

MELCOR Best Practices in SOARCA AMUG 2017

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SOARCA Project

- NRC initiated the State-of-the-Art Reactor Consequence Analyses (SOARCA) project to develop best estimates of the offsite radiological health consequences for potential severe reactor accidents.
 - Peach Bottom Atomic Power Station
 - NUREG/CR-7110 “State-of-the-Art Reactor Consequence Analyses Project, Volume 1: Peach Bottom Integrated Analysis”
 - Surry Power Station
 - NUREG/CR-7110, “State-of-the-Art Reactor Consequence Analyses Project, Volume 2: Surry Integrated Analysis”
- State-of-the-Art (2007)
 - Up-to-date information about the plants’ layout and operations
 - Up-to-date local population data and emergency preparedness plans.
 - State-of-the-art computer codes
 - Incorporating decades of research into severe reactor accidents
 - Latest (2007) ‘Best Practices’

SOARCA Best Practice Report

NUREG/CR-7008



NUREG/CR-7008

MELCOR Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project

Office of Nuclear Regulatory Research

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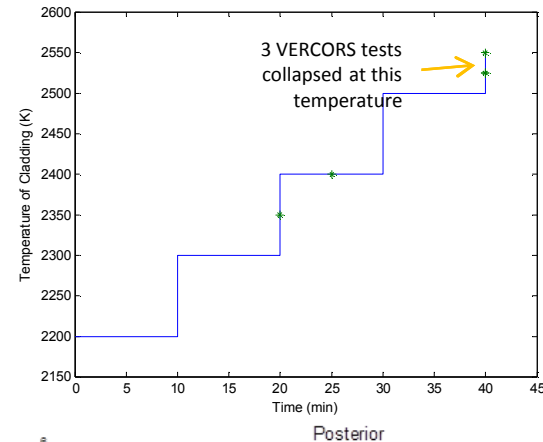
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MELCOR 2.2 Fuel Rod Collapse Model

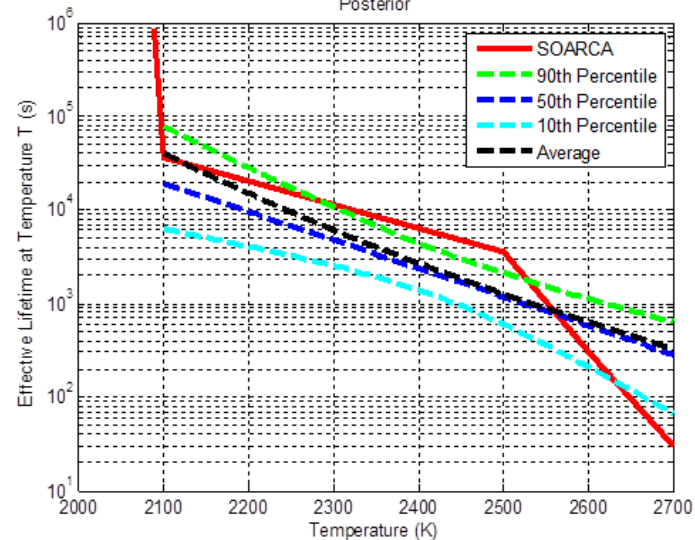
- Time-at-temperature model
 - Available in M186 but not default until now
 - Characteristics had to be provided by user
 - Eliminates temperature threshold effect from failure temperature model

- 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

Modified ORNL-Booth Fuel Fission Product Release

- Motivation

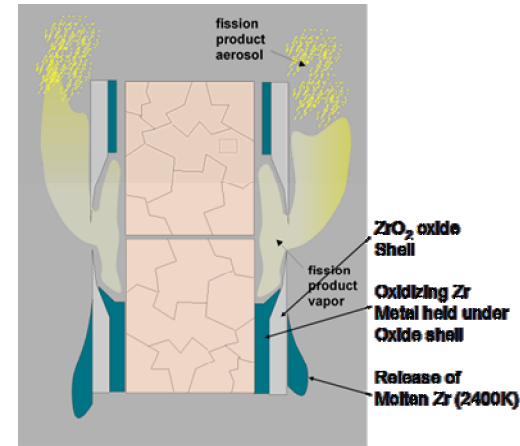
- Though CORSOR-M predicted reasonable results for ISP-46 (FPT-1) though CORSOR-Booth did not.

- Though Booth model was considered more physically defensible
 - Investigated more recent parameter-fits to the Booth solution

- ORNL-Booth gave best results

- Improvements made by fitting to FPT1 & VERCORS/VI tests

- RN Class Speciation important



	CORSOR-Booth	ORNL-Booth	Adjusted ORNL-Booth
Diffusion coeff. D_0	$2.5 \times 10^{-7} \text{ m}^2/\text{sec}$	$1 \times 10^{-6} \text{ m}^2/\text{sec}$	$1 \times 10^{-6} \text{ m}^2/\text{sec}$
Activation Energy Q	$3.814 \times 10^5 \text{ joule/mole}$	$3.814 \times 10^5 \text{ joule/mole}$	$3.814 \times 10^5 \text{ joule/mole}$
Grain radius, a	$6 \mu\text{m}$	$6 \mu\text{m}$	$6 \mu\text{m}$
Class Scale Factors	---	---	---
Class 1 (Xe)	1	1	1
Class 2 (Cs)	1	1	1
Class 3 (Ba)	3.3×10^{-3}	4×10^{-4}	4×10^{-4}
Class 4 (I)	1	0.64	0.64
Class 5 (Te)	1	0.64	0.64
Class 6 (Ru)	1×10^{-4}	4×10^{-4}	0.0025
Class 7 (Mo)	0.001	0.0625	0.2
Class 8 (Ce)	3.34×10^{-5}	4×10^{-8}	4×10^{-8}
Class 9 (La)	1×10^{-4}	4×10^{-8}	4×10^{-8}
Class 10 (U)	1×10^{-4}	3.6×10^{-7}	3.2×10^{-4}
Class 11 (Cd)	0.05	0.25	0.25
Class 12 (Sn)	0.05	0.16	0.16

MELCOR RN Class Structure

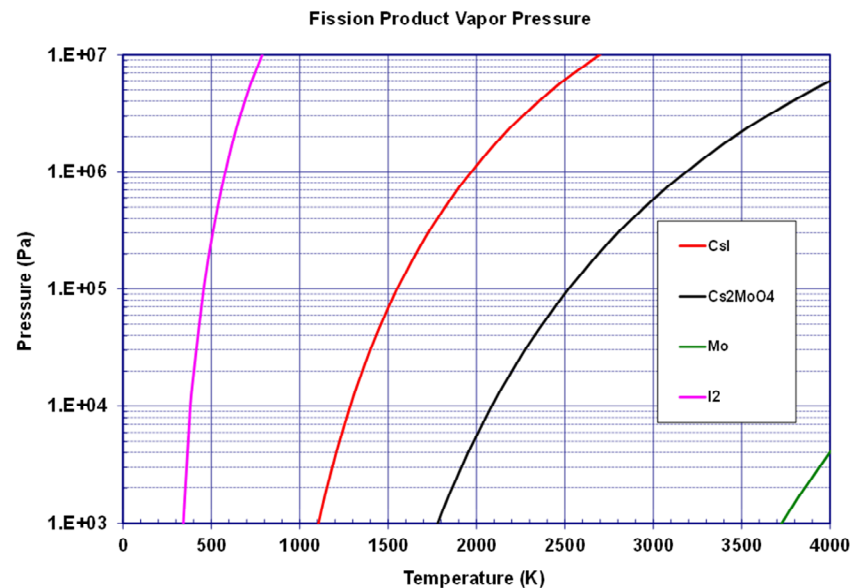
MELCOR Class Number ¹	Class Name	Representative	Element Members
1	Noble Gases	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkaline Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	I ₂	F, Cl, Br, I, At
5	Chalcogens	Te	O, S, Se, Te, Po
6	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalents	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalentes	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10	Uranium	UO ₂	U
11	More Volatile	Cd	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12	Less Volatile Main	Ag	Ga, Ge, In, Sn, Ag
13	Boron	BO ₂	B, Si, P
16	Cesium Iodide ²	CsI	Classes 2 and 4
17	Cesium Molybdate ²	Cs ₂ MoO ₄	Classes 2 and 7

¹Classes 14 and 15 do not contain fission products and are not relevant to this section.

²Masses are derived from the speciation process and are not initially populated by the ORIGEN data.

RN Class Speciation- CsMoO₄

- Evidence from the Phebus experiments increasingly indicates that the dominant chemical form of released Cs is that of Cs₂MoO₄.
 - Cesium Molybdate-Cesium Hydroxide split of 80:20
- While having little effect on the net release of Cs, this change had a significant effect on the release of Mo.
 - Mo vapor pressure is so exceedingly low that the net release is limited by the vapor transport term



SOARCA Fission Product Classes Definition

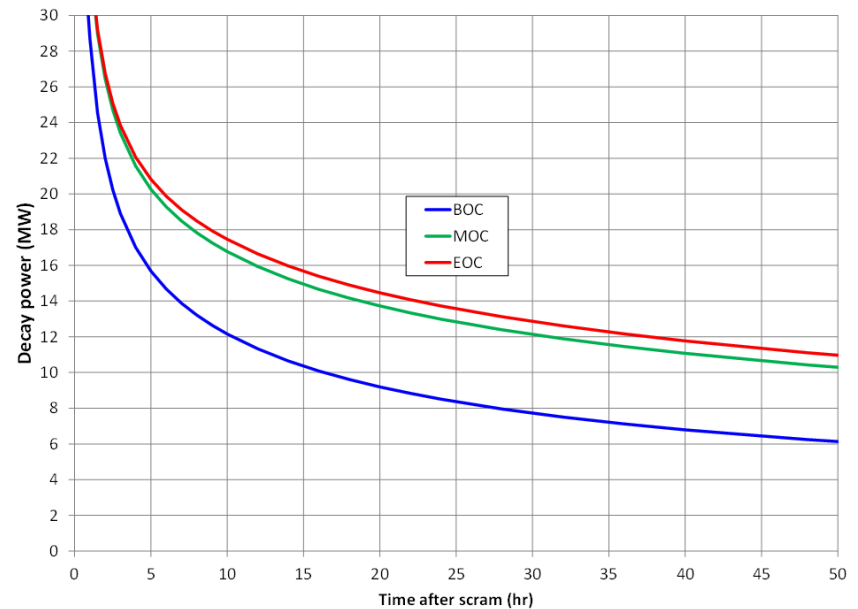
- Modeling methodology draws from the following resources
 - Phebus experiments
 - Cs_2MoO_4 used across all of SOARCA
 - Gaseous iodine (I_2 , methyl iodine neglected) only applied in SOARCA UA
 - Prior best-estimate SOARCA studies assume chemical form CsI only for iodine
NUREG/CR-7155, “SOARCA Project – Uncertainty Analysis of the Unmitigated LTSBO of the Peach Bottom Atomic Power Station, Draft Report”
 - VERCORS, ORNL VI&HI, Phebus, and the CORSOR/ORNL-Booth release models
 - Modification of the Booth-ORNL model parameters
NUREG/CR-7008, “MELCOR Best Practices as Applied in the SOARCA Project”
Modification of CORSOR/Booth Parameters in MELCOR
 - NUREG-1465
 - Assumed gap fractions

Modeling Fission Products

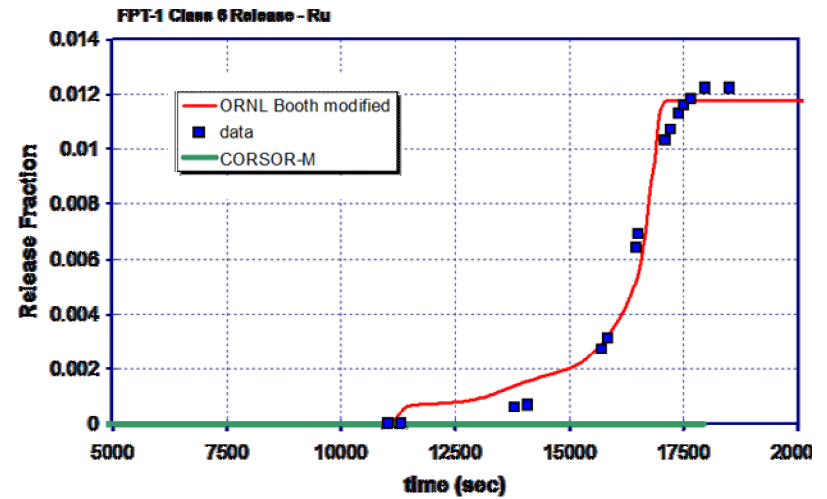
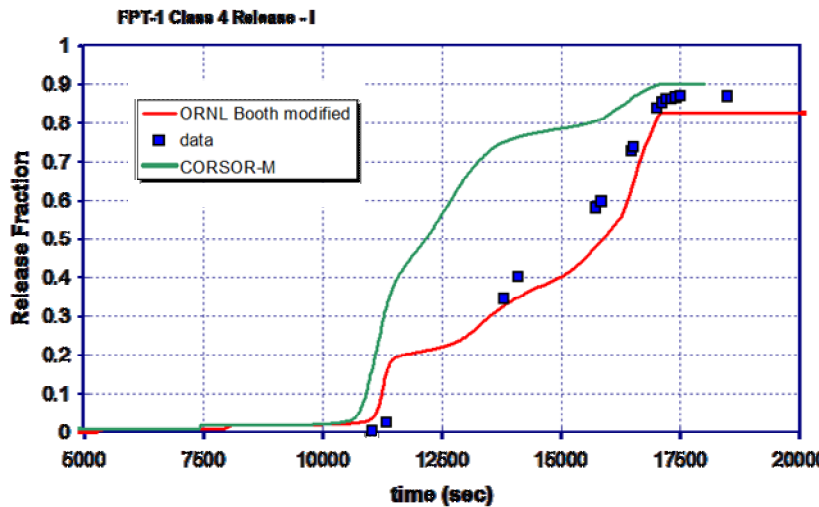
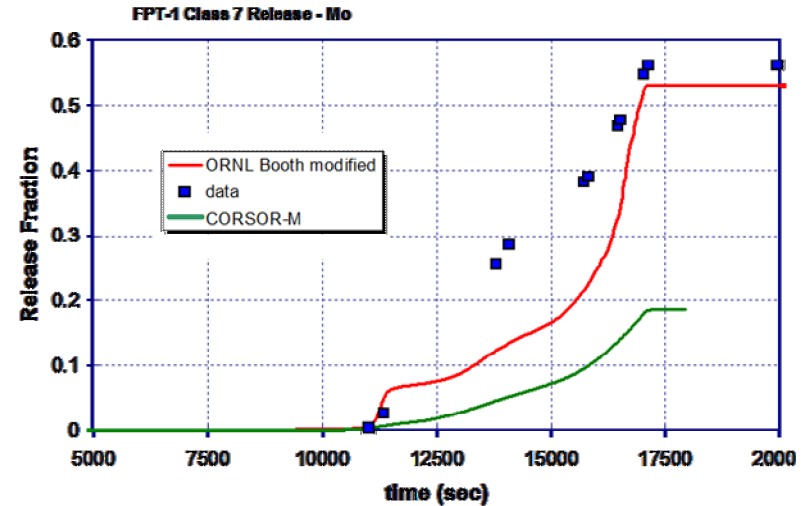
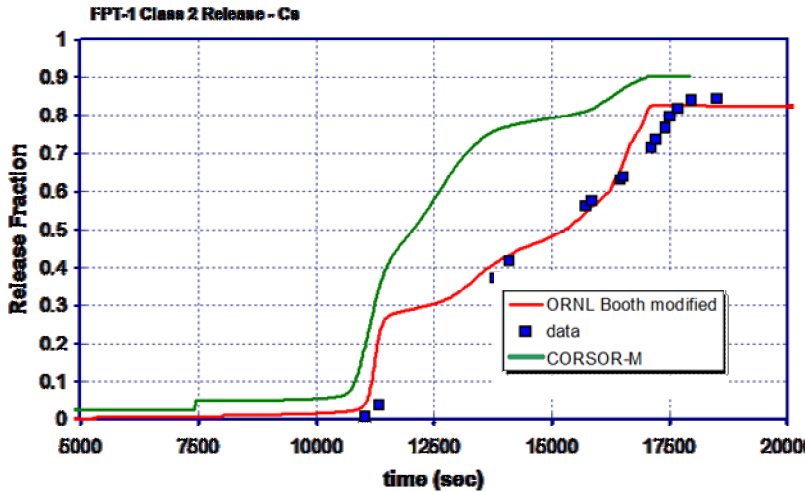
- Pre-defined mass for all classes
 - No application of the class combination model
 - Prescriptive containment concentrations are being directly specified within the fuel
 - User must combine decay heat tables appropriately
 - Specify radioactive mass for Cs (CsOH), CsI, Mo, Cs₂MoO₄
- SOARCA practice
 - Class 2 – 5% of available Cs (all placed into the fuel gap)
 - Class 4 – 0%
 - Class 16 – All Iodine combined (5% placed into the fuel gap)
 - Class 17 – Remaining Cs combined to form Cs₂MoO₄
 - Specifying radioactive mass in the fuel
 - Class 7 – Mo decremented by formation of Cs₂MoO₄

SOARCA UA Total Decay Heat

- Sampled – Time at Cycle
 - Baseline decay heat power curves for scenario initiating at different times
 - Time of shutdown correspond to 7, 200, and 505 days for BOC, MOC, and EOC, respectively



Assessment of ORNL-Booth with FPT-1



SNL Lifetime Breakaway Model

- Lifetime rule similar to Larson-Miller creep
 - Used to capture the time-at-temperature characteristics of breakaway
- Local damage is tracked for all Zircaloy components

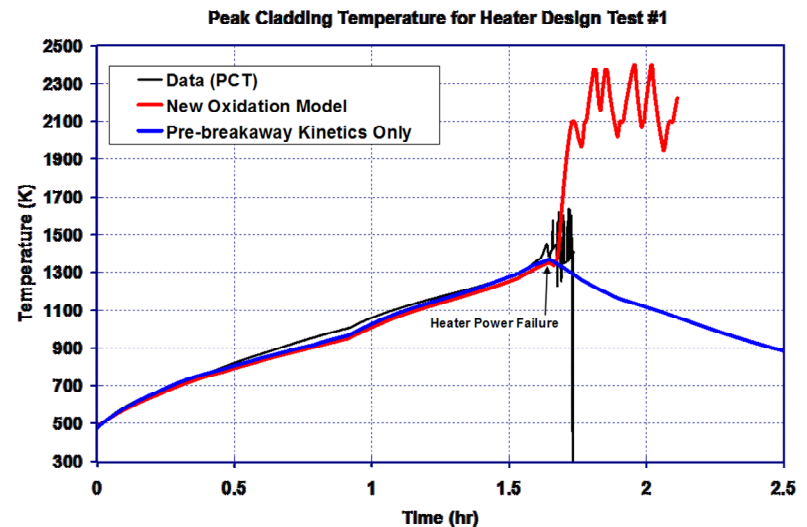
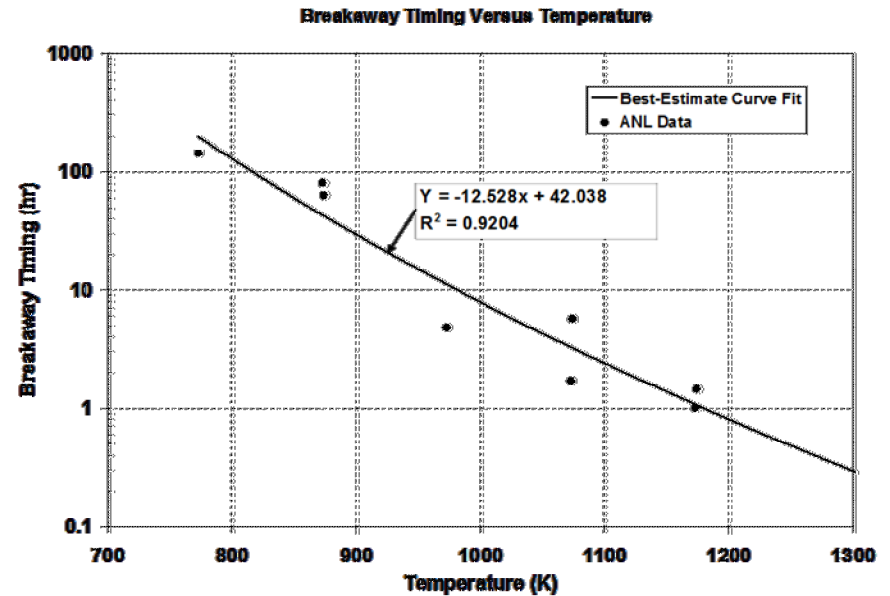
$$LF = \int_0^t dt' \frac{t'}{\tau(T)}$$

where,

$$\tau(T) = 10^{P_{LOX}}$$

$$P_{LOX} = -12.528 \cdot \log_{10} T + 42.038$$

- Parameters come from experimental curve fit
- Failure occurs when damage function reaches 1



PSI Air Oxidation Model

- Initially, oxidation kinetics follows a parabolic law
 - Uses Arrhenius law similar to default MELCOR

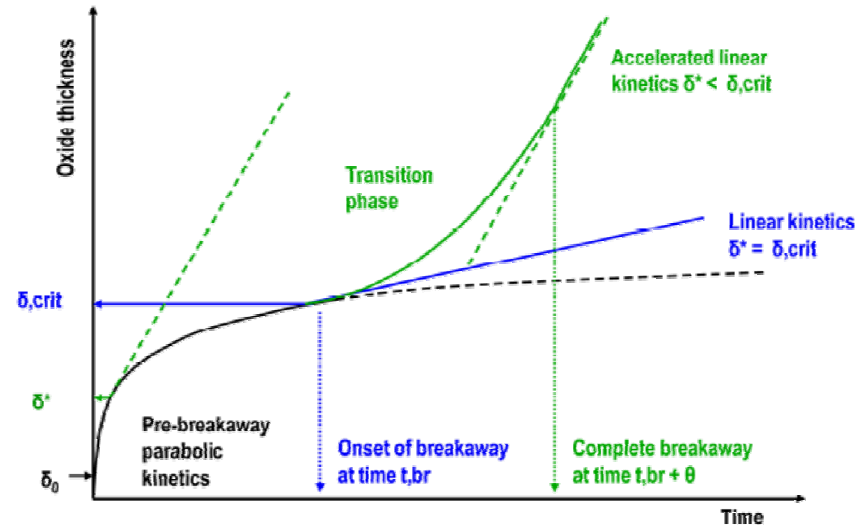
$$C = A \exp(-B/T)$$

- Oxide Thickness
 - Does not account for oxygen dissolved in metallic zirconium, $\alpha(\text{Zr-O})$

$$d(\delta) / dt \sim C' / \delta_{\text{eff}}$$

$$\delta = \Delta m \frac{M(\text{ZrO}_2)}{\rho(\text{ZrO}_2)M(\text{O}_2)}$$

Δm is the mass gain / area
 $M(X)$ is the molecular weight of species X



- Transition to linear initiates at critical thickness
 - When δ reaches δ_{crit} transition to linear (breakaway) is initiated
 - The 'effective' oxide thickness (more porous microstructure) decreases from δ_{crit} to δ^* during transition
 - When oxide thickness reaches δ^* , transition is complete
 - Empirical fits to δ_{crit} and δ^*
 - Empirical fit for rate of change in δ_{eff} during transition

Change in MELCOR Defaults Based on MELCOR Best Practices

- Default values for sensitivity coefficients should represent the best available value for general application
 - Recognize that there is uncertainty in each value and the default represents something like the mean in a probability distribution
- Recent changes in default values based on SNL 'Best Practices'
 - Many proposed by Scott Ashbaugh, and Randy Gauntt, Mark Leonard, and K.C. Wagner
 - Some were based on MELCOR 1.8.5 experience only
 - Many sensitivity coefficients were typically overridden by users and it was desired to make the changes more generally available
 - Default values changed in MELCOR 2.1 (Sept 2008)
 - User can revert to original default values through input
 - CORDEFAULT 1.8.6
 - CAVDEFAULT 1.8.6
 - RN1DEFAULT 1.8.6
 - HSDEFAULT 1.8.6
 - CVHDEFAULT 1.8.6
 - New defaults and best practices presented at 2008 Workshop
 - "New and Improved MELCOR Models," Joonyub Jun
 - "Best Practices," K.C. Wagner

Review of Several Modified Sensitivity Coefficients

- Heat Transfer
 - COR Heat Transfer
 - Candling Heat Transfer
 - COR radiant view factors
 - Lower head and penetration heat transfer coefficients.
 - Falling Debris Quench Model
 - CAV Package
 - Multipliers for heat transfer
- Numerical Stability Parameters
 - Criteria for Solving the Flow Equations in Sparse Form
 - HS Error Tolerance for Transient Conduction
 - Flow Blockage Friction Parameter
 - COR Package Min. Porosity for Flow & Heat Transfer

COR Package Candling Heat Transfer Coefficient

- COR00005 (1.8.6) or COR_CHT (2.1)
 - Refreezing heat transfer coefficients to be used in the candling model
 - Specified for each molten core material.
 - Default values are order-of-magnitude estimates that appear to produce plausible simulations of relocation phenomena
 - should be varied in sensitivity studies to determine their impact on overall melt progression behavior.

Material	Old Default (W/m ² -K)	New Default (W/m ² -K)
UO ₂	1000	7500
Zr	1000	7500
SS	1000	2500
ZrO ₂	1000	7500
SSX	1000	2500
CP	1000	2500

Candling Heat Transfer Coefficient Estimates Based on Conduction Analogy

- From conduction analogy, appropriate for slow moving melt:

$$Q = -k \frac{dT}{dx} A \Delta t \cong hA (T_{melt} - T_{surf})$$

- The heat transfer coefficient can then be reasonably estimated from

$$h_{cond} \approx k / dx$$

- Estimate of the maximum conduction length can be approximated from

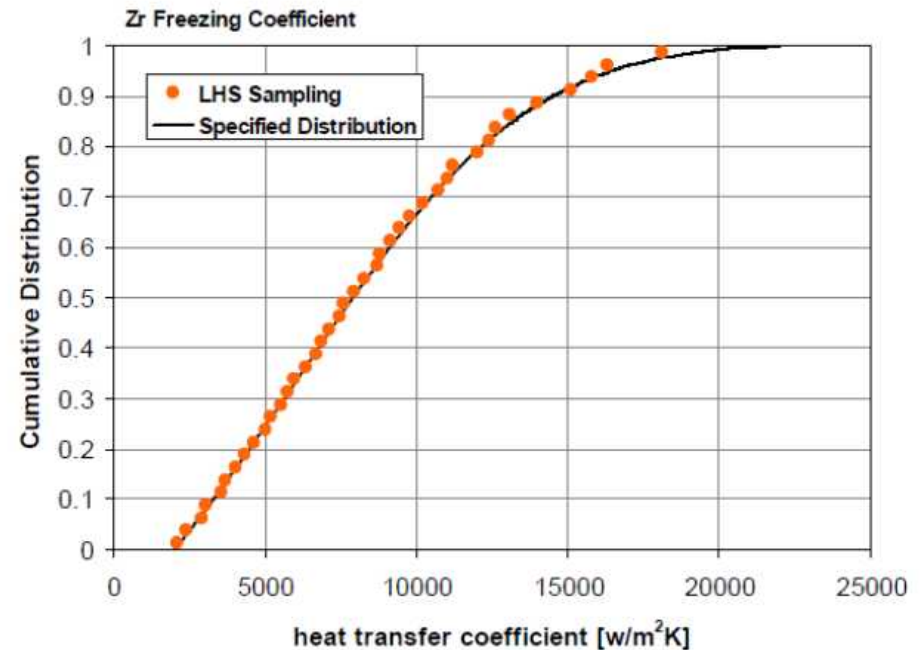
$$dx \approx ((\sqrt{2} \square pitch - diameter) / 2) \approx .005m$$

Candling Heat Transfer Coefficient

Material	Old Default (W/m ² -K)	Thermal Conductivity (W/m-K)	Calculated (W/m ² -K)	New Default (W/m ² -K)	High Values (W/m ² -K)
UO ₂	1000	3.96	800	7500	1000
Zr	1000	58.4	10000	7500	10000
SS	1000	34.5	7000	2500	7000
ZrO ₂	1000	2.49	500	7500	1000
SSOX	1000	20	4000	2500	4000
CP	1000	48	10000	2500	10000

Uncertainty Distribution in Zr Heat Transfer Correlation

- Values calculated for Zr may be as large as 10,000 W/m²-K
- Value selected was biased low to avoid large changes from old defaults
- Sampling distribution chosen is a log-normal form to assure that half of the cases use values between 5,000 and 10,000 W/m²-K and the mean is the current default value.
- Note, use of a high heat transfer coefficient does not result in complete blockage unless sufficient heat sink is available



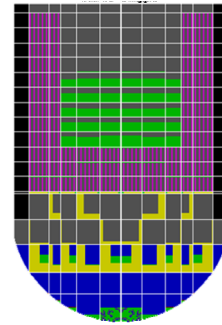
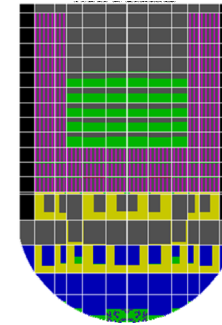
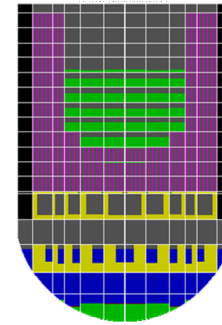
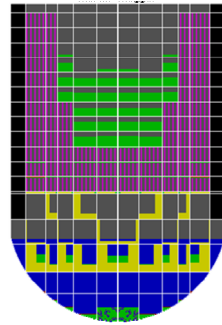
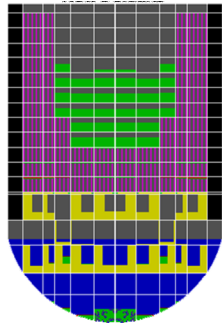
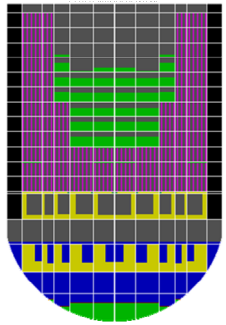
Candling Heat Transfer Coefficient Time of Vessel Failure

Test Case	Old Defaults	New Defaults	High Defaults
BWR Demo (2 rings)	6693(sec) 7152 (cycle)	5892(sec) 6465 (cycle)	6300 (sec) 6926 (cycle)
PWR Demo(2 rings)	5297 (sec) 5505 (cycle)	6559 (sec) 6783 (cycle)	5916 (sec) 6224 (cycle)
PWR – 6 radial 19 radial (SBO)	24300 (sec) 94243 (cycle)	22785 (sec) 138568 (cycle)	22092 (sec) 94326 (cycle)
BWR -6 radial 17 axial (SBO)	21,822 (sec) 123456 (cycle)	24,993 (sec) 121500(cycle)	25,927 (sec) 134559(cycle)
BWR2 -6 radial 17 axial (SBO)	Still running	Still running	21,242 (sec) 101618 (cycle)

Candling Heat Transfer Coefficient Core Degradation Progression (PWR)

14900 sec

15200 sec



Old Defaults

New Defaults

Conduction HTC

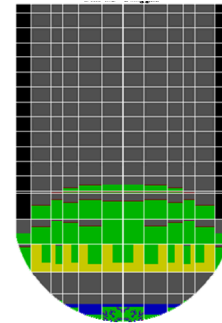
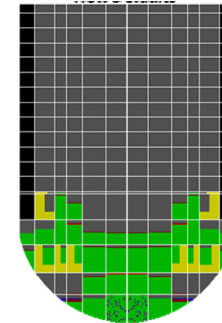
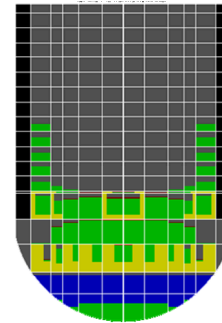
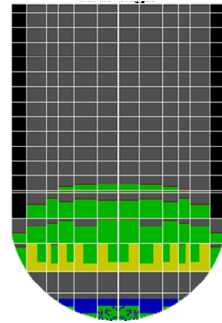
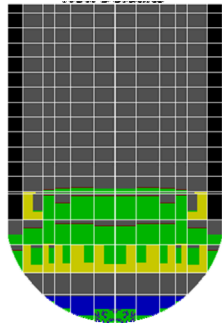
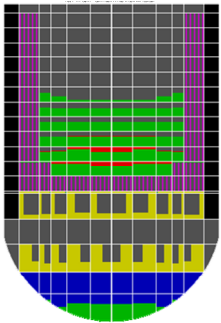
Old Defaults

New Defaults

Conduction HTC

16790 sec

17000 sec



Old Defaults

New Defaults

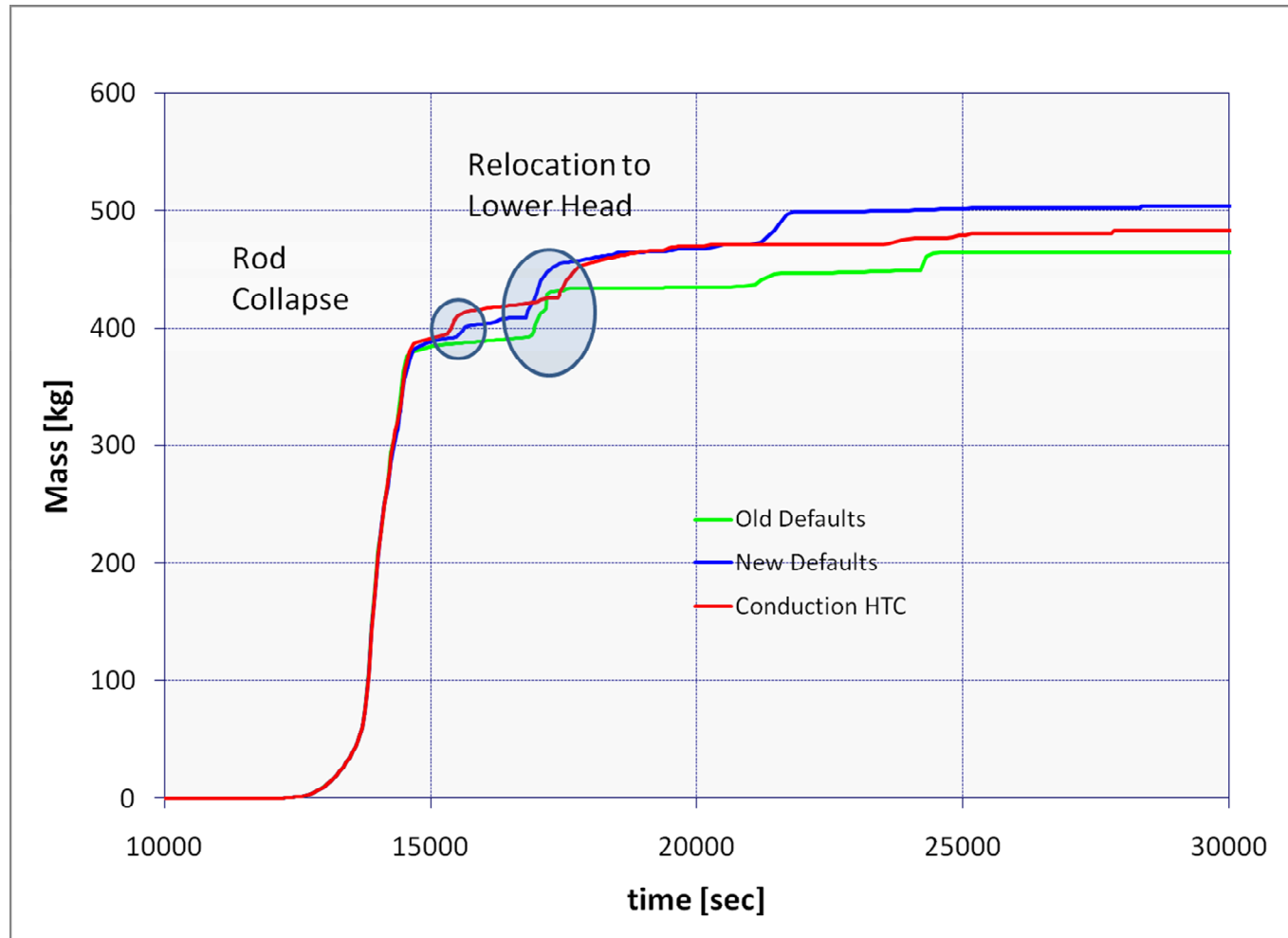
Conduction HTC

Old Defaults

New Defaults

Conduction HTC

Candling Heat Transfer Coefficient Hydrogen Generation (PWR)



COR Package Radiation Heat Transfer Parameters

- COR00003 Record
 - FCELR: COR package radial radiation heat transfer parameter
 - 0.25 (Old Default)
 - 0.1 (New Default)
 - FCELA: COR package axial radiation heat transfer parameter
 - 0.25 (Old Default)
 - 0.1 (New Default)
- From User Guide
 - “These values should be based on standard expressions for simple geometries, where possible, or on experimental data or detailed radiation calculations for complicated geometries involving intervening surfaces, such as for radiation between “representative” structures in cells containing a number of similar structures (e.g., fuel rod bundles). In the absence of any information to aid in selection of view factors, they should be used as arbitrarily varied parameters to examine the effects of radiation on the course of a calculation..”

MELCOR Radiant Heat Transfer Sandia National Laboratories

in COR Package

- MELCOR radiation model is extremely simple
 - Only five user input “view factors “(FCNCL, FSSCN, FCELR, FCELA, FLPUP)
 - “View factors “do not depend on time (except for debris)
 - Little guidance given users in selecting values
 - Values are problem dependent
- Rod surfaces more than a few rod diameters from the cell boundary have small visibility (view factor) from the boundary
 1. The appropriate radiation area is the cell boundary area for very large cells and the rod surface area (axially) or perhaps half of it (radially) for very small cells;
 2. The appropriate difference in T^4 for radiation across the boundary is much less than $(T_1^4 - T_2^4)$ for large cells.

Continuum Model for Estimating View Factor as a Function of Depth

First consider a simple 1-D “continuum” model with some qualitative relationship to the “real” world (ignore rod geometry). Assume that the combination of distance between differential surfaces (the factor of r^{-2} in the solid angle subtended) and the obscuring of line of sight by intervening surfaces may together be approximated by a simple exponential. That is, we assume that the fraction of unobscured solid angle remaining visible from a differential surface at depth x is $e^{-\alpha x}$. In consequence, the rate at which solid angle *becomes* obscured—i.e. is intercepted by other differential surface—is $\alpha e^{-\alpha x} dx$.

Simple “Continuum” View Factor Derivation

- The view factor between a cell of length (perpendicular to the cell boundary) of L_1 and one of length L_2 may be calculated as

$$A_1 F_{12} = \int_{-L_1}^0 dx_1 A_{cell} \left(\frac{A}{V} \right)_1 e^{-\alpha_1 x_1} \int_0^{L_2} dx_2 \alpha_2 e^{-\alpha_2 x_2}$$

- In terms of dimensionless variables:

$$A_1 F_{12} = A_{cell} \left(\frac{A}{\alpha V} \right)_1 \int_{-\alpha_1 L_1}^0 dy_1 e^{y_1} \int_{-\alpha_2 L_2}^0 dy_2 e^{y_2} = A_{cell} \left(\frac{A}{\alpha V} \right)_1 (1 - e^{-\alpha_1 L_1}) (1 - e^{-\alpha_2 L_2})$$

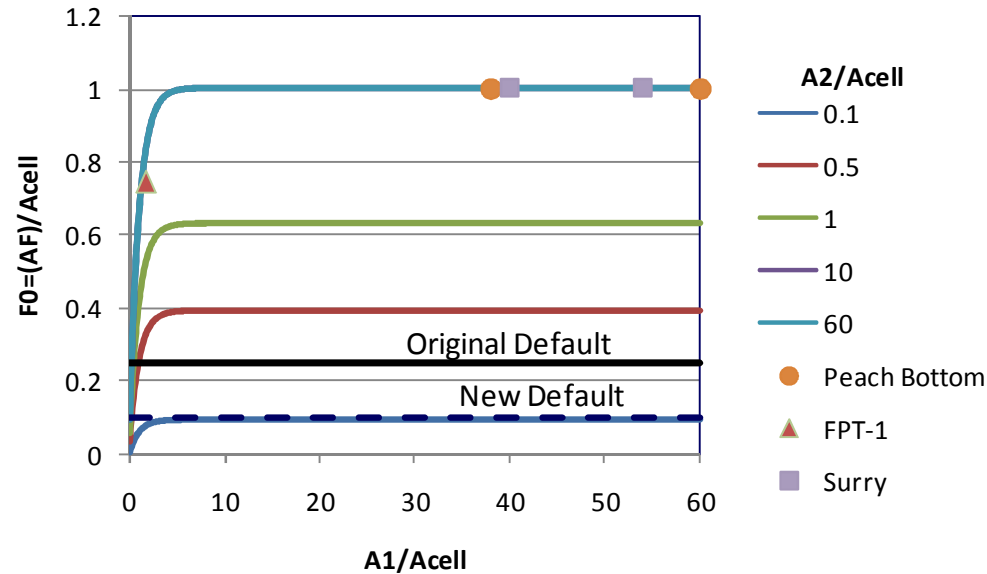
- And by reciprocity:

$$A_2 F_{21} = A_1 F_{12} = AF = A_{cell} F_0 = A_{cell} K (1 - e^{-\alpha_1 L_1}) (1 - e^{-\alpha_2 L_2})$$

- Where $K = \left(\frac{A}{\alpha V} \right)_1 = \left(\frac{A}{\alpha V} \right)_2$ and since $V_i = A_{cell} L_i$:

$$\alpha_i L_i = \frac{A_i}{K A_{cell}}$$

Simple “Continuum” View Factor



However, this does not account for the rod geometry or the variation of T^4

$$A_2 F_{21} = A_1 F_{12} = AF = A_{cell} F_0 = A_{cell} K (1 - e^{-\alpha_1 L_1}) (1 - e^{-\alpha_2 L_2})$$

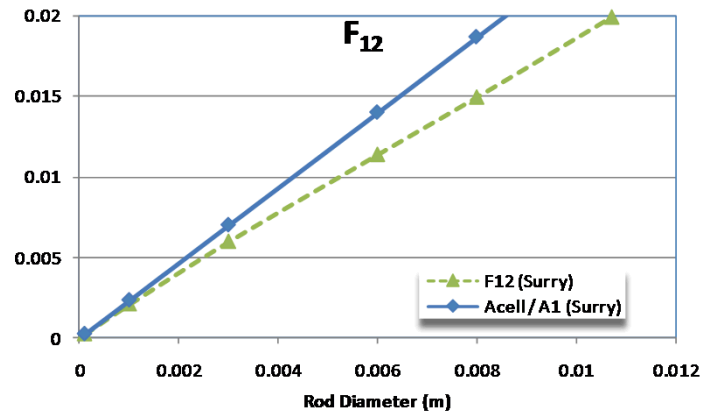
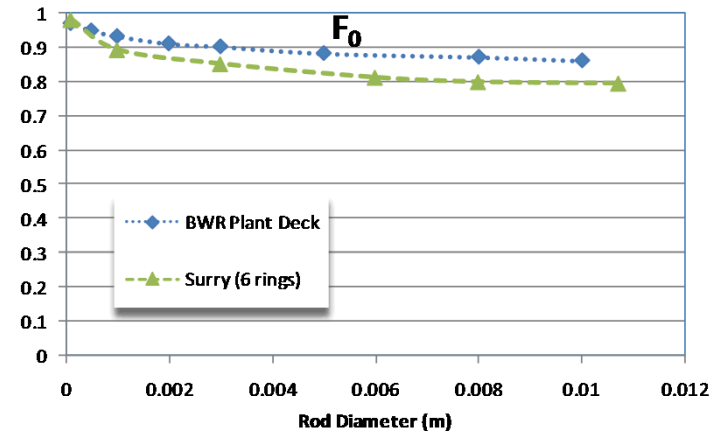
- Limits for the equation:
- $AF \rightarrow A_{cell} K$ for both cells large ($K=1$ gives the correct behavior)
- $AF \rightarrow A_1$ for cell 1 small and cell 2 large
- $AF \rightarrow \frac{A_1 A_2}{KA_{cell}}$ for both cells small

Effect of Rod Geometry on View Factor

Monte Carlo Simulation

$$F_0 = \frac{A_2}{A_{cell}} F_{21} = \frac{A1}{A_{cell}} F_{12}$$

- Monte Carlo calculation of “View Factor “
 - Calculate view factor as function of diameter
 - Surface to volume density varied while maintaining mass (pitch to diameter ratio)
 - Calculated values are +/- 1%
 - Continuum model predicts larger F0 because surface to volume ratio is larger



Effective View Factor Derivation

The “effective” view factor that accounts for the restricted temperature difference is modeled as

$$(AF)_{\text{eff}} = -A_{\text{cell}}K \int_{-\alpha_1 L_1}^0 dy_1 e^{y_1} \int_{-\alpha_2 L_2}^0 dy_2 e^{y_2} \frac{2(y_1 + y_2)}{\alpha_1 L_1 + \alpha_2 L_2}$$

where the fraction in the integrand is the fraction of the average difference in T^4 between point 1 and point 2.

- We have assumed that T^4 is linear in αx

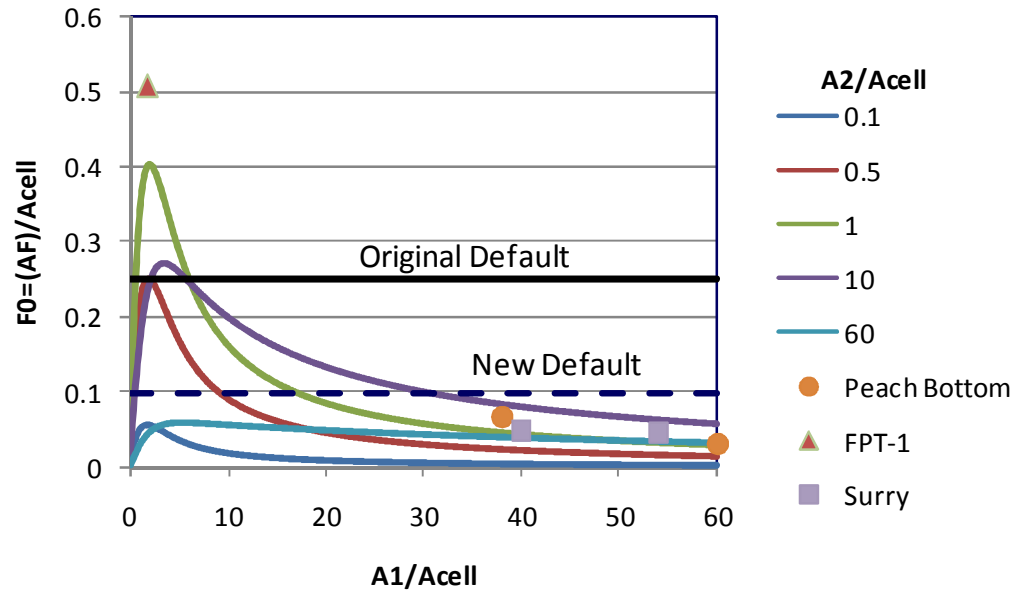
Thus,

$$(AF)_{\text{eff}} = -2 \frac{A_{\text{cell}}K}{\alpha_1 L_1 + \alpha_2 L_2} \int_{-\alpha_1 L_1}^0 dy_1 e^{y_1} \int_{-\alpha_2 L_2}^0 dy_2 e^{y_2} (y_1 + y_2)$$

Using previous relation between K and alpha:

$$(AF)_{\text{eff}} = 2 \frac{(A_{\text{cell}}K)^2}{A_1 + A_2} = \left\{ \left[1 - (1 + \alpha_1 L_1) e^{-\alpha_1 L_1} \right] (1 - e^{-\alpha_2 L_2}) + (1 - e^{-\alpha_1 L_1}) \left[1 - (1 + \alpha_2 L_2) e^{-\alpha_2 L_2} \right] \right\}$$

Effective View Factor



$$(AF)_{eff} = 2 \frac{(A_{cell}K)^2}{A_1 + A_2} = \left\{ \left[1 - (1 + \alpha_1 L_1) e^{-\alpha_1 L_1} \right] (1 - e^{-\alpha_2 L_2}) + (1 - e^{-\alpha_1 L_1}) \left[1 - (1 + \alpha_2 L_2) e^{-\alpha_2 L_2} \right] \right\}$$

- Limits:

- $(AF)_{eff} \rightarrow 4 \frac{(A_{cell}K)^2}{A_1 + A_2}$ for both cells large

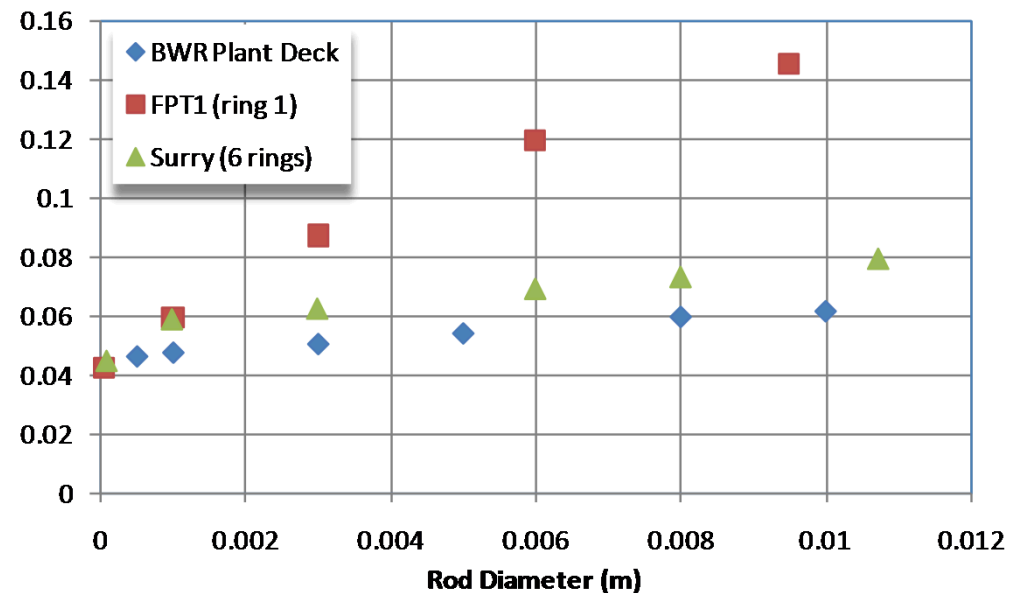
- $(AF)_{eff} \rightarrow K \frac{A_1 A_{cell}}{A_1 + A_2}$ for cell 1 small and cell 2 large

- $(AF)_{eff} \rightarrow \frac{1}{2} \frac{A_1^2 + A_2^2}{A_1 + A_2}$ for both cells small

Effect of Rod Geometry on Effective View Factor

Monte Carlo Simulation

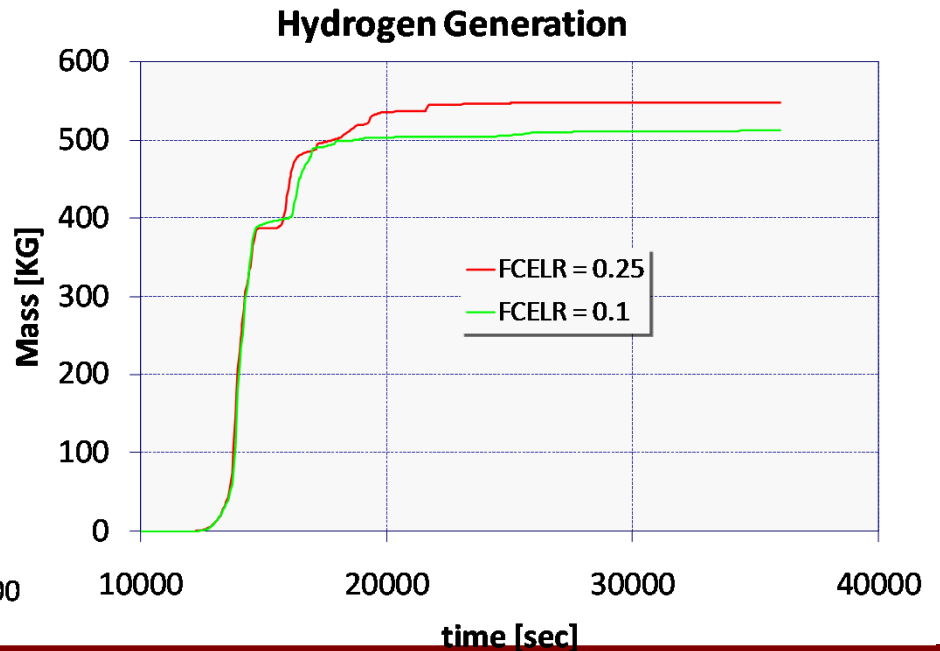
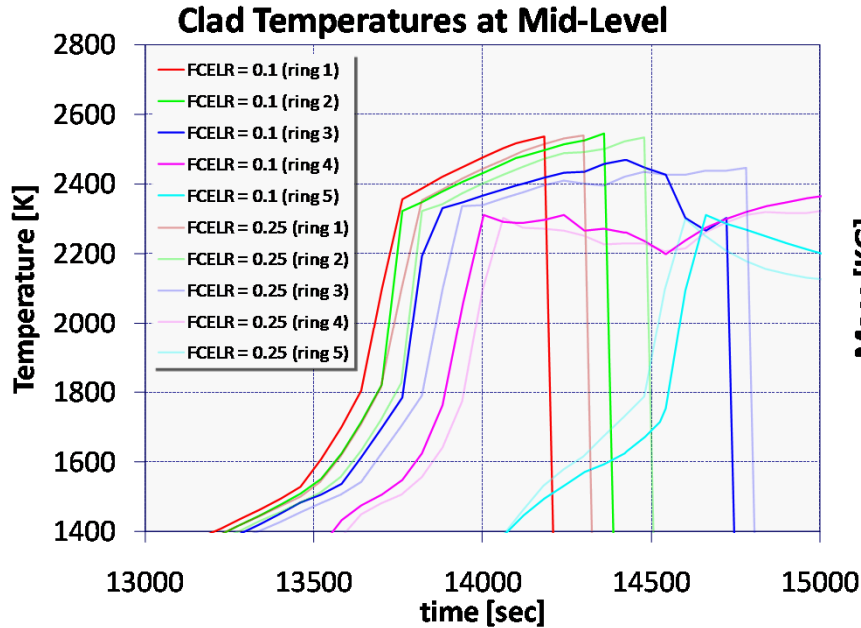
- Monte Carlo calculation of View Factor
 - Again, it is assumed that T^4 is linear in x
 - Calculated values are +/- 1%
 - Effective view factor may be somewhat larger than continuum results
 - More surfaces near interface for continuum approximation
 - Analysis supports the continuum results



Sensitivity of Calculations to FCELR

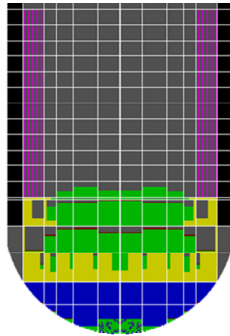
Zion SBO (6 rings)

Event	FCELR	
	0.25	0.1
Gap Release	12,610 s	12,576 s
Core support failure	14,355s	14,122 s
Vessel Failure	24,729 s	21,720 s

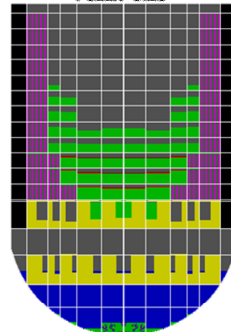


Core Degradation Progression

16043 sec

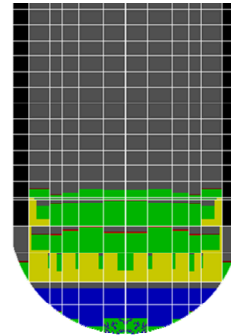


FCELR=0.1

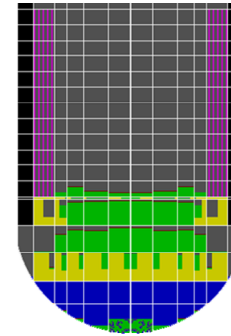


FCELR=0.25

16393 sec

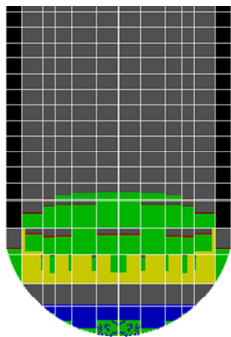


FCELR=0.1

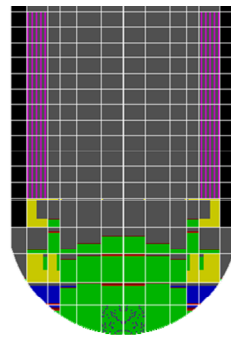


FCELR=0.25

17060 sec

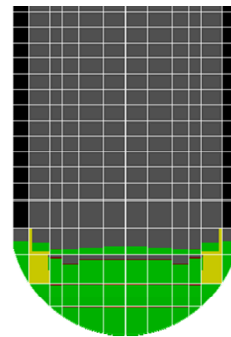


FCELR=0.1

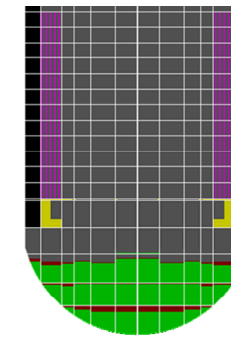


FCELR=0.25

18920 sec



FCELR=0.1



FCELR=0.25

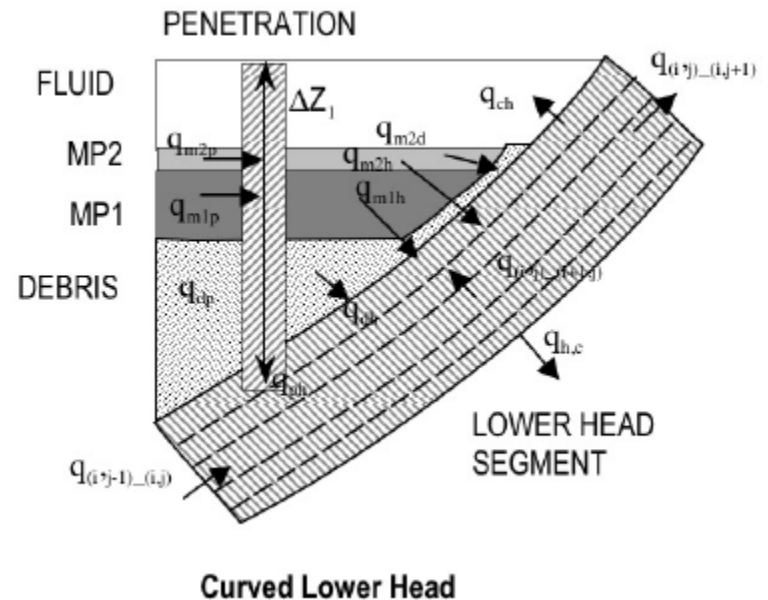
Debris to Penetration/Lower Head Heat Transfer Coefficient

- COR00009 (MELCOR 1.8.6) COR_LHF (MELCOR 2.1)
 - HDBPN: Heat transfer coefficient from debris to penetrations
 - 1000.0 w/m²/s (Old Default)
 - 100.0 w/m²/s (New Default)
 - HDBLH: Heat transfer coefficient from debris to lower head
 - 1000.0 m/s (Old Default)
 - 100.0 m/s (New Default)
 - Recommend using 'MODEL'
- TPFAIL: Failure Temperature of the penetrations
 - 1273.15 K (Old Default)
 - 9999. K (New Default)

$$h_0 = 2 \frac{k}{dz_{cell}}; \quad h = h_0 e^{-\frac{h_0 \cdot A_{PD-LH} \cdot dt}{CP_{PD}}}$$

MELCOR Modeling of Penetration

- Penetration failure is not modeled as a mechanism for vessel failure.
 - In the SNL LHF tests it was observed that gross creep rupture of the lower head was the most likely mechanism for vessel failure.
 - Penetration ejection was highly unlikely.
 - Penetration failure occurred at relatively large strains
 - Weld failure due to strain
- MELCOR penetration model lacks sufficient resolution to adequately model multi-dimensional heat transfer
 - Lumped capacitance
 - No possibility of modeling replugging
 - Typically predicted failure long before the vessel strains observed in LHF



Debris to Penetration/Lower Head Heat Transfer Time of Vessel Failure

Testing was with r1675

	New Defaults		Old Defaults	
Test Case	seconds	Failure mode	seconds	Failure mode
PWR – 6 radial 19 radial with penetrations (SBO)	23980	vessel	Calculation did not complete	
BWR -6 radial 17 axial with penetrations (SBO)	25,890	vessel	10,815	penetration

Debris to Lower Head Heat Transfer Coefficient Calculated from Debris Thermal Conductivity



- Heat transfer from particulate debris to lower head doesn't need to be defined as a heat transfer coefficient
 - Was probably implemented as a heat transfer coefficient when there was no separate field for molten mass
 - Possible to use control function
- User can request internal conduction calculation from debris to lower head
 - User specifies 'model' on input field and code calculates effective heat transfer coefficient from thermal conductivity of debris
 - $$h_0 = 2 \frac{k}{dz_{cell}}; \quad h = h_0 e^{-\frac{h_0 \cdot A_{PD-LH} \cdot dt}{C_{PPD}}}$$
 - dz_{cell} = half the height of debris in cell adjacent to lower head
 - Doesn't account for any gap between debris and lower head

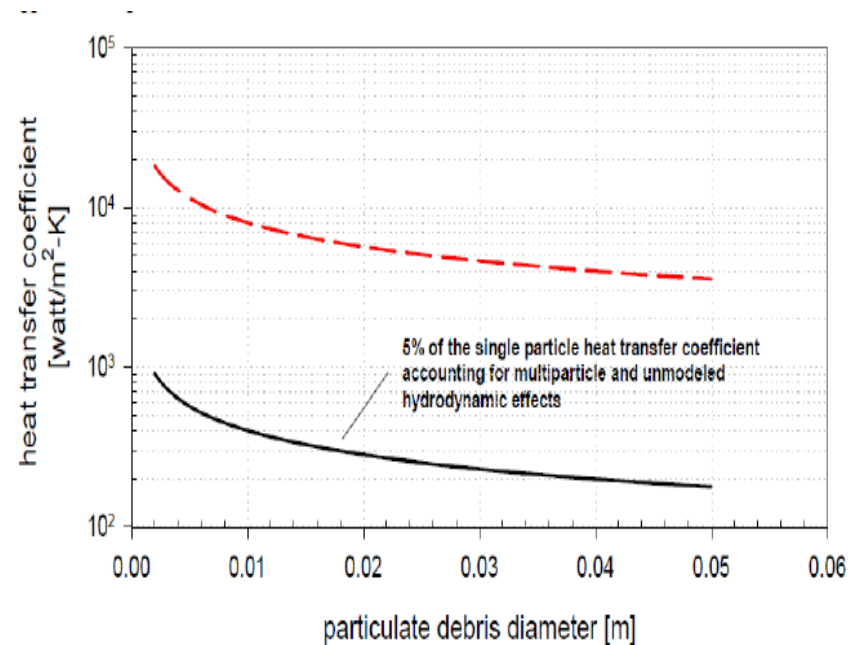
In-Vessel Falling Debris Quench Model Parameters

- COR00012 (MELCOR 1.8.6) COR_LP (MELCOR 2.1)
 - HDBH2O: Heat transfer coefficient from in-vessel falling debris to pool
 - 100.0 w/m²/s (Old Default)
 - 2000.0 w/m²/s (New Default)
 - VFALL: Velocity of falling debris
 - 1.0 m/s (Old Default)
 - 0.01 m/s (New Default)

In-Vessel Falling Debris Quench Model Parameters

Estimation from FARO data

- The heat transfer for a single spherical particle falling through a fluid can be obtained from the following correlation.
- Using values for water and corium, the curve at right shows the dependency of the HTC on particle size.
- Interference from other particles would lead to a reduced heat transfer.
- Review of FARO data shows that for fragmented particle sizes on the order of 0.005 m, the HTC may be 1000 W/m²-K
- This would indicate that the ideal heat transfer was reduced by 5%
- We assume particle sizes of 0.002 m in the lower head



In-Vessel Falling Debris Quench Model Parameters

Observations From BWR Calculations



- Many BWR calculations showed debris relocating to the lower head and quickly failing the lower head, even though there was more than a meter of water above.
 - Experiments showed that the distance a molten jet must travel to fully quench was between 20 & 50 jet diameters (no unoxidized metals) and 10 to 20 diameters for melts with unoxidized metals.
 - Using a jet diameter of ~ 10 cm (unit cell of a fuel assembly) quenching could be achieved in 2 to 5 m (oxidic melts) or 1 to 2 m (metallic melts)
- It was assumed that if a sufficient pool exists, the falling debris would quench
 - Debris hydraulic diameter corresponds to average end-state conditions observed in the FARO tests
 - 'fall velocity' was set to a value that caused the temperature of falling debris to decrease by an amount that ensured debris temperatures in the lower head were below the film boiling limit.
 - The one-dimensional counter-current flow limitation (CCFL) limitation was removed from the overlying debris heat transfer model to represent water penetration into the debris bed, perhaps through 2- or 3-dimensional circulation flow patterns.

In-Vessel Falling Debris Quench Model Parameters Comparison of Representative Calculations

Testing was with r1675

Test Case	New Defaults		Old Defaults	
	LHF mode	LHF time seconds	LHF mode	LHF time seconds
BWR	yielding	6693	yielding	5956
PWR	yielding	5297	yielding	4919
Test_Inew	yielding	6888	yielding	7006
PWR – 6 radial 19 radial (SBO)	Creep rupture (ring 6)	20,770.	Creep rupture (ring 1)	24,015.
BWR -6 radial 17 axial (SBO)	Penetration 1	21,240	Penetration 2	21,822

Criteria for Solving the Flow Equations in Sparse Form: SC4415(1)



- SC4415(1)
 - The maximum fraction of nonzero coefficients for use of the sparse form.
 - A value of 0.0 ensures that the direct solution will always be used, while a
 - value of 1.0 ensures that the iterative solution will always be used.
 - CVH/FL maximum iteration criterion
 - 0.5 (Old Default)
 - 1.0 (New Default)
 - It should be noted that we are currently reviewing the flow equations solver for MELCOR 2.1. These recommendations may be changed.

SC4415(1) Performance Comparison

Testing was with r1675

	New Defaults		Old Defaults	
Test Case	Runtime seconds	LHF time seconds	Runtime seconds	LHF time seconds
BWR	18:00	6693	35:27	6693
PWR	17:37	5297	12:54	5297
Test_Inew	23:11	6888	21:04	6888
LOFT	10:36	-	12:38	-
Falcon1	19:45	-	15:24	-
PWR – 6 radial 17 axial (LOCA depressurization)	6:32:31	-	7:01:57	-
PWR – 6 radial 19 radial (SBO)	10:58:07	24015	10:28:33	24015
BWR -6 radial 17 axial (SBO)	12:56:51	24778	16:03:39	24778

HS Error Tolerance for Transient Conduction SC4055(2)



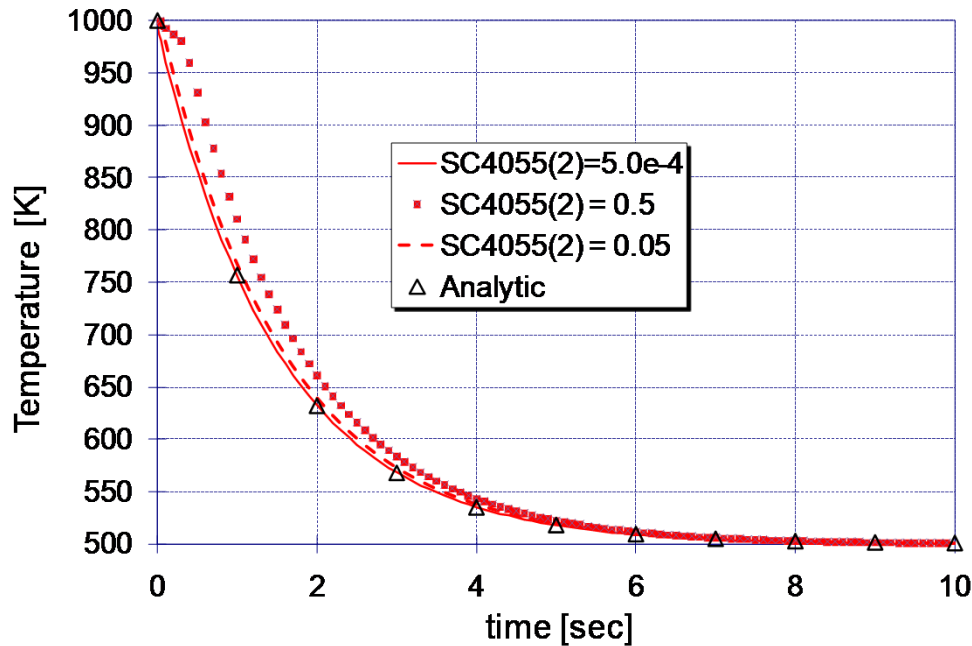
- SC4055(2)
 - Desired relative error tolerance for transient conduction calculations; NOTE: the conduction calculation is declared converged when the maximum relative error in the temperature profile within the structure is less than this value, normally.
 - However, if degassing or mass transfer (condensation/evaporation) is occurring, then the iteration continues until the maximum relative error in the temperature profile (including the film surfaces) is less than the value specified by C4055(6) described below. If the relative error is still larger than C4055(6) but smaller than C4055(2) after XITMAX iterations, then the solution is accepted as converged .
 - Default Values
 - 5.0e-4 (Old Default)
 - 0.5 (New Default)

SC4055(2) Performance Comparison

Testing was with r1675

	SC4055(2)=0.5		SC4055(2)=0.0005		SC4055(2)=0.05	
Test Case	Runtime seconds	LHF time	Runtime seconds	LHF time seconds	Runtime seconds	LHF time seconds
BWR	24:02	6693	35:27	6693	19:27	6693
PWR	18:12	5297	12:54	5297	18:56	5297
Test_inew	14:17	6888	21:04	6888	20:20	6888
LOFT	11:57	-	12:38	-	10:46	-
Falcon1	15:44	-	15:24	-	22:05	-
PWR – 6 radial 17 axial (LOCA depressurization)	4:40:35	-	7:01:57	-	6:22:09	-
PWR – 6 radial 19 radial (SBO)	14:47:02	24015	10:28:33	24015	14:06:32	24015
BWR -6 radial 17 axial (SBO)	23:17:38	24778	16:03:39	24778	16:50:25	25000

Cooling of a 1-D Heat Structure Comparison with Analytic Results



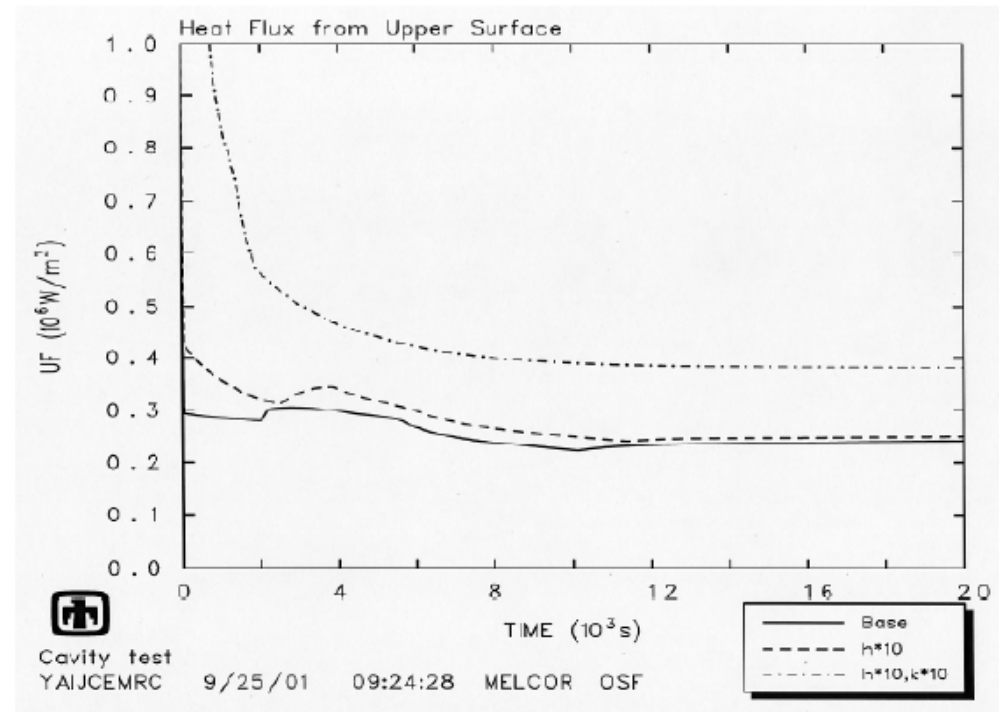
Thermal conductivity	50.0 W/m-K
Density	1.0 kg/m ³
Specific heat capacity	1500 J/kg-K
Heat transfer coeff	50.0 W/m ² -K
HS initial temperature	1000 K
Fluid initial temp	500 K
Cylindrical radius	0.1 m
Cylindrical height	1.0 m

Multipliers for Surface Boiling Heat Transfer and Material Conductivity

- CAV_U (MELCOR 2.1)
 - BOILING
 - CORCON-Mod3 (Old Default)
 - 10.0 (New Default)
- SC4055(2)
 - COND.OX multiplier for oxidic phase thermal conductivity
 - 1.0 (Old Default)
 - 5.0 (New Default)
- SC4413(5)
 - COND.MET: multiplier for metallic phase thermal conductivity
 - 1.0 (Old Default)
 - 5.0 (New Default)

Effect of Increasing Pool Heat Transfer Independent of Crust Thermal Conductivity

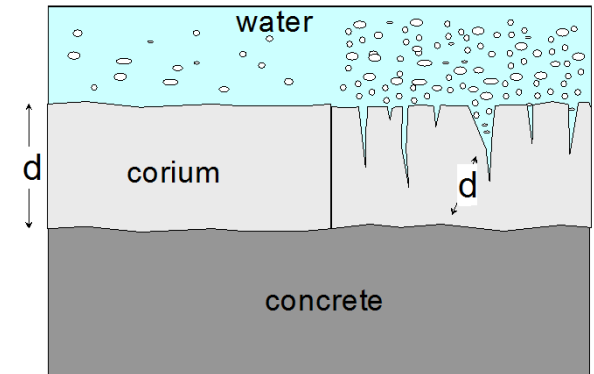
- Increasing the pool heat transfer alone cannot increase the cooling rate.
- Increasing the crust conductivity together with an increase in the pool heat transfer can produce debris cooling by overlying water.



Pre 2015 MELCOR Best Practice

- 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 has been focused 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

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

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

MELCOR BurnPackage Methodology Sandia National Laboratories

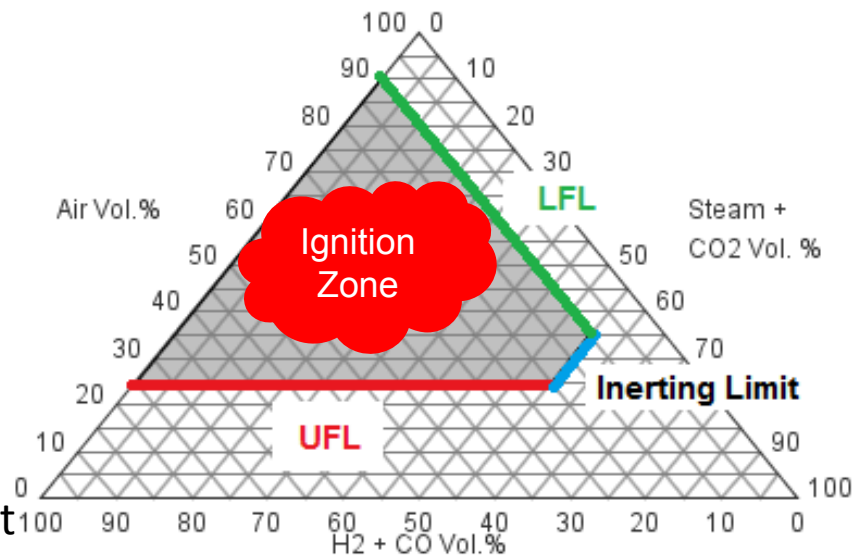
- Burns in MELCOR involve the following determinations
 - **Ignition Criteria** – Mole fraction criteria permitting a burn to occur
 - Two limits may be defined (burns may also be disallowed in user specified volumes)
 - Spontaneous deflagrations / Igniter initiated deflagrations
 - » Control function (CF) may be used to actuate an igniter
 - » Recent SOARCA modeling use the igniter CFs to incorporate all of the ignition criteria
 - **Burn Rate** – Moles of gases reacted during a time step (HECTR 1.5)
 - Burn Completeness – Mole fraction of combustible left at end of burn (solved at start of burn)
 - Burn Duration – Duration of a given burn (solved at the start of burn)
 - = Characteristic volume length / Flame Speed (HECTR Correlation)
 - Rate = $(X(t) - \text{BurnComplete}) / (\text{BurnDuration} - \text{TimeSpentBurning})$
 - **Propagation Criteria** – Mole fraction criteria permitting a burn to transfer to another control volume
 - Propagation directional ignition criteria (4%/6%/9%)
 - Ignition criteria check after $\text{Const}(\text{def}=0.0) * \text{BurnDuration}$

MELCOR BurnPackage Ignition Criteria

- Shapiro Model – Spontaneous Combustion

- Constant limits

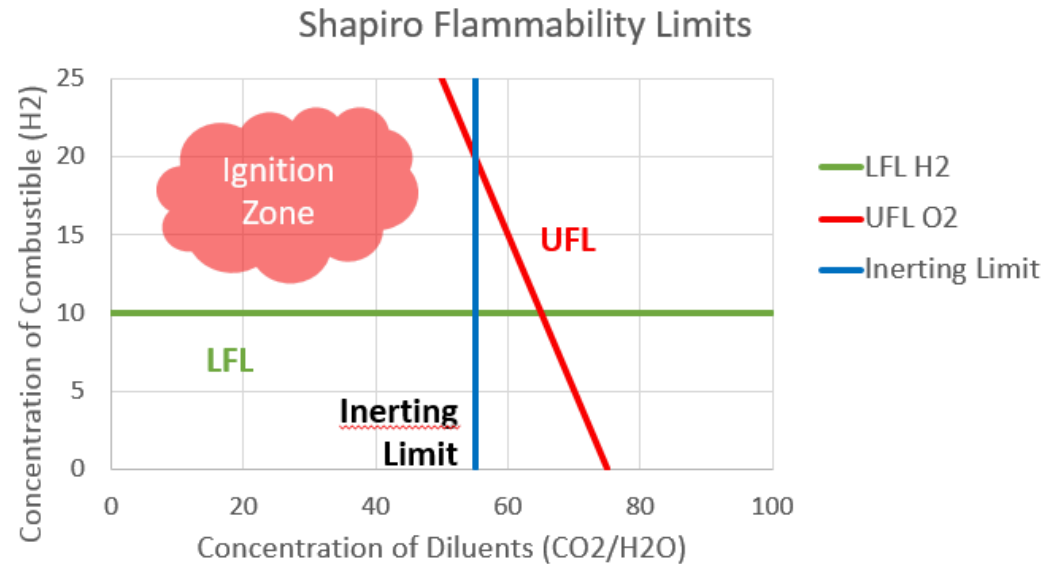
- Lower Flammability Limit (LFL)
 - 10% H₂ (+CO adjusted)
 - Upper Flammability Limit (UFL)
 - 5% O₂
 - Inerting Limit
 - 55% CO₂ + H₂O
 - Control volume mole fractions are evaluated against these limits



- Note the use of “Air” implies set N₂/O₂ concentrations

Shapiro Model

- Shapiro Model – Depicted on an XY plot
 - LFL – 10% Hydrogen
 - UFL – 5% Oxygen (for 80/20 N₂/O₂ – 5% Oxygen corresponds to 25% “Air”)
 - Inerting Limit 55%

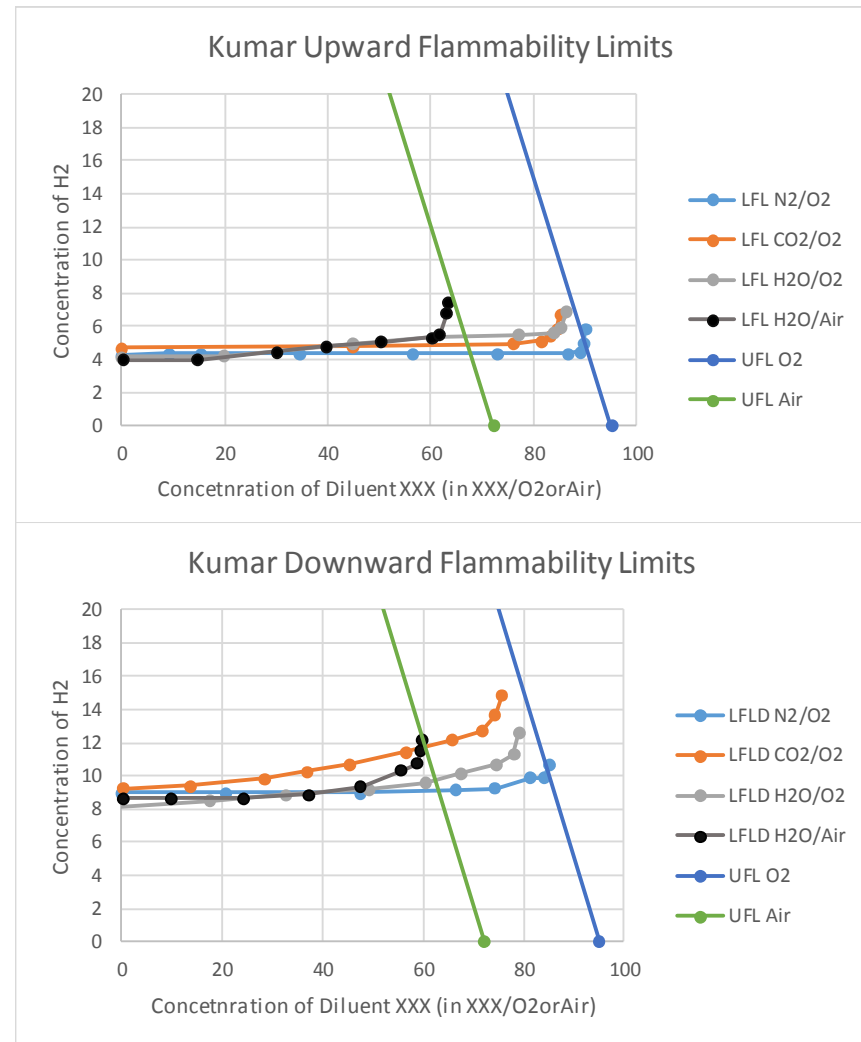


Kumar-Inspired Model

- Integrating directionality (up/down/horizontal) with ignition criteria
 - Performed for Uncertainty Analysis sampling in recent SOARCA studies
 - Uniform distribution for the three possible directions
 - Lower flammability limits vary with regard to relevant flame direction
 - Data from Kumar* was employed
 - Tabular functions using the diluent mole fractions to determine lower flammability limits
 - Upward directional flame front requires less hydrogen than downward traveling flame fronts
 - Horizontal is taken as the average between upward and downward propagation
 - Lower flammability limits vary with atmospheric temperature
- Known ignition sources employed
 - Disable spontaneous ignition criteria
 - Adjust igniter ignition criteria to reduced ignition criteria (maintain CO/H₂O ratio)
 - Create control function logic which combines ignition criteria and ignition source
 - H₂ + CO limit; O₂ limit
 - Hot jet temperature at break site
 - Debris in cavity

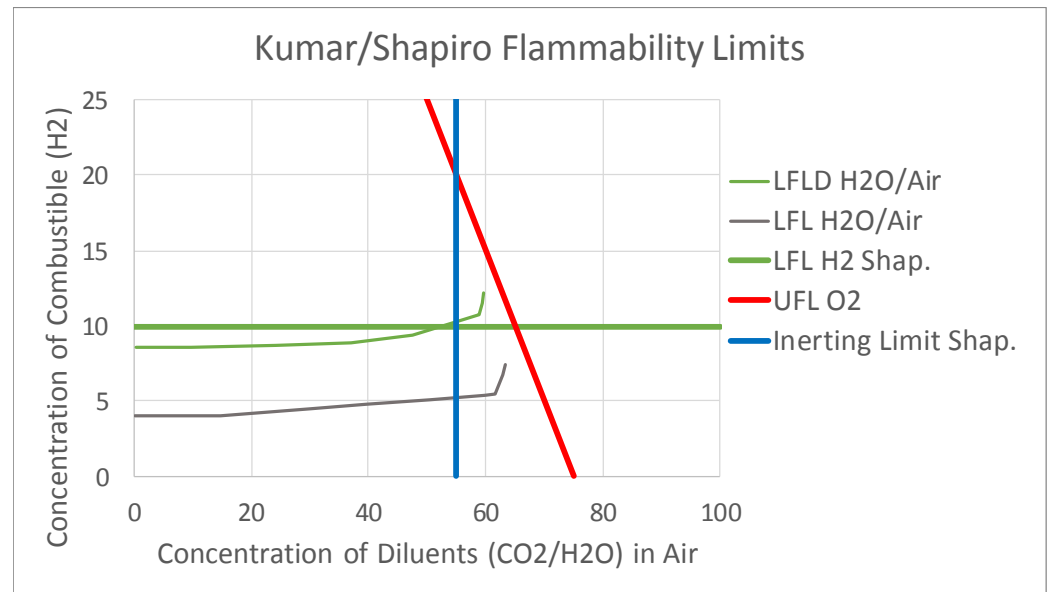
Imposing Data

- Kumar investigated various systems to determine up/downward limits
 - $H_2 - N_2 - O_2$
 - $H_2 - CO_2 - O_2$
 - $H_2 - H_2O - O_2$
 - $H_2 - H_2O - Air$
- Kumar purports N_2 may be treated as a diluent in context of paper



SOARCA Compared to Default MELCOR Model

- Applies the Air data set for upward/downward and computes horizontal limit as the average from the up and downward ignition criteria limits
- Increases overall envelope supporting deflagrations
- Fidelity near inerting limit



COR Package Min. Porosity for Flow & Heat Transfer



- SC1505(1) and SC1505(2)
 - These coefficients specify the geometric parameters affecting core flow resistance and heat transfer under conditions of flow blockage.
 - Were modified because modeler experience indicated that default values led to more code failures (robustness issue)

- SC1505(1): Used to determine the maximum pressure drop for blocked flows

$$(\Delta P)_{pourous\ bed} = \frac{1}{2} \rho j^2 \frac{L}{D_p} \left(\frac{1-\varepsilon}{\varepsilon^3} \right) \left[C_1 + C_2 \left(\frac{1-\varepsilon}{Re} \right) + C_3 \left(\frac{1-\varepsilon}{Re} \right)^{C_4} \right]$$

- 0.001 (Old Default)
 - 0.05 (New Default)
- SC1505(2): To avoid overheating a vanishing CVH fluid, the sum of the surface areas of the intact component and its associated conglomerate debris, which constitutes the total effective surface area for heat transfer to CVH, cannot exceed

$$A_{tot,max} = \max(V_{CVH} R_{SVR}, \varepsilon_{min} V_{COR})$$

- 0.001 (Old Default)
 - 0.05 (New Default)

Time of Vessel Failure

- Testing was with r1675

Test Case	New Defaults		Old Defaults	
	Runtime seconds	LHF time seconds	Runtime seconds	LHF time seconds
BWR	-	-	35:27	6,693
PWR	10:29	6,157	12:54	5,297
Test_Inew	18:19	6,700	21:04	6,888
PWR – 6 radial 19 radial (SBO)	-	24,015	10:28:33	24,015
BWR -6 radial 17 axial (SBO)	-	>18,701	16:03:39	24,778
Grand Gulf	-	21,822.	Calculation Failed	

Flow Blockage Friction Parameter SC4413(5)

- SC4413(5)
- Minimum porosity to be used in evaluating the correlation, imposed as a bound before the Ergun equation is evaluated.

$$K_{eff} = \left[C4413(1) + C4413(2) \left(\frac{1-e}{Re} \right) + C4413(3) \left(\frac{1-e}{Re} \right)^{C4413(4)} \right] \frac{(1-e)L}{\epsilon D}$$

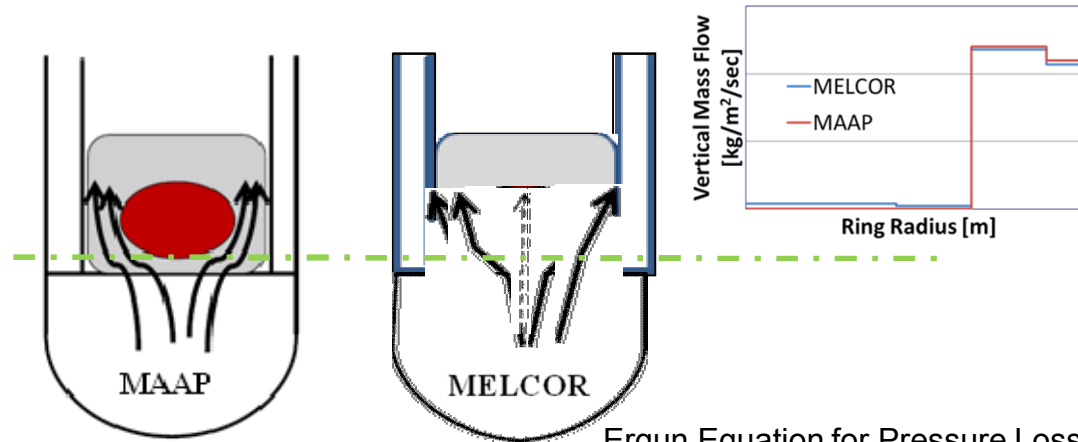
- 1.0e-6 (Old Default)
- 0.05 (New Default)

SC4413(5) Performance Comparison Sandia National Laboratories

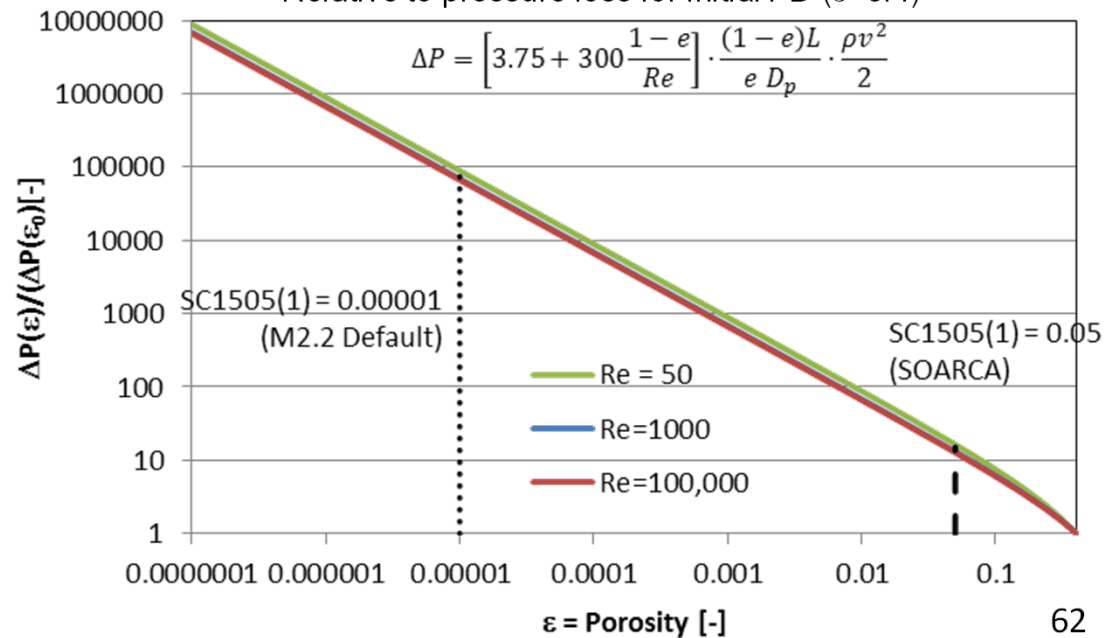
Testing was with r1675

	New Defaults SC4413(5)=0.05		Old Defaults SC4413(5)=1E-6	
Test Case	Run time seconds	Vessel Failure	Run time seconds	Vessel Failure
BWR	17:20	6693	35:27	6693
PWR	18:33	5297	12:54	5297
Test_Inew	14:37	6888	21:04	6888
LOFT	11:20	-	12:38	-
Falcon1	24:50	-	15:24	-
PWR – 6 radial 17 axial (LOCA depressurization)	4:34:46	-	7:01:57	-
PWR – 6 radial 19 radial (SBO)	13:54:48	24015	11:15:00	24015
BWR -6 radial 17 axial (SBO)	17:34:39	26673	17:31:55	24778

MELCOR- MAAAP Cross-Walk Flow Resistance



Ergun Equation for Pressure Loss from Blockages
Relative to pressure loss for initial PD ($\epsilon=0.4$)



- A lot of attention was focused on the fact that MELCOR does not completely block fluid flow where MAAP does
 - However, for blockages, large pressure drop result in greatly reduced flow
 - MELCOR sensitivity coefficients for flow blockage SC1505(1)
 - 0.05 for SOARCA Best Practice
 - 1e-5 for M2.2 default
 - Recent sensitivity studies demonstrated that this is a second order effect on results (little impact on melt mass)

Future MELCOR Manual Updates

SAND2015-6693 R

MELCOR Computer Code Manuals

Vol. 3: MELCOR Assessment Problems
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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 III: Assessments

R&A Complete
SAND2015-6693 R

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

Questions