat structures defined by the user.
 - Memory dynamically allocated
 - User defines all surfaces exchanging radiant heat
 - Matrix of view factors connecting surfaces
 - Participating gas
 - Transmissivity accounts for reduction in radiation between surfaces
 - Only 1 CV associated with all surfaces
 - User supplies beam length (similar to COR package)

$\tau_{j,i}$ is the transmissivity through gas

$$J_i = (1 - \epsilon_i) \cdot \sum_j^N [F_{ij} \cdot \tau_{j,i} \cdot J_j] + \epsilon_i \cdot \sigma \cdot T_i^4 + \rho_i \epsilon_m E_{bm}$$

$$G_i = \sum_j^N [A_j \cdot F_{ji} \cdot \tau_{j,i} \cdot J_j] / A_i + \epsilon_m E_{bm}$$

$$q_i = A_i (J_i - G_i)$$



HS_RAD	NET3	!EM	BeamL	VF
1	HS1C LEFT	EM1	0.5	0.0 0.2 0.4 0.4
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
5	HS4C LEFT	-	0.5	0.4 0.5 0.1 0.0

TF_ID	TEMP	1.0	0.0	!T Surface Defined
TF_TAB 4				
1	0.0	500.0		
2	500.0	1500.0		
3	1000.0	1500.0		
4	30000.0	1500.0		

Re-suspension Model

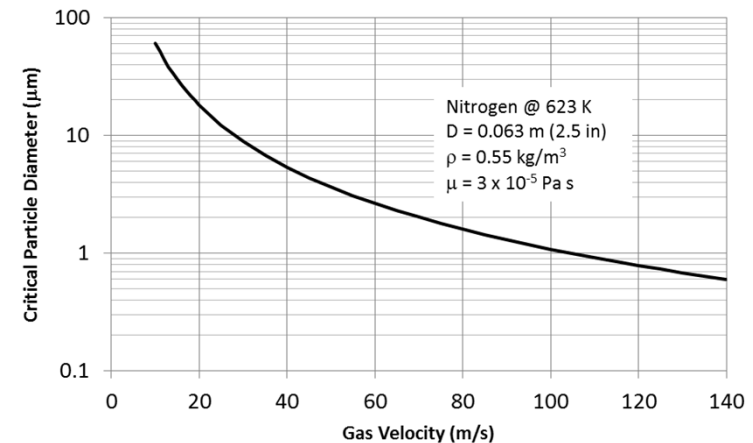
- Deposited material can be re-suspended
 - All sections for which the lower section boundary particle diameter is greater than a critical diameter
 - Critical diameter is calculated from gas flow conditions

$$D_{\text{crit}} = \frac{4 \times 10^{-5}}{\pi \tau_{\text{wall}}} \text{ (m)}, \quad \tau_{\text{wall}} = \frac{f \rho v^2}{2} \text{ (N/m}^2\text{)}$$

Wall shear stress

$$f = \frac{0.0791}{\text{Re}^{0.25}}$$

- Uses CV velocity
- Critical diameter can be specified by user
 - Control function
 - Constant value
- By default, surfaces do not re-suspend
- Wet surfaces cannot re-suspend.
 - Pools and surfaces with condensed water
- Relaxation time for resuspension
- Reference
 - “Liftoff Model for MELCOR,” Mike Young
 - SAND2015-6119
- Validation against Tests
 - STORM tests (SR11 and SR12)
 - Validation against LACE tests



Examples

To fully activate resuspension, specify a value of **FractResuspend** as 1.0, and let MELCOR determine the critical diameter:

HS_LBAR 1. ! Left surface
 HS_RBAR 1. ! Right surface

Zukauskas Heat Transfer Coefficient

- Heat transfer for external cross-flow across a tube bundle
 - Aligned or staggered
- Implemented as option for HS boundary condition (HS_LB & HS_RB IBCL=2 or ZUKAUSKAS).
- Correction factor $C_2(N_L)$ can be specified or determined from number of rows
- Option to smooth at discontinuities

$$Nu_D = C_2(N_L) C Re_{D,max}^m Pr^n \left(\frac{Pr}{Pr_s} \right)^{0.25}$$

Aligned:

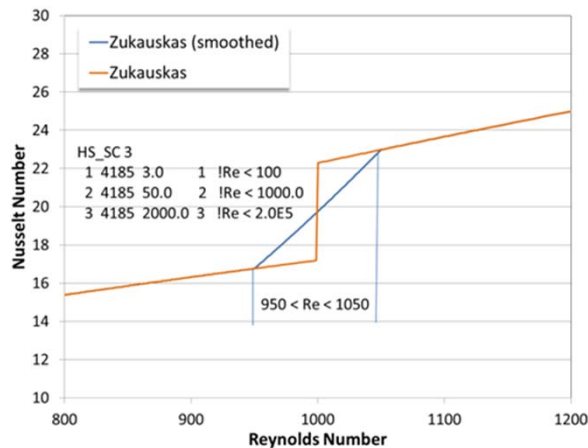
$$V_{max} = \frac{S_T}{S_T - D} V$$

Staggered:

$$if S_D = \left[S_L^2 + \left(\frac{S_T}{2} \right)^2 \right]^{1/2} < \frac{S_T + D}{2} \quad V_{max} = \frac{S_T}{2(S_D - D)} V$$

else

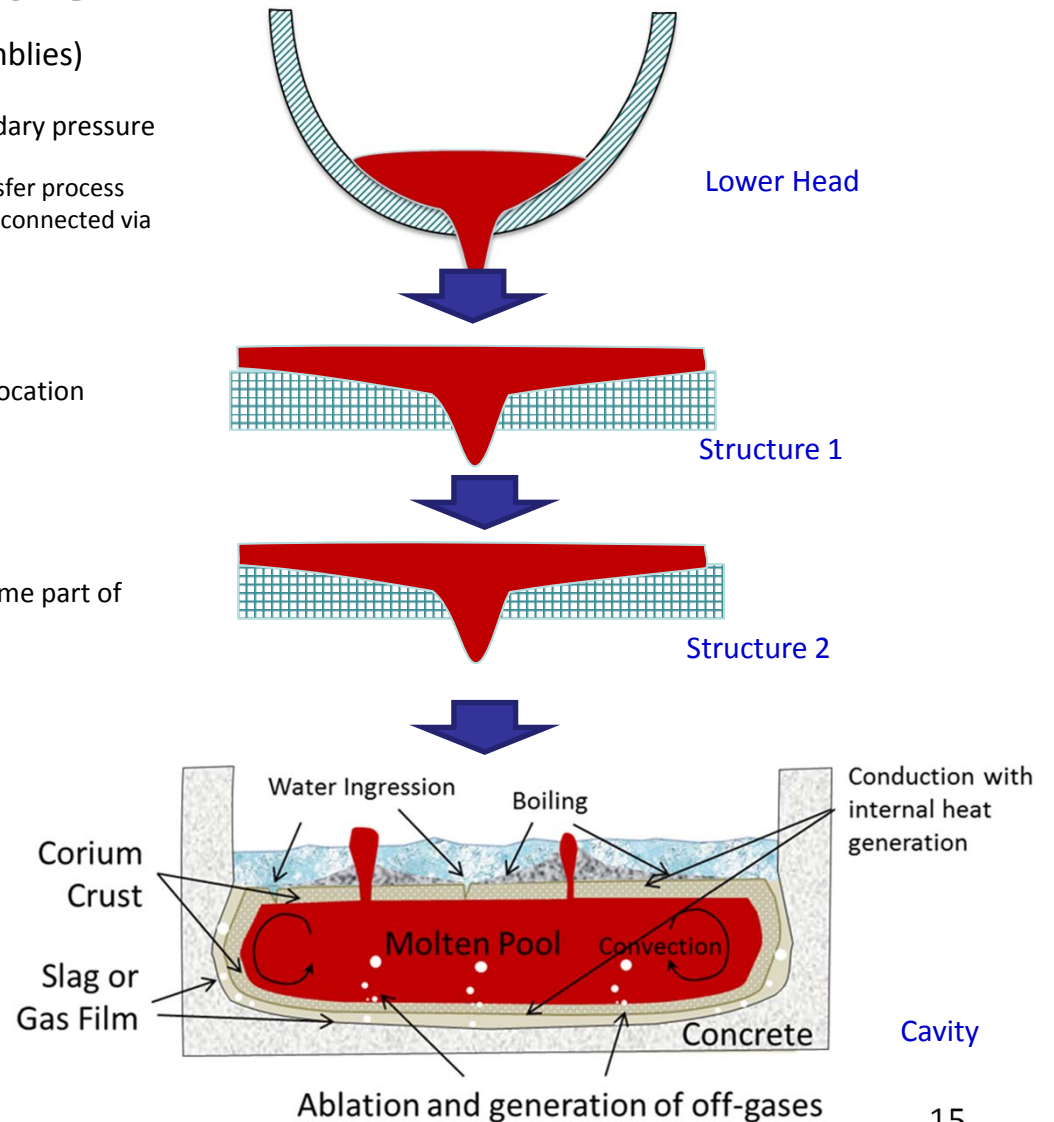
$$V_{max} = \frac{S_T}{S_T - D} V$$



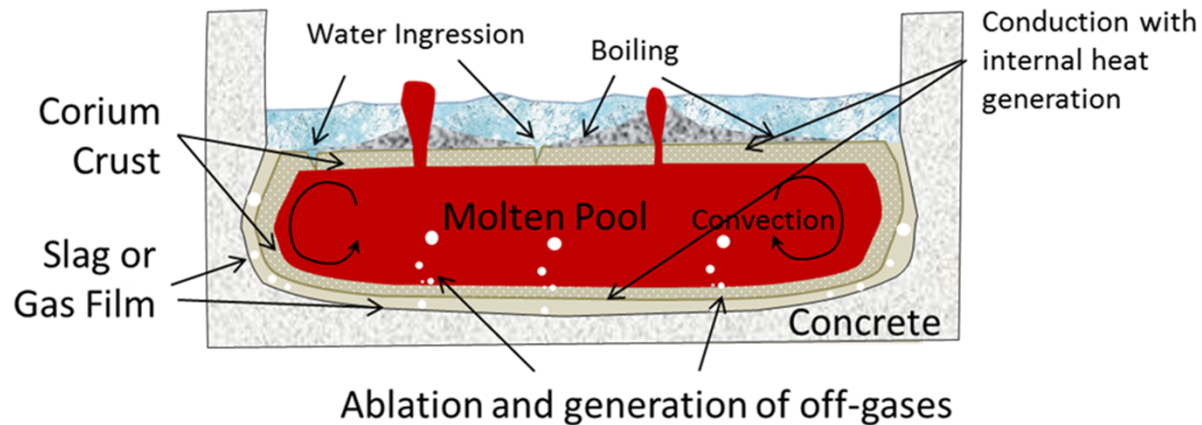
	$Re_{D,max}$	Condition	C	m	n
Aligned	$10 < Re_{D,max} < 100$		0.8	0.4	0.36
	$100 < Re_{D,max} < 1000$	Pr < 10	0.51	0.5	0.37
		Pr > 10	0.51	0.5	0.36
	$1000 < Re_{D,max} \leq 2 \times 10^5$		0.27	0.63	0.36
	$2 \times 10^5 < Re_{D,max} \leq 2 \times 10^6$		0.021	0.84	0.36
Staggered	$10 < Re_{D,max} < 100$		0.9	0.4	0.36
	$100 < Re_{D,max} < 1000$	Pr < 10	0.51	0.5	0.37
		Pr > 10	0.51	0.5	0.36
	$1000 < Re_{D,max} \leq 2 \times 10^5$	$S_T/S_L < 2$	$0.35(S_T/S_L)^{1/5}$	0.6	0.36
		$S_T/S_L > 2$	0.4	0.6	0.36
	$2 \times 10^5 < Re_{D,max} \leq 2 \times 10^6$		0.022	0.84	0.36

Core Catcher / Ex-Vessel Structure Model

- New model for simulating core catcher assembly (assemblies) outside the lower head.
 - Can also be used to simulate multiple lower heads or secondary pressure vessels
 - Debris relocated from lower head to core catcher via transfer process
 - Allow for multiple core catcher objects (pressure vessels) connected via transfer processes
- 2-D core catcher nodalized through the wall
 - Through-wall and transverse heat conduction
 - CV volumes serve as boundary conditions
 - Available volume between structures can constrain melt relocation
 - Heat transfer between debris and 'upper' (inner) structure
 - Radiation
 - Possible contact
 - Material composition of structure varies through mesh
 - Allows insulation or other non-structural material
 - Allow for vessel structure to melt and molten material become part of molten debris.
 - Simple eutectics
 - Homogeneous molten debris
 - Crust between molten debris and structure
 - Special features (like penetrations) modeled
- Multiple failure criteria
 - Failure by melt-through
 - Failure by control function
 - Secondary Pressure Vessel
 - Larson-Miller Creep
 - Yield Stress
- Work completed in September 2015

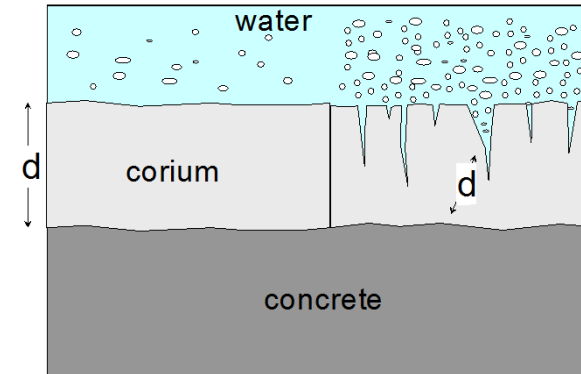


New Modeling for Top-Quenched Debris in Cavity



- 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

- Water ingressions 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



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

- 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 ingressions 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

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

MELCOR Debris Spreading Model

- By default, corium relocated to the cavity will spread instantaneously
- Users are able to specify a spreading radius through a CF or TF
- Current model development adds an internally calculated spreading radius.
 - Balance between gravitational and viscous forces

CAV_SP – Definition of Parametric Debris Spreading Optional

This record may be used to model the spreading of debris in the cavity. Users can define a maximum debris radius as a function of time through a tabular function, control function, channel of an external data file, or an internal model.

(1) SOURCE

Source of data for maximum debris radius as a function of time

1 or 'TF'

Use data from tabular function.

-1 or 'CF'

Use data from control function.

2 or 'CHANNELEDF',

Use data from channel of external data file NameCF_TF_EDF.

0 or 'MODEL',

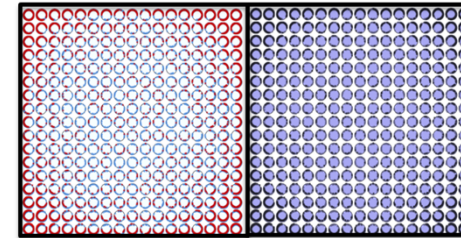
This option allows the code to internally calculate the debris radius as a function of time. However, this option requires the initial debris radius (RADTINI).

If SOURCE = 0, the following record is required:

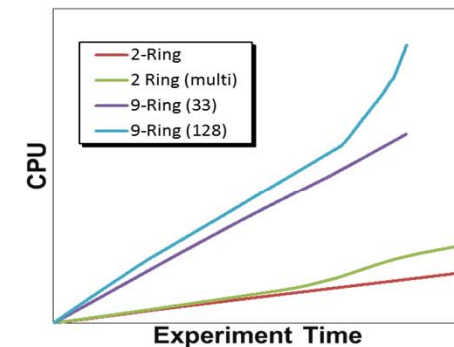
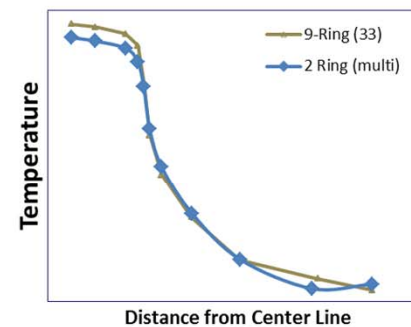
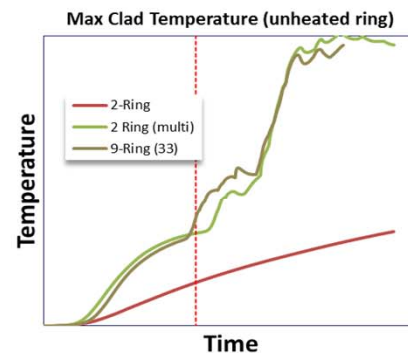
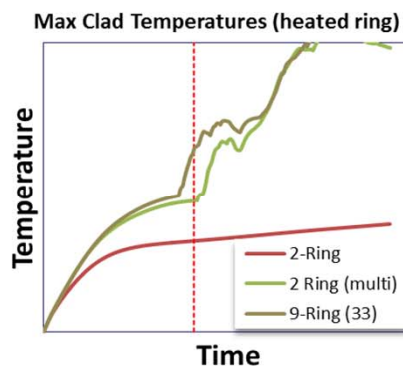
(2) RADTINI - Initial time-dependent debris radius for the internal model

Multi-Rod Model

- Motivation
 - It is desirable to model an entire assembly within a single MELCOR ring
- Challenge
 - When hot assembly reaches ignition, heat transfer to cold assembly is problematic



Hot Assembly Cold Assembly



- Validation
 - Validation was performed against the Sandia PWR Spent Fuel Pool Experiments
 - Comparisons between 2-ring (2 rods) model; 2-ring, (9 rods) model; and 9-ring model.
- CPU time is greatly reduced for multi-rod model
- Simplified input requirements
- Fuel rod degradation modeling is nearly complete
- Recently extended to PWR reactor type in addition to PWR-SFP

Generalized Fission Product Release Model

- A cumulative burst fission product release fraction is described by the following equation:

$$FB_{j,i} = a_burst_j (c_0 + c_1 * T_i + c_2 * T_i^2 + c_3 * T_i^3)$$

Where

T_i is the fuel temperature that existed during the time interval Dt_i

c_0, c_1, c_2, c_3 are constant coefficients provided in user input

a_j is a constant class dependent coefficient provided in user input.

- A cumulative diffusive fission product release fraction is described by the following equation:

$$FD_{j,i} = b_diff_j (FD_{j,i-1} + (1 - FB_{j,i-1} - FD_{j,i-1}) \cdot [1 - e^{-kd_{j,i} \Delta t_i}])$$

Where

$FD_{j,i}$ is the cumulative fraction of diffusive fission product released up to time t_i

B_diff_j is a constant class dependent coefficient provided in user input

$FD_{j,i-1}$ is the cumulative fraction of diffusive fission product released up to time t_{i-1}

FB_i is the cumulative fraction of burst fission product released up to time t_i

$[1 - e^{-kd_{j,i} \Delta t_i}]$ is the fractional release due to diffusion during the time interval Dt_i

$kd_{j,i}$ is the release rate coefficient for fission product class j calculated using the temperature, T_i , that existed during the time interval Dt_i

$$kd_{j,i} = A_j e^{-B_j / (RT_i)}$$

Where A_j and B_j are class dependent coefficients provided in user input.

- The total cumulative fission product release fraction at time t_i for fission product j is determined by:

$$F_{j,i} = d_total_j \cdot (FB_{j,i} + FD_{j,i})$$

- The cumulative release fraction cannot exceed the amount of fission product available

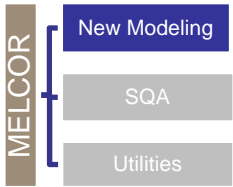
$$FB_{j,i} = FB_{j,i-1} \text{ and } FD_{j,i} = FD_{j,i-1} \text{ when } FD_{j,i} \geq 1.0$$

- The derivative of the cumulative burst release with respect to time cannot be less than zero; if the temperature decreases, the cumulative burst release remains constant.

$$FB_{j,i} = FB_{j,i-1} \text{ when } T_{i-} \geq T_{B-max} \text{ or } T_{melting}$$

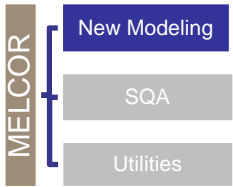
- The cumulative burst release reaches its maximum when the fuel temperature reaches T_{B-max} or $T_{melting}$ whichever is lower

$$FB_{j,i} = FB_{j,i} \text{ when } T_i \geq T_{B-max} \text{ or } T_{melting}$$



DOE Models: CONTAIN/LMR Models for

- Phase 1 – Implement sodium as replacement to the working fluid for a MELCOR calculation
 - Implement properties & Equations Of State (EOS) from the fusion safety database
 - Implement properties & EOS based on SIMMER-III
- Phase 2 – Review of CONTAIN/LMR and preparation of design documents
 - Detailed examination of LMR models with regards to implementation into MELCOR architecture
 - Implementation of CONTAIN/LMR models into CONTAIN2
- Phase 3 – Implementation and Validation of:
 - Implementation of CONTAIN/LMR models into CONTAIN2
 - Sodium spray fires (ongoing)
 - Upper cell chemistry (ongoing)
 - Sodium pool chemistry (ongoing)
- Phase 4 – Implementation and Validation of:
 - Condensation of sodium
 - Sodium pool fire models
 - Debris bed/concrete cavity interactions.



Extensions to the CF Package (September 2016)



- Ranges
 - User defined construct that generates an ordered list of objects to be used by vectorized CFs
- Vectorized CF arguments
 - Control Function arguments can now be specified as a vector of values by specifying an index with a range
- Vector Control Functions
 - Certain control functions now permit vector operations such as add, multiply, divide, equals, L-GT, L-GE, etc.
- Package input support of vector CFs
 - Some input records have been modified to allow vector fields in place of scalar fields
- Analytic Control Functions
 - Ultimate flexibility allowing users to pass vectors to a user specified FORTRAN function.

Vectorized CF Arguments

- Traditionally, MELCOR recognizes scalar control function arguments that can be used as parameters in evaluating the control function. For example, the masses in several control volumes can be summed by including an **itemized list of each control volume**.
- The user can now specify a **vectorized control function argument** that can be recognized by modified control functions (such as the the 'ADD' control function type) which can greatly reduce the number of arguments required by the control function

```

CF_ID    'CVMass' 1010ADD
CF_ARG 1
1  CVH-MASS('CORE',POOL)  1.0  0.0
2  CVH-MASS('BYPASS',POOL) 1.0  0.0
3  CVH-MASS('LP',POOL)     1.0  0.0
4  CVH-MASS('UP+UH',POOL)  1.0  0.0
5  CVH-MASS('DC',POOL)     1.0  0.0
  
```

```

CF_ID    'CVMass2' 1010 ADD
CF_ARG 1
1  CVH-MASS(#CVRANGE,POOL) 1.0  0.0
  
```



Vector Control Functions

- Control functions can now return a vector of values. The dimension of the vector must be specified on the CF_VF record

CF_VF 5

The field on this record indicates that the function returns a vector with 5 elements.

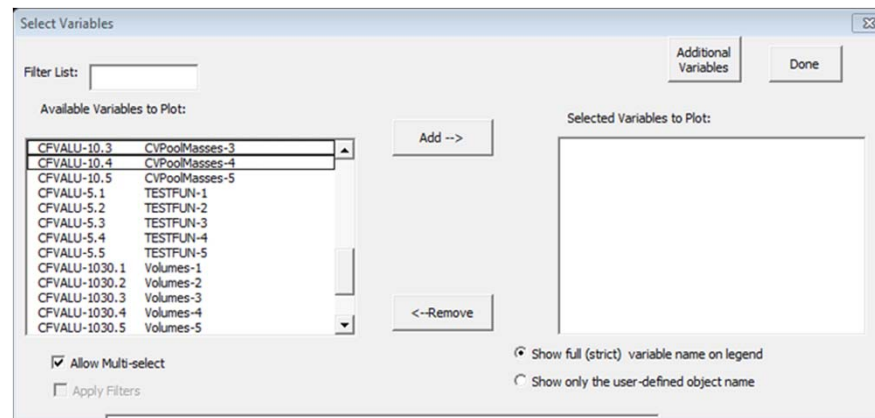
CV_VF #CVVOLUMES

The dimension is taken implicitly from the dimension of the #CVVOLUMES range

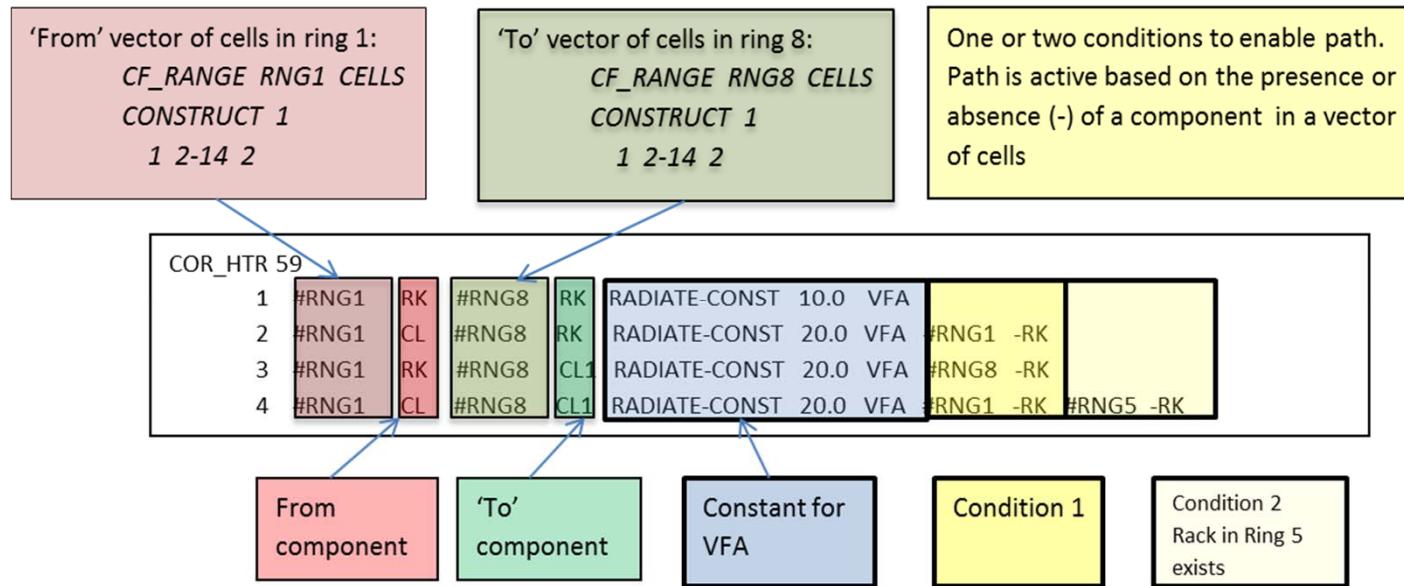
- If the user would like to reference a particular element from the vector results (e.g., the 4th element of the vector function 'TESTFUN'), that reference is made as follows:

```
CF_ID      'OXIDE-FR71'      71      EQUALS
CF_ARG 1
1 CF-VALU('TESTFUN')[4] 1.0 0.0
```

- Elements of a vector CF can be referenced from plotting routines like PTFREAD



Vectorized COR_HTR Input



- 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

Temporal Relaxation of the “Rate-of-Change”

■ Introduction

- Many physical processes in MELCOR are modeled by correlation based relationships developed from steady-state experiments. These models do not represent the time it takes for these processes to respond if conditions change. As a result, temporal “rate-of-change” aspects of MELCOR simulations are not expected to be highly accurate and numerical instabilities can be magnified when sudden changes occur.
- Temporal relaxation is a simple way to introduce a user-imposed time-scale based model that limits how quickly processes being modeled can change in time. Note that “steady-state” values are not changed, only the temporal rate-of change.

■ Fundamental Equation

- $f^{n+1} = \omega f^* + (1 - \omega)f^n$

Where

$$\omega = \min[1.0, dt/\tau_{rel}]$$

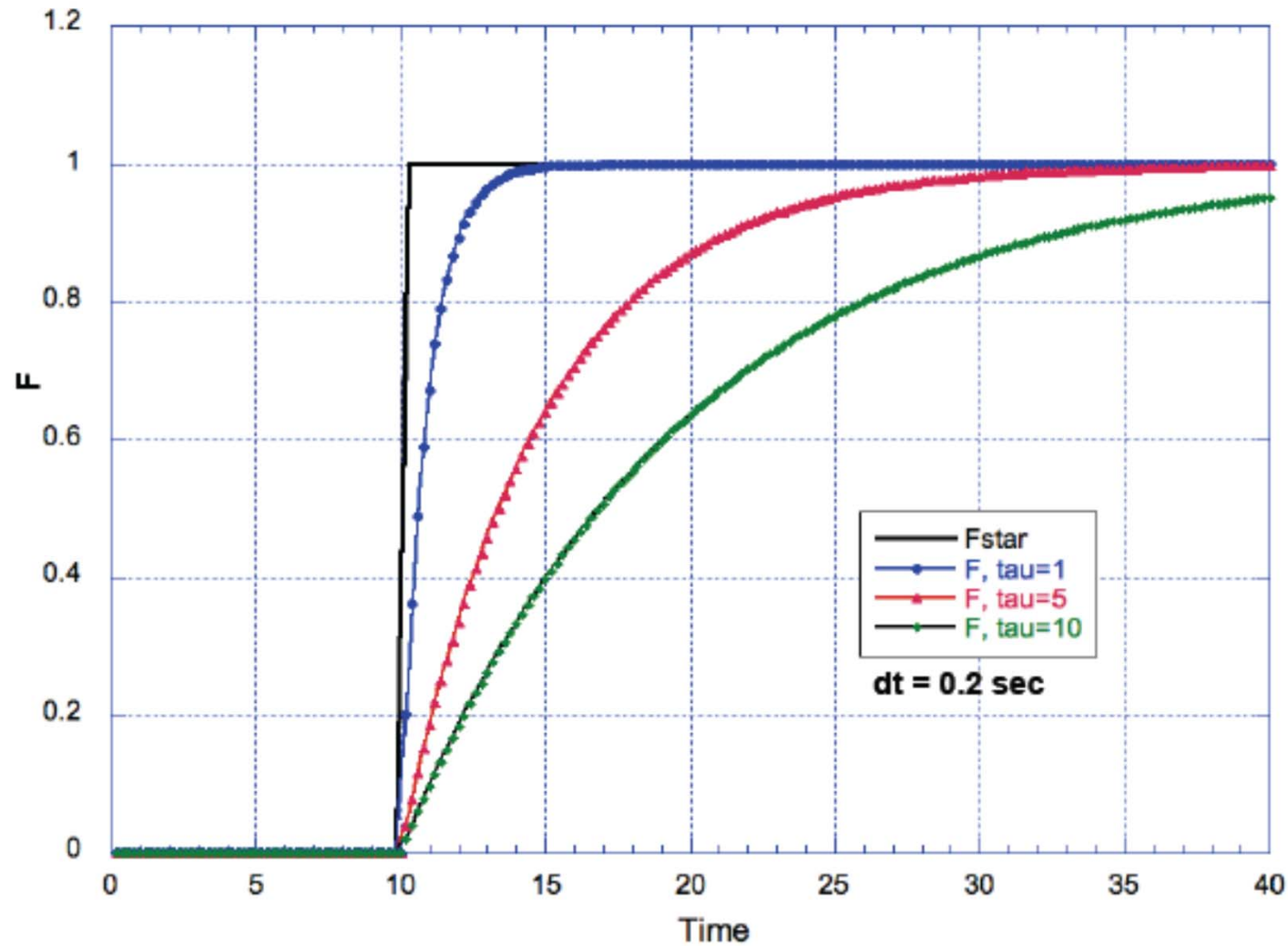
f^{n+1} = value of f at time step $n + 1$

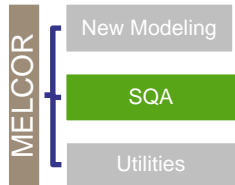
f^n = relaxed value of f at time step n

f^* = unrelaxed value of f at time step $n + 1$

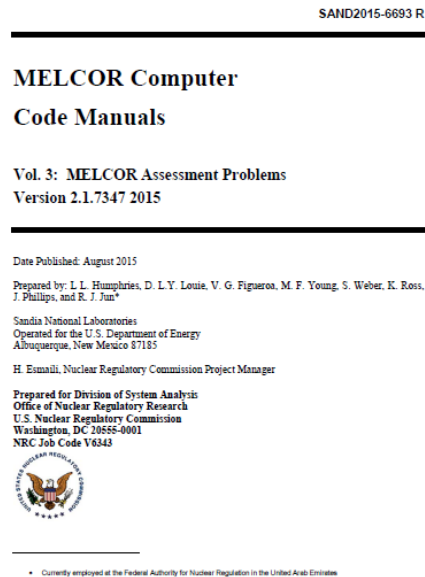
τ_{rel} = temporal relaxation time scale

Example plot for different temporal relaxation time-scales





Future MELCOR Manual Updates



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



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

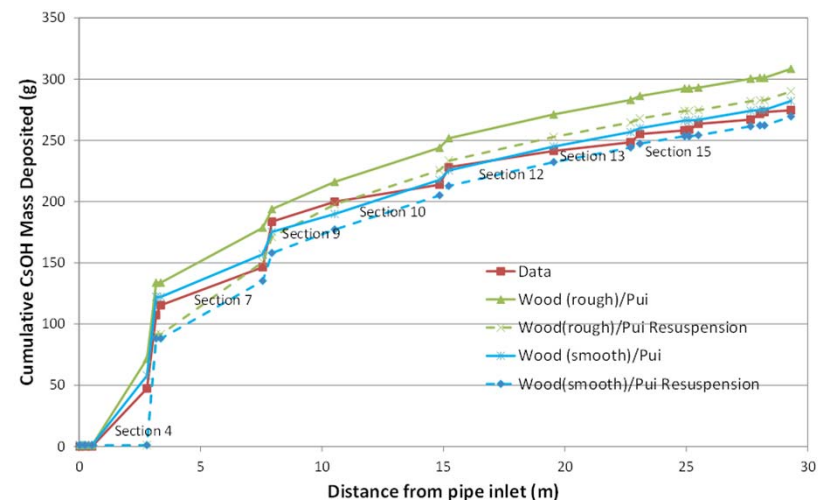
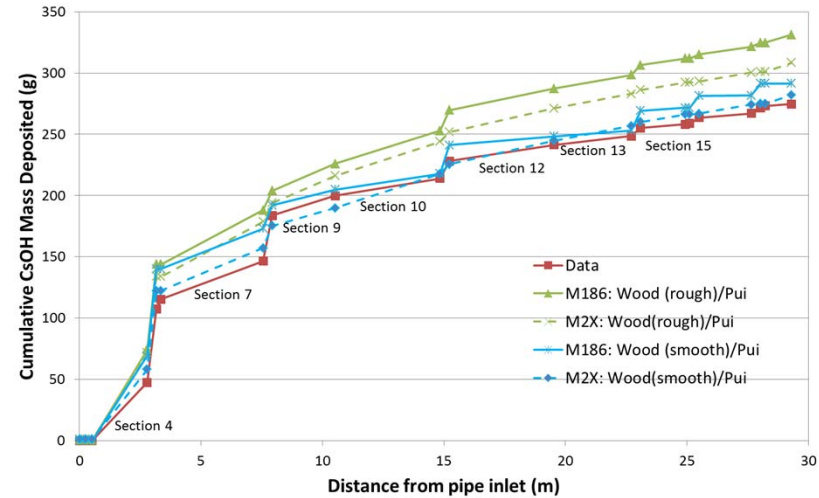
- **MELCOR ASSESSMENTS AGAINST EXPERIMENTS**

- 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

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
 - Workshop exercise
 - Updated in recent manuals
 - 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



ISP-45 Quench06 Experiment

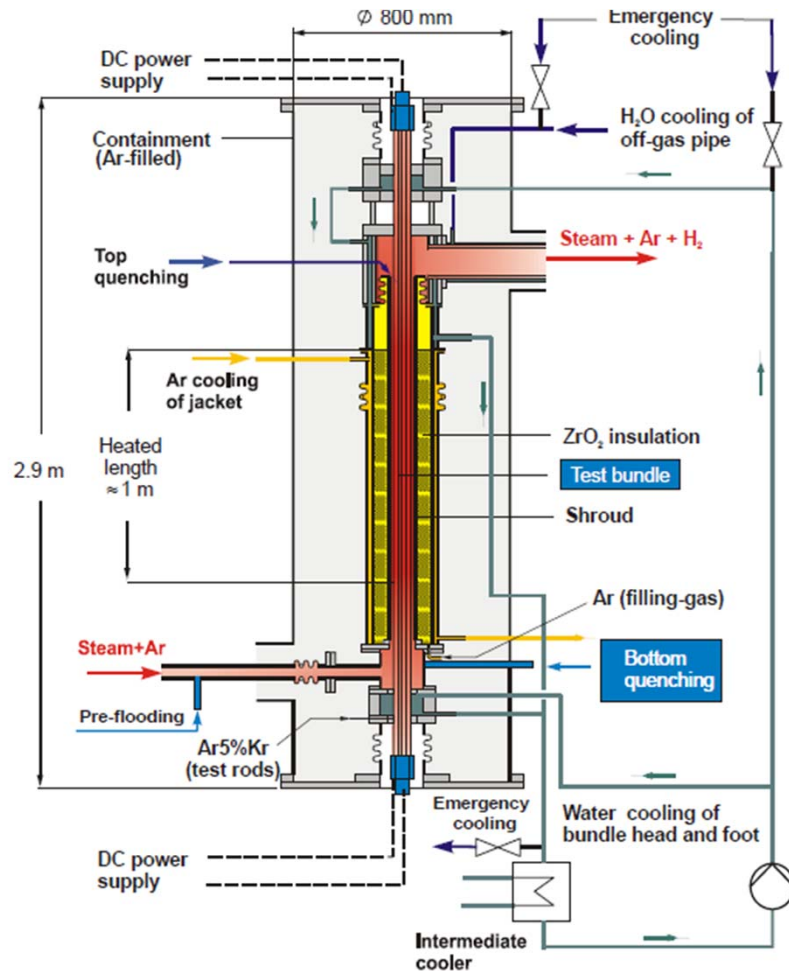
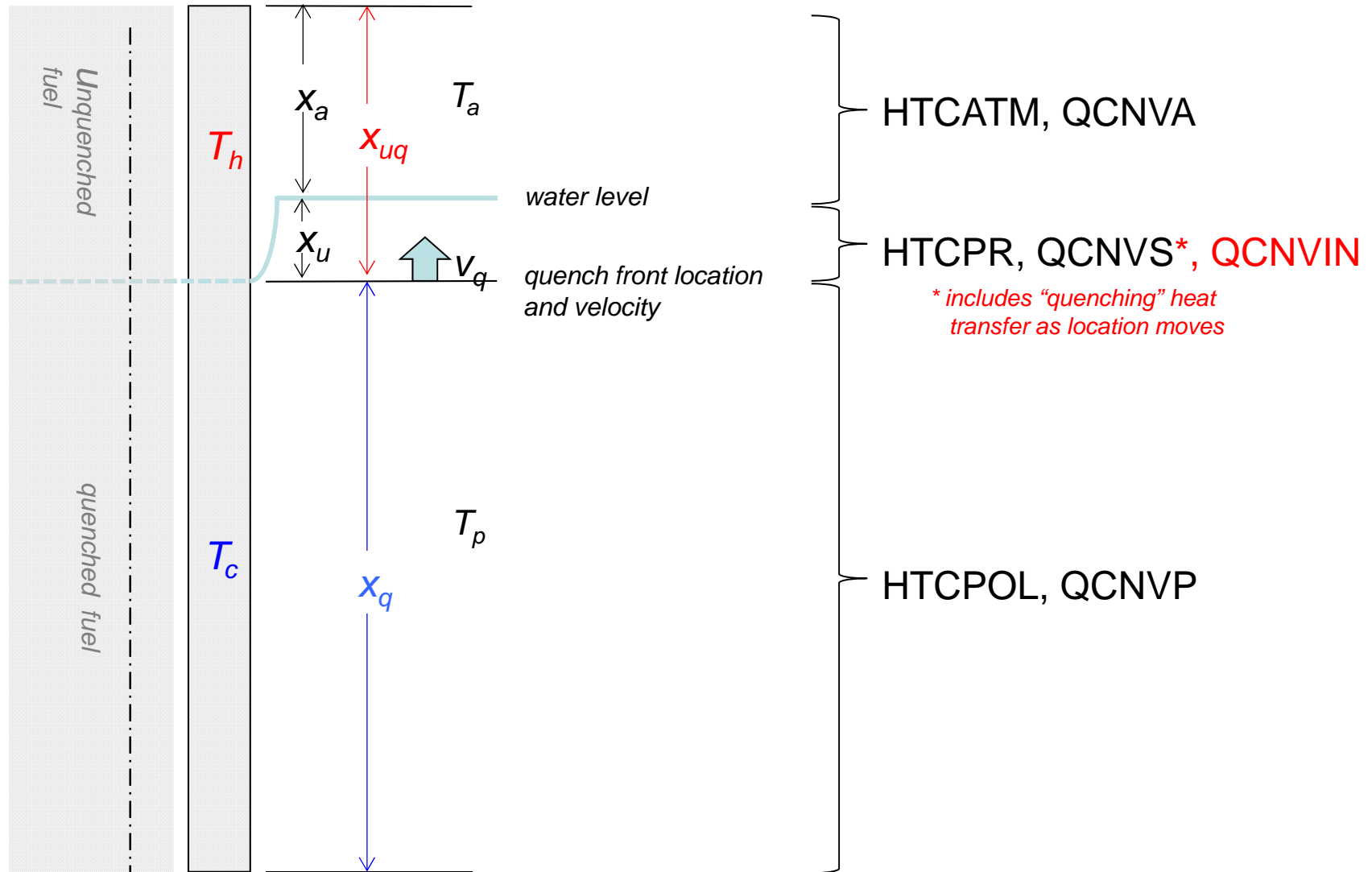


Figure 2.1 Main flow paths in the QUENCH facility.

Table 3.1 Events and phases of QUENCH-06

Time	Event	Phase
0	Start of data acquisition	
30	Heat up to about 1500 K	Pre-oxidation
1965	Pre-oxidation at about 1500 K	
6010	Initiation of power transient	Power transient
6620	Initiation of pull-out of corner rod (B)	
7179	Quench phase initiation Shut down of steam supply Onset of fast water injection Start of quench water pump Detection of clad failure First temperature drop at TFS 2/1	Reflow
7181	Steam mass flow rate zero	Quench
7205	Onset of electric power reduction	
7221	Decay heat level reached	
7430	Onset of final power reduction	
7431	Shut down of quench water injection	Post-reflood
7431	Electric power < 0.5 kW	
7435	Quench water mass flow zero	
11420	End of data acquisition	

Illustrative picture for COR convective heat transfer



Reflood Quench Model

- MELCOR computes a quench velocity, distinct from pool water level
 - The quench velocity correlation implemented is that of Dua and Tien¹

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

- Where

- Pe is the dimensionless quench velocity or Peclet number

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

- \bar{B} is a dimensionless Biot number

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

- 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).

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

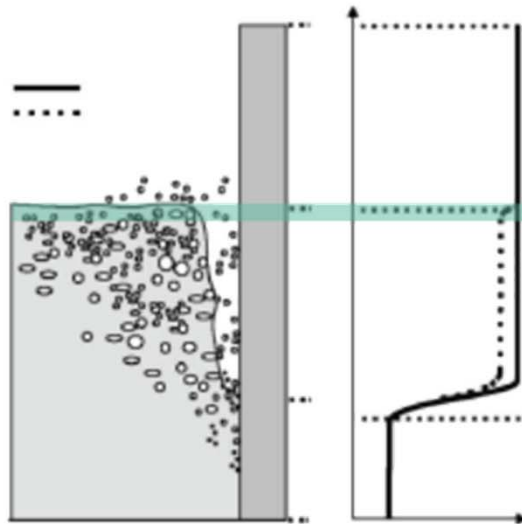
Observations on Model Implementation

1. All of the thermal energy associated with the change in temperature across the quench front is transferred into a direct vaporization of liquid water into steam.
2. The thermal capacitance of the COR components relative to that of the surrounding coolant is typically quite large.
3. Because the quench velocity model is based on “steady” (i.e. non time-varying”) conditions, when conditions change, no matter how quickly, the computed quench velocity will also change instantaneously.

Revised Quench Front Velocity

This revision prevents the code from producing unphysical pressure oscillations by enabling the quench front velocity to

- (1) Have its rate-of-change temporally relaxed, and
- (2) be smoothly driven to zero within a small user-specified distance of the pool level (C1260(5), DXQNCH).



Example specification of DXQNCH:

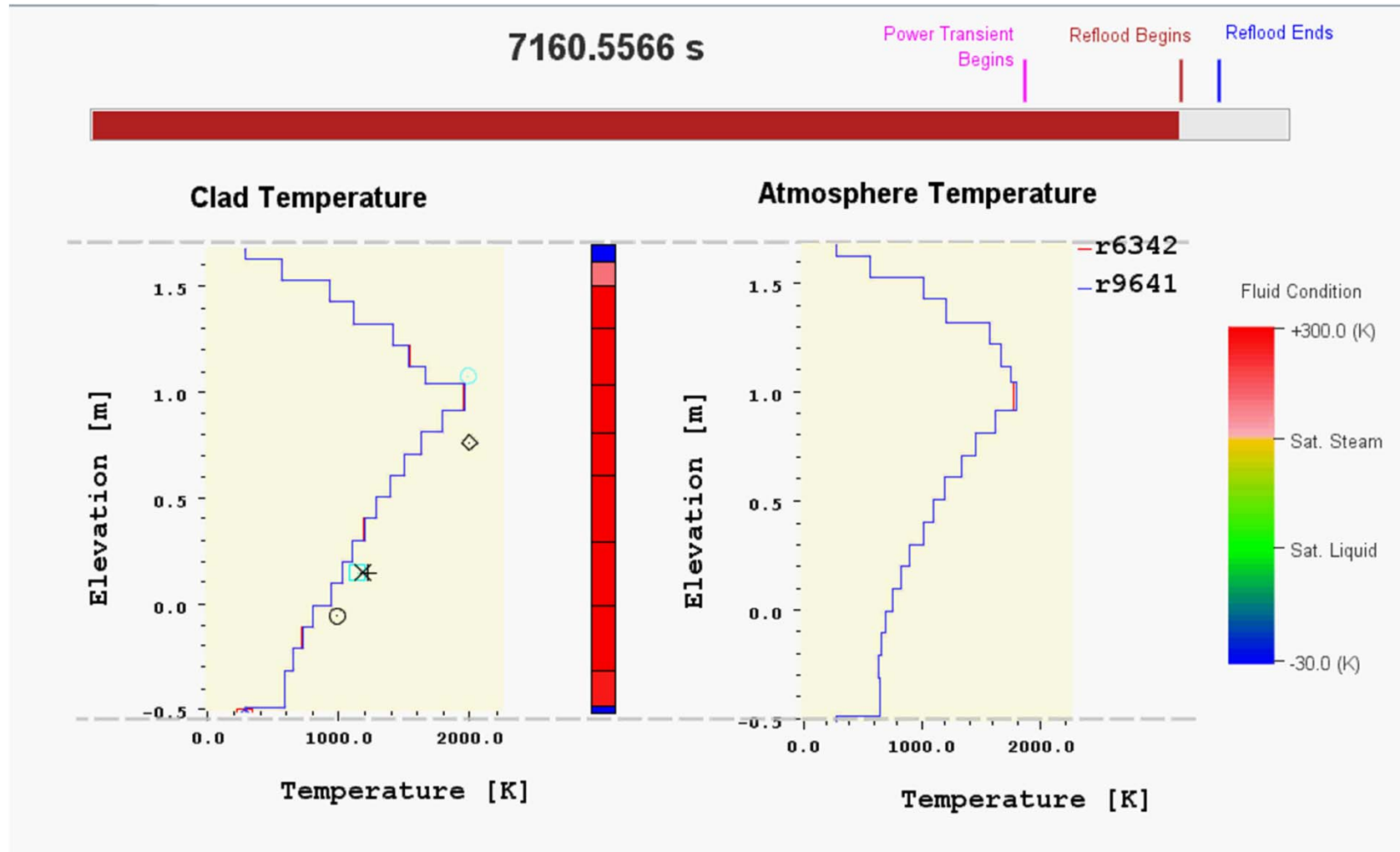
```
COR_SC 1 ! n nnnn value index
          1 1260 0.02 5
```

DXQNCH: fractional width of quench vel. Reduction zone near pool level (default is 0.02)

Temporal relaxation is not applied to receding quench fronts

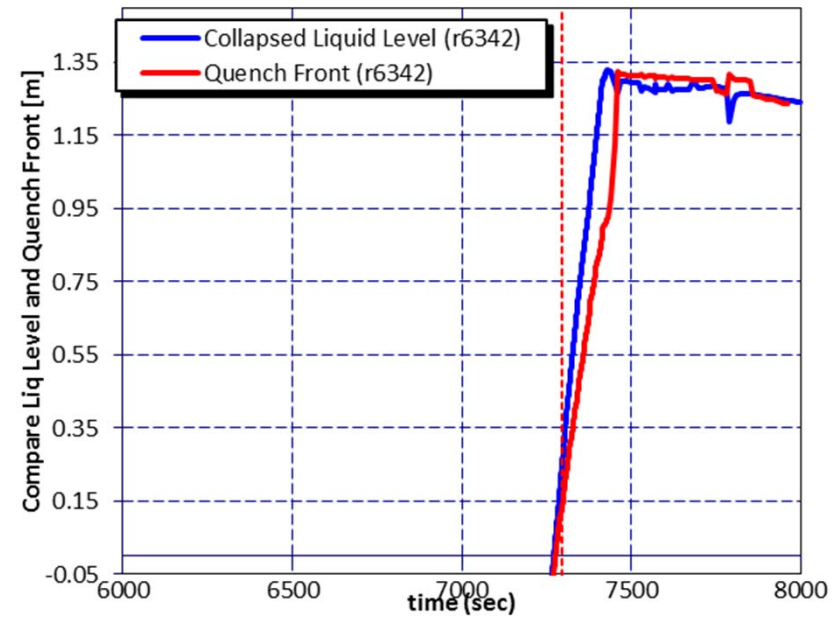
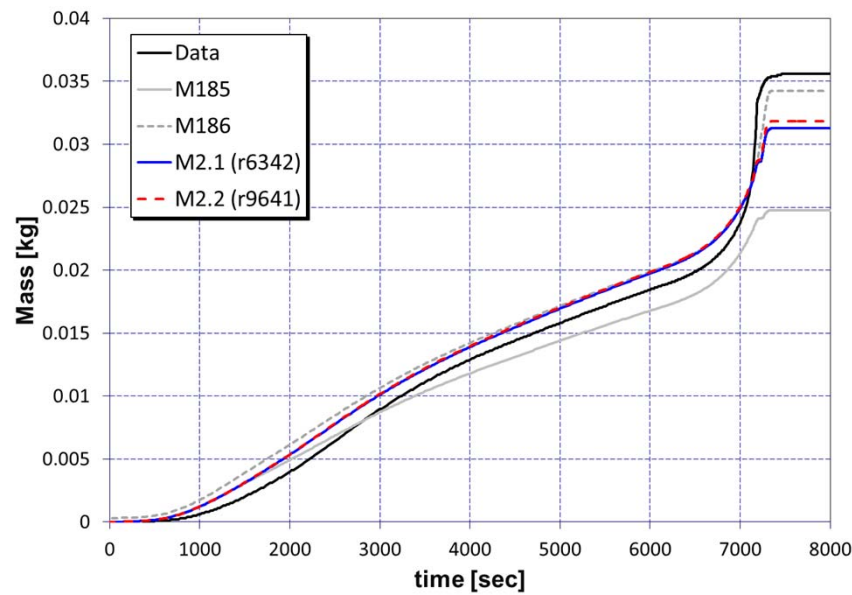
The reduction in velocity near the surface is computed using a simple cubic polynomial-based multiplier that drives the value to zero.

ISP-45 (Quench-06 experiment) MELCOR Simulation

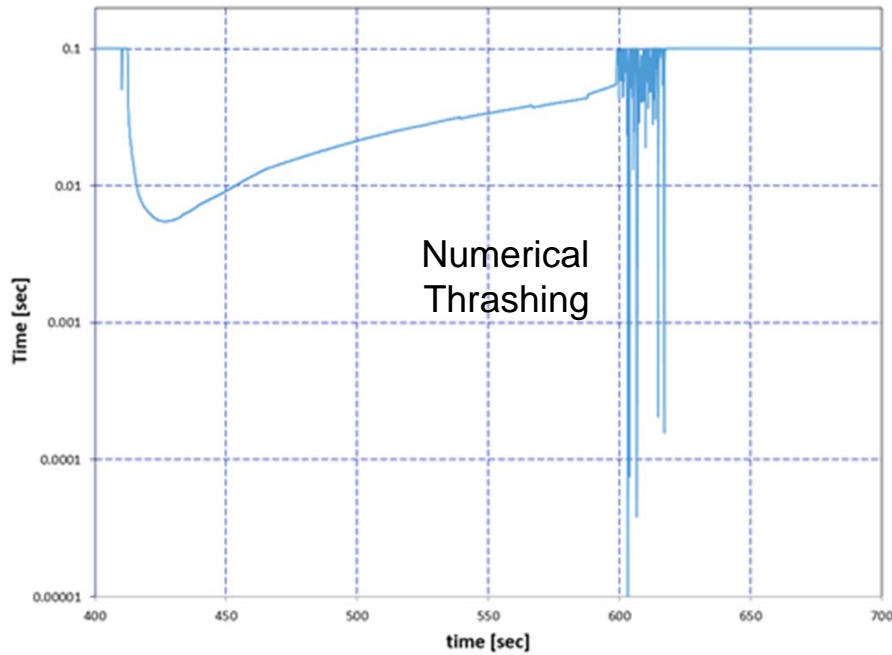


ISP-45 (Quench-06 experiment) MELCOR Simulation

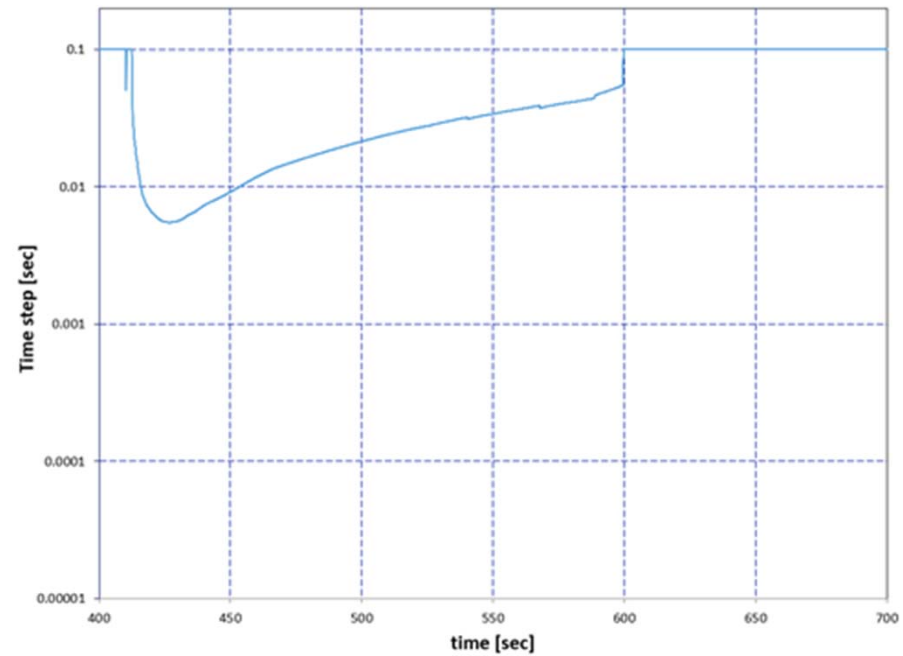
- Quench model effects oxidation
 - Changes component temperatures
 - Oxidation of submerged components
 - Little change in total oxidation since last release (r6342)



Time-step size vs. simulation time

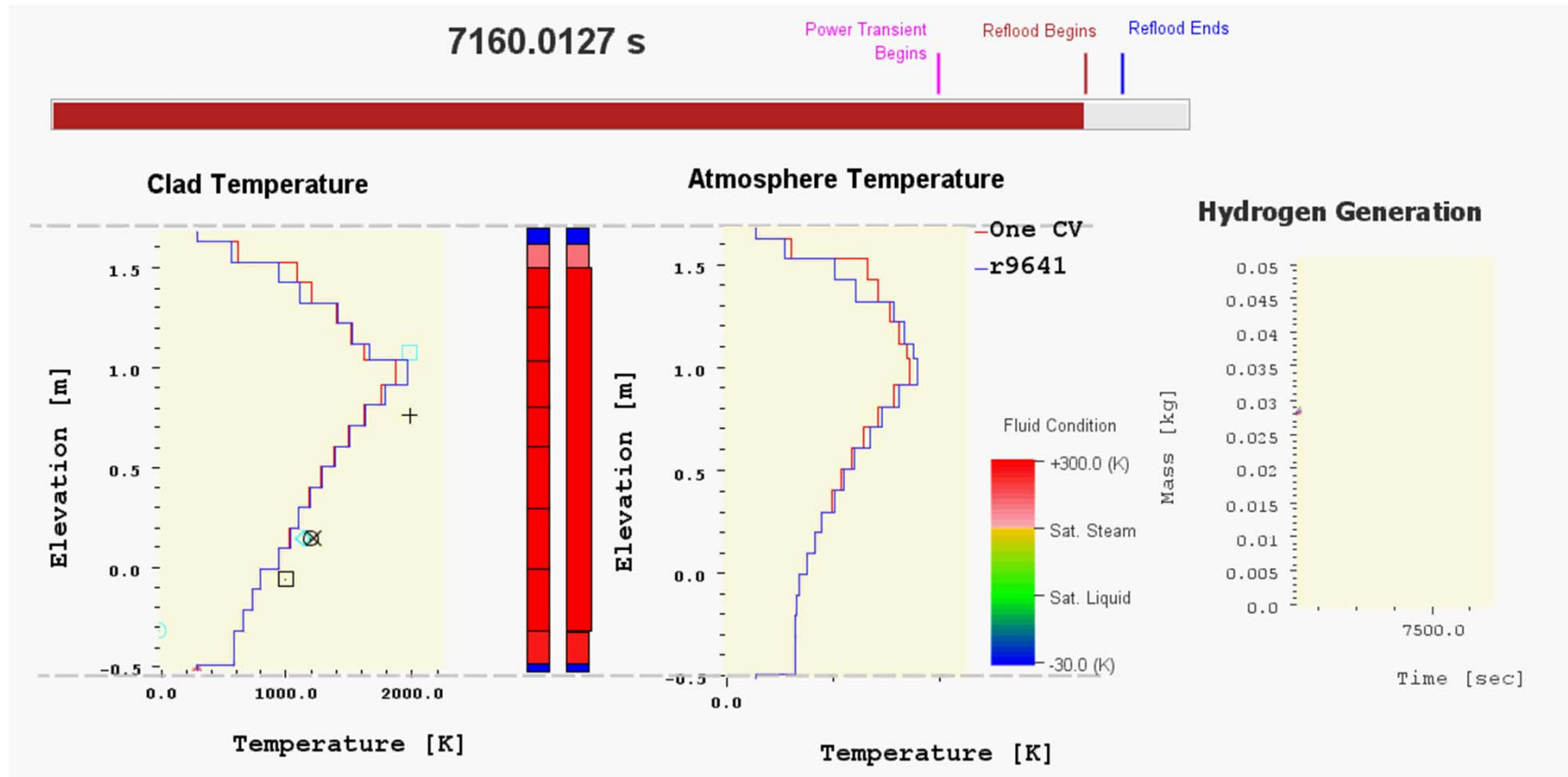


Modeling changes inactive



Modeling changes active

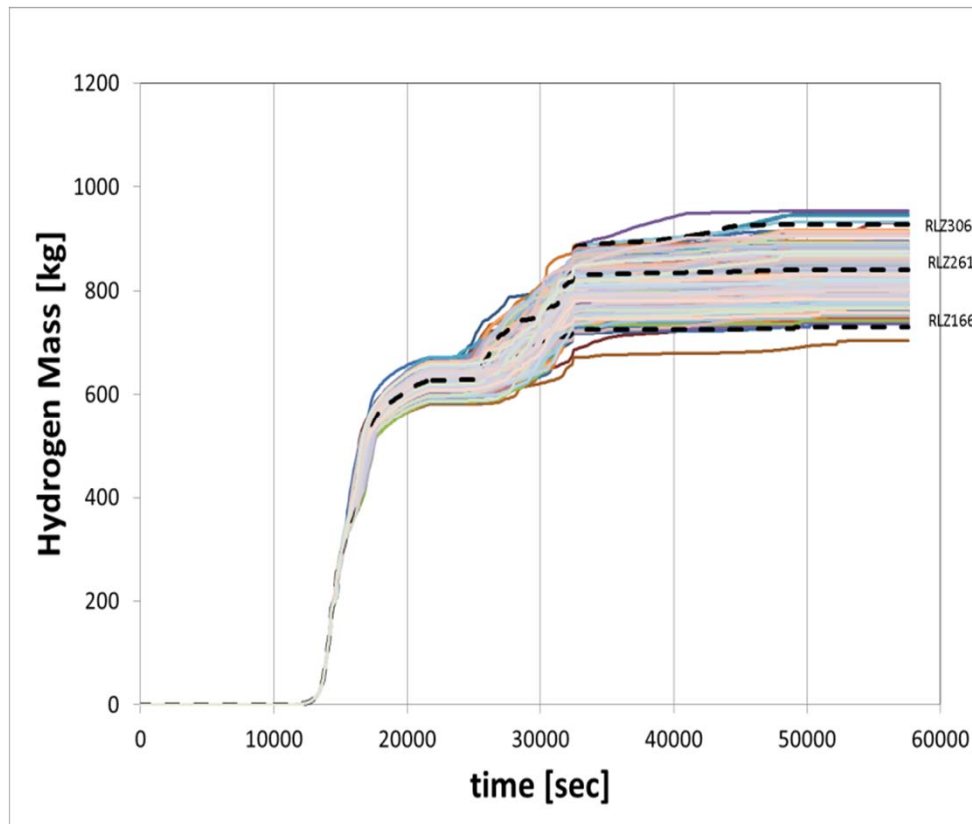
Nodalization – Compare Single CV to CV stack (Preliminary Results)



Numerical Variance

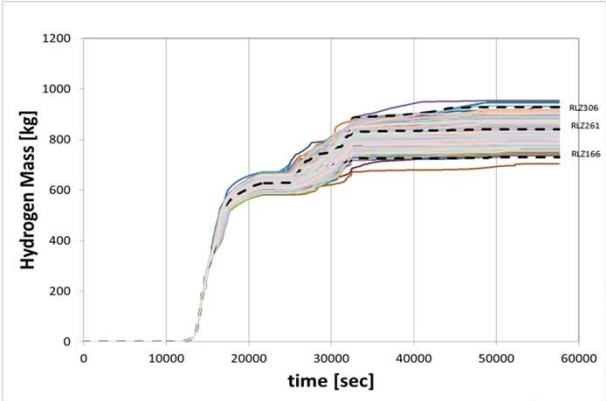
- Characterization of Numerical Variance
 - Background code variance
 - Sources of variance
 - Amplifiers
 - Effect of COR Nodalization on Numerical Variance
 - COR cell nodalization
 - CVH nodalization
 - Assess the sensitivity of the variance to COR degradation models
 - Time step variations & time 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

Variance from Perturbation of Flow Equations

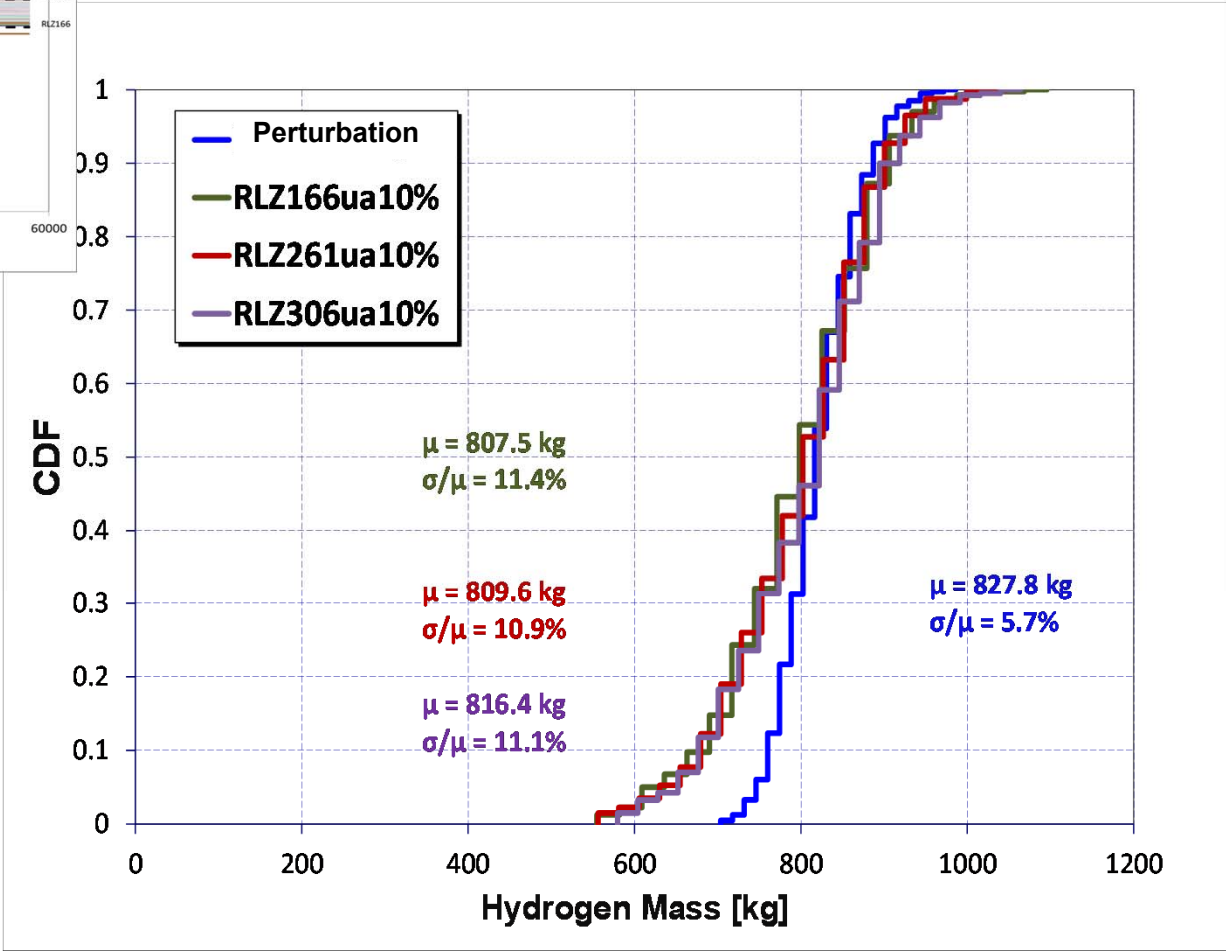


- Each realization is essentially equivalent descriptions of problem
- Order of input definition randomly varied
- Representative extremes examined separately by Monte Carlo sampling over state of knowledge uncertain parameters
- Do different but equivalent flow path descriptions produce different distributions in UA ?

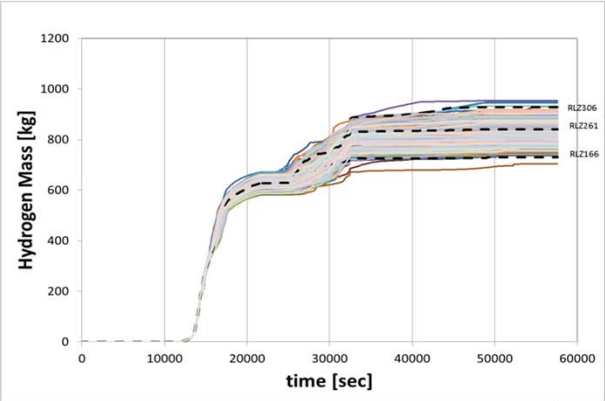
Representative Extremes of Perturbation used as seed for 10% UA variations



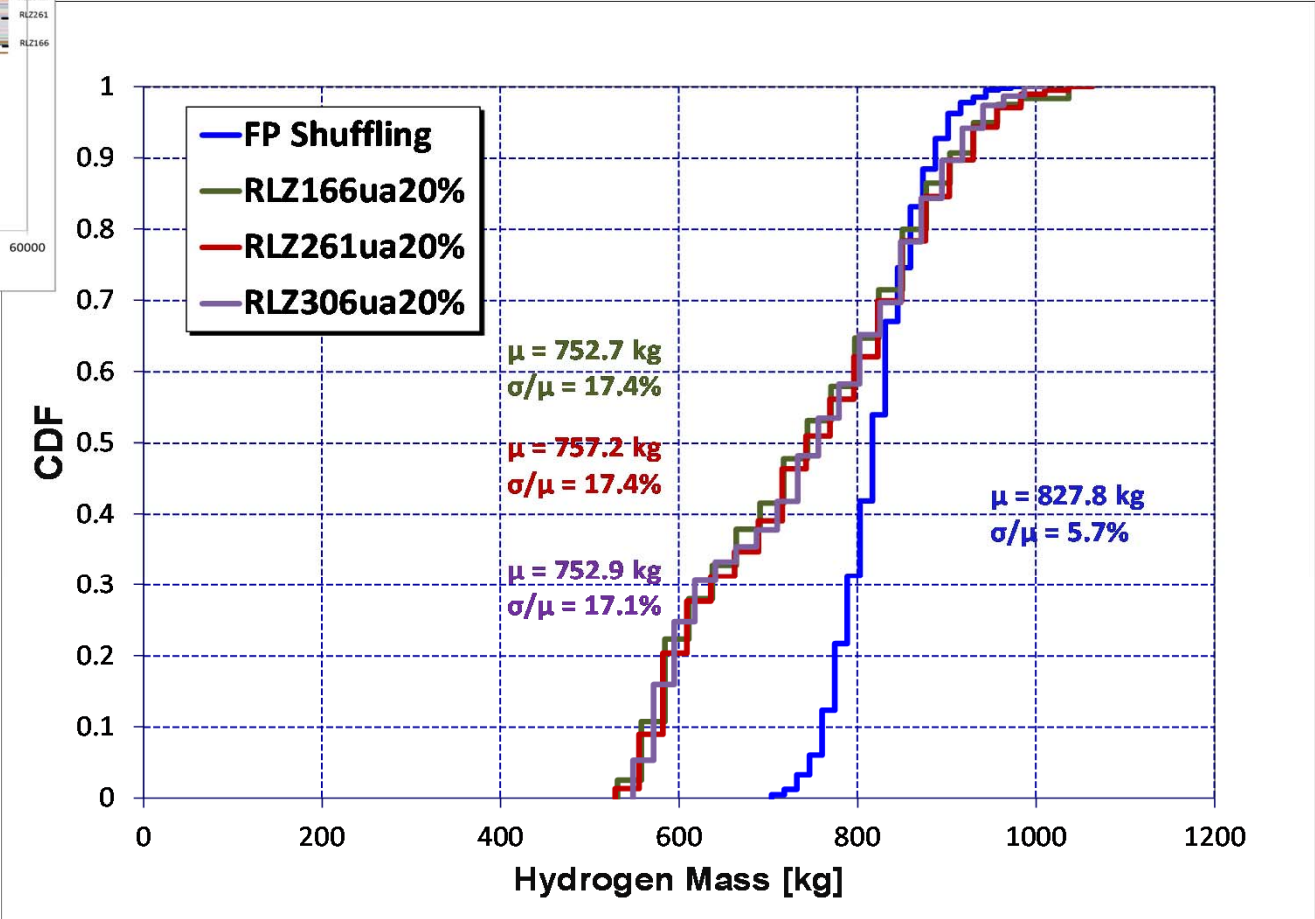
Each representative member of the “shuffle” ensemble returns the same resultant distribution when UA parameters are varied



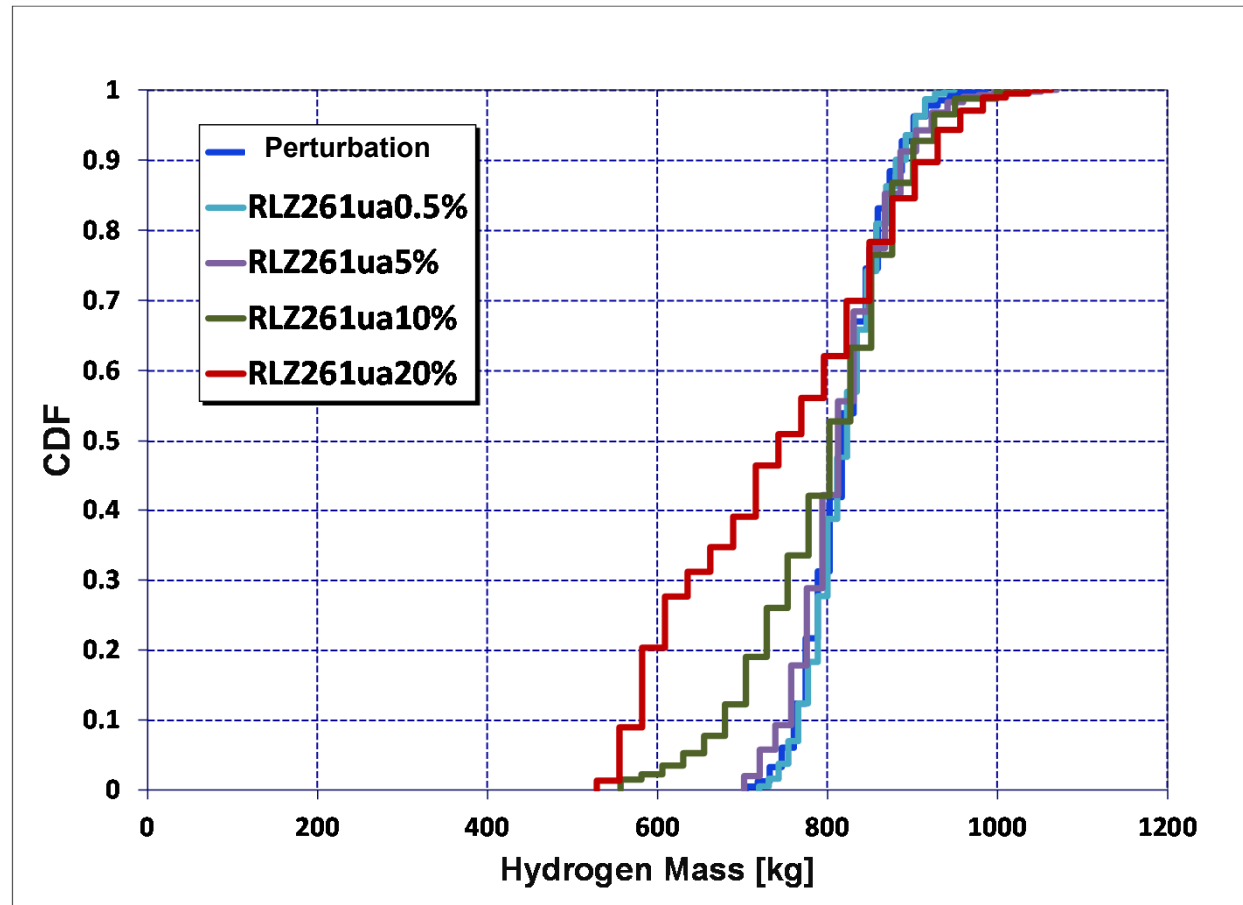
Representative Extremes of Perturbation used as seed for 20% UA variations



Same result for 20% UA Variation
Note: that mean is shifting down, Upper H2 limited by core degradation

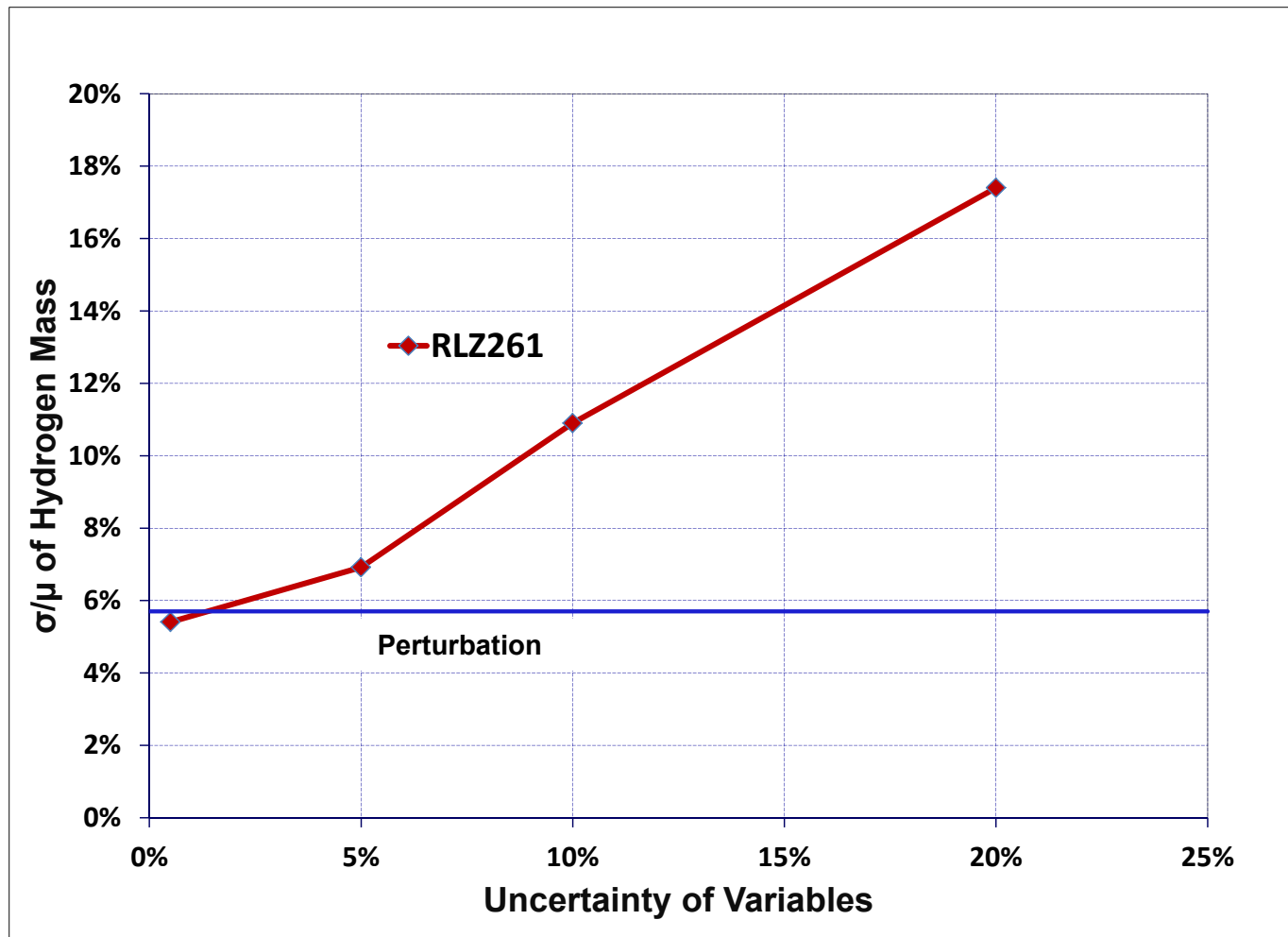


UA Variation Explored to Characterize Signal to Noise Ratio



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



Questions?

