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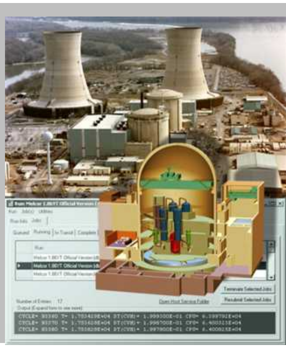

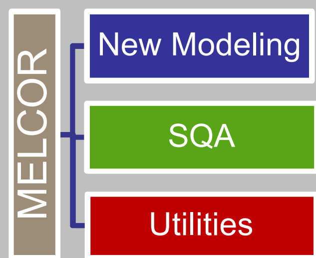

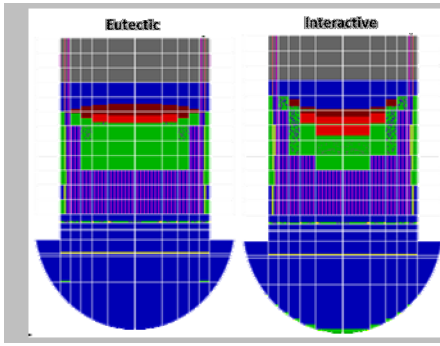

IVR Phenomena, Modeling of Lower Plenum and Modifications of RN Package (1.8.6 to 2.2)

Presented by Larry Humphries
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Outline

- Modeling of lower plenum
  - Representation of Molten Pools
    - Sub-grid model
    - Melt/liquefaction temperatures
    - Stratification of molten pools
    - Molten Pool convection models
    - Radiation from molten pool
    - Stefan model
  - Lower head modeling
    - Nodalization
    - Failure criteria
      - Creep failure
      - Penetration failure
- In-Vessel Retention (IVR) Phenomenon
  - Ex-vessel boiling heat transfer
  - Critical heat flux
  - Metal layer and focusing effect
  - Melting of lower head structure
- Modifications of RN Package
  - Turbulent Deposition
  - Resuspension
  - MAEROS improvements
  - Hygroscopic model improvements

Molten Material is First Removed from Fuel through Candling Process

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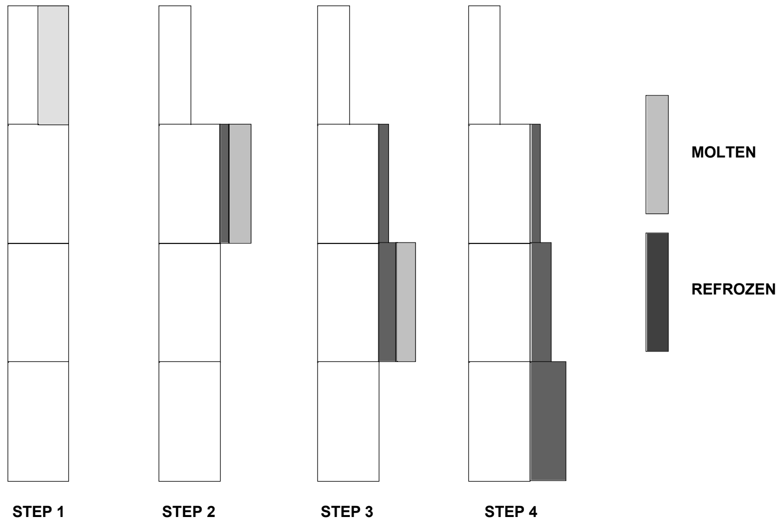
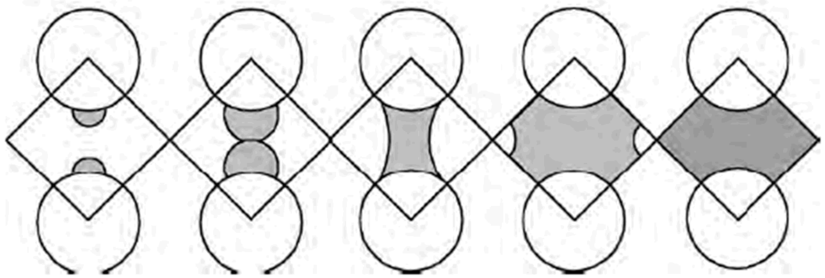
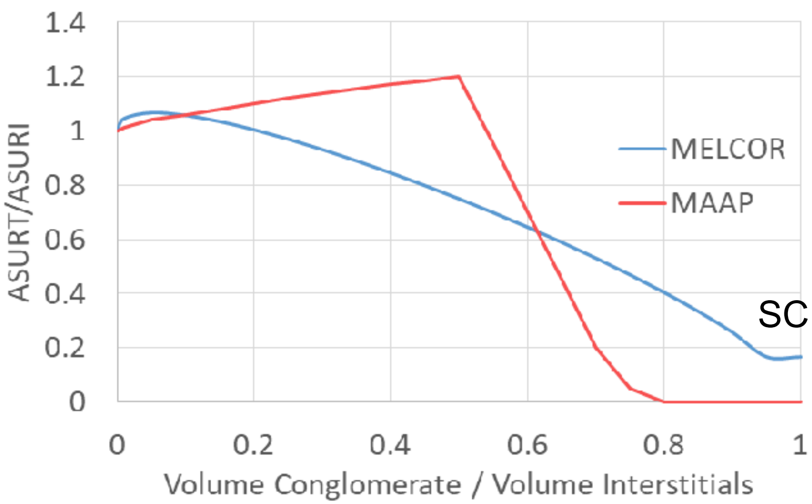
- Candling - Downward flow of molten core materials and subsequent refreezing (creation of 'conglomerate')
  - Semi-mechanistic
    - Based on fundamental heat transfer principles with user-specified refreezing heat transfer coefficients for each material
  - Assumptions
    - Steady generation and flow of molten material
      - Does not solve a momentum equation for velocity
      - All material generated in a time step reaches its final destination in that step
        - There is no separate field for conglomerate and must equilibrate with a component
      - relatively independent of time step history
    - Molten material is held up behind oxide shell or retained behind blockage.
      - For breakaway melt, assumption of steady generation no longer valid
    - Freezes on originating component or alternate component if non-existent at lower elevation



MELCOR- MAAP Cross-Walk Conclusions

- Cross-walk concluded that heat transfer degradation does not occur in MELCOR with decreasing *debris bed porosity*. This is wrong!
  - Erroneous statement from report: *"MELCOR represents a particulate debris bed in terms of fixed diameter particles – additional debris does not accumulate within open volume and limit the heat transfer surface area"*
- The MELCOR candling model calculates modified surface areas used for both oxidation and heat transfer
  - Similar to rodded geometry but modified for spheres
  - Oxidation and convective heat transfer use reduced surface areas:
    - ASURC - Conglomerate
    - ASURY - exposed intact surface area
  - Sensitivity coefficient used to set minimum surface area
    - SC1505(2) = 0.05 SOARCA Best Practice
    - Was 0.001 in M186
    - Currently 0.001 for M2.2 default





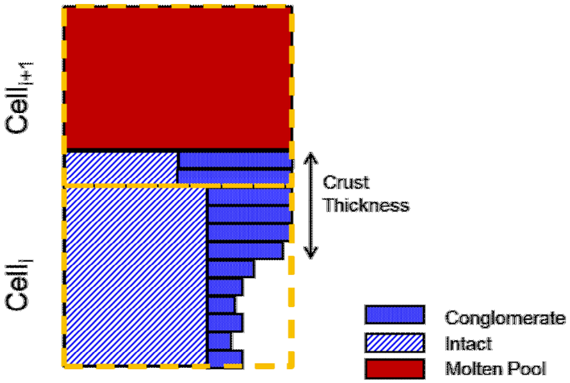
How Are they Used

- ASURT - Convective Heat Transfer
- ASURI - Radiation
- ASURI - Intact component area
- ASURC, ASURY – Oxidation

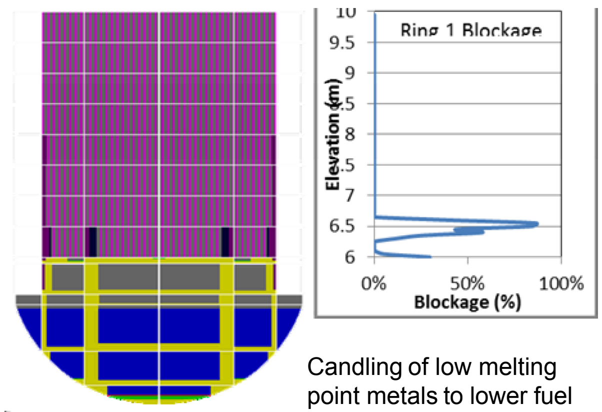
ASURT=ASURC+ASURY

MELCOR Crust

- There is no separate component to model crust
  - Crust is represented as PD component
  - No distinct temperature for crust
  - Crust thickness is inferred from sub-grid model
- Blockage associated with ‘crust’ obstructs downward relocation of molten pool
- Radial Crust
  - Crust calculated for cells adjacent to lower head
    - intact PD is always available to spreading routine
    - Fraction of conglomerate associated with crust is frozen to lower head
  - No radial crust modeled for molten pool in upper core
    - Time constant for radial spreading of molten pool component into fuel rod region is 10 times longer than elsewhere

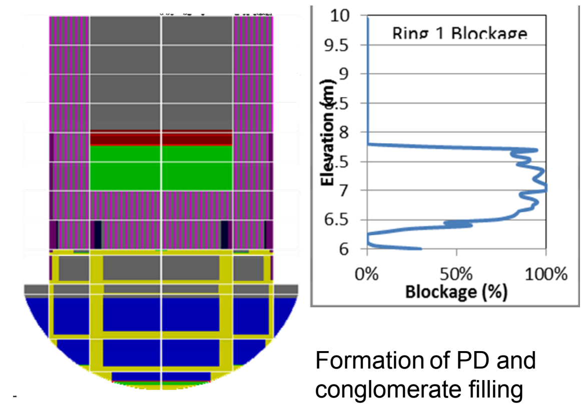


Sub-Grid Model Prediction of Blockages



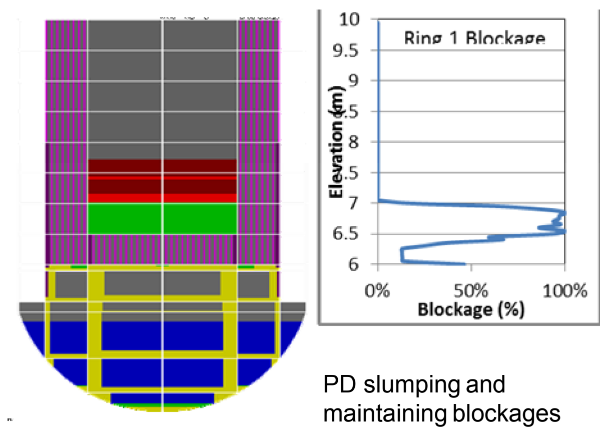
1998 (sec)

Candling of low melting point metals to lower fuel rods



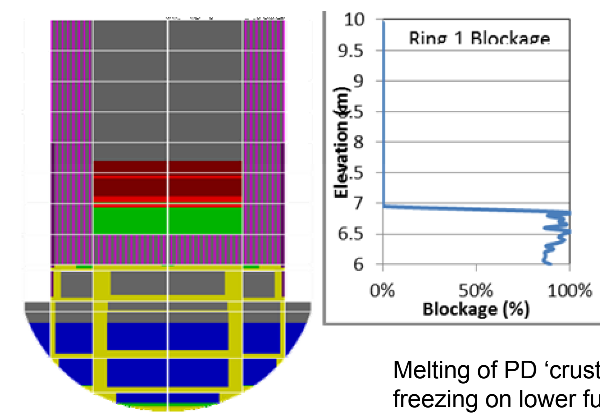
2008 (sec)

Formation of PD and conglomerate filling interstitials



2414 (sec)

PD slumping and maintaining blockages

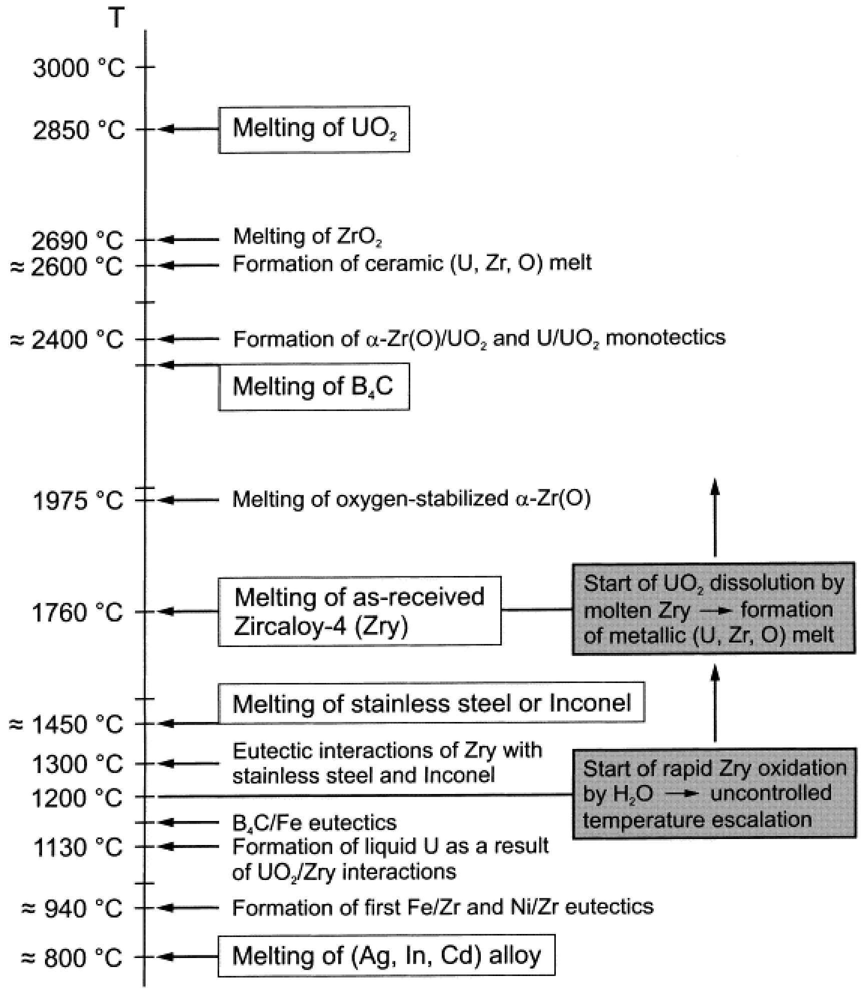


2462 (sec)

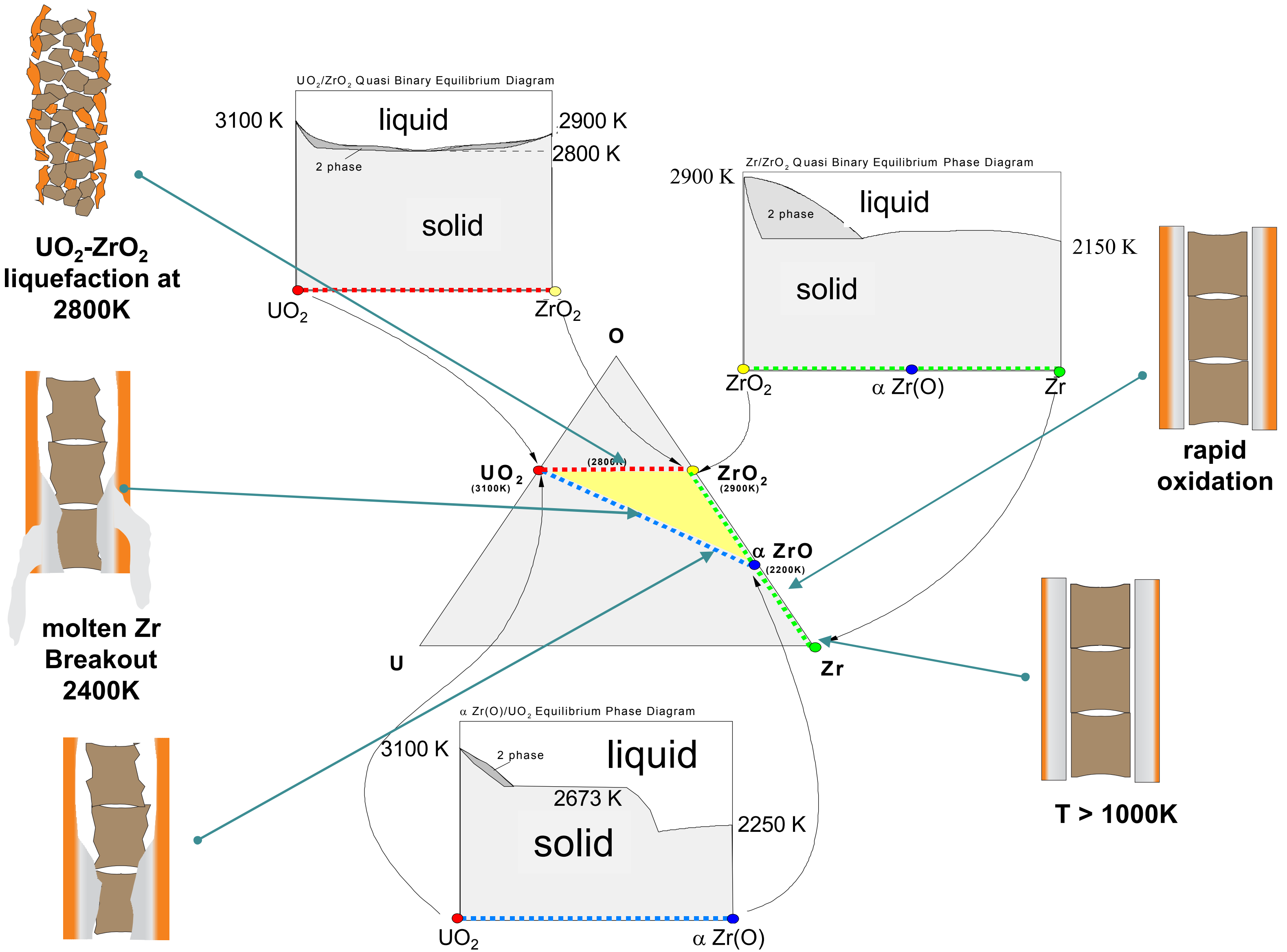
Melting of PD ‘crust’ and freezing on lower fuel rods

MELCOR Eutectic Model Overview

- Eutectics model has been in the code since M1.8.2
  - Eutectic model was not functioning since at least 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
    - Effective melt temperature was user specified with no default.
- 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



MELCOR Eutectic Temperature

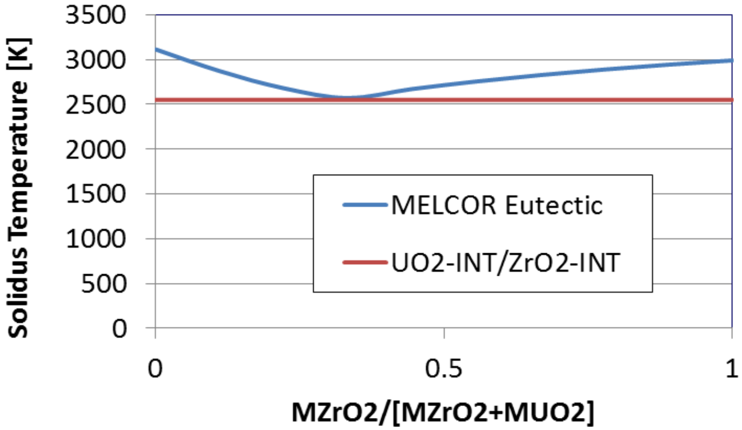
UO2-INT/ZRO2-INT

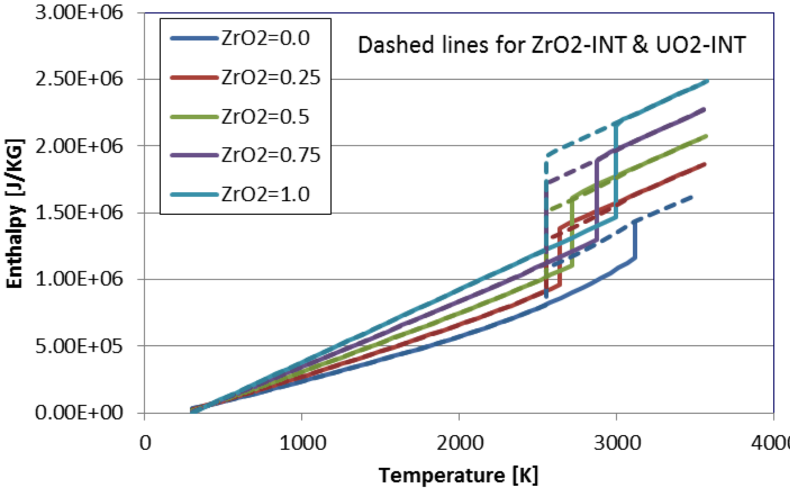
- Melt temperature for UO2 & ZrO2 is the same for intact materials as it is for conglomerate.
- Does not depend on composition

Eutectic Model

- Melt temperature of intact material uses elemental melting points while conglomerate uses eutectic temperature
  - Liquefaction of solids in contact from calculated rates
- Melt temperature dependent on composition

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 along 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 records should be removed from input

TMI Melt Progression –Preliminary Results

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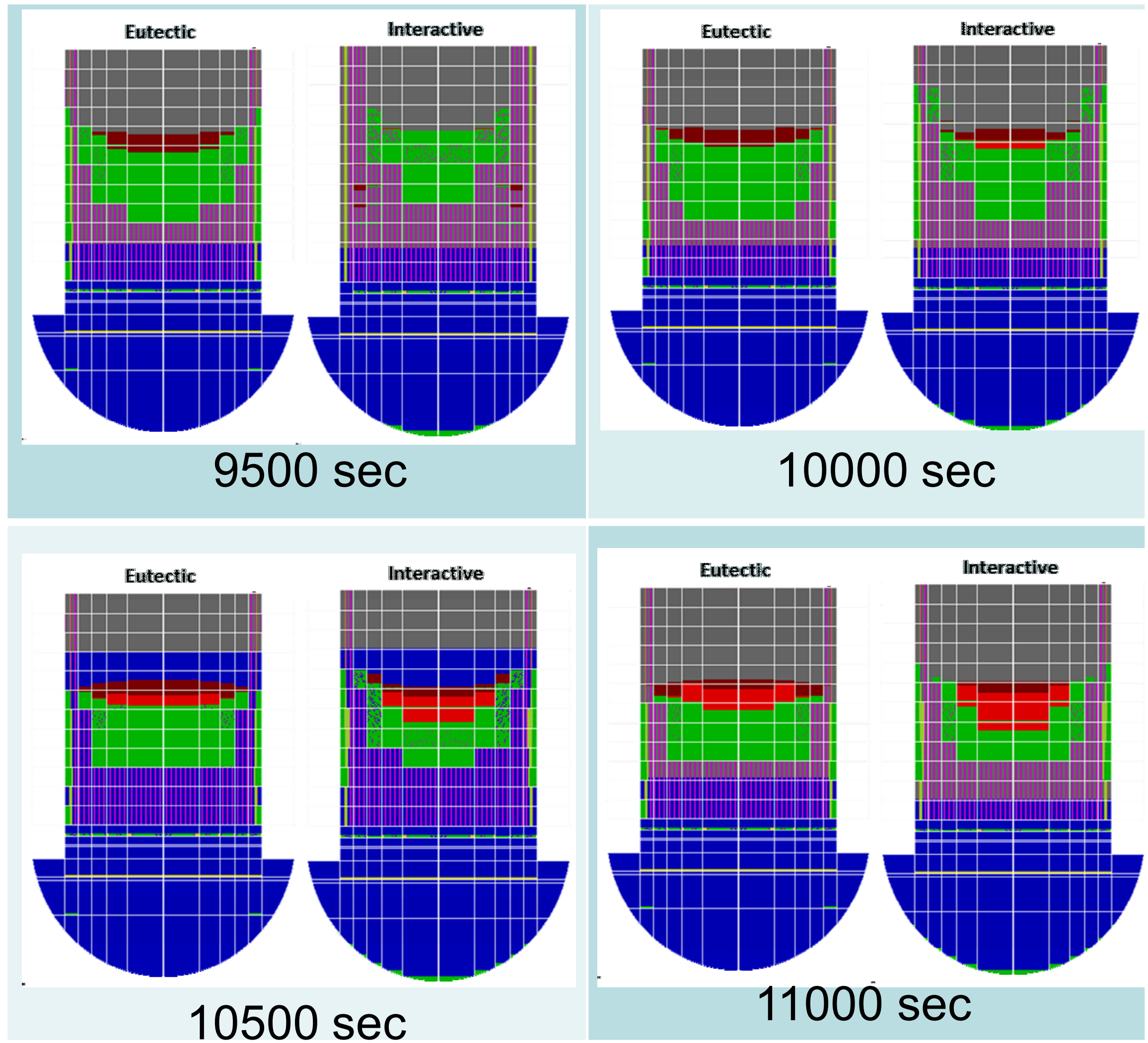
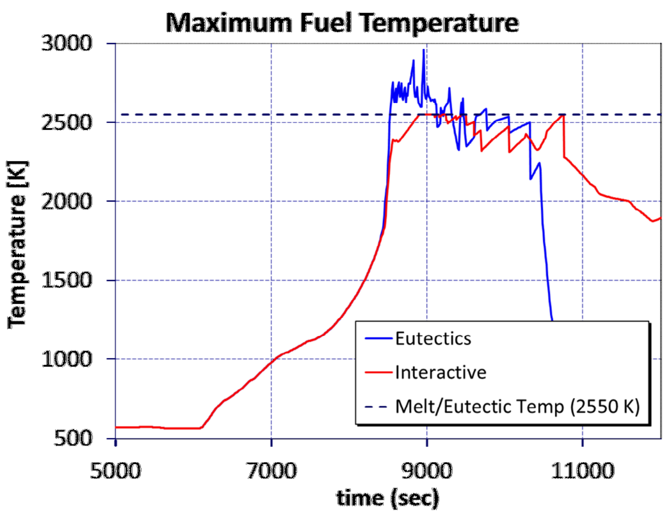
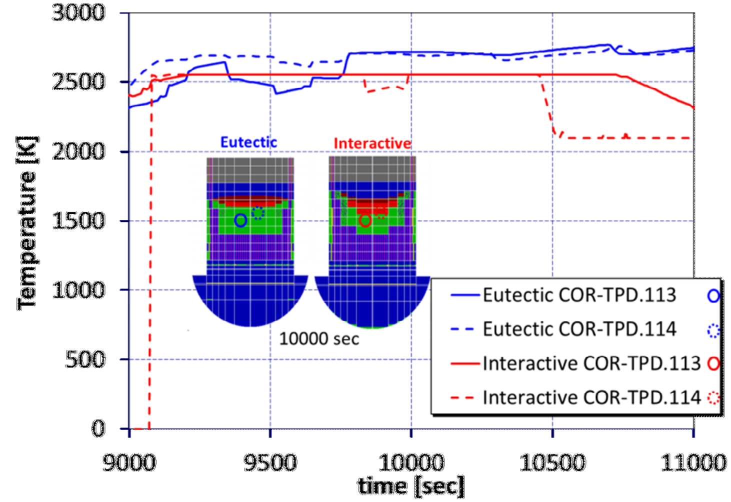
- Compare two TMI-2 test cases
  - Eutectics point = 2550 K
  - Interactive UO2-INT/ZRO2-INT 2550 K
- Similarities but notable differences
  - Core damage
    - Greater for eutectics
  - Size of Molten pool
    - Early: Greater for interactive
    - Later: Greater for eutectics
  - Material relocating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

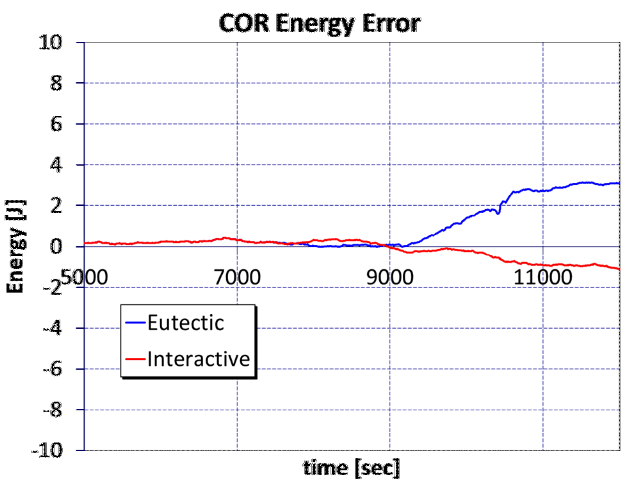


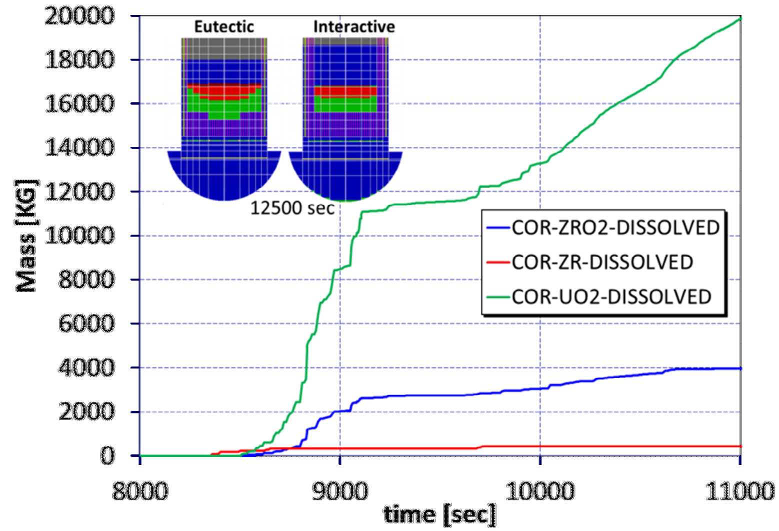
TMI Melt Progression –Preliminary Results

Sandia National Laboratories



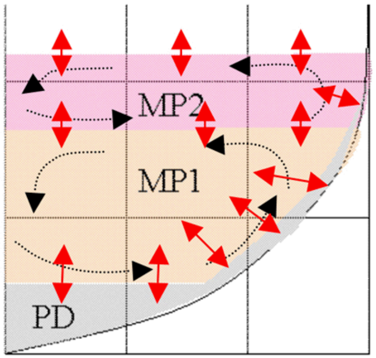




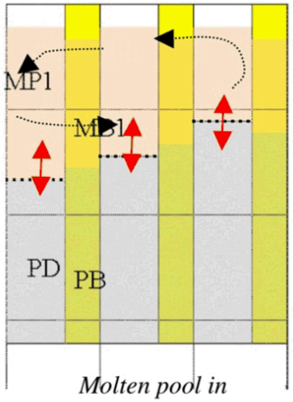


MELCOR Core Phenomenon Stratified Molten Pool Model (1)

- Treat molten pools, both in core and lower head
  - Can contain oxidic and metallic materials
  - May be immiscible, and separate by density
  - Same approach in core and lower head
    - Requires distinguishing pool in channel from that in bypass
- Stratified melt pool - Additional material relocation models
  - Downward and radial flow of molten pools
  - Sinking of particulate debris in molten pool
    - Particulate displaces pool
  - Stratification of molten pools by density
    - Denser pool displace less dense
      - Currently oxide pool is assumed denser
  - Partitioning of fission products between metallic and oxidic phases
    - Can affect heat generation and natural convection in core molten debris.
    - User can specify partitioning factor on RN1_MPCR record



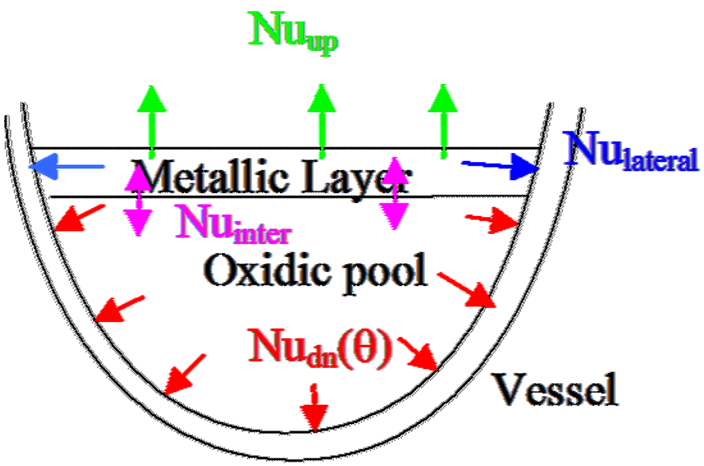
Molten pools in lower plenum



Molten pool in upper core

Stratified Molten Pool Model

- Molten material may be part of contiguous molten pool
  - Homogenized after heat transfer and relocation
    - Redistribute mass and energy
    - Redistribute radionuclides
  - Higher-level treatment of pool heat transfer
    - HTC based on pool Rayleigh number
    - HTC distribution correlation
- Stray (noncontiguous) molten pool material
  - Heat transfer treated same as conglomerate PD
  - Relocation treated as molten pool material
  - Temperature and composition distinct from convecting pool



Average Heat Transfer Coefficient

- A number of quasi-steady state experiments performed to obtain heat transfer characteristics.
  - *J.M. Bonnet, J.M. Seiler, "In-Vessel Corium Pool Thermalhydraulics for the Bounding Cases," RASPLAV Seminar, Munich, 2000.*
  - *Theofanous T.G., Angelini S., "Natural Convection for In-Vessel Retention at Prototypic Rayleigh Numbers", Eighth International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Kyoto, Japan, September 30-October 4, 1997.*
  - *Globe S., Dropkin D., "Natural-Convection Heat Transfer in Liquids Confined by Two Horizontal Plates and Heated from Below", J. Heat Transfer, 81, pp24-28, 1959.*
- It was recognized that a finite amount of time is required for quasi-steady state convection to occur

$$Ra^{new} = Ra^{old} + \left(Ra^{calculated} - Ra^{old}\right) \cdot \left(1 - e^{-\frac{dt}{\tau}}\right)$$

Internal Rayleigh Number

$$\overline{Nu} = C \cdot Ra_i^n$$

$$Ra_i = \frac{g\beta Q H^5}{\lambda \nu^2} \Pr$$

External Rayleigh Number

$$Nu = C \cdot Ra_i^n$$

$$Ra = \frac{g\beta \Delta T H^3}{\nu^2} \Pr$$

Description	Rayleigh Number	A(J)	N(J)	M(J)
Oxide pool to interface	Internal	.381	.234	0
Oxide pool to atmosphere	Internal	.381	.234	0
Metallic pool to lower surface	External	.069	.333	0.074
Metallic pool to radial surface	External	.3	.22	0
Metallic pool to upper surface	External	.3	.22	0

Spatial Distribution of Heat Transfer Correlation for Convecting Molten Pool

- Experimental heat transfer coefficients reflect average heat removal from surface.
- Need for local spatial distribution of heat transfer coefficient
  - *J.M. Bonnet, J.M. Seiler, "In-Vessel Corium Pool Thermalhydraulics for the Bounding Cases," RASPLAV Seminar, Munich, 2000.*

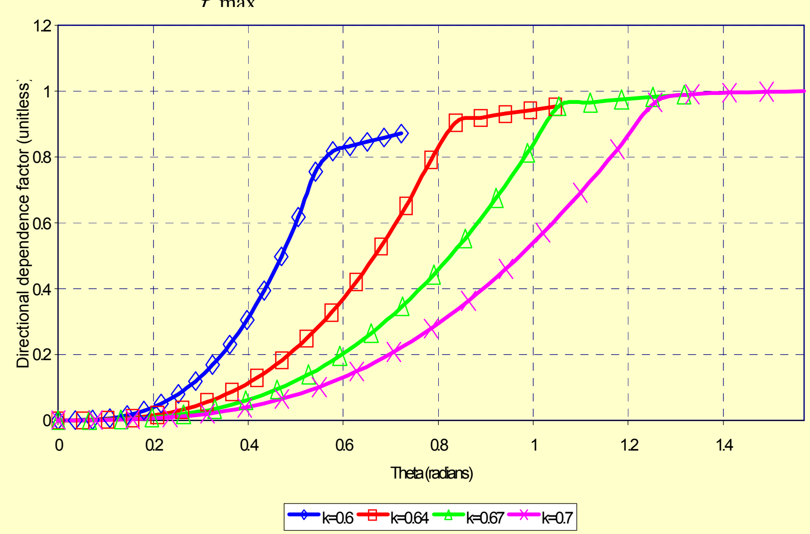
Heat transfer correlation angular dependence

$$\theta \le \arccos(1 - k(i)\tfrac{H}{R})$$

$$\frac{\varphi}{\varphi_{\max}} = c(i)\cdot\theta + b(i)\cdot\theta^2 + a(i)\cdot\theta^3$$

$$\arccos(1 - k(i)\tfrac{H}{R}) < \theta \le \arccos(1 - \tfrac{H}{R})$$

$$\frac{\varphi}{\varphi_{\max}} = f(i)\cdot\theta + e(i)\cdot\theta^2 + d(i)\cdot\theta^3$$



Molten Pool Convective Heat Transfer

Energy Balance on MP1:

$$MC_{P,MP1}\frac{T^{n}_{MP1}-T^{o}_{MP1}}{\Delta t} = \dot{Q}_{MP1,decay} - \sum_{s\in seg} h_{MP1\to s}A_s\left(T^{n}_{MP1}-T_s\right) - h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right) - \left\langle h_{MP1-fluid}A_f\left(T_{MP1}-T_{fluid}\right) - \sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP1}-T^{4}_{ambient}\right)\right\rangle$$

Energy Balance on MP2:

$$MC_{P,MP2}\frac{dT^{n}_{MP2}}{\Delta t} = \dot{Q}_{MP2,decay} - \sum_{s\in seg} h_{MPs\to s}A_s\left(T^{n}_{MP2}-T_s\right) + h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right) - h_{MP2-fluid}A_f\left(T^{n}_{MP2}-T_{fluid}\right) - \sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP2}-T^{4}_{ambient}\right)$$

Implementation Into MELCOR

- Heat transfer correlations from experiments strictly valid for steady state heat transfer
  - Rayleigh number based on internal heat generation only
    - Internal heat generation equal to total heat loss at steady state
    - May not reflect high heat losses to cold boundary conditions (i.e., hot molten material with no internal heat generation in contact with cold lower head)
- Steady state model adapted for transient conditions
    - Considers heat losses to boundaries as well as internal heat generation in determining effective Rayleigh number
    - At steady state, the effective Rayleigh number would agree with experimental correlation

Heat Transfer Correlations In Oxide Pool For Case of a Transient

Steady State

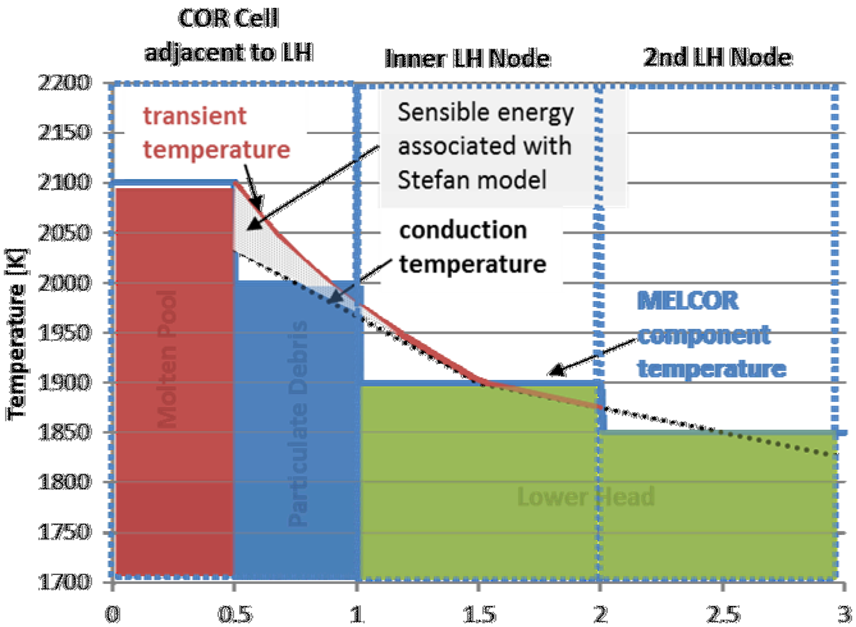
$$Ra_{\text{int},MP1} \propto \dot{Q}_1 = \dot{Q}_{MP1,decay} = \begin{pmatrix} \sum_{s \in seg} h_{MP1 \to s} A_s \left(T_{MP1} - T_s\right) + \\ h_{MP1 \to MP2} A_{1,2} \left(T_{MP1} - T_{MP2}\right) \end{pmatrix}$$

Transient

$$Ra_{\text{int},MP1} \propto \dot{Q}_1 = \frac{1}{2} \begin{bmatrix} \dot{Q}_{MP1,decay} + \\ \sum_{s \in seg} h_{MP1 \to s} A_s \left|T_{MP1} - T_s\right| + \\ h_{MP1 \to MP2} A_{1,2} \left|T_{MP1} - T_{MP2}\right| \end{bmatrix}$$

Integral Solution to Stefan Problem

- Convective molten pool supported by solid substrate
  - May be PD, lower head, or core support plate
  - Thermal properties vary greatly between phases
  - Temperature gradient in substrate may be highly nonlinear within the dimension of a COR cell
  - Position of the interface may move (Stefan Problem)
- Integral model for transient calculation
  - Does not require many nodes
  - Assumes a shape for the temperature profile (quadratic) in the substrate
  - Integration of the conduction equations over the spatial domain
  - Impose convective boundary condition at interface



MELCOR Lower Head Failure Models

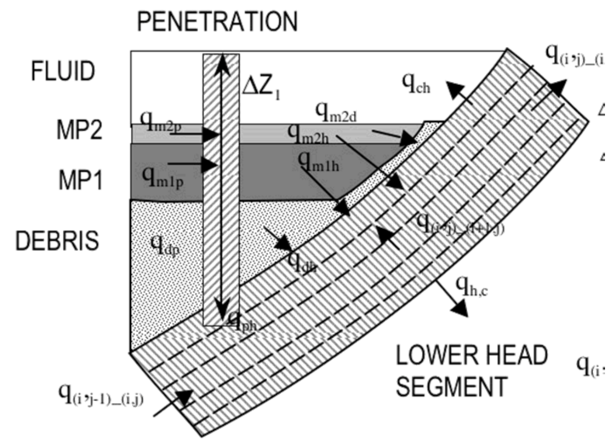
- Failure based on Robinson's Rule, i.e., lifetime rule from Larson-Miller parameter
- Two models are available in MELCOR:
  - Zero-Dimensional Model
    - Default Model
  - One-Dimensional Model
    - Selected by setting sensitivity coefficient SC1600(1) = 1
    - Recommended Model
  - Part of thickness can be non-load-bearing (e.g., insulation)
    - `NINSLH` (from record `COR00000`) outer meshes, with default 0, will be excluded from the calculation

One- Dimensional Model

- Larson-Miller Parameter evaluated at local temperature through vessel wall.
- Larson-Miller Parameter evaluated at local engineering hoop stress (initial geometry and time-dependent pressure load).
- Plastic strain determined from Larson-Miller Parameter
- Local stress is limited to local ultimate (yield) stress and excess load is redistributed to other nodes.
- Stress is not uniform across the wall thickness.
- Local elastic strain and local elastic modulus used to determine local stress.
- Thermal strain is considered in determining stress redistribution.
- Total plastic strain varies across vessel wall. COR-VSTRAIN is the plastic strain
- Solved implicitly and iteratively

MELCOR Core Modeling
Modeling of Lower Head Penetrations (2)

- Each "penetration" represents the aggregate of all like penetrations in a single segment
  - Can have up to three distinct types in a single segment
    - Allows for instrumentation tubes, control rod guide tubes, and drain plugs
  - Can have a maximum of 19 distinct penetrations
- Failure defined by failure temperature or LOGICAL control function
  - Initial hole size, discharge coefficient for debris defined
    - Discharge rate calculated from Bernoulli equation
  - Ejection of debris may be delayed, During debris ejection, ablation increases hole size (Pilch and Tarbell)
    - – Ablated material is *not* added to debris



Curved Lower Head

MELCOR Core Modeling
Vessel Failure Consequences (2)

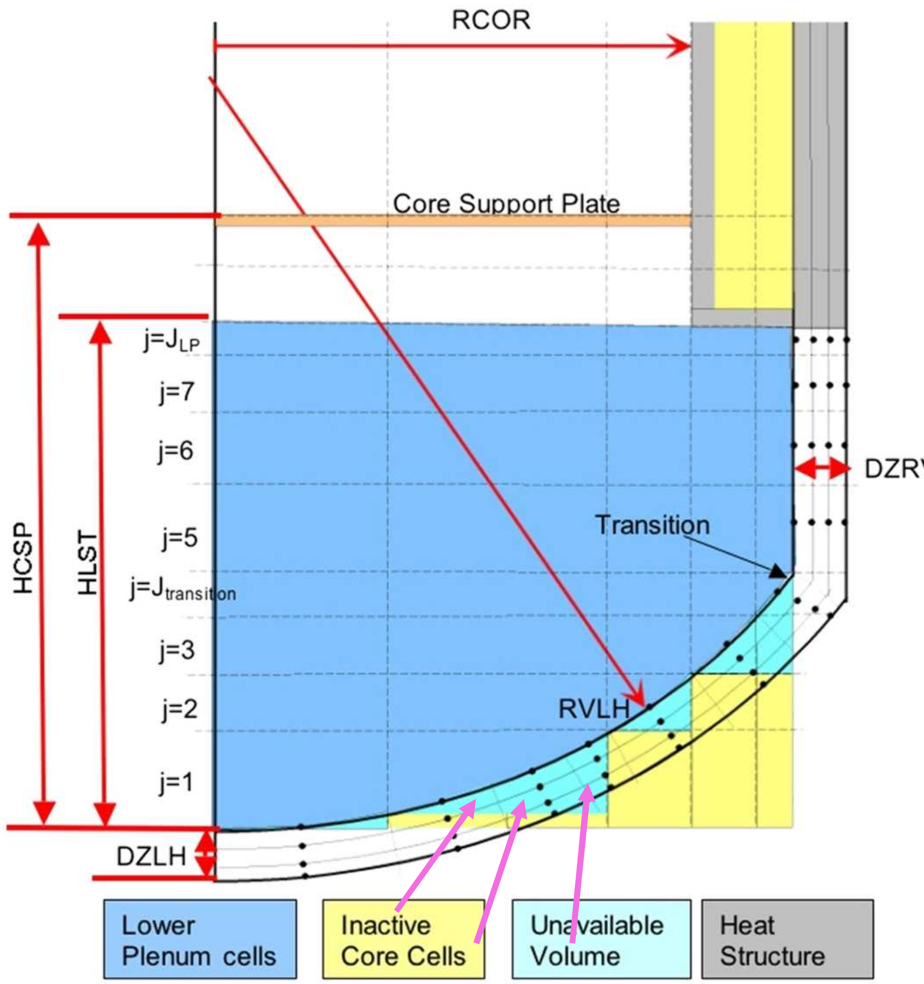
- Failure of penetration or lower head provides path for debris to reach cavity
  - Threshold imposed to avoid problems in CAV package
  - No ejection until 5000 kg debris in lowest core cell (or molten material fills more than 10% of its volume)
- Ejected debris is “handed off” to Transfer Process (TP) package
  - Input must specify number of appropriate transfer process

```
! COR_TP defines transfer process to receive debris
!       NTPCOR is name of ‘IN’ transfer process or NO
COR_TP  NTPCOR
```

  - NTPCOR=0 is allowed, even though it is not an acceptable transfer process number
    - Calculation will be terminated if ejection is predicted
    - MELGEN will issue a warning to this effect

MELCOR Core Modeling
Lower Head Geometry

- Lower head defined in segments
  - Outer radius defined independently of core cells
    - Used to calculate area and inclination
  - Each communicates with core cell above, control volume outside, and adjacent segments
- Total thickness DZLH with NLH nodes
  - Default is CARBON STEEL, equally-spaced nodes
    - Can modify to add liner or insulation
- Unavailable volume
  - Cells that lie below the curved lower head surface can be specified as "Null" cells



Lower Head Failure Criteria

- Creep-rupture failure of a lower head ring occurs
- Temperature dependent failure
  - Failure Temperature, TPFAIL, set on COR_LHF card
- Failure dependent on control function
  - Control function identified on COR_RP records
- Overpressure from the falling-debris quench model
  - Default failure criterion is 20 MPa
    - Redefine on record COR_LP, but not greater than P_{crit}
  - Temperature of inner node exceeds defined failure, TFAIL
    - Input on record COR_LHF (default 1273.15 K)
    - Penetration failure

Two SNL LHF Testing Programs

USNRC Program

- 10 MPa experiments
- Small temperature gradient
- Multiple Heat Flux Profiles
  - Center-peaked
  - Uniform
  - Side-peaked
- Local features such as penetrations or weldments
- Local failures (except LHF-5) that initiate at vessel weak spots (hot spots or thin spots)

Dates

March 1996 – March 1998

Reference

NUREG/CR-5582, SAND98-2047

OECD Program

- Lower pressure 5 MPa
- Large temperature drop across vessel > 300 K
  - Thicker wall (pressure scaled to maintain hoop stress)
  - Un-insulated outer surface
  - Larger power supply
- Uniform heating
- Localized failure with the exception of OLHF-3
- Failure determined by strength of outer wall
  - Failure occurred at much higher average temperature

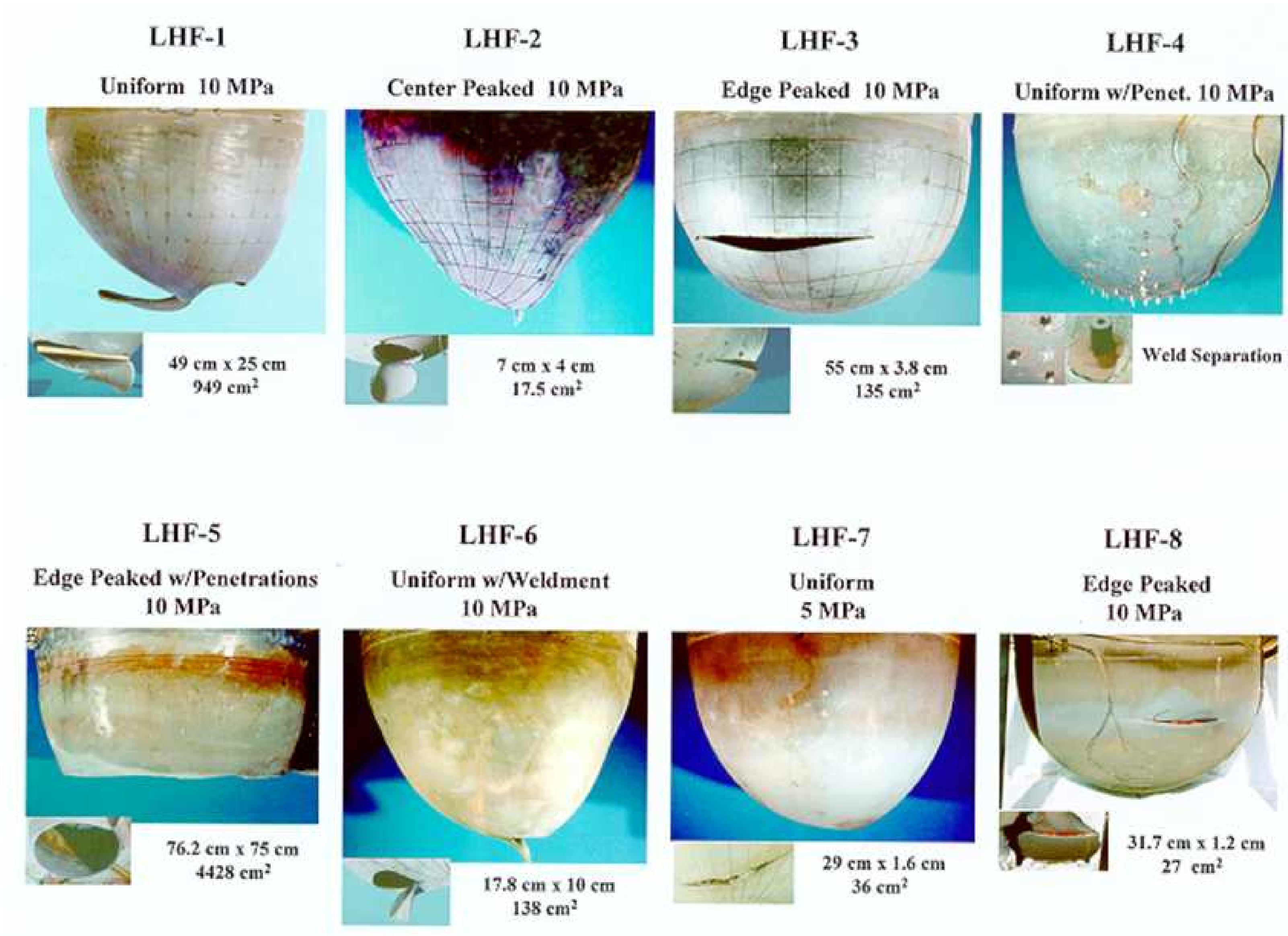
Dates

Sept 1998 to June 2002

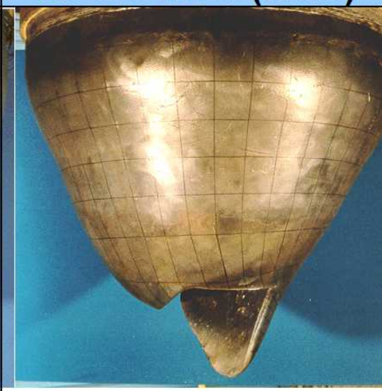
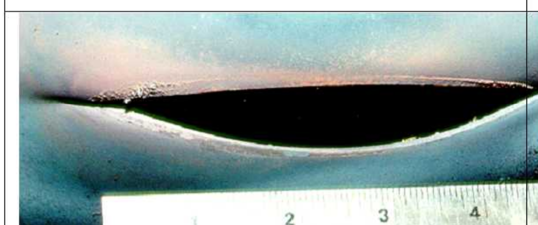
Reference

ICONE 14-89159 pp. 39-52

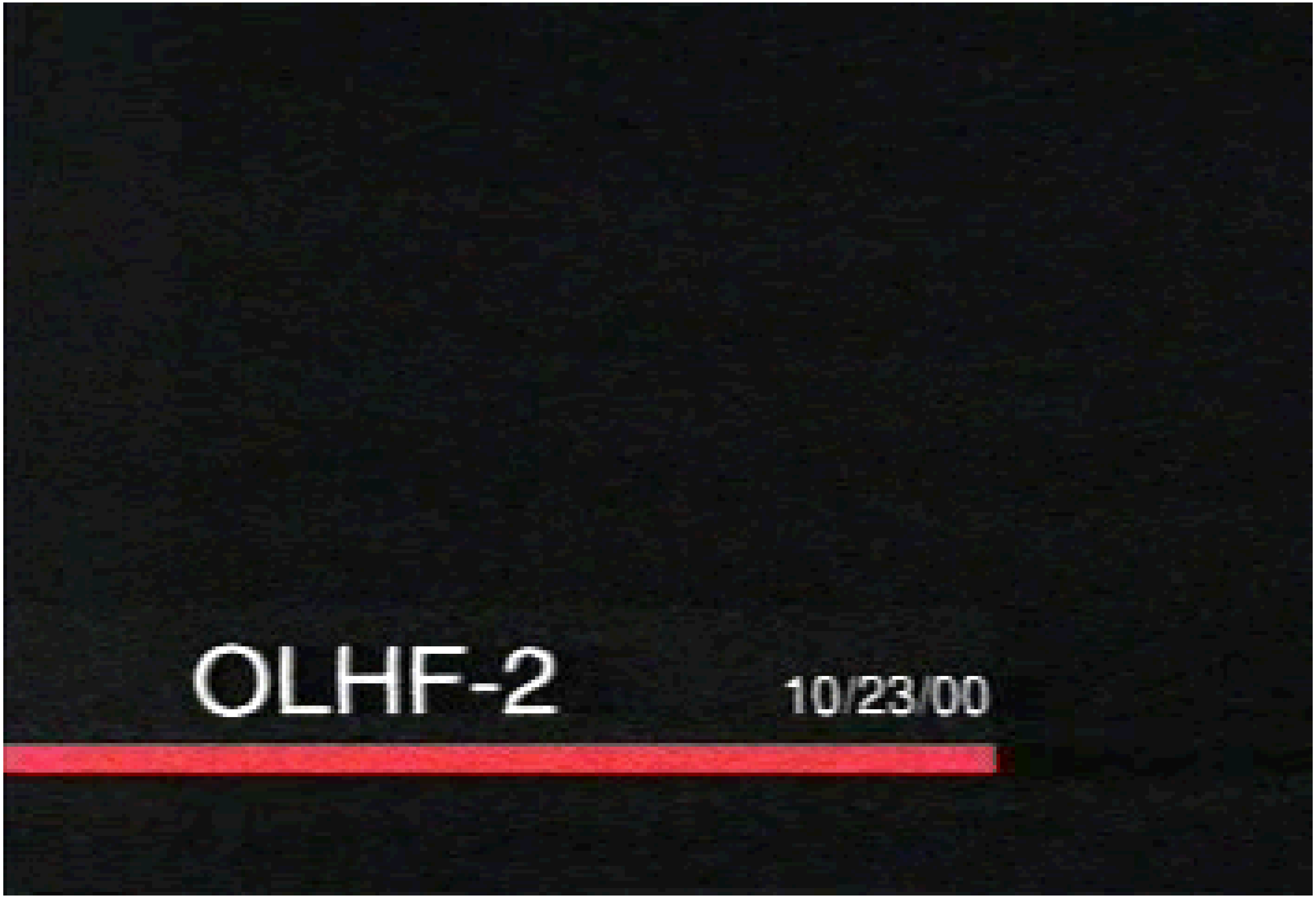
USNRC Sponsored LHF Tests



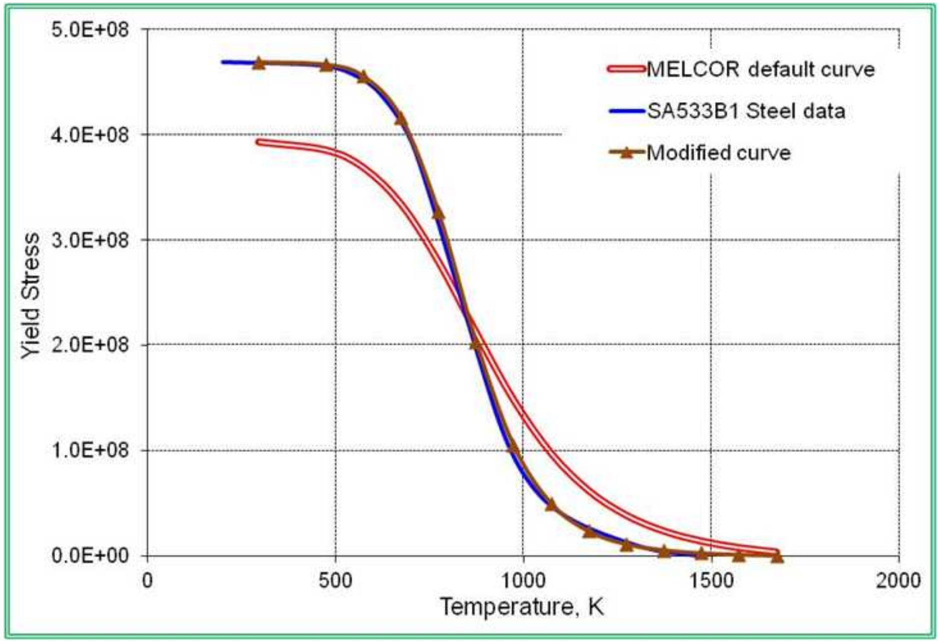
OECD Sponsored OLHF Tests

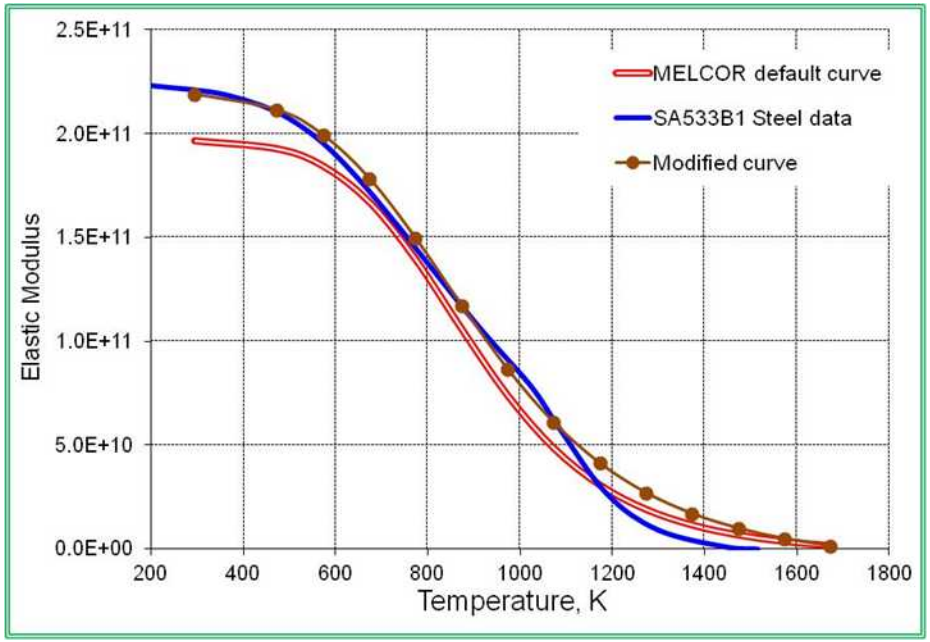
OLHF-1 4.7 MPa (RCS)	OLHF-2 2.02 MPa (RCS)	OLHF-3 Transient: 2.02 MPa (RCS) to 4. 7 MPa (RCS)	OLHF-4 2.02 MPa (RCS)
			
			 *Separation of the penetration welds from the base material.*
Tinside = 1450 K Area of failure = 17.1 cm2 (.22 m FSE diameter) tfailure - t800 = 56 min	Tinside = 1750 K Area of failure = 36.5 cm2 (.33 m FSE diameter) tfailure - t800 = 96 min	Tinside = 1380 K Area of failure =1180 cm^2(1.9 m FSE diameter) tfailure - t800 = 52 min	Tinside = 1650 K Failure area ~ 1 cm^2tfailure - t800 = 73 min

OLHF-2 Video Summary



MELCOR Mechanical Properties of Vessel Steel





Larson-Miller Parameter Relations

Sandia National Laboratories

MELCOR

- Time-to-Failure (sec)
- Larson-Miller Parameter (σ_e in Pa)

$$t_R = 10^{\left(\frac{P_{LM}}{T} - 16.44\right)}$$

$$P_{LM} = 7.722x10^4 - 7.294x10^3 \log_{10} \sigma_e$$

SC1601

LHF Experiments

- Time-To Failure (sec)
- Larson-Miller Parameter (σ_e in Pa)

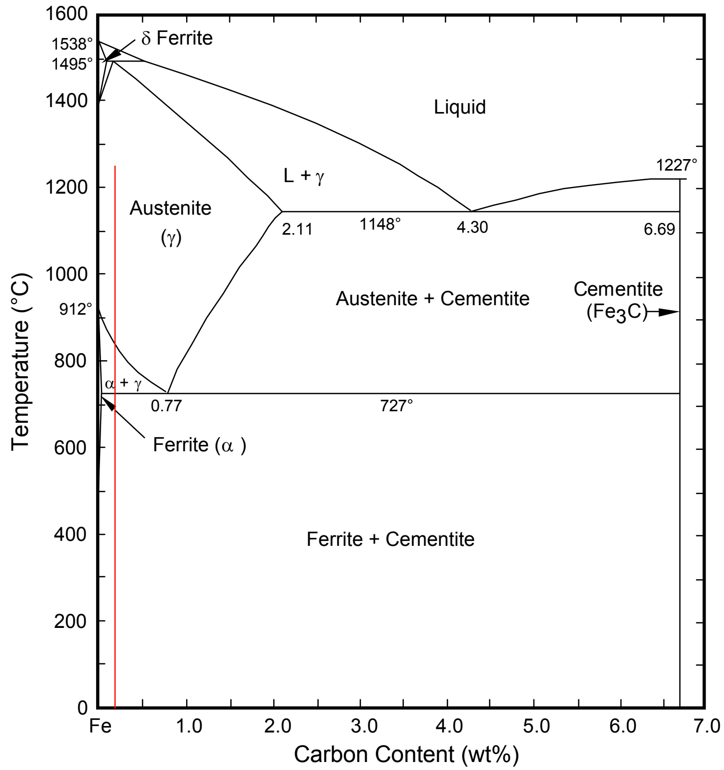
$$t_{fail} = 10^{\frac{LMP}{T} - C} e^{\pm \sigma_{err}}$$

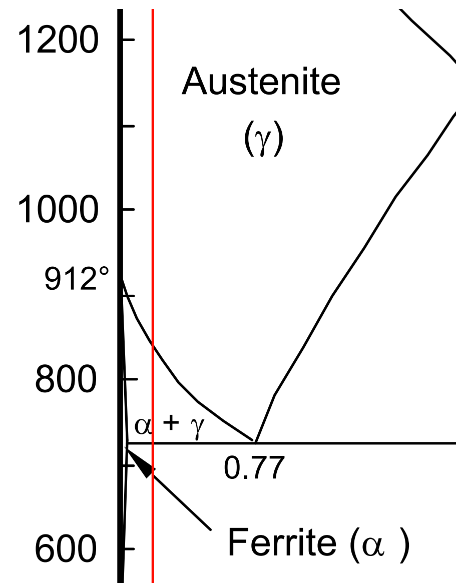
$$P_{LM} = A - B \log_{10} \sigma_e$$

	T ≤ 1050 K	T > 1050 K
A	48620	48120
B	4080	4725
C	12.682	7.042
Error Estimates		
σ_{err}	0.824	0.824

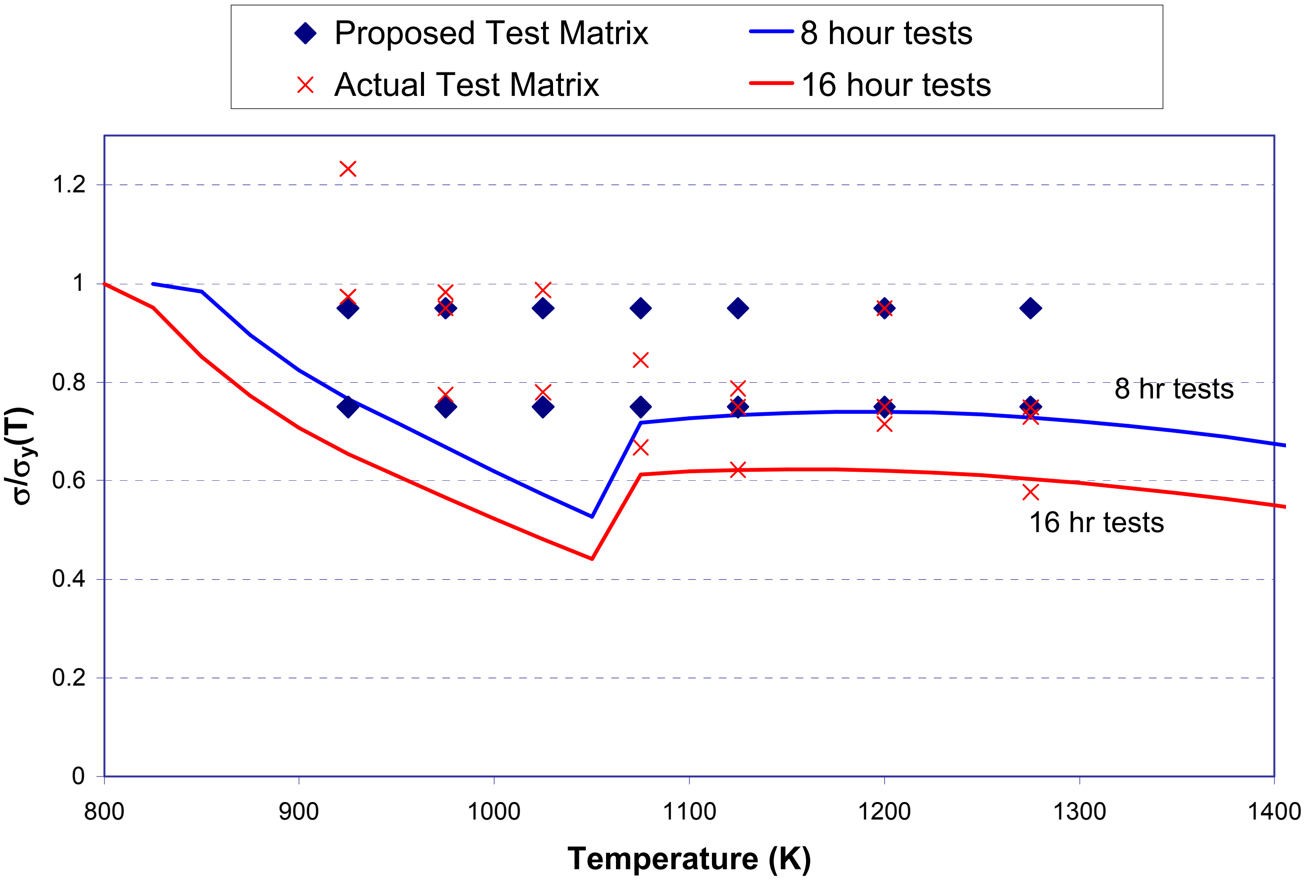
Assumed Temperature Dependence of Larson-Miller Parameter Correlation

Phase Transformation for SA533B Steel at ~1000-1100 K

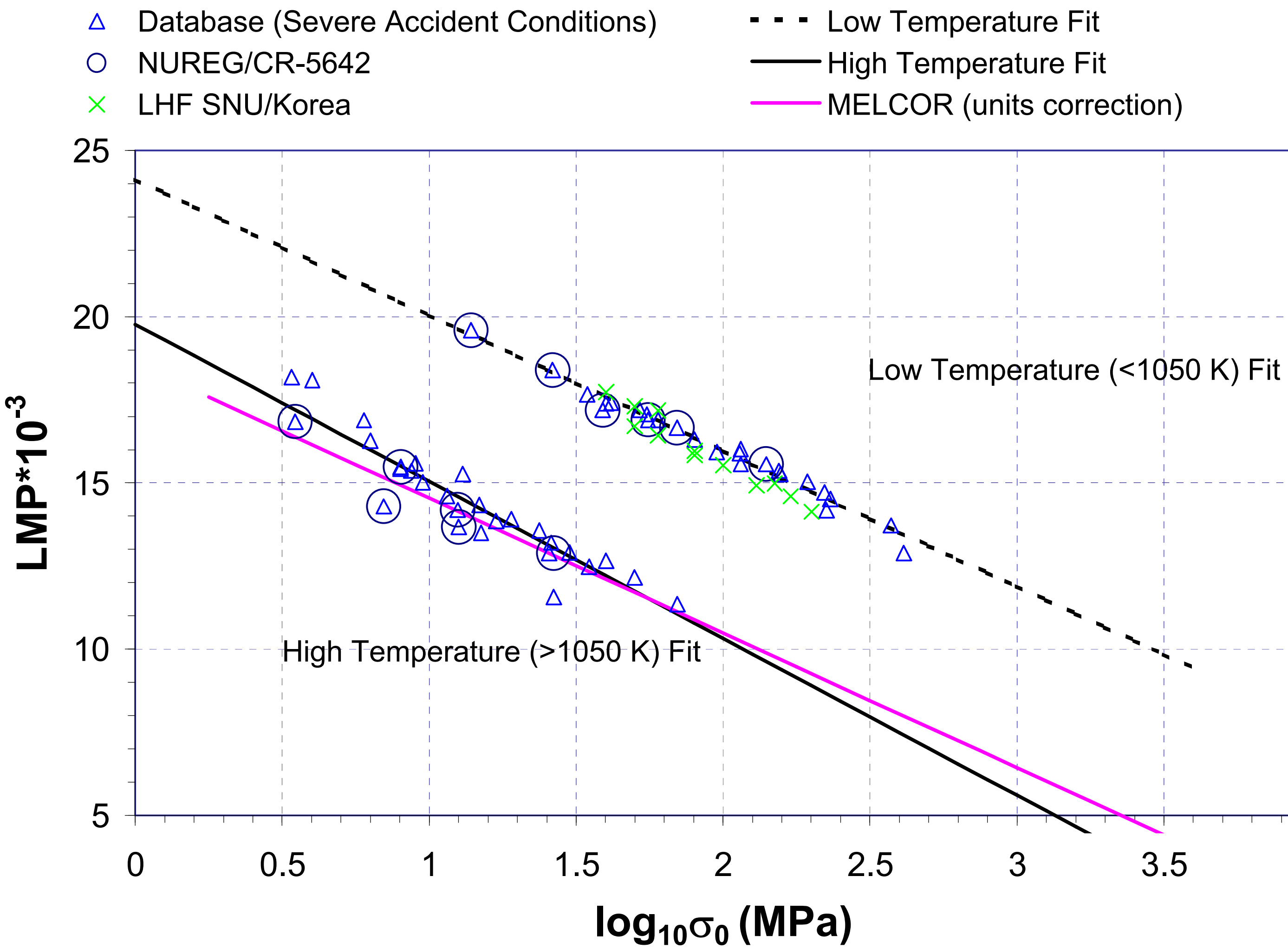




OLHF High Temperature Creep Tests



Corrected MELCOR LMP Correlation Plotted With LHF LMP Correlation



MELCOR Lower Head Failure Models

- Failure based on Robinson's Rule, i.e., lifetime rule from Larson-Miller parameter
- Two models are available in MELCOR:
  - Zero-Dimensional Model
    - Default Model
  - One-Dimensional Model
    - Selected by setting sensitivity coefficient SC1600(1) = 1
- Model could be modified to calculate strain evolution based on constitutive law and simplified spherical model
- Model could be extended to include other failure criteria, i.e., necking criteria

MELCOR 0-Dimensional Model Equations

Load Distributed Uniformly Across Vessel Wall

$$\sigma_e = \frac{(\Delta P + \rho_d g \Delta z_d) R_i^2}{R_o^2 - R_i^2}$$

SC1604(4)

Plastic Strain Calculated at Each Ring - *Requires Assumed Maximum Strain*

$$\varepsilon_{pl}(t + \Delta t) = \varepsilon_{pl}(t) + 0.18 \frac{\Delta t}{t_R}$$

Equivalent Damage Function - *Does Not Require Assumed Maximum Strain*

$$damage(t + \Delta t) = damage(t) + \frac{\Delta t}{t_R}$$

MELCOR 0-Dimensional Model

- Failure determined by life-time rule.
- Larson-Miller Parameter evaluated at mass-averaged temperature through vessel wall.
- Larson-Miller Parameter evaluated at engineering hoop stress (initial geometry and time-dependent pressure load).
- The temperature only affects the material properties (no thermal stresses).
- Plastic strain determined from Larson-Miller Parameter
- Stress is uniform across the vessel wall.
- Stress redistribution ignored.

MELCOR 1-Dimensional Model Equations

- Stress/Load Balance (stress redistribution)

$$[\Delta P + \rho_d \, g \, \Delta z_d] R_0^2 = \sum_{i}^{N_{NY}} \sigma_i \left(R_i^2 - R_{i-1}^2 \right) + \sum_{j}^{N_Y} \sigma_Y (T_j) \left(R_j^2 - R_{j-1}^2 \right)$$

- Stress/Elastic Strain Relationship

$$\sigma_i = E(T_i) \left[\varepsilon_{tot} - (\varepsilon_{pl,i} + \varepsilon_{th,i}) \right]$$

SC1600(2)

- Thermal Strain

$$\varepsilon_{th,i} = 1.0x10^{-5} \left(T_i - T_{ref} \right)$$

MELCOR 1-Dimensional Model

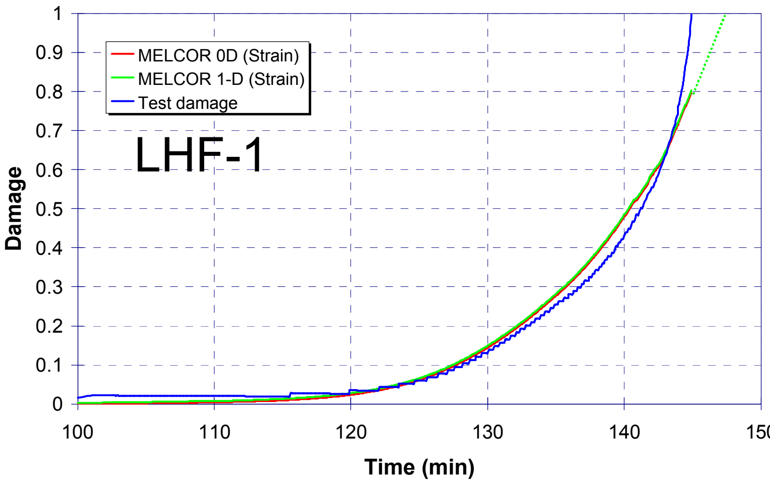
- Failure determined by maximum total strain.
- Larson-Miller Parameter evaluated at local temperature through vessel wall.
- Larson-Miller Parameter evaluated at local engineering hoop stress (initial geometry and time-dependent pressure load).
- Plastic strain determined from Larson-Miller Parameter
- Local stress is limited to local ultimate (yield) stress and excess load is redistributed to other nodes.
- Stress is not uniform across the wall thickness.
- Local elastic strain and local elastic modulus used to determine local stress.
- Thermal strain is considered in determining stress redistribution.
- Total plastic strain varies across vessel wall. COR-VSTRAIN is the plastic strain
- Solved implicitly and iteratively

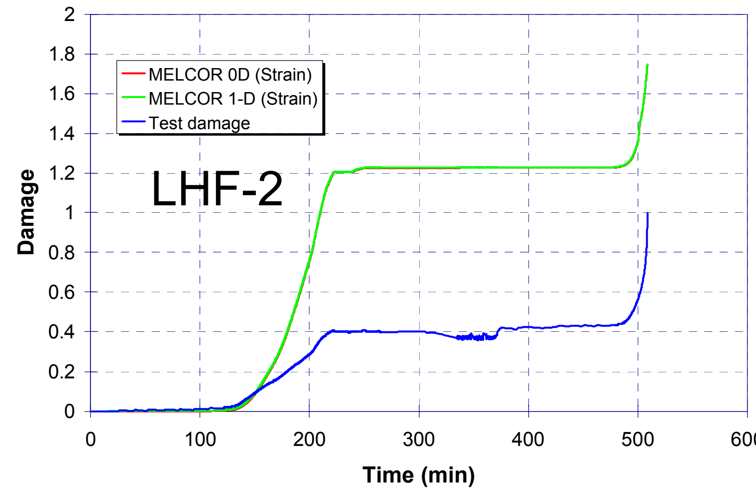
Assessment of Models Against LHF Test Data

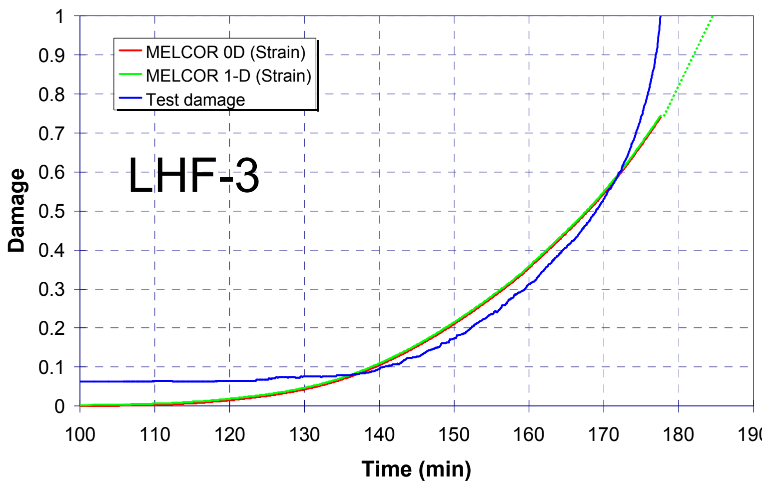
- Creep Failure Models assessed against LHF test results
- Material Properties from LHF program (not MELCOR default or OLHF) implemented in assessment
- Assessment is valid for high pressure (10 MPa) tests though LHF-7 was performed at 5 MPa
- Assessment is valid for small through-wall temperature differential
  - LHF ΔT_{wall} ~ 25-50 K
  - Actual $\Delta T_{wall} > 250$ K
  - Stress Redistribution to outer vessel wall is important and distinguishes 0-dimensional and 1-dimensional models
  - OLHF tests performed at large temperature differential

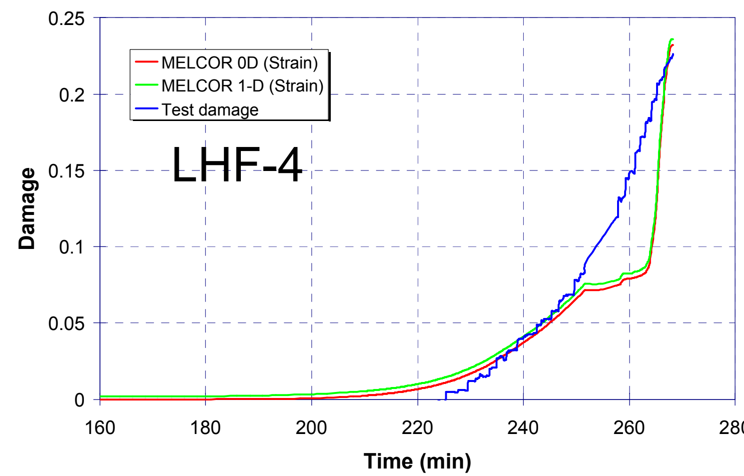
Damage Calculated using MELCOR Models and L-M Parameter Based on LHF Properties

(LHF-1 through LHF-4)



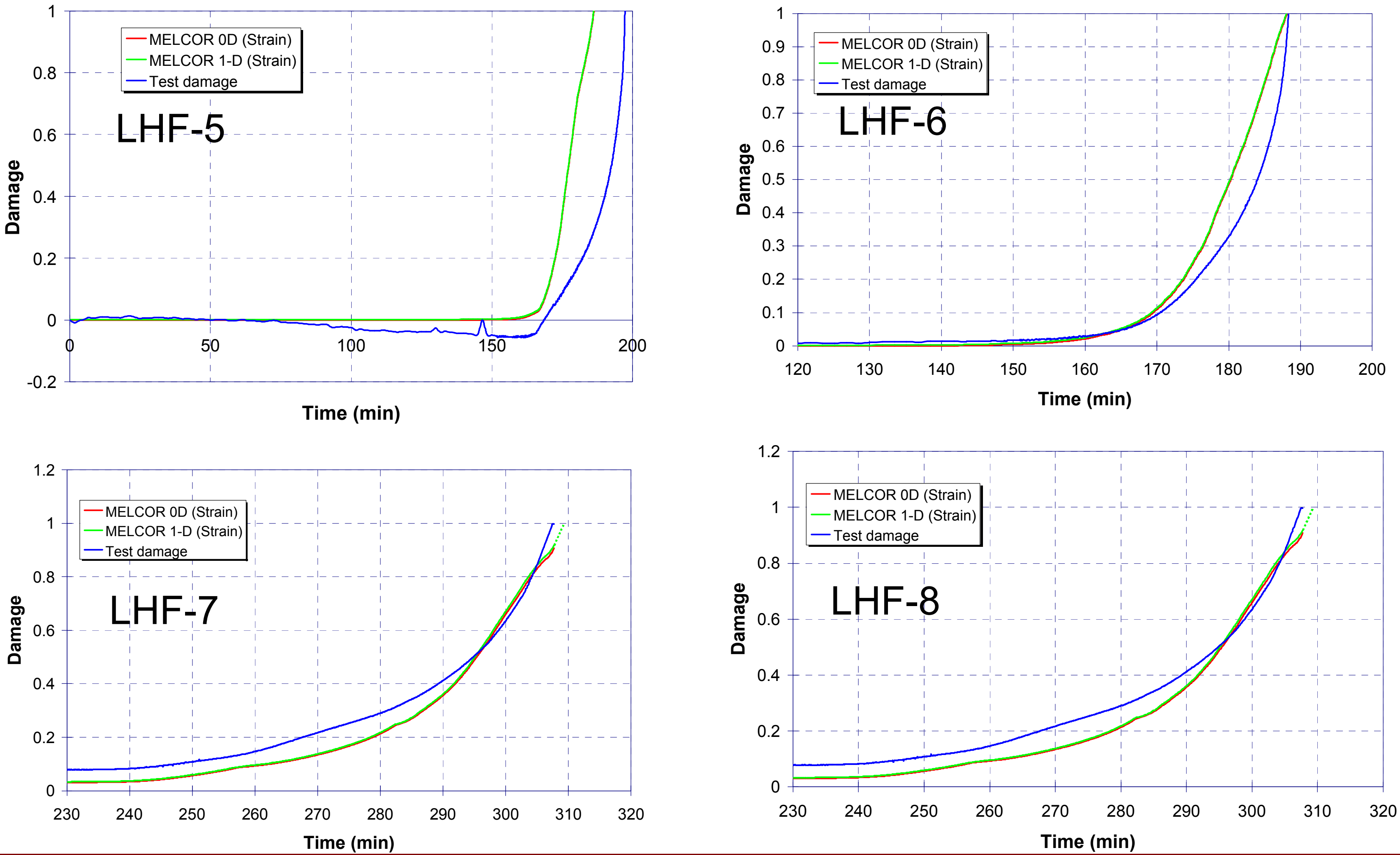




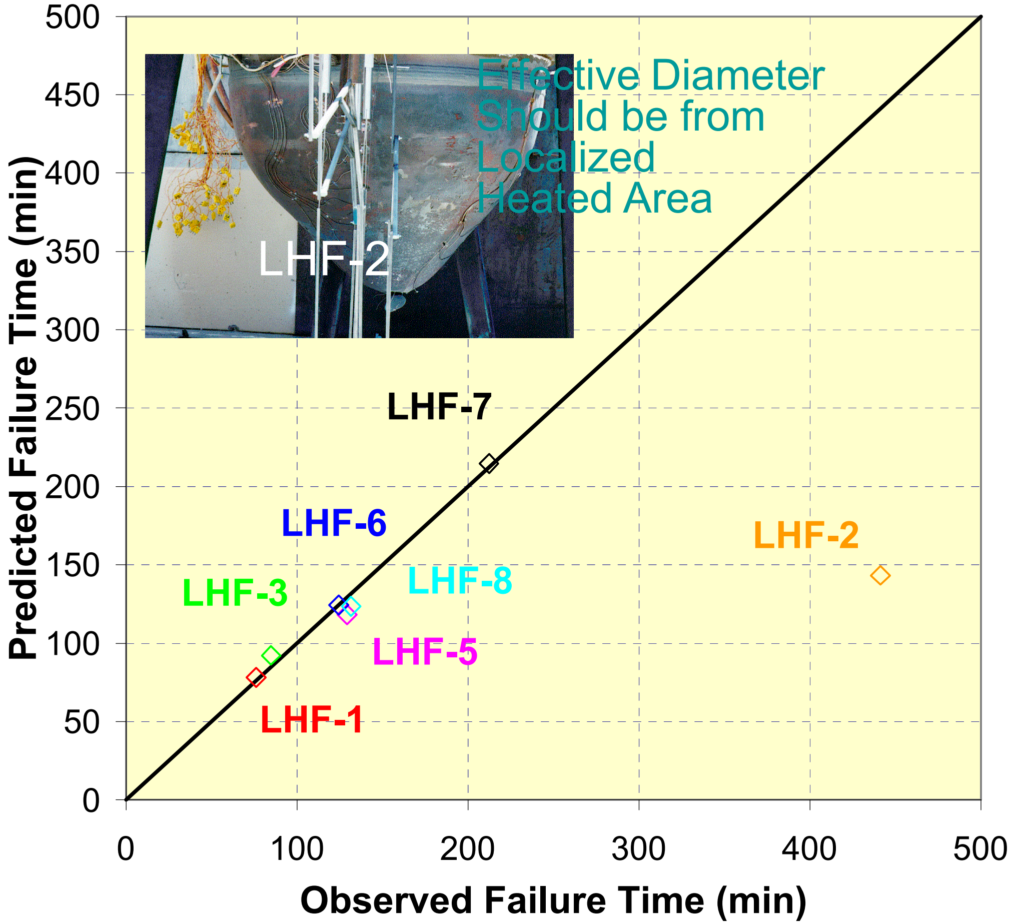


Damage Calculated using MELCOR Models and L-M Parameter Based on LHF Properties

(LHF-5 through LHF-8)



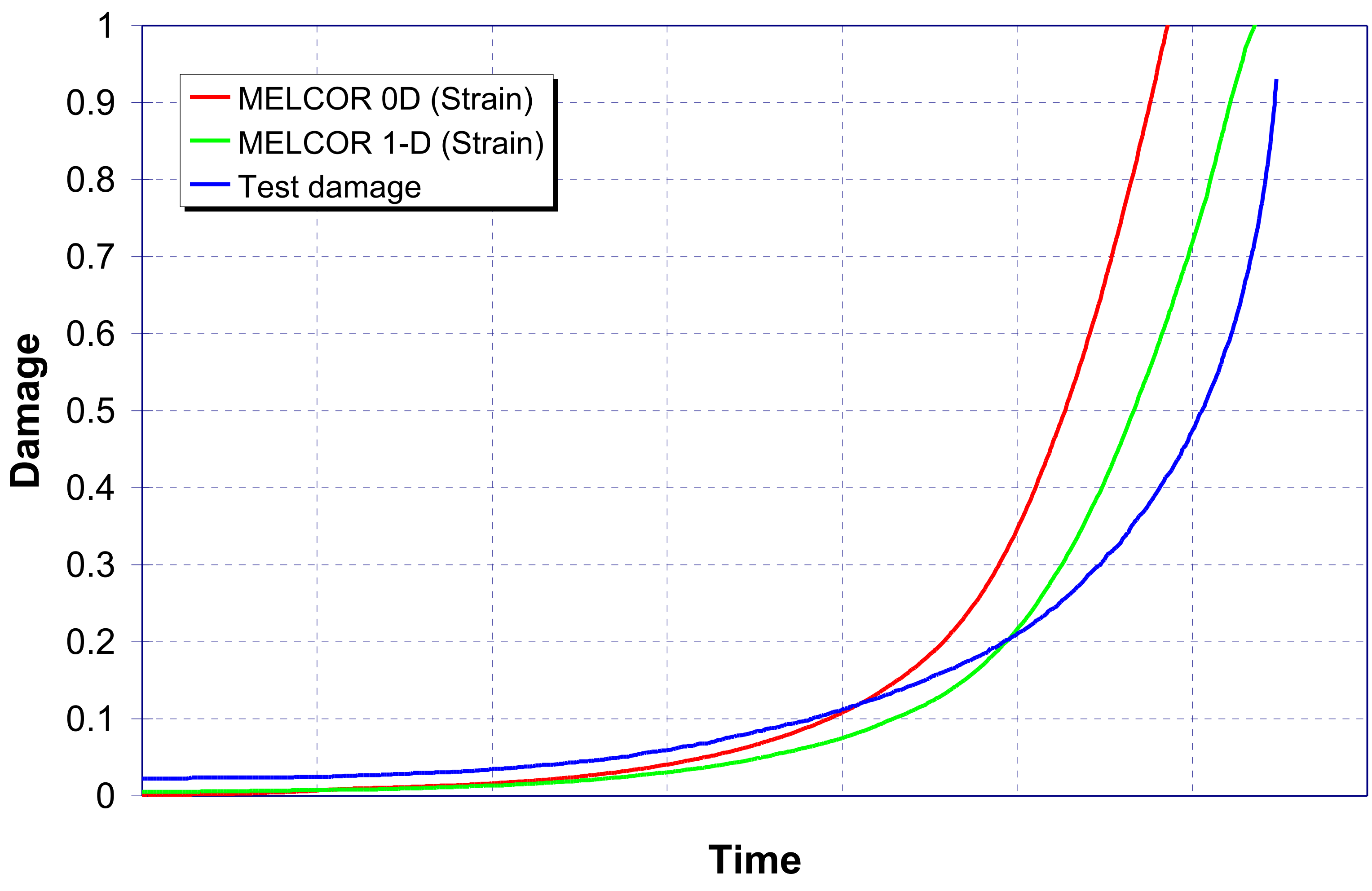
Summary of Predicted Time-to-failure vs. Observed Time-to-failure



*Time Relative to Onset of Plastic Deformation

- LHF-1 Uniform Heat Flux (10 MPa)
- LHF-2 Center Peaked Heat Flux (10 MPa)
- LHF-3 Edge Peaked Heat Flux (10 MPa)
- LHF-5 Edge Peaked Heat Flux (10 MPa)
- LHF-6 Uniform Heat Flux (10 MPa)
- LHF-7 Uniform Heat Flux (5 MPa)
- LHF-8 Edge Peaked Heat Flux (10 MPa)

Results of OLHF-1 Test

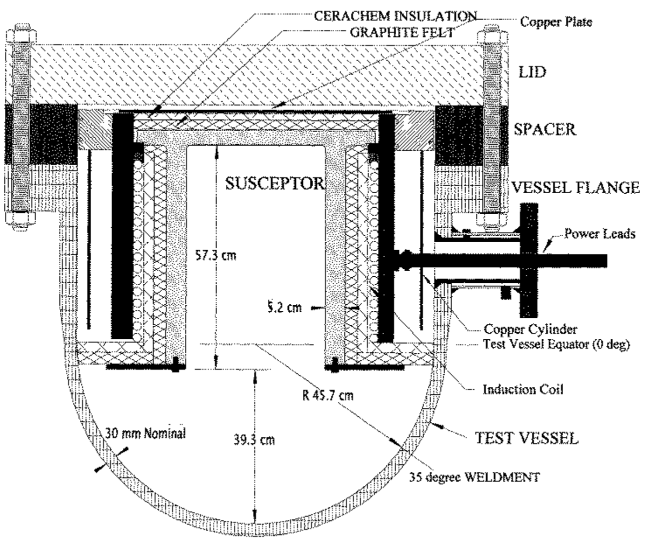


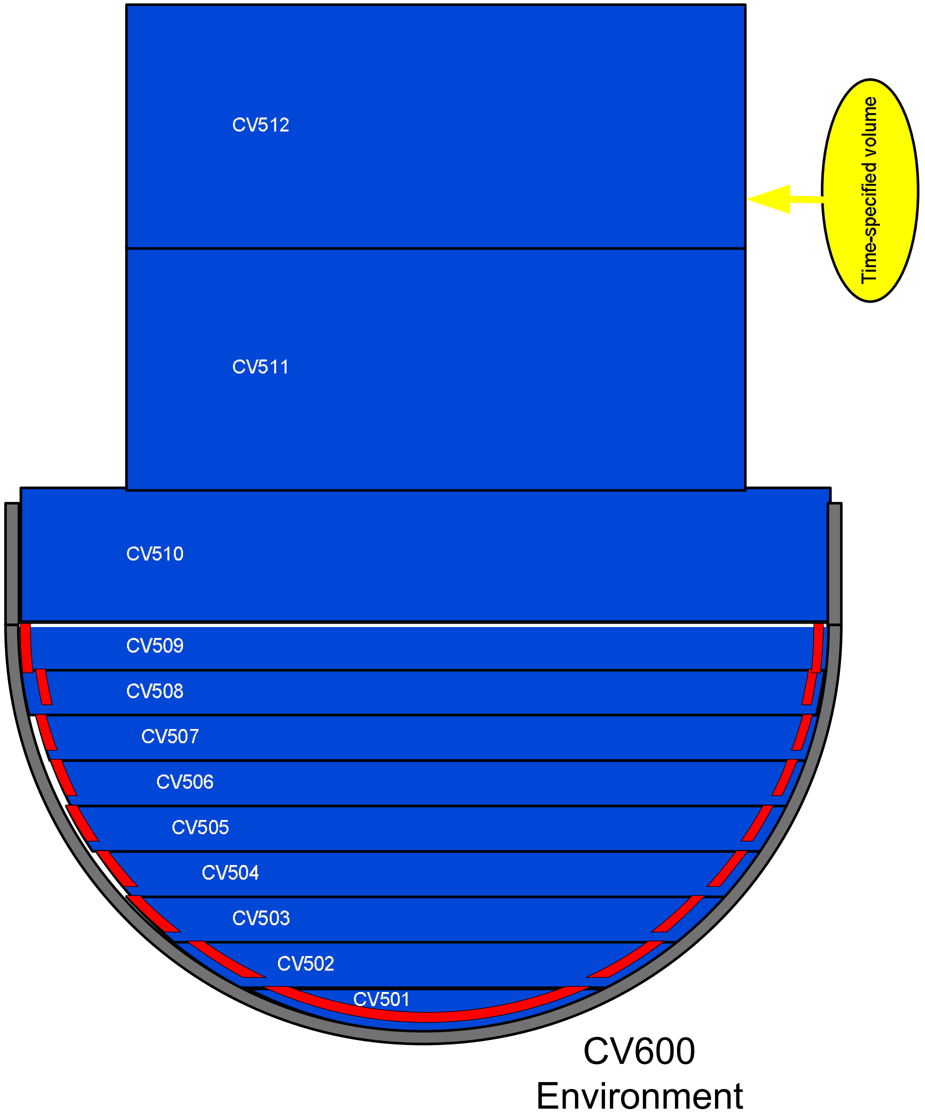
Independent Validation by IBRAE
LHF Test Nodalization Scheme

14 Control volumes

9 Lower Head segments

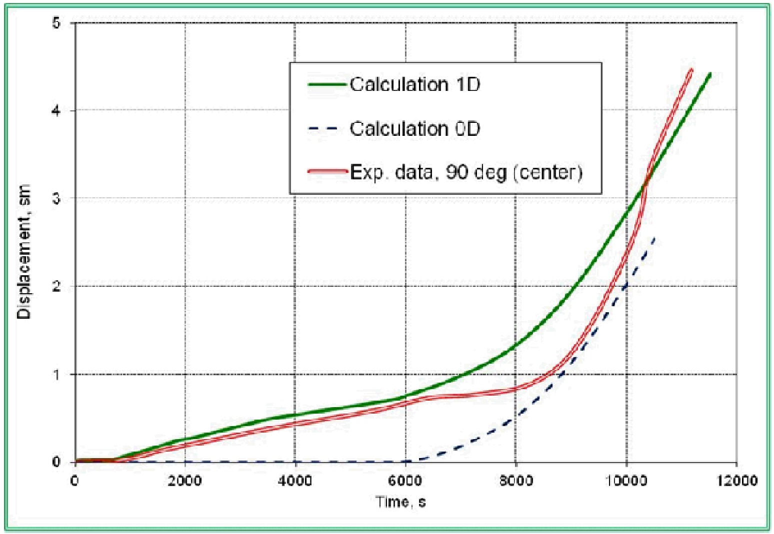
9 heated Support Plates in Lower Head

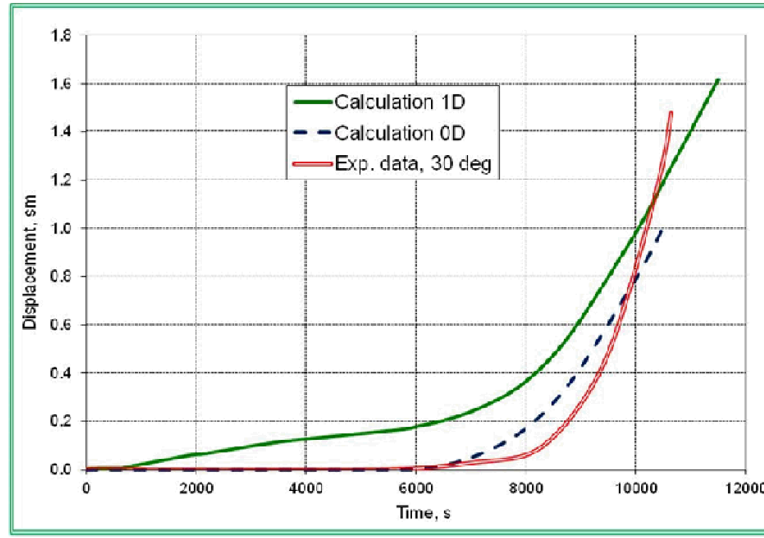




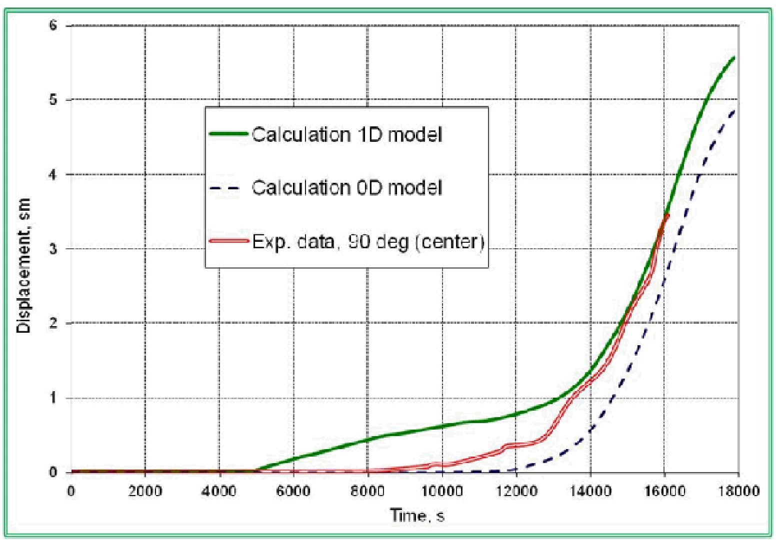
Independent Validation by IBRAE

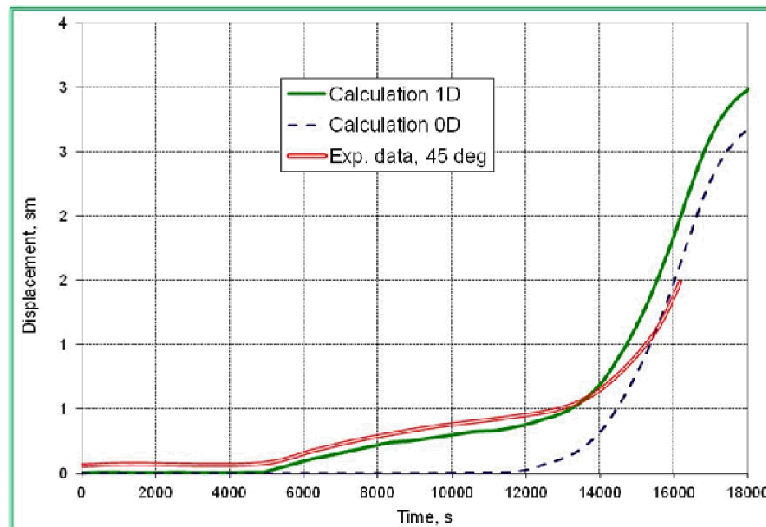
LHF-4





LHF-3





Downward-facing Saturated Pool Boiling Model

Heat transfer to the cavity pool prior to boiling is currently ignored by default, as is subcooling of the pool; it is calculated only when the temperature of the outer surface of the lower head exceeds the saturation temperature in the reactor cavity.

- Fully-developed nucleate boiling

$$h = 34.5 \; P^{1/4} \; \Delta T^{1.523} \qquad (\Delta T < 23.4 \, \mathrm{K})$$

SC1241

- Transition boiling

$$h_{TRN} = \frac{q_{MIN}}{\Delta T} \left(\frac{\Delta T}{\Delta T_{MIN}} \right)^{\left[\frac{\log(q_{CHF}/q_{MIN})}{\log(\Delta T_{CHF}/\Delta T_{MIN})} \right]}$$

- Stable film boiling

$$h_{FLM}(\Delta T) = 0.142 \; k_v \left[\frac{h_{lv} \rho_v g (\rho_l - \rho_v)}{\mu_v k_v \Delta T} \right]^{1/3} (\sin\theta)^{0.3333333}$$

$$h_{FLM}(\Delta T) = \left(0.055 + 0.016 \, \theta^{0.5} \right) k_v \left[\frac{h_{lv} \rho_v g (\rho_l - \rho_v)}{\mu_v k_v \Delta T} \right]^{1/3}$$

SC1245

Alternate Film Boiling Heat Transfer Correlations

H_{flm-1} *Default*

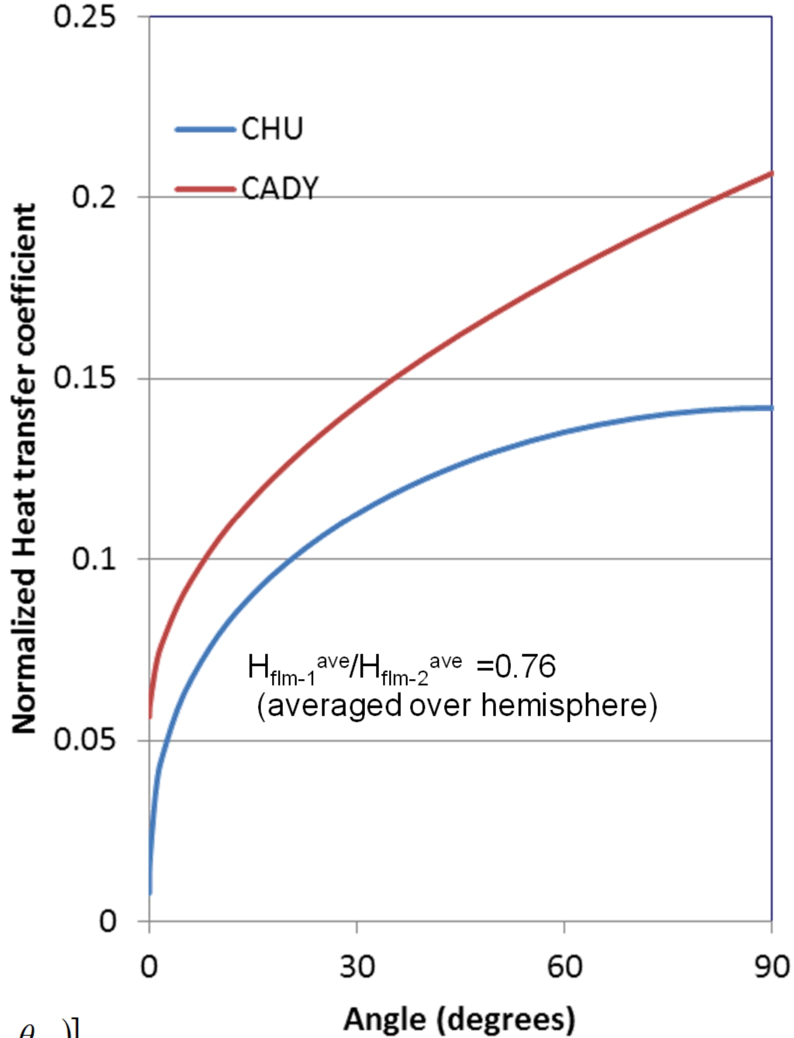
$$h_{FLM}(\Delta T) = 0.142\, k_v \left[\frac{h_{lv}\,\rho_v\, g\,(\rho_l - \rho_v)}{\mu_v\, k_v\, \Delta T}\right]^{1/3} (\sin\theta)^{0.3333333}$$

T. Y. Chu, Journal of Heat Transfer, Volume 115, November 1993.

H_{flm-2} *SC1245(7)= 1.0*

$$h_{FLM}(\Delta T) = \left(0.055 + 0.016\,\theta^{0.5}\right) k_v \left[\frac{h_{lv}\,\rho_v\, g\,(\rho_l - \rho_v)}{\mu_v k_v\, \Delta T}\right]^{1/3}$$

K. B. Cady, V. K. Dhir and R. J. Witt, ERI/NRC 94-202 March 1994.



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*Averaged over pool height in a ring

$$f_i = \frac{\int_{\theta_{i-1}}^{\theta_u} f(\theta)\, \sin\theta\; d\theta}{\cos\theta_{i-1} - \cos\theta_u}$$

$$\theta_u = \min\left[\theta_i, \max\left(\theta_{i-1}, \theta_{PL}\right)\right]$$

Transition Between Boiling Regimes

- Critical Heat Flux Correlation

SC1245

$$q_{CHF}(\theta) = \left(0.034 + 0.0037\,\theta^{0.656}\right)\rho_v^{1/2} h_{lv}\left[g\,\sigma\left(\rho_l - \rho_v\right)\right]^{1/4}$$

- Minimum Stable Film Boiling Heat Flux

SC1245

$$q_{MIN}(\theta) = \left(4.8x10^{-4} + 82.x10^{-4}\,\theta^{0.407}\right)\rho_v^{1/2} h_{lv}\left[g\sigma\;\rho_l - \rho_v)\right]^{1/4}$$

Where,

θ	=	inclination angle of the surface in degrees
ρ_l,ρ_v	=	densities of water and steam, respectively,
g	=	acceleration of gravity,
σ	=	interfacial surface tension between steam and water,
h_{lv}	=	latent heat of vaporization of water,

Sub-cooled Heat Transfer

- By default, outer surfaces of LH segments submerged in a CAV/LHC pool do not transfer heat unless surfaces are superheated with respect to the pool
- New COR model switch on **COR_MS** optionally turns on lower head segment-to-pool heat transfer when segment surface temperature is sub-cooled with respect to the pool
  - Will be enabled by default in future versions
- No new physics, apply existing convection correlations (HS subroutine)
- 5th field **ILHHT** on **COR_MS** - “1”/“ACTIVE” to activate, inactive by default

```
!          IEUMOD      IHSDT     IDTDZ     ICORCV      ILHT
COR_MS       0           0         0          0          1     ! Activate sub-cooled LH HT to pool
```

Net Energy Transfer
Increase in Sensible Heat

- Penetration

$$C_{p,p}\left(T_p^n - T_p^o\right) = \left(q_{d,p} - q_{p,h} - q_{p,v}\right)\Delta t$$

- Debris

$$C_{p,d}\left(T_d^n - T_d^o\right) = \left(q_s - q_{d,p} - q_{d,h} - q_{d,v} - q_{d,d}\right)\Delta t$$

- Head (inner node)

$$C_{p,h,n}\left(T_{h,n}^n - T_{h,n}^o\right) = \left(q_{n-1,n} + q_{d,h} + q_{p,h} - q_{h,v}\right)\Delta t$$

- Head (internal node)

$$C_{p,h,i}\left(T_{h,i}^n - T_{h,i}^o\right) = \left(q_{i-1,i} - q_{i,i+1}\right)\Delta t$$

- Head (outer node)

$$C_{p,h,1}\left(T_{h,1}^n - T_{h,1}^o\right) = \left(-q_{d,c} - q_{1,2}\right)\Delta t$$

Estimate of Heat Transfer Coefficient Magnitude

$k_s := 30 \frac{watt}{m \cdot K}$	■ Thermal conductivity of lower head carbon steel
$k_f := 2.5 \cdot \frac{watt}{m \cdot K}$	■ Thermal conductivity of UO_2
$f_{cond} := 0.6$	■ Discount factor for thermal conductivity to account for porosity
$\Delta t_{wall} := 10 \cdot cm$	■ Wall thickness of lower head
$\Delta t_{crust} := 25 \cdot cm$	■ Effective thickness of debris - this might be the half-thickness of the lower COR cell in contact with the head

Effective Heat Transfer Coefficients Between Debris and Vessel

$$\frac{k_s}{\Delta t_{wall}} = 300 \frac{watt}{m^2 \cdot K}$$

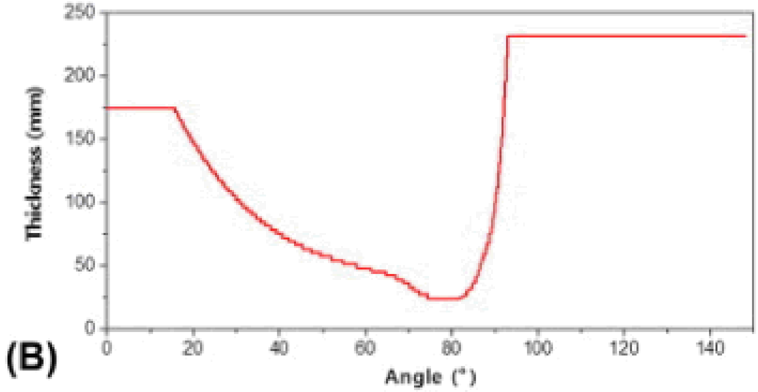
$$\frac{k_f \cdot f_{cond}}{\Delta t_{crust}} = 6 \frac{watt}{m^2 K}$$

- Carbon Steel
  - Large Compared to conduction through the Debris Crust
- Porous Urania Debris
  - Does not account for radiation enhancement

Default Heat Transfer coefficient for conduction between the Debris and the Vessel is 1000 watt/m^2/K

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

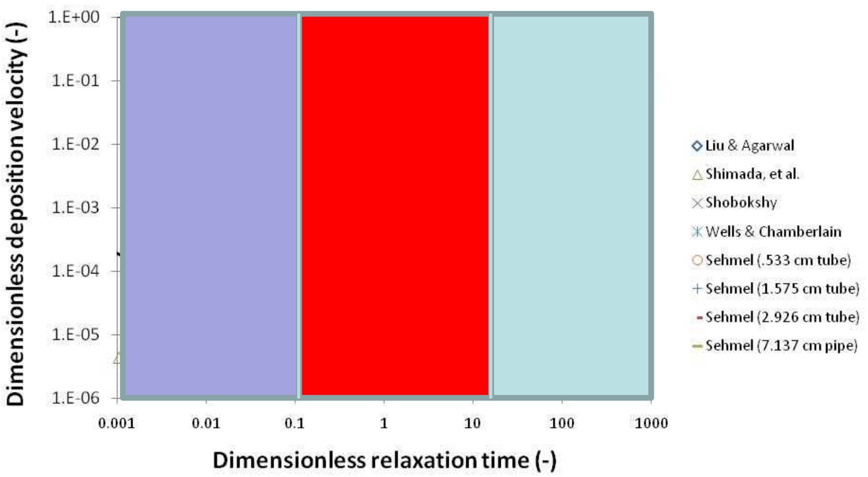
Evaluation of heat-flux distribution at the inner and outer reactor vessel walls under the in-vessel retention through external reactor vessel cooling condition
Jaehoon Jung, KAERI, January 2015

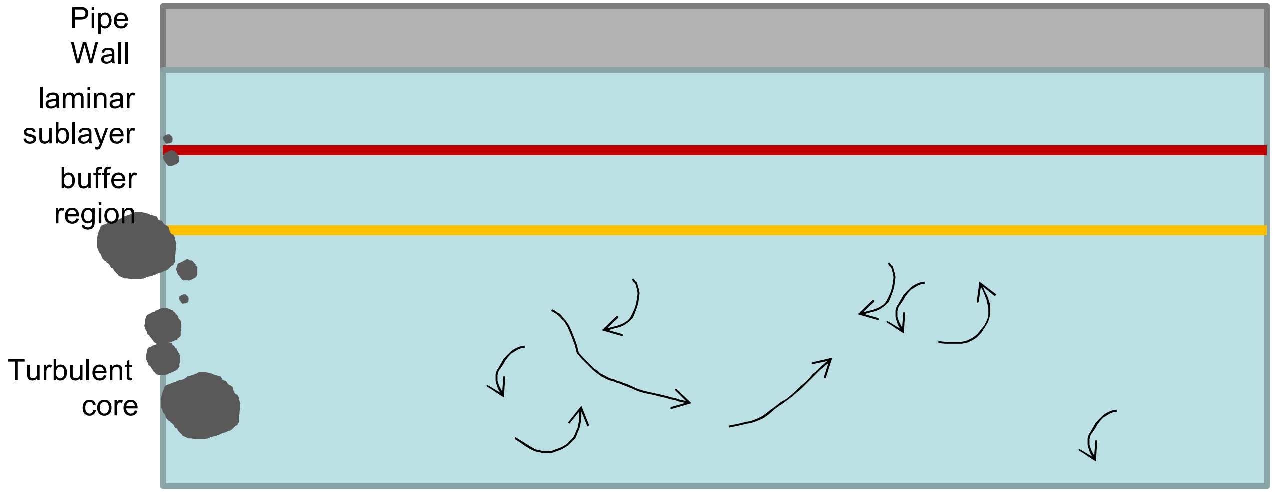
MELCOR Aerosol Deposition

- MELCOR has long had aerosol deposition models for various mechanisms
  - Gravitational
  - Brownian diffusion to surfaces
  - Thermophoresis (Brownian process causing migration to lower temperatures)
  - Diffusiophoresis (induced by condensation of water vapor onto surfaces)
- Newly added deposition mechanisms
  - Turbulent deposition in pipe flow
    - Wood's model for smooth pipes
    - Wood's model for rough pipes
    - Sehmel's model for perfect particle sinks (VICTORIA)
  - Bend Impaction Models
    - Pui bend model
    - McFarland bend model
    - Merril bend model

Turbulent Deposition Cartoon

- Inertia moderated regime
- **Eddy diffusion impaction regime**
- **Turbulent particle diffusion**





Turbulent Deposition Model

- Particle Diffusion Regime
  - Davies equation

$$V_d^* = \qquad + K\tau_*^2$$

- Eddy Diffusion –Impaction Regime

$$V_d^* = \frac{3\sqrt{3}}{29\pi\tau_*^{1/3}} Sc^{-2/3} \quad \tau_*^{1/3}$$

- K is often determined empirically

Investigator	k_2
Kneen & Strauss (1969)	3.79×10^{-4}
Liu & Agarwal (1974)	6×10^{-4}
Wood (1981b)	4.5×10^{-4}
Papavergos & Hedley (1984)	3.5×10^{-4}

- Or calculated from a Fick's law equation (Wood)

$$N = (D_p + \varepsilon)\frac{dc}{dy}$$

- Inertia Moderated Regime
  - Deposition velocity is either constant

$$V_d^* = \sqrt{\frac{f}{2}} \qquad 10 \le \tau_* < 270$$

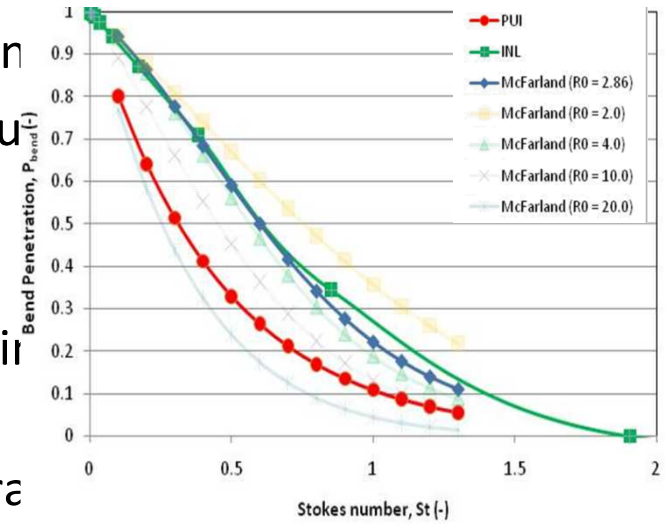
  - Or may decrease with increasing dimensionless relaxation time

$$V_d^* = \frac{2.6}{\sqrt{\tau_*}}\left(1 - \frac{50}{\tau_*}\right) \qquad \tau_* \ge 270$$

MELCOR Bend Models

- Merril’s Bend Model - Theoretic
  - Based on centrifugal force on particle, drift velocity, and geometry
- Pui Bend Model - Empirical
  - Based on experiments by Pui et al. For con
  - Correlates the deposition efficiency, η_b du
- McFarland’s Bend Model - Empirical
  - Based on fitting an equation to data obtai experiments and Lagrangian simulations.
  - Applicable to arbitrary bend angles and ra

$$\eta_b = 1 - 10^{-0.963St}$$



Overview of LACE Containment Bypass Tests

- Test Characteristics:
  - Mixed hygroscopic/nonhygroscopic aerosols
  - 30,000 < Re < 300,000

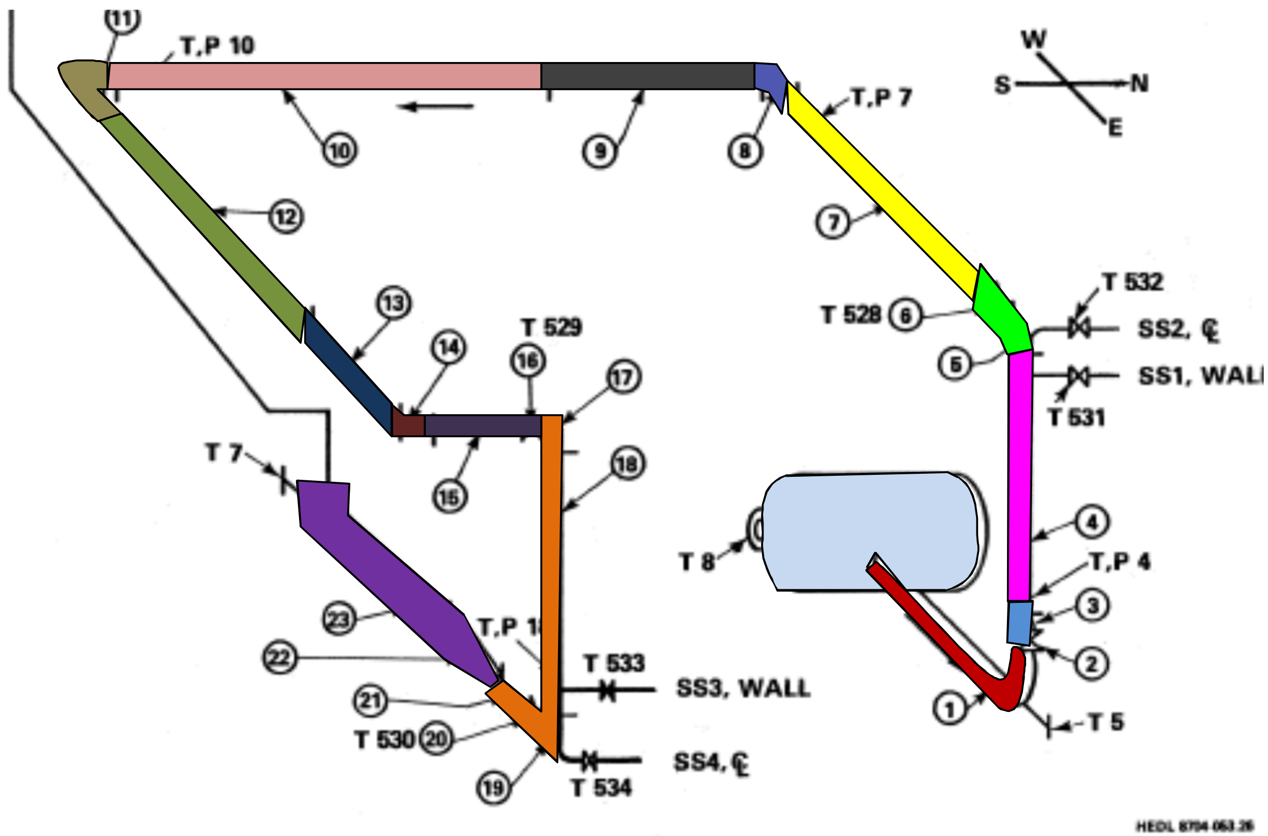
Test	Aerosol	NaOH or CsOH Mass Fraction	Carrier Gas	Gas Velocity (m/s)	Temp. (^{o}C)	Aerosol Source Rate (g/s)	Aerosol Size AMMD (μm)	Mass Retention Fraction
LA1	CsOH	0.42	Air-steam	96	247	1.1	1.6	> 0.98
	MnO							
LA3A	CsOH	0.18	N_2-steam	75	298	0.6	1.4	> 0.7
	MnO							0.7
LA3B	CsOH	0.12	N2-steam	24	303	0.9	2.4	> 0.4
	MnO							> 0.7
LA3C	CsOH	0.38	N2-steam	23	300	0.9	1.9	> 0.7
	MnO							> 0.7

- Assumed Properties
  - σ=surface tension of possible surface film =0.077 (N/m2)
  - μ =surface viscosity of surface film = 0.0646 (kg/m-s)

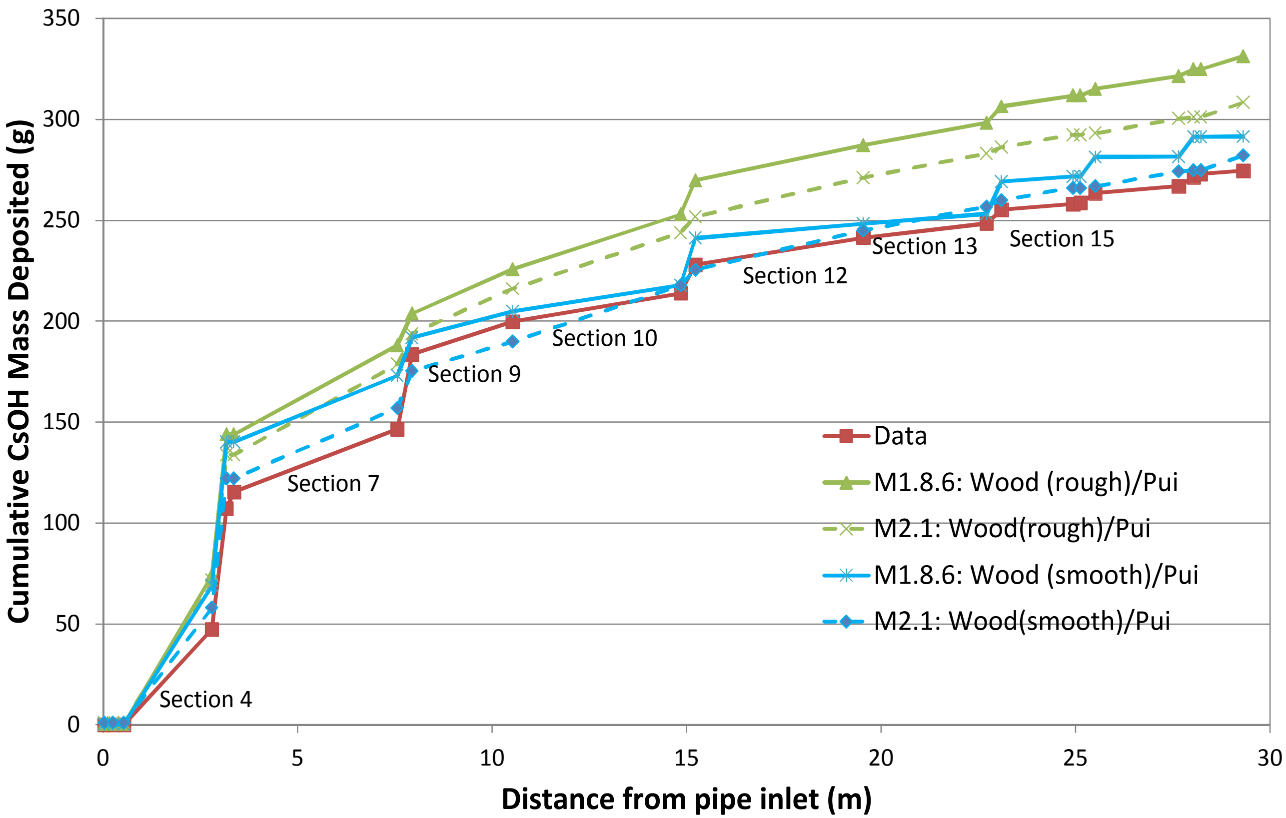
Pipe Nodalization (Isolates Bends from Straight Pipe Sections)

MELCOR Model Nodalization:

Control Volume	HS	Pipe Sections
CV011	1110	1a,1b,1c
CV012	1120	2,3
CV013	1130	4
CV014	1140	5,6
CV015	1150	7
CV016	1160	8
CV017	1170	9
CV018	1180	10
CV019	1190	11
CV020	1200	12
CV031	1210	13
CV032	1220	14
CV033	1230	15,16
CV034	1240	17,18,19,20,



Validation of Turbulent Deposition Model with LA3A test



RN1_TURB - Deposition Modeling Record

Several options for modeling turbulent deposition in pipes are available in MELCOR. Turbulent deposition is only calculated for those heat structure surfaces specified by the user as calculation of turbulent deposition can impact code performance and is only of importance for high Re number flow in pipes and bends. This record specifies the models that will be used in the calculation of turbulent deposition for those heat structures specified in the RN1_TDS table. A description of the models used in MELCOR for predicting turbulent deposition in pipes and bends is provided in the RN reference manual.

(1) TURBMODEL

Deposition Modeling flag for turbulent component

='OFF' or 0, No turbulent deposition modeling

="VICTORIA' or 1, VICTORIA modeling of deposition in straight pipe sections

='WOODS' or 2, Wood's model for rough pipes

='WOODS_S' or 3, Wood's model for smooth pipes

(type = integer/ character*16, default = 2, units = none)

(2) TRANSMODEL

Deposition Modeling flag for impact deposition in bends and transitions

='OFF' or 0, No deposition modeling in bends

='VICTORIA' or 'PUI' or 1, PUI modeling of deposition in bends

='INL' or 2, INL modeling of deposition in bends

='MCF' or 3, McFarland modeling of deposition in bends.

(type = integer/ character*16, default = 2, units = none)

(3) IMODEL

Deposition Modeling flag

=0, Gravitational, thermophoresis, and diffusiophoresis velocities are calculated at the beginning of the calculation

=1, Gravitational, thermophoresis, and diffusiophoresis velocities are recalculated at each time step. Note that if this option is used, it will affect deposition calculated for all deposition mechanism, regardless of whether turbulent deposition is calculated.

(type = integer/ character*16, default = 0, units = none)

RN_TDS Record – RN Turbulent Deposition Surfaces

Turbulent deposition may be important for high Re flow in a pipe or in pipe bends and can be activated for each surface. If a surface is not defined in this table, it is assumed that turbulent deposition is not calculated. On this record the user supplies characteristic lengths, surface roughness, and the number of bends and angle of bends associated with this structure. The models used for predicting turbulent deposition are defined on the RN1_TURB record. A complete description of the modeling approach is further described in the RN reference manual.

(1) NDEP – Number of deposition surfaces associated with turbulent deposition modeling

The following data are input as a table with length NDEP

NUMTDS – Index for turbulent deposition associated with a particular heat structure surface
(type = integer, default=none, units = none)

HS_ID - The heat structure to apply the bend and/or turbulent deposition model
(type = integer or character*16, default=none, units = none)

ISUR - Surface ('LHS' or 'RHS')to which the deposition modeling is applied
(type = character*3, default=none, units = none)

CHARL - Characteristic length (i.e., pipe diameter)
(type = real, default=none, units = m)

NO_BND - Number of bends associated with the volume
(type = integer, default=none, units = none)

ANGLE - Turning angle of the bends
(type = real, default=none, units = radians)

RAD_BND - Radius of curvature for bend
(type = real, default=none, units = m)

ROUGH - Surface roughness for the turbulent deposition model (not used in VICTORIA model)
(type = real, default=none, units = none)

VelocityFP - The Flow path used to determine flow velocities. This field is optional. If not provided, MELCOR uses the control volume velocity which is calculated from the CV area that is either provided on the CV_ARE record or calculated from the volume divided by the height. If VelocityFP is provided, MELCOR uses the atmosphere velocity for the flow path provided.
(type = integer or character*16, default=none, units = none)

Control Arguments

RN1-ADEP(NameHS,s,NameCLS,y)

Aerosol mass of class *NameCLS*, deposited on side *s* (s='LHS' or s='RHS') of heat structure name *NameHS*. The parameter *y* specifies total mass (y='TOT') or radioactive mass only (y='RAD').

(units = kg)

RN1-DEPHS-DIST(NameHS,s,NameCLS,m)

Aerosol mass of class *NameCLS*, deposited on side *s* (s='LHS' or s='RHS') of heat structure name *NameHS in section m*. If m=0 then the total mass deposited is returned.

(units = kg)

Control Arguments

RN1-DEPHS(NameHS,s,*NameCLS*,p)

Total aerosol mass of class *NameCLS* deposited on side s (s='LHS' or s='RHS') of heat structure HS *NameHS* from deposition physics model p. This is the total mass deposited from each mechanism and does includes mass that may be later resuspended.The deposition models that are tracked are as follows:

p = 'DIFF', Diffusion deposition

p = 'THERM', Thermophoresis

p = 'GRAV', Gravitational settling

p = 'TURB', Turbulent deposition in straight sections

p = 'BEND', Deposition in pipe bends

p = 'VENT', Deposition in venturi transitions

p = 'CONT', Deposition in contraction transitions

(units = kg)

RN1-TOTRES(NameHS,s)

Total radionuclide mass that has been resuspended.

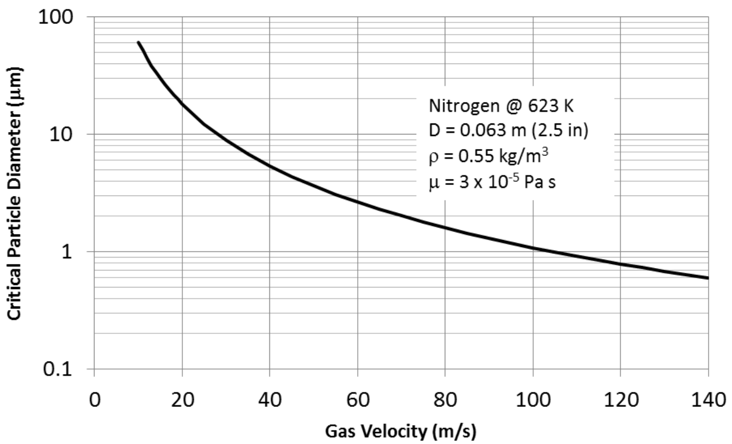
(units = kg)

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

$$D_{crit} = \frac{4 \times 10^{-5}}{\pi \tau_{wall}} \text{ (m)}, \qquad \tau_{wall} = \frac{f \rho v^2}{2} \text{ (N/m}^2\text{)} \qquad f = \frac{0.0791}{Re^{0.25}}$$

  - 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
- Reference
  - "Liftoff Model for MELCOR," Mike Young
  - SAND2015-6119
- Validation against Tests
  - STORM tests (SR11 and SR12)
  - Validation against LACE tests



Examples

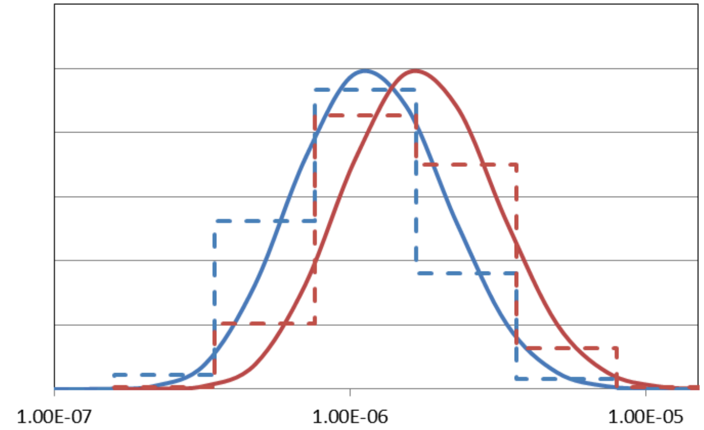
To fully activate resuspension, specify a value of FractResuspend as 1.0, and let MELCOR determine the critical diameter:

HS_LBAR 1. ! Left surface

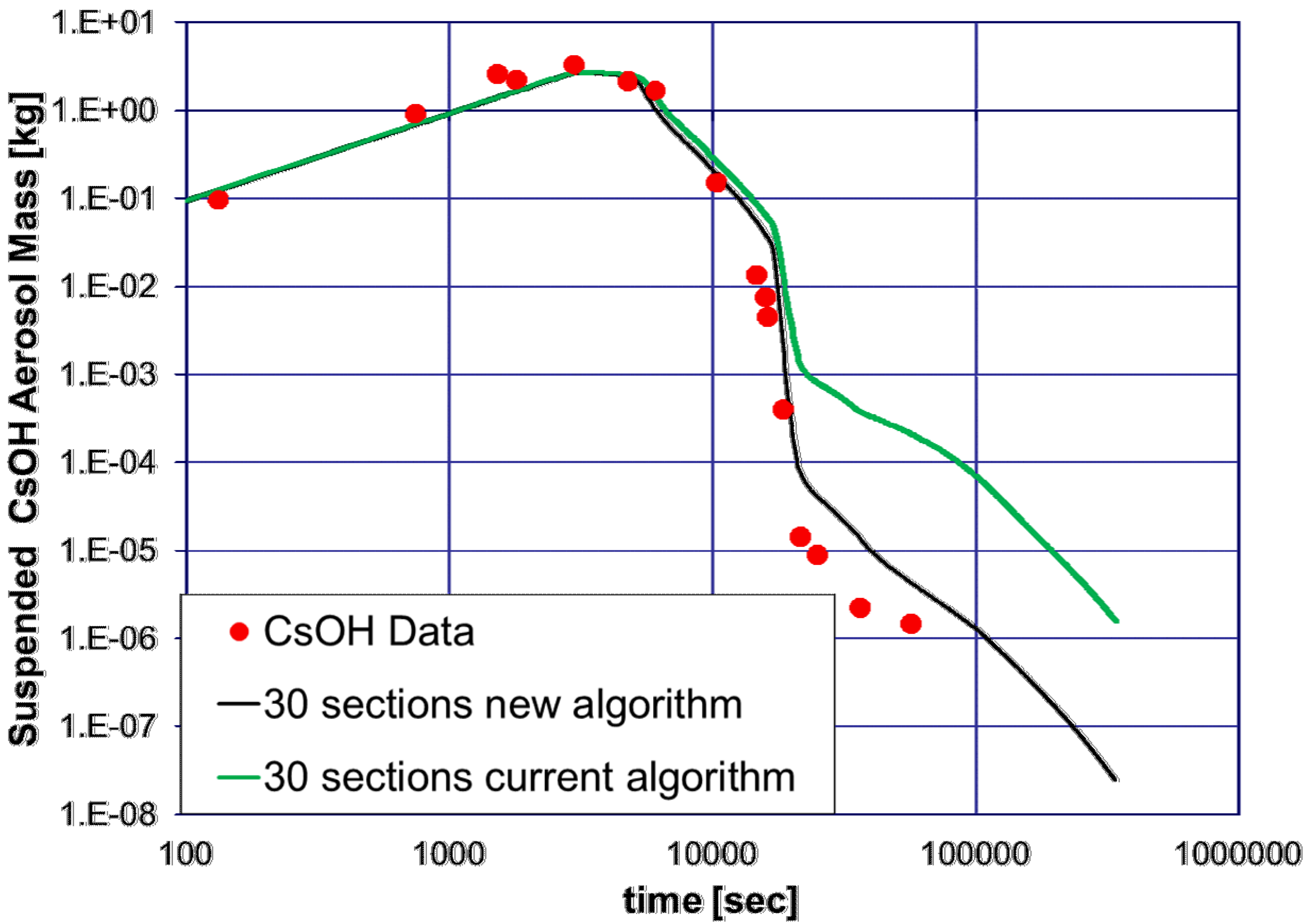
HS_RBAR 1. ! Right surface

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)



Questions