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Injectable Sacrificial Material System to Contain Ex-Vessel Molten Corium in Nuclear Accidents

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NNSA National Nuclear Security Administration

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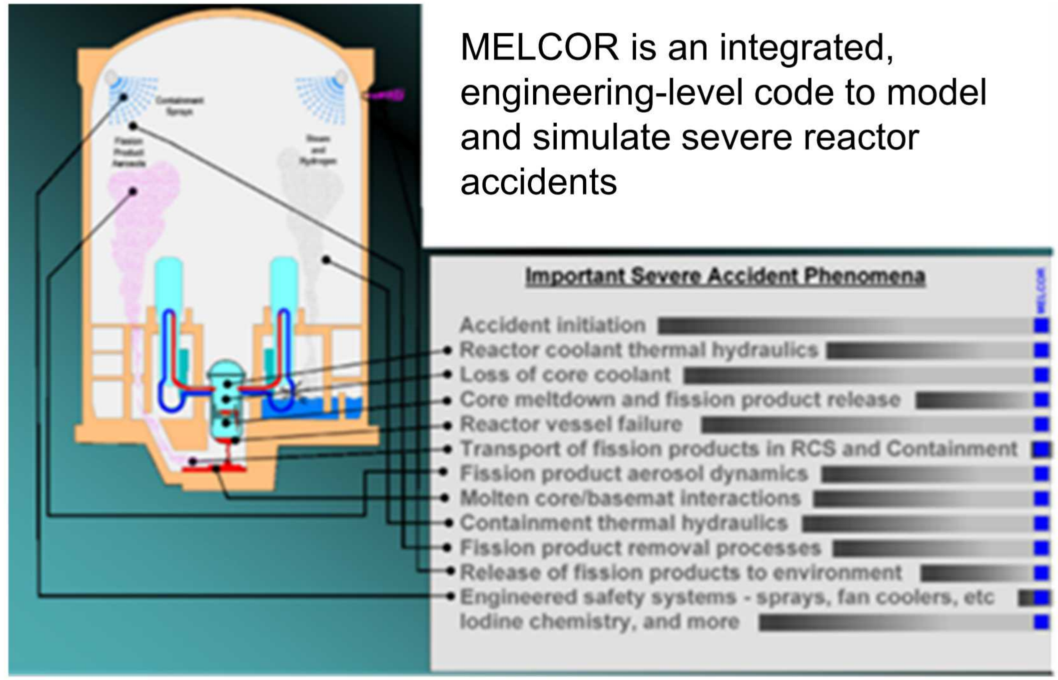
Outline

- Why Injectable sacrificial material (SM) system?
- Novel SM concept
- Experimental works
- Modeling works



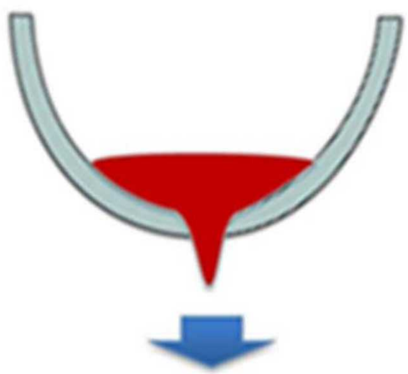
- Injectable SM delivery system
- Testing of the system using MELCOR
- Summary and Path forward

Why Injectable SM system?

- Core catcher device and SM solid systems (i.e., ceramic and concrete slabs) in new reactor designs
  - Difficult to implement into existing operating reactors
- Injectable SM system easily retrofits to existing reactors
- It also provides flexibility to new reactor designs

Sandia SM Concept

- Utilize the injectable SM system so even existing reactors could be retrofit
- Proposes to SM to be carbonate-mineral based granular material

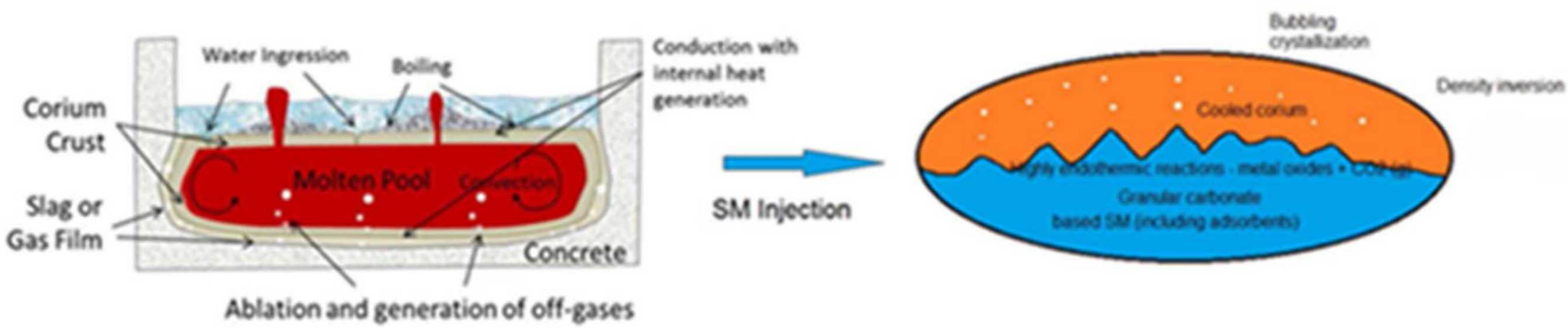


Major Reactions:

$CaCO_3 \rightarrow CaO + CO_2$

$FeCO_3 \rightarrow FeO + CO_2$

$Zr + FeO \rightarrow Fe + ZrO_2$

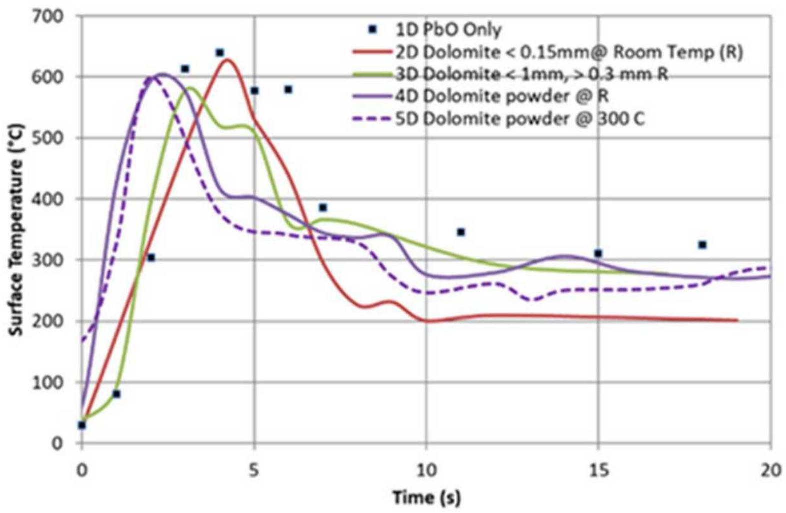


Demonstration of Concept

- Experimental Front
  - Benchtop exploratory experiments conduced as experiments to scope the important parameters of the concept
    - Use PbO as surrogate material for corium and use Mg and Ca based carbonate minerals for SM materials
    - Using compatible crucible to conduct experiments with one to two furnaces
  - Larger scaled tests at the SURTSEY facility are underway
- Modeling Front
  - Modeling effort using Sandia's Sierra Mechanics–Aria for PbO-SM experiments and simulated reactor accident scenario from MELCOR
  - Aria – simulate the detailed corium spreading for MELCOR accident scenario. Use new model to update MELCOR reduced order model
  - Aria – models the PbO melt and carbonate reaction
  - Theoretical feasibility study was conducted on the injectable SM delivery system for the current U.S. commercial LWRs.

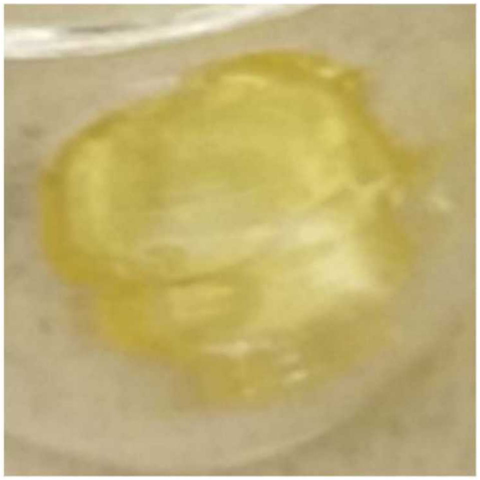
Benchtop Experiments

- Use a surrogate system – MCO_3-PbO to avoid very high temperature and cost
- Corium: PbO ~ density similar to UO2, melts at 880 C
- SM: MCO3 – decomposition energies–endothermic reactions
  - CaCO3 – 179.1 kJ/mole, MgCO3 –100.7 kJ/mole
  - Over 20 benchtop experiments conducted – including carbonate minerals (i.e., calcite, dolomite and magnesite)
    - Small crucible contains PbO heating at 950 to 975 C
    - MCO3 bed at room temperature or at elevated temperatures (550 C for CaCO3)
    - Video and surface temperatures

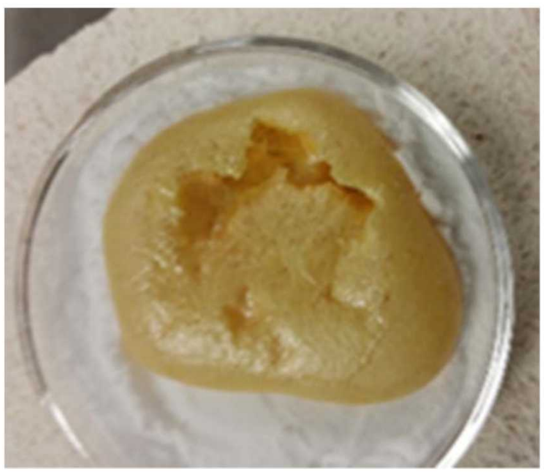


Infrared Surface Temperature Measured in the D-Series Experiments. R temperature ranges from 22 to 24 °C. (Note the peak temperature as shown reflects the pouring of the melt into the carbonate bed.)

Benchtop Experiment Results (1)

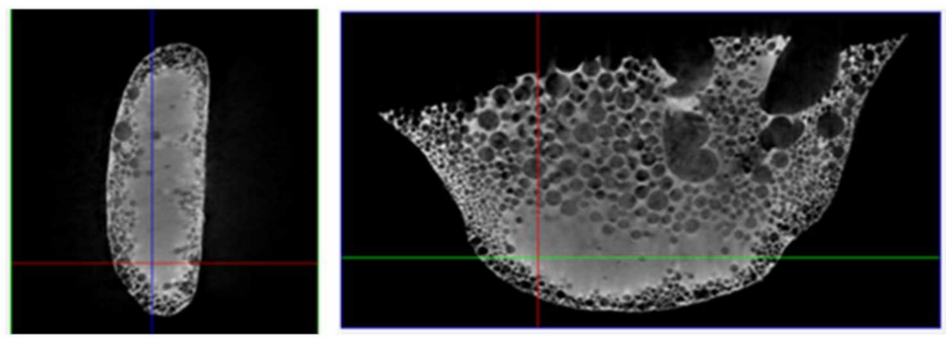


(a) Unreacted PbO



(b) PbO reacted in 550 °C $CaCO_3$ powder (6C test)

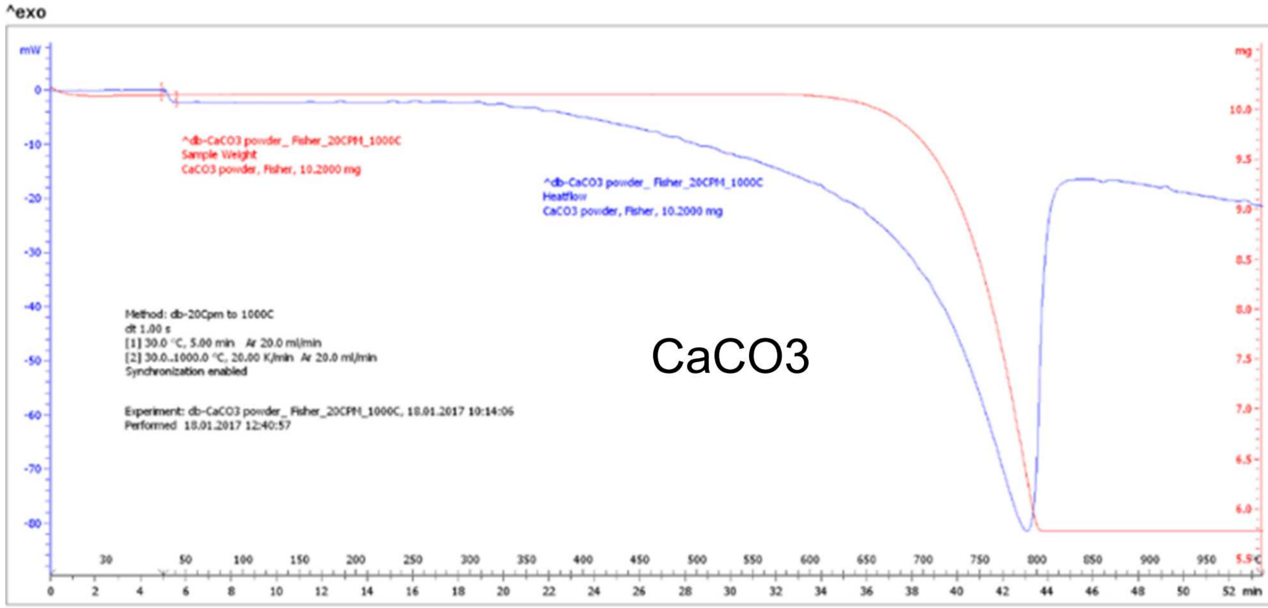
(c) PbO reacted in 22 °C dolomite of sizes between 0.3 and 1 mm (3D test)

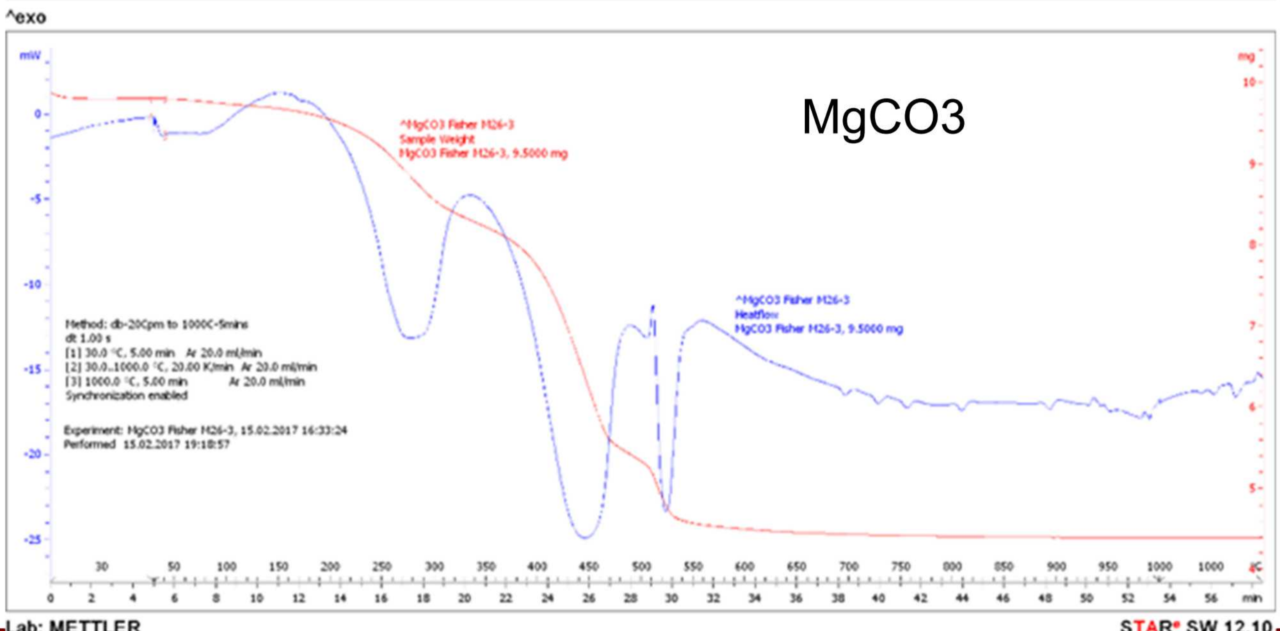


X-ray micro CT imaging of solidified PbO melt (4B test with $CaCO_3$ at 24 °C). The diameters of the largest bubbles are ~ 0.1 mm

Benchtop Experiment Results (2)

TGA Measurements





Modeling using SIERRA/Aria

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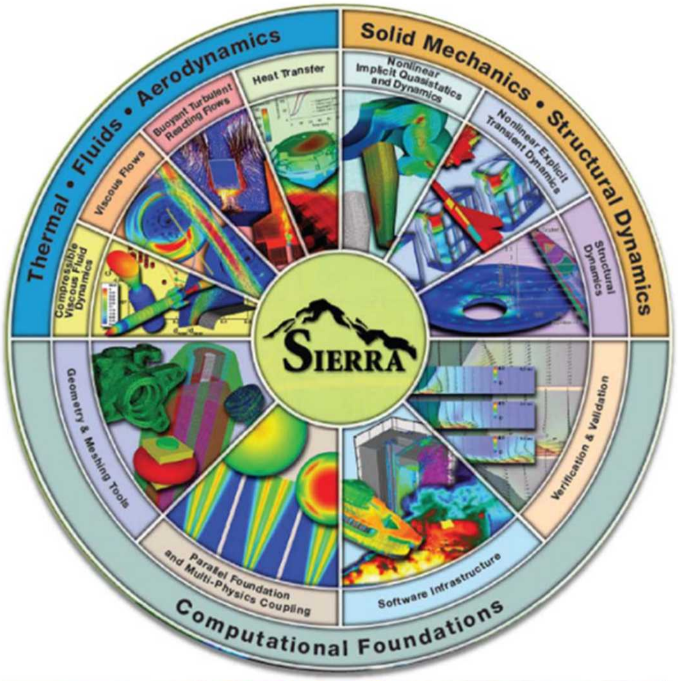
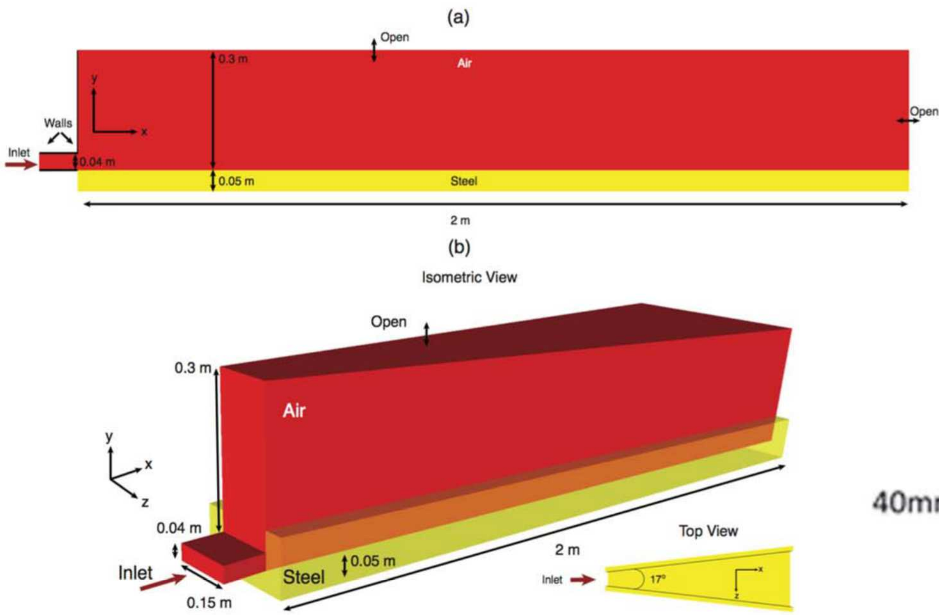
- Motivation: Extend reactor safety using detailed multi-physics modeling (using SIERRA/Aria)
  - Aria – multi-physics, chemistry, fluid, free surface, heat transfer.
  - Develop more accurate model to help understand molten reactor material transport in severe reactor accidents
- Enhance ability to model corium flow
  - Multiphase flow and heat transfer
  - Follow surface topology and material breakup with level-set based free surface flow algorithms
  - Implement stabilized finite-element methodologies



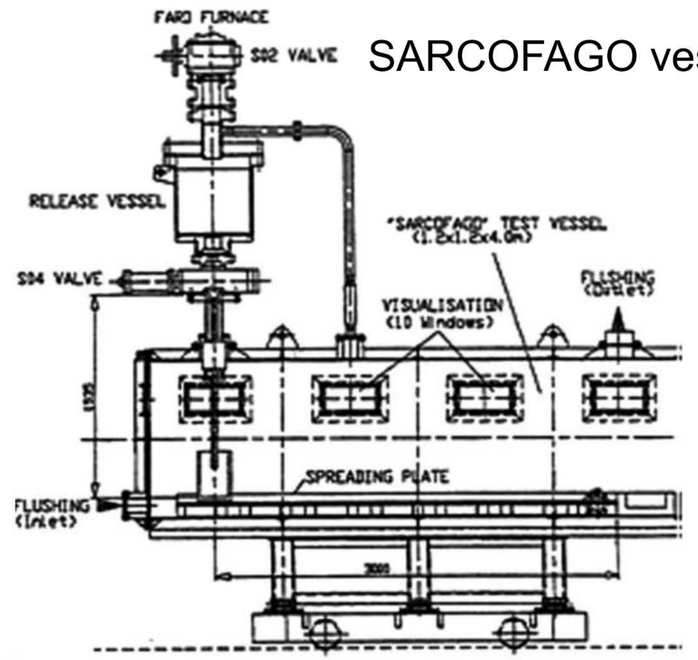
C. Journeau et al., Progress in Nuclear Energy 48 (2006) 215-234

FARO L26 Corium Spreading Exp.

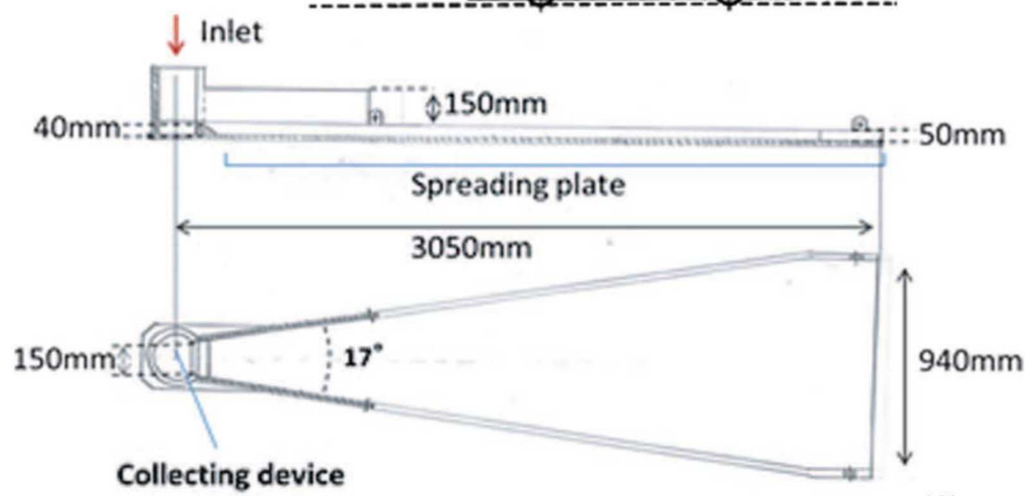
- Approximately 160 kg - 80% UO_2, 20% ZrO_2
- Spreading plate – stainless steel
- Pressure constant



Geometry for simulations of corium spreading in the FARO L26s experiment (a) 2D geometry (b) 3D geometry



SARCOFAGO vessel



Methodology

- Incompressible Navier-Stokes equations with heat transfer

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\mathbf{u}\right) = -\nabla p + \nabla\cdot\left(\mu\left(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}}\right)\right)$$

$$\rho C_{\mathrm{P}}\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) - \nabla\cdot(k\nabla T) = \dot{q}$$

- Corium/Air interface, Γ_{F} :

$$[\mathbf{u}]_{\Delta} = 0, \qquad \mathbf{x}\in\Gamma_{\mathrm{F}}$$

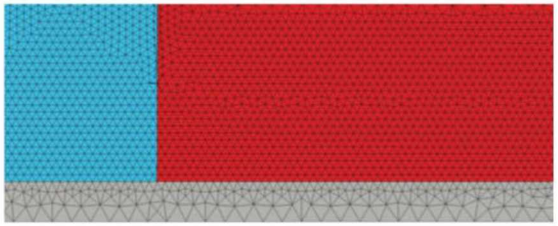
$$[-p\mathbf{I} + \mu(\mathbf{x})\left(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}}\right)]_{\Delta}\cdot\hat{\mathbf{n}} = -\gamma\kappa\hat{\mathbf{n}}, \qquad \mathbf{x}\in\Gamma_{\mathrm{F}}$$

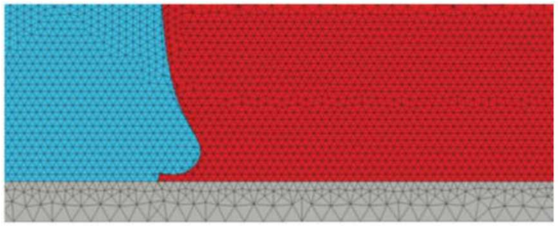
- Interface movement (level set)

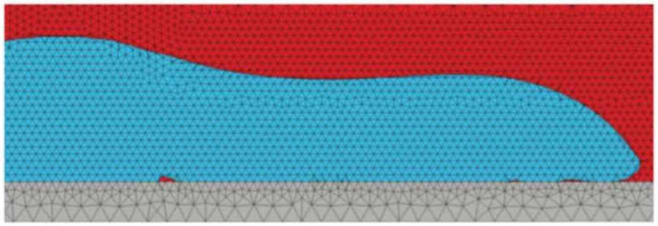
$$\frac{\partial \phi}{\partial t} + (\mathbf{u}\cdot\nabla)\,\phi = 0$$

Conformal Decomposition Finite Element Method (CDFEM) Used

- Properties
  - Supports wide variety of interfacial conditions (identical to boundary fitted mesh)
  - Avoids manual generation of boundary fitted mesh
  - Supports general topological evolution (subject to mesh resolution)
- Similar to finite element adaptivity
  - Uses standard finite element assembly including data structures, interpolation, quadrature
- Modeling the molten flowing corium poses challenges for numerical models due to presence of large Peclet numbers and Reynolds numbers
  - GFEM technique is inadequate for suppressing spurious oscillations
  - CVFEM discretization for advection dominated flow and heat transport
  - CDFEM tracks the corium/air interface on an existing background mesh
- CVFEM-CDFEM approach
  - Spreading of molten corium in 2D and 3D
  - CVFEM formulation suppress spurious oscillations associated with high Pe and Re flow regimes





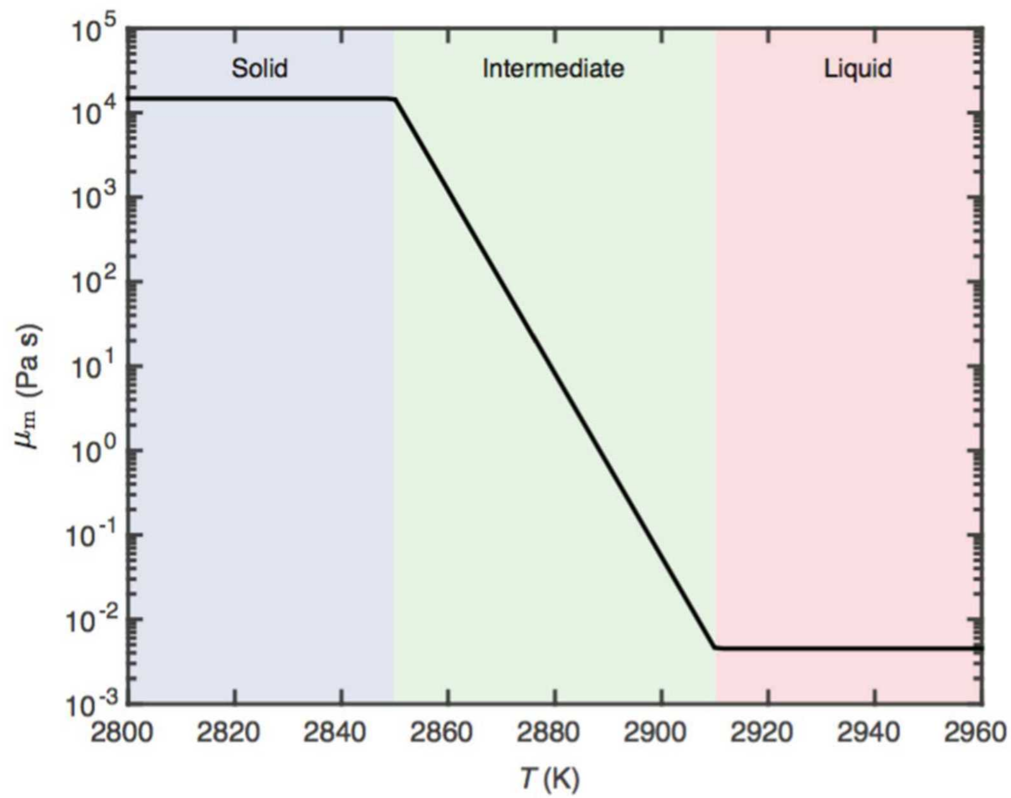


Viscosity model

- Ramacciotti (2001) temperature-dependent viscosity model used for psuedo-solidification.

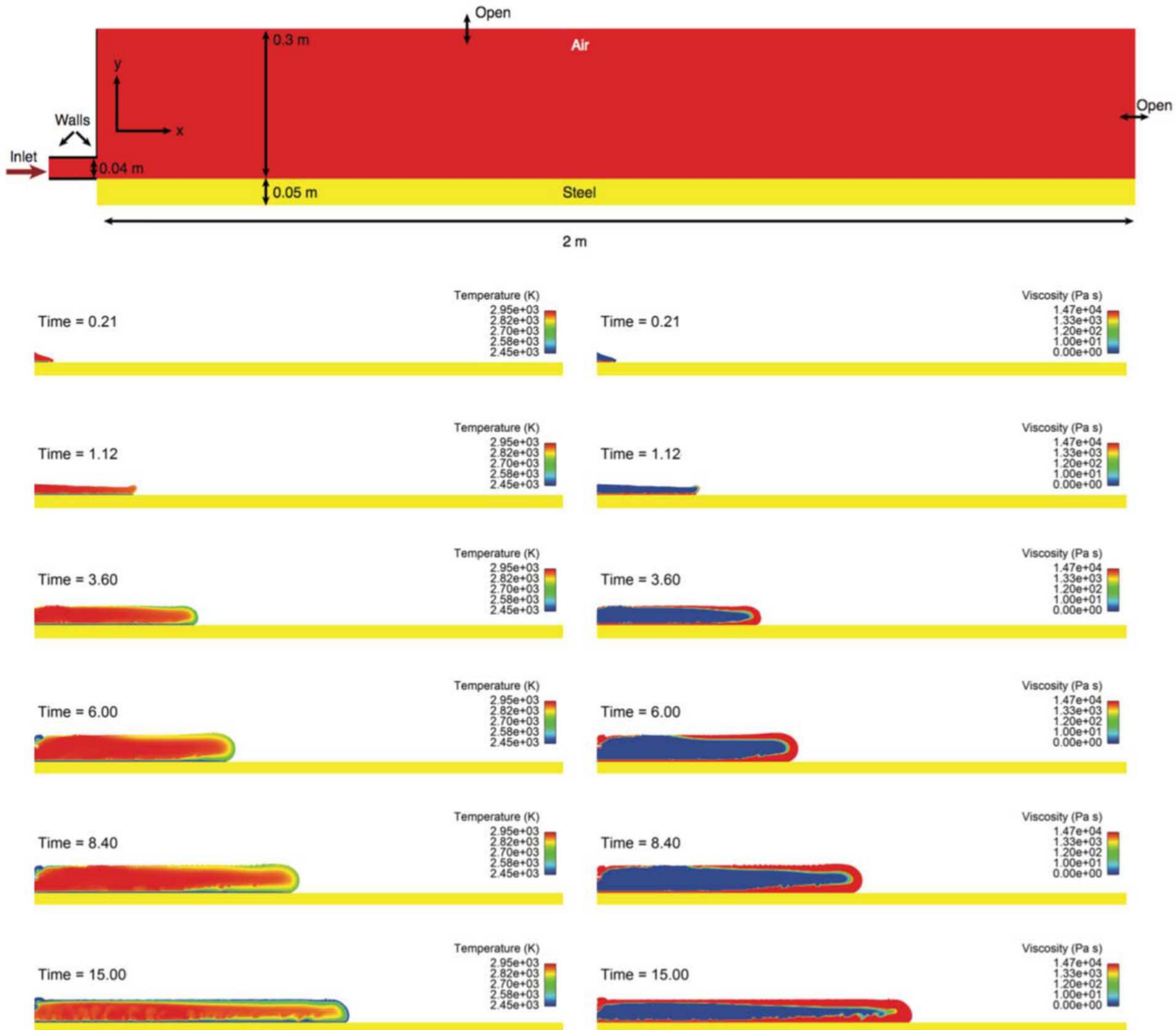
$$f = \frac{T_L - T}{T_L - T_S}$$

$$\mu_m = \mu_L e^{2.5 \cdot C \cdot f}$$



Viscosity as a function of temperature (Ramacciotti, 2001)

2D Corium Spread Modeling



2D Corium Spread Modeling (cont.)

3D Corium Spread Modeling

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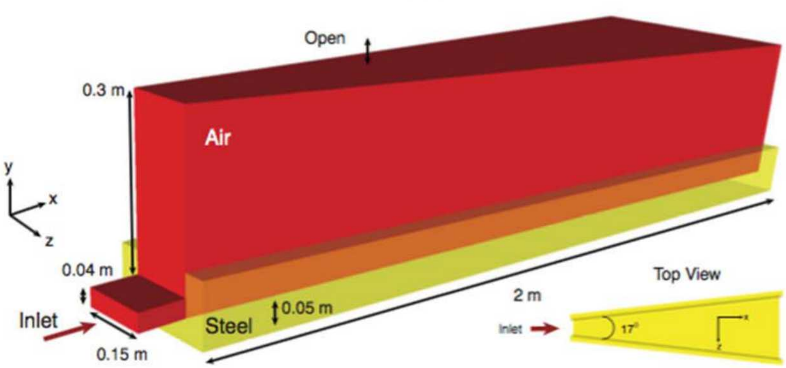
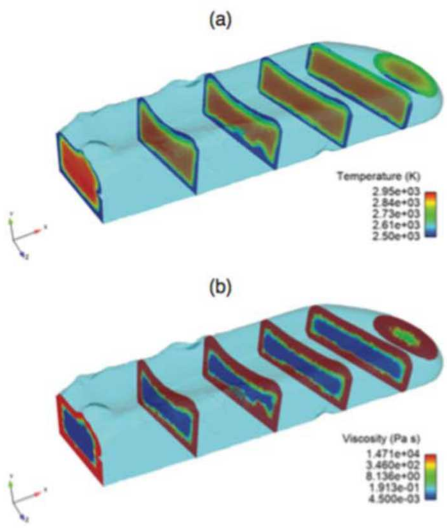




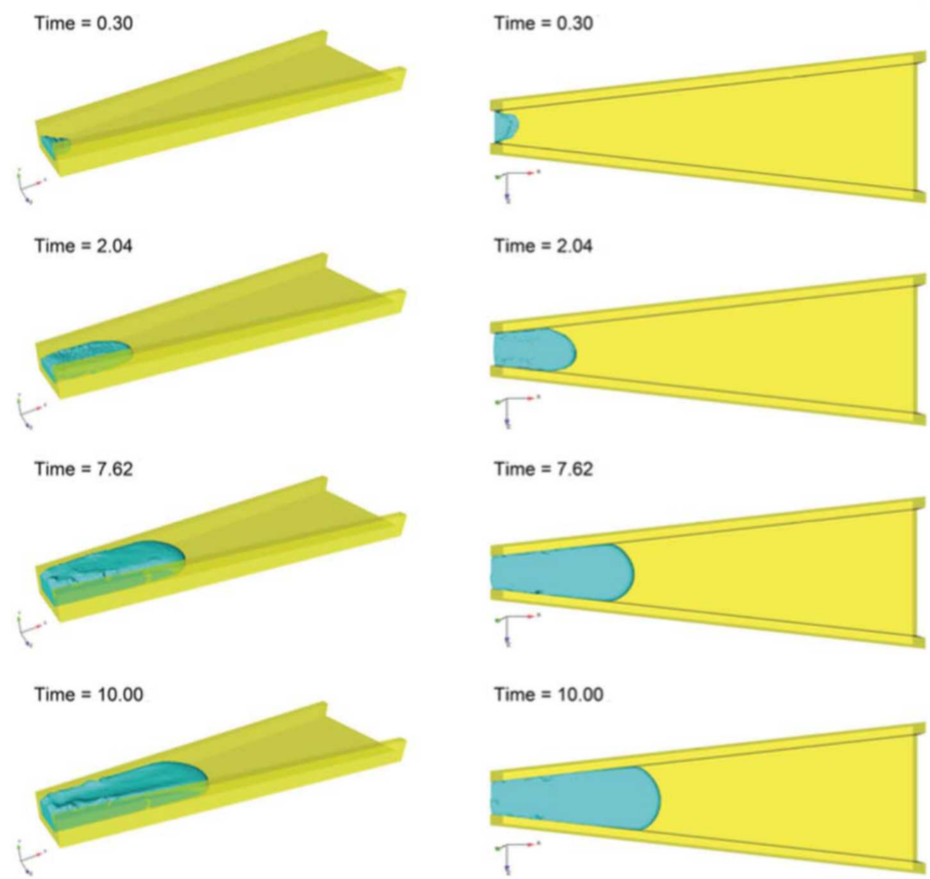
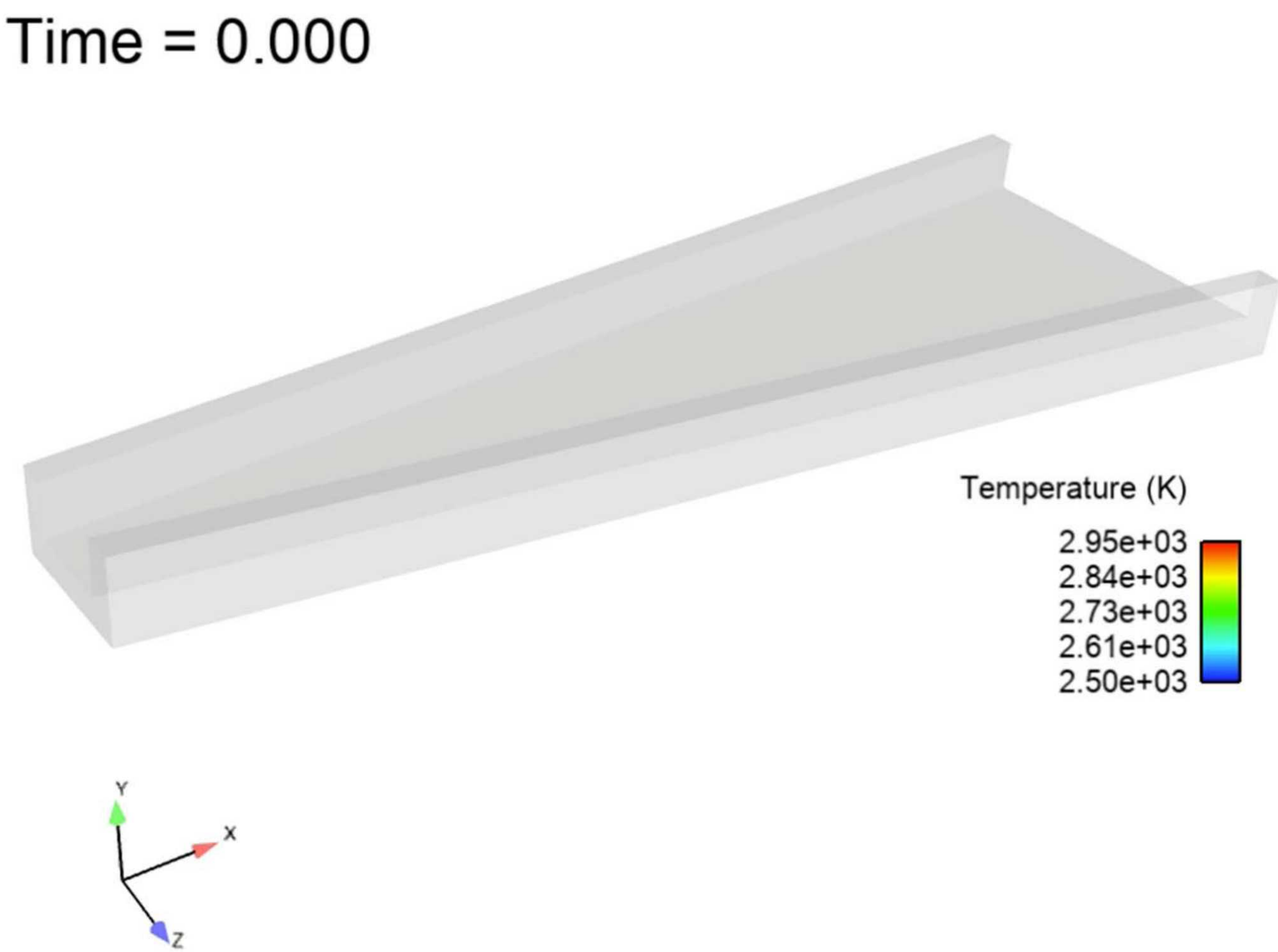


Figure 12: Contours of (a) temperature and (b) viscosity taken at a time snapshot t = 10 s at various (y-z) planes showing the three-dimensional effects of the melt solidification process.

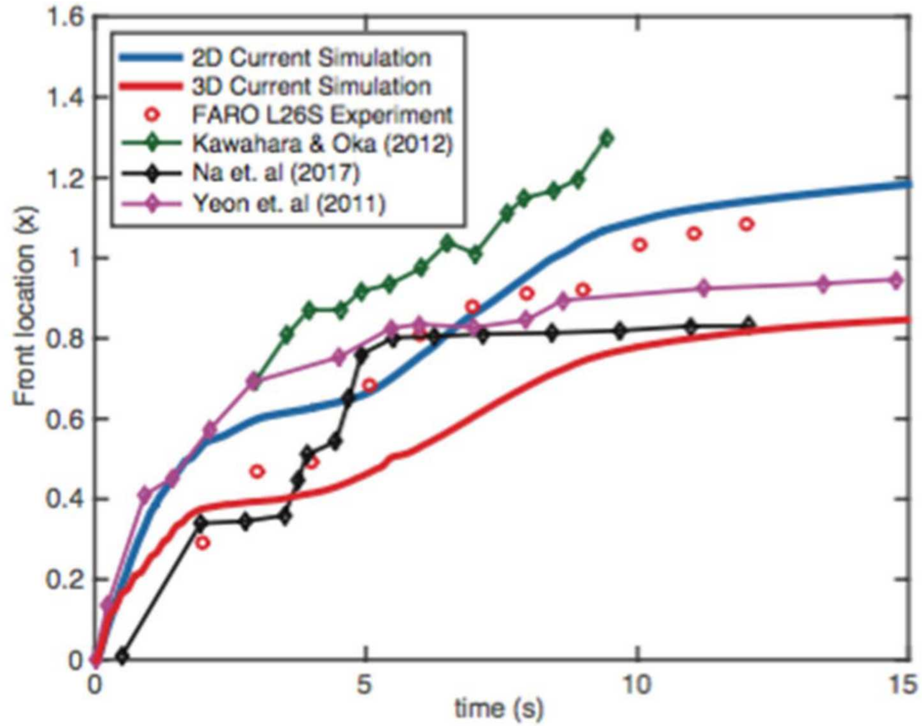
Figure 11: Material phase blocks of the melt (blue), and steel (yellow) as a function of time as the melt spreads and solidifies for the 3D simulation in an isometric view (left) and top-down view (right). First evidence of solidification occurs at t = 2.04 s.

3D Corium Spread Modeling (cont.)



2D Corium Spreading

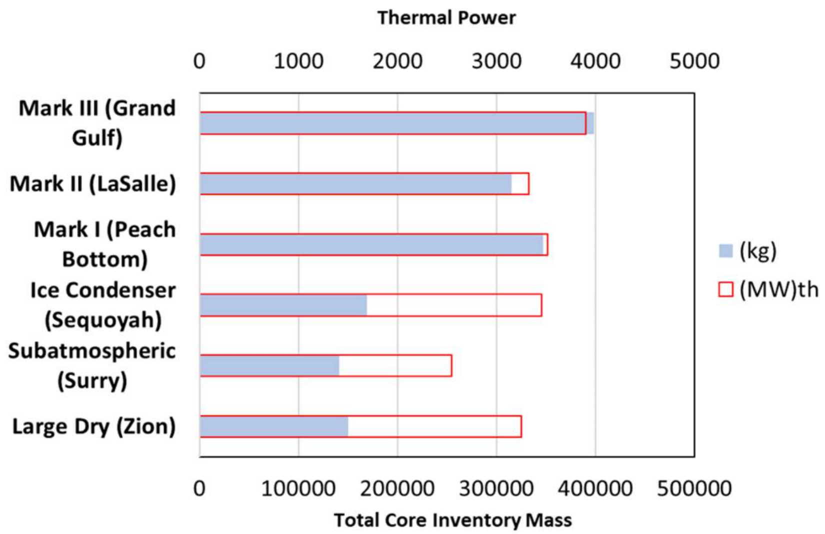
- FARO-L26s Experiment simulated – 80% UO_2, 20% ZrO_2
- 2D/3D simulations completed
- Heat loss through the melt boundary modeled
- Psuedo-solidification modeled using Ramacciotti viscosity model.
- Excellent agreement with experiments

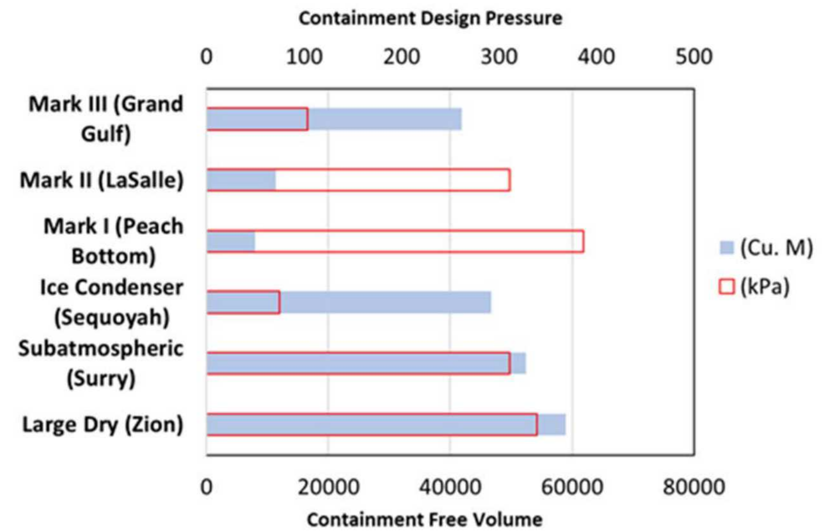


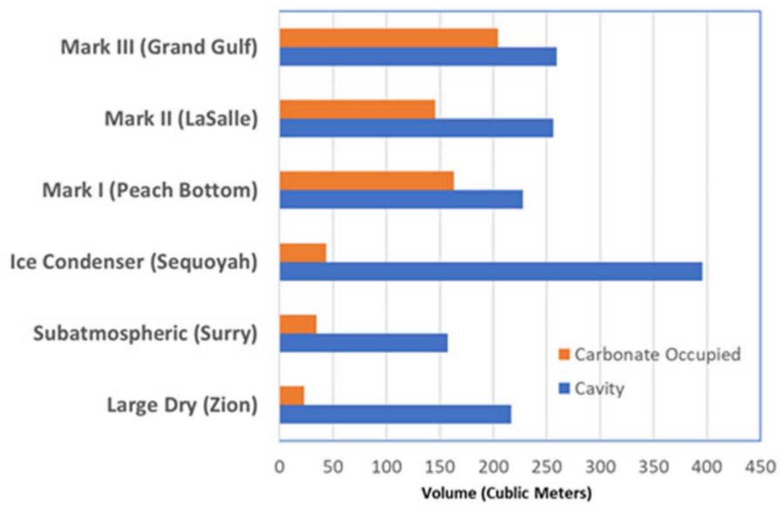
Simulation results compared to experiment and other computations

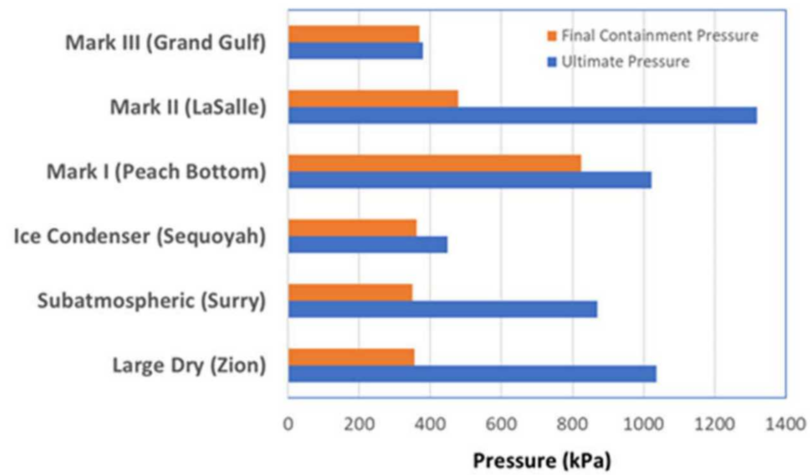
Feasibility Study on Granular SM Delivery System

- Six LWR Plant Designs of U.S. have been simulated, and require granular SM needed to contain an ex-vessel breach accident



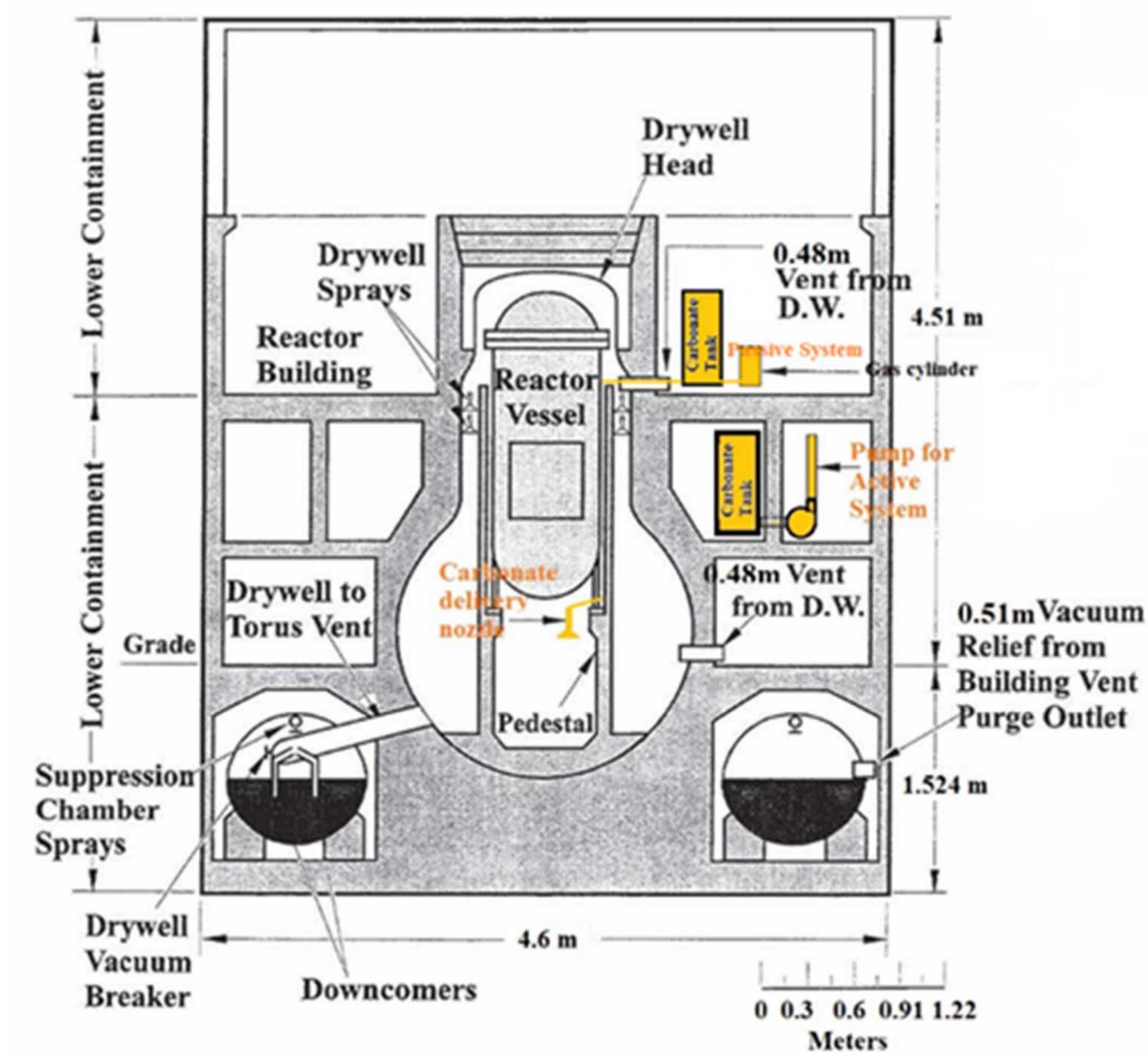






SM Granular Delivery System

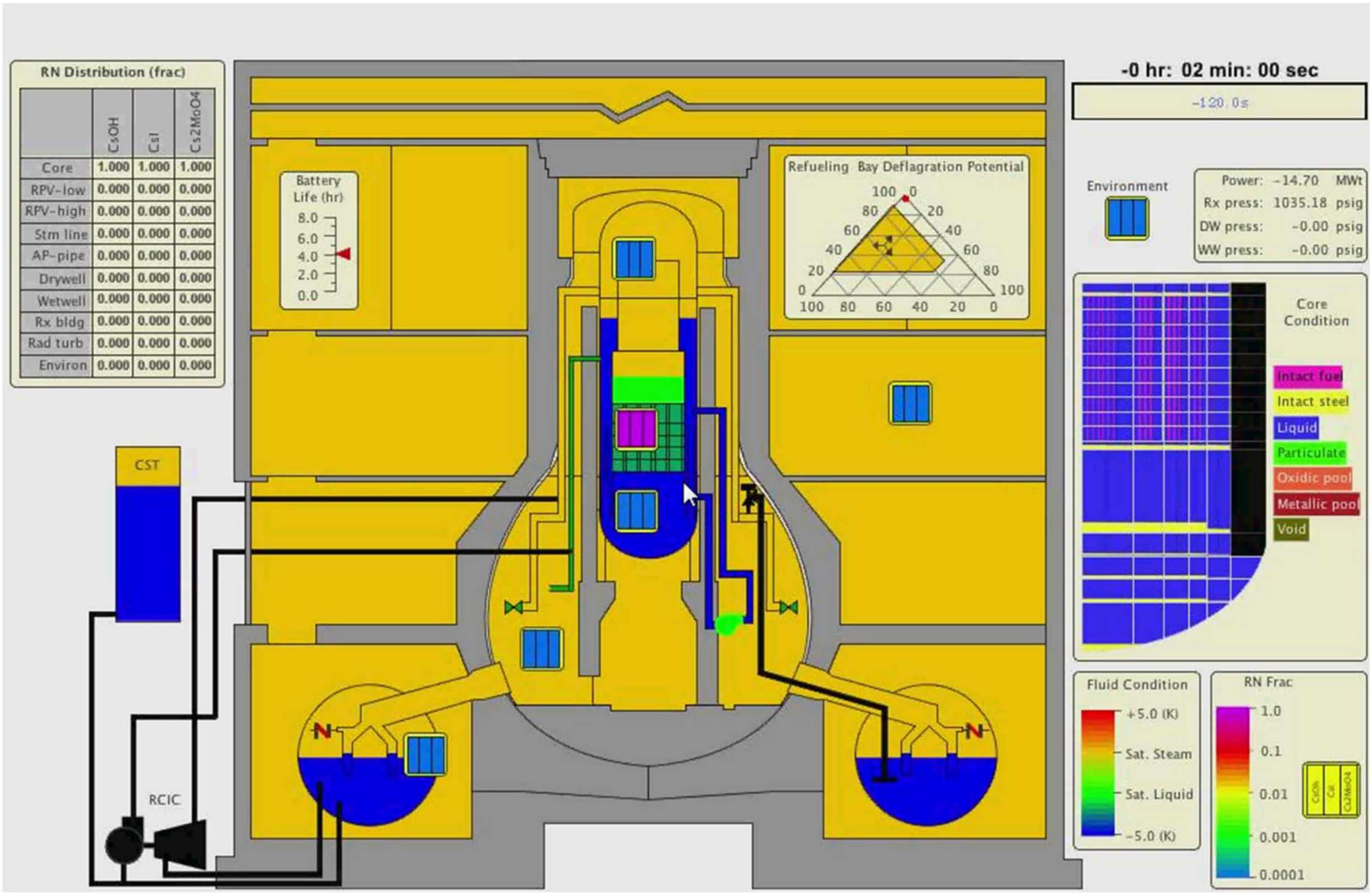
- Injection must be done before anticipated lower head failure:
  - Presence of the carbonates may delay the lower head failure by removing the heat from the lower head
  - Molten corium would fall onto a carbonate bed that reacts quickly to solidify and generate open porosity structures
  - Decomposition of carbonates would also allow the atmosphere of the containment to be cooled
  - Generation of CO2 from the decomposition would displace the other gases, such as hydrogen and oxygen. Thus, it reduces the potential for hydrogen explosions
- Two delivery systems have been investigated, depending on the final size of the carbonate granular used.
  - Ranging from mm to cm
  - Considering passive and active systems
- Testing of the system using MELCOR code



Lower Containment
Lower Containment
Drywell Head
Drywell Sprays
Reactor Building
Reactor Vessel
0.48m Vent from D.W.
4.51 m
Carbonate Tank
Carbonate Tank
Drywell to Torus Vent
Grade
0.48m Vent from D.W.
0.51m Vacuum Relief from Building Vent Purge Outlet
Pedestal
Suppression Chamber Sprays
1.524 m
Drywell Vacuum Breaker
Downcomers
4.6 m
0 0.3 0.6 0.91 1.22
Meters

MELCOR Simulation Example

SBO Progression – Peach Bottom (Mark I) – No Injectable SM added



Path forward

- This FY, we have demonstrated:
  - Calcite (minerals of $CaCO_3$) and dolomite (minerals of $MgCO_3$ and $CaCO_3$), including pure $CaCO_3$ can be used as SM for cooling melt (PbO) effectively
  - Creating open pore material structures that can be subsequently cooled by water, ideally for the severe nuclear reactor accident management.
  - SIERRA/Aria model can be used to model molten corium spreading (demonstrated in a corium spreading experiment).
  - Analysis performed to develop an injectable SM delivering system for the common six existing light water reactor plants in the U.S.
- FY19, we will develop models:
  - PbO/carbonate experiments and corium/carbonate interactions using Aria
  - Using Aria to develop a lower level model for MELCOR to demonstrate the concept for this LDRD project
- Patent application in progress.
- Seek sponsors and collaborations to conduct large scaled tests

Acknowledgement

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