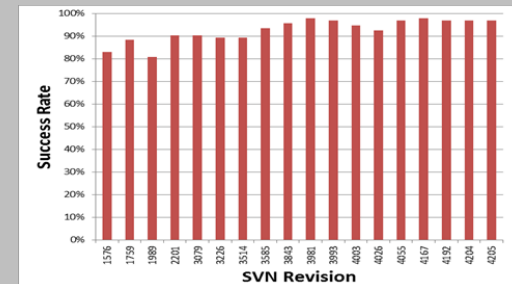
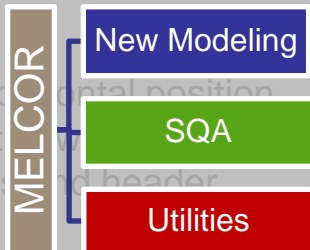
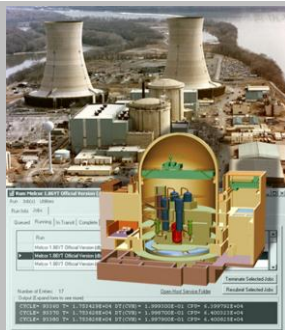


Exceptional service in the national interest



Nuclear Severe Accident Modeling and Analysis

Presented by Larry Humphries
llhumph@sandia.gov

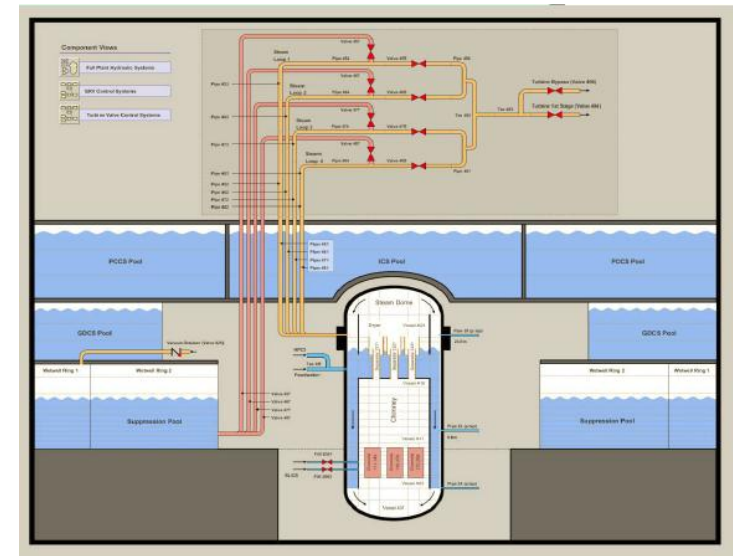
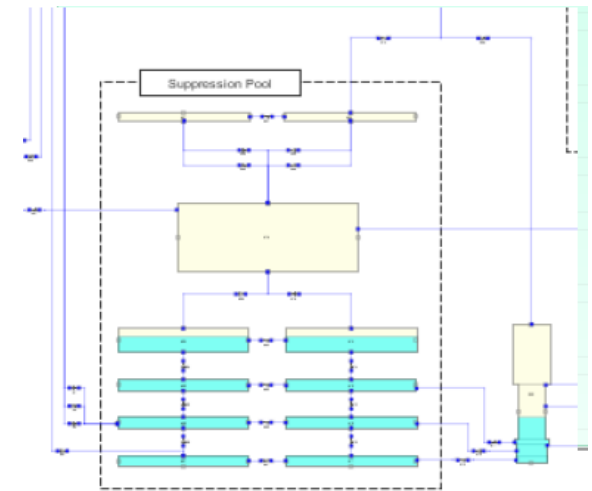
Nuclear SAC Modeling and Analysis

Outline of Presentation

- Severe accident code overview
- Code development history
- 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, PWR-SFP, BWR-SFP
- 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

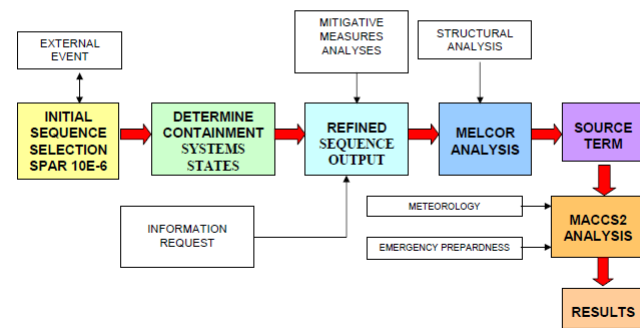


SAC Applications

- 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
 - DOE Safety Software “Toolbox” code

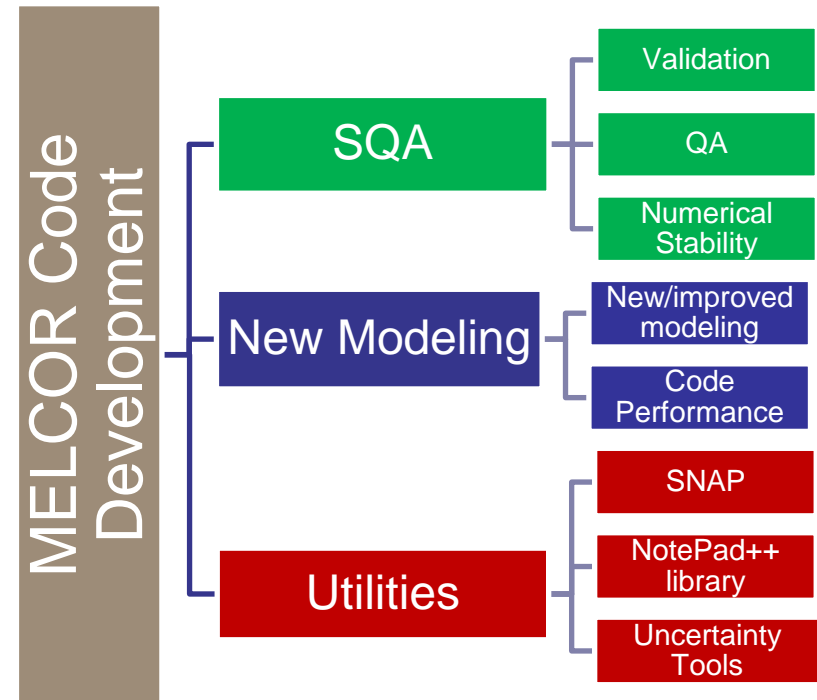


SOARCA PROCESS

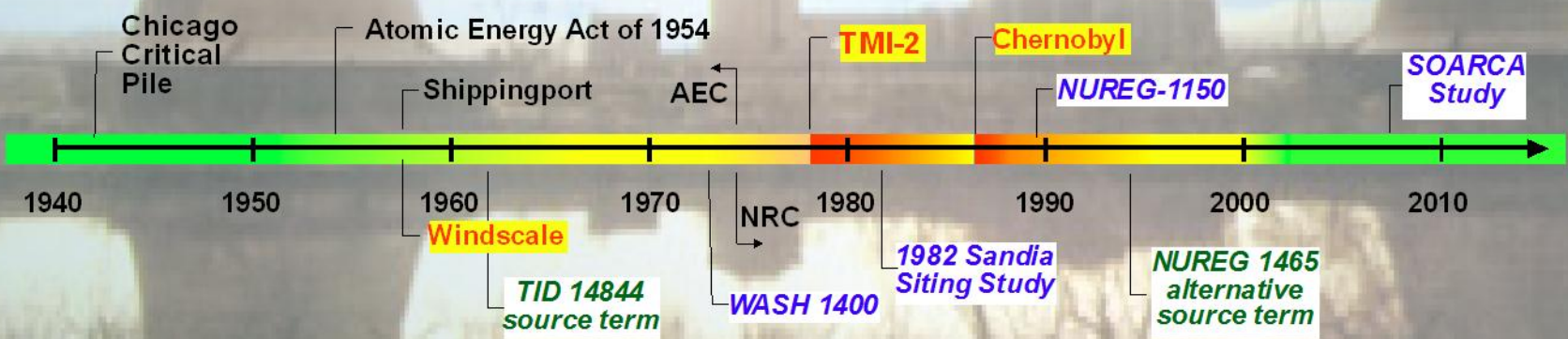


MELCOR Code Development

- 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



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

Timeline for Evolution of MELCOR Modeling Practices

Circa 1985

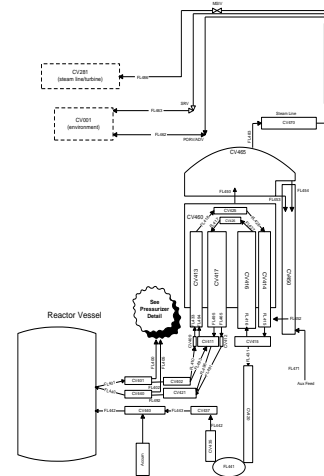
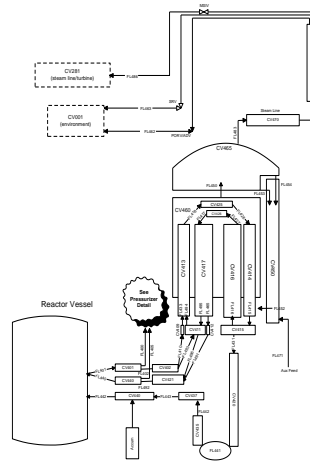
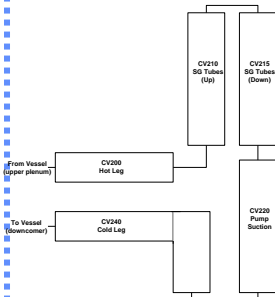
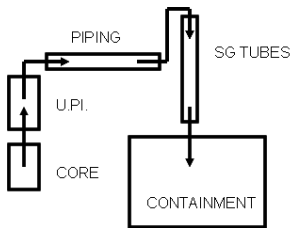
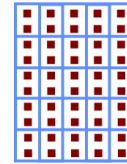
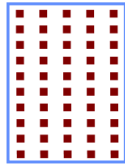
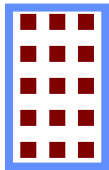
Circa 1990

Circa 1995

Circa 1998 - Present

Future

Modeling Techniques



- MELCOR 2.1
- Core design details
- FP Chemistry, Impaction, other

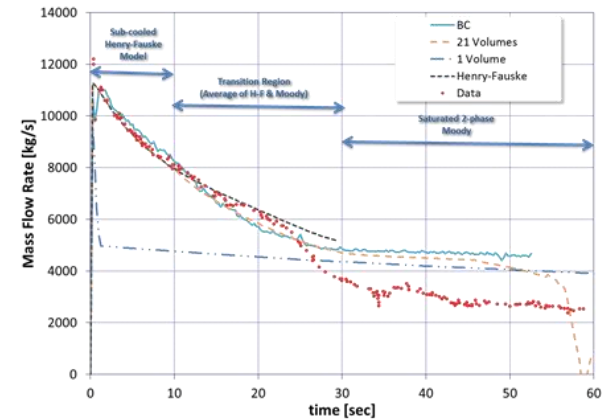
MELCOR Code Development – Past Decade

- 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”
 - RELAP
 - SCDAP / MELPROG
 - CONTAIN / VICTORIA

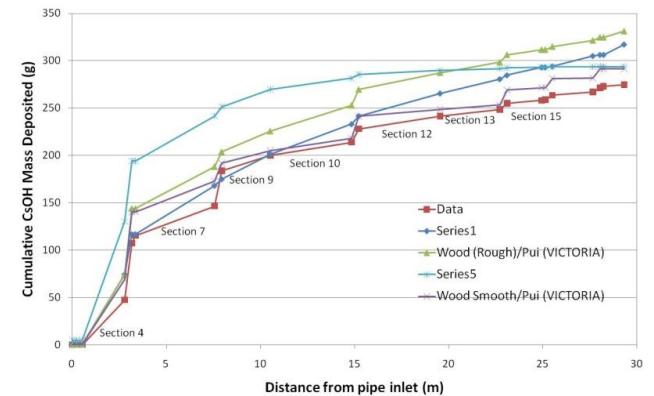
MELCOR Code Validation

- 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

Critical Flow:

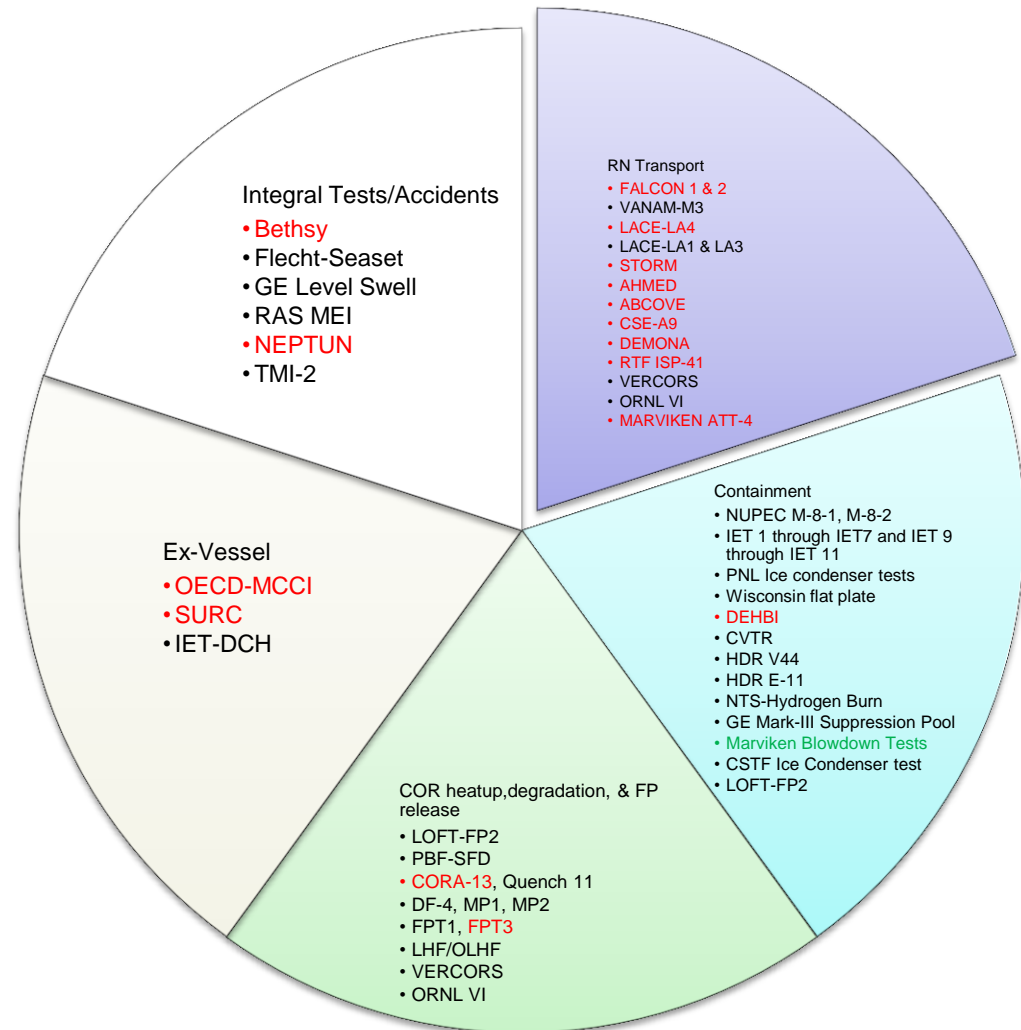


Turbulent Deposition:



MELCOR Code Validation

- Both Separate Effects and Integral Tests
- Part of our regression test suite
 - Many of these are ongoing analyses
- Coverage of most important physics
 - Heatup/Heat transfer
 - Oxidation
 - Reflood
 - Degradation
 - Molten pool
 - FP Release
 - Vessel failure
 - Critical Flow
 - MCCI
 - DCH
 - Condensation
 - Containment stratification
 - Hydrogen Burn
 - Hygroscopic effects
 - Aerosol deposition
 - RN transport
 - Iodine pool chemistry
 - Suppression pool level response
 - Vent clearing
 - Engineering Safety Features
 - Sprays
 - Ice Condensers
- Sensitivity Analysis of Input Analysis
- Will be published as Volume III Documentation Report

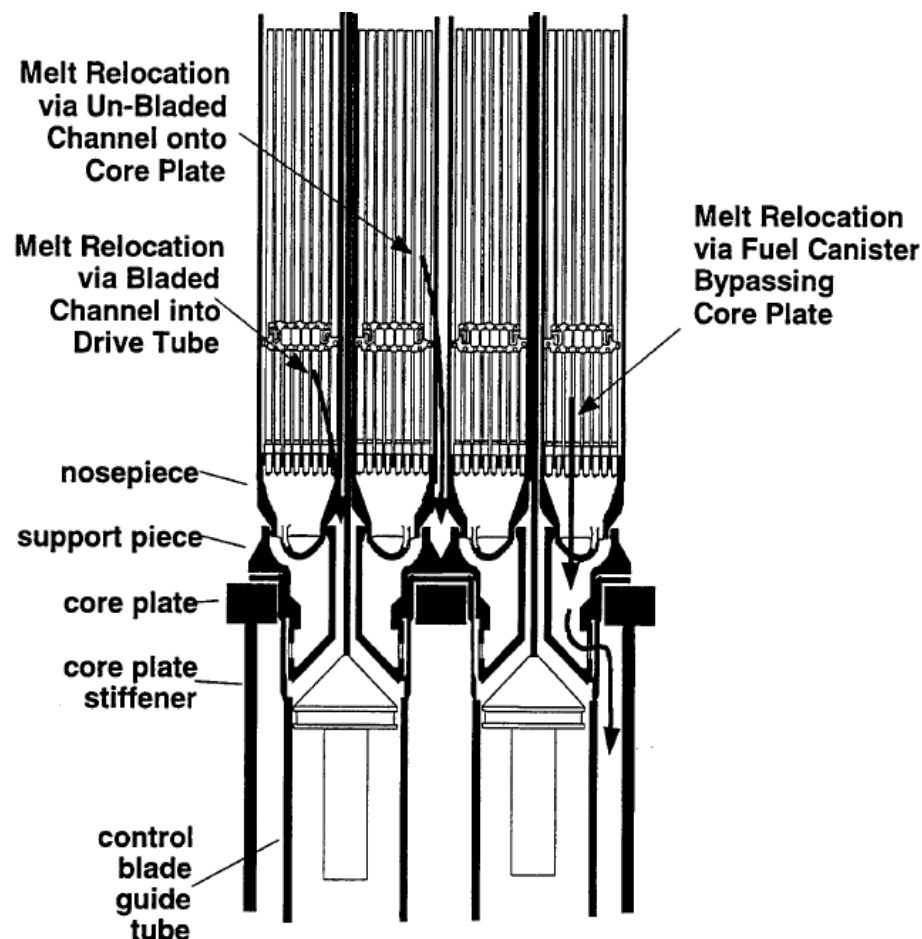


Specific Code Development Challenges Sandia National Laboratories

- Current Issues and Uncertainties
 - Current modeling challenges, recent model development,
 - Phenomenon
 - Core Degradation
 - RPV Failure Modes
 - Lower Head Failure
 - MCCI Uncertainties
 - Iodine Chemistry
- 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



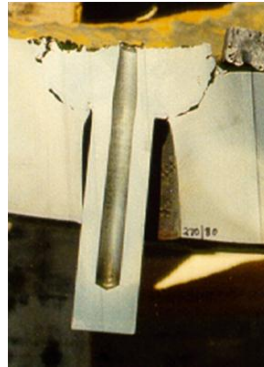
Lower Head Modeling

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

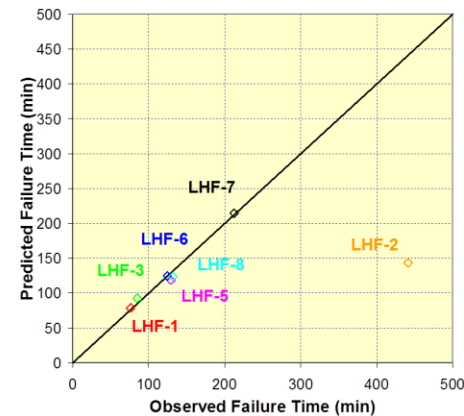
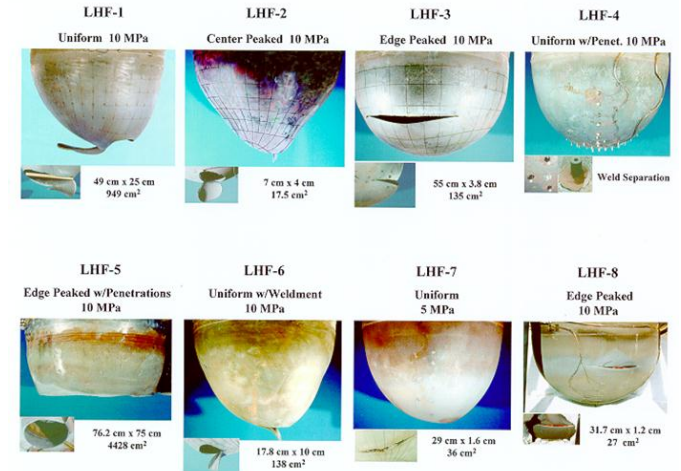
Experiments

- 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



- ◆ 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)

*Time Relative to Onset of Plastic Deformation

Alternate RPV Failure Mechanisms

Current Issues and Uncertainties

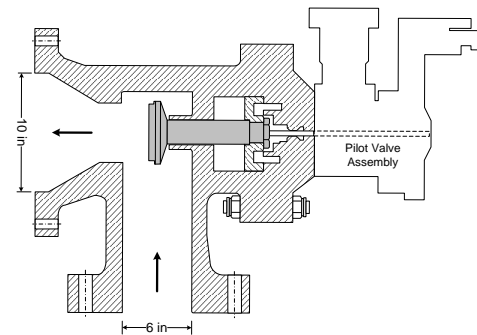
- BWR Competing Failure Mechanisms
 - Vessel failure
 - Discharge to drywell
 - Molten corium ejected
 - Seizure of an SRV
 - Delays failure of Lower Head
 - Accelerates oxidation of metallic components
 - Discharge to wetwell and scrubbing of RNs
 - Creep failure of main steam line
 - Discharge to drywell

Data for Validation of Models

- Vessel Failure (see previous slide)
- SRV Failure - little

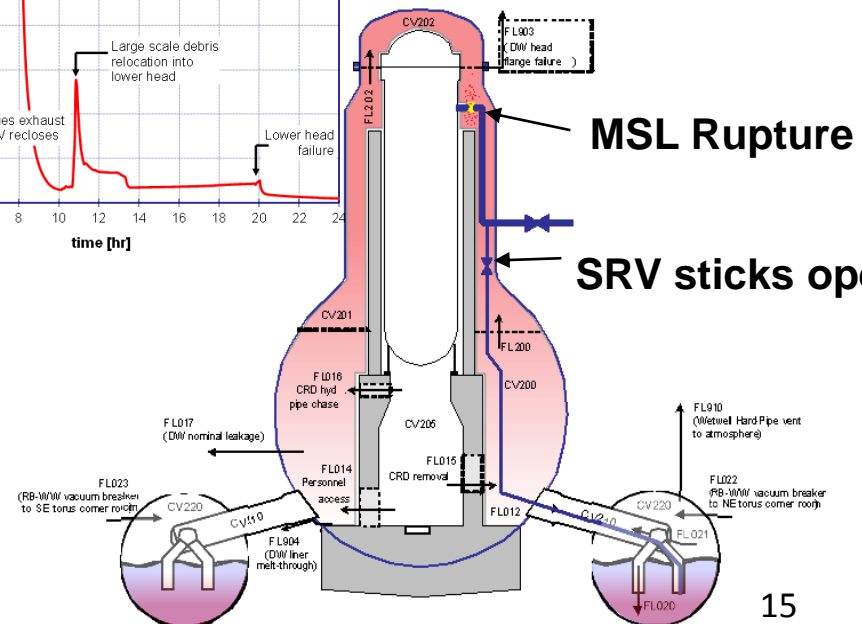
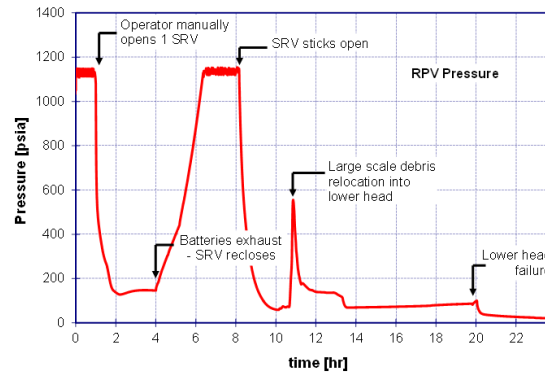
Post-Fukushima Data

- 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)



Modes of Valve Seizure

- Excessive cycling
- Differential thermal expansion
- Material deformation



MCCI Uncertainties

Cooling of molten corium by cavity flooding

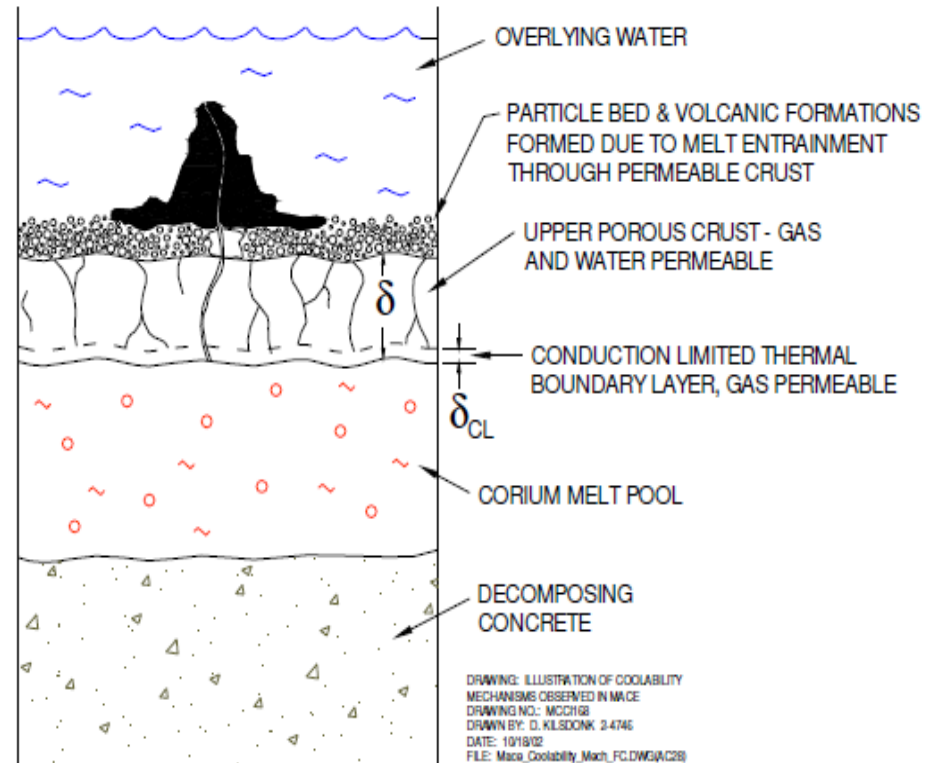
- Cooling occurs at upper surface while ablation can occur at concrete interface
 - Conduction limited cooling across a thin crust at the melt/water interface
 - Potential for crust instabilities and eruptions
 - MELCOR currently does not model such instabilities but the current 'best practice' is to apply multipliers to conduction and convection terms
 - » Multipliers were chosen to better predict MACE tests
 - Future development of improved modeling of corium cooling

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



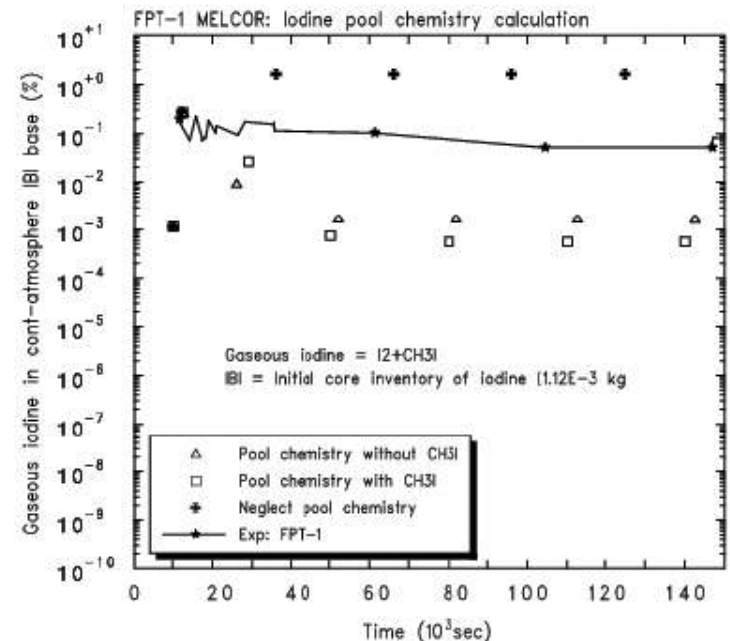
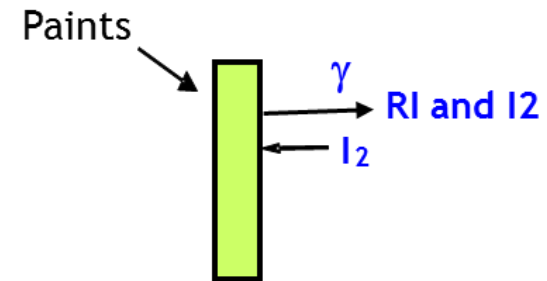
Iodine Chemistry

■ 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

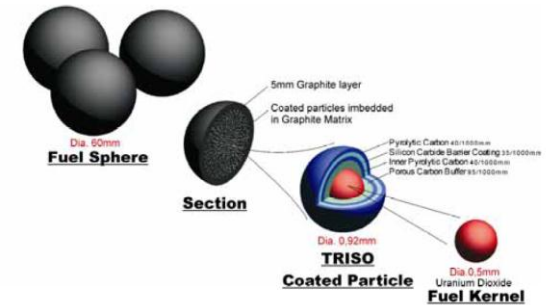


JONG-HWA PARK*, DONG-HA KIM and HEE-DONG KIM
Korea Atomic Energy Research Institute,

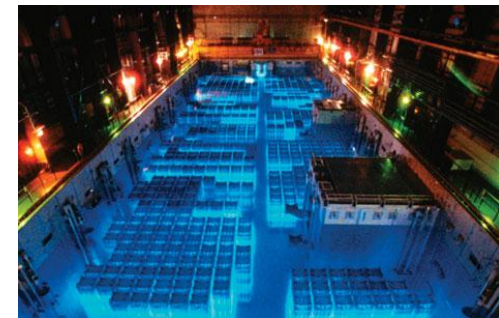
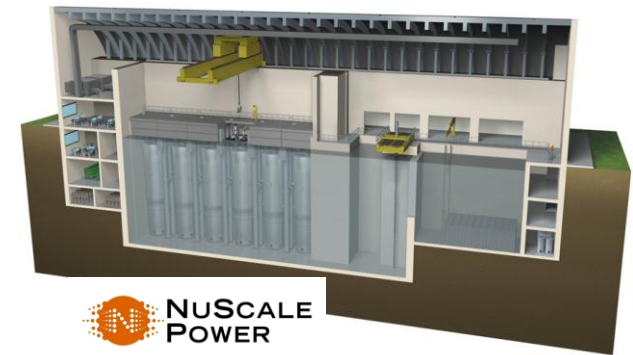
Development of New or Alternate

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.



Modern Software Quality Assurance

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

- Changelist
 - 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

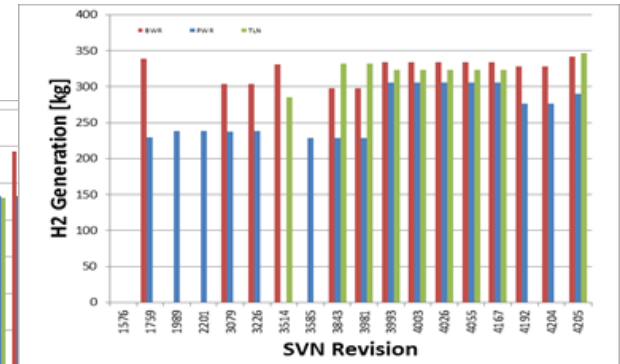
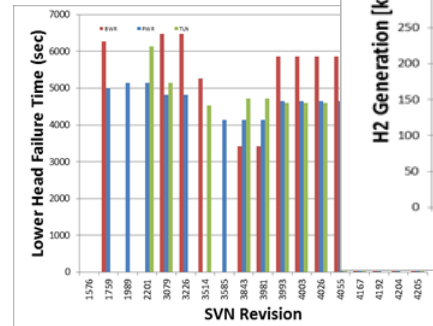
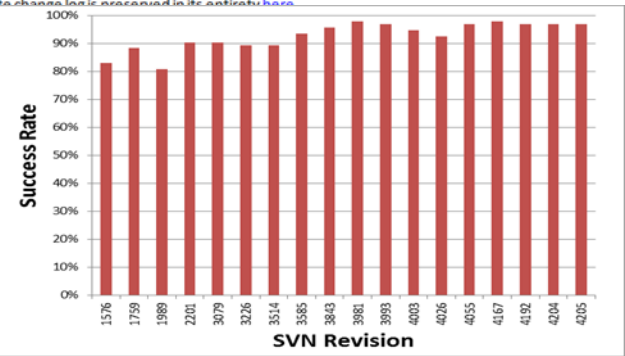
This is a list of important changes in MELCOR since revision 3228, which was released at the 2011 MELCOR User's Workshop. Content in this document was adapted from the the MELCOR source code configuration system change log. Some details were removed to improve readability. Other details have been expanded 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 available at [this base](#).

Where bug numbers are listed, a hyperlink is provided to the defect-tracking system. Please note that bug numbers are generated for features to be fixed. These numbers are generated for features to be fixed.

Revision: 4011
Official 2.1.4011 release.

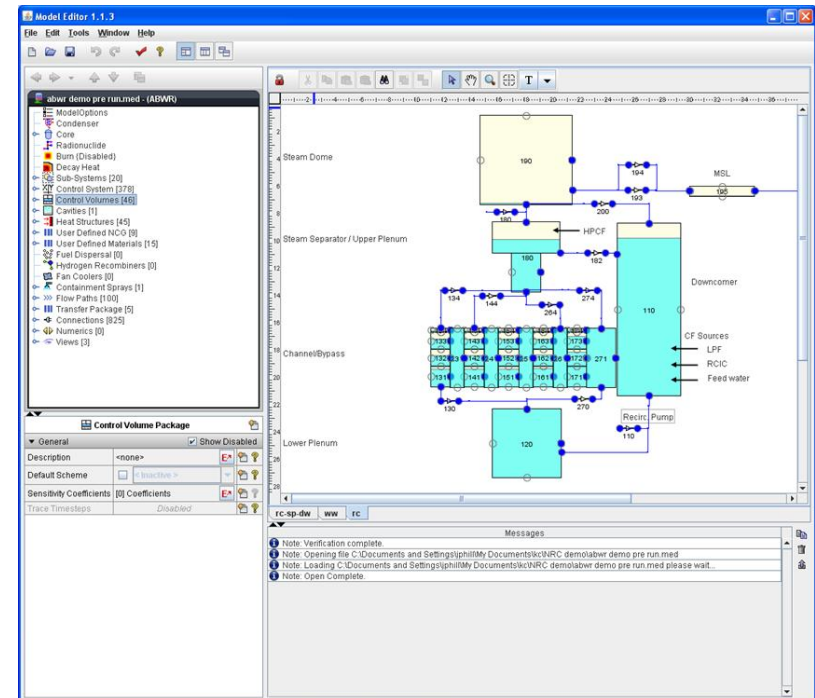
Revision: 4003
Disable the eutectics model by giving an error message.

Revision: 4002
Redo the NCF computation for a flowpath that contains a valve.
Bug#: [907](#)



Visualization and Graphical Interface Sandia National Laboratories

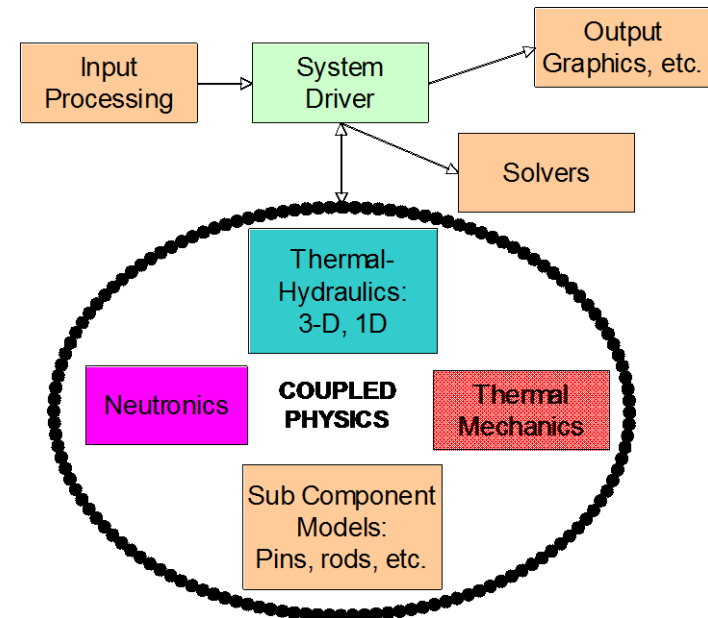
- Visualization is important for improving quality of calculations
 - Identification of modeling errors and issues
- Graphical user interface
 - Can reduce input errors
 - Simplifies input for new users
- SNAP MELCOR 2.1 Plugin
 - Version 1.0.0 - Released 7/17/09
 - Current version 2.1.1 – Released 2/24/12
 - 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
 - DIFF capability for components
- Views
 - Trend plots
 - Custom animations
 - Others



Future Code Development Possibilities

Multi-Physics Coupling Strategy

- Different codes for different physics
 - RIO, MELCOR,
 - ARIA,
 - NEUTRONICS-ORNL
- Strong coupling enabled through using a Jacobian-Free Newton-Krylov (JNFK) method
- Overall solution is orchestrated by a Multi-Physics Driver/Solver Code
 - Written in Python
 - Various PhysicsModules (codes) are defined, whose primary job is taking a complete state vector and returning a partial residual
 - The Driver/Solver accepts an arbitrary number of PhysicsModules, and can build and solve the global coupled problem



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?