MELCOR CAV Package Overview

SAND2015-9563PE

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Tokyo, Japan

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MELCOR/CORCON MCCI Models
Outline of Presentation

- Overview of MCCI* models in MELCOR
  - How MELCOR models ex-vessel debris
    - Models inherited from CORCON-Mod3
    - Internal interfaces replace stand-alone input
    - Generalizations possible in MELCOR application
    - Limitations resulting from integration into MELCOR
- Details of phenomenological models
  - Debris geometry
  - Mass and energy transport and conservation
    - Concrete ablation
    - Chemistry

* "MCCI" is "Melt Coolability and Concrete Interactions"

MELCOR/CORCON MCCI Models Physical Processes

- Debris ejected from vessel attacks concrete
  - Attack is primarily thermal: surface ablates
    - Concrete decomposes
    - Gases (H_2O and CO_2) interact with debris
      - Stir and mix it, enhance heat transfer
      - Are reduced by active metals to H_2, CO, and possibly C(c)
      - Drive release of fission products by reactive vaporization
    - Oxides (CaO, SiO_2, Al_2O_3, etc.) add to debris
- Top surface communicates with surroundings
  - Heat is lost by radiation, convection, or boiling
  - Gaseous reaction products pass to atmosphere
- Sustained by decay and chemical heat
  - Heat balance determines progression

MELCOR/CORCON MCCI Models Framework (1)

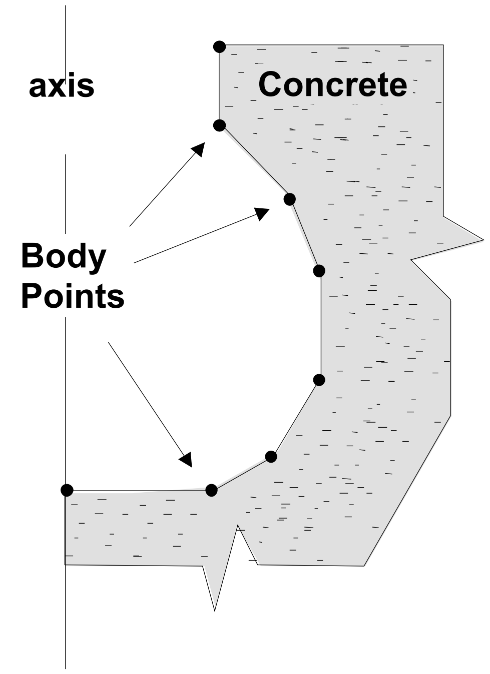
- MELCOR models based on CORCON-Mod3
  - Uses CCM3 routines for phenomenological models
    - Geometry, heat transfer, chemistry, concrete ablation
  - Obtains boundary condition and source data from other MELCOR packages rather than user input
    - Stand-alone options available (in MELCOR format)
  - Interface to VANESA preserved
    - VANESA is fission product release model
      - Implemented as part of the RN package
      - Separate scrubbing model replaced by general SPARC model
- MELCOR executive replaces top coding levels
  - Controls input, advancement, output
  - Input format consistent with other MELCOR packages
  - Allows integrated restart, plot, and fallback capabilities

MELCOR/CORCON MCCI Models Framework (2)

- **Generalizations in MELCOR implementation**
  - —Internally consistent calculation of boundary conditions
    - ✶ Volume conditions (pressure, temperature, and presence of water pool) respond to heat and gases
  - —Calculate MCCI in more than one location
    - ✶ Allow cavity rupture/debris overflow between locations
- **Limitations in MELCOR integration**
  - —CORCON does not use MELCOR elevation reference
    - ✶ Z is measured positive *downward*
  - —Debris doesn't displace water or gases
  - —Hydrodynamic fluids don't "see" concrete
  - —Some CORCON user "flexibility" inputs are not accessible
    - ✶ These are connected only as a need is perceived

MELCOR/CORCON MCCI Models
Concrete Cavity

- **Domain of MCCI model is a concrete "cavity"**
  - Axisymmetric shape defined by a series of "body points"
  - Flexible definition of concrete properties
  - Contains debris
- **Thermal attack on concrete**
  - Shape changes as concrete erodes
  - Ablated oxides added to debris
  - Evolved gases (H_2O and CO_2) stir debris, react with it (producing H_2 and CO), and rise to surface



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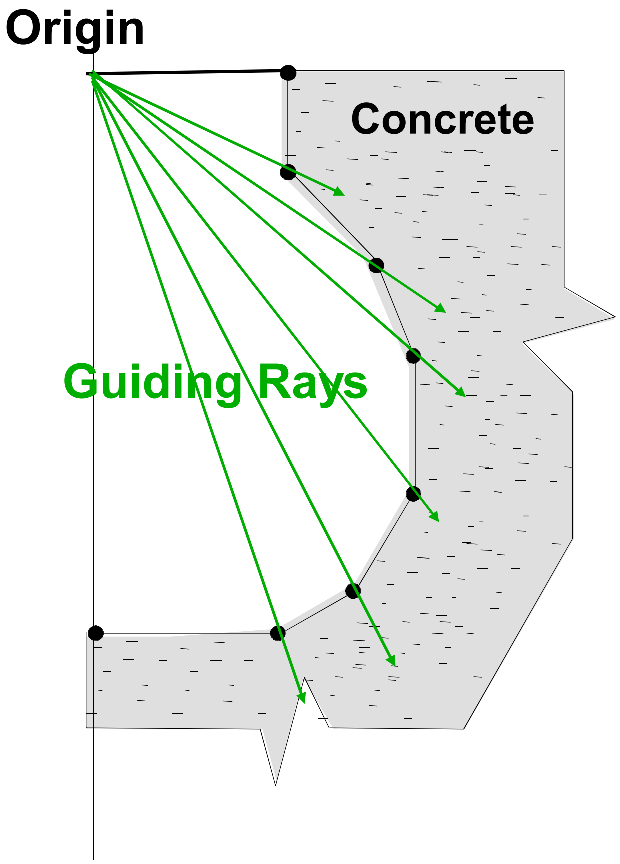
MELCOR/CORCON MCCI Models
Cavity Shape Changes

- Guiding rays emanate from origin on the vertical axis to body points at start of calculation.
  - Exception is the tangent ray
- Assume that concrete recession follows local normal
  - Calculated as bisector of angle formed by lines from the body point to nearest neighbors
- Resulting surface points are projected back onto guiding rays
  - Circle passed through receded point and its two nearest neighbors. Intersection of ray and circle defines new body point



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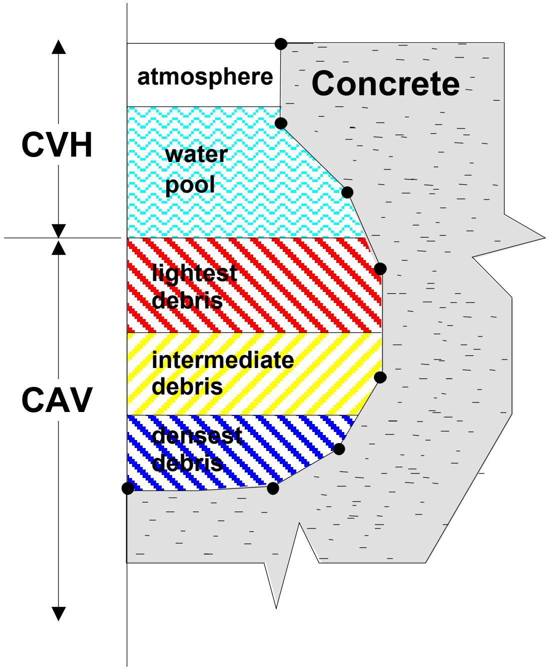
MELCOR/CORCON MCCI Models
Cavity Contents

- Debris and fluids in cavity
  - Debris treated by MCCI models
    - May be stratified by density
  - Pool, atmosphere treated by CVH hydrodynamic models
  - Limited interfaces
    - CVH defines upper boundary conditions for debris
      - Temperature, pressure, water
      - Sink for heat and evolved gases
    - CVH "sees" nothing else
      - No thermal interaction with concrete wall
      - No volume displaced by debris
      - No volume change by concrete ablation



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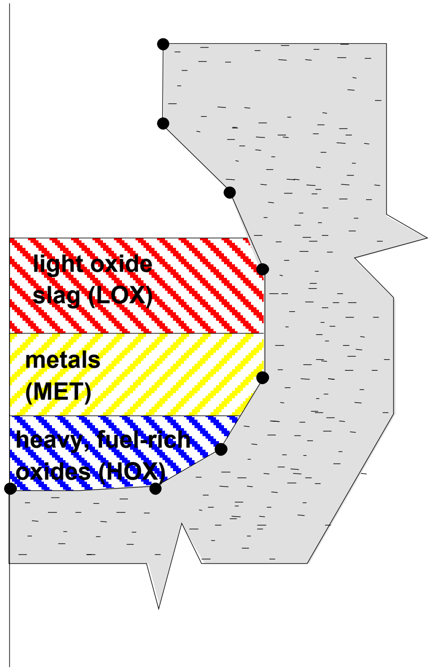
MELCOR/CORCON MCCI Models
Debris Layering and Mixing (1)

- **CORCON-Mod2 considered only complete stratification**
  - —Assumed immiscible metals and oxides
  - —Allowed one to three layers
    - ✶ Oxide slag layer above metals (LOX)
    - ✶ Unoxidized metal layer (MET)
    - ✶ Possible denser, fuel-rich oxide layer below metal (HOX)
  - —If HOX became less dense than MET (by dilution), debris “flipped”
    - ✶ Instantaneous combination of HOX and LOX into LOX

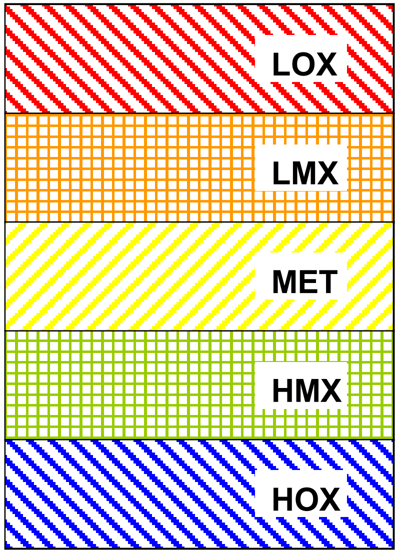


MELCOR/CORCON MCCI Models
Debris Layering and Mixing (2)

- Structure of CORCON-Mod2 allowed mixed layers, but there were no mixing models
- CORCON-Mod3 added mixing models
  - Two distinct mixing processes considered
    - Metal entrained by rising gases into lighter slag to form a "light mixture" (LMX)
    - Heavy (fuel) oxides entrained into metal to form a "heavy mixture" (HMX)
  - Mechanistic models for rates
    - Balance between entrainment and separation under gravity determines degree of mixing
- Density Stratification
  - HOX>HMX>MET>LMX>LOX

Density Stratification

Note: some layers may not co-exist. This graphic is intended just to show density variation



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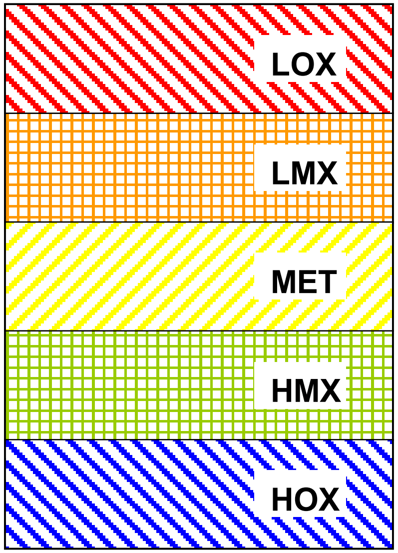
MELCOR/CORCON MCCI Models
Debris Layering and Mixing (3)

- **Possible transport of metals**
  - Entrain from MET or HMX into LMX
    - Can have LMX or LOX, but not both
    - Limit is complete mixing of metals into LMX
- **Possible transport of dense oxides**
  - Entrain from HOX into HMX or LMX
    - Can have HMX or MET, but not both
    - Limit is complete mixing of dense oxides into HMX
- **Many possible debris layerings**
  - Two possibilities for complete mixing
    - Metal-in-light-oxide (LMX)
    - Heavy-oxide-in-metal (HMX)
  - Eight 2- or 3-layer configurations

Density Stratification

Note: some layers may not co-exist. This graphic is intended just to show density variation

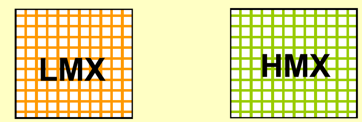


MELCOR/CORCON MCCI Models
Mixing Options

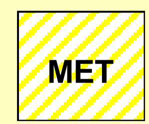
- **MELCOR allows three options**
  - **Enforced Mixing** (MELCOR default)
  - **Enforced Stratification** (as in CORCON-Mod2)
  - **Mechanistic Mixing**
    - Eliminates “Layer Flip”
  - **Calculation of mechanistic mixing rates**

Enforced Mixing

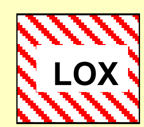
Both Phases present: HMX or LMX depending on relative densities of metals and oxides



Metals Only: MET



Oxides Only: LOX



MELCOR/CORCON MCCI Models
Heat Transfer

- Three heat transfer mechanisms within debris
  - Natural convection, based on conventional correlations
  - Conduction
  - Bubble-enhanced convection, using Kutateladze and surface renewal models
- Other heat transfer models
  - Convection and radiation, or boiling at top surface
    - Bubble-enhanced boiling uses Greene correlation
  - Added thermal resistance of film adjacent to concrete

Natural convection

Nusselt based on Rayleigh Number

Axial:

$$Nu = \max(0.54\,Ra^{1/4}, 0.14\,Ra^{1/3})$$

Radial:

$$Nu = \max(0.59\,Ra^{1/4}, 0.10\,Ra^{1/3})$$

Nusselt number based on layer thickness:

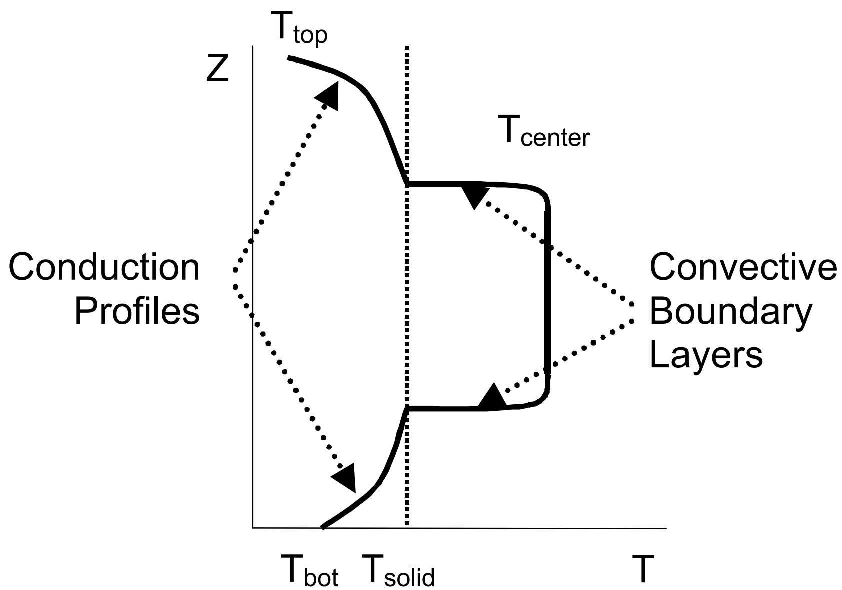
$$Nu = \frac{hL}{k}$$

The Rayleigh number based on fluid to boundary temperature difference

$$Ra = \frac{g\beta\Delta T l^3}{\nu\alpha}$$

MELCOR/CORCON MCCI Models
Heat Transfer Within a Layer

- **Code determines quasi-steady axial (shown) and radial temperature profiles**
  - **Known average temperature**
  - **Conduction below solidus temperature, thin boundary layers in liquid center**
  - **Constant divergence of heat flux**
  - **Superposition of 1-D axial and radial transfers**
- **Iterate to match boundary conditions**



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MELCOR/CORCON MCCI Models
Heat Transfer to Concrete (1)

- **Film of concrete decomposition products between debris and concrete adds resistance**
  - CORCON-Mod2 assumed gas film (MELCOR default)
  - CORCON-Mod3 allows slag film

Gas film model

- Gases (from concrete ablation) enter debris at bottom
  - Heat transfer is analog of nucleate boiling
- Gases flow between debris and concrete at side
  - Heat transfer through laminar or turbulent flowing film
- Transition region for angles between 15º and 30º
  - Based on apportioning entering gases between bubbles and film flow

MELCOR/CORCON MCCI Models
Concrete Ablation

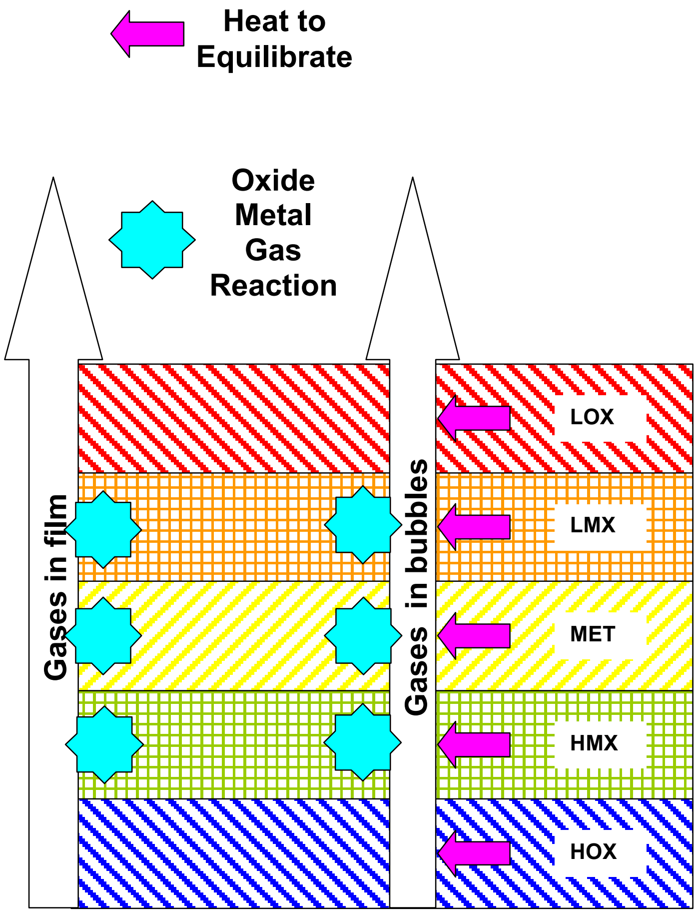
- **CORCON considers only ablation of concrete**
  - —No precursor heating or decomposition
  - —Valid for modest ablation rates
    - Thermal penetration length $\ell \sim \alpha / v_{ablation}$
      - On the scale of the aggregate
  - —Heat to concrete is determined by continuity of heat flux
    - Concrete surface temperature is $T_{surface} \leq T_{ablation}$
      - Heat flux defines ablation rate

$$\dot{q}'' = \rho \, h_{ablation} \, \dot{s}$$

      - $T_{ablation}$ and $h_{ablation}$ are properties of the concrete
      - Heat flux is 0.0 if $T_{surface} < T_{ablation}$
  - —Ablation rate determines gas generation rate
    - Affects all heat transfer coefficients, requiring iteration

MELCOR/CORCON MCCI Models
Mass/Heat Transfer: Gases

- **Gases leave concrete as H_2O and CO_2**
  - Some pass through the film between debris and concrete
    - Assumed to enter at the average film temperature (which is essentially the ablation temperature)
    - React with metals in the debris, at the average debris surface temperature
  - Some pass through the debris
    - Enter at the average film temperature, thermally equilibrated with debris
    - React with metals in the debris, at the average debris layer temperature

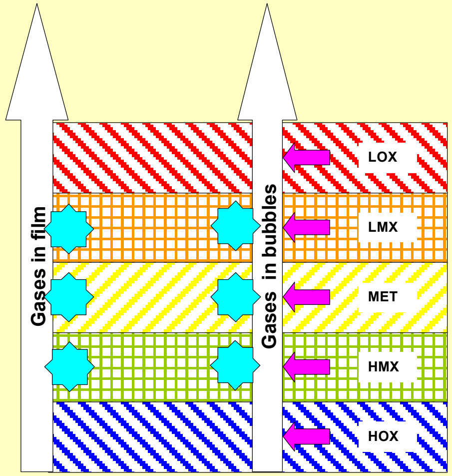


MELCOR/CORCON MCCI Models
Chemistry

- **CORCON calculates chemical equilibrium**
  - —Algorithm
  - —Two reaction Locations
- **Two options**
  - —CORCON-Mod2
  - —CORCON-Mod3 (MELCOR default)

Reaction Locations

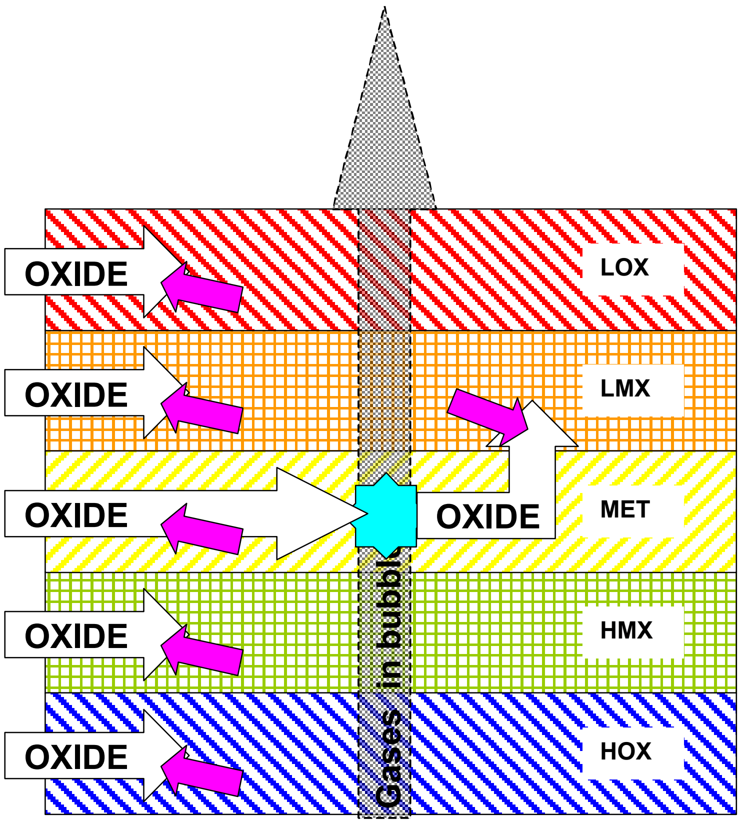
- **Gases passing through melt as bubbles**
  - Reaction at average temperature
- **Gases bypassing melt in film**
  - Reaction at surface temperature



MELCOR/CORCON MCCI Models
Mass/Heat Transfer: Metals & Oxides (1)

Condensed oxides from ablated concrete

- Enter debris at concrete ablation temperature, brought to temperature of ablating layer
- If entering HOX, HMX, LMX, or LOX, added to layer
- If entering MET, rise to become part of LMX or LOX
  - Additional heat transfer



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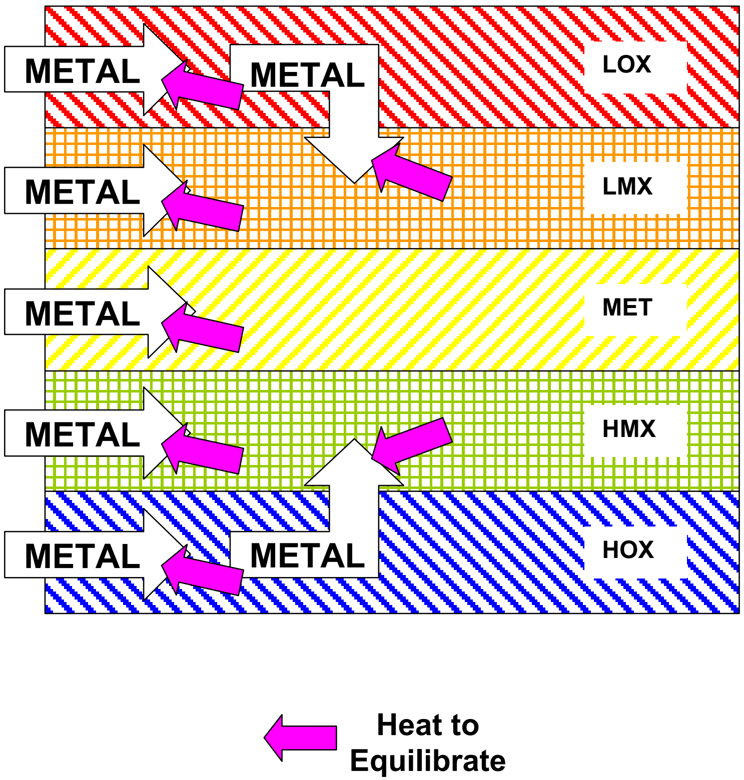
MELCOR/CORCON MCCI Models
Mass/Heat Transfer: Metals & Oxides (2)

- **Condensed metals (rebar) from ablated concrete**
  - Enter debris at concrete ablation temperature, brought to temperature of ablating layer
  - If entering HMX, MET, or LMX, added to layer
  - If entering LOX, sink to become part of MET or HMX
    - Additional heat transfer
  - If entering HOX, rise to become part of MET or LMX
    - Additional heat transfer



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MELCOR/CORCON MCCI Models
Mass/Heat Transfer: Metals & Oxides (3)

- **Core debris (from COR, FDI, or input file)**
  - Sinks to become part of first suitable layer
  - Equilibrated with every layer encountered
  - Definition of initial temperature is subtle
    - CORCON has independent thermal equations of state, phase diagrams
    - Enthalpy may differ from that in source package
    - Can match source temperature or enthalpy, not both
  - Attempt to match sensible heat and latent heat
    - Liquid and solid materials added separately
    - Each assigned enthalpy from (possibly extrapolated) CORCON equation of state for same state

MELCOR Debris Spreading Model

- By default, corium relocated to the cavity will spread instantaneously
- Current model (r7483) adds an internally calculated spreading radius.
  - Balance between gravitational and viscous forces
- Optionally, users are able to specify a spreading radius through a CF or TF

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/CORCON MCCI Models
Debris Spreading

- Parametric model
- User-defined maximum radius of debris bed
  - Specified as function of time by tabular function, control function, or external data file
  - If current radius is less than cavity radius, radial surface is considered adiabatic
    - Standalone CORCON-Mod3 allows heat transfer to water
- Internal calculation
  - Simple analytic form

$$[R(t)]^8 = [R(t_0)]^8 + C\frac{\rho g}{\mu\pi^3}\left(\pi R^2 H\right)^3 (t - t_0)$$

    - Gives reasonable fit to RAS results for C=0.4

MELCOR/CORCON MCCI Models
Thermochemical Properties

- **CORCON needs chemical potential (Gibbs function) as well as thermal equation of state**
  - **Does not use MELCOR material properties**
  - **Internal properties based on fits to specific heat**

$$c_P(T) = A + 10^{-3}\frac{B}{T} + 10^{-6}CT^2 + 10^5\frac{D}{T^2}$$

  - **Integrals (in analytic form) provide enthalpy and Gibbs function**

$$h(T) = h(T_0) + \int_{T_0}^{T} dT'\, c_P(T')$$

$$g(T) = h(T) - Ts(T) \quad , \quad s(T) = s(T_0) + \int_{T_0}^{T} dT'\, c_P(T')/T'$$

  - **Tables of coefficients and integration constants**
    - **More than one temperature range for some materials**
    - **Discontinuities define phase changes**

MELCOR/CORCON MCCI Models
Other Materials Properties

- **Density**
  - **Constant expansion coefficient for condensed materials**
    $$v(T) = v(T_0)[1 + c(T - T_0)]$$
  - **Ideal gas law for gases**
- **Viscosity**
  - **Andrade form**
    $$\mu = \mu^0 \; e^{\alpha/T}$$
- **Thermal conductivity and surface tension**
  - **Tabulated constants**
- **Emissivity**
  - **User input**

MELCOR/CORCON MCCI Models
Mixture Properties

- **Density**
  - Mass-weighted specific volume
- **Thermal conductivity, surface tension**
  - Mole-weighted average
- **Viscosity**
  - Iron viscosity used for all metals
  - FeO, Al_2O_3, UO_2, CaO, ZrO_2, Cr_2O_3 implemented for oxides
    - ZrO_2 and Cr_2O_3 by analogy with UO_2 and FeO
  - Kendell-Monroe expression used for low-SiO_2 oxides

$$\mu = \left(\sum_i x_i \, \mu_i^{1/3} \right)^3$$

MELCOR/CORCON MCCI Models
Mixture Properties (2)

- Shaw correlation used for high-SiO2 oxides

$$\mu = \exp\left[s\left(\frac{10^4}{T} - 1.50 \right) - 6.40 \right]$$

- **Viscosity enhancement multiplier for presence of solids**
  - Kunitz correlation (default)

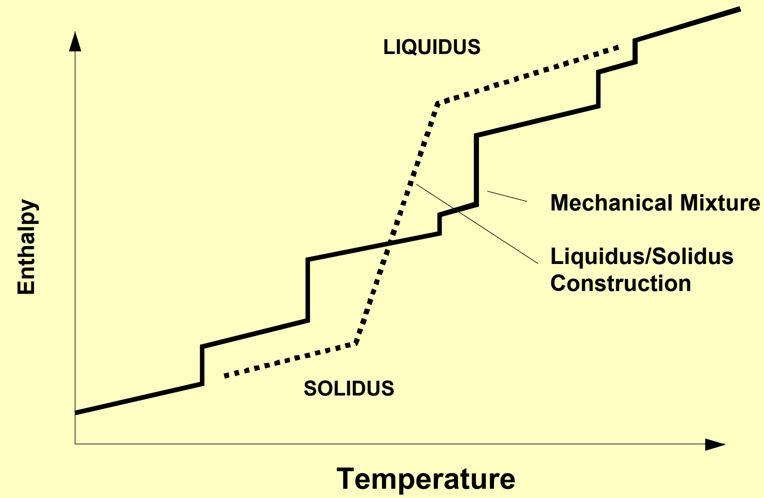
$$\mu = \mu_m \left[\frac{1 + \phi / 2}{(1 - \phi)^4} \right]$$

  - Ramacciotti (new)

$$\mu = \mu_m e^{2.5 C \phi}$$

MELCOR/CORCON MCCI Models
Phase Diagrams

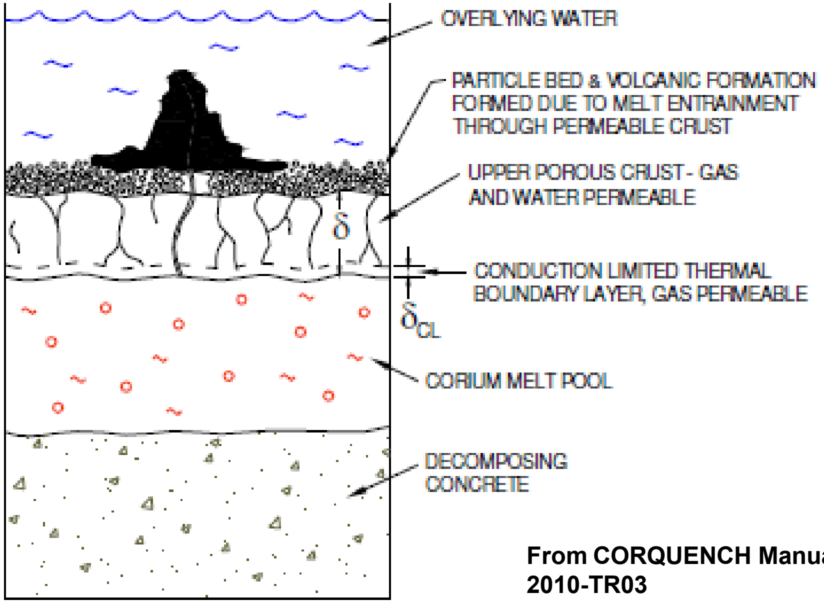
- CORCON has very **simple phase diagrams**
  - See CORCON-Mod3 Manual for details
- **Neglects** many species and interactions
- Only effect considered is on **melt range**



- Extrapolate solid and liquid enthalpies if necessary
- Add latent heat, linear with temperature, between solidus and liquidus

New Models from CORQUENCH

- **MCCI results indicate two new effects**
  - Water ingress into top crust
  - Melt eruption through top crust forming debris layer



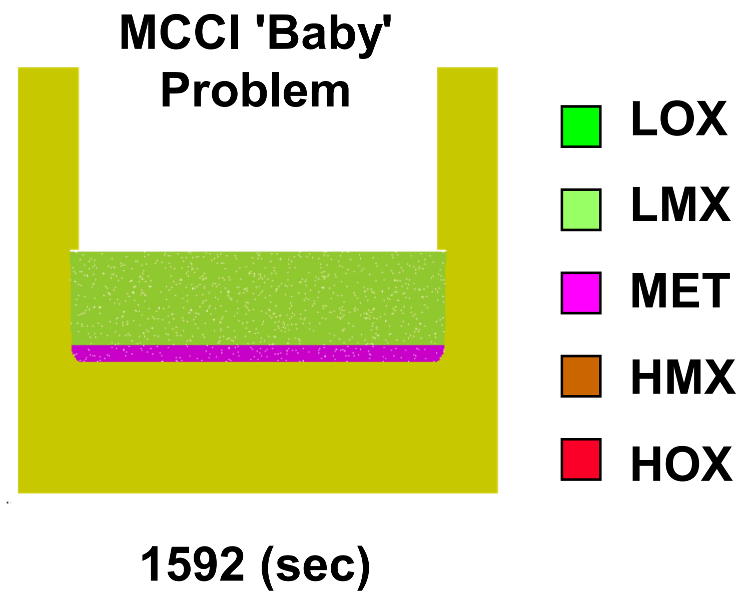
From CORQUENCH Manual OECD/MCCI-2010-TR03

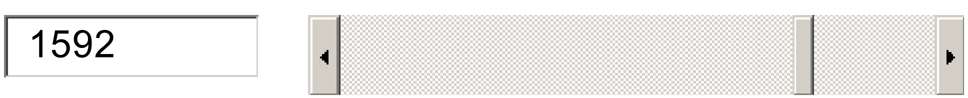
New Models (2)

- Implemented as new layers in CAV
- Water-permeable top crust layer
  - Rate of growth, conduction zone thickness from Epstein, “Dryout Heat Flux During Penetration of Water Into Solidifying Rock” (2006)
- Debris layer
  - Formed with user-input debris size, void fraction
  - Entrainment rate from Ricou-Spalding correlation
- Models still being tested

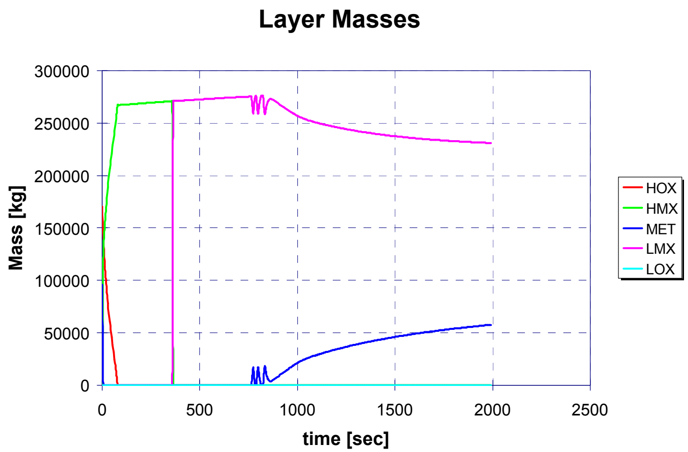
MELCOR/CORCON MCCI Models Demonstration 'Baby' Problem

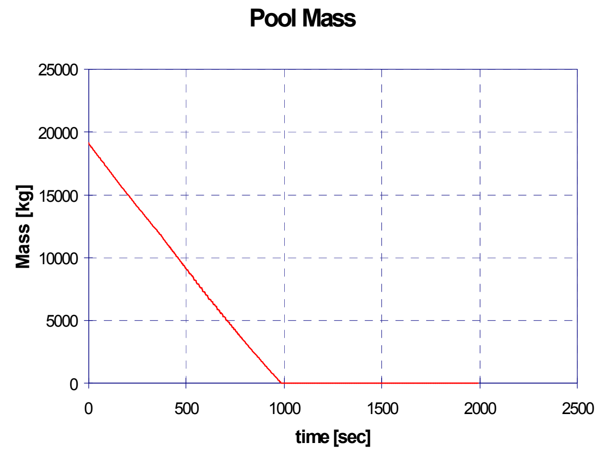
- **Initial Inventory**
  - Oxides (TEMP = 2300.)
    - UO2   1.0E5
    - ZRO2 2.0E4
    - FEO   5.0E4
  - Metals (TEMP = 2300.)
    - ZR   1.0E4
    - FE   7.0E4
    - CR   1.0E4
    - NI   6.0E3
- **Model Assumptions**
  - Limestone/common sand concrete
  - No reinforcing bar
  - Calculated mixing (not MELCOR default)
  - CORCON-Mod2 chemistry (not MELCOR default)

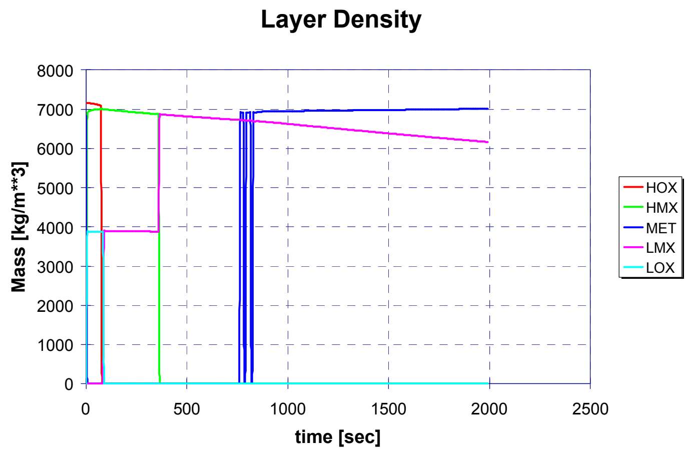


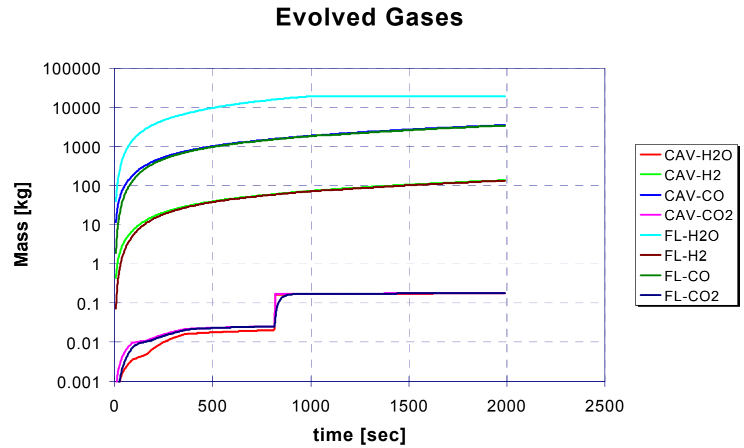


MELCOR/CORCON MCCI Models Examples: Base Case

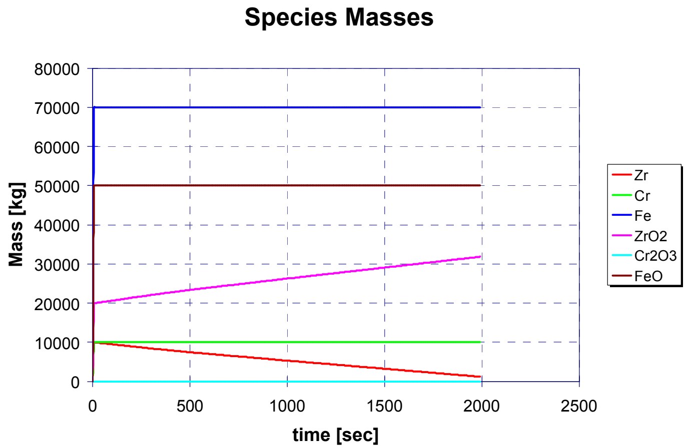


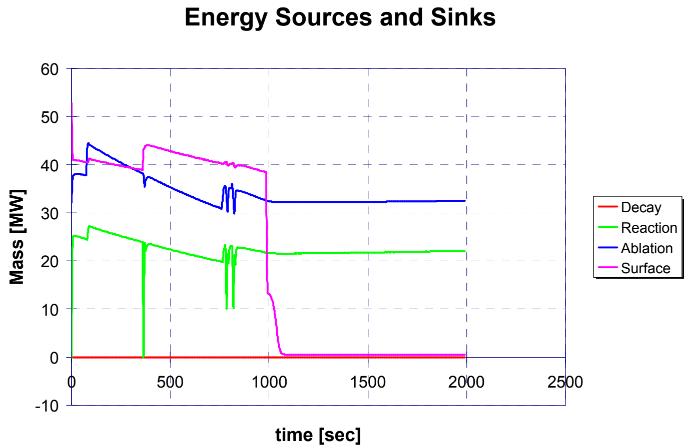






MELCOR/CORCON MCCI Models Examples: Base Case (2)





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