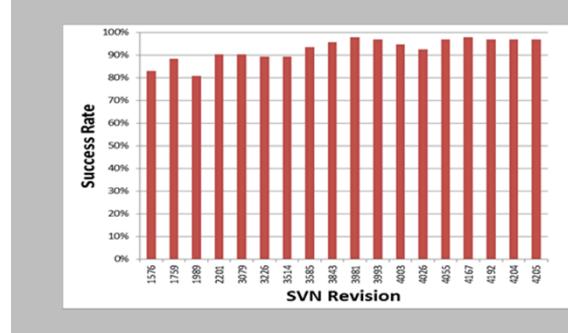
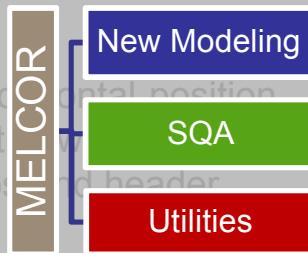
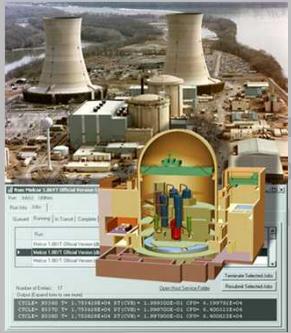


Exceptional service in the national interest



Nuclear Severe Accident Modeling and Analysis

Presented by Larry Humphries

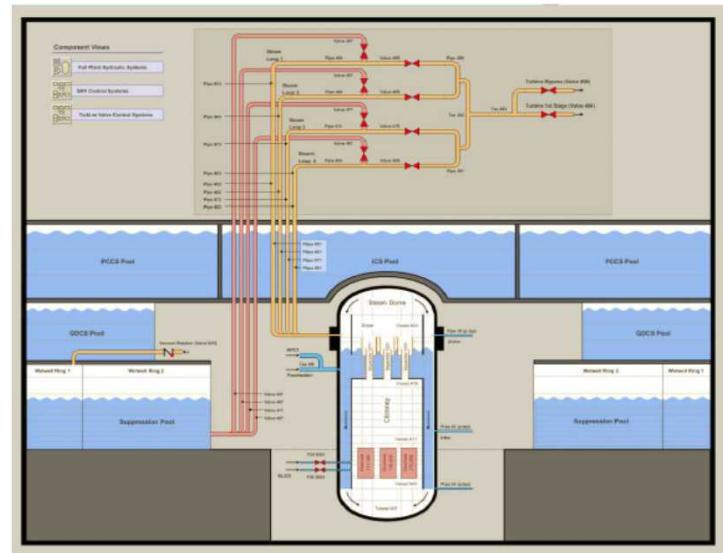
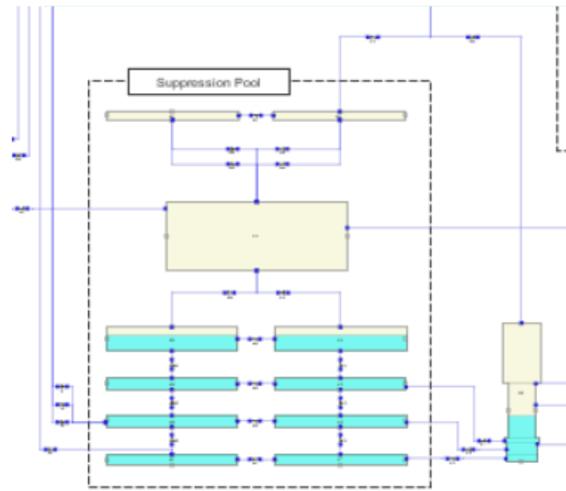
lhumph@sandia.gov

Outline of Presentation

- Severe accident code overview
- MELCOR code development
- Code development challenges
- Modeling new/alternate reactor designs
- Software Quality Assurance (SQA)
- User interface
- Future development

What is Required of a Severe Accident Code

- Designed for reactor severe accident and containment DBA simulation
 - PWR, BWR, HTGR (Pebble Bed & PMR), PWR-SFP, BWR-SFP, SMR, Sodium (Containment)
- 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
- Desk-top application
 - Windows/Linux versions
 - Relatively fast-running
 - Capabilities for post-processing, visualization, and GUI

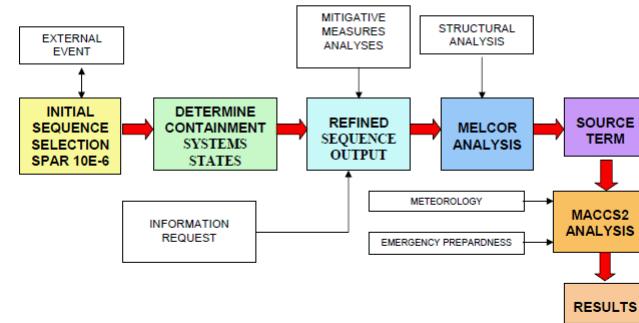


SAC Applications

- Forensic analysis of accidents – Fukushima, TMI, PAKS
- Consequence Analysis SOARCA
- License Amendments
- Risk informed regulation
- Design Certification
- Preliminary Analysis of new designs
- Support of International Regulatory Bodies
- Non-reactor applications
 - Leak Path Factor Analysis
 - Transport of radiological releases, toxins, and biohazards in buildings, building complexes
 - DOE Safety Software “Toolbox” code

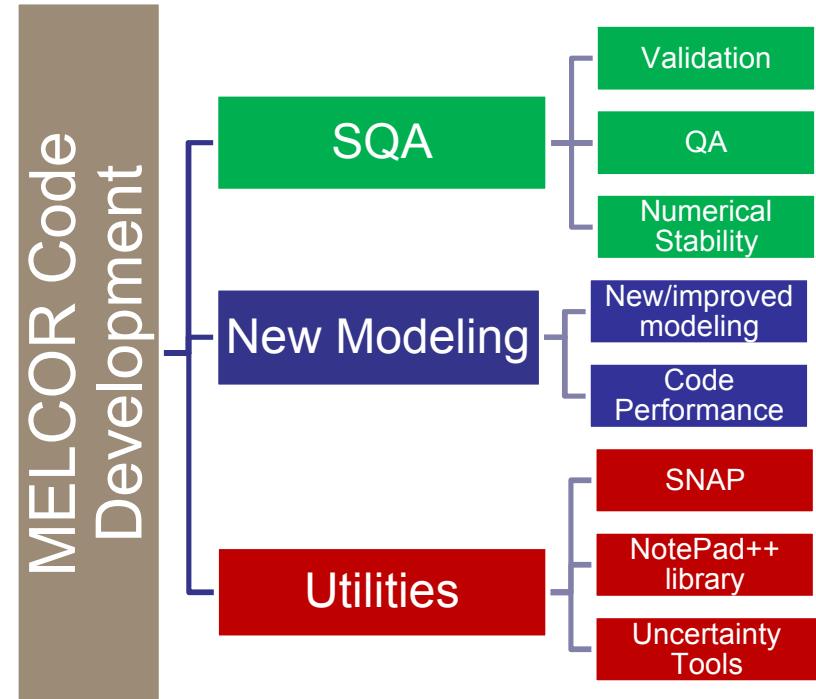


SOARCA PROCESS

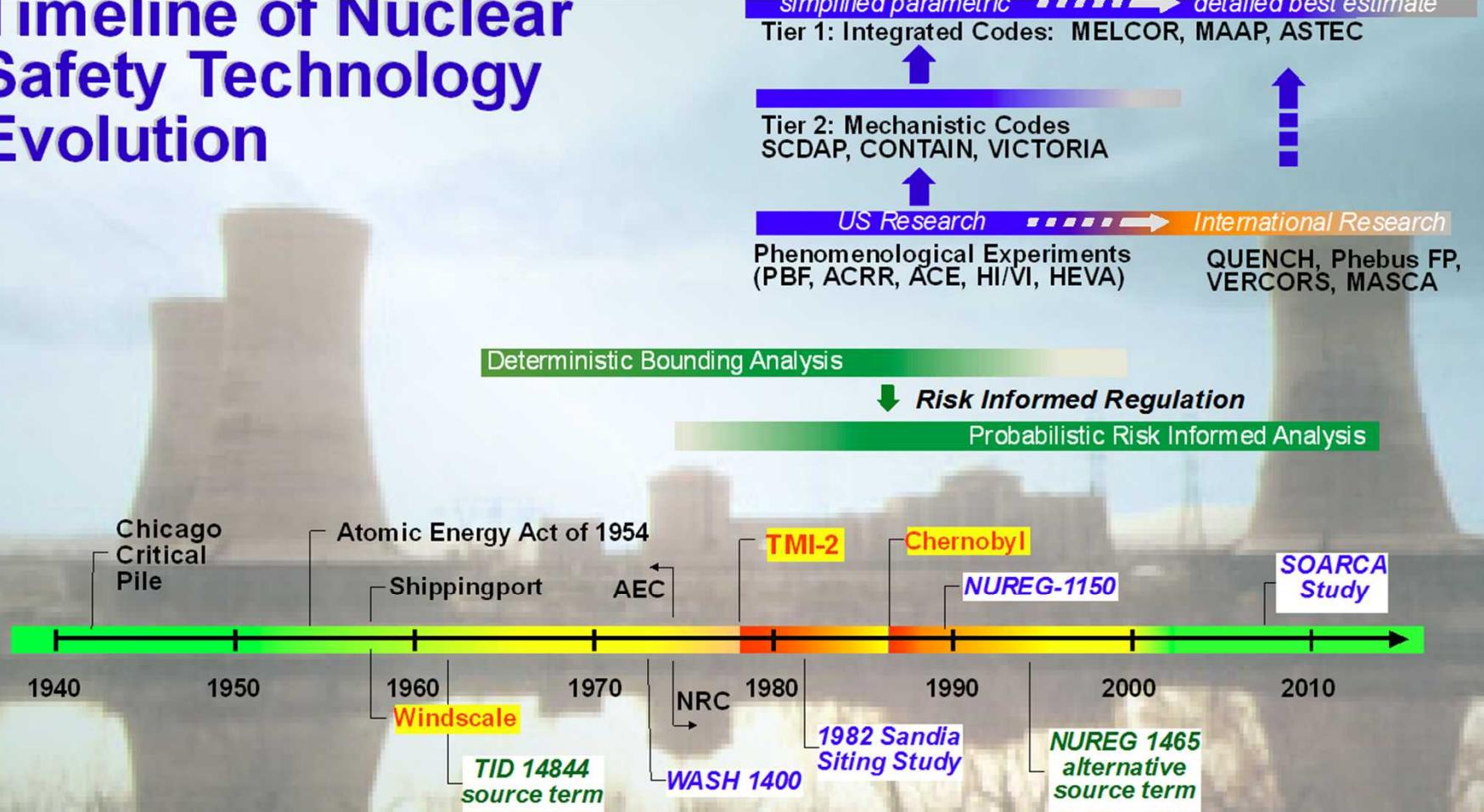


MELCOR Code Development

- MELCOR is developed by:
 - US Nuclear Regulatory Commission
 - Division of Systems Analysis
- MELCOR Development is also strongly influenced by the participation of many International Partners through the US NRC Cooperative Severe Accident Research Program (CSARP)
 - Development Contributions – New models
 - Development Recommendations
 - Validation



Timeline of Nuclear Safety Technology Evolution



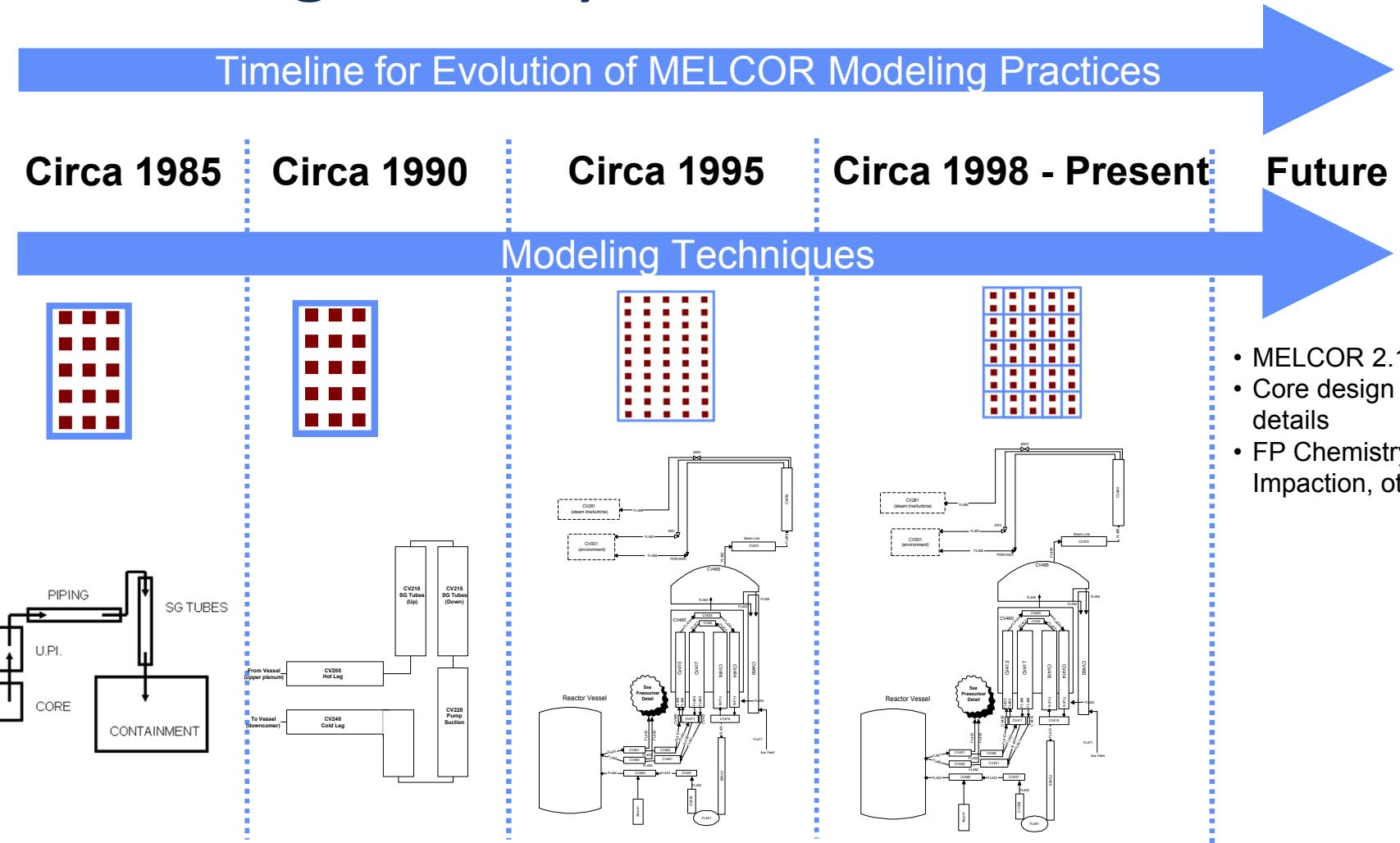
Nuclear Power Outlook

- Optimistic
- Guarded
- Pessimistic

Emerging Issues.....

- Risk Informing Regulation
 - Modernization, NUREG-1465
 - License Amendments and Extension
 - MOX, High Burnup
 - Plant aging
- Emergency Response Planning
- Advanced Reactors
 - AP1000, ESBWR, US-EPR
 - NGNP - HTGR, VHTGR, H2 Economy
 - GNEP - Fast Burner Reactor, Reprocessing

Improvements to MELCOR Modeling Fidelity

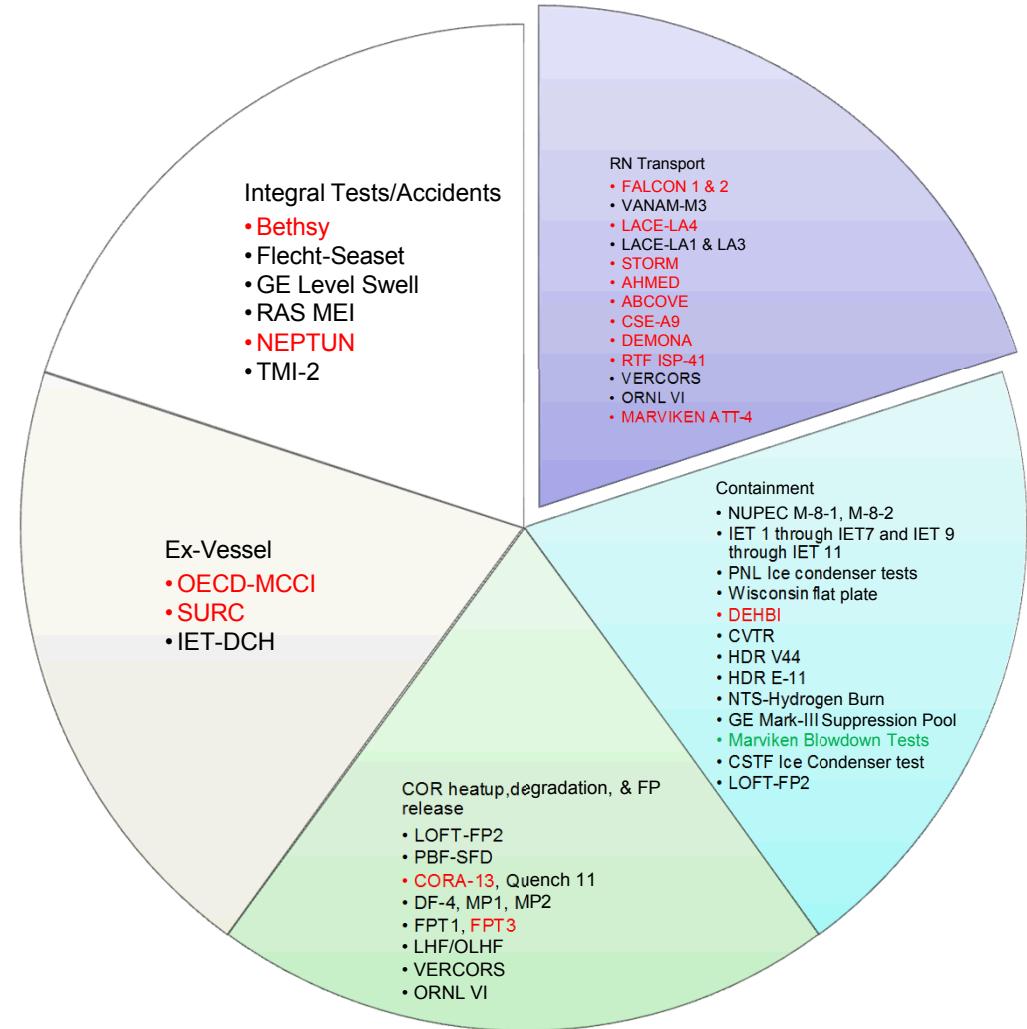


MELCOR Code Development – Past Decade

- Significant progress in severe accident modeling has been made over last 10 years
- Evolution in severe accident modeling concentrated in three areas
 - Hydrodynamic improvements (CVH/FL/HS)
 - Core damage progression (COR)
 - Fission product release, transport and removal (RN)
 - Insights from PHEBUS and VERCORS experimental programs have been used to enhance CORSOR-Booth fission product release models
- Advancements have reduced reliance on other specialized codes as shown in “parity assessments”
 - SCDAP / MELPROG
 - CONTAIN / VICTORIA

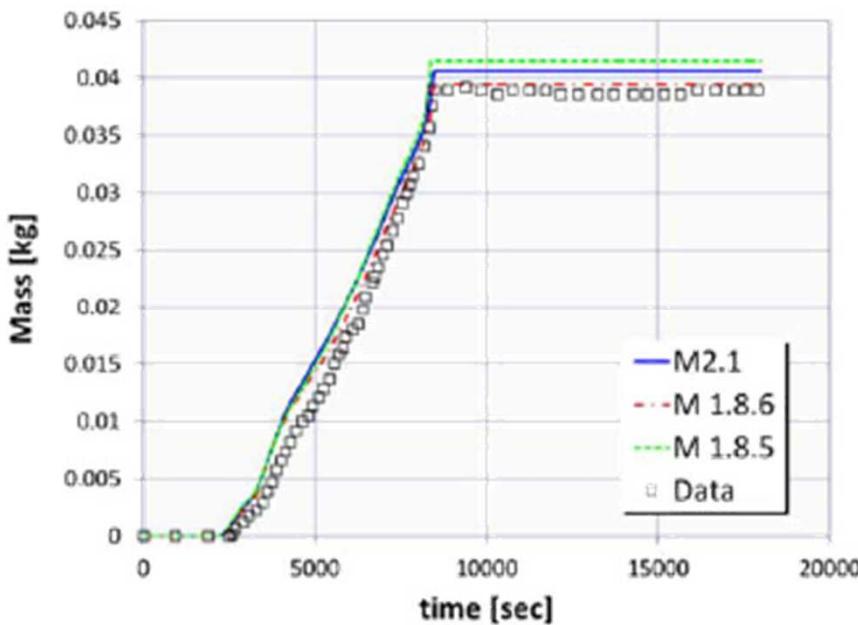
MELCOR Code Validation

- Separate effects tests
 - More tightly controlled conditions
 - Limited or specific range of phenomena
- Integral tests
 - Combine many simultaneous physics aspects
 - Often less precisely characterized test conditions
 - Broader range of phenomena investigated
- Actual Accident Studies: TMI-2, Fukushima
 - Combines all relevant physics at full scale
 - Least well instrumented and characterized “experiment”
 - An ultimate basis for code validation
 - Bearing in mind, not every accident should be expected to be the same as TMI-2
- Participation in multiple International Standard Problems

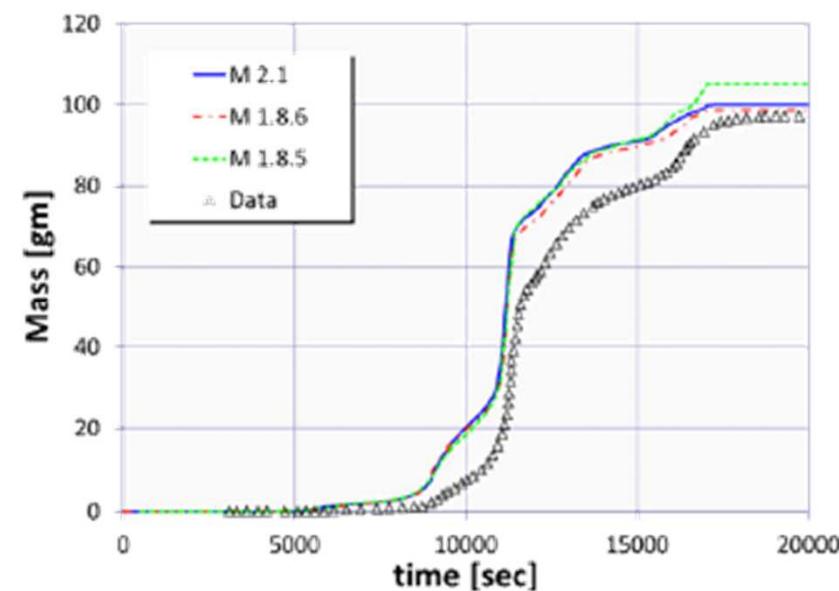


Validation of Hydrogen Generation

PHEBUS-B9

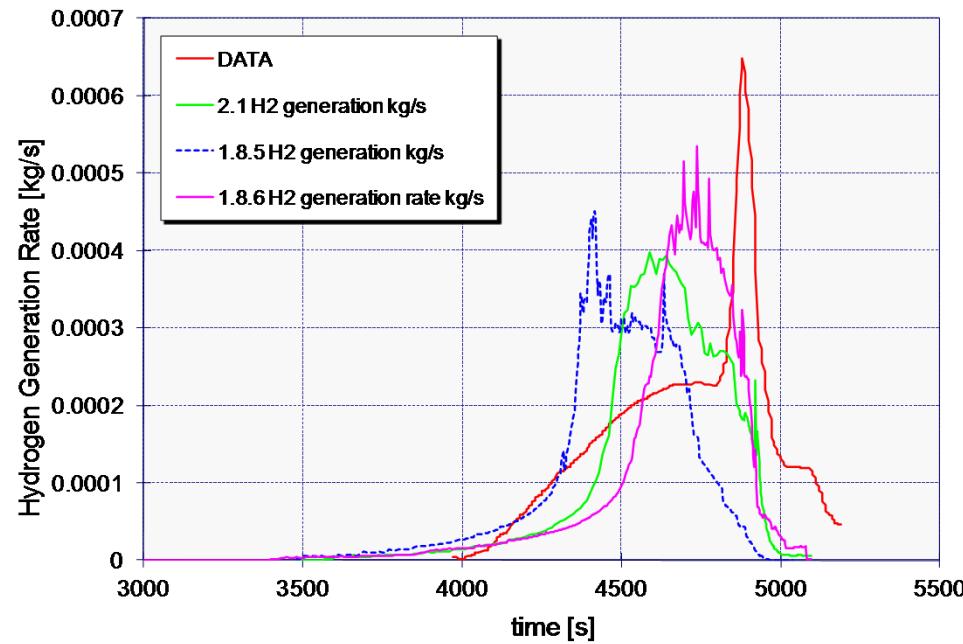


FPT-1



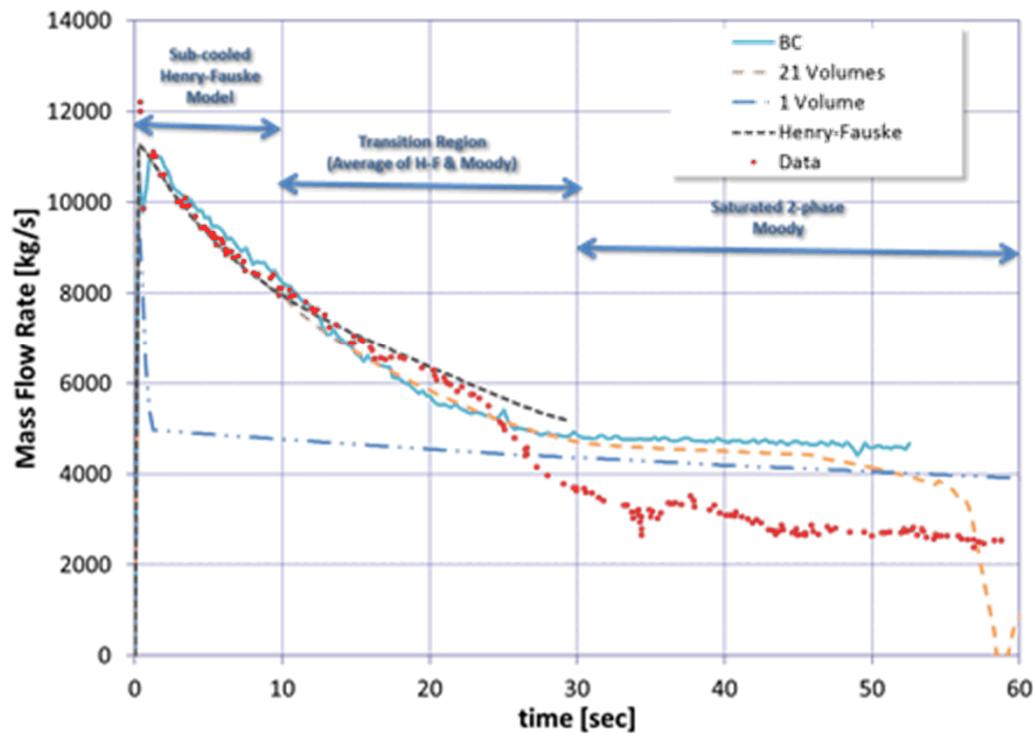
Complications to validation of oxidation modeling

- **CORA-13 Validation does not predict the spike in hydrogen production during the rapid quench**
 - No modeling for possible damage to oxide layer from thermal stress
- **During core degradation, changes in exposed surface area and blocked flow are more important than nuances in the rate equations**



Results of MELCOR CFT-21 Calculation

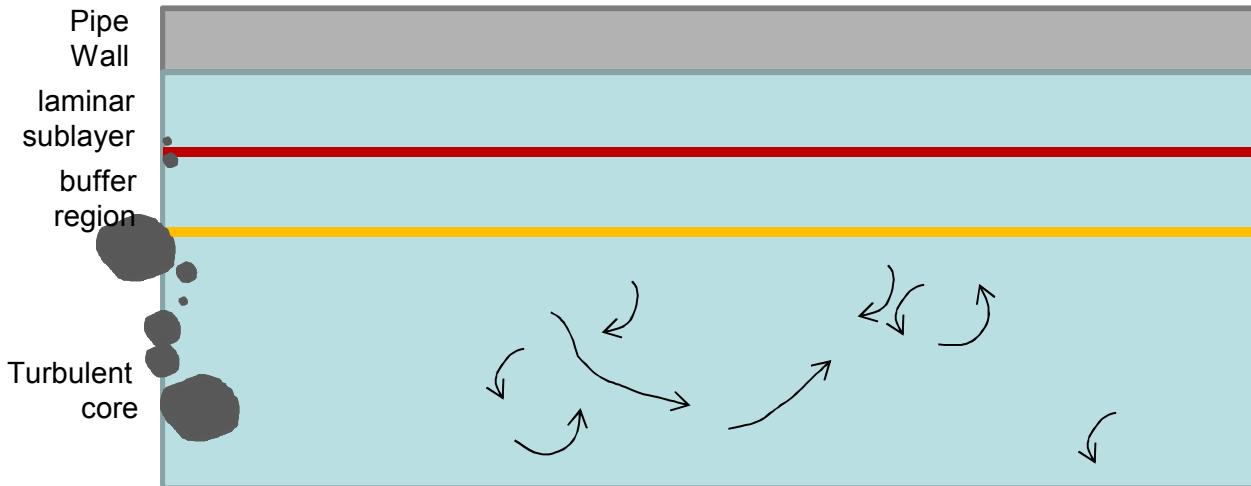
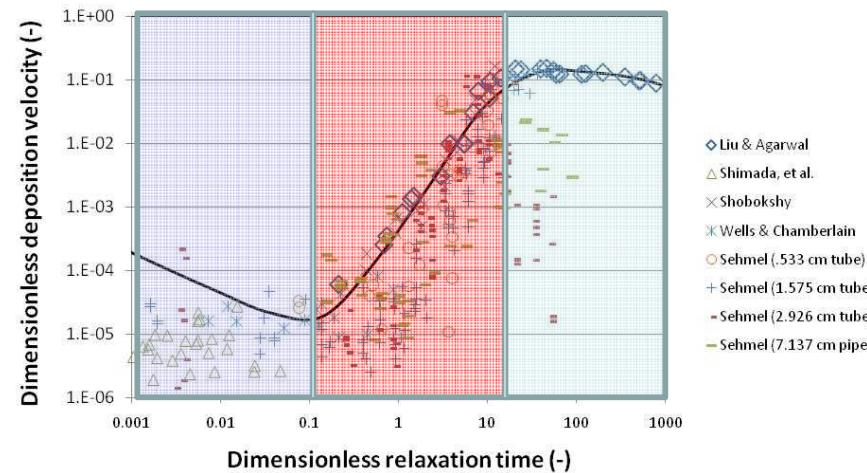
- MELCOR calculation matches closely for sub-cooled conditions at exit (extended Henry-Fauske critical flow)
- MELCOR over-predicts flow for two-phased conditions
 - Moody multiplier, C_M , of 0.6 for area ratio = 0.5 & $P = 5$ MPa consistent with other data*
 - Moody model always over estimates critical flow.
 - Rapid formation of high vapor concentrations at inlet to exit pipe
 - Moody theory overestimates flowrates for stagnation quality > 1%.



*Ardron, K.H., A STUDY OF THE CRITICAL FLOW MODELS USED IN REACTOR BLOWDOWN ANALYSIS, Nuclear Engineering & Design 39 (1976) 257-266.

Turbulent Deposition Regimes

- Turbulent particle diffusion
- Eddy diffusion impaction regime
- Inertia moderated regime



Larger particles, very small particles, dominate where diffusion where particles are accelerated to the wall due to turbulent and little particles acceleration is small across the sublayer. particles in the core and near the wall.

Turbulent Deposition Model

- Particle Diffusion Regime

- Davies equation

$$V_d^* = \frac{3\sqrt{3}}{29\pi\tau_*^{1/3}} Sc^{-2/3} \tau_*^{1/3} + K\tau_*^2$$

- Eddy Diffusion –Impaction Regime

$$V_d^* = \frac{3\sqrt{3}}{29\pi\tau_*^{1/3}} Sc^{-2/3} \tau_*^{1/3} + K\tau_*^2$$

- K is often determined empirically

Investigator	k_2
Kneen & Strauss (1969)	3.79×10^{-4}
Liu & Agarwal (1974)	6×10^{-4}
Wood (1981b)	4.5×10^{-4}
Papavergos & Hedley (1984)	3.5×10^{-4}

- Or calculated from a Fick's law equation (Wood)

$$N = (D_p + \varepsilon) \frac{dc}{dy}$$

- Inertia Moderated Regime

- Deposition velocity is either constant

$$V_d^* = \sqrt{\frac{f}{2}} \quad 10 \leq \tau_* < 270$$

- Or may decrease with increasing dimensionless relaxation time

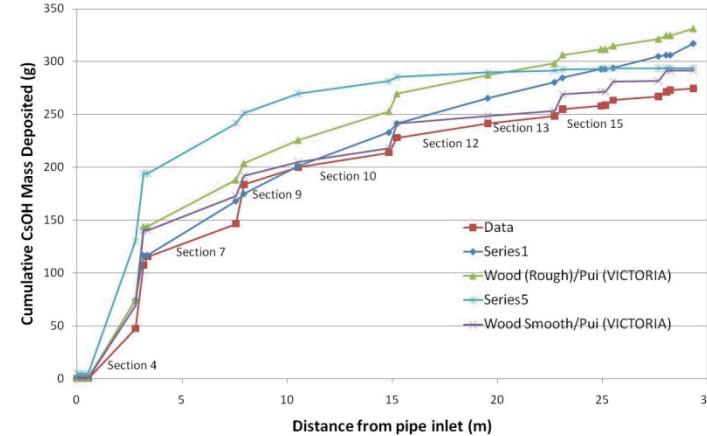
$$V_d^* = \frac{3.6}{\sqrt{\tau_*}} \left(1 - \frac{50}{\tau_*}\right) \quad \tau_* \geq 270$$

LACE LA3A Tests

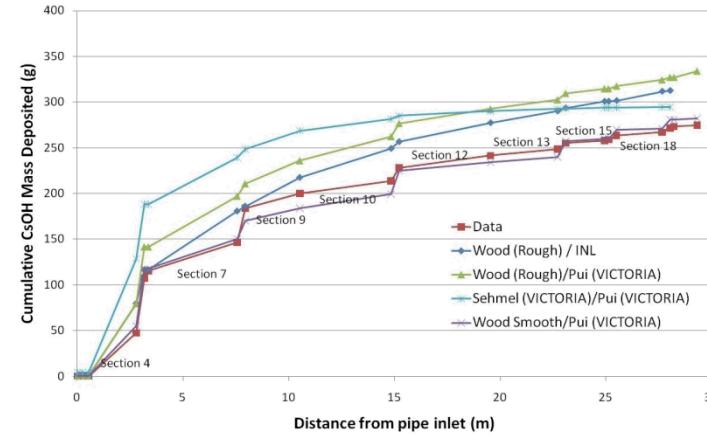
Re $\sim 133,000$

- Wood (Smooth)/Pui combination gives best agreement through pipe, though over predicts deposition downstream
- Sehmel/Pui combination gives best cumulative deposition at end of pipe but over predicts deposition upstream
- Pui model does a better job of predicting deposition in bends.
- Dependency on number of sections is small though results are modestly improved

10 Sections

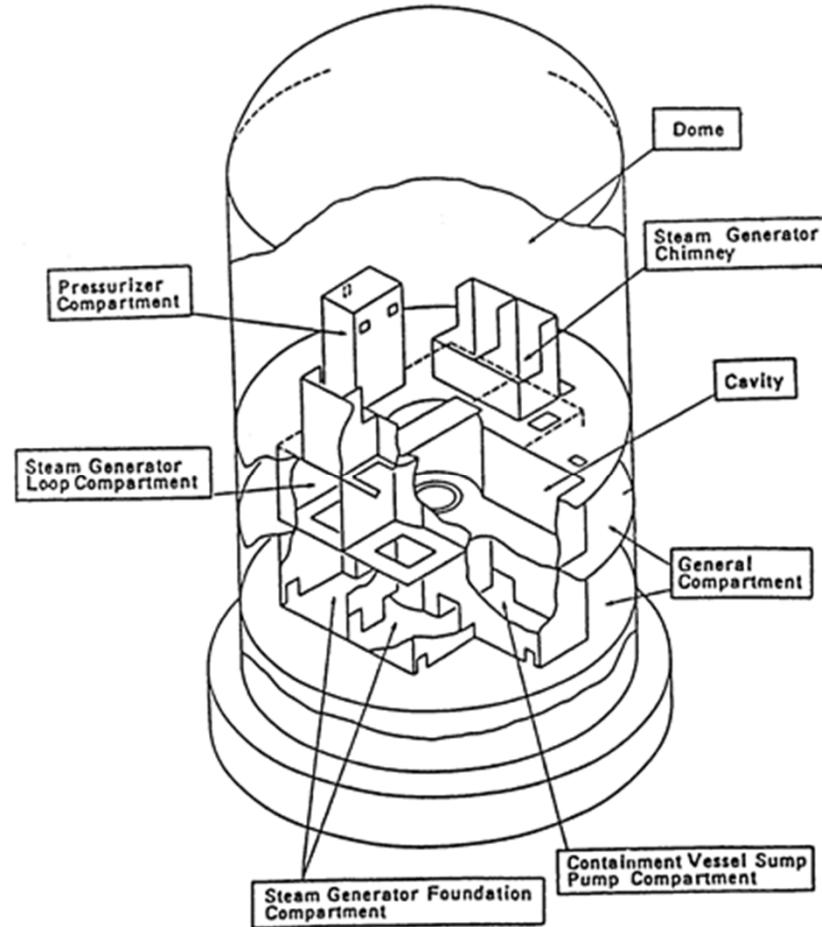


20 Sections



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
- $\frac{1}{4}$ Scale Containment
 - 10.8 m OD domed cylinder,
 - 17.4 m high
 - 25 interconnected compartments (28 total)
- Sprays
 - M-8-1 No Sprays
 - M-7-1 and M-8-2 Sprays modeled

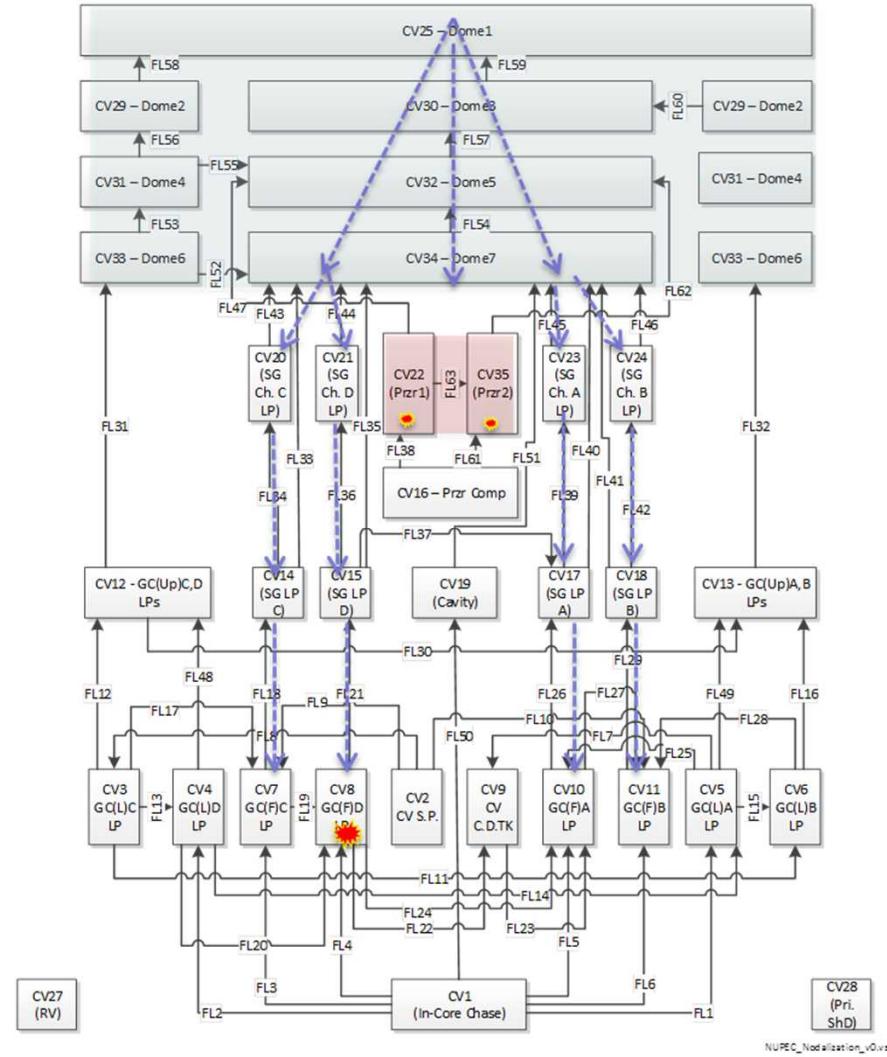


NUPEC Tests

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 ³ /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 ³ /s 313 K

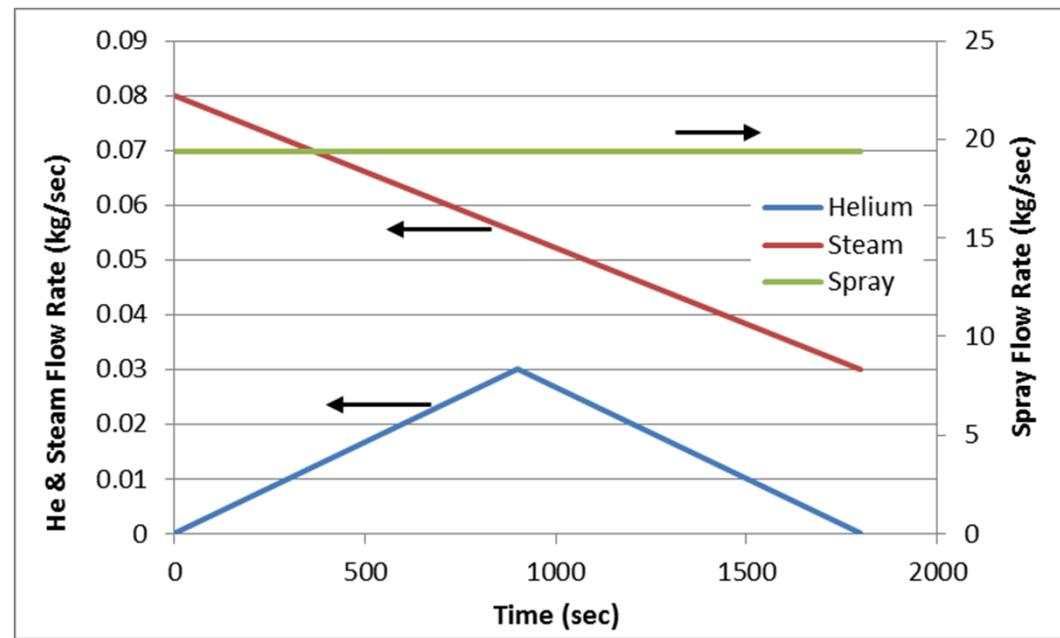
NUPEC MELCOR Nodalization

- Total of 35 CVs
 - Dome compartment subdivided into 7 CVs (green)
 - Allows convection loops
 - Upper pressurizer subdivided into two CVs (red)
 - Allows circulation from upper pressure compartment to lower compartment (dead end)
 - All other compartments represented by a single CV
- M-8-1 & M-8-2 He source in Pressurizer Compartment (CV 22 and CV 35) 
- M-7-1 He source in CV8 
- Spray junctions (M-8-2) shown by dashed arrows
 - Sprays not active in M-8-1

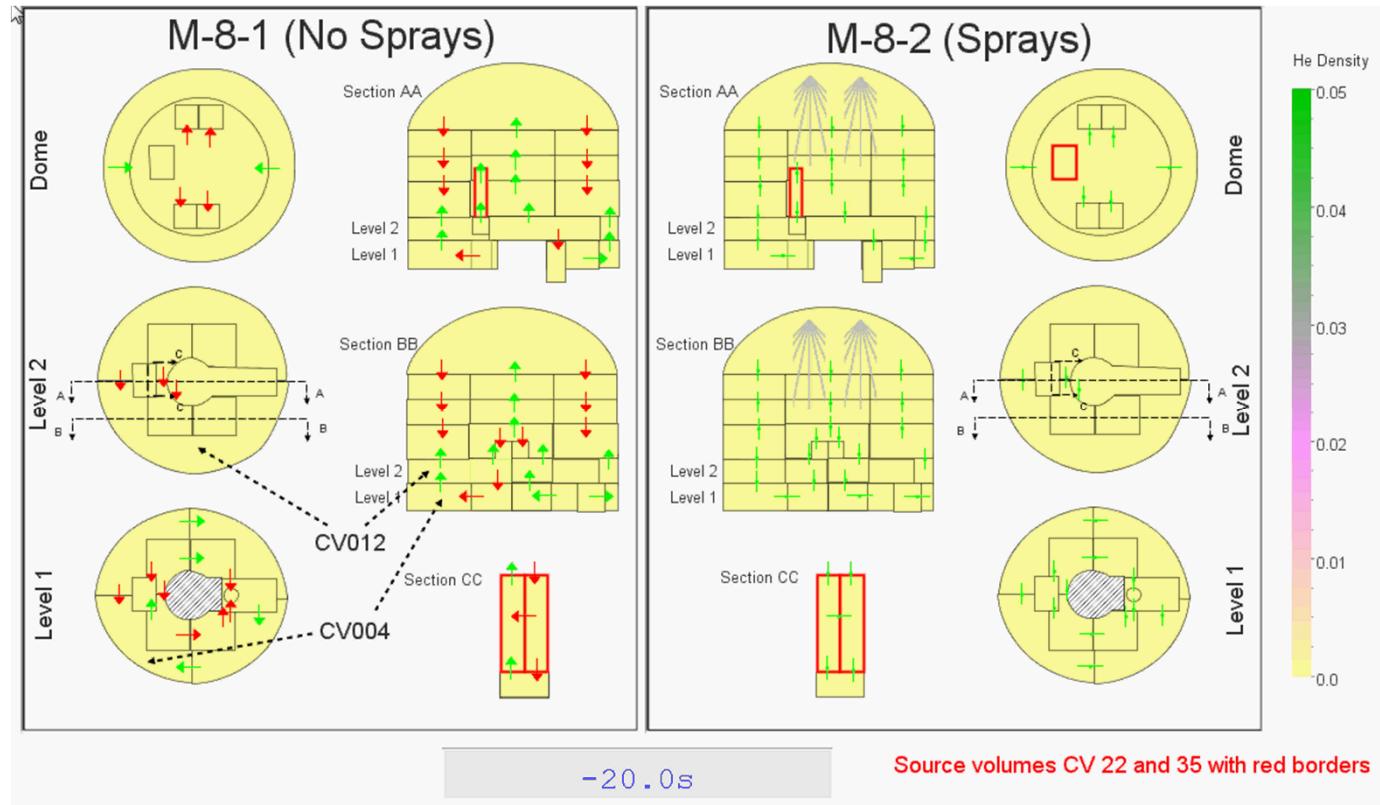


He, Steam, and Spray Sources

- Steam released into a compartment to simulate break of a steam generator system. Total helium volume was decided by volumetric scaling of hydrogen release from 10% Zr-H₂O reaction
 - CVH mass and energy sources in a CV
- At the same time, containment spray was activated to simulate the impact of spray water on mixing.



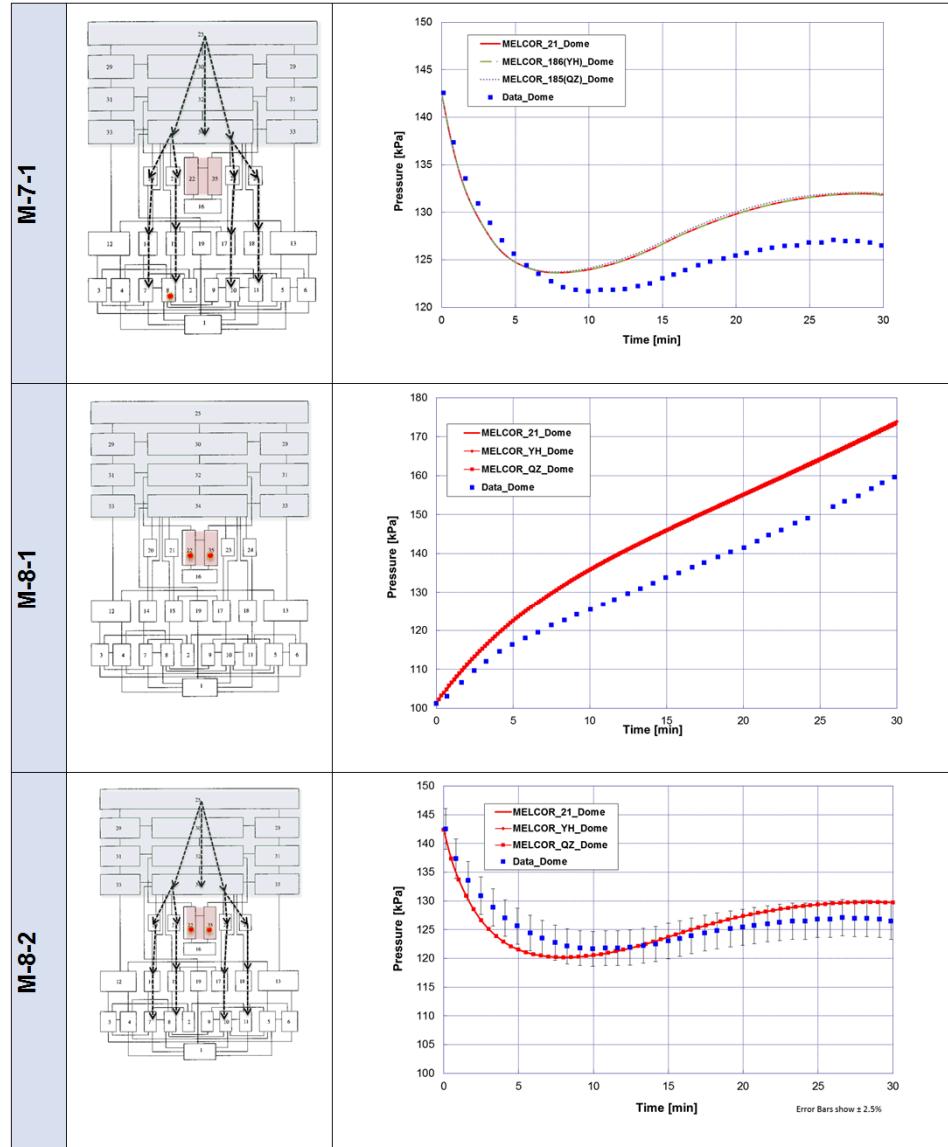
He Concentration Distributions



- 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

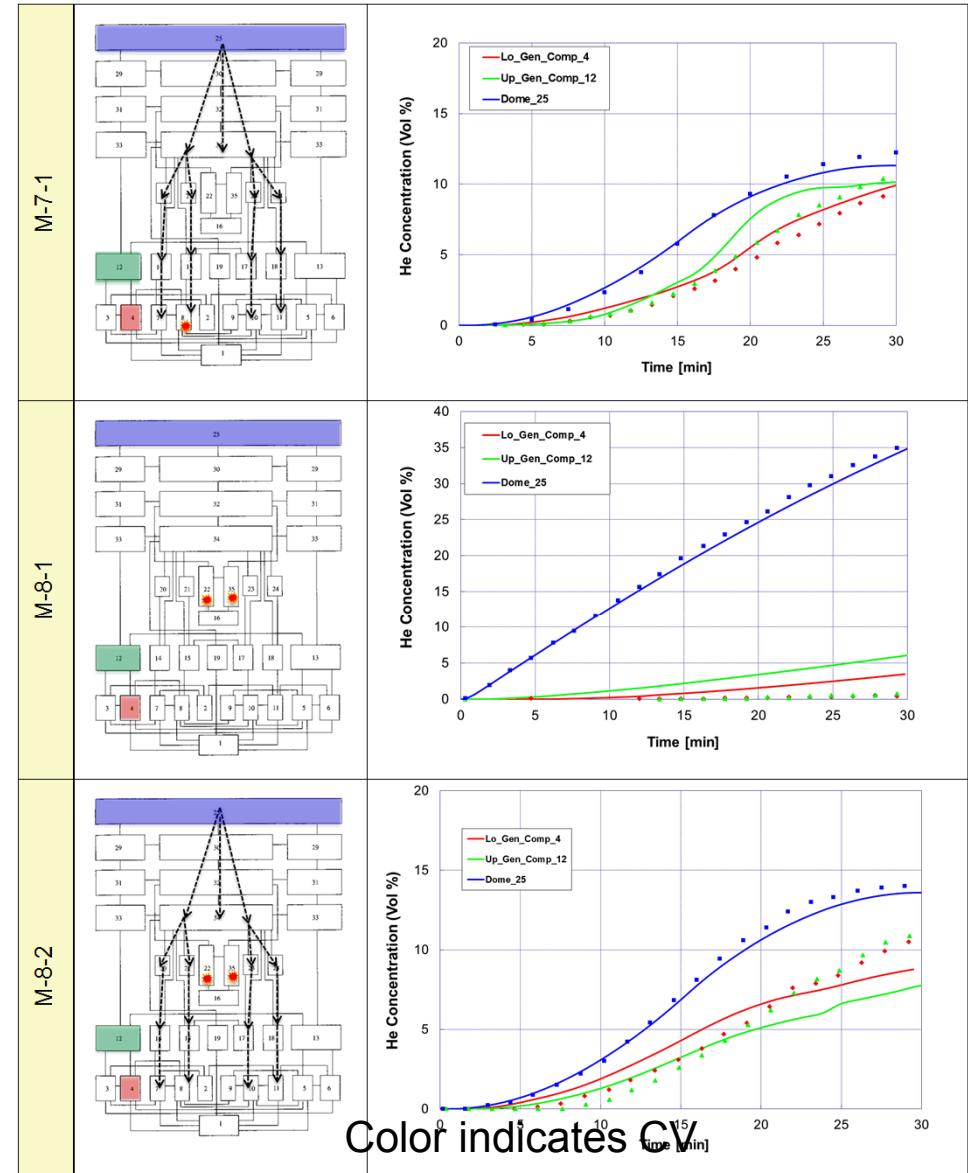
Pressure Response

- Pressure calculated for M-7-1 exceeds experiment pressure
- M-8-1 without sprays shows excessive pressure



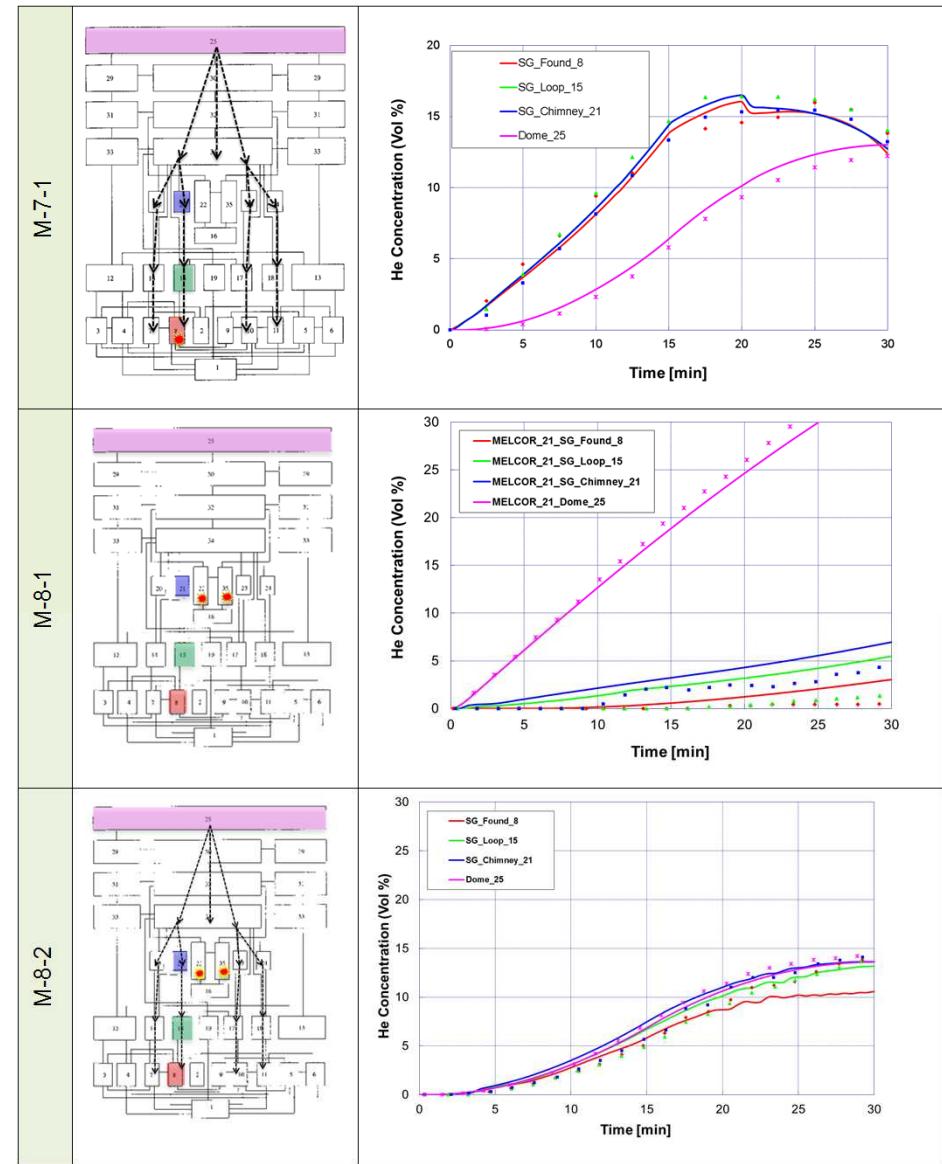
He Concentrations for vert. distribution of general region

- Without sprays
 - MELCOR significantly overpredicts concentration in lower general compartments
- With sprays
 - He concentration well-predicted for all compartments



He Concentrations for vertical distribution of SG loop D

- Concentration in dome is well-predicted for all cases
- M-7-1 shows underprediction of He in mid-level compartments for source in lower level
- Slight under-prediction of concentration for lower compartments in M-8-2 otherwise, well predicted



Color indicates CV

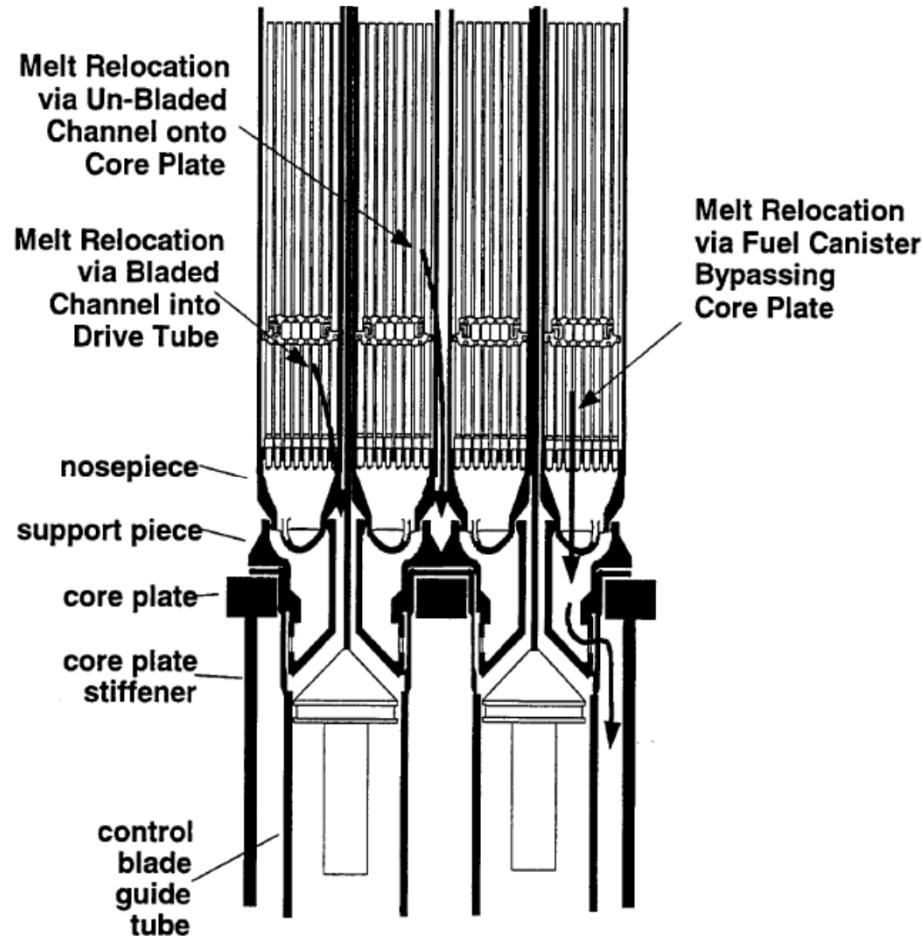
Specific Code Development Challenges



- Current Issues and Uncertainties
 - Current modeling challenges, recent model development,
 - Phenomenon
 - Core Degradation
 - RPV Failure Modes
 - Lower Head Failure
 - MCCI Uncertainties
 - Iodine Chemistry
 - Hydrogen generation and migration
- Data for Validation of Models
 - Extensive current experimental database for validation of code models
- Post-Fukushima Data
 - Forensic investigation of accident can provide valuable missing data for benchmarking code modeling and assumptions

CORE Degradation Modeling Issues

- Current Issues and Uncertainties
 - Failure of Intact Geometry
 - Debris Melt Relocation
 - MELCOR 1.8.6 molten pool modeling (2005)
- Data for Validation of Models
 - Three-mile Island
 - Phebus, MP, DF, XR, LOFT, CORA, QUENCH
- Post Fukushima Data
 - Debris material composition in various locations
 - Physical condition of core barrel (any indication of plastic deformation)
 - Hot gas attack on core upper shroud and upper structures – melting, etc
 - Degree of interstitial blockages between assembly canisters relative to blockages inside of canisters
 - Degree of melt accumulation on core plate and mode of melt attack and relocation to lower head
 - Physical state of “intact” assemblies at core periphery
 - Relative stability of channel boxes when heavily oxidized



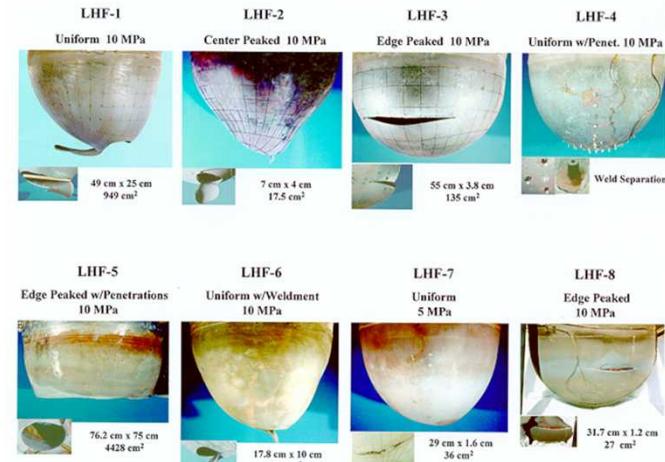
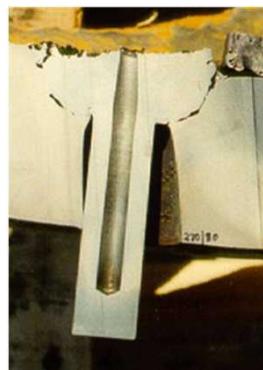
Lower Head Modeling

■ Issues and Uncertainties

- Creep Rupture of Vessel
 - MELCOR uses life-time rule
 - Benchmarked against LHF tests
- Penetration Attack/Failure
 - Temperature based failure
 - Current best practice is to disable penetration failure for best estimate and include in uncertainty analysis
 - strain-based failure may be more reasonable

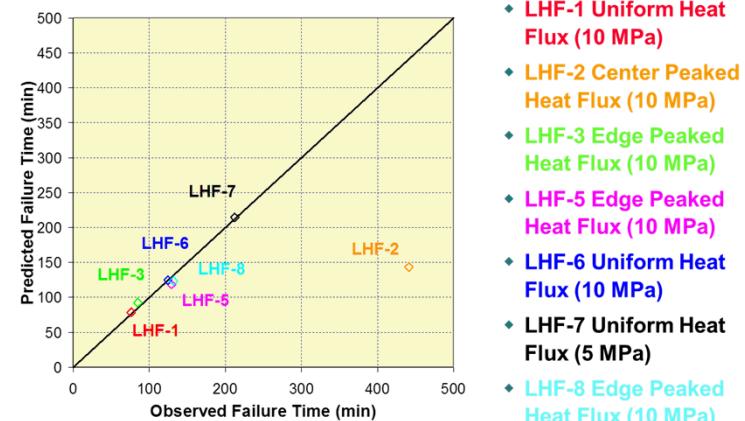
■ Experiments

- Mechanical Failure
 - USNRC LHF Tests (SNL)
 - OECD OLHF Tests (SNL)
 - FOREVER (RIT)
- Molten Corium
 - MASCA (RAS)
 - COSMOS (KAERI)
 - LIVE (KIT)



■ Important Post-Fukushima Observations

- Degree of melt intrusion to inside of drive tubes below the core region through the canister nose piece nozzles
- Extent of melting and collapse of lower plenum drive tubes and incorporation into lower plenum debris
- Extent and nature of melt attack on lower head penetrations or localized head attack by draining melt

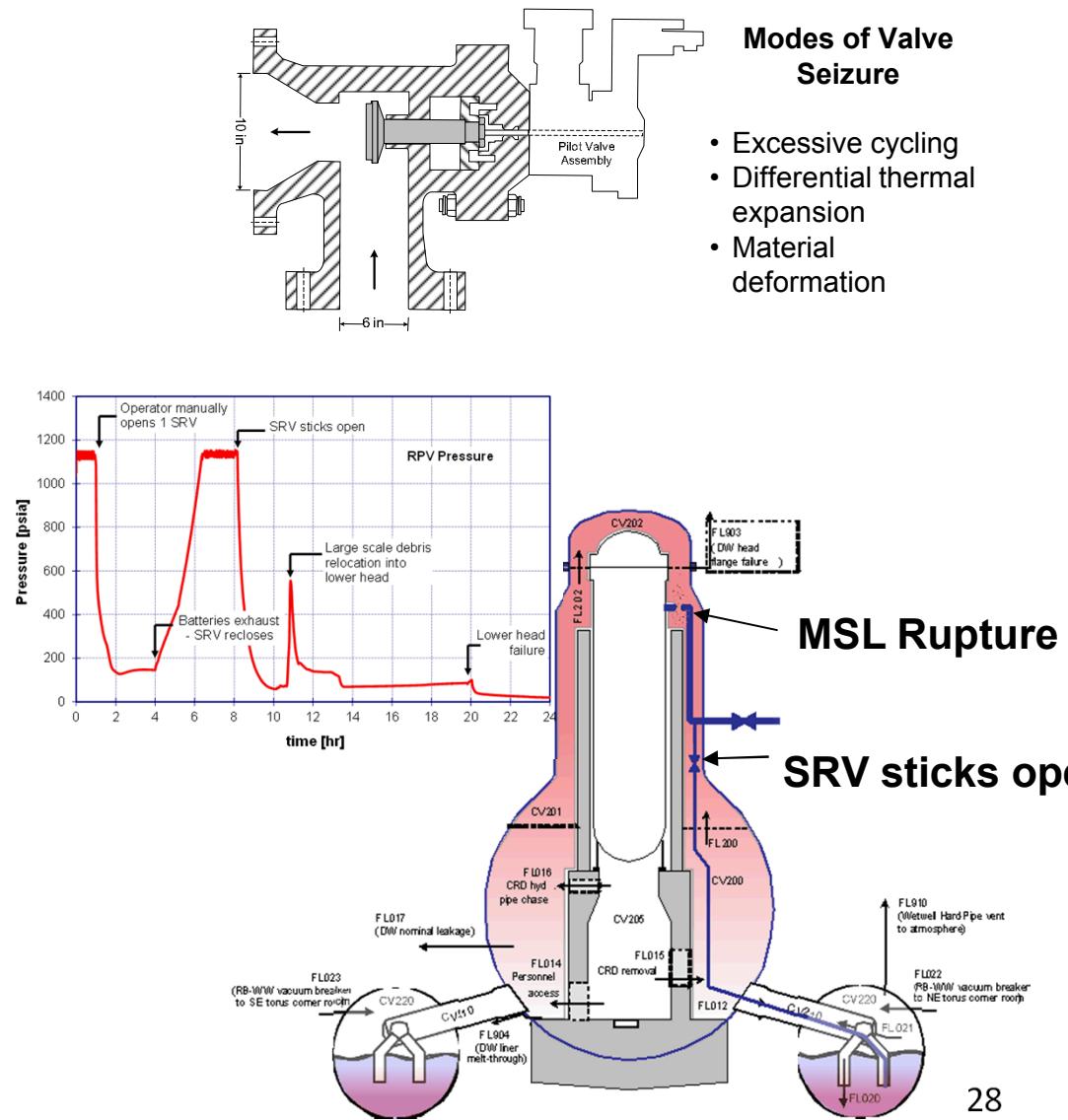


**Time Relative to Onset of Plastic Deformation*

- ◆ 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)

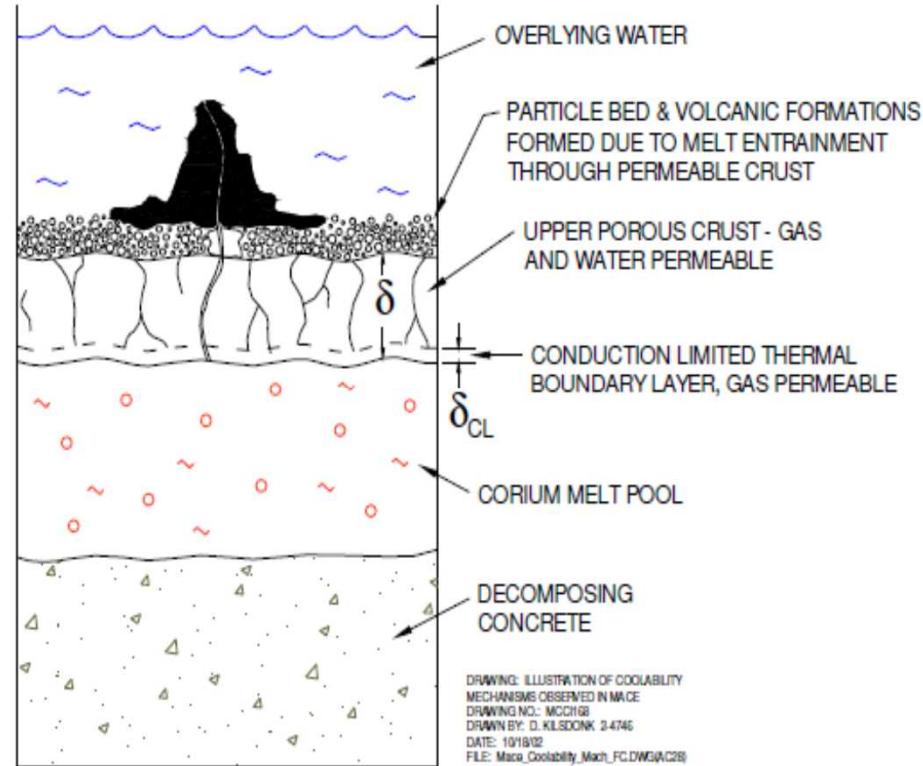
Alternate RPV Failure Mechanisms

- Current Issues and Uncertainties
 - BWR Competing Failure Mechanisms
 - Vessel failure
 - Discharge to drywell
 - Molten corium ejected
 - Seizure of an SRV
 - Delays failure of Lower Head
 - Accelerates oxidation of metallic components
 - Discharge to wetwell and scrubbing of RNs
 - Creep failure of main steam line
 - Discharge to drywell
- Data for Validation of Models
 - Vessel Failure (see previous slide)
 - SRV Failure - little
- Post-Fukushima Data
 - Physical state of SRVs (material degradation and disc re-seating)
 - Metallurgical state of main steam line nozzles and safe-end (look for indicators of creep)



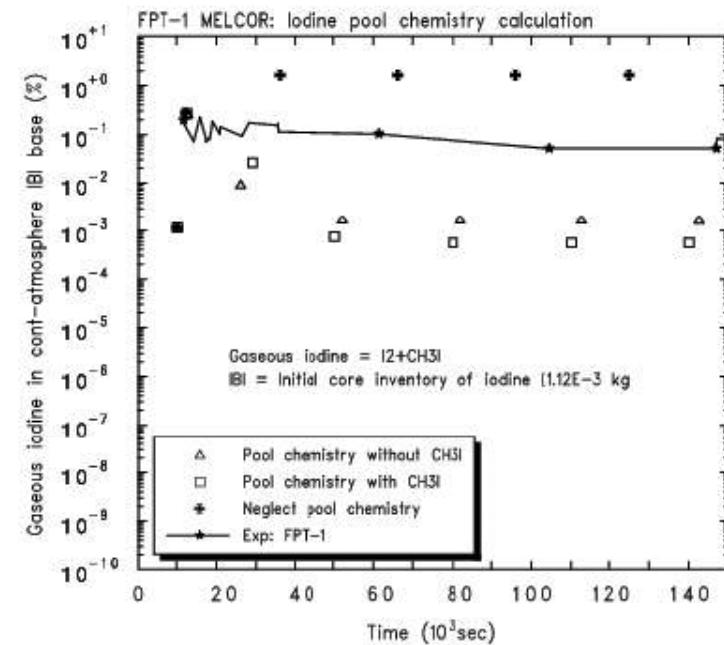
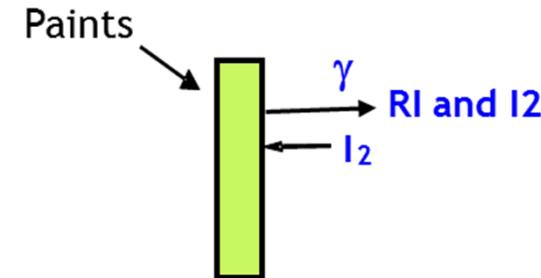
MCCI Uncertainties

- Cooling of molten corium by cavity flooding
 - Cooling occurs at upper surface while ablation can occur at concrete interface
 - Conduction limited cooling across a thin crust at the melt/water interface
 - Potential for crust instabilities and eruptions
 - Validation of new modeling recently added to MELCOR
- Spreading of debris on cavity floor
- Validation
 - Experiments
 - Increase our understanding of cooling mechanisms to better predict and/or demonstrate ex-vessel coolability from cavity flooding
 - NRC/Argonne CCI experiments
 - Improve predictability of axial vs radial ablation to determine basemat failure
 - SARNET/CEA VULCANO Tests
 - Important Post-Fukushima Observations
 - Evidence of crust stability
 - Evidence of existence of eruptions



Iodine Chemistry

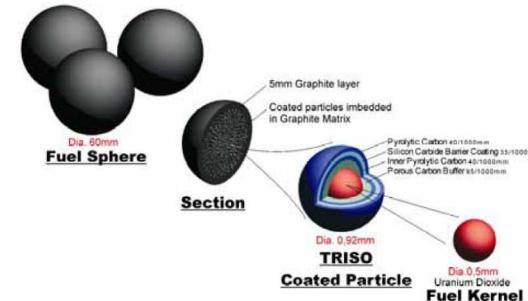
- Issues
 - Gaseous Iodine an important component of source term
 - Interaction of molecular Iodine with paint
 - The chemical mechanisms leading to the trapping of iodine by paints
 - The chemical mechanisms that lead to the formation of organic iodides (RI) and I₂ desorption Temporal effects
 - Paint aging
 - Irradiation effects
- Experiments
 - EPICUR, BIP
 - Adsorption of iodine on surfaces
 - Formation of organic iodides from irradiated paint



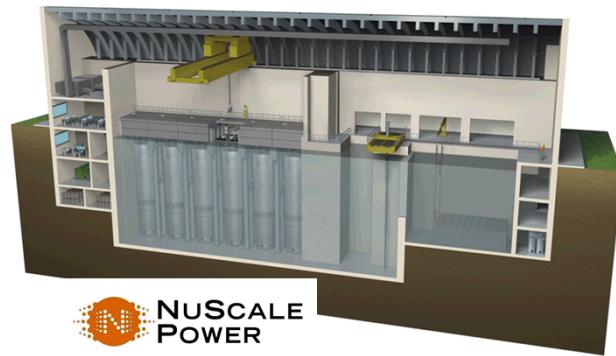
JONG-HWA PARK*, DONG-HA KIM and HEE-DONG KIM
Korea Atomic Energy Research Institute,

Development of New or Alternate Reactor 'Types'

- Gas Cooled – Recent model development for HTGR and PBMR components completed. Radionuclide release model development nearly complete. Lift-off models would need to be added.
 - VHTR
 - PBMR
 - GT-MHR
 - Prismatic gas-cooled design
- LWR – Possible changes to containment (multiple lower heads)
 - NuScale (Nuscale)
 - IRIS (Westinghouse)
 - mPower (B&W)
- LMR – MELCOR would need capability to model liquid metal working fluid as well as modeling other Na containment issues (fires)
 - SFR (Toshiba)
 - PRISM (Hitachi)
- Spent Fuel Pools



Source: "PBMR Project Status and the Way Ahead", D. Matzner, 2nd Int'l Topical Mtg on High Temperature Reactor Technology, Beijing, China, 2004.



Best Practices

Emphasis is on Automation

Affordable solution
Consistent solution

- MELCOR Wiki
 - Archiving information
 - Sharing resources (policies, conventions, information, progress) among the development team.
- Code Configuration Management (CM)
 - 'Subversion'
 - TortoiseSVN
 - VisualSVN integrates with Visual Studio (IDE)
- Code Review
 - Code Collaborator
- Nightly builds & testing
 - DEF application used to launch multiple jobs and collect results
 - HTML report
 - Regression test report

- Regression testing and reporting
 - More thorough testing for code release
 - Target bug fixes and new models for testing
- Bug tracking and reporting
 - Bugzilla online
- Validation and Assessment calculations
- Documentation
 - Available on Subversion repository with links from wiki
 - Latest PDF with bookmarks automatically generated from word documents under Subversion control
 - Links on MELCOR wiki
- Sharing of information with users
 - External web page
 - MELCOR workshops
 - LinkedIn User Group

MELCOR Quality Assurance:

Tracking Code Changes

- Changelog
 - List of code issues and modifications by revision
 - References to bugzilla site
- MELCOR Trends
 - Provide a very general assessment of code modifications
 - Code stability
 - Performance
 - Metrics
 - H2 generated, Cs deposition, deposition on filters, CAV ablation
 - Provided with each public code release
 - Automated as part of testing

MELCOR 2.1.4011 Changes

January 20, 2012

This is a list of important changes in MELCOR since revision 3228, which was released at the 2011 MELCOR User's Workshop. Content in this document was adapted from the the MELCOR source code configuration system change log. Some details were removed to improve readability. Other details have been expanded upon to improve clarity. If you wish to see a chronological log of comments entered by the developers as the code evolved, the complete change log is provided in its entirety [here](#).

Where bug numbers are listed, a hyperlink is provided to the bugzilla defect-tracking system. Please note that bug numbers are not unique to this release. These numbers are generated for feature

Revision: 4011
Official 2.1.4011 release.

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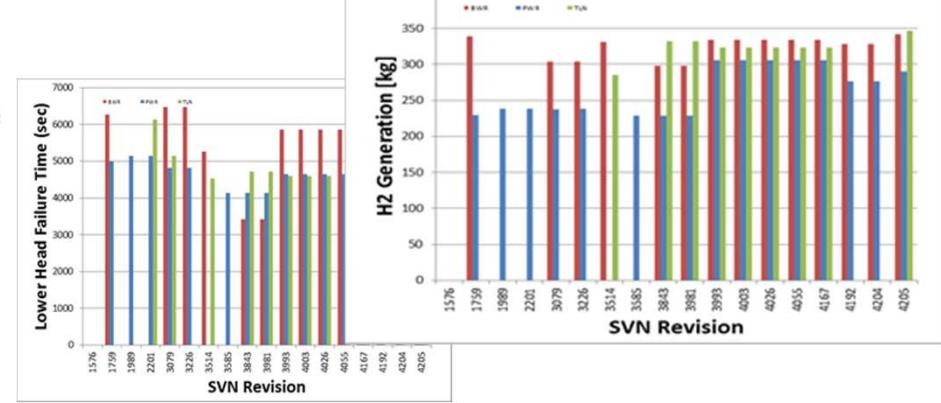
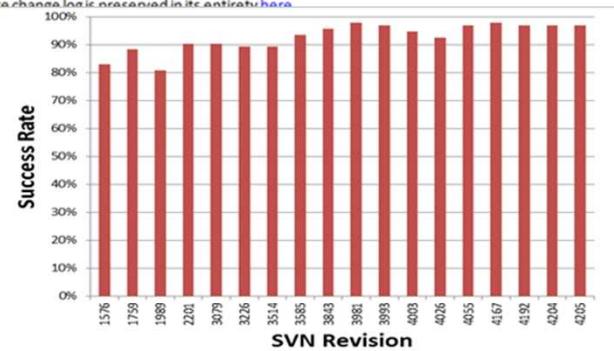
Revision: 4003
Disable the eutectics model by giving an error message if it is

....

Revision: 4002
Redo the NCF computation for a flowpath that contains

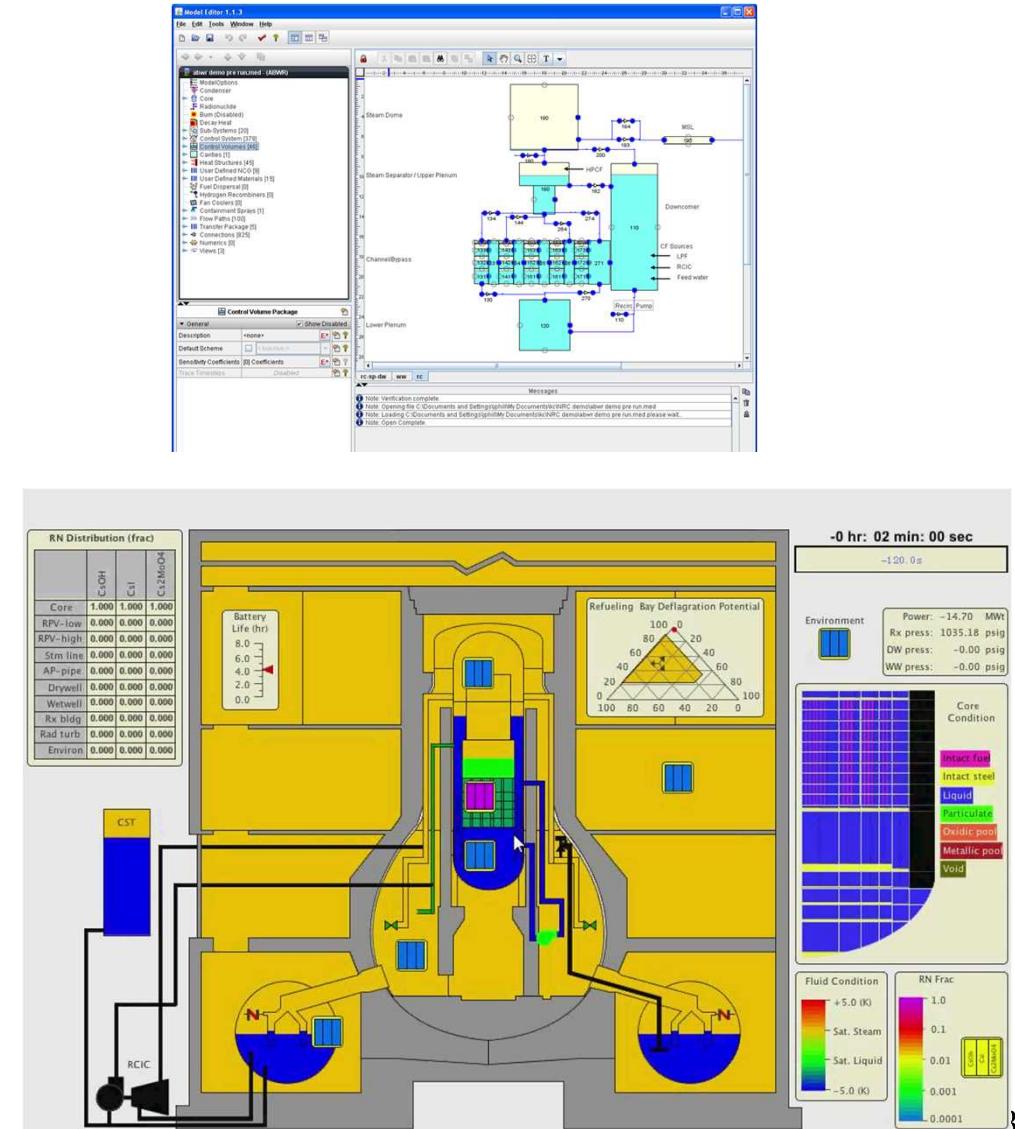
Bug#: [907](#)

....



Visualization and Graphical Interface

- Visualization is important for improving quality of calculations
 - Identification of modeling errors and issues
- Graphical user interface
 - Can reduce input errors
 - Simplifies input for new users
- SNAP MELCOR 2.1 Plugin
 - Version 1.0.0 - Released 7/17/09
 - Current version 2.1.1 – Released 2/24/12
 - Will convert a 1.8.6 input deck to 2.1 and back to 1.8.6
 - Sandia is working with SNAP developers to recommend enhancements for MELCOR plug-in
- 2011 workshop focused on the use of SNAP
- Model Editor -Components
 - Tree Structure organization
 - Arranged according to MELCOR package
 - ASCII view of object available
 - Organize components
 - DIFF capability for components
- Views
 - Trend plots
 - Custom animations
 - Others



Summary

- Severe accident modeling has advanced significantly over the past 30 years
- Validation against accidents and experiments important to identify weaknesses and guide future code development
- Codes must be able to adapt to new reactor design concepts
- Importance of the user interface in improving quality of calculations
- Questions?