Idaho National Engineering and Environmental Laboratory

SCDAP-3D Analyses

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Outline

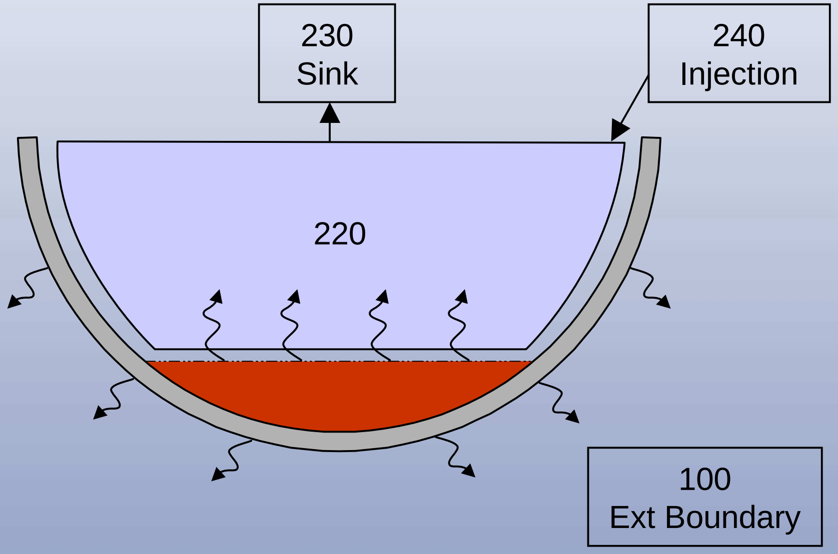
- *Introduction to recent SCDAP analyses*
- *Analyses of potential for in-vessel retention (IVR)*
  - *Modeling approach*
  - *Typical results*
- *Vessel lower head model improvements (in progress)*
- *Summary*

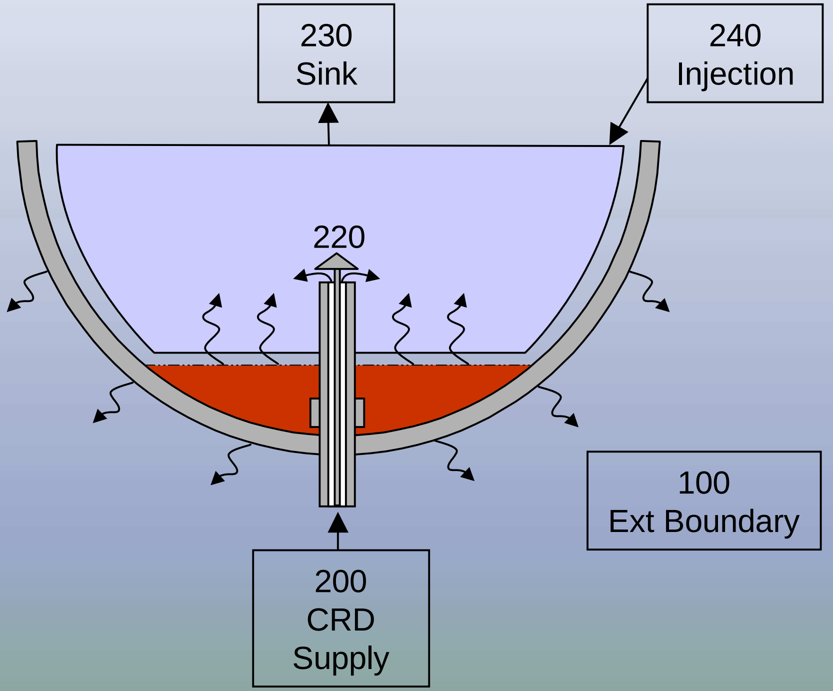
Wide Range of Analyses Completed

- Station blackout analyses supporting
  - NRC severe accident management programs
  - Resolution of direct containment heating issue
- Fuel pin failure timing analyses (PWRs and BWRs)
- Analyses of potential for SGTR
- Electrosleeving analyses for SG life extension
- Vessel lower head analyses supporting
  - AP600 design certification relative to external reactor vessel cooling (ERVC)
  - Assessment of IVR potential
  - Addition of corium-to-vessel gap cooling (in progress)

Minimal T-H Requirements for IVR Analyses

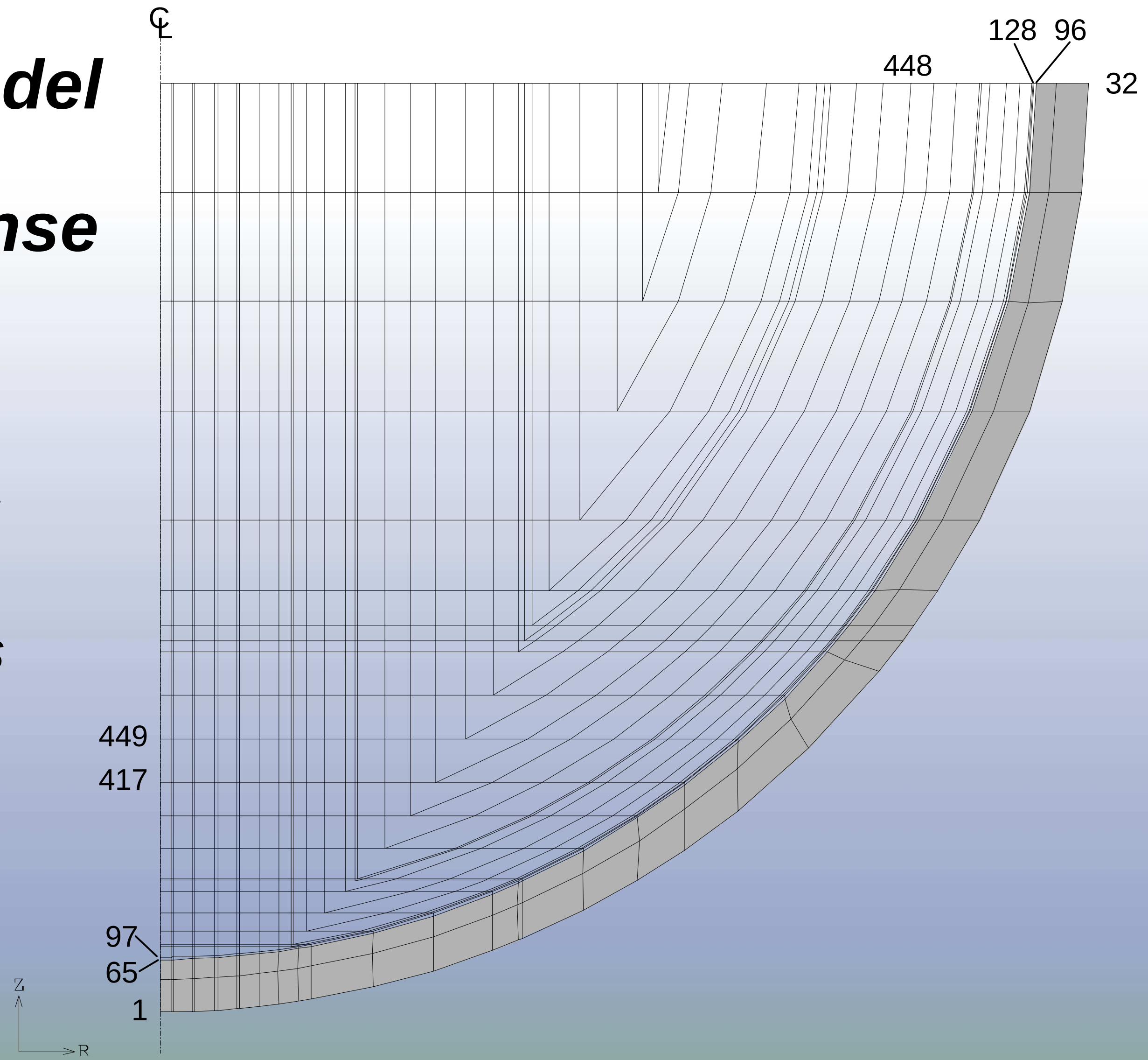
- *Sink*
- *Injection source*
- *Simulation of external boundary conditions*
  (Radiation, spray cooling, external flooding, CRD supply)





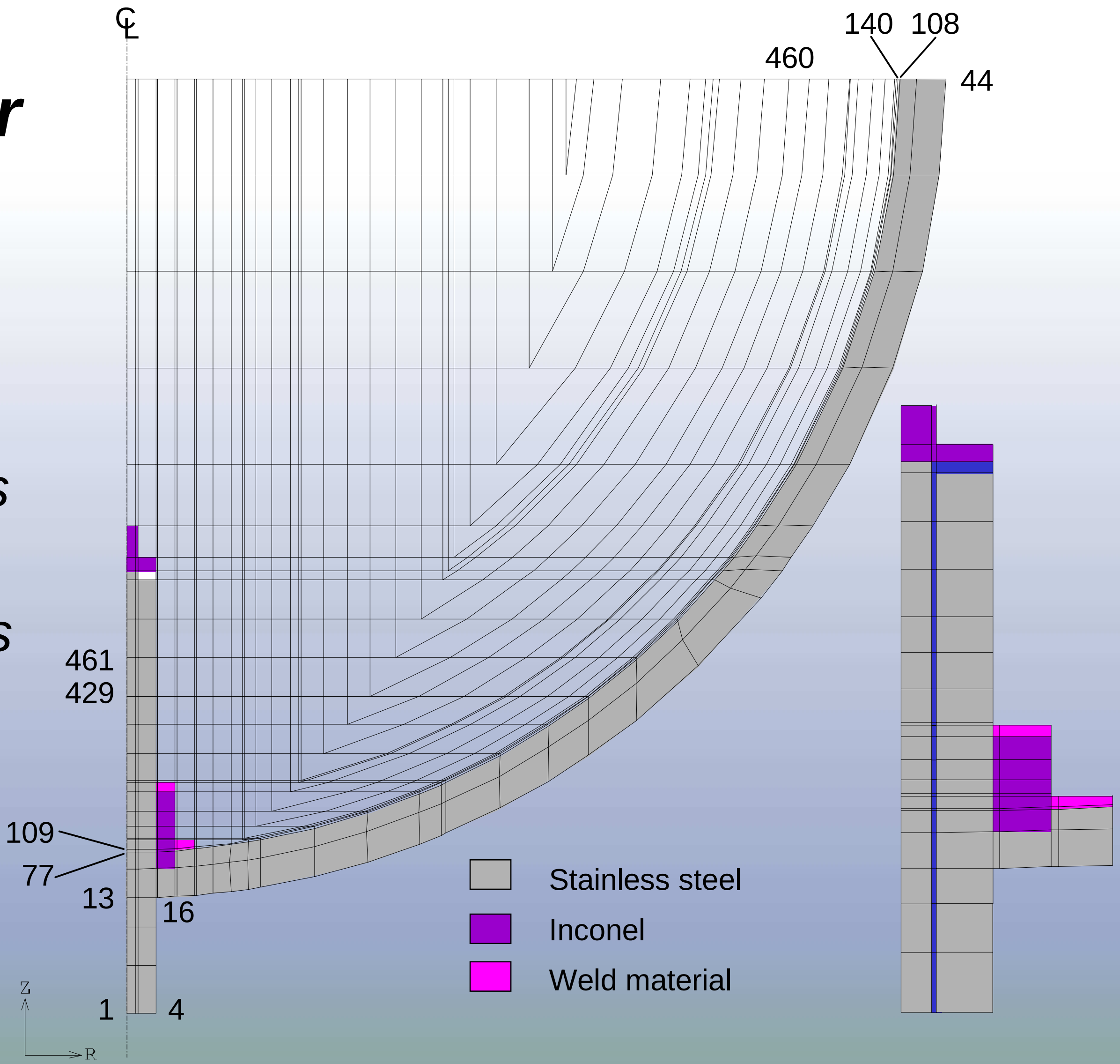
Detailed IVR Model for Lower Head Thermal Response without CRD

- *744 finite elements with 800 nodes*
- *“Contact” elements at all corium/structural interfaces*

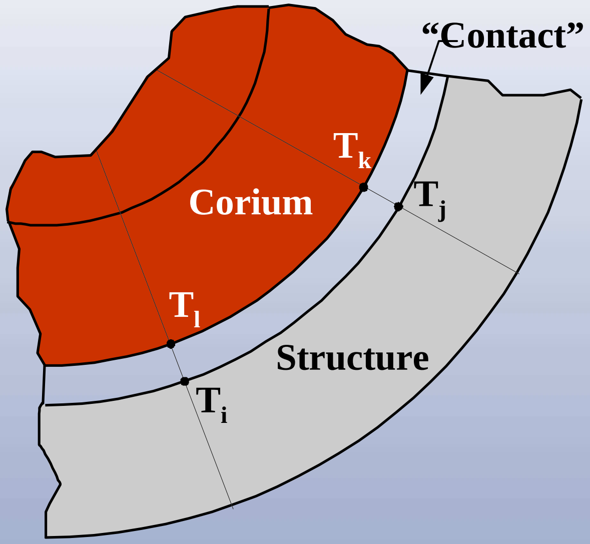


Detailed IVR Model for Lower Head Thermal Response with CRD

- *753 finite elements with 812 nodes*
- *“Contact” elements at all corium/structural interfaces*



“Contact” Heat Transfer Assumed to be Temperature Dependent



Solid interface (low conductance) if:

$$\frac{T_i + T_j}{2} < T_{solidus,structure}$$

Molten interface (high conductance) if:

$$\frac{T_i + T_j}{2} > T_{liquidus,structure}$$

Transition interface (intermediate conductance) if:

$$T_{solidus,structure} \leq \frac{T_i + T_j}{2} \leq T_{liquidus,structure}$$

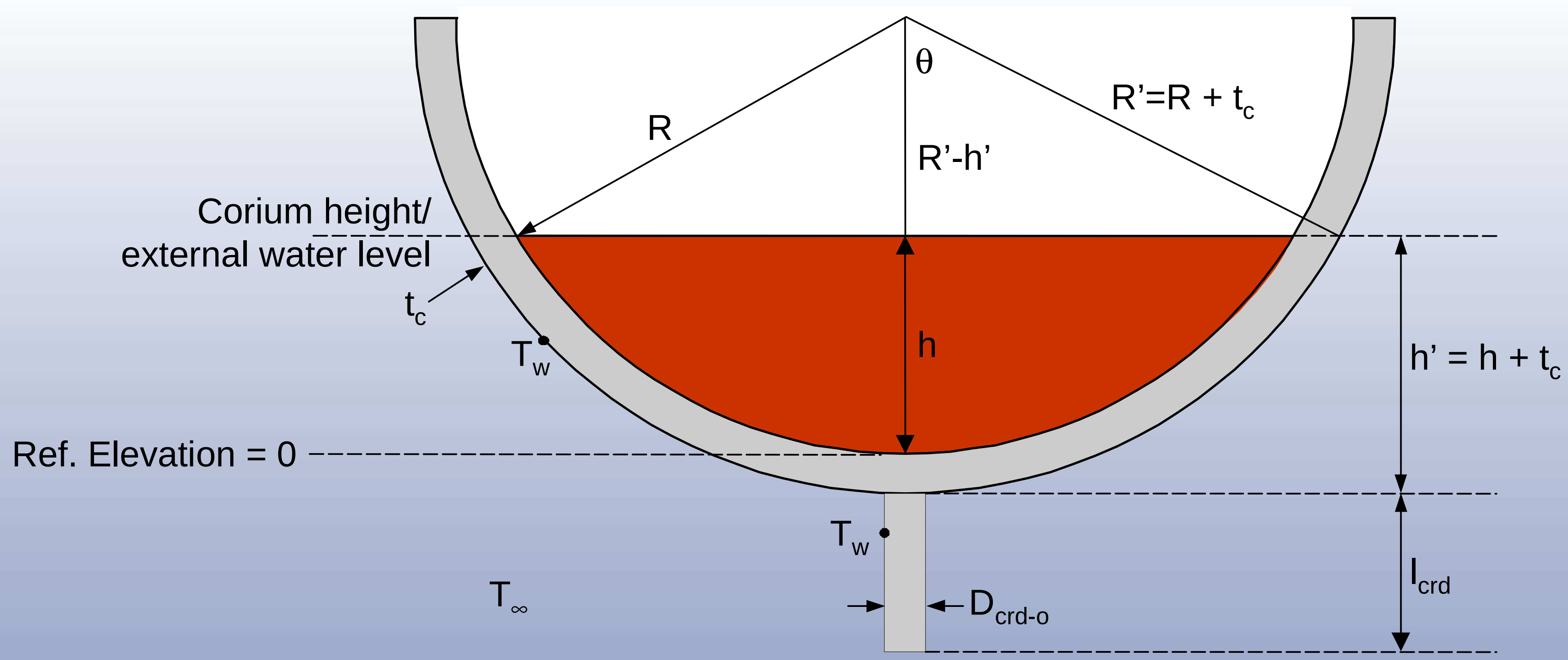
Three Mechanisms Considered in IVR External Crucible Cooling (ECC)

- *ECC consists of heat transfer associated with*
  - *Radiation from crucible/CRD surfaces to surroundings*
  - *Spray cooling of external crucible/CRD surfaces*
  - *Nucleate boiling at submerged crucible/CRD locations*

- *Code modification made to allow specification of equivalent heat transfer coefficients using (user defined) control variables*

- *Control variables developed to implement heat transfer correlations at all affected nodes*

Notation Used to Develop IVR ECC Simulation



Radiation Heat Transfer Applied When Sprays are Off

- *Radiation heat transfer only applicable (at non-submerged nodes) when sprays "off"*
- *Equivalent radiation heat transfer coefficient given by*

$$h_{e-rad} = \frac{\varepsilon\sigma F\left(T_w^4 - T_\infty^4\right)}{\left(T_w - T_\infty\right)}$$

$$\begin{aligned} \textit{where} \quad & \varepsilon = 0.14 \textit{ for polished steel at } 800\ K \\ & \sigma = \textit{Stefan} - \textit{Boltzmann constant} \\ & F = 1.0 \textit{ (view factor to surroundings)} \\ & T_w = \textit{crucible or CRD surface temperature} \\ & T_\infty = \textit{surface temperature of surroundings} \end{aligned}$$

Spray Cooling Applied Above External Water Level

- Spray cooling only applicable for non-submerged nodes when sprays "on"
- Crucible spray cooling estimated using Breen and Westwater film boiling correlation

$$h_{e-spray-cru} = h_{e-rad} + h_{film}$$

$\textit{where } h_{e-rad} \textit{ as previously defined}$

$$h_{film} = \left[0.59 + \frac{0.069(2\pi)}{D_{cru}} \left\{ \frac{\sigma_f}{g(\rho_f - \rho_g)} \right\}^{0.5} \right] \left[\left(\frac{\{ g\sigma_f (\rho_f - \rho_g) \}^{0.5} \rho_g k_g{}^3}{2\pi\mu_g (T_w - T_\infty)} \right) \left(h_{fg} \left\{ 1.0 + 0.68 \left[\frac{c_{pg}(T_w - T_\infty)}{h_{fg}} \right] \right\} \right) \right]^{0.25}$$

D_{cru} = crucible outer diameter

σ_f = surface tension of saturated water

g = acceleration due to gravity

ρ_f = density of saturated water

ρ_g = density of saturated vapor

k_g = thermal conductivity of saturated vapor

μ_g = dynamic viscosity of saturated liquid

h_{fg} = heat of vaporization of saturated water

c_{pg} = specific heat of saturated vapor

Spray Cooling Applied Above External Water Level (cont)

- CRD spray cooling estimated using Bromley film boiling correlation

$$h_{e-spray-crd} = h_{e-rad} + h_{film}$$

$$\text{where } h_{film} = 0.62\frac{D_{crd-o}}{2\pi}\left[\frac{g(\rho_f-\rho_g)}{\sigma_f}\right]^{0.5}\left[\frac{g(\rho_f-\rho_g)\rho_g k_g^3\left[h_{fg}+0.5\left\{\rho_{fg}\left(T_w-T_\infty\right)\right\}\right]}{D_{crd-o}\mu_g\left(T_w-T_\infty\right)}\right]^{0.25}$$

$$D_{crd\text{-}o} = \text{CRD outer diameter}$$

$$\rho_{fg} = \text{difference in density between saturated liquid and saturated vapor}$$

Spray Cooling Heat Transfer Limited by Flow

- Crucible/CRD spray cooling heat transfer cannot exceed spray flow heat capacity
- Crucible/CRD equivalent heat transfer coefficient scaling required for consistency with spray flow heat capacity

$$h'_{e-spray} = f_{spray} h_{e-spray}$$

$$where \qquad f_{spray} = \min\left[\frac{\dot{m}_{spray} c_p \left(T_{sat} - T_{spray}\right) + \dot{m}_{spray} h_{fg}}{\sum^{ext\ nodes} h_{e-spray} \Delta A \left(T_w - T_\infty\right)}, 1.0 \right]$$

$$\dot{m}_{spray} = spray\ mass\ flow\ rate$$
$$c_p = specific\ heat\ of\ spray\ flow$$
$$T_{sat} = saturation\ temperature\ for\ spray\ flow$$
$$T_{spray} = spray\ flow\ temperature$$
$$h_{fg} = heat\ of\ vaporization\ of\ spray\ flow$$
$$\Delta A = surface\ area\ associated\ with\ external\ nodes$$

Boiling Heat Transfer Applied Below External Water Level

- *Nucleate boiling assumed for all submerged nodes*
- *Boiling heat transfer assumes*

$$h_{e-boil-cru} = \frac{0.7 q_{CHF}}{\max(1.0, T_w - T_\infty)}$$

where

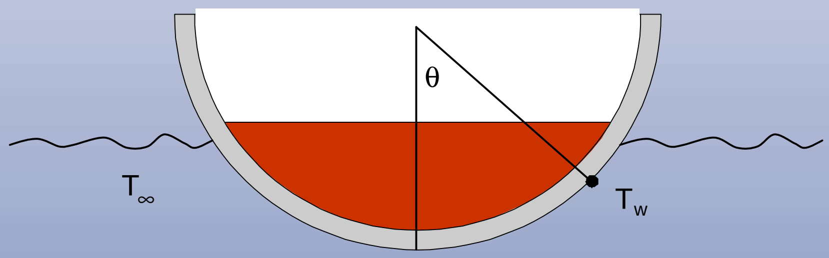
$$q_{CHF} = 49000 + 302200\theta - 888\theta^2 + 13.5\theta^3 - 0.0665\theta^4 \,(W/m^2)$$

$$T_W = surface\ temperature\ (K)$$

$$T_\infty = pool\ temperature$$

$$\theta = angle\ (in\ degrees)\ from\ vertical$$

$$centerline\ to\ elevation\ of\ interest$$



- *Boiling for all CRD surfaces based on $\theta = 0°$*

External Water Level Based on ECC Conditions

- External water level as function of spray cooling flow rates, spray cooling heat transfer, and boiling heat transfer

$$external\ water\ level = f(accumulated\ water\ volume)$$

$$accumulated\ water\ volume = spray\ accumulation\ -\ volume\ boiled$$

$$spray\ accumulation = \frac{\left[\dot{m}_{spray} c_p \left(T_{sat} - T_{spray}\right) + \dot{m}_{spray} h_{fg} - \sum^{ext\ nodes} h_{e-spray} \Delta A \left(T_w - T_\infty\right)\right] dt}{\rho_f h_{fg}}$$

$$volume\ boiled = \frac{\sum^{ext\ nodes} h_{e-boil} \Delta A \left(T_w - T_\infty\right) dt}{\rho_f h_{fg}}$$

$$where\ \ dt = SCDAP\ time\ step$$

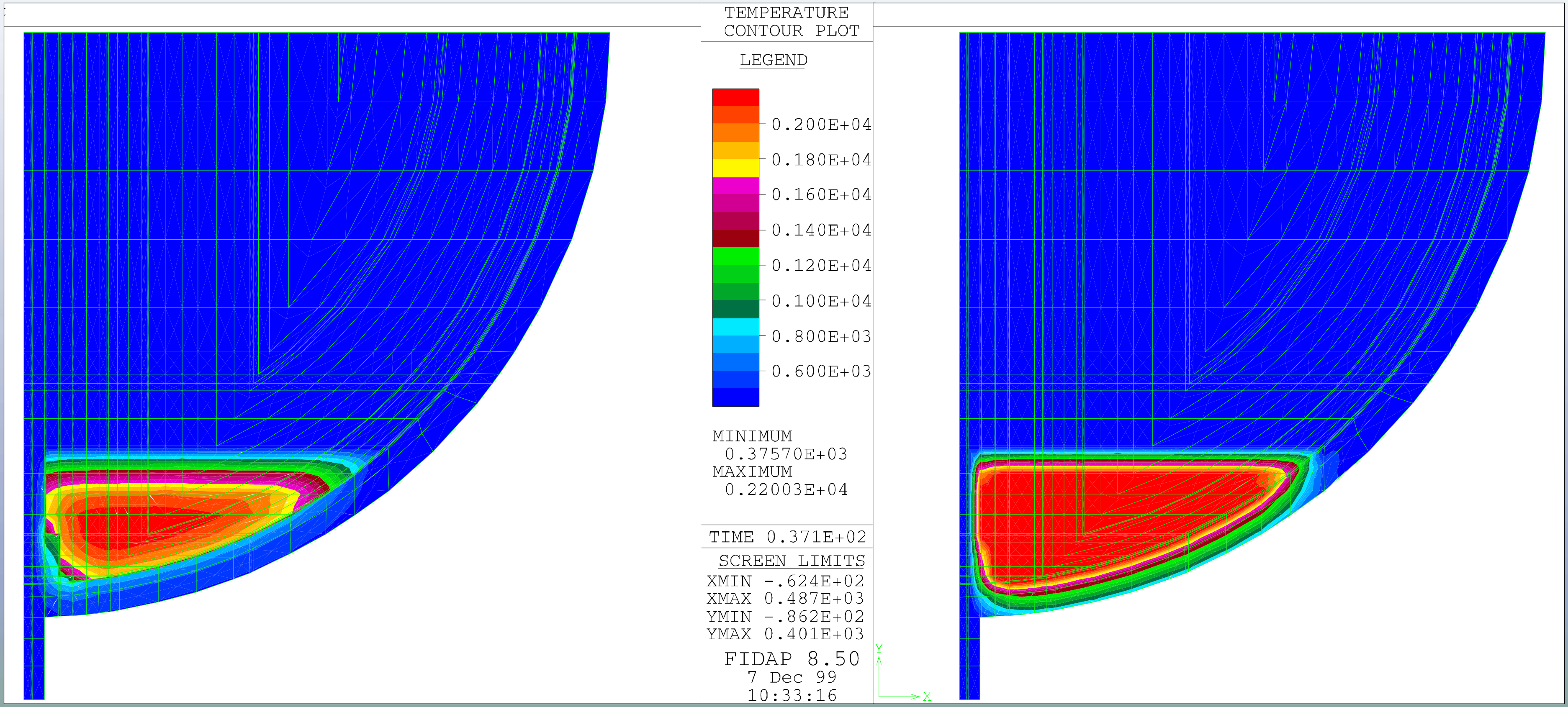
IVR Results Dependent on Boundary Conditions

- *Wide range of boundary conditions considered*
- *Most significant conditions included*
  - *Corium temperature at time of relocation*
  - *Corium decay power density*
  - *Spray cooling flow rates*
  - *Corium/coolant interaction during relocation*

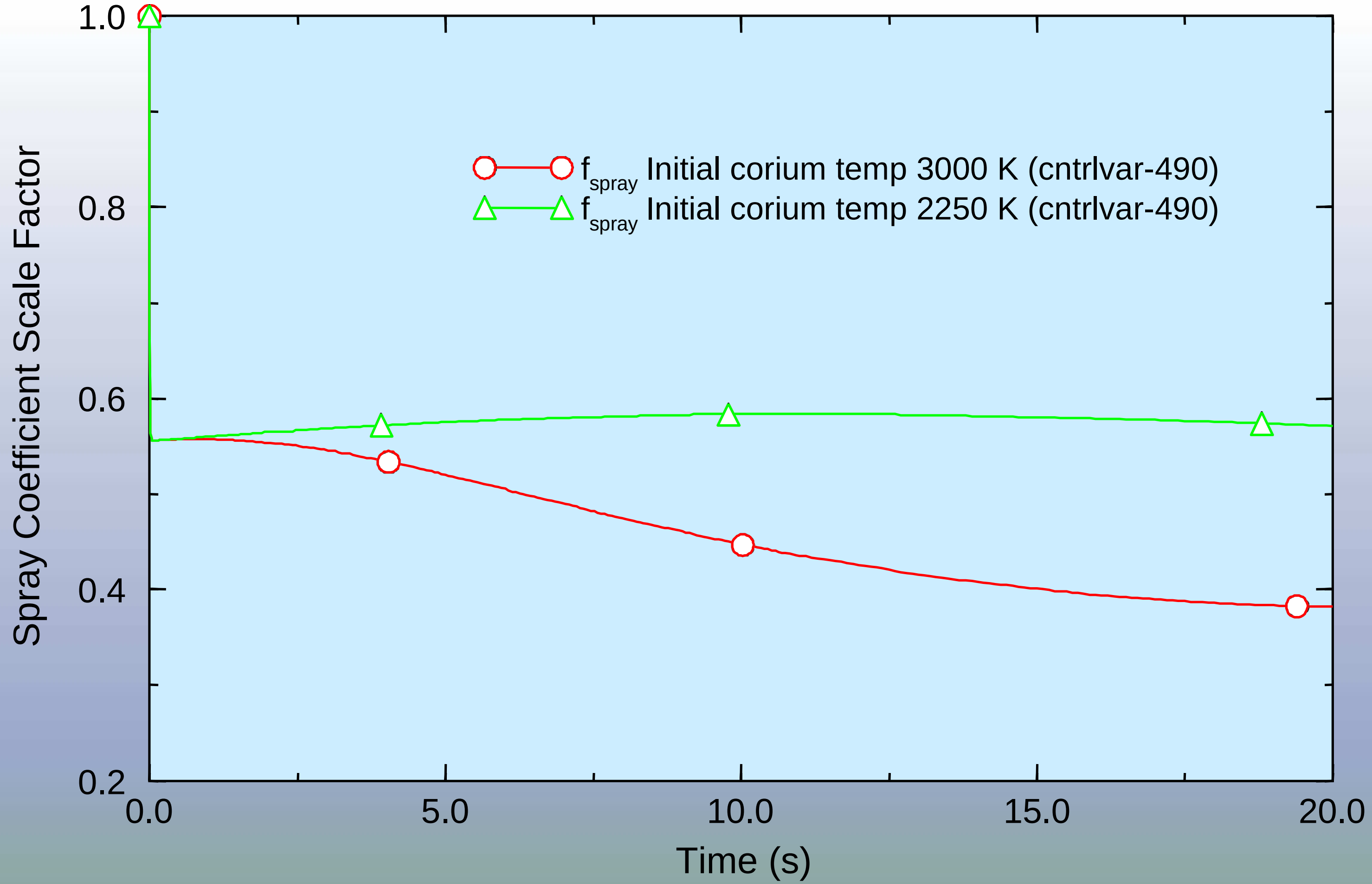
Structural Melting Sensitive to Initial Corium Temperature

Initial corium temperature 2250 K

Initial corium temperature 3000 K



Spray Scaling Requirement Increases with Initial Corium Temperature



Key Conclusions From IVR Analyses

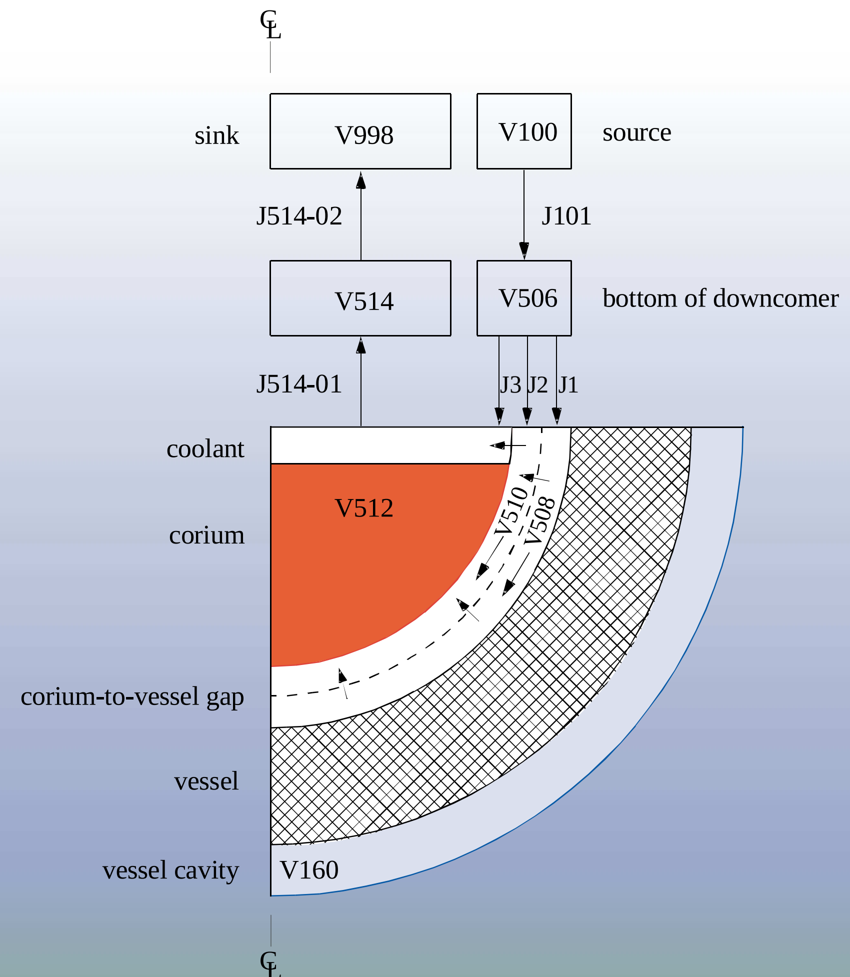
- *Initial corium temperature significant relative to prediction of structural melting*
- *Spray flows considered were too small relative to external heat load*
- *CRD flows important for CRD integrity but ineffective relative to corium cooling*
- *In-vessel injection inadequate for replenishing/ maintaining vessel water level*
- *Conclusions could change with addition of corium-to-vessel gap cooling*

Addition of Corium-to-Vessel Gap Cooling Significant SCDAP-3D Enhancement

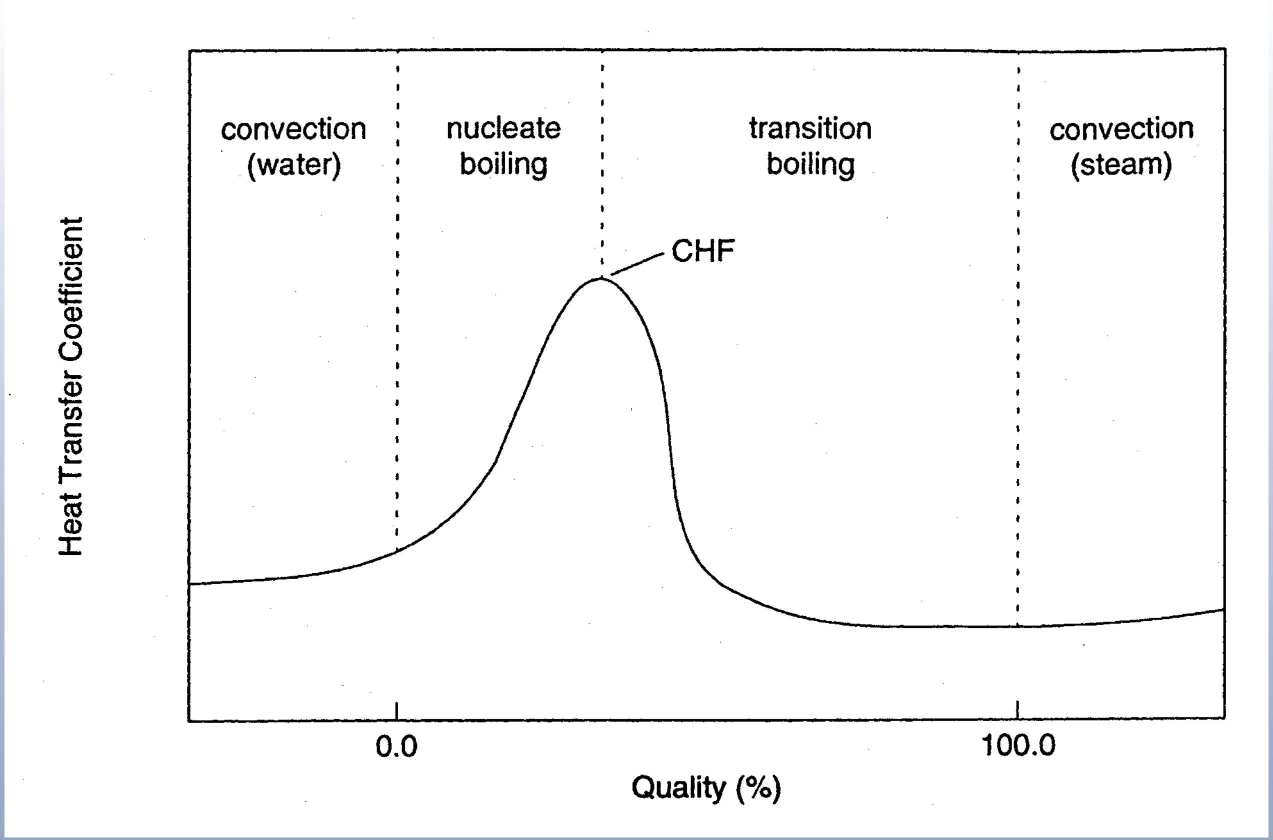
- *Evidence suggests presence of corium-to-vessel gap*
  - *TMI-2 data*
  - *JAERI ALPHA experiments*
  - *KAERI LAVA tests*
- *Gap representation critical to accurate simulation of vessel lower head thermal response*
- *SCDAP-3D will contain high fidelity heat transfer model (not limited to simple CHF relationship used in some codes)*

Configuration Needed for Corium-to-Vessel Gap Cooling

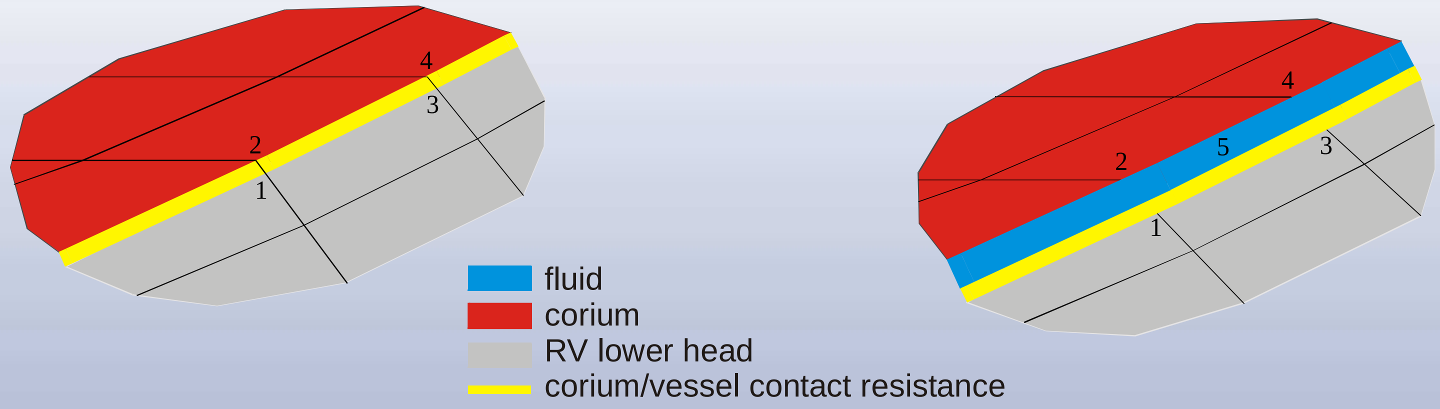
- *Two volume gap allowing countercurrent cooling flow*
- *Crossflow connections incorporated in finite element mesh*
- *Heat transfer correlations*



Development of Complete Boiling Curve Anticipated



Addition of Corium/Vessel Gap Does Not Alter Existing "Contact" Modeling Approach



(a) Section AA without recommended modifications.

(b) Section AA with recommended modifications.

Summary

- *SCDAP-3D versatility demonstrated in completing wide variety of analyses*
- *Results have addressed regulatory and safety issues*
- *Recent IVR analyses provide insights into corium coolability (hence, reactor safety)*
- *SCDAP-3D modifications underway to add corium-to-vessel gap cooling capabilities*