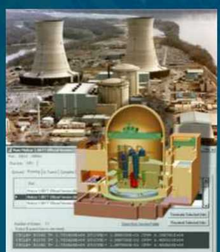
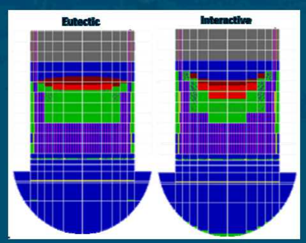
SAND2019-3105PE

MELCOR
New Modeling
SQA
Utilities

Lower Head/Plenum Modeling
2019 European MELCOR User Group Workshop





PRESENTED BY

Larry Humphries, Sandia National Laboratories

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Outline

- Modeling of lower plenum
  - Heat Transfer to/from LH
    - Heat Transfer coefficients from components to lower head and penetrations
    - Boiling heat transfer
  - Representation of Molten Pools
    - 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

Heat Transfer Coefficients for Lower Head

Parameters for modeling heat transfer to the lower head are provided on the COR_LHF record.

User specifies heat transfer for the following:

- Debris to penetrations
- Debris to lower head
- Heat transfer from oxidic molten pool to lower head
- Heat transfer for 'stray' metallic molten pool to lower head

User can optionally specify a control function for each HTC

By default, All heat transfer coefficients are assumed to be 1000.0 W/m2-k

- Completely arbitrary and not always representative
- Does not reflect thermal conductivities of materials and composition
- Does not reflect conduction path which is dependent on nodalization

Optionally, the user can specify an internal model for calculating heat transfer.

- Available for PD to LH and MP1 to LH and MP2 to LH
- Model uses locally calculated thermal conductivity and a conduction path using half the current calculated component height
- These internal models will become default in next code release

	Conduction Path Length (m)		
	0.5	0.25	0.1
UO2	5.86	23.44	234.40
ZR	106.66	426.64	4266.40
ZRO2	6.40	25.60	256.00
SS	90.66	362.64	3626.40
SSOX	53.34	213.36	2133.60

Using Thermal Conductivity of Material at 1700 K

Example

```
!       HDBPH/CF HDBLH/CF HMPOLH/CF HMPMLH/CF TPFAIL     CDISPN
COR_LHF 1.00E-02 1.00E+02 MODEL     MODEL     1525.0     1.0
```

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

SC1245

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

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

Alternate Film Boiling Heat Transfer Correlations

H_{flm-1} *Default*

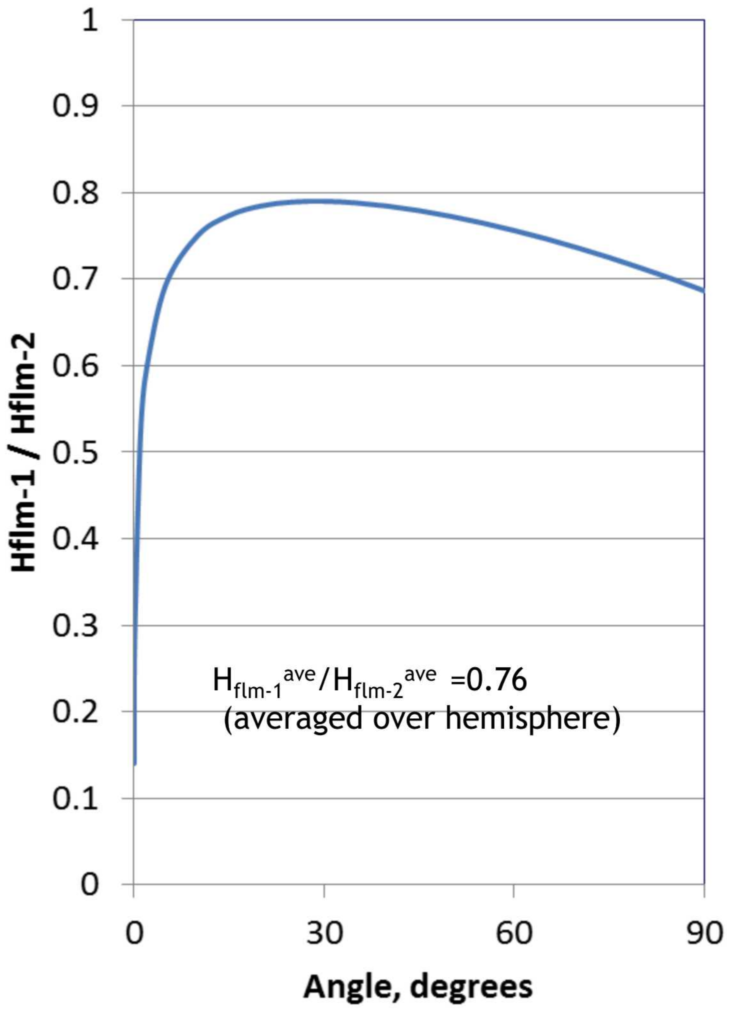
$$h_{FLM}(\Delta T) = 0.142\, k_v \left[\frac{h_{lv}\, \rho_v\, g\,(\rho_l - \rho_v)}{\mu_v\, k_v\, \Delta T} \right]^{1/3} (\sin\theta)^{0.3333333}$$

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
```

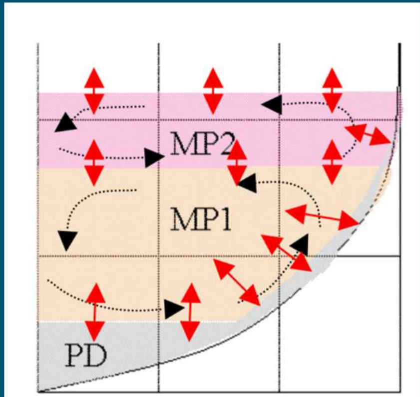
MELCOR Core Phenomenon Stratified Molten Pool Model (1)

Treat molten pools, both in core and lower head

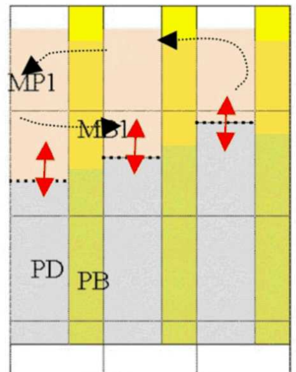
- Can contain oxidic and metallic materials
- May be immiscible, and separate by density
- Same approach in core and lower head
  - Requires distinguishing pool in channel from that in bypass

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

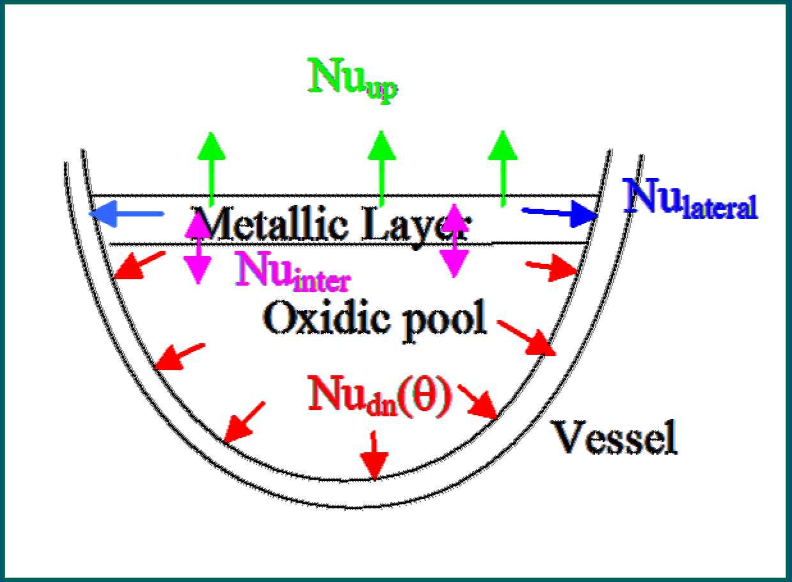


Molten pool in upper core

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

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

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

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.*

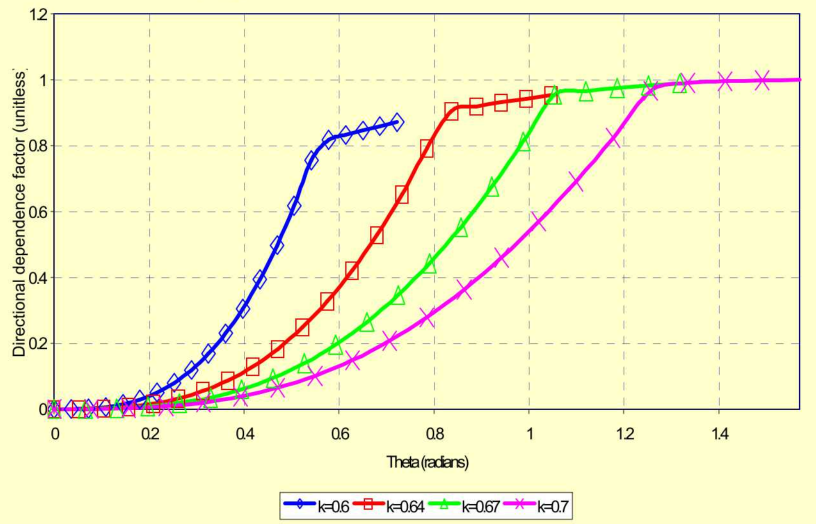
Heat transfer correlation angular dependence

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

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

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

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



Molten Pool Convective Heat Transfer

Energy Balance on MP1:

$$MC_{P,MP1}\frac{T^{n}_{MP1}-T^{o}_{MP1}}{\Delta t} = \dot{Q}_{MP1,decay} - \sum_{s \in seg} h_{MP1\to s}A_s\left(T^{n}_{MP1}-T_s\right) - h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right) - \left\langle h_{MP1-fluid}A_f\left(T_{MP1}-T_{fluid}\right) - \sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP1}-T^{4}_{ambient}\right)\right\rangle\cdot\delta \qquad (2.100)$$

where

$$\delta(MP2) = \begin{cases} 0 & \text{when molten pool } MP2 \text{ exists} \\ 1 & \text{otherwise} \end{cases} \qquad (2.101)$$

$$MC_{P,MP2}\frac{dT^{n}_{MP2}}{\Delta t} = \dot{Q}_{MP2,decay} - \sum_{s \in seg} h_{MPs\to s}A_s\left(T^{n}_{MP2}-T_s\right) + h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right) - h_{MP2-fluid}A_f\left(T^{n}_{MP2}-T_{fluid}\right) - \sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP2}-T^{4}_{ambient}\right) \qquad (2.102)$$

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

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

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

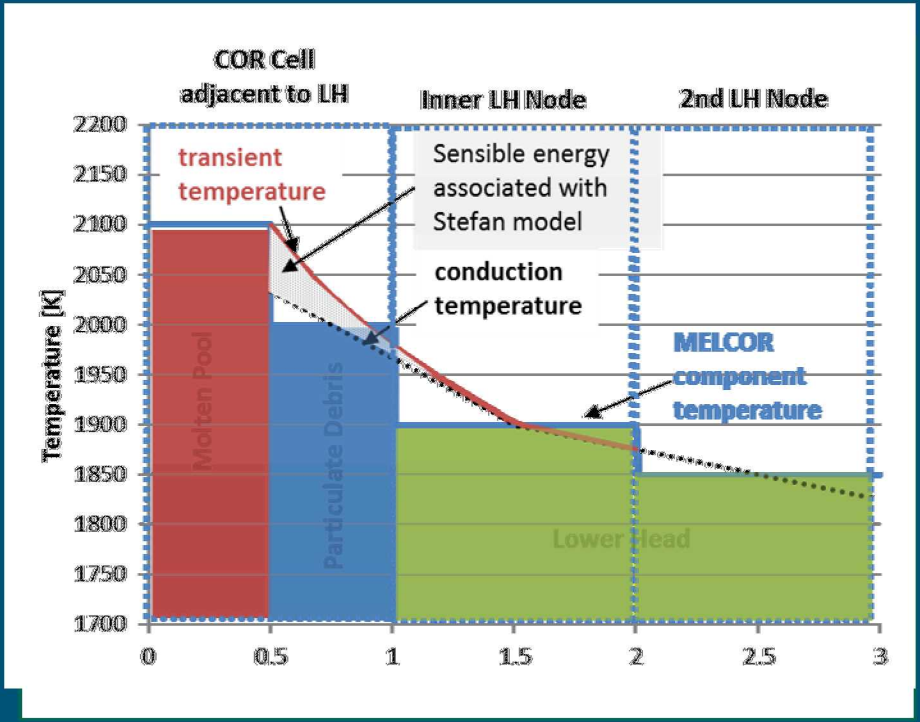
Integral Solution to Stefan Problem

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
  - Selected by setting sensitivity coefficient SC1600(1) = 0.0
- One-Dimensional Model
  - Default Model
  - 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

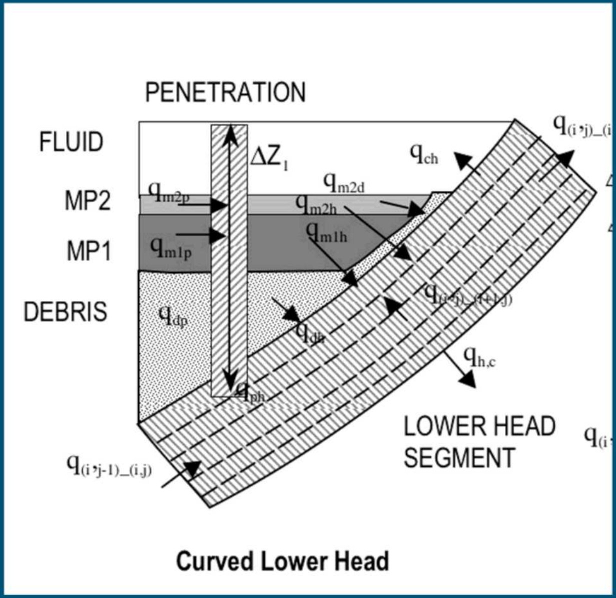
One- Dimensional Model

- 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

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

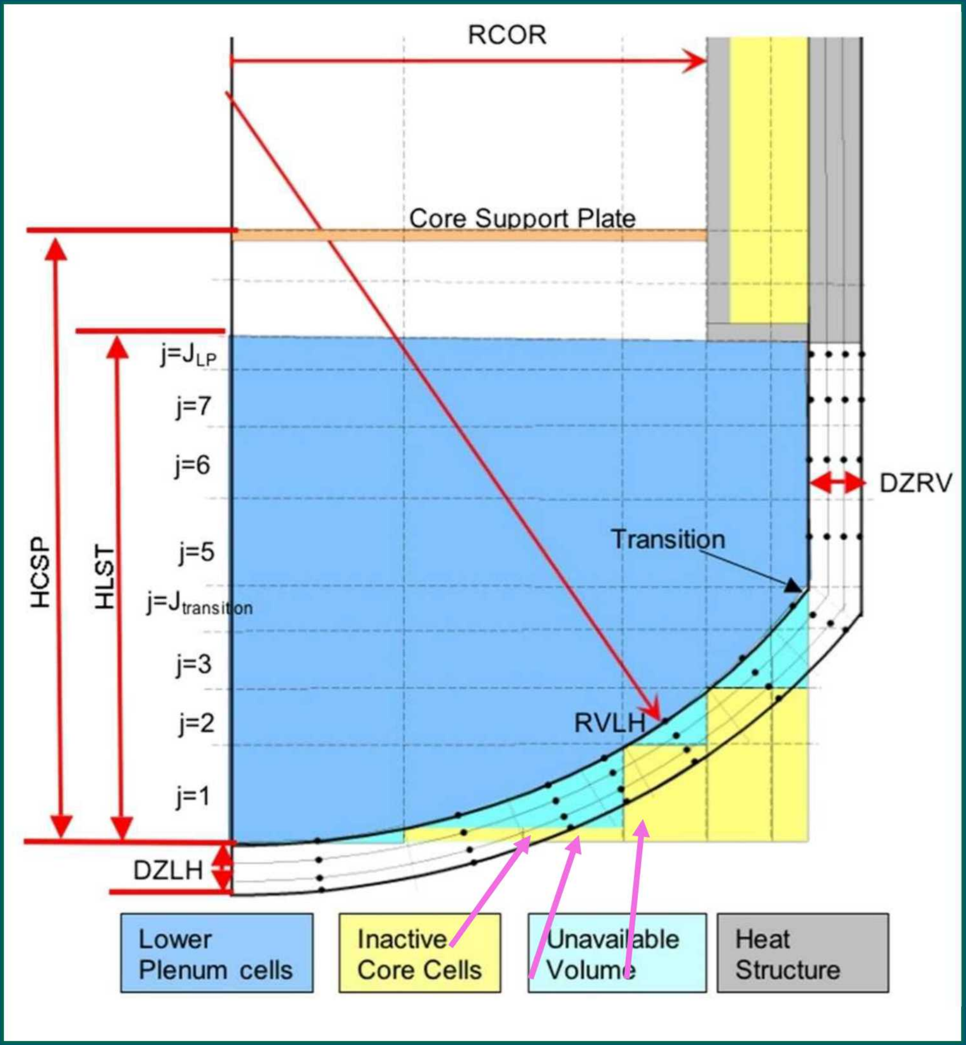
- Input must specify number of appropriate transfer process

```
! 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

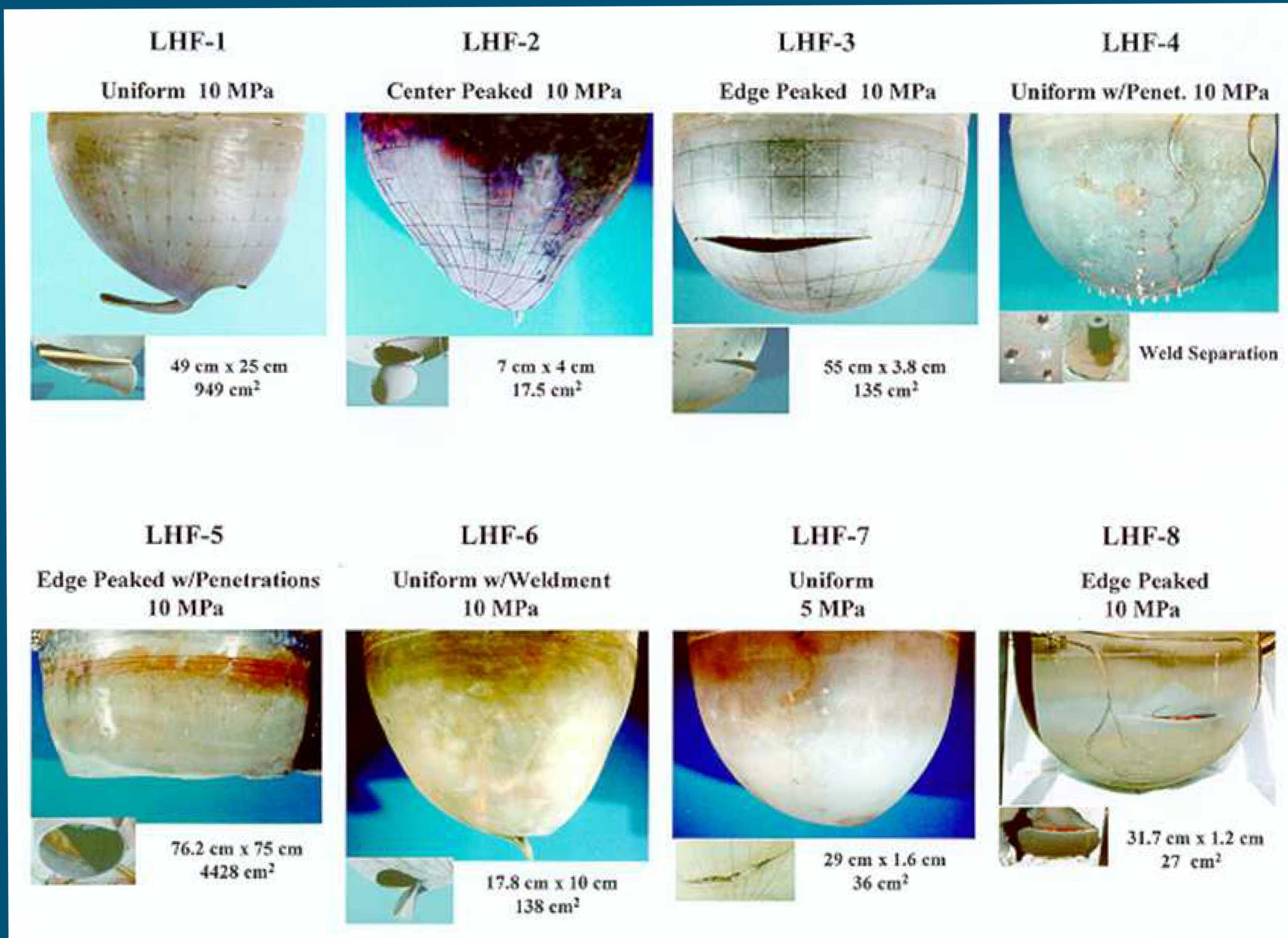
Localized failure with the exception of OLHF-3

Failure determined by strength of outer wall
- Failure occurred at much higher average temperature

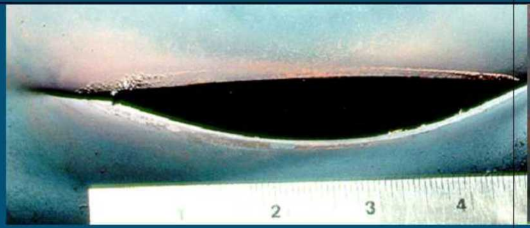
Dates
Sept 1998 to June 2002

Reference
ICONE 14-89159 pp. 39-52

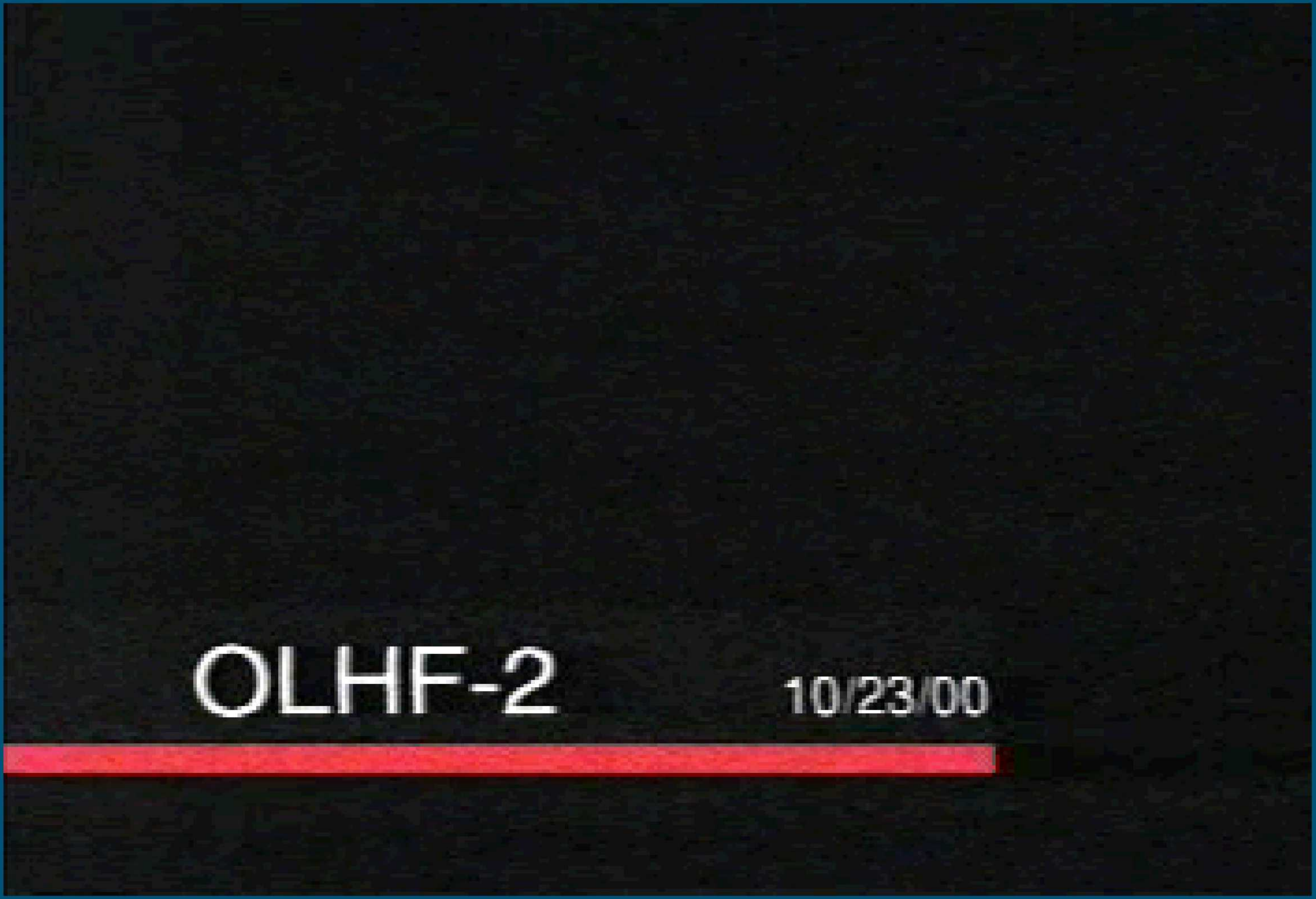
USNRC Sponsored LHF Tests



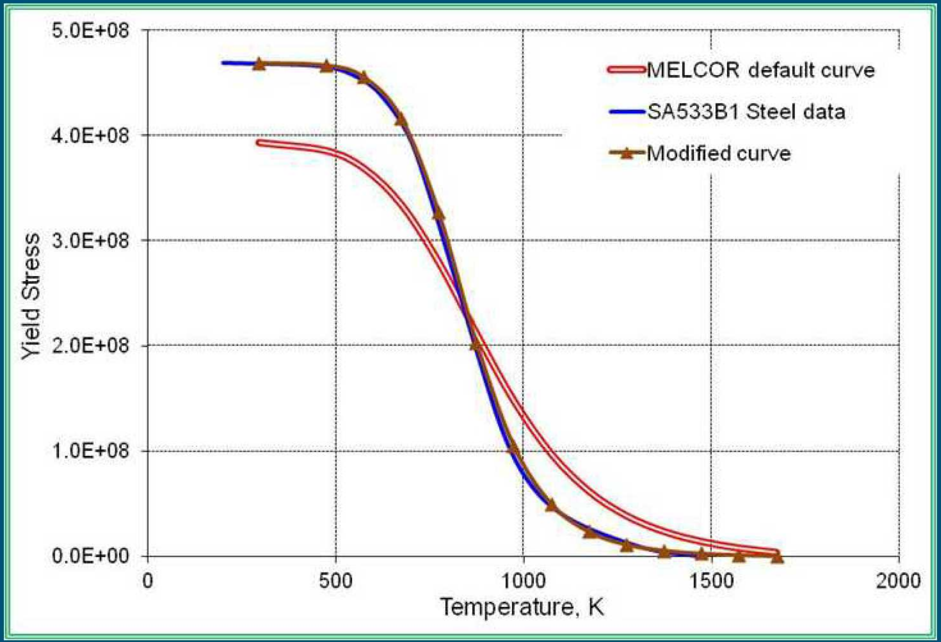
OECD Sponsored OLHF Tests

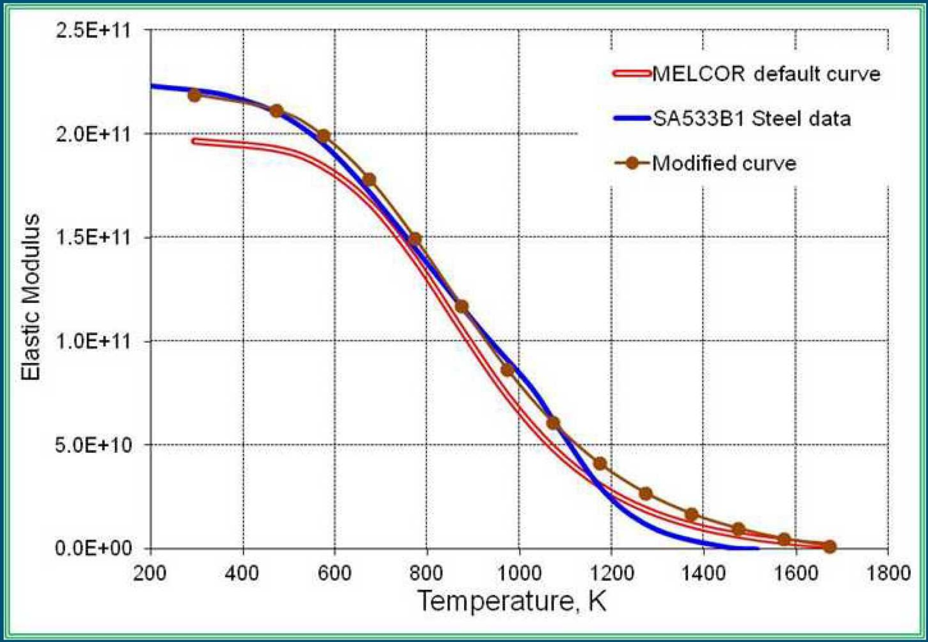
OLHF-1 4.7 MPa (RCS)	OLHF-2 2.02 MPa (RCS)	OLHF-3 Transient: 2.02 MPa (RCS) to 4. 7 MPa (RCS)	OLHF-4 2.02 MPa (RCS)
			
			 *Separation of the penetration welds from the base material*
Tinside=1450 K Area of failure = 17.1cm2(.22 m FSE diameter) Tfailure-t800=56 min	Tinside=1750 K Area of failure = 36.5cm2(.33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

OLHF-2 Video Summary



MELCOR Mechanical Properties of Vessel Steel





Larson-Miller Parameter Relations

MELCOR

Time-to-Failure (sec)

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

Larson-Miller Parameter (σ_e in Pa)

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

SC1601

LHF Experiments

Time-To Failure (sec)

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

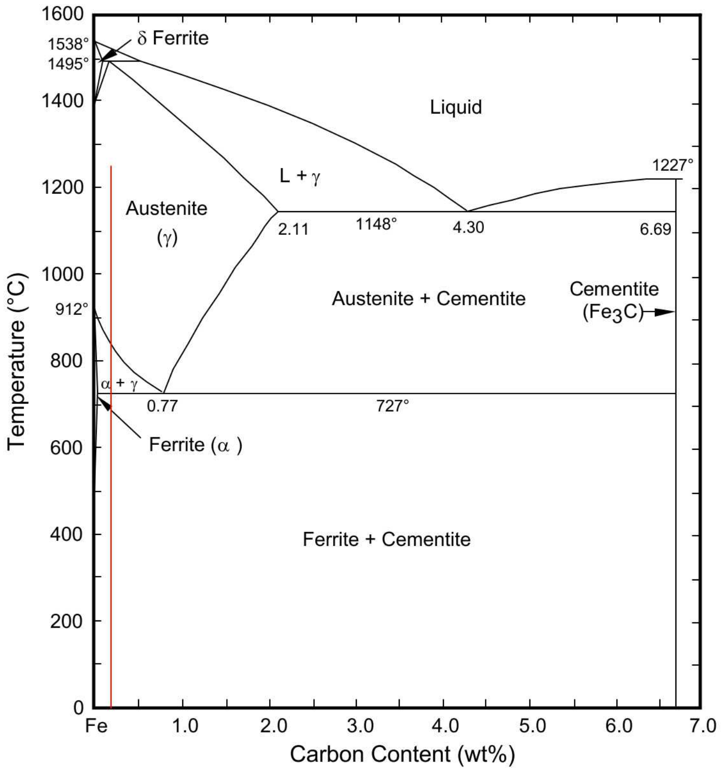
Larson-Miller Parameter (σ_e in Pa)

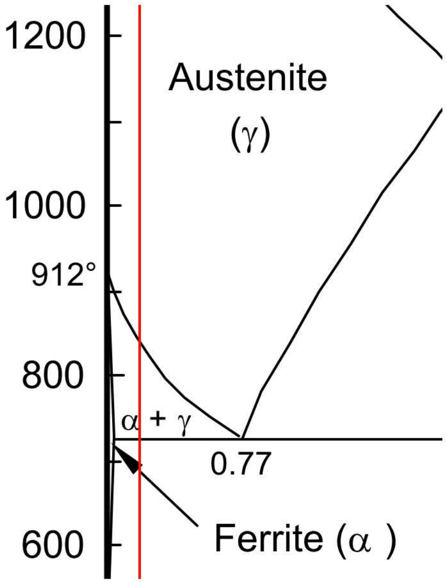
$$P_{LM} = A - B \log_{10} \sigma_e$$

	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

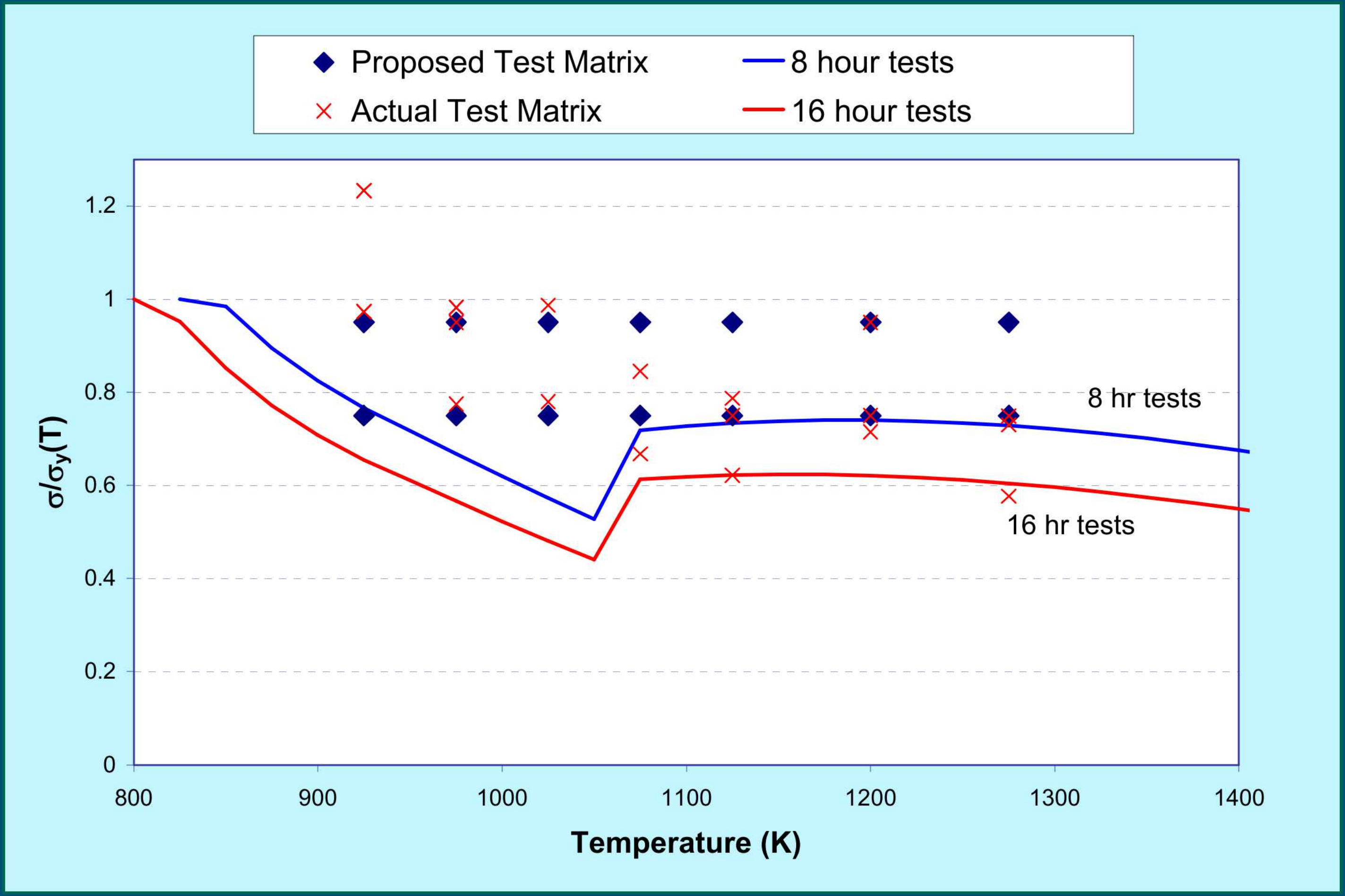
Assumed Temperature Dependence of Larson-Miller Parameter Correlation

Phase Transformation for SA533B Steel at ~1000-1100 K

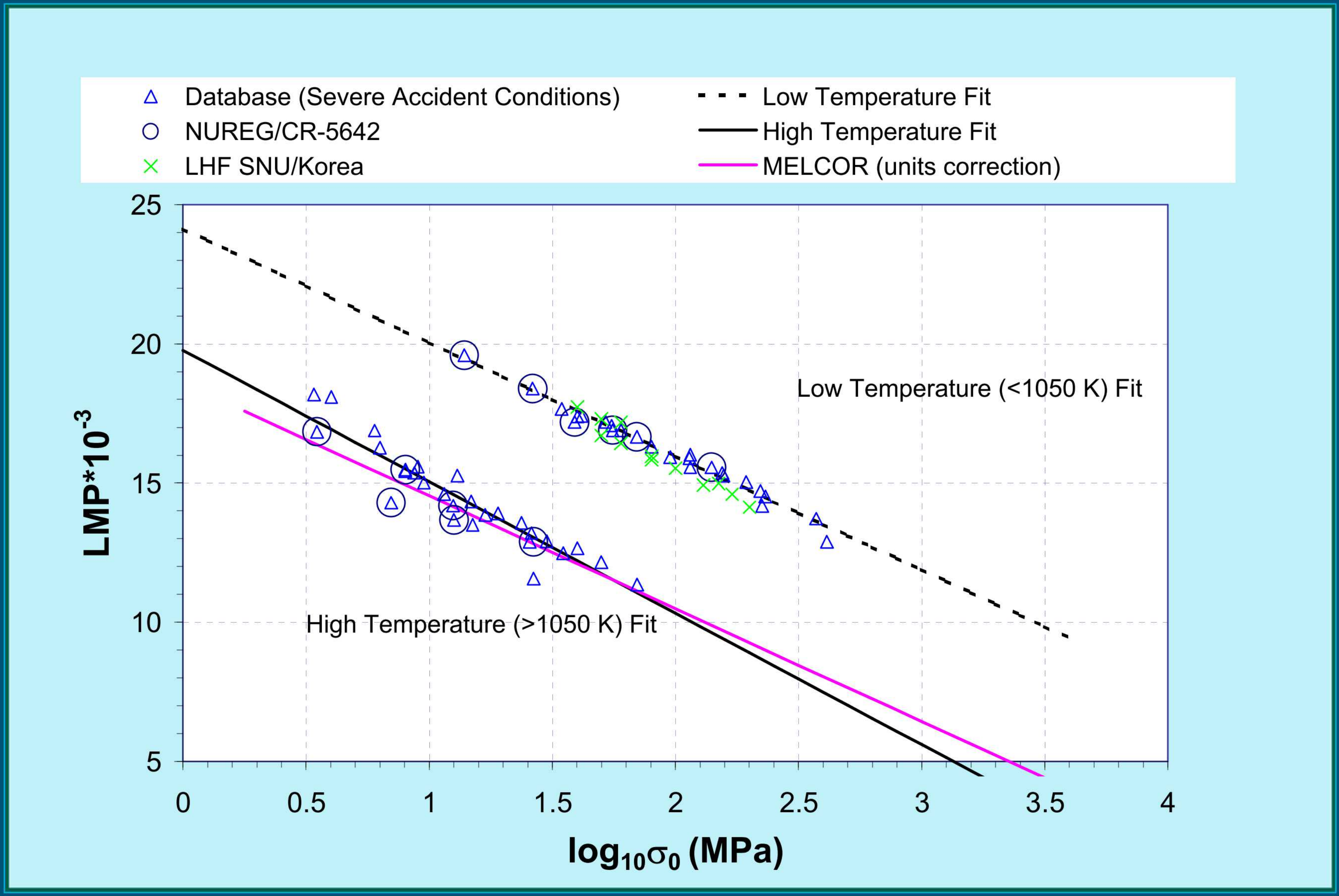




OLHF High Temperature Creep Tests



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

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

Thermal Strain

SC1600(2)

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

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

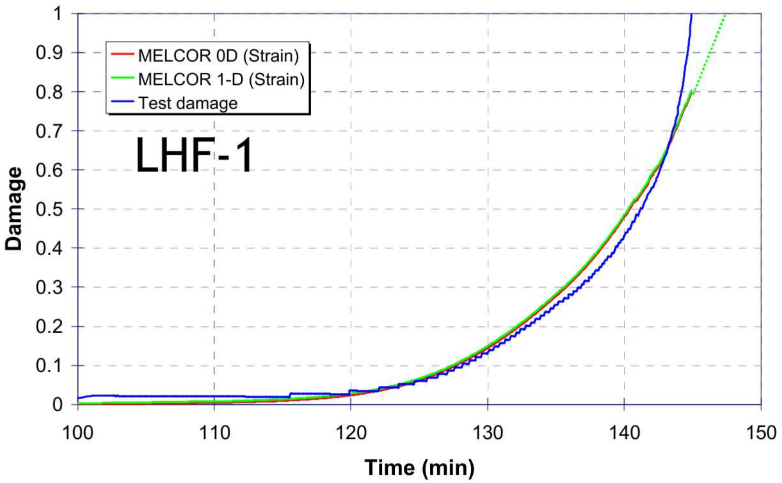
Material Properties from LHF program (not MELCOR default or OLHF) implemented in assessment

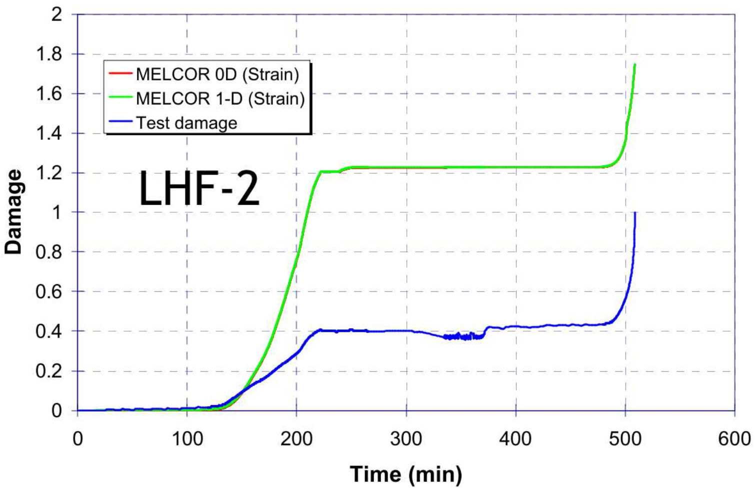
Assessment is valid for high pressure (10 MPa) tests though LHF-7 was performed at 5 MPa

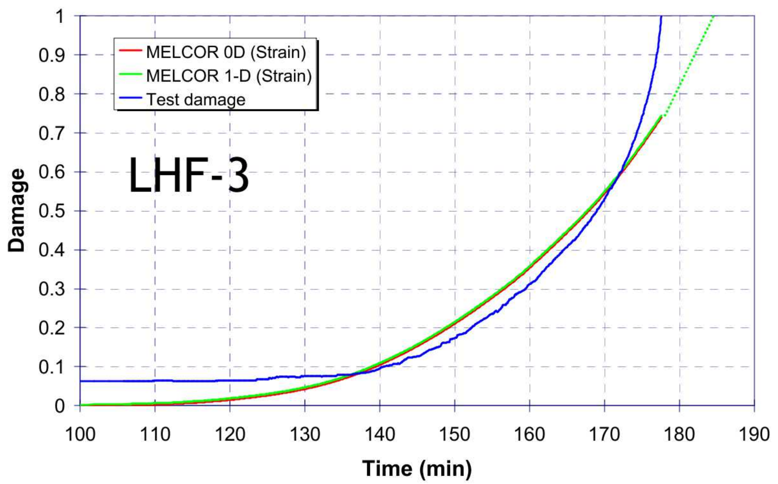
Assessment is valid for small through-wall temperature differential

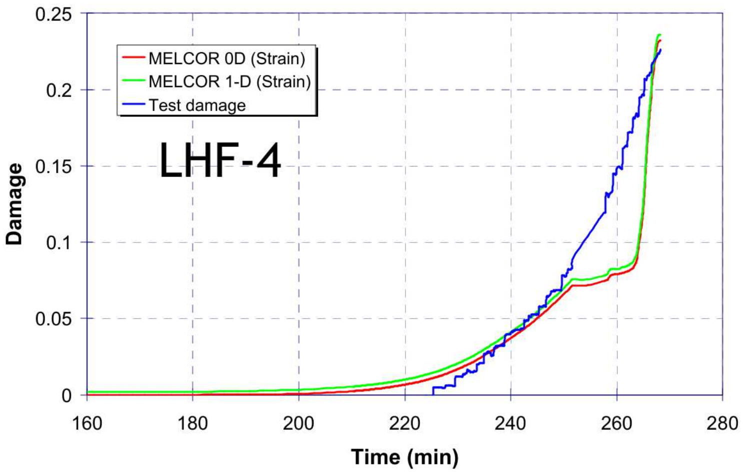
- LHF ΔT_{wall} ~ 25-50 K
- Actual $\Delta T_{wall} > 250$ K
- Stress Redistribution to outer vessel wall is important and distinguishes 0-dimensional and 1-dimensional models
- OLHF tests performed at large temperature differential

Damage Calculated using MELCOR Models and L-M Parameter Based on LHF Properties (LHF-1 through LHF-4)



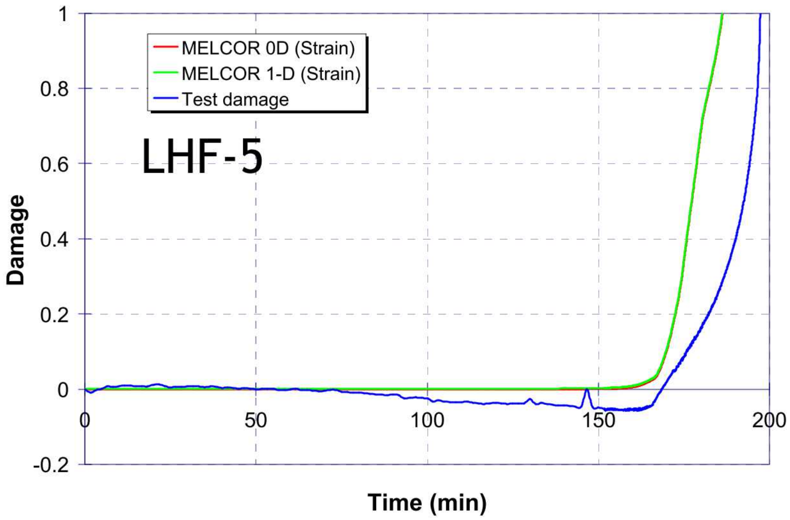


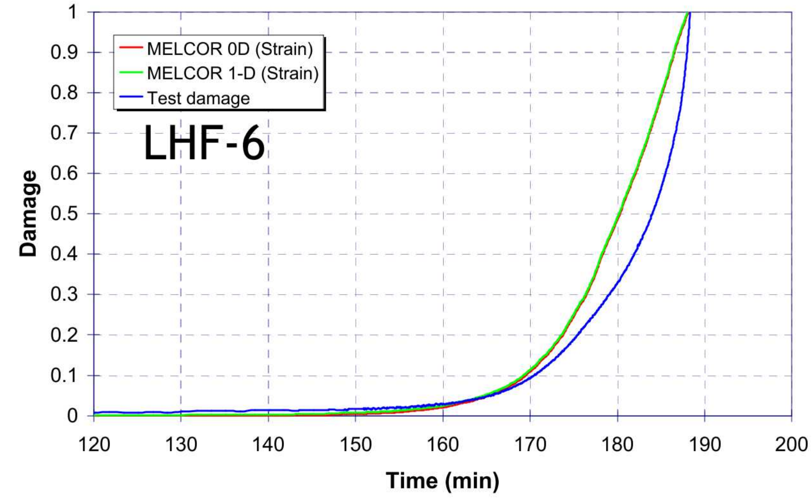


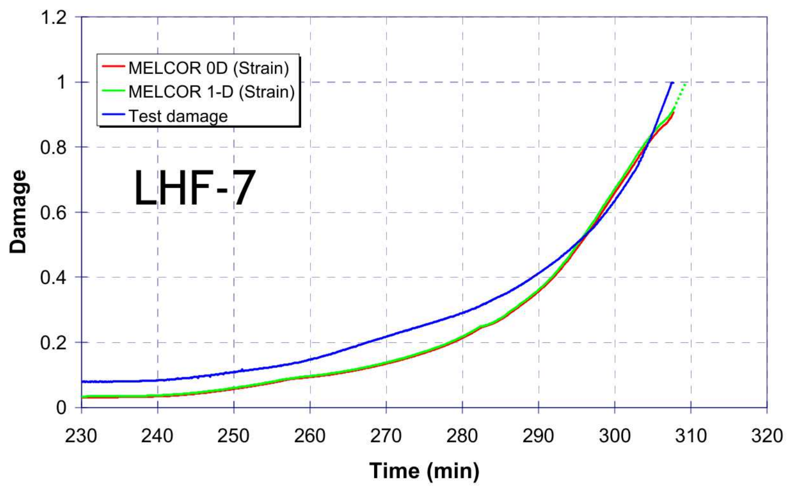


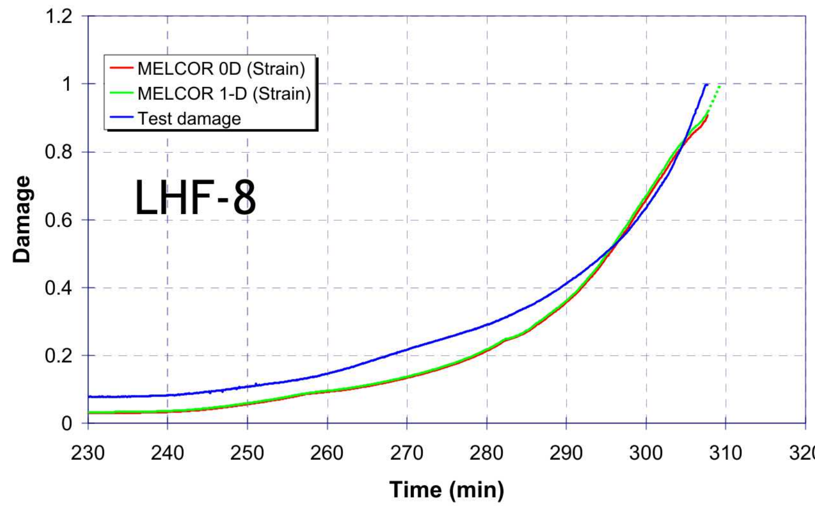
Damage Calculated using MELCOR Models and L-M Parameter Based on LHF Properties

(LHF-5 through LHF-8)

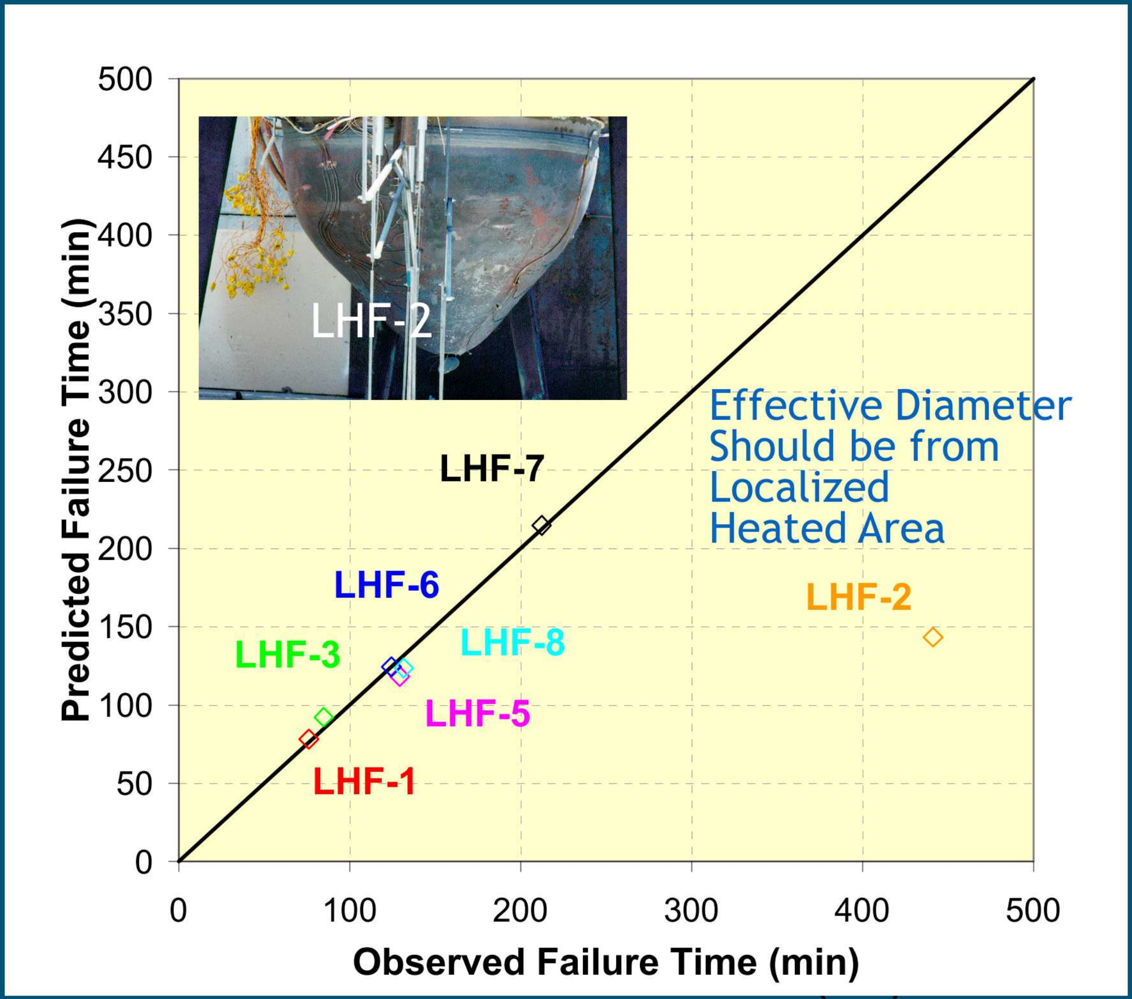








Summary of Predicted Time-to-failure vs. Observed Time-to-failure



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)

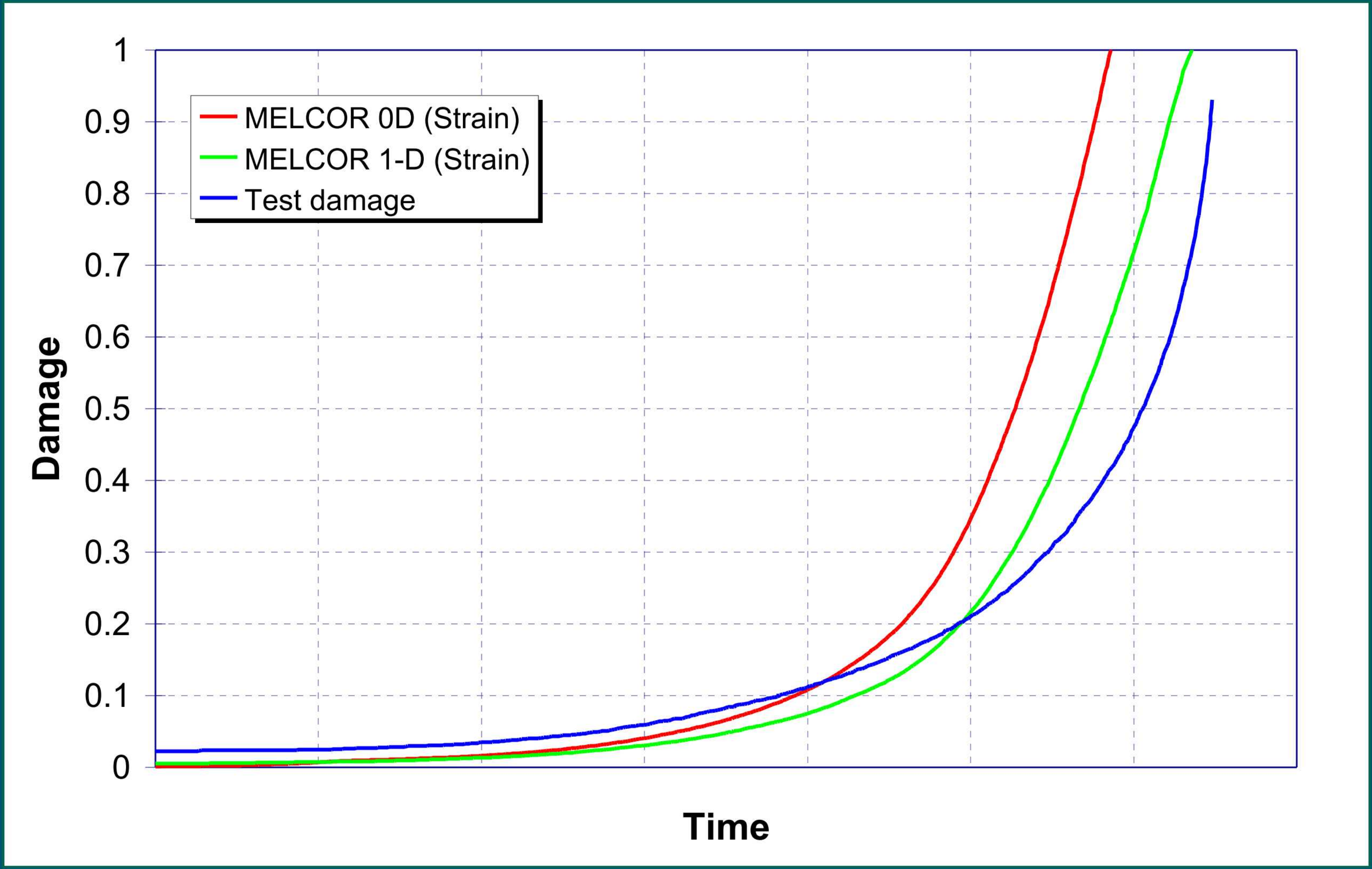
LHF-6 Uniform Heat Flux (10 MPa)

LHF-7 Uniform Heat Flux (5 MPa)

LHF-8 Edge Peaked Heat Flux (10 MPa)

Time Relative to Onset of Plastic Deformation

Results of OLHF-1 Test

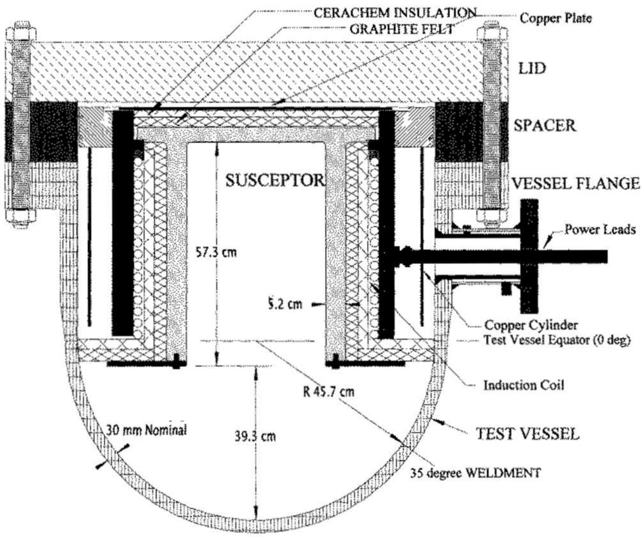


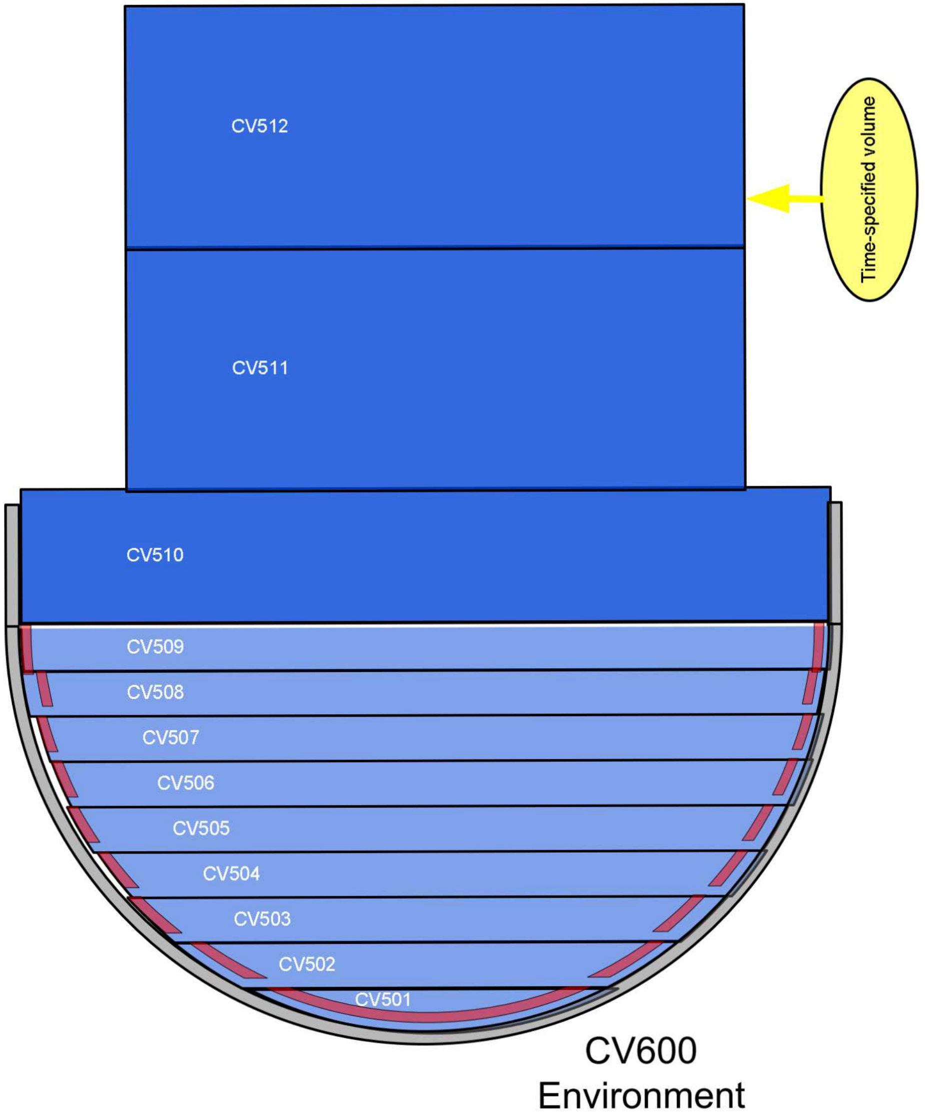
Independent Validation by IBRAE LHF Test Nodalization Scheme

14 Control volumes

9 Lower Head segments

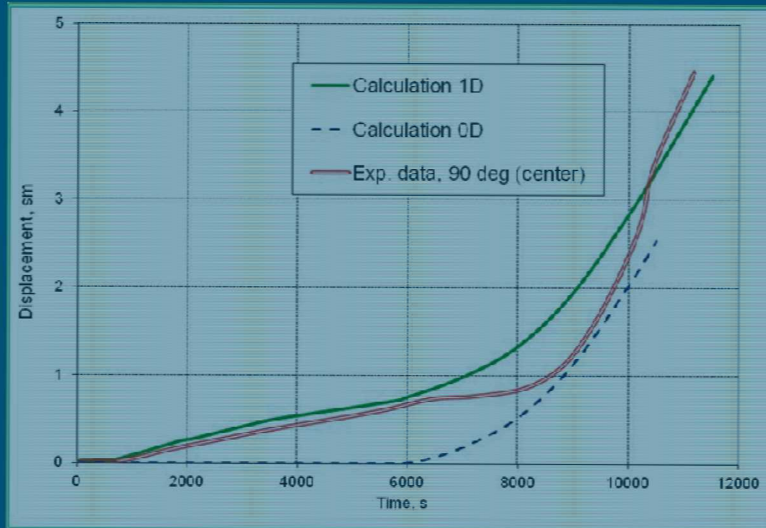
9 heated Support Plates in Lower Head

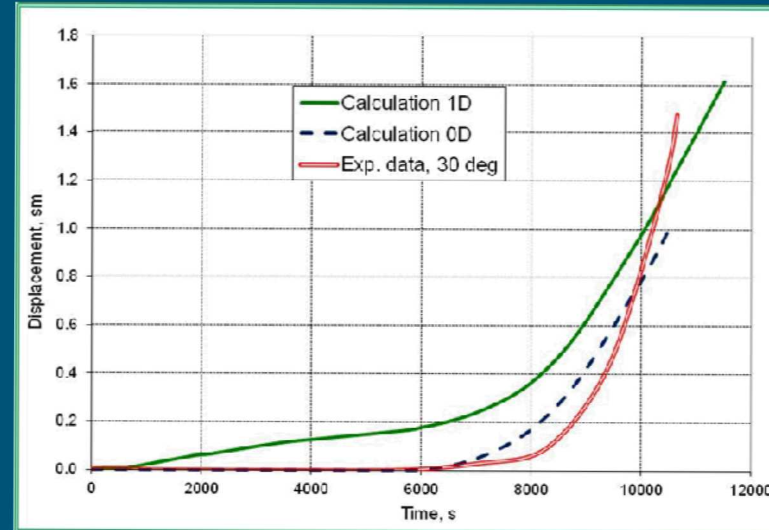




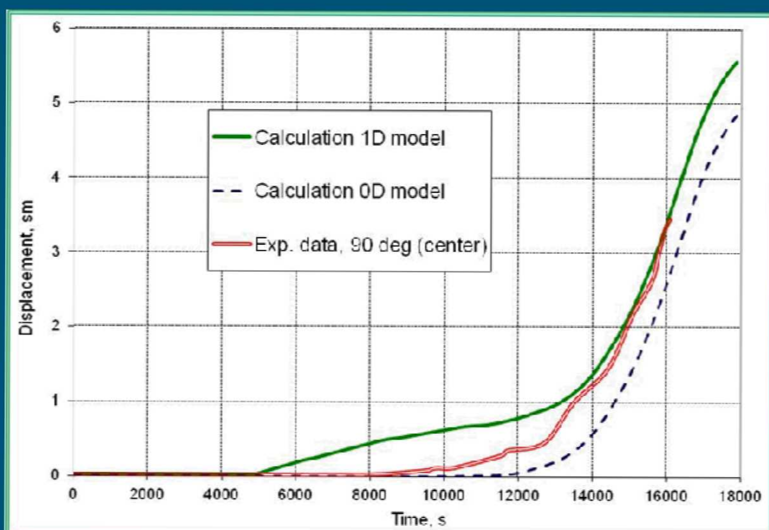
Independent Validation by IBRAE

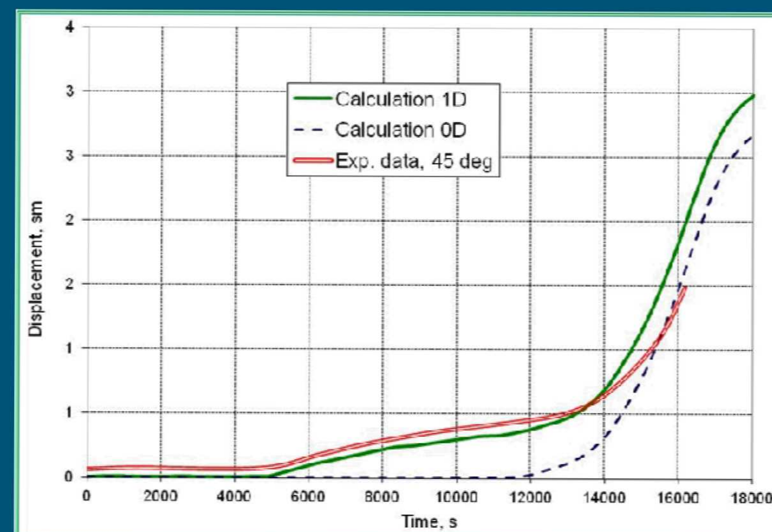
LHF-4





LHF-3





Melt Ejection From Failed Vessel

Two models for determining debris mass available for ejection

- Default Slurry/Oatmeal Model
  - The total debris mass and molten pool material masses
    - Regardless of whether they are molten or not
  - May lead to ejection of more solid debris than is realistic
- Alternate Model - Solid retention
  - SS, Zr, UO_2 liquid masses available for ejection
  - SSOX, CRP mass multiplied by SS melt fraction (assumed proportional mixing)
  - ZrO_2 mass multiplied by Zr melt fraction (assumed proportional mixing)
  - UO_2 solid mass (fraction assumed in candling model)
  - Currently enabled on COR_TST record

(9) IDEJ

Disable switch for solid debris ejection model.

(type = integer, default = 0, units = none)

Mass ejection rate calculated from pressure head on debris

$$M_{ej} = \rho_m A_f v_{ej} \Delta t \qquad v_{ej} = C_d \left(\frac{2\Delta P}{\rho_{PD}} + 2g\Delta Z_d \right)^{1/2}$$

- Ablation calculated for failure area.

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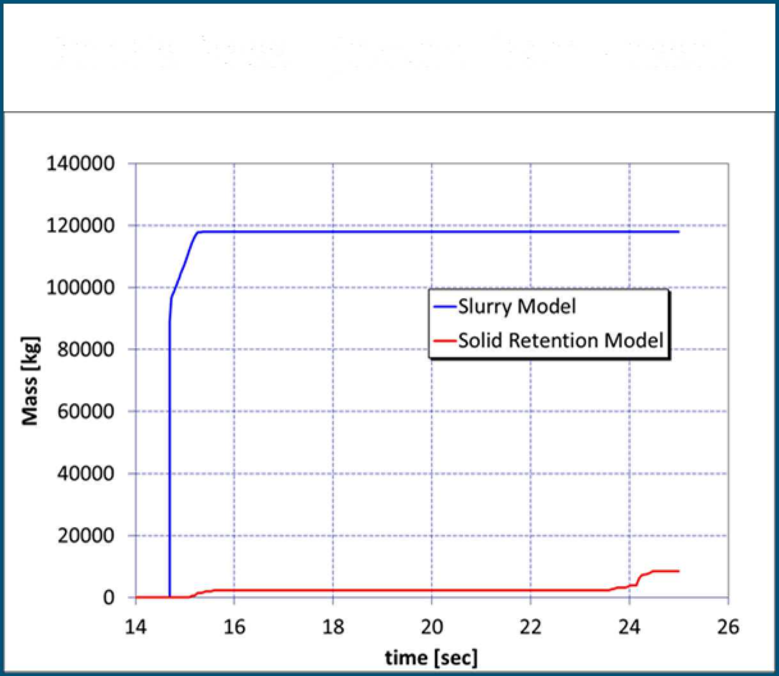

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Questions