

MELCOR

New Modeling

SQA

Utilities



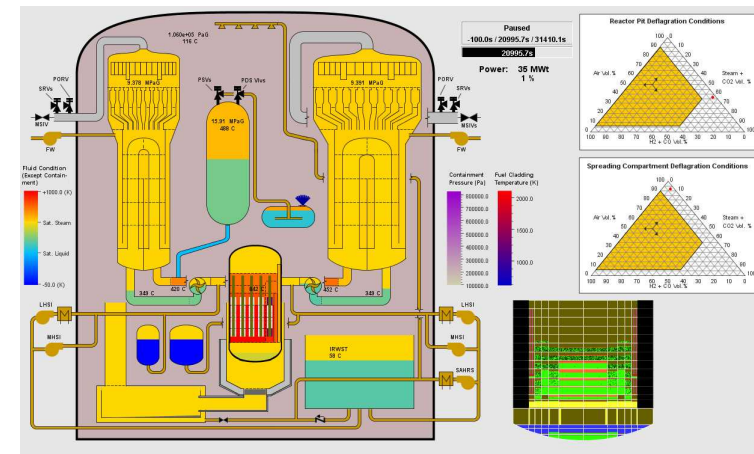
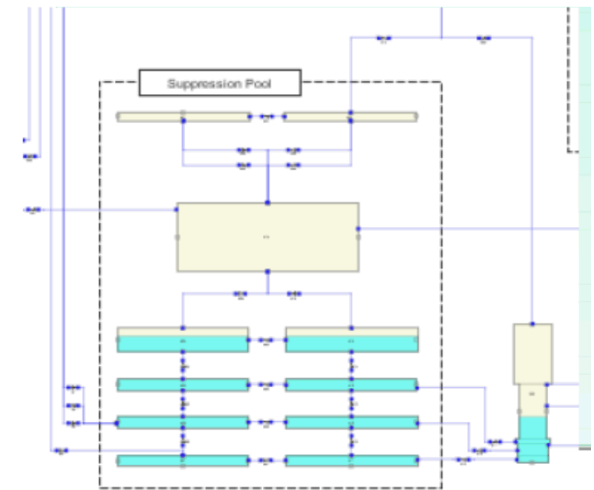
# Recent Developments of the MELCOR Integral Code for Modeling Severe Accidents- July 17-21, 2017

Presented by Larry Humphries  
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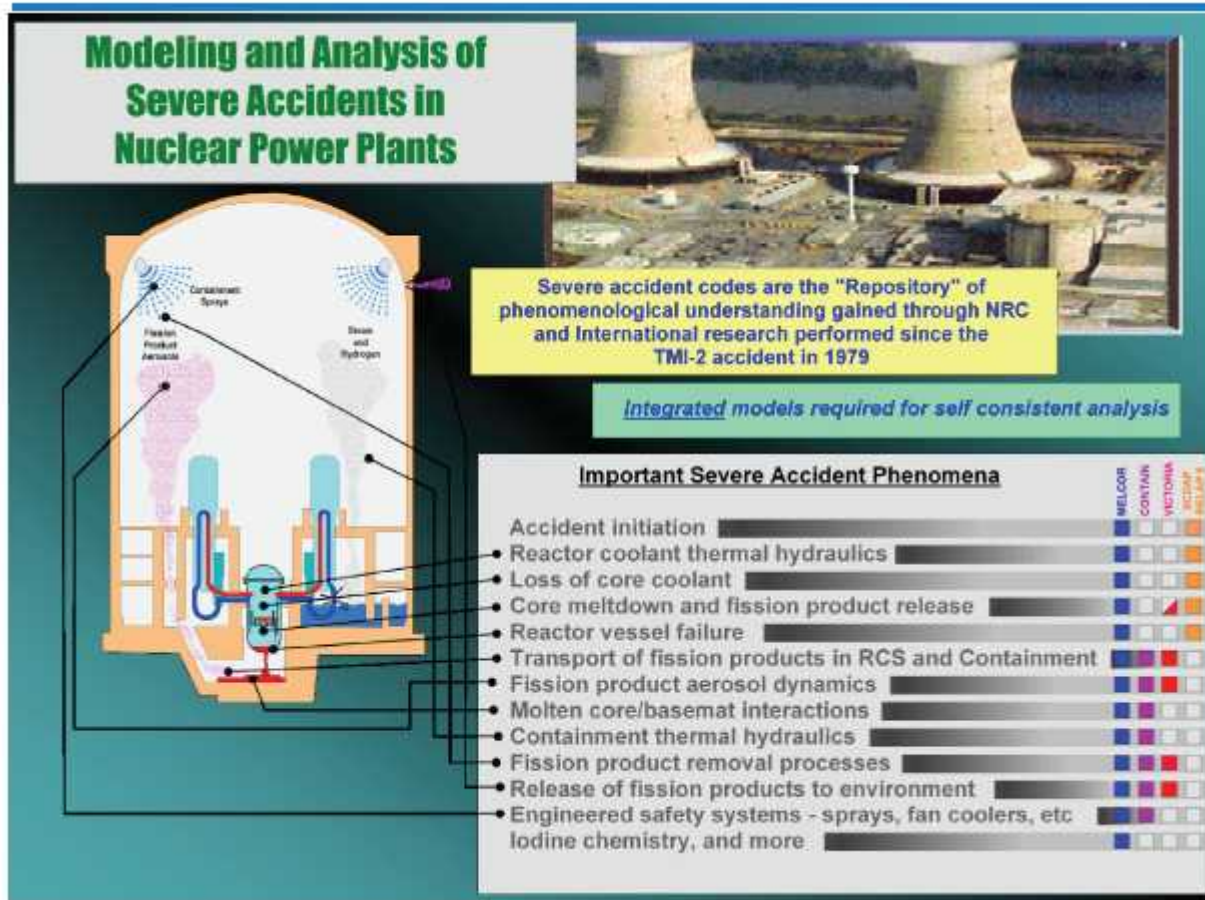
# What is Required of a Severe

# Accident Code

- Fully Integrated, engineering-level code
  - Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
  - Core heat-up, degradation, and relocation;
  - Core-concrete attack;
  - Hydrogen production, transport, and combustion;
  - Fission product release and transport behavior
- Application
  - User constructs models from basic constructs
    - Control volumes, flow paths, heat structures,
  - Multiple 'CORE' designs
    - PWR, BWR, HTGR (Pebble Bed & PMR), PWR-SFP, BWR-SFP, SMR, Sodium (Containment)
  - Adaptability to new reactor designs
- Validated physical models
  - ISPs, benchmarks, experiments, accidents
- Uncertainty Analysis
  - Relatively fast-running
  - Characterized numerical variance
- User Convenience
  - Windows/Linux versions
  - Utilities for constructing input decks (GUI)
  - Capabilities for post-processing, visualization
  - Extensive documentation



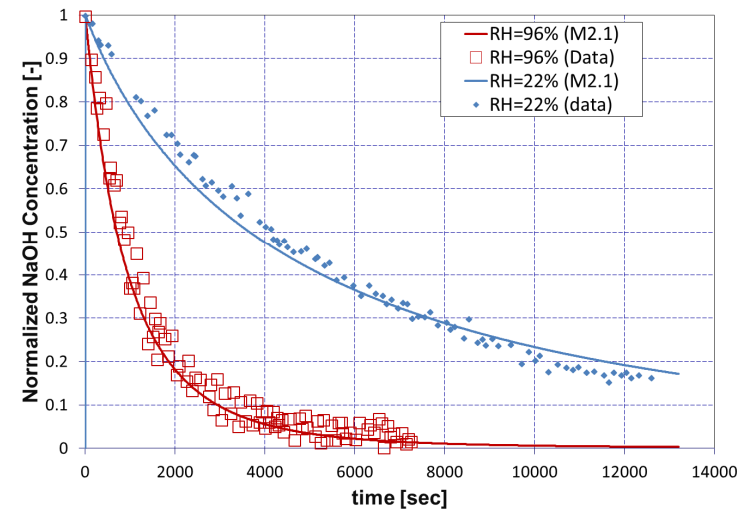
# MELCOR Equation set represents models for a host of Severe Accident Phenomena



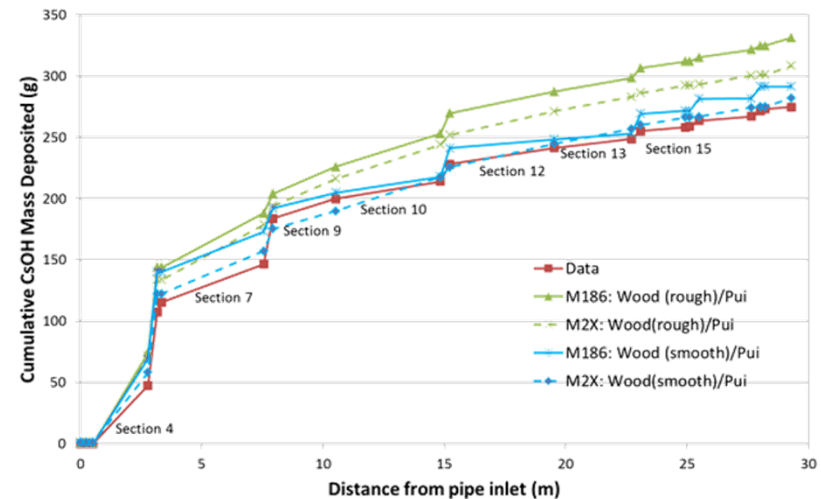
# Radionuclide Package

- Tracks the release and transport of
  - Fission product vapors & aerosols
  - Non-radioactive masses such as water, concrete, etc.
  - Traces hosted by other materials
    - Negligible volume and heat capacity
- Aerosol physics
  - MAEROS
- Agglomeration of aerosols
  - Several mechanisms cause collisions and sticking to produce larger particles
    - Brownian diffusion
    - Differential gravitational settling
    - Turbulent agglomerating by shear and inertial forces
- Hygroscopic effects
- Condensation & evaporation
  - TRAP-MELT
- Deposition on surfaces
  - Modeled as always sticking to surfaces contacted
  - Several mechanisms drive aerosols to surfaces
    - Gravity
    - Brownian diffusion
    - Thermophoresis
    - Diffusiophoresis
    - Turbulent deposition
- Pool Scrubbing
  - SPARC
- Validation
  - ABCOVE, ACE, AHMED, DEMONA, LACE, LOFT, PHEBUS, POSEIDON, STORM, ...

## AHMED – Hygroscopic Effects



## LA3 – Turbulent Deposition

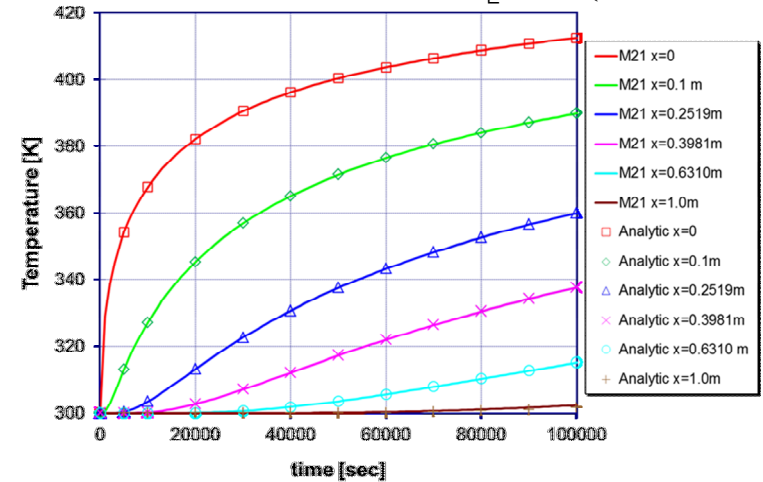


# Heat Structure Package

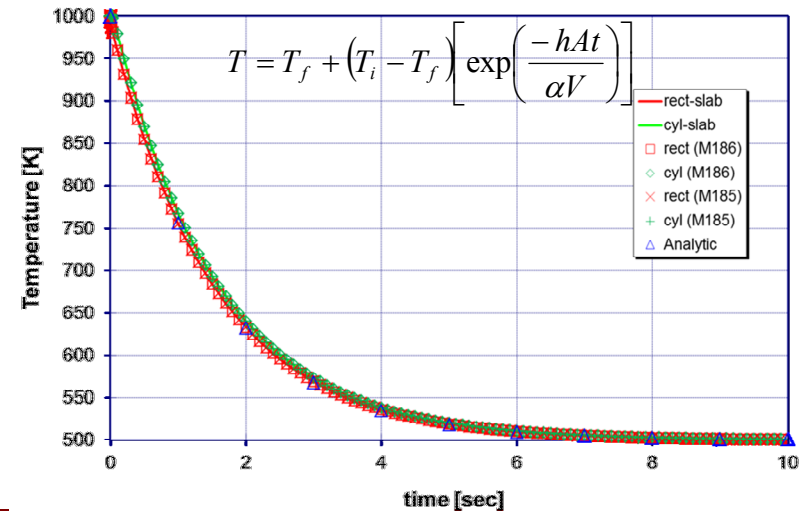
- Used to model containment objects (Walls, floors, ceilings), system structural components (steam generator tubes, piping, tank walls), some reactor core components (shroud, upper core components)
  - Not used for most reactor components
- One-dimensional heat transfer
  - Multi-material nodes
- Condensation at surfaces
- Multiple boundary conditions (convective, etc)
- Condensation at surfaces
- Drainage of films on surfaces
- Radiation between surfaces and to gases

$$\frac{T - T_i}{T_o - T_i} = 1 - \operatorname{erf}\left[\frac{x}{2\sqrt{\alpha t}}\right] - \exp\left[\frac{hx}{k} + \frac{h^2\alpha t}{k^2}\right] \left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{k}\right)\right]$$

Transient Heat Flow in a Semi-Infinite Heat Slab



Cooling of Heat Structures in a Fluid



# COR Heat Transfer

- Conduction
  - Axial Conduction
  - Radial Conduction
  - Intracell
- Convection
  - Heat transfer rates calculated for each component using heat transfer coefficients
    - Uses Local cell temperature predicted from dT/dz model
  - Does not use a critical Reynolds number to determine laminar or turbulent flow regimes
    - Maximum of laminar/turbulent, forced/free
  - Convective heat transfer from contiguous molten pools treated separately
- Radiation
  - Simple radiative exchange model
    - Global radiation exchange factors
    - Local radiation exchange factors
  - Geometric radiation exchange model
  - Multi-rod model

$$A_1 F_{12} \equiv A_2 F_{21} \equiv AF = \min(A_1, A_2, A_{cell,x}) F_{cell,x}$$
$$= A_{cell,x} F_{cell,x} \min(A_1/A_{cell,x}, A_2/A_{cell,x}, 1)$$

# COR Degradation Models

- **Ballooning Model**
  - There is no comprehensive model for clad ballooning in the code though MELCOR provides limited capabilities for simulating the effects.
    - Gap release model
      - Gap release at user temperature (1173 K default)
- **Candling**
  - Thermal-hydraulic based
    - (does not account for viscosity or surface tension)
    - Does not have a separate field (temperature)
  - Simple holdup model for melt inside an oxide shell
  - Formation of blockages from refrozen material
- **Formation of Particulate debris**
  - Failure temperature / component thickness / CF / support structures
  - Clad optional time at temperature modeling (best practice)
  - Downward relocation of (axial and radial) by gravitational settling
    - not modeled mechanistically but through a logical sequence of processes through consideration of volume, porosity, and support constraints.
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates
  - Support structure modeling for COR components leads to failure of supported intact components when support structure is lost
- **Molten Pool Modeling**
  - Forms when downward candling molten material reaches a blockage and still has superheat
    - Settling similar to particulate debris but particulate debris displaces molten pool
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates

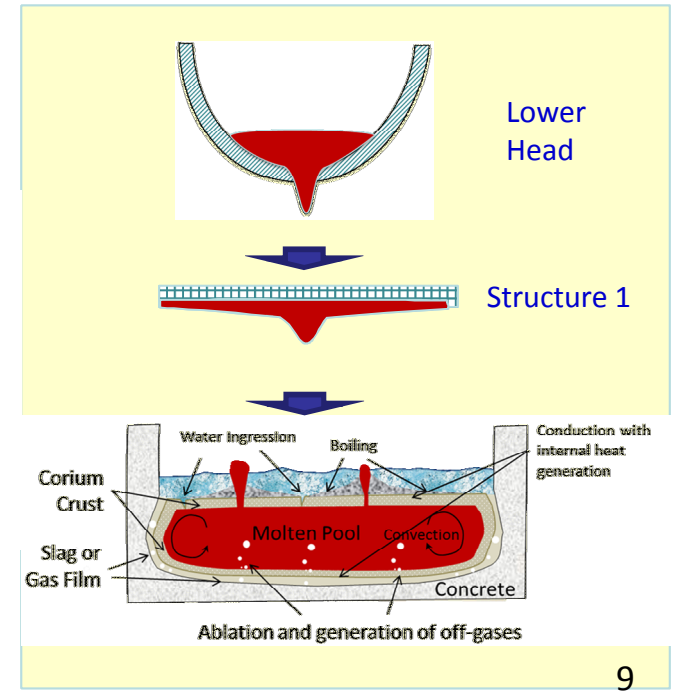
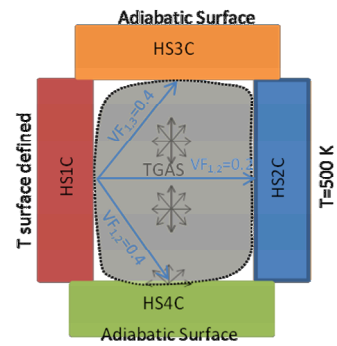
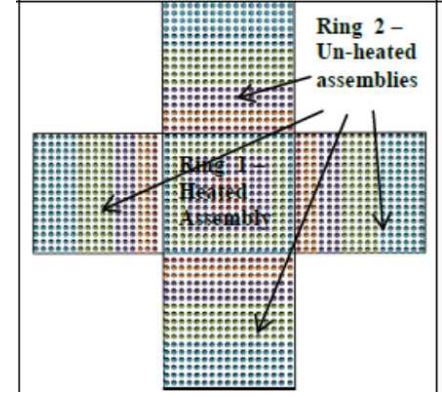
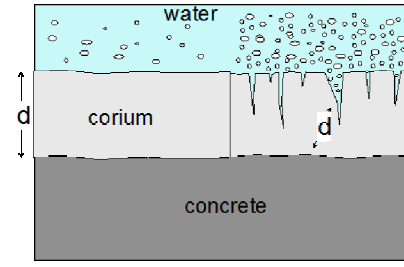
# New Model Development Tasks (2014-2016)

## Completed

- Fuel Rod Collapse Model
- Homologous pump model
- Multi-HS radiation enclosure model
- Aerosol re-suspension model
- Zukauskas heat transfer coefficient (external cross-flow across a tube bundle)
- Core Catcher (multiple containment vessels)
  - Multiple fuel rod types in a COR cell
  - Generalized Fission Product Release Model
  - New debris cooling models added to CAV package
    - Water-ingression
    - Melt eruption through crust
- Spreading model implemented into CAV package
- Miscellaneous models and code improvements
  - COR\_HTR extended to heat structures
  - LAG CF
  - MACCS Multi-Ring Release
  - Valve Flow Coefficient
  - MACCS release types

## In Progress

- Vectorized Control Functions
- CONTAIN/LMR models for liquid metal reactors
- CVH/FL Numerics
- RCIC Terry Turbine model



# Homologous Pump Model

- Transient Pump operation characterized by
  - Rotational speed, Volumetric flow rate, dynamic head, hydraulic torque
- Pump characteristic curves or four quadrant curves
  - Any one of the above quantities can be expressed as a function of any other two
    - Dynamic head and hydraulic torque are expressed as functions of volumetric flow and rotational speed ratios
      - Eight curves for the dynamic head
      - Eight curves for hydraulic torque
  - Empirically characterized by manufacturer
  - Similarities to RELAP and TRACE models
- Curve Definitions
  - Built-in pump curves
    - Semi-scale
    - Loft
  - User defined curves
    - Uses tabular function (32 TFs for full coverage)
    - If user does not define all modes, error occurs when pump enters undefined domain
  - Universal correlation
    - Systematic approach for predicting pump performance where data does not exist
    - Fits to several data sets (including LOFT & Semiscale)
    - Only valid in normal operating mode
    - Lahssuny, Jedral. Universal Correlations for Predicting Complete Pump Performance Characteristics. 2004.
- MELCOR specific implementation
  - Equations cast in polar form which reduces to two closed curves
    - Simplifies programming
      - Independent variable is always positive and bounded
      - Octants are ordered in monotonically increasing fashion, simplifying interpolation
    - Dynamic head
    - Hydraulic torque

Table I. Possible pump operating modes

Plot Quadrant	Nondim. Speed/Capacity	Mode Identifier
1 <sup>st</sup> (Upper Right)	$\alpha > 0$ and $v > 0$	Normal (N)
2 <sup>nd</sup> (Upper Left)	$\alpha > 0$ and $v < 0$	Dissipation (D)
3 <sup>rd</sup> (Lower Left)	$\alpha < 0$ and $v < 0$	Turbine (T)
4 <sup>th</sup> (Lower Right)	$\alpha < 0$ and $v > 0$	Reversal (R)

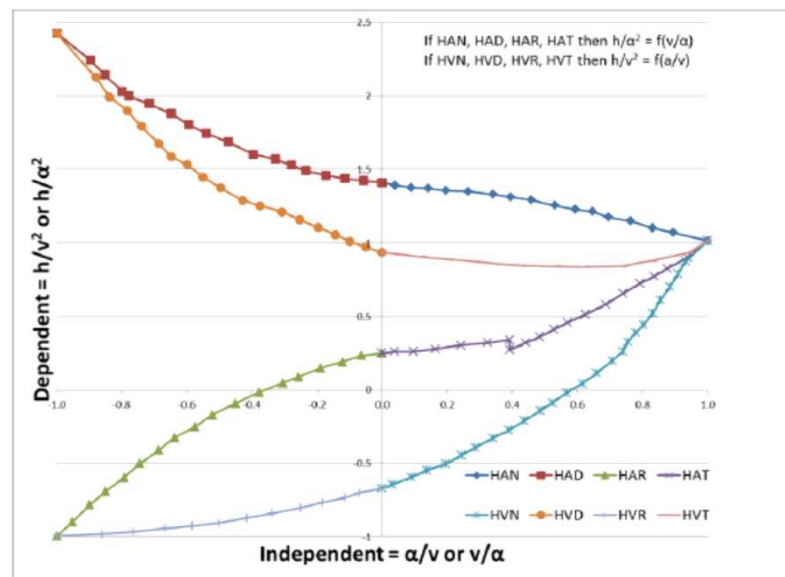
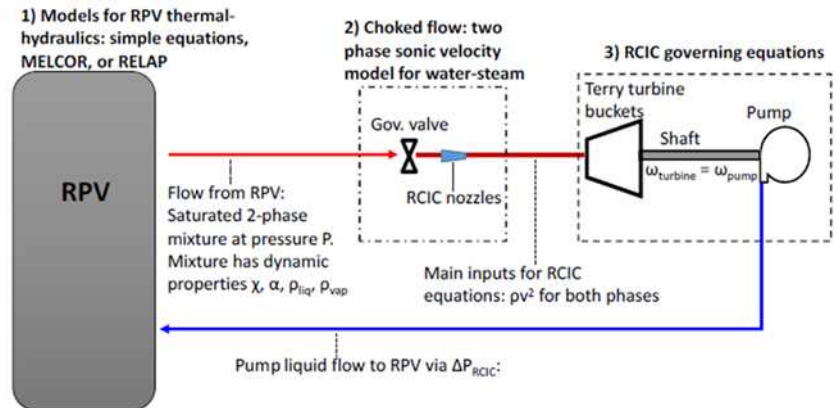
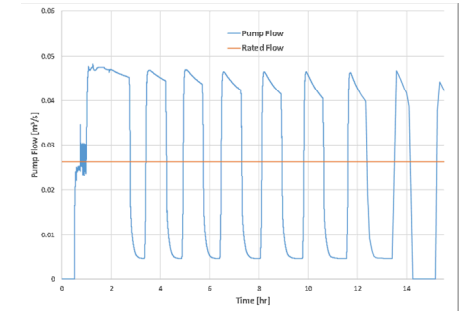
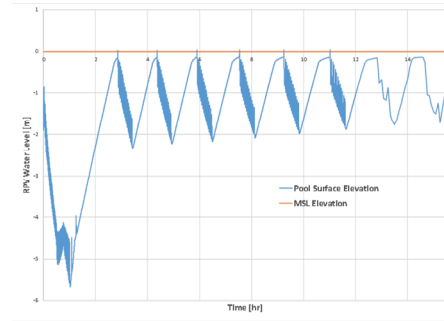


Figure 4. LOFT single-phase head curve

$$\alpha = \frac{\omega}{\omega_R} \text{ and } v = \frac{Q}{Q_R}, \text{ for rated speed and capacity } \omega_R, Q_R$$

# MELCOR Terry Turbine Model(s) Overview

- Terry turbine pressure-stage model (rapid steam expansion across nozzles)
  - Isentropic steam expansion or analytical Wilson point approach to capture phase non-equilibrium effects
  - Back-pressure effects for either under-expanded or over-expanded flow
- Terry turbine compound velocity-stage model (impulse of steam on turbine rotor)
  - Interfaces to pressure-stage model
  - Predicts rotor torque from initial impingement of steam plus subsequent stages (reversing chambers)
- Turbo-shaft model
  - Rigid coupling of the turbine to the homologous pump model
  - Solves a torque-inertia equation to govern turbo-shaft speed



*New models have been exercised in-house on a pseudo-Fukushima RCIC.*

# Valve Flow Coefficient

## ■ Description

- Valve flow coefficients are typically used in characterizing flow properties of valves.
- By definition, a valve has a  $C_v$  of 1 when a pressure of 1 psi causes a flow of 1 US gallon per minute of water at 60° F (i.e.  $SG = 1$ ) through the valve.
- Since the pressure drop through a valve is proportional to the square of the flow rate:

$$C_v = Q * \sqrt{\frac{SG}{\Delta P}}$$

- Q=Flow in gpm
- $C_v$  = Valve flow coefficient
- $\Delta P$  = Difference in pressure (psi)
- $SG$  = specific gravity of liquid relative to water at 60 F

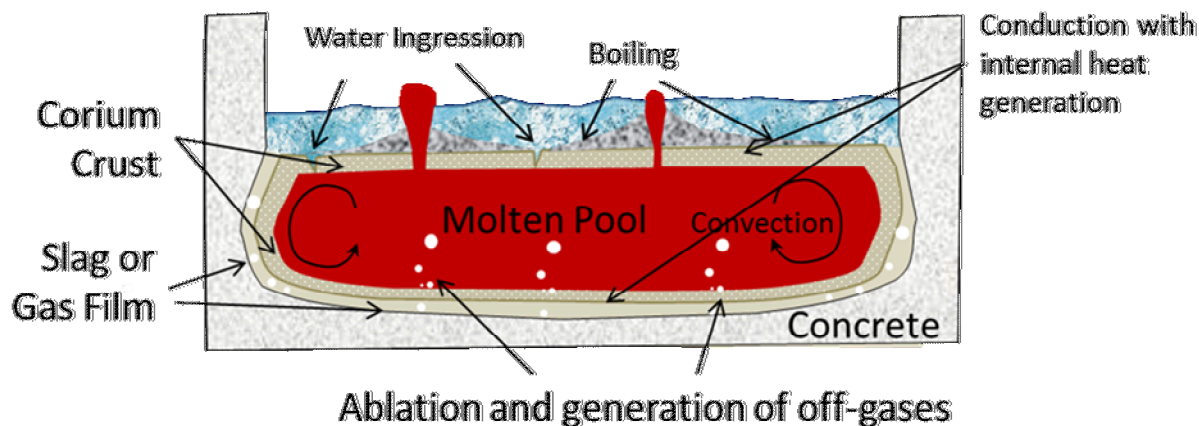
## ■ Implementation

- The user indicates that the valve is a 'NoTRIPCV' and then supplies a CF for specifying the value of  $C_v$  for the valve
- The valve must be on a single segment flowpath and takes the pipe diameter from this segment
- Standard engineering units for flow coefficient are gpm/sqrt(psi) are expected.

fl\_vlv 1

1 'TestValve' 'VALVE' NoTRIPCV 'CVvsTime'

# New Modeling for Top-Quenched Debris in Cavity



- Quenching of the upper crust at the top of the corium debris can lead to a considerable density change ( $\sim 18\%$  volume) leading to cracking and formation of voids
  - Water ingress ion reduces conduction path to molten pool and increases surface area of contact
- Molten corium extruded through crust by entrainment from decomposition gases as they escape through fissures and defects in the crust.
  - Enhance the coolability of the molten corium
    - by relocating enthalpy from the internal melt through the crust
    - more coolable geometry that is more porous and permeable to water

# MELCOR Runtime and Robustness

- Code Corrections & Modeling Improvements
  - Corrections to reported bugs
  - Model reviews
  - Targeted efforts to improve code performance
    - Examination of calculations showing time step reduction scenarios.
- Code Performance Improvements
  - Improvement of runtime (for 100 hours) Rev. 5864 → Now
    - 1F1 – 4 day calc. = 4 day CPU → 500 hours calc. = 50 hours CPU
    - 1F3 - 4 day calc. = 8 days CPU → 500 hours calc. = ~150 hours CPU
  - Enabled extension of Fukushima simulation time
    - 100 hours => 500 hours
- Robustness Improvements
  - 2013 – 75% success rate
  - 2015 - 84% success rate
  - 2017 (Recent Sequoyah UA) – 95% success rate

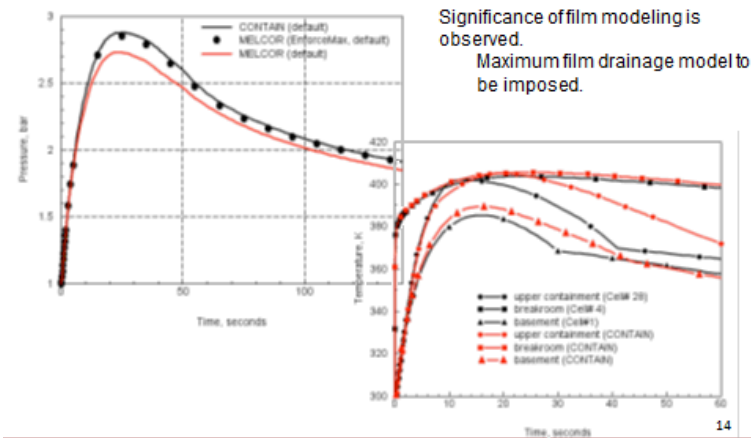
# Experimental Validation

- Importance of validation
  - Provide necessary guidance in developing and improving models
  - Desirable to have validation test at time of model implementation
  - Increased confidence in applying code to real-world application
  - proved understanding of modeling uncertainties
- Separate Effects Tests
  - Designed to focus on an individual physical process
  - Eliminates complications from combined effects
  - May be difficult or impossible to design a single test to isolate a single process
  - Sometimes geometry or boundary conditions for SETs are difficult to model within an integral code
- Integral Tests
  - Examines relationships between coupled processes
  - Tests should be selected that are applicable to the calculation domain of the code
- Actual Plant Accidents
  - TMI, Fukushima, etc.
  - Captures all relevant physics
  - Poorly 'instrumented'
- International Standard Problems (ISPs)
  - Well documented
  - Often there are code-to-code comparisons to compare modeling approaches

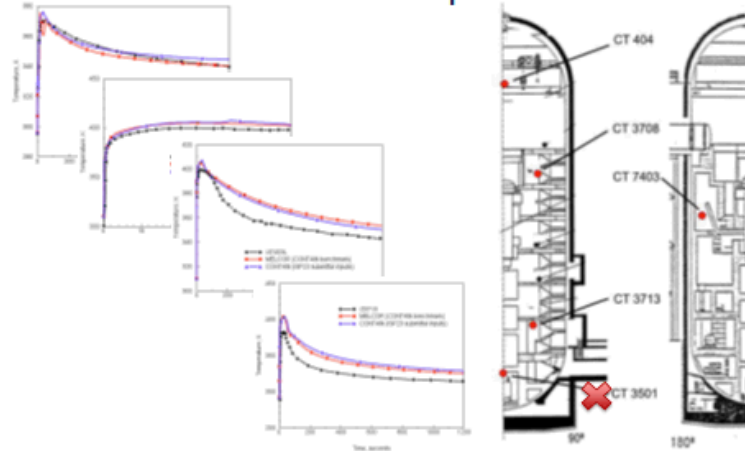
# MELCOR Containment Thermal Hydraulics

## V44 (ISP 16) CONTAIN/MELCOR Comparison

- Test provides an indication of the effect of forced convective condensation during a blowdown event.
- Significance of film modeling is observed.
  - Code enhancement to permit a maximum film drainage model to be imposed (like CONTAIN).
  - New model permits investigation of the relevance of film depth, the corresponding heat transfer, and impact to peak pressure



## T31.5 (ISP-23) CONTAIN/MELCOR Comparison



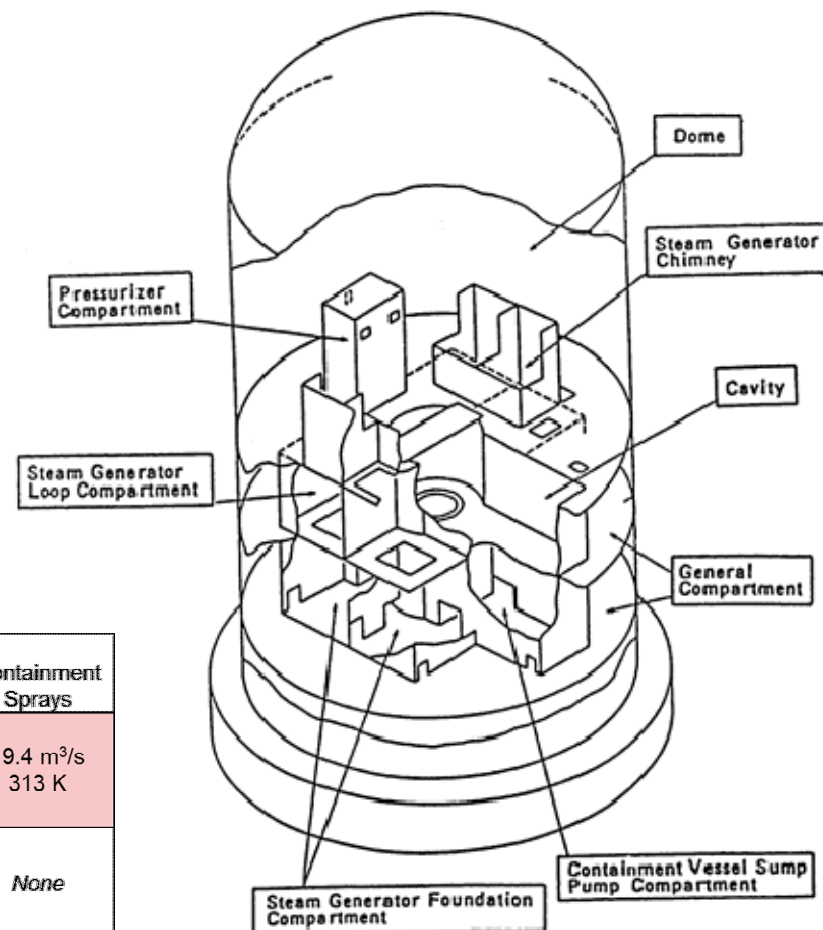
# NUPEC M-7-1, M-8-1, and M-8-2

## Validation objectives

- Pressure response;
- Temperature distribution and stratification
- Hydrogen mixing
- Spray modeling
- Film Tracking Model

## ¼ Scale Containment

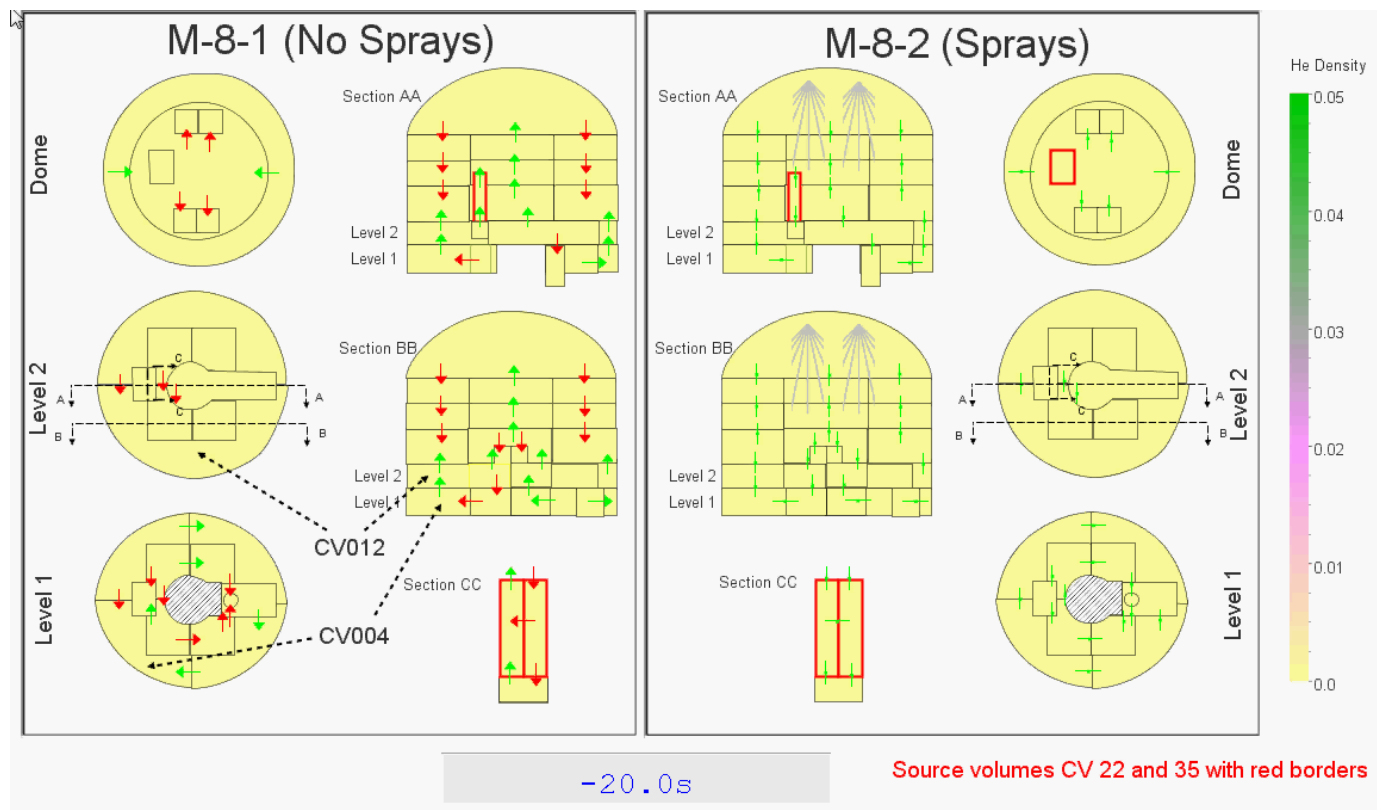
- 10.8 m OD domed cylinder,
- 17.4 m high
- 25 interconnected compartments (28 total)



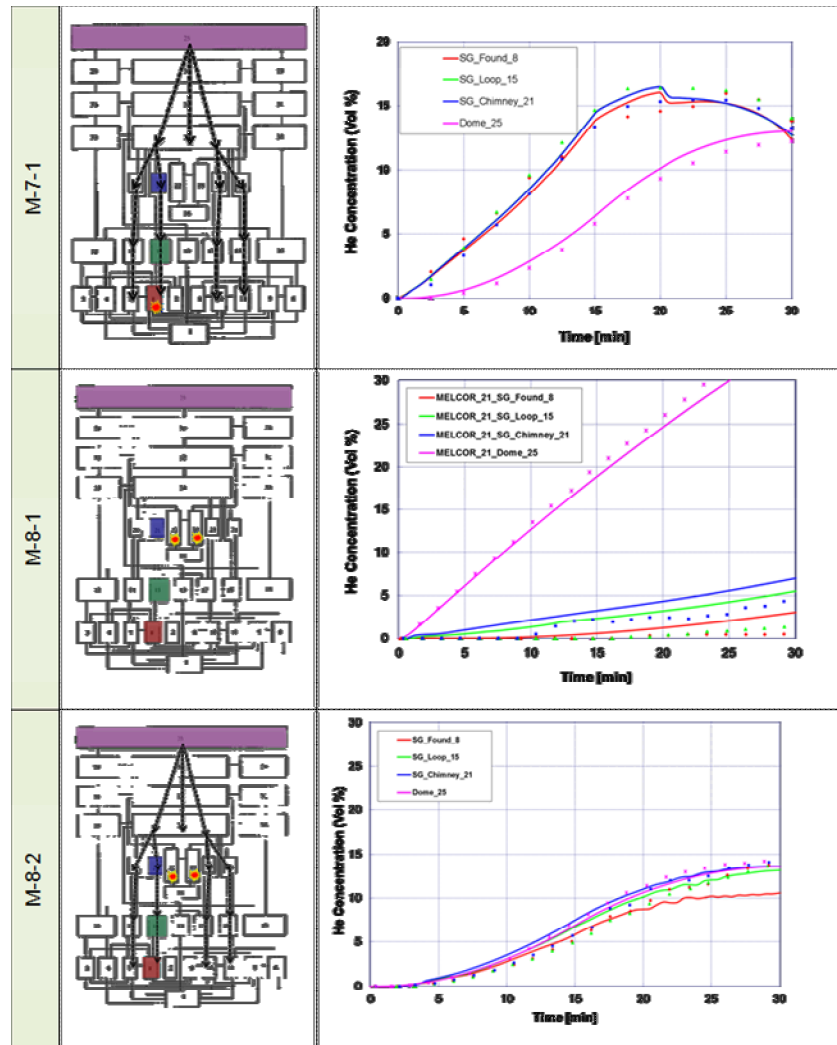
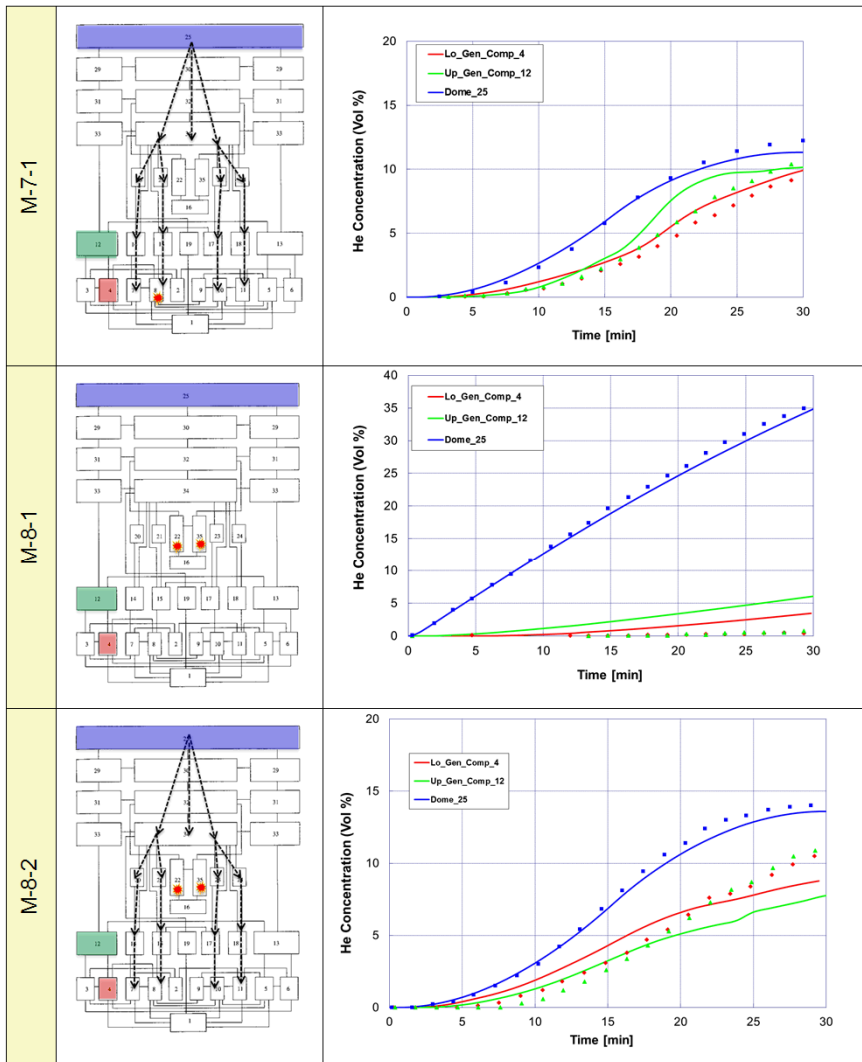
Test	Injection Location	Initial Conditions	Relative Humidity	Helium Source	Steam Source	Containment Sprays
M-7-1	Bottom of SG Comp D (8)	343 K, 146 kPa	0.95	0 → 0.03 kg/s → 0 283 K	0.08 kg/s → 0.03 kg/s 383 K	19.4 m <sup>3</sup> /s 313 K
M-8-1	Upper Pressurizer Comp (22)	303 K, 101 kPa	0.7	0.027 kg/s 283 K	0.33 kg/s, 388 K	None
M-8-2	Upper Pressurizer Comp (22)	343 K, 146 kPa	0.95	0 → 0.03 kg/s → 0 283 K	0.08 kg/s → 0.03 kg/s 363 K	19.4 m <sup>3</sup> /s 313 K

# He Concentration Distributions

- Similarly, stratification of helium in the upper dome is much more significant for M-8-1 than M-8-2
- Stratification by floor in outer, lower compartments



# He Concentrations for vertical distribution volumes SG loop D



Color indicates CV

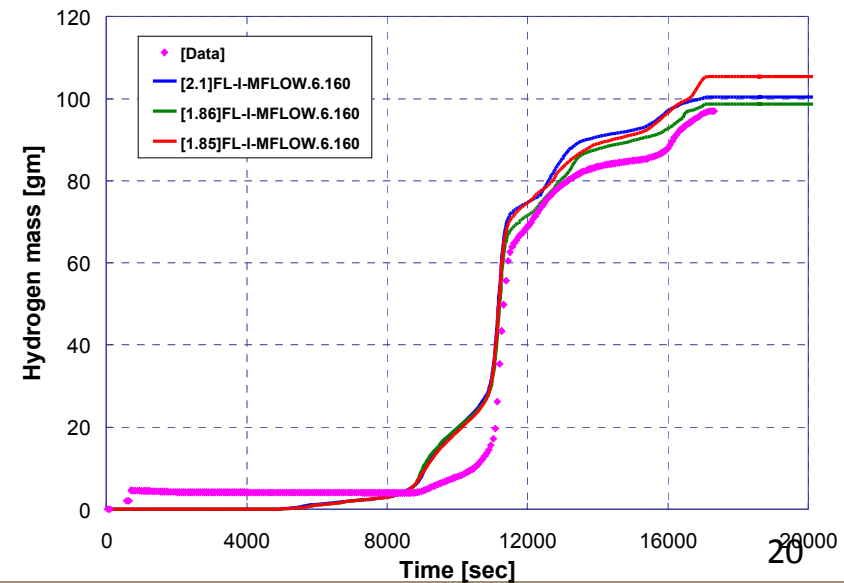
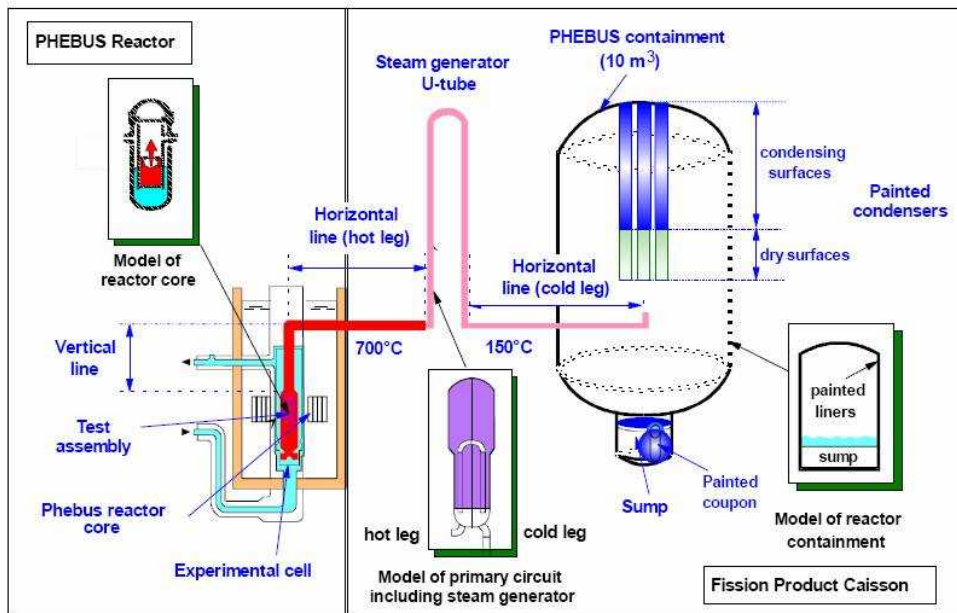
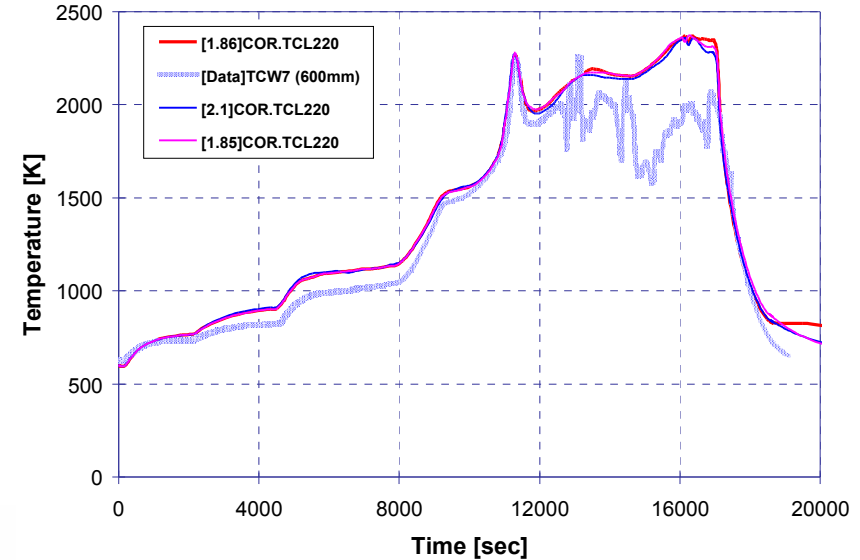
# FPT-1 (ISP-46)

## General Description

- FPT-1 experiment was an in-pile, irradiated fuel experiment conducted in the PHEBUS Fission Product Facility by the Nuclear Safety and Protection Institute (IPSN) at Cadarache, France, on July 26, 1996. The objective of the fuel bundle assembly was to assess fuel degradation and fission product release

## Important Physics

- Oxidation
- Material relocation
- Fission product release, transport, and deposition



# Alternative TMI-2 (ATMI)

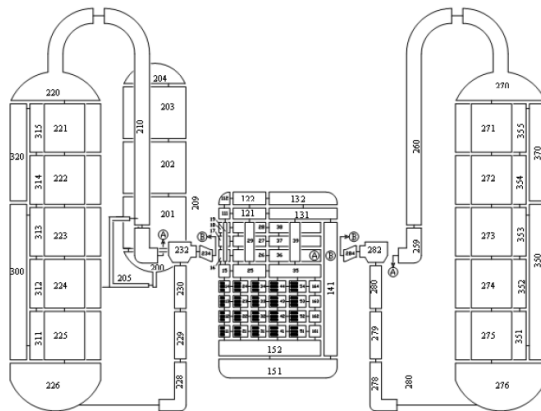
## ABILITY OF CURRENT ADVANCED CODES TO PREDICT CORE DEGRADATION, MELT PROGRESSION AND REFLOODING

NEA/CSNI/R(2009)3

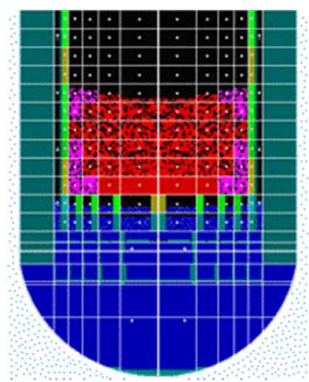
### Benchmark Exercise on an Alternative TMI-2 Accident Scenario

Computer Code	Organization	Country
ASTEC V1.3	ENEA	Italy
ASTEC V1.3	IVS	Slovakia
MELCOR 1.8.5	Univ. Pisa	Italy
ATHLET-CD	GRS	Germany
ATHLET-CD / WABE / MEWA	IKE	Germany
ICARE/CATHARE V2	IRSN	France
MELCOR 1.8.6	NRC/SNL	U.S.A
MAAP4 / RELAP5	Seoul Nat. Univ.	S. Korea

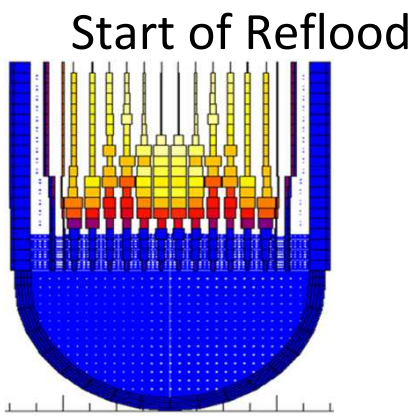
- Initial event:
  - Loss of main feedwater
  - Opening of a small break in hot leg A
    - size: 0.001 m<sup>2</sup>
- Assumptions
  - No PORV failure
  - HPI
    - Begins 5000 sec after pump trip
    - 30 kg/s, per loop (60 kg/s total).
  - Primary pumps stop when primary mass < 85,000 kg
- Boundary Conditions
  - Make-up flow = 3.0 kg/s
  - Steam generator secondary side pressure and water level



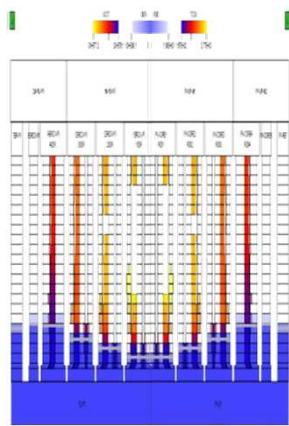
# Alternative TMI-2 (ATMI)



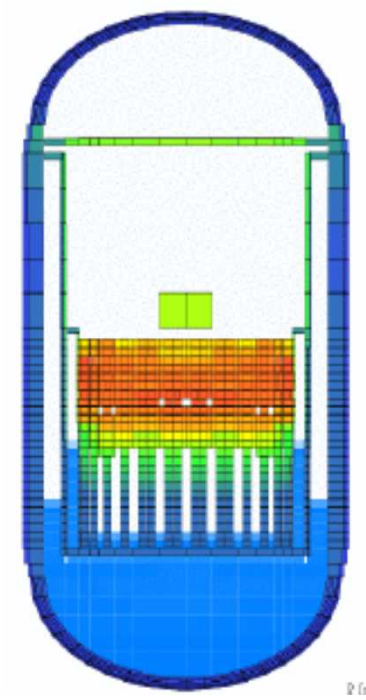
SNL MELCOR  
(1.8.6 YR)



ENEA (ASTEC V1.3)

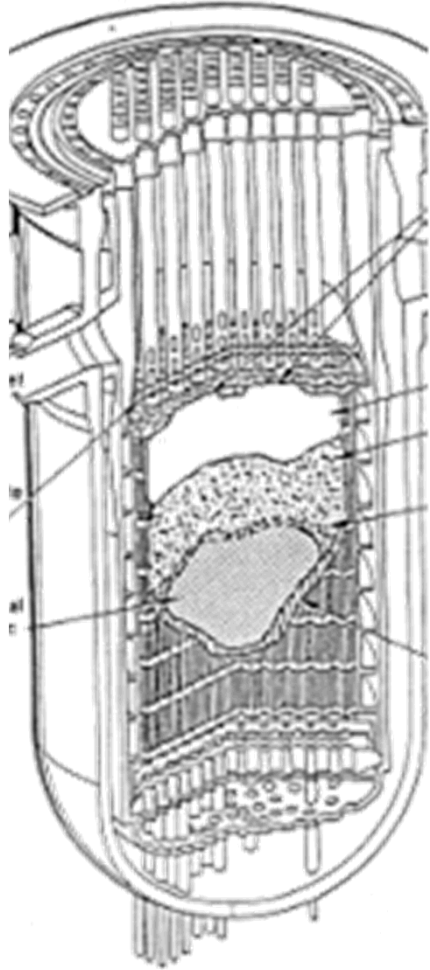


GRS  
ATHLET-CD

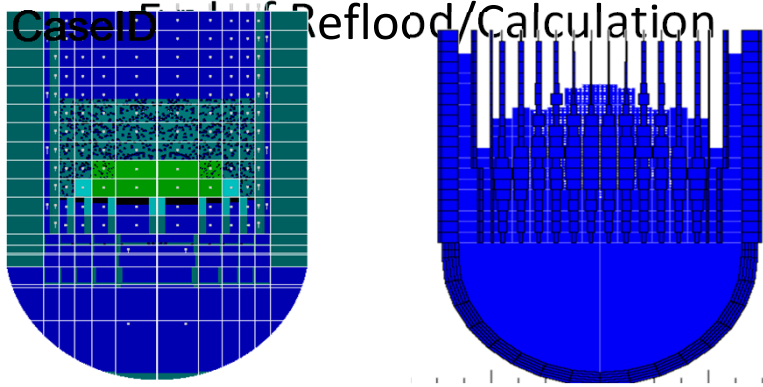


IRSN  
ICARE/CATHARE V2

# Alternative TMI-2 (ATMI)

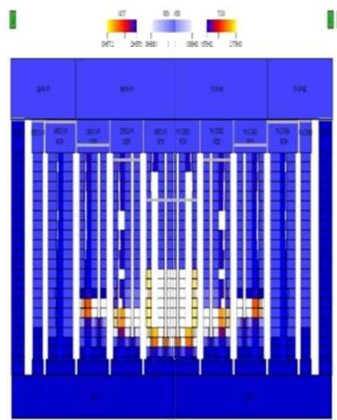


TMI

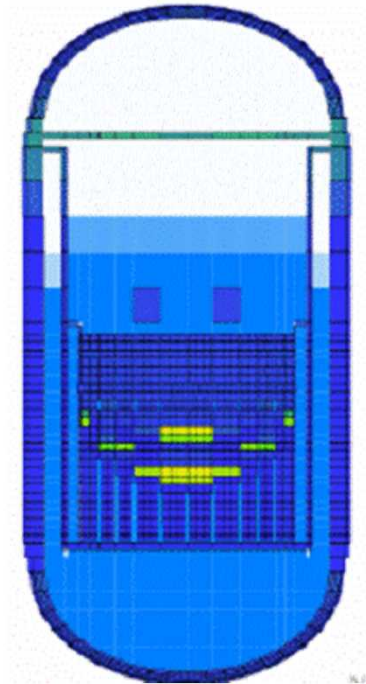


SNL MELCOR  
(1.8.6 YR)

ENEA  
(ASTEC V1.3)



GRS  
ATHLET-CD



IRSN  
ICARE/CATHARE V2

# Reflood Quench Model

- MELCOR computes a quench velocity, distinct from pool water level

- The quench velocity correlation implemented is that of Dua and Tien<sup>1</sup>

$$Pe = \left[ \bar{B}(1 + 0.4\bar{B}) \right]^{1/2}$$

- Where

- Pe is the dimensionless quench velocity or Peclet num

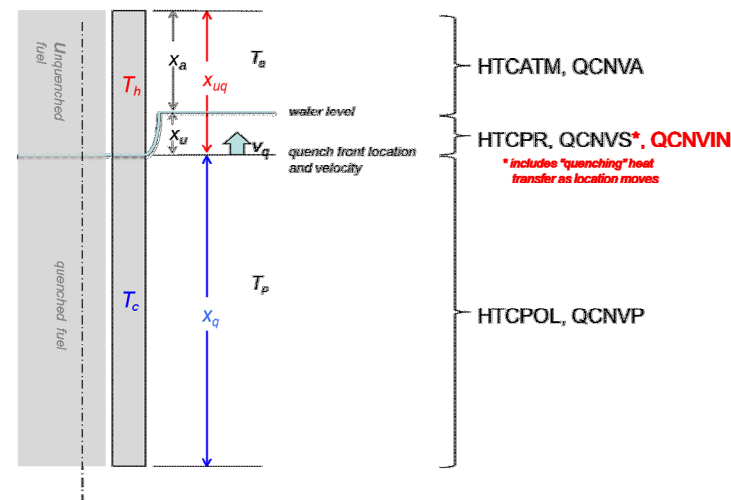
$$Pe = u^* = \frac{u\delta}{\alpha}$$

- $\bar{B}$  is a dimensionless Biot number

$$\bar{B} = Bi(1 - \Theta)^2 / \Theta \quad Bi = \frac{h^* \delta}{k} \quad \Theta = \frac{T_b - T_{\text{sat}}}{T_{\text{max}} - T_{\text{sat}}}$$

- May be thought of as an interpolation between a result based on one-dimensional conduction in thin surfaces (small Bi), and one based on two-dimensional conduction in thick surfaces (large Bi).

- For small  $\bar{B}$ ,  $Pe = \sqrt{\bar{B}}$
- For large  $\bar{B}$ ,  $Pe = 0.63\bar{B}$



<sup>1</sup>S. S. Dua and C. L. Tien, *Intl. J. Heat and Mass Transfer* 20, pp.174-176 (1977).

# ISP-45 Quench06 Experiment

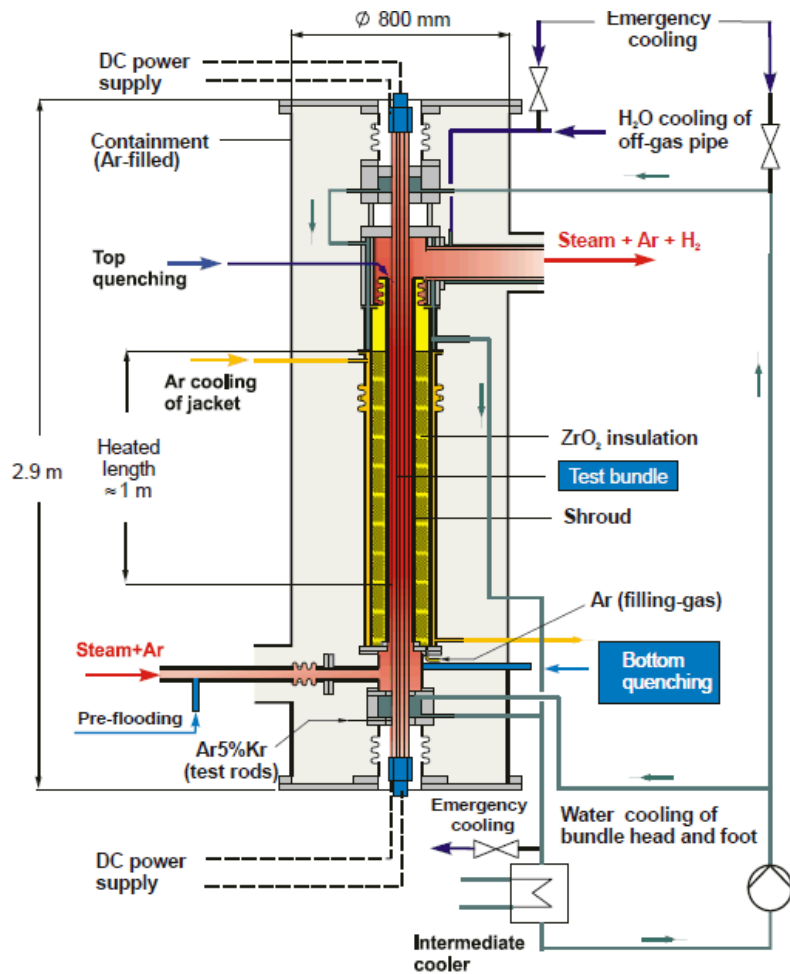


Figure 2.1 Main flow paths in the QUENCH facility.

Time	Event	Phase
0	Start of data acquisition	
30	Heat up to about 1500 K	Pre-oxidation
1965	Pre-oxidation at about 1500 K	
6010	Initiation of power transient	Power transient
6620	Initiation of pull-out of corner rod (B)	
7179	Quench phase initiation Shut down of steam supply Onset of fast water injection Start of quench water pump Detection of clad failure First temperature drop at TFS 2/1	Reflow
7181	Steam mass flow rate zero	Quench
7205	Onset of electric power reduction	
7221	Decay heat level reached	
7430	Onset of final power reduction	
7431	Shut down of quench water injection	Post-reflood
7431	Electric power < 0.5 kW	
7435	Quench water mass flow zero	
11420	End of data acquisition	

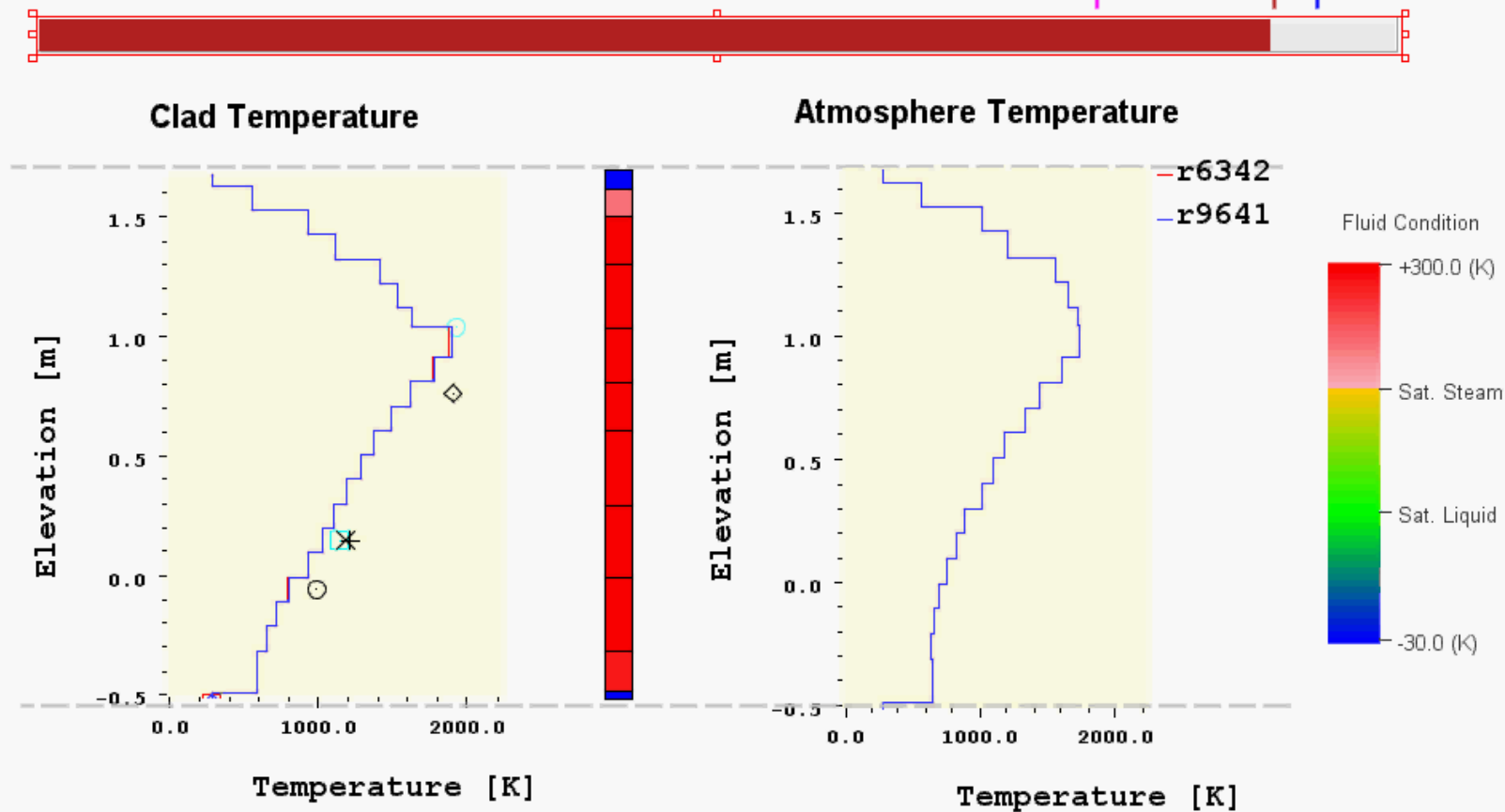
# Visualization of Quench Phenomenon – ISP 45

7140.0054 s

Power Transient  
Begins

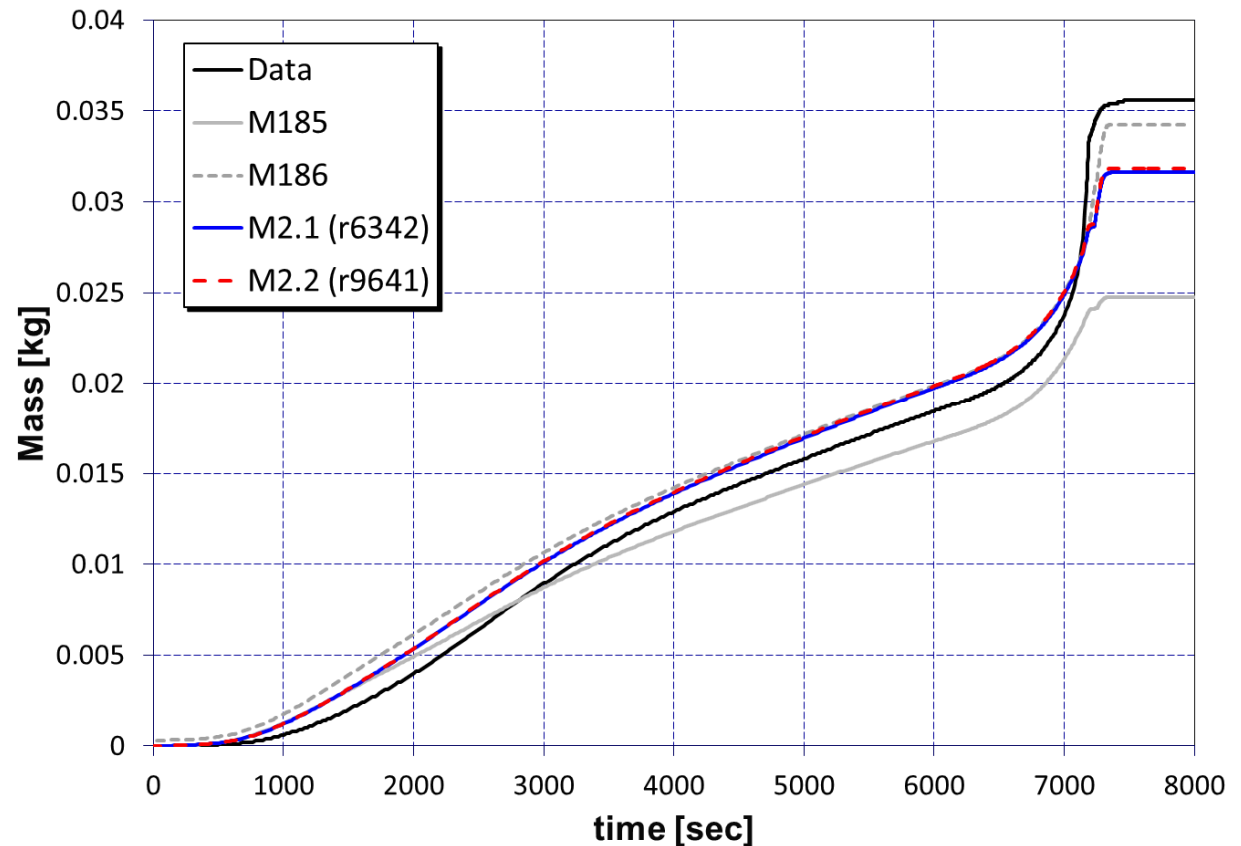
Reflow Begins

Reflow Ends

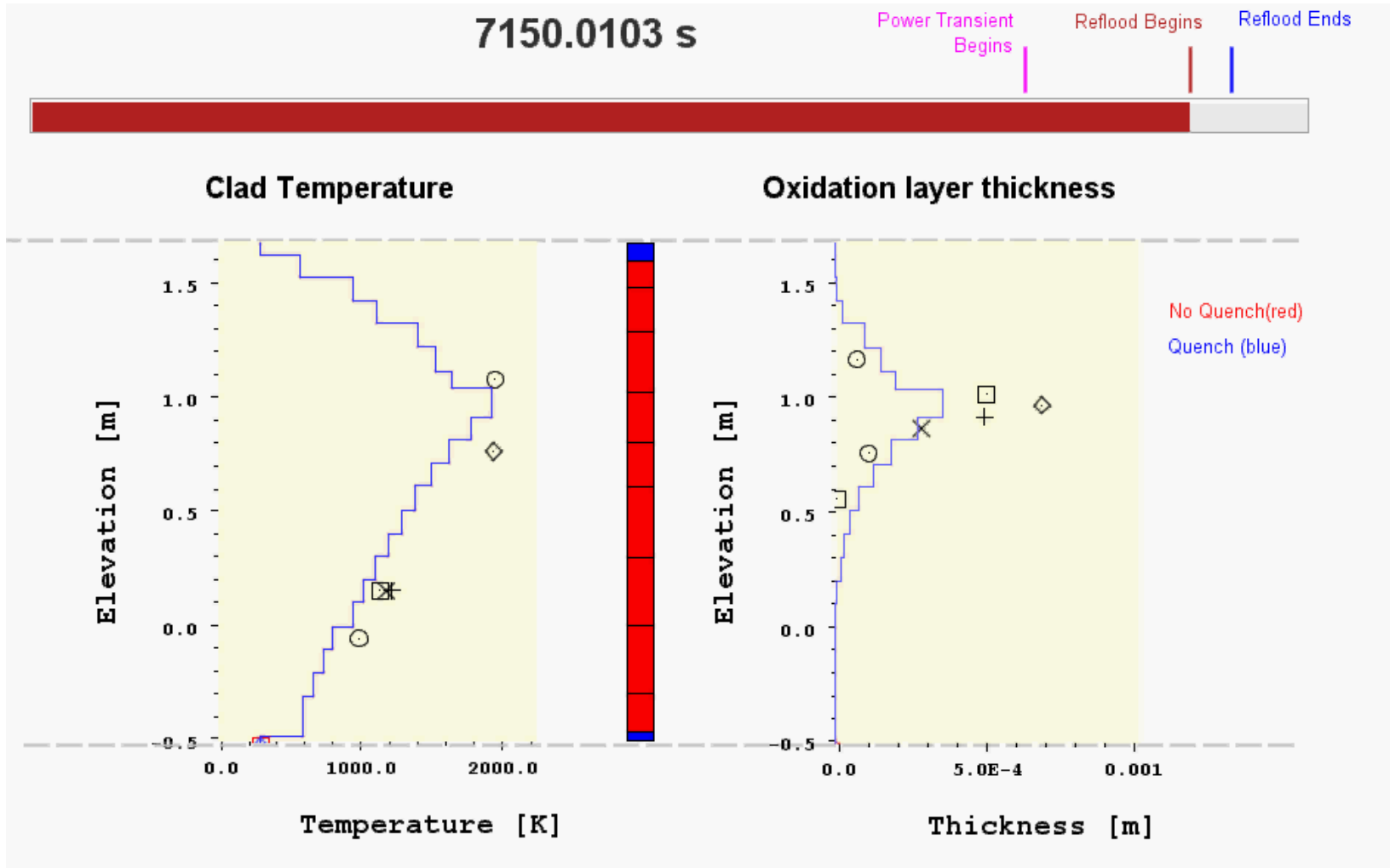


# ISP-45 Quench 6 Oxidation

- Little change between revision M186, 6342, and 9641
- M185 differences largely due to mass of heater rods



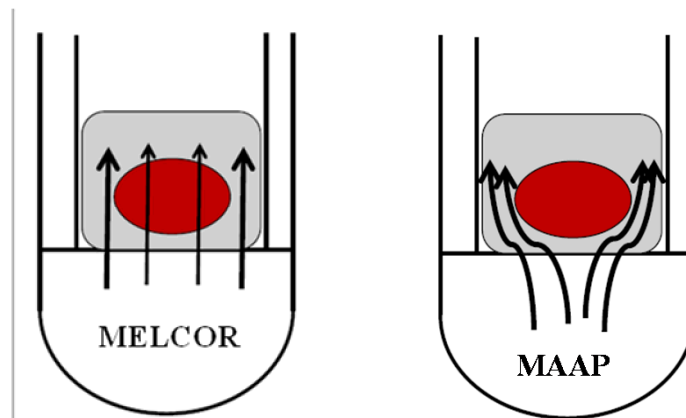
# Axial Oxidation Profile – ISP 45



# Core Degradation Modeling – Cross walk comparisons

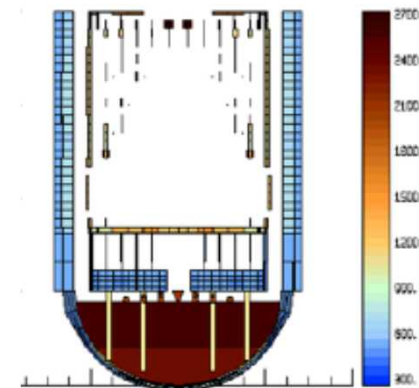
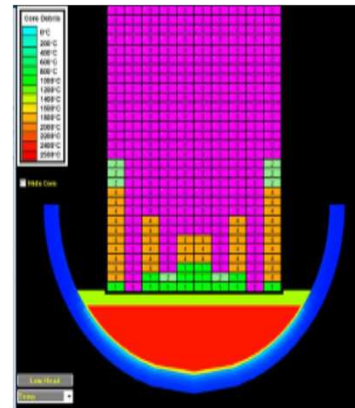
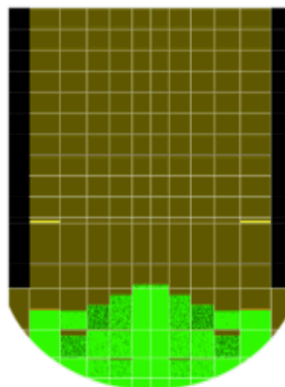
- Differences in assumption of permeability of debris crust

- MELCOR – flow blockage model with permeable crust
- MAAP –impermeable crust



- Fuel rod collapse modeling

- MELCOR/MAAP – fuel rod collapse model
- ASTEC – Rods melt to form magma but no collapse



# MELCOR 2.2 Code Release

SAND2017-0445 O

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**MELCOR Computer Code Manuals**

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**Volume III:  
Assessments**  
SAND2015-6693 R  
Update in Progress

SAND2017-0876 O

By December 2017  
Demo PWR plant deck  
Demo BWR plant deck  
COR/CVH Nodalization  
Containment DBA  
Numerical Variance  
Steady State Initialization

By December 2018  
FL/CVH Modeling  
Uncertainty Analysis  
Spent Fuel Pool Modeling  
Radionuclide Class  
Modeling MELCOR/MACCS  
Integration Troubleshooting  
MELCOR runtime issues  
Lower Head Modeling  
Heat Structure Modeling  
Cavity Related Modeling

**Volume IV:  
Modeling Guide**  
Under Development