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Phenomenological Advances of Severe Accident Progression

R.O. Gauntt, Reactor Analysis and Modeling Department
Sandia National Laboratories
Albuquerque, New Mexico
Dept 6762 rogaunt@sandia.gov

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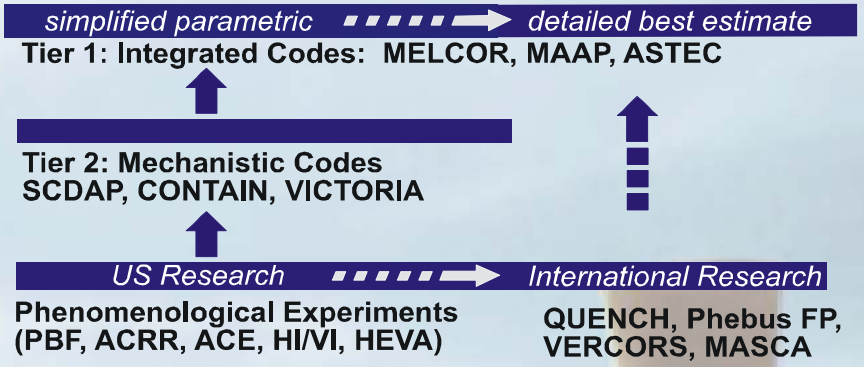
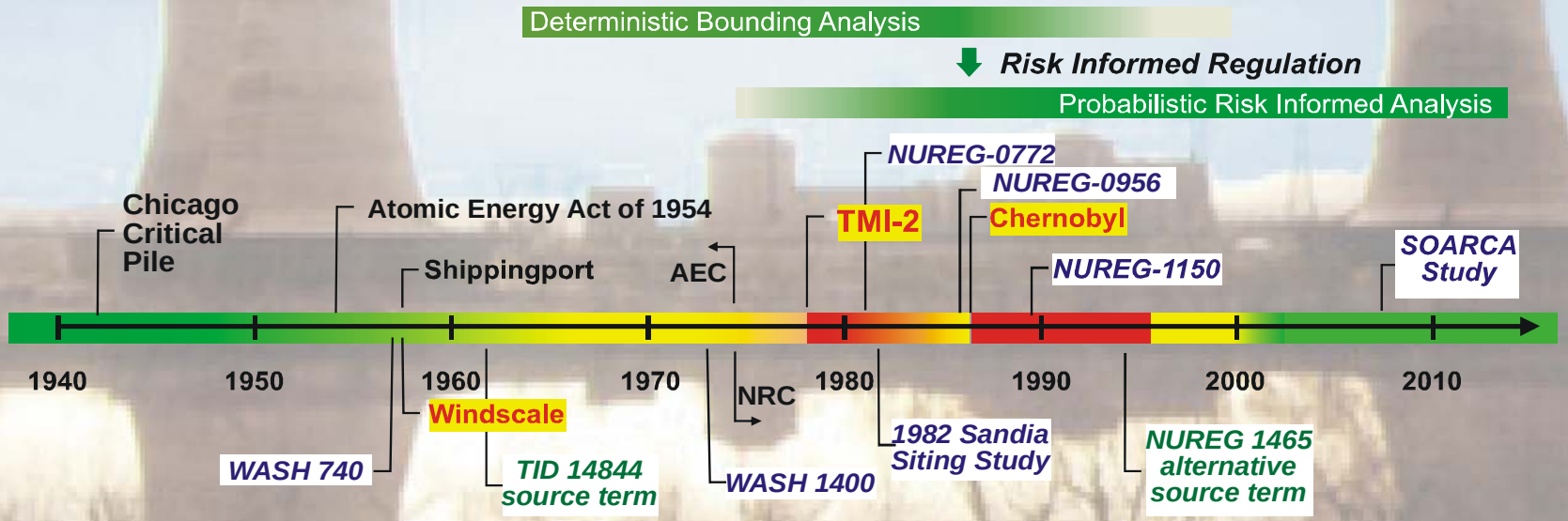
SOARCA Objectives

- Perform a state-of-the-art, realistic evaluation of severe accident progression, radiological releases and offsite consequences for important low likelihood accident sequences
- State of Art in
  - Understanding and modeling of physics and phenomena
  - Fidelity and realism in system representation

Timeline of Nuclear Safety Technology Evolution



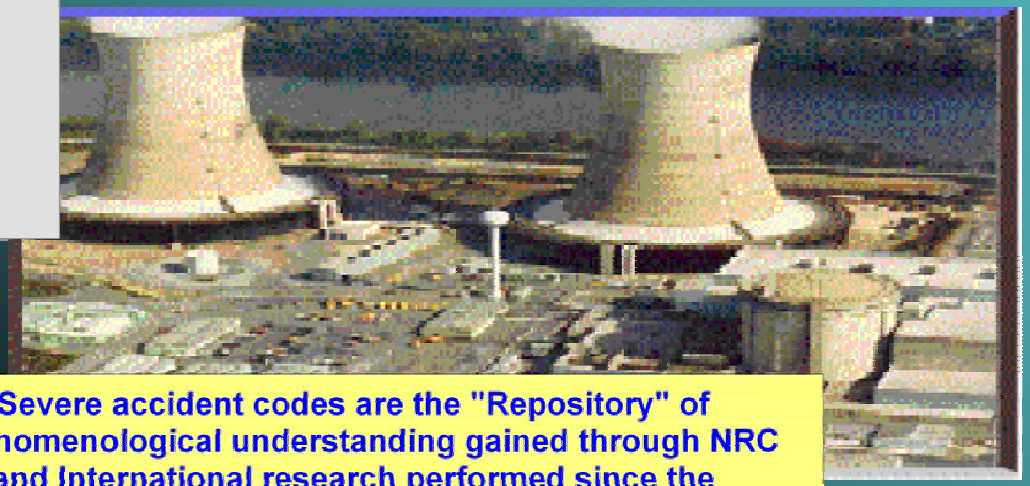


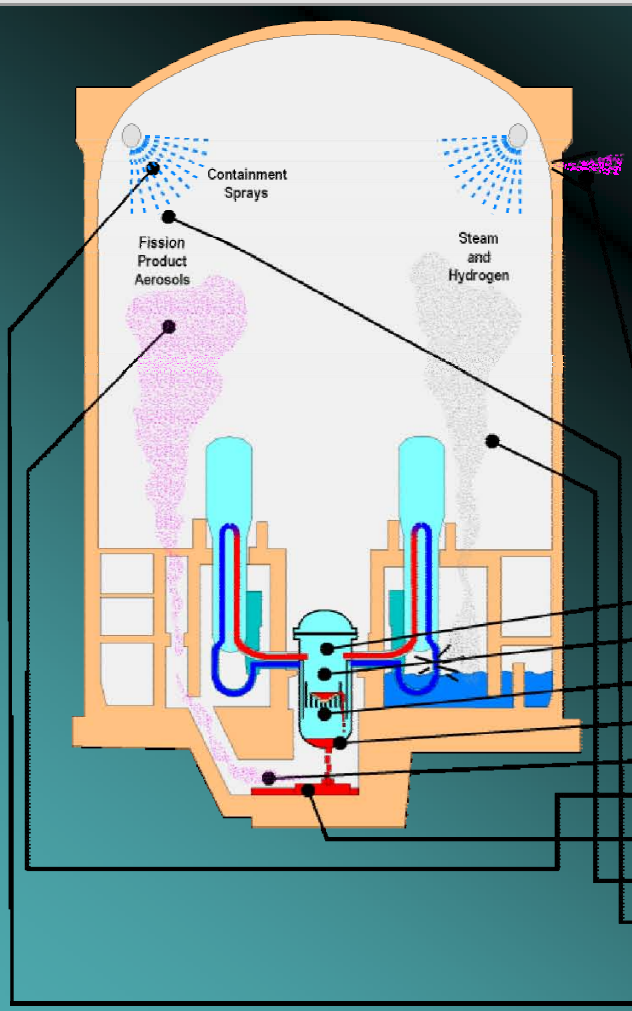
Nuclear Power Outlook

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

Modeling and Analysis of Severe Accidents in Nuclear Power Plants





Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979

***Integrated* models required for self consistent analysis**

Important Severe Accident Phenomena

	MELCOR	CONTAIN	VICTORIA	SCDAP RELAP 5
Accident initiation	■			■
Reactor coolant thermal hydraulics	■			■
Loss of core coolant	■			■
Core meltdown and fission product release	■		◪	■
Reactor vessel failure	■			■
Transport of fission products in RCS and Containment	■	■	■	
Fission product aerosol dynamics	■	■	■	
Molten core/basemat interactions	■	■		
Containment thermal hydraulics	■	■		
Fission product removal processes	■	■	■	
Release of fission products to environment	■	■	■	
Engineered safety systems - sprays, fan coolers, etc	■	■		
Iodine chemistry, and more	■			

MELCOR Development Advances in Core Heatup and Fission Product Release

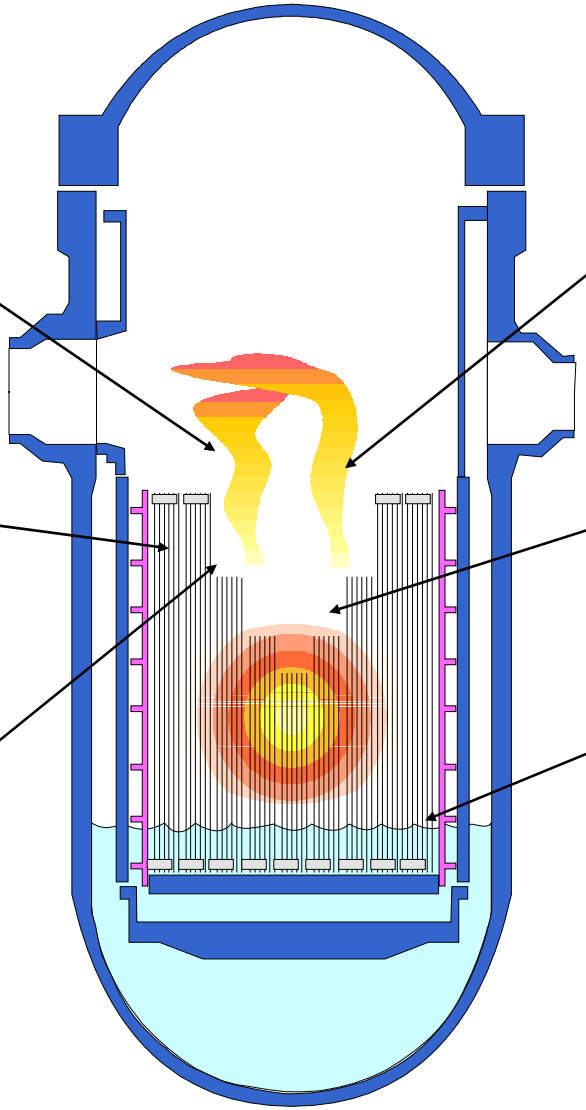
Fission product specie/volatility modified (Cs_2MoO_4) – Phebus Tests – affects RCS deposition

RN Package expanded to allow analysis of FP release from mixed MOX/LEU core

(French VERCORS and RT tests)

Fuel failure criteria expanded via control function – Phebus tests – affects hydrogen generation and melt progression

BWR failure criteria expanded



Ag release model added – Phebus Tests – important for iodine chemistry

- Important to agglomeration

B_4C oxidation model added (PWR) – QUENCH Tests, Phebus FPT-3

Quench-reflood modeling – QUENCH tests – quench front not necessarily water level

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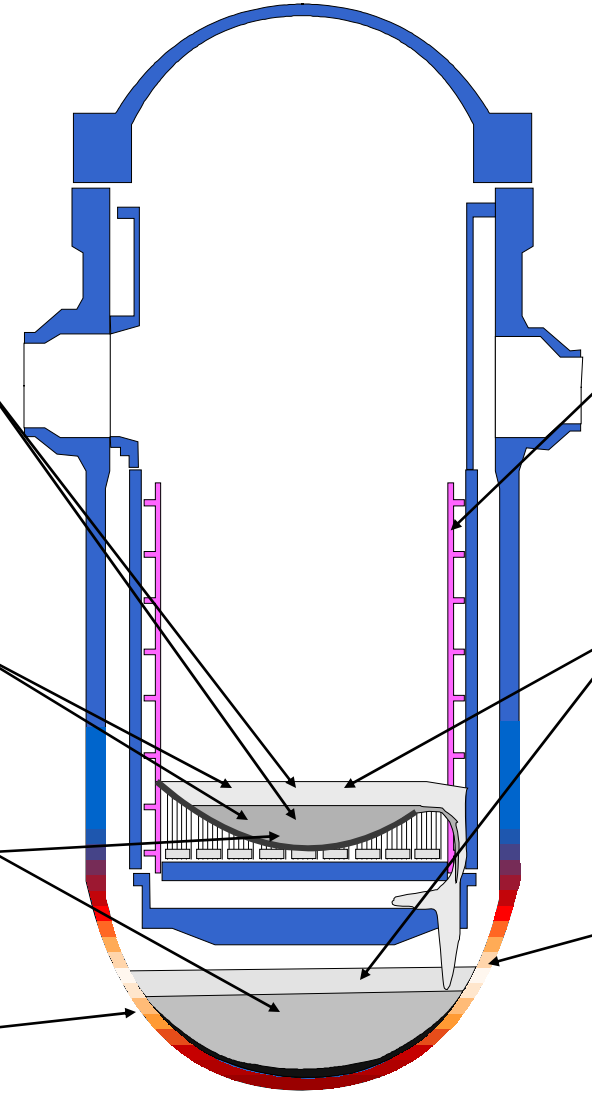
MELCOR Development Activities
Late Phase Melt Progression



Molten pool stratification into light and heavy layers in core and lower head (RASPLAV,MASCA)

Fission product partitioning between melt phases (RASPLAV,MASCA)

Natural convection heat transfer in circulating melt pools

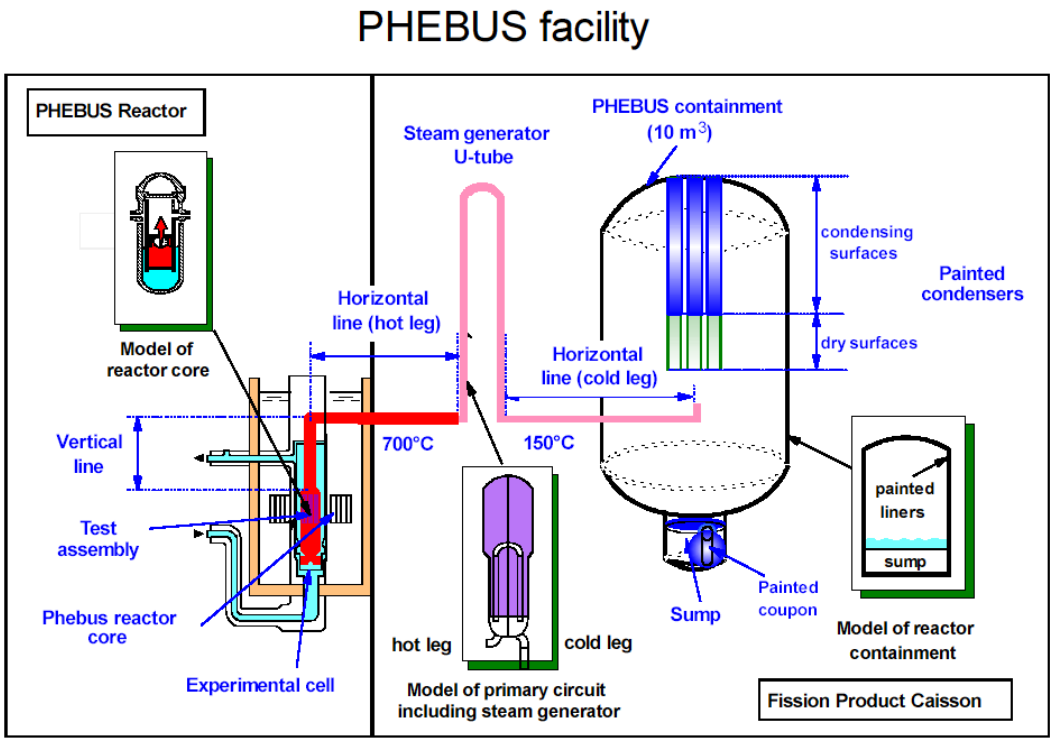
Insights from OECD LH program in creep-rupture models for lower head

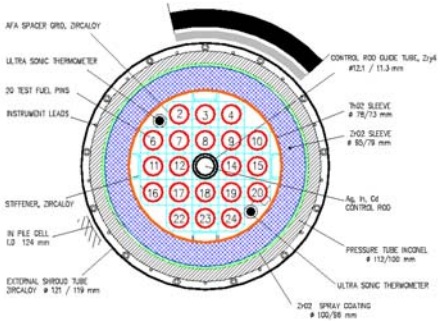
Core periphery baffle and formers added to COR package – allows TMI-like side wall melt release

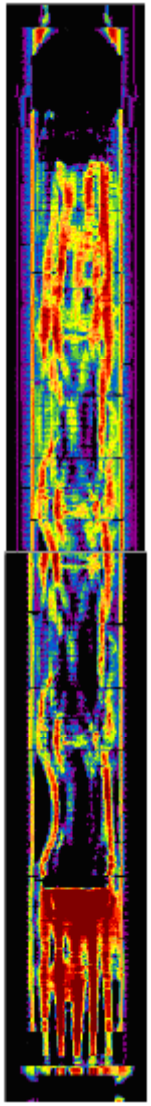
Molten pool / crust model added to core and lower head regions (TMI-2)

Curved lower head description added to COR (BH integration) including 2-D heat transfer

Phebus Program Benchmarking with MELCOR

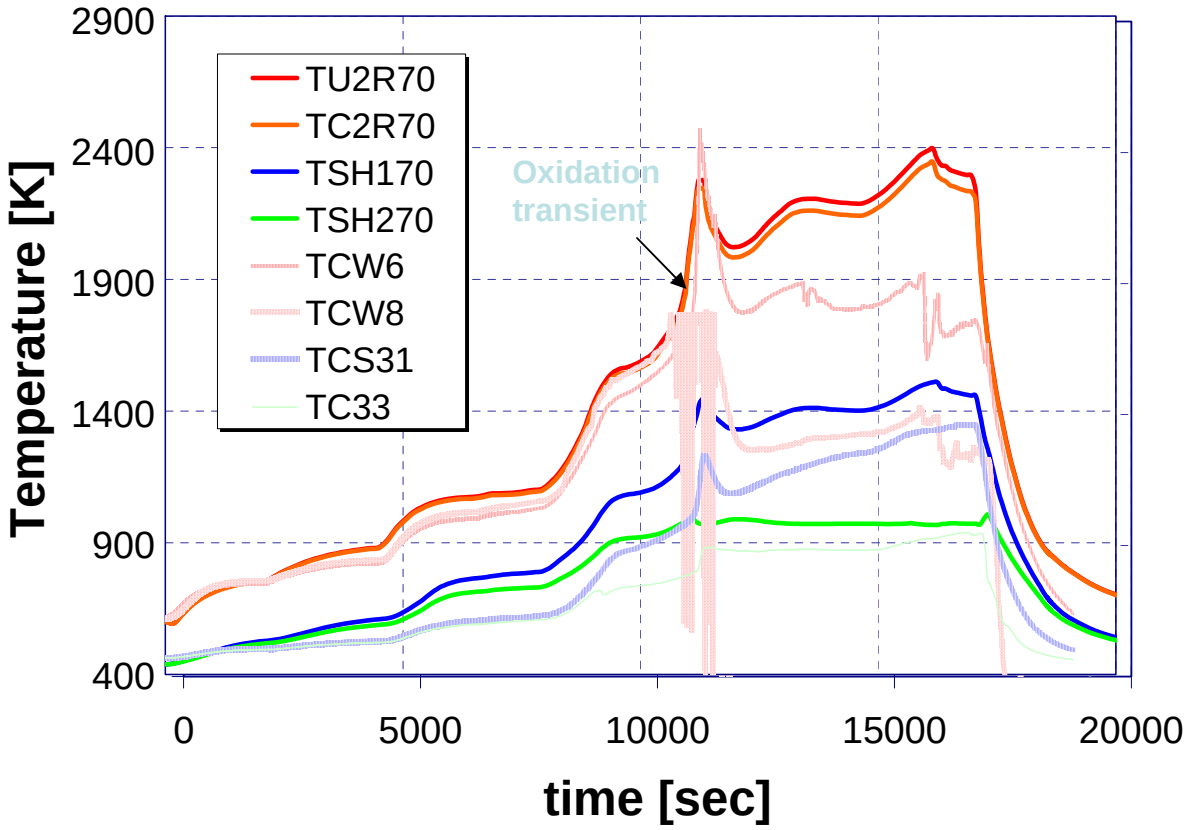






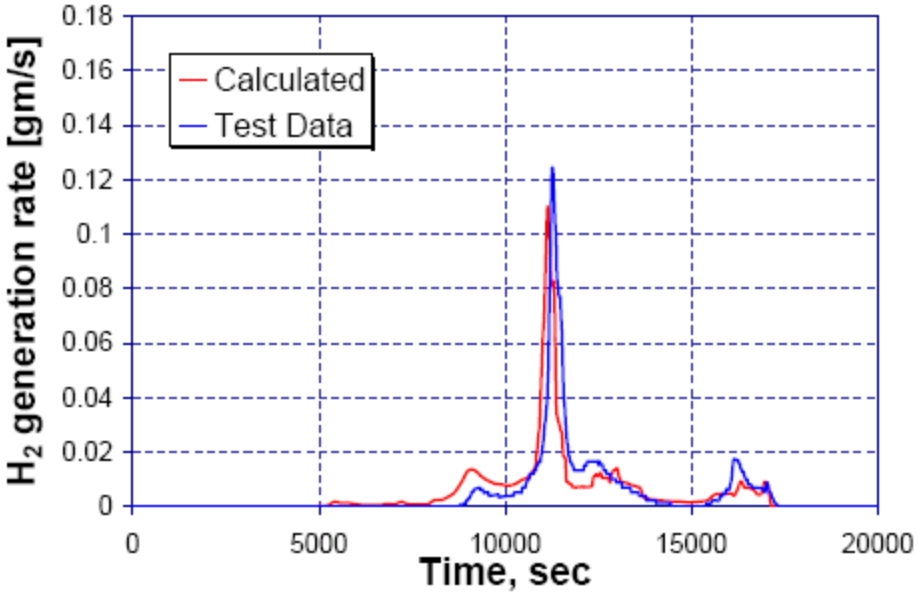
- Integral tests
- Prototypic fuel
  - Fission heating
  - Pre-irradiated fuel
- Verification of
  - Fuel damage
  - Melt progression
  - Hydrogen generation
  - Fission product release and transport
  - Deposition in RCS
  - Containment behavior

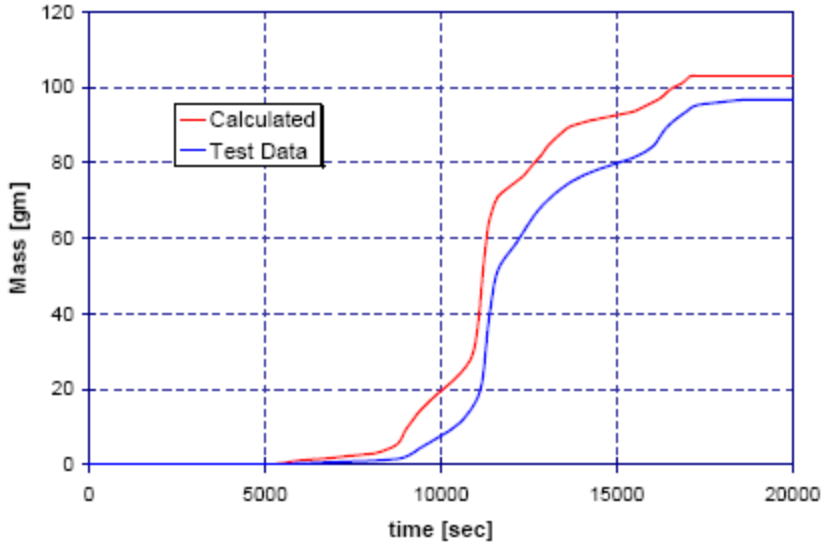
Fuel Heatup and Degradaion



- Fission heat in FPT-1 initially drives thermal response
- Steam oxidation transient drives FP release and fuel melting

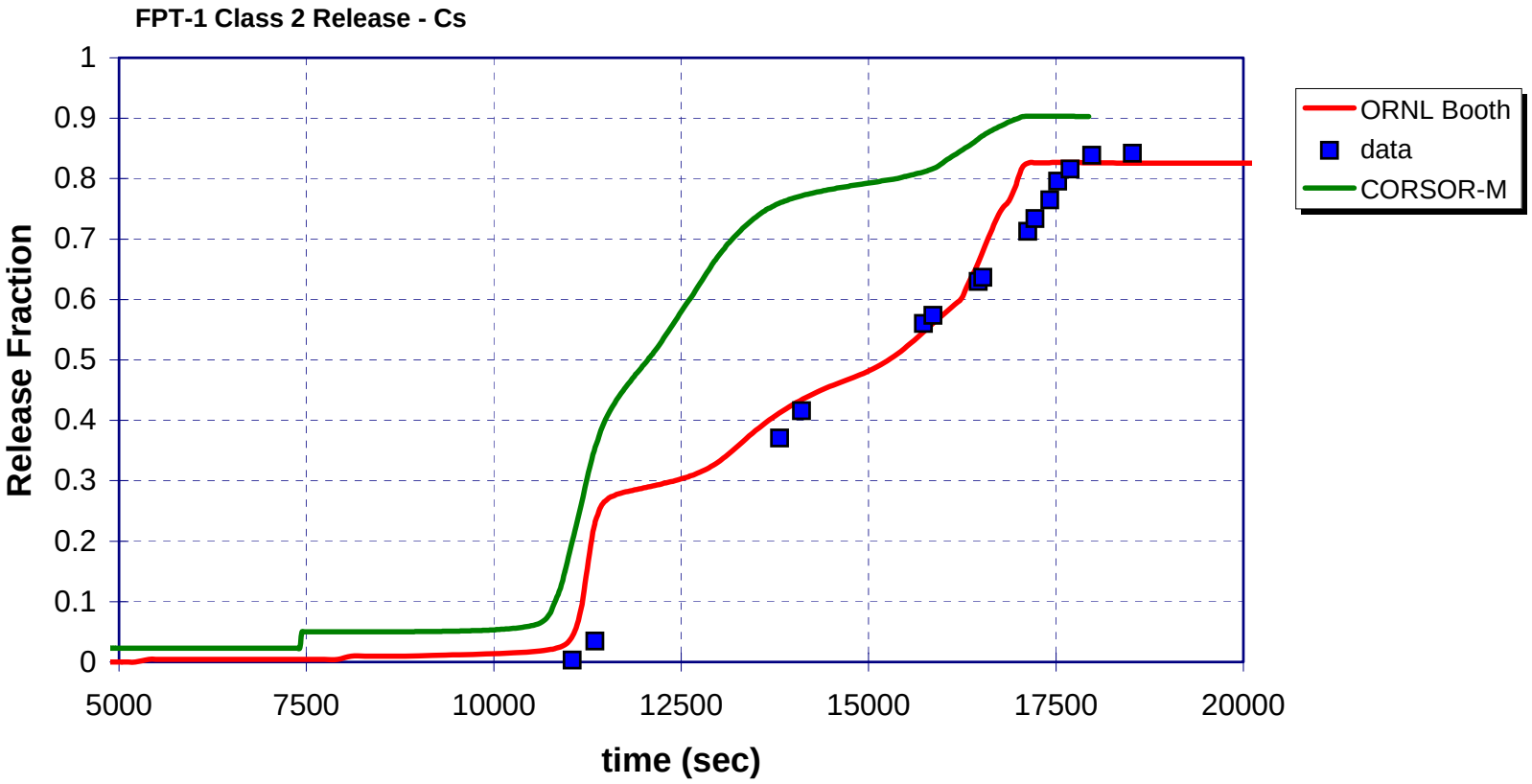
Cladding Oxidation and Hydrogen Generation





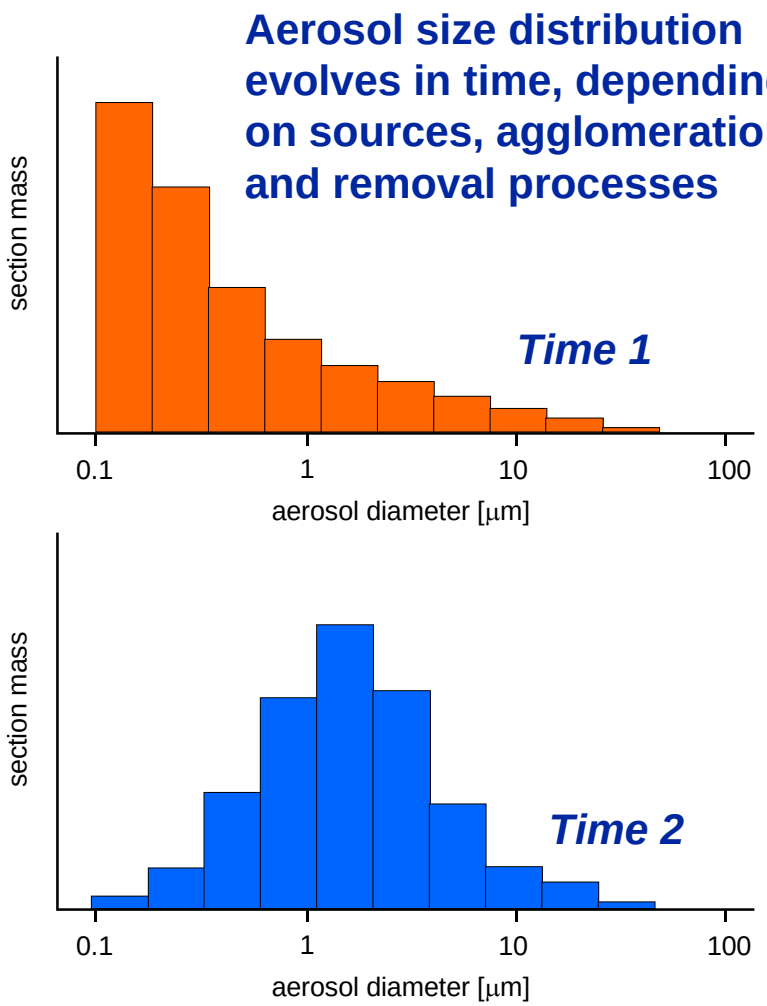
- Steam oxidation models verified by calculated thermal response and by calculated hydrogen generation

Fission Product Release and Source Term



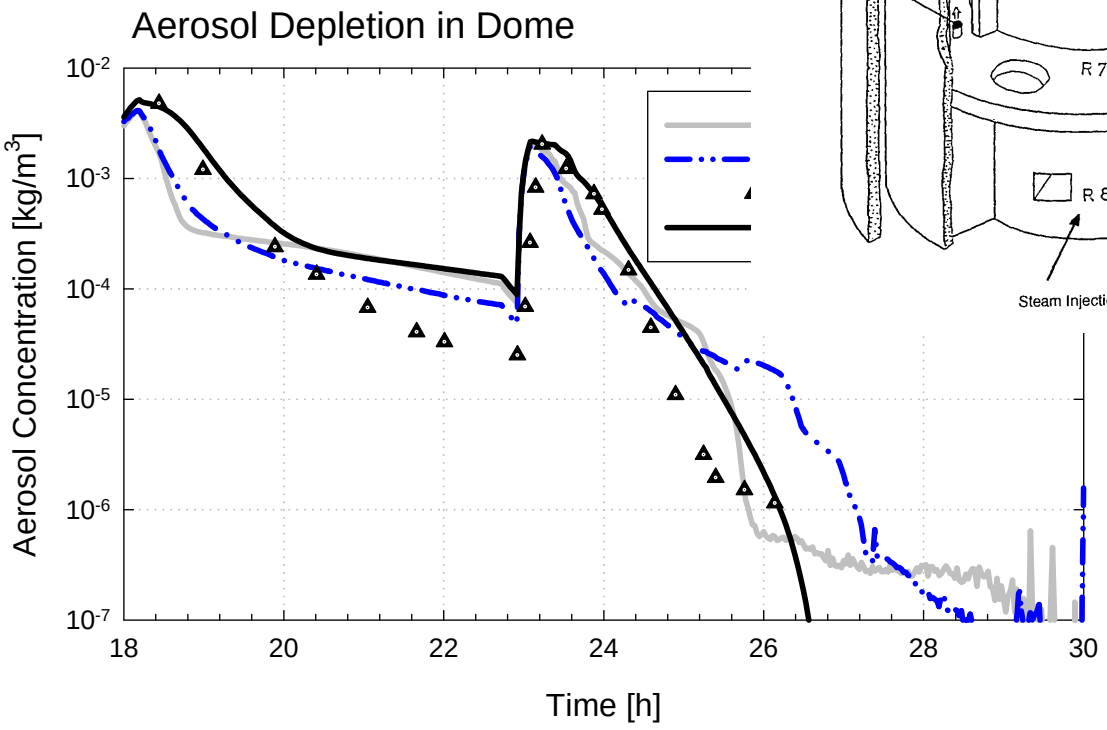
- ORNL Booth model captures kinetics well
- CORSOR-M over-predicts early release

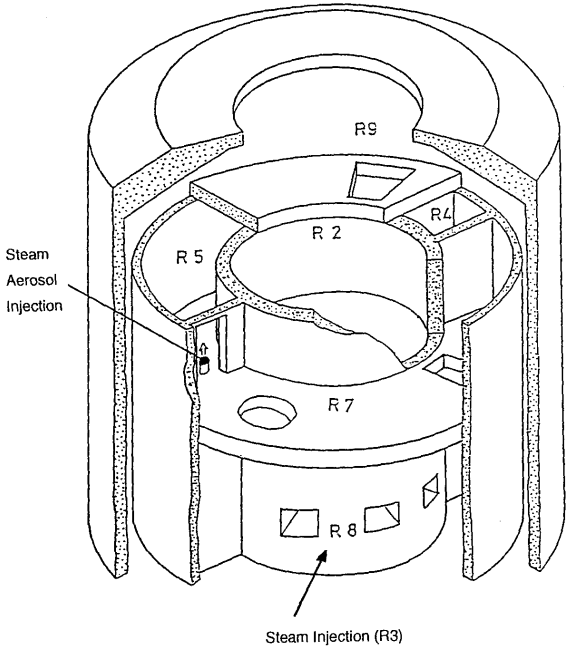
MELCOR Aerosol Mechanics - MAEROS



- MAEROS sectional model of Gelbard
  - 10 sections [.1 - 50 μm]
  - Condensed FP vapor sourced into smallest section
- Particles grow in size
  - Agglomeration
  - Water condensation
- Particle fallout by gravitational settling
- Particle deposition processes
  - Thermophoresis
  - Diffusiophoresis
  - Brownian motion
- PWR Ag aerosol release from control rods modeled
  - Significant aerosol mass
  - Affects agglomeration, growth and fallout
- Cs chemisorption in RCS modeled
  - Iodine from CsI revolatilizes when reheated

VANAM M3 Containment Aerosol Behavior Test





Multi-compartment containment model

- Steam and helium injection
- Aerosol injection

Validation of MELCOR containment and aerosol mechanics models

- Compartment flows
- Temperatures and pressures
- Aerosol transport and deposition

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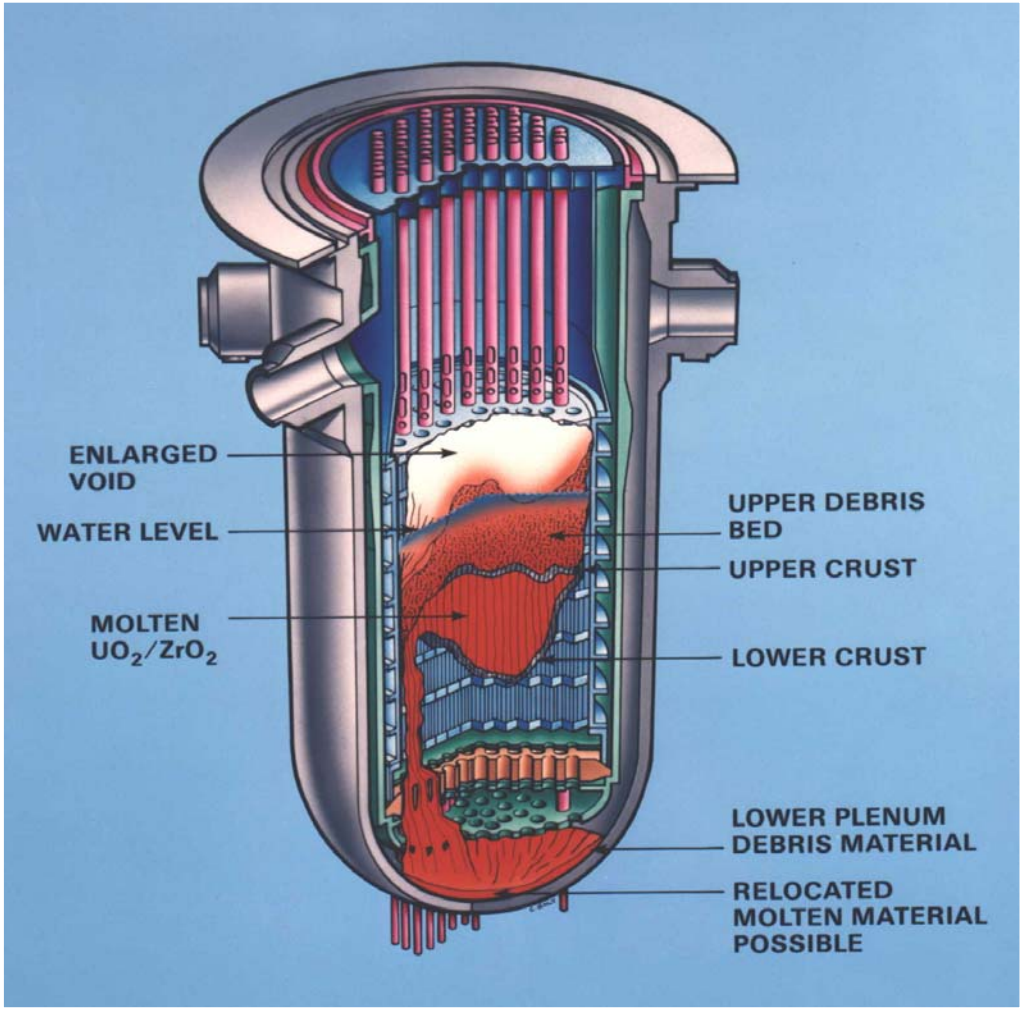
TMI-2 Assessments



- Accident code assessments against TMI-2 ongoing in international comparison exercises
- MELCOR models for melt progression significantly refined based on TMI-2 and experiments

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Realism in Modeling

- Early work required considerable abstraction in representation of plant
  - Computer limitations on problem size
  - Problem “dumbed down” to permit analysis
- Current emphasis is on realism
  - Spatial resolution (node size for resolving physics)
  - Accurate representation of plant
    - Rooms and compartments
    - Heat structures
    - Transport time and deposition

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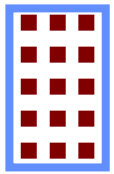
Reactor Severe Accident Modeling Evolution of the State-of-the-Art

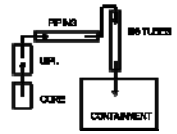
Timeline for Evolution of MELCOR Modeling Practices

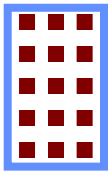
Circa 1985	Circa 1990	Circa 1995	Circa 1998	Present	Future

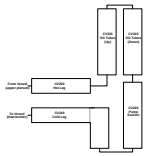
Modeling Techniques

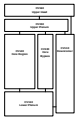


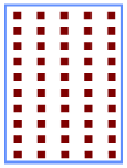
STCP

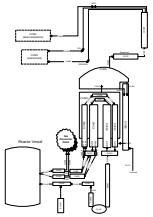


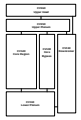


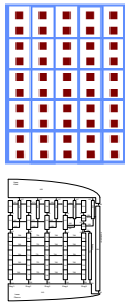


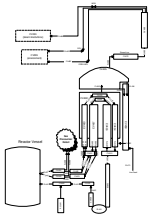


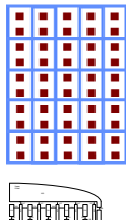


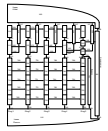


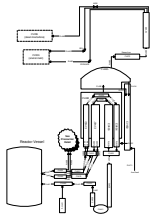












core plate detail, etc.

- MELCOR 2.0
- Core design details
- FP Chemistry, Impaction, other

Example Regulatory Applications

- NUREG-1150
- Basis for NUREG-1465 revised source term

- AP-600 design certification
- ESBWR design certification
- AP-1000 design certification

- Begin SGTR

- Finish SGTR

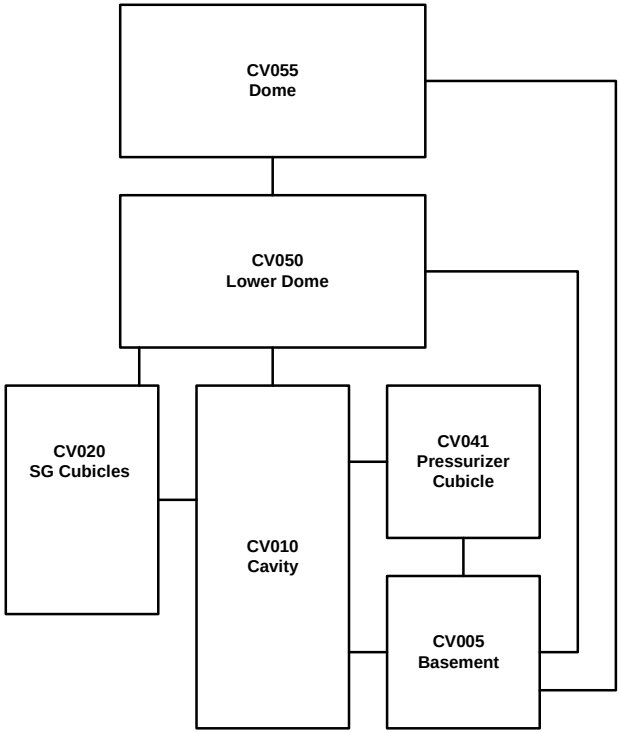
- MOX source terms
- High burn-up source terms

SOARCA

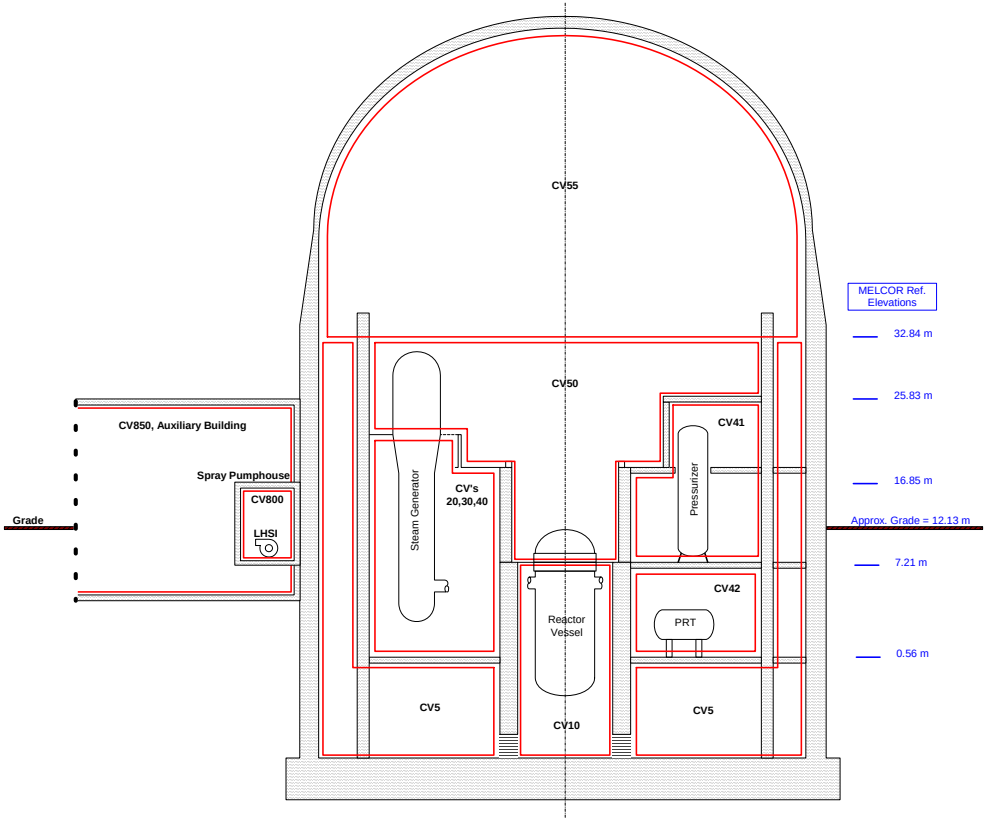
- Emerging user needs

Modeling Detail
Minimizing Abstraction

Old Nodalization



Enhanced Nodalization



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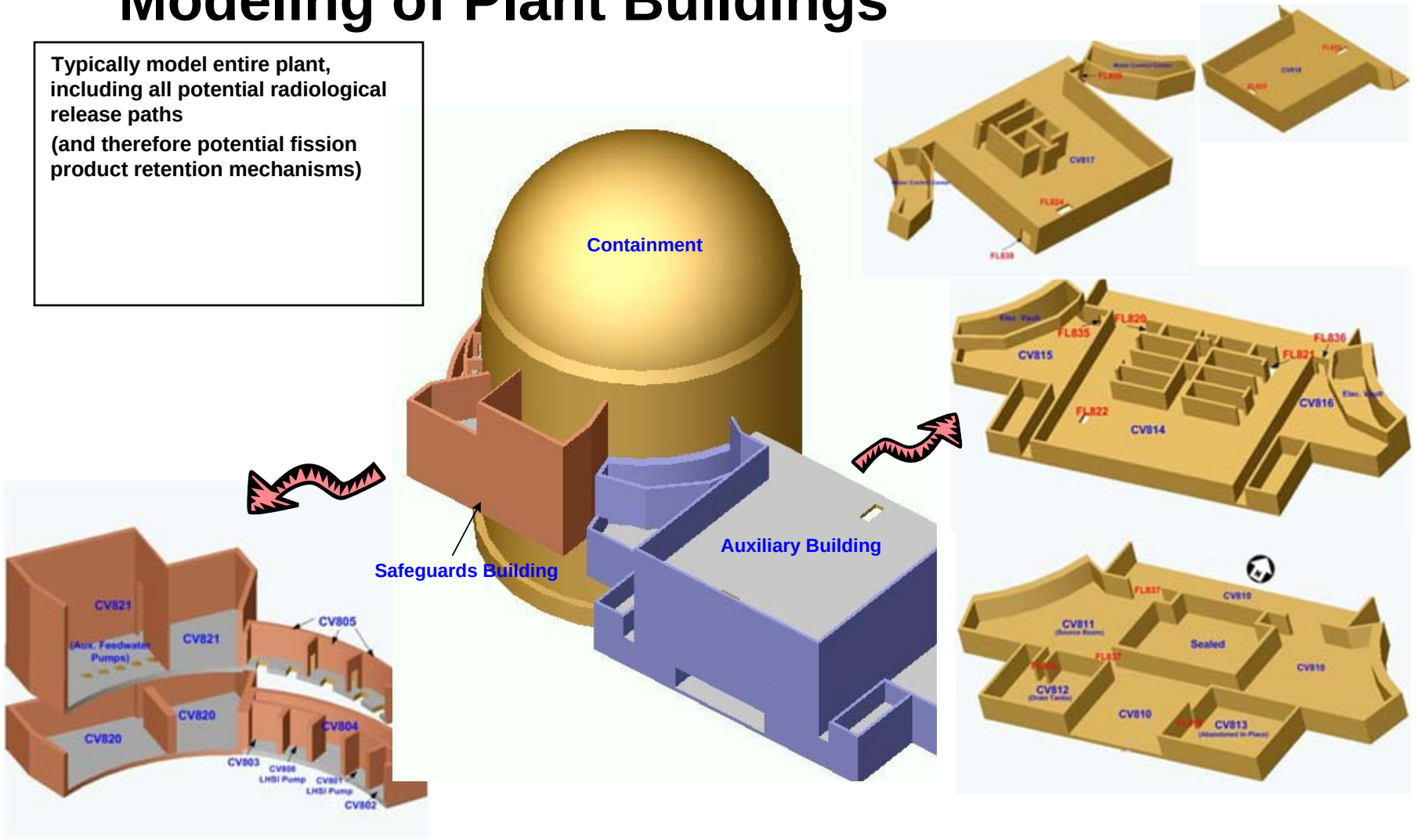
Modeling of Plant Buildings

Typically model entire plant, including all potential radiological release paths

(and therefore potential fission product retention mechanisms)



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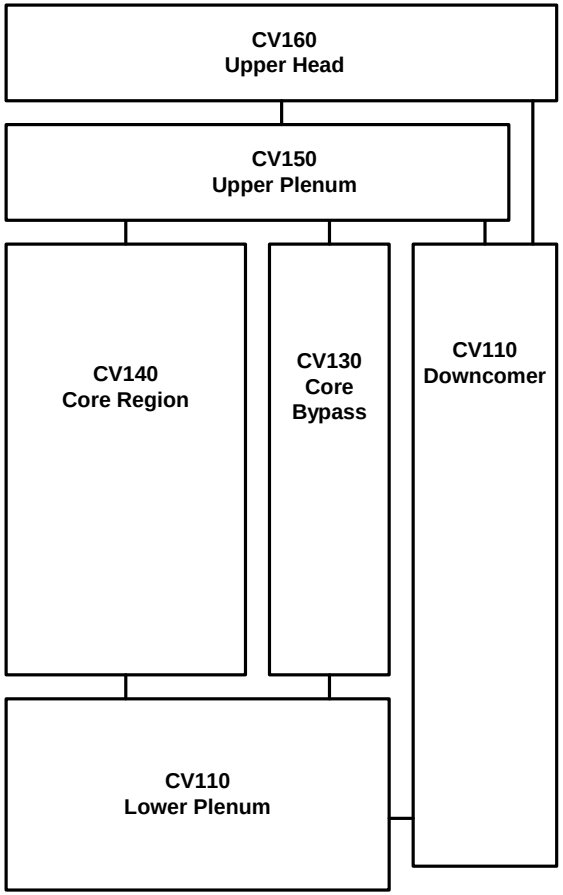
Model Upgrades
- Vessel Nodalization -

Old Nodalization



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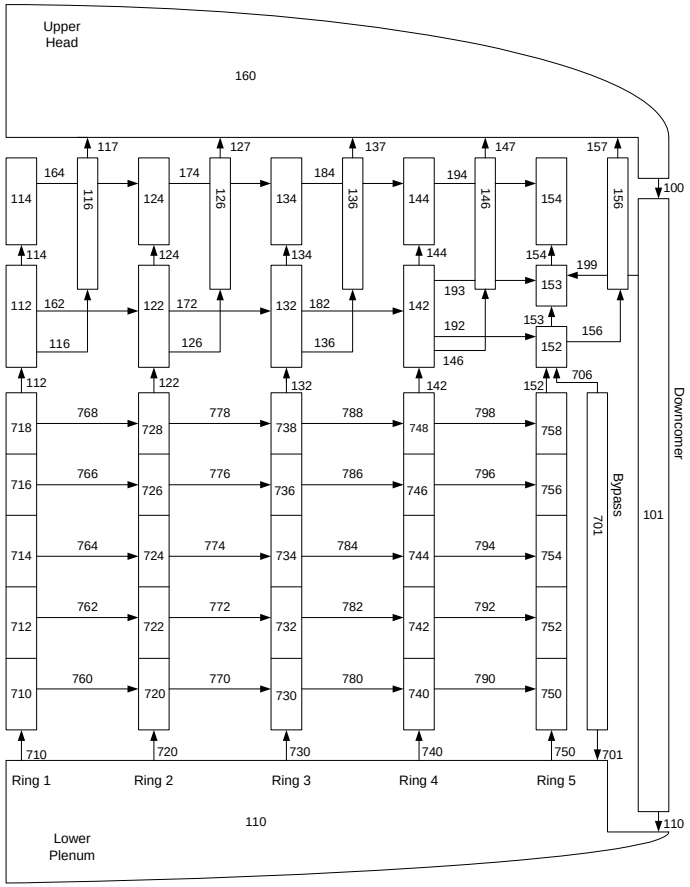

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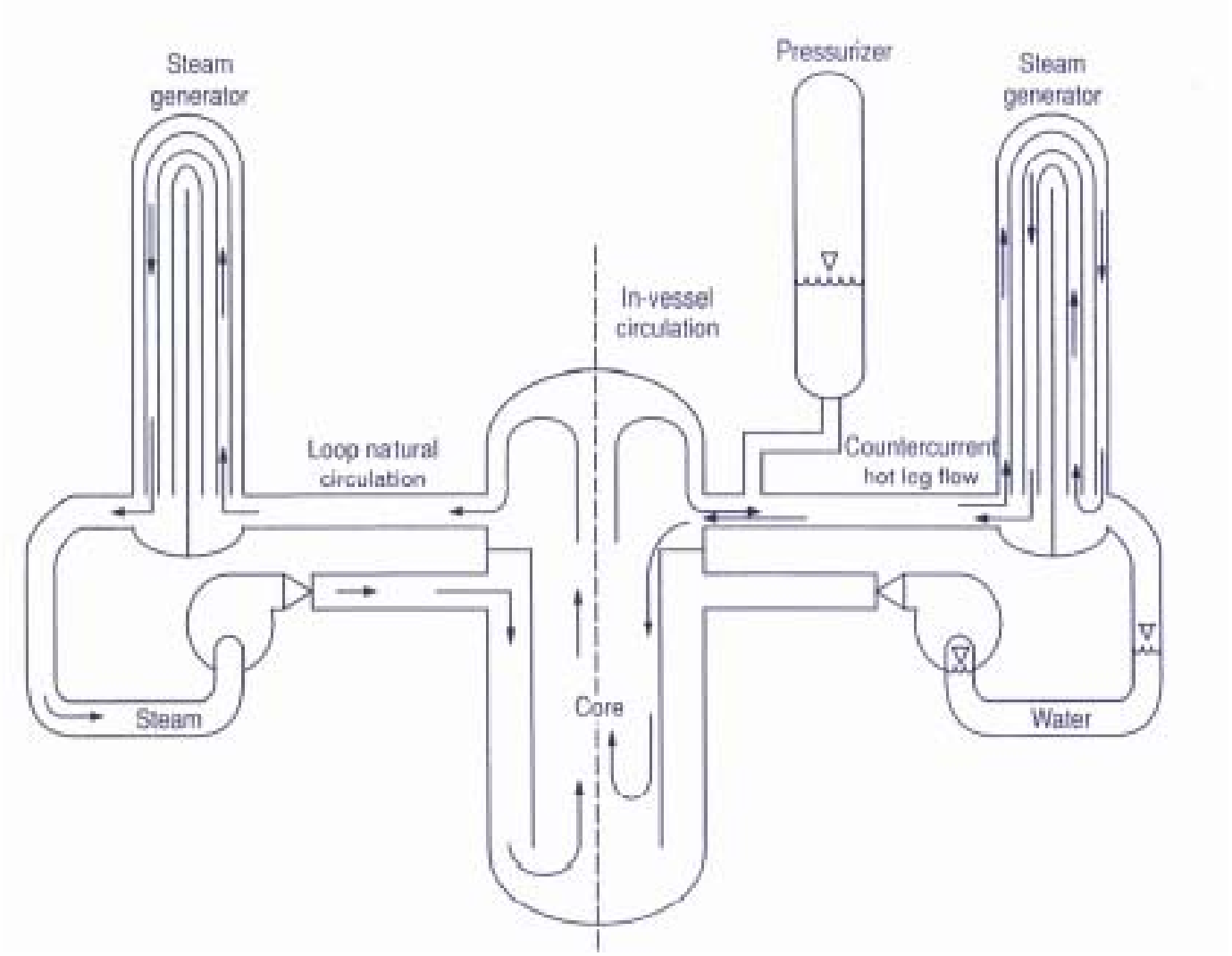
Natural Circulation Modeling



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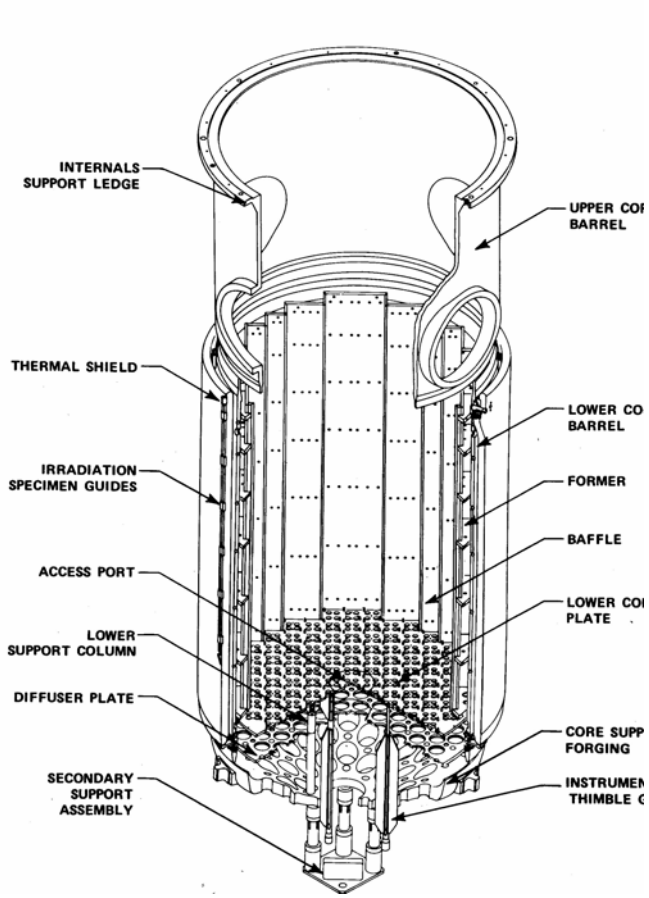
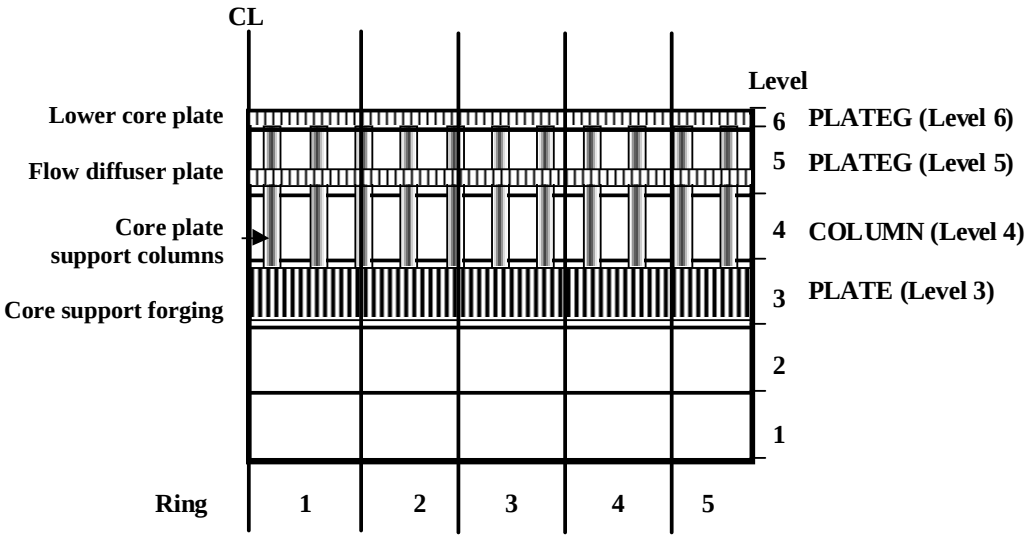
Westinghouse PWR Core Plate



- Weight of core material mass
- Engineering stress formulae used (e.g. Roark)
- Failure based on exceeding yield stress at temperature
- Sequential failure of multiple supporting structures treated



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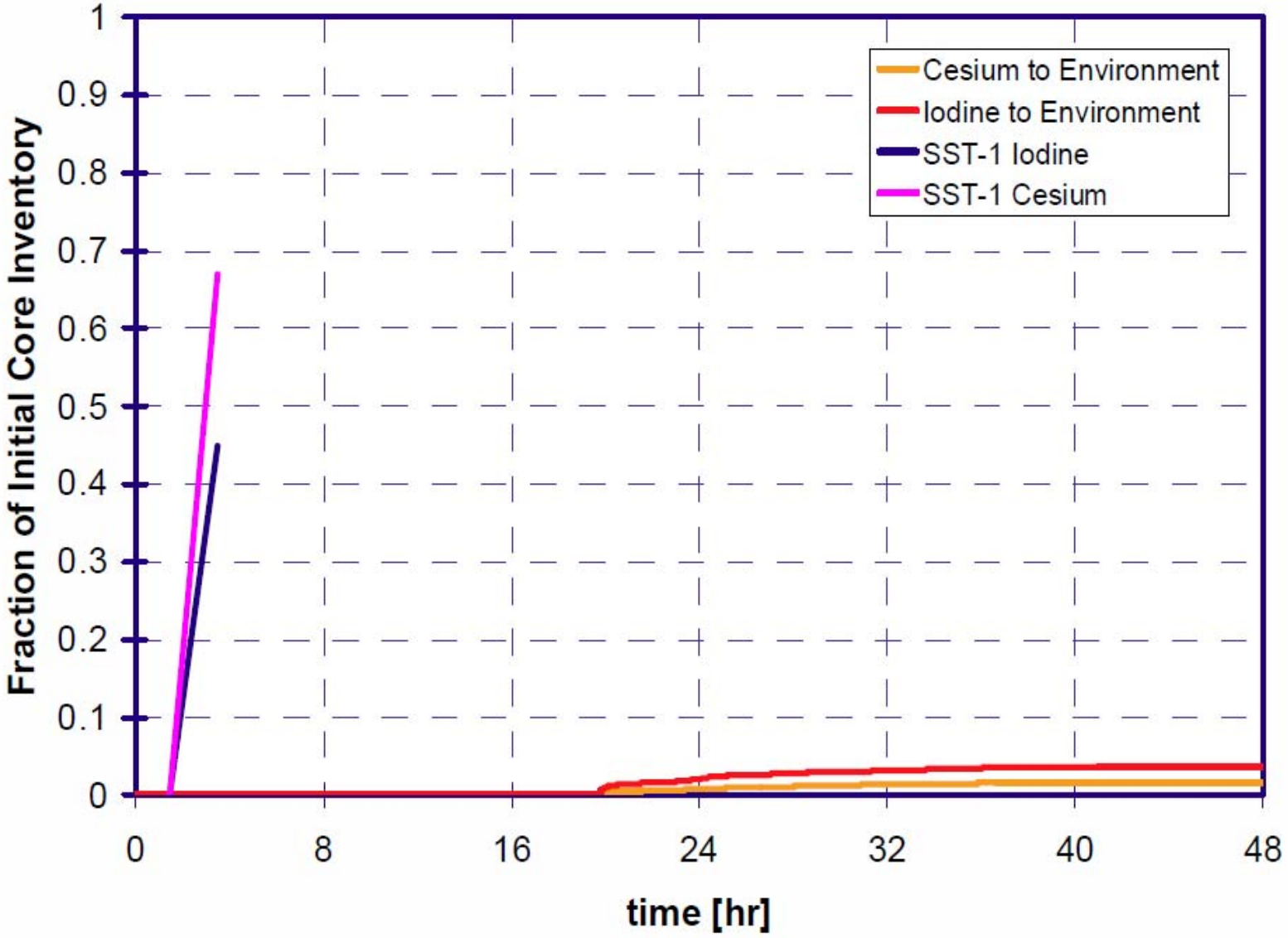
Impact of Modeling Advances

- Accident progression generally significantly more slowly developing
- Significantly more fission product retention in RCS and containment
- More time for mitigation of accident
- Significantly reduced source terms
- Even SGTR bypass source term less than traditionally thought owing to RCS rupture in containment

Peach Bottom Long Term Station Blackout Compared to SST-1



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Summary

- Releases much delayed compared to SST-1
  - Mostly many hours to 10's compared to ~1
  - Due to detail modeling of reactor systems and operator mitigations
- Releases to environment much less than SST-1
  - Detailed transport treatment and deposition accounting
  - Delayed release enhances natural depositions
- Plant models account for
  - Improvements in modern plant design
  - Important operator actions
- Peer review and uncertainty quantification work next