MELCOR Best Practices - An Accident Sequence Walkthrough

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and

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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Best Practices adopted for NRC SOARCA Program

- Introduction
- BWR
- PWR
- Other Best Practices

- State of the Art Reactor Consequence Analyses (SOARCA)
  - Realistic evaluation of severe accident progression, radiological releases and offsite consequences
    - Provide a more accurate assessment of potential offsite consequences
  - Focus on a spectrum of scenarios most likely to contribute to release and subsequent offsite consequences, using a risk-informed approach
- SOARCA expert review panel meeting
  - Solicit discussion from experts
    - Experts also supplied additional recommendations
  - Discussion of base case approach on some key complex and uncertain events for MELCOR calculations
  - Best Practices distilled from these findings
- Model defaults updated as result of this work
- Uncertainty recognized as important
  - Separate task evaluating uncertainty using uncertainty engine

- Introduction
- BWR
  - LTSBO
  - Nodalization
  - 1.S/RV
  - 2.Fuel rod Failure
  - 3.Volatile FP speciation
  - 4.Structural aerosol
  - 5.Aerosol Deposition
  - 6.Debris HTF in LP
  - 7.RPV failure with penetrations
  - 8.H2 combustion
  - 9.Debris Spreading (Cavity)
  - 10.MCCI
- PWR
- Other Best Practices

BWR Topics for Consideration

1. **Thermal response and seizure of cycling S/RVs during late phase of in-vessel fuel damage**
2. **Criteria for representing mechanical failure of highly-oxidized but erect fuel assemblies**
3. **Volatile fission product speciation**
4. **Structural (non-radioactive) aerosol generation**
5. **Aerosol deposition on reactor and containment surfaces**
6. **Debris heat transfer in reactor vessel lower plenum**
7. **RPV failure mode and criteria in heads with varied and multiple penetrations**
8. **Hydrogen combustion and ignition**
9. **Debris spreading and Mark I shell melt-through**
10. **Under-cutting of reactor pedestal wall via long-term molten corium-concrete interaction**

BWR Walk-through: BWR/4 Mark I LT-SBO

- Total loss of off-site power
- RCIC operation on batteries for 8 hrs
- Manual S/RV control available, but partial depressurization not reflected in the example calculation
- Containment venting not available due to loss of power

BWR/4 Reactor Vessel Model

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  - – LTSBO
  - – **Nodalization**
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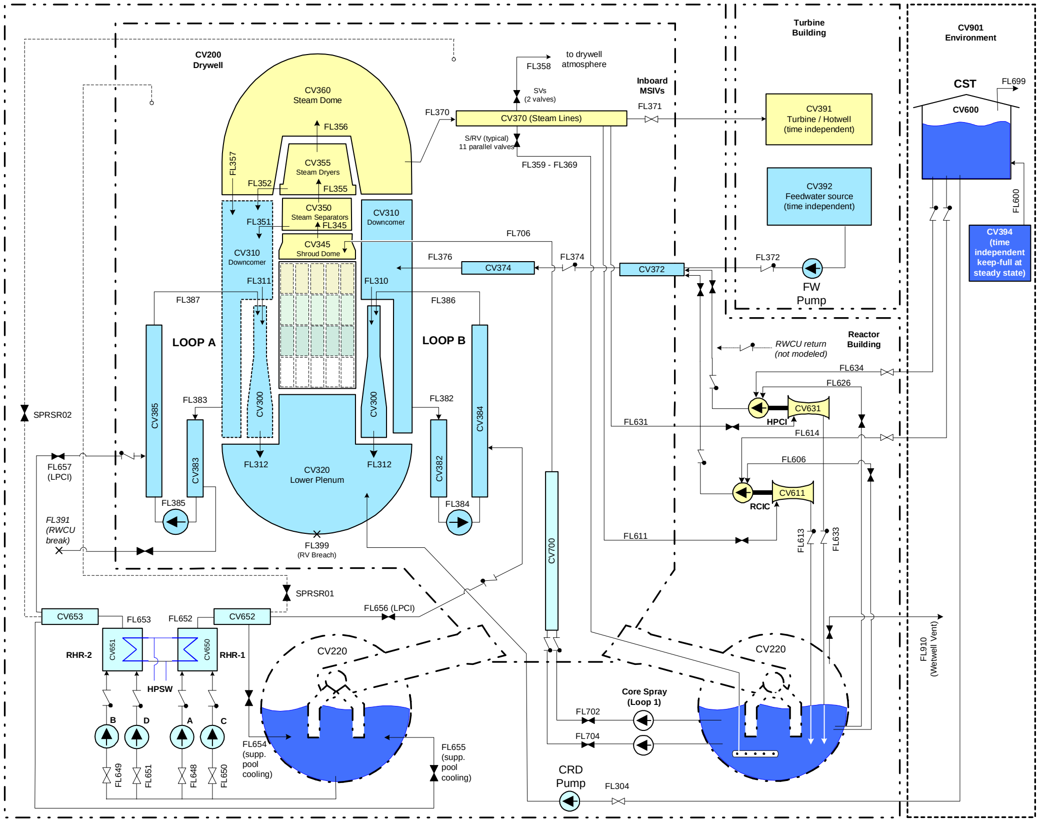
- BWR/4 Reactor Vessel Model
  - Important features & components
  - Nodalization
- Reactor Coolant System
- Cavity Model
  - Elevation View
  - Aerial View



LT-SBO: Early Thermal-Hydraulic Response

•Introduction

•BWR

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5.Aerosol Deposition

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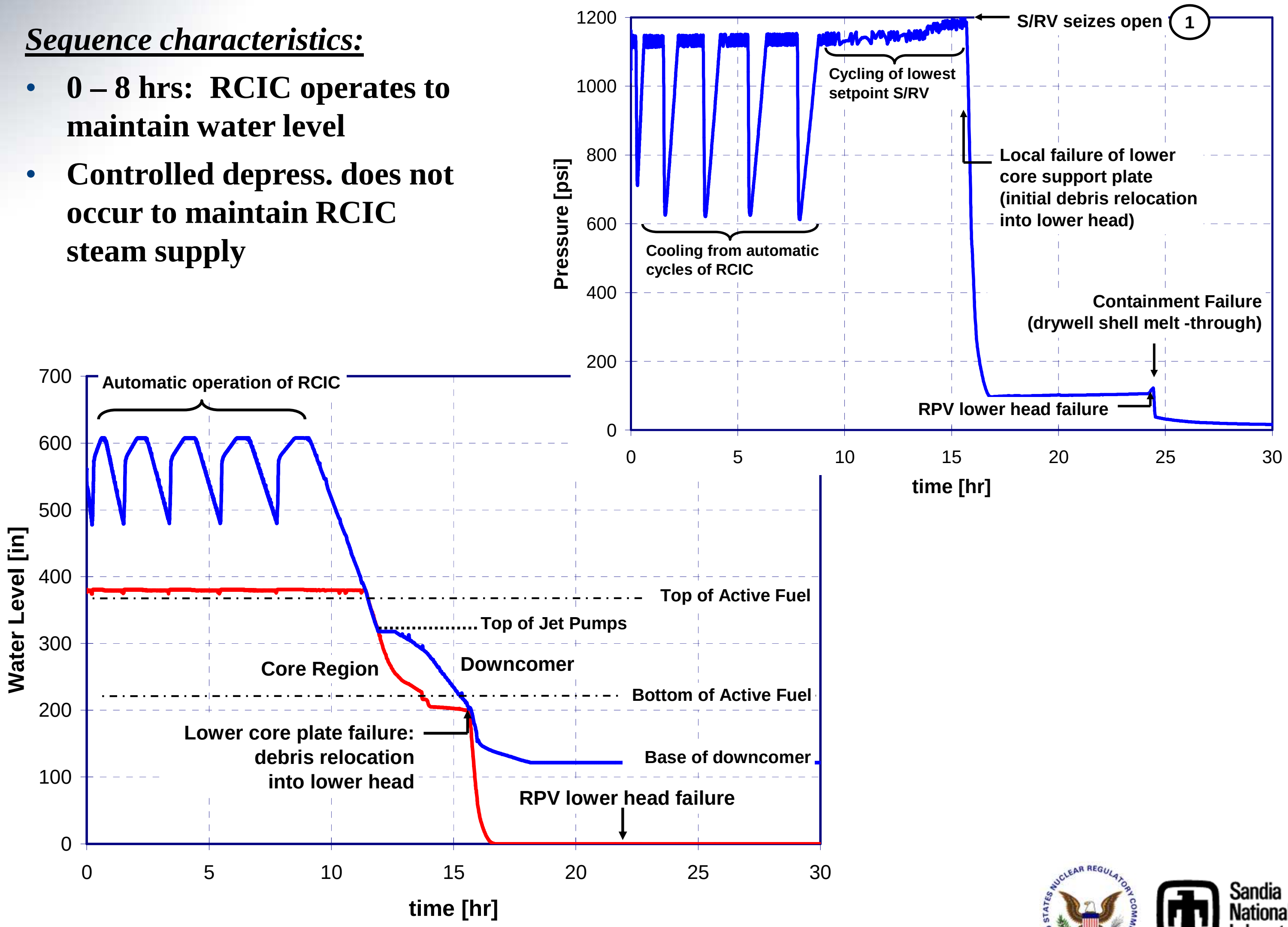
•PWR

•Other Best Practices

Sequence characteristics:

- **0 – 8 hrs: RCIC operates to maintain water level**
- **Controlled depress. does not occur to maintain RCIC steam supply**



S/RV Seizure at High Temperature

- •[Introduction]
- •[BWR]
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  - –[Nodalization]
  - 1.[S/RV]
    - 1.Seizure @ high temperature
    - 2.[Valve designs]
      - 1.[depressurization rate]
      - 2.[FP transport]
  - 2.[Fuel rod Failure]
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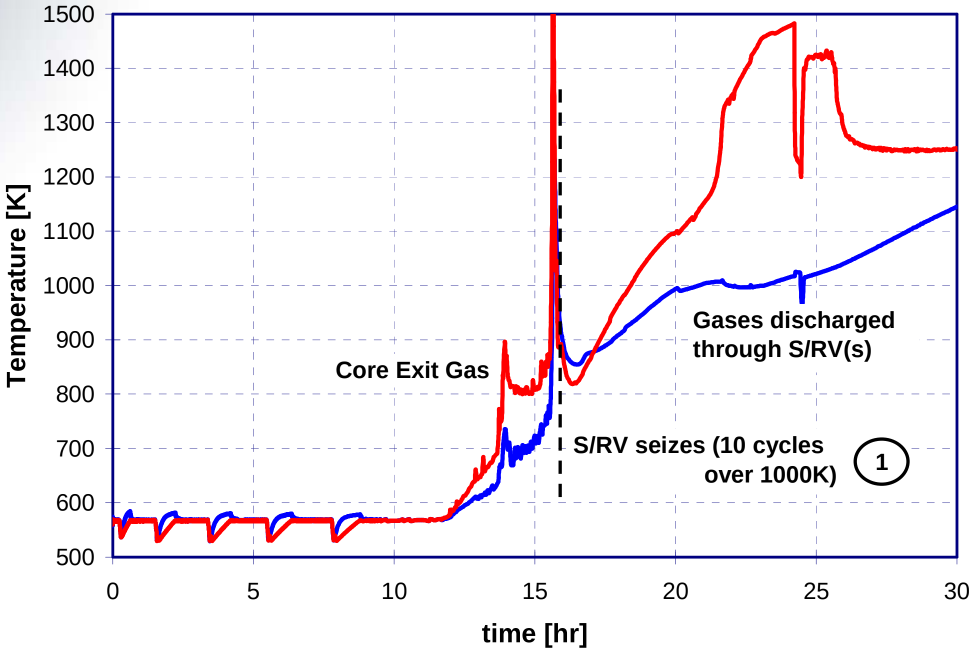
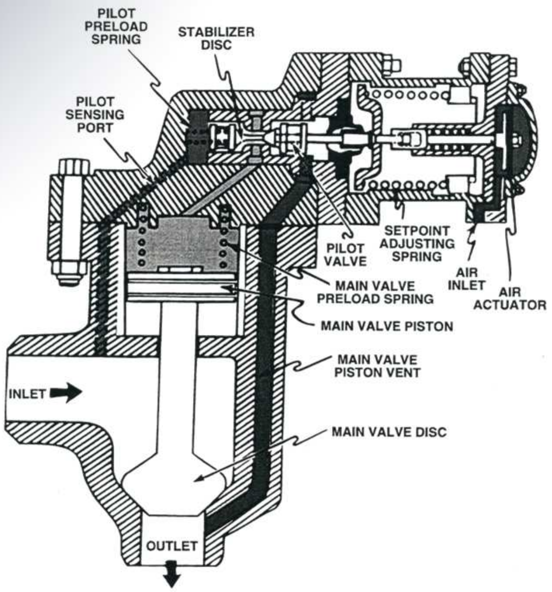
- •[Other Best Practices]



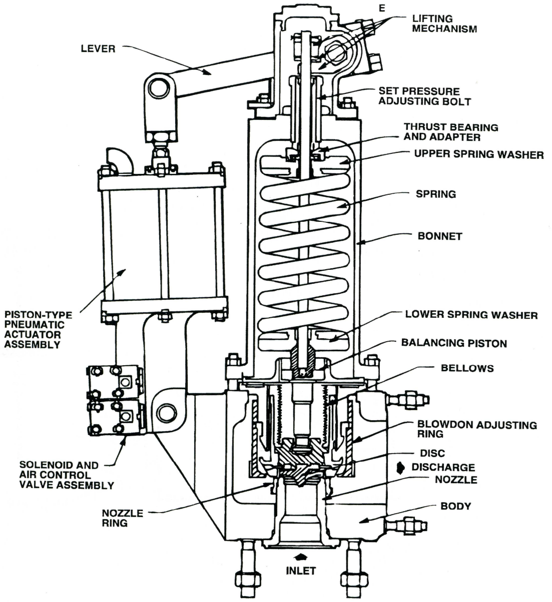
- Automatic S/RV actuation after battery depletion
- Typically a single cycling valve
- Demand frequency: One cycle every 3-4 min at onset of core damage
- Steam/H_2 discharge with variable temperatures
- Gas temperature exceeds 1000 K close to time of lower core plate failure

Valve Design Affects Response



- **BWR/3 and /4: 2- or 3-Stage Target Rock Pilot-Operated relief valves**
  - – **Valve disk cycles between full-open & full-closed**
  - – **Model: Seize in open position at 10th cycle above 1000 K**

PBAPS (3-stage TR)



- **BWR/5 and /6: Spring-actuated, direct-acting relief valves [Crosby or Dikkers]**
  - – **Disk opens to position proportional to pressure against spring**
  - – **Model: Seize in last position based on residual lifetime**
    - **60 min @ 1000 K**
    - **30 min @ 1500 K**

GGNS

Depressurization Rate Depends on Valve Position at Seizure

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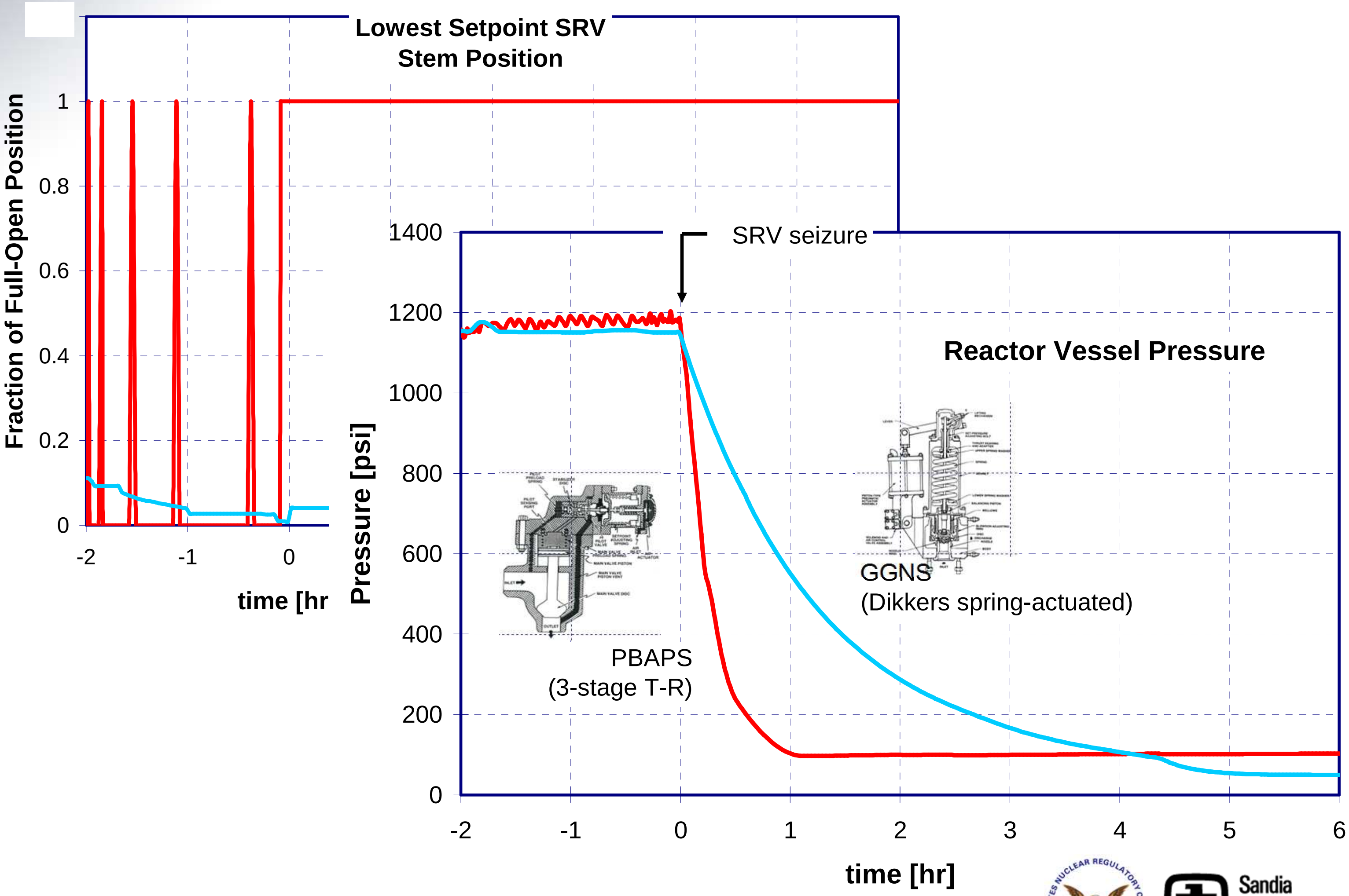

Pressure History Influences
Fission Product Transport / Deposition

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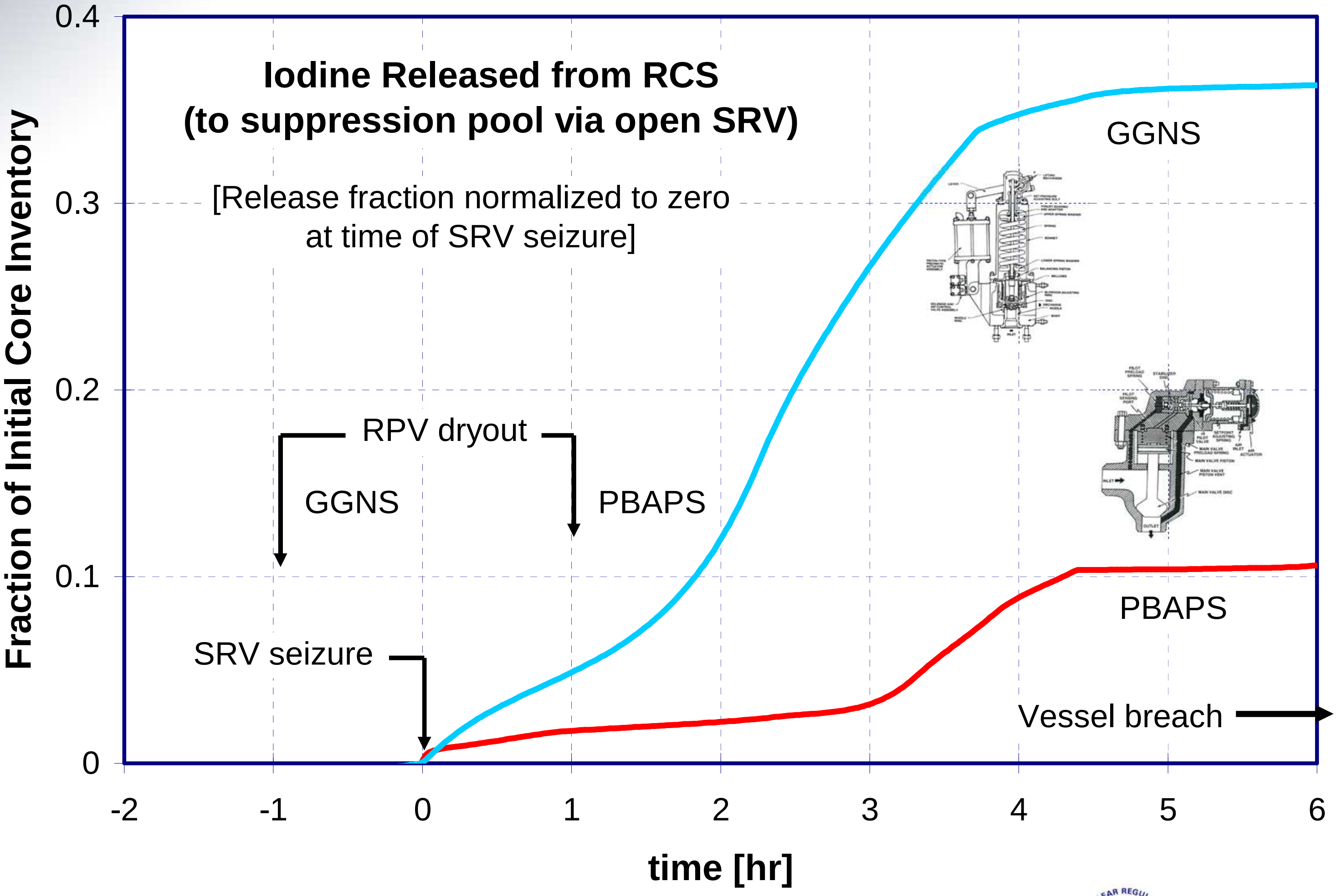
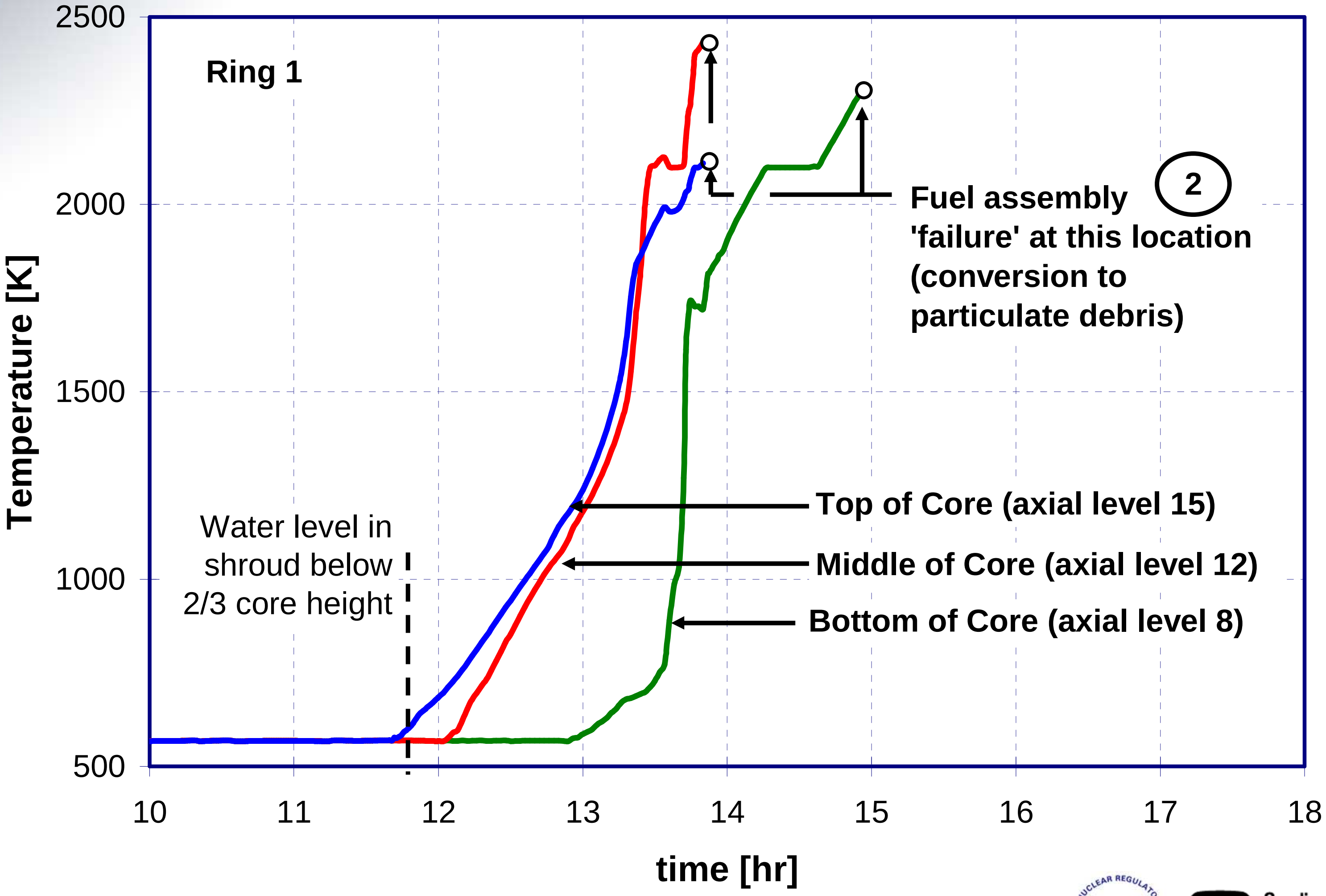


Iodine Released from RCS
(to suppression pool via open SRV)

[Release fraction normalized to zero at time of SRV seizure]

Core Response to Oxidation Transient



Damage Function for Local Collapse of Fuel Rods

- **Mechanical failure of fuel rods assumed to result from combination of:**
    - **Loss of intact, unoxidized clad materal**
    - **Thermal stress**
- **Molten Zr ‘breaks out’ from ZrO_2 shell at 2400 K**
- **Standing fuel rods collapse (forming particulate debris) based on a cumulative damage function**
    - **Concept: Swelling, thermal expansion and mechanical stresses increase with temperature. Insults to fuel integrity build with time at temperature.**

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    3.Failure model
    4.New input
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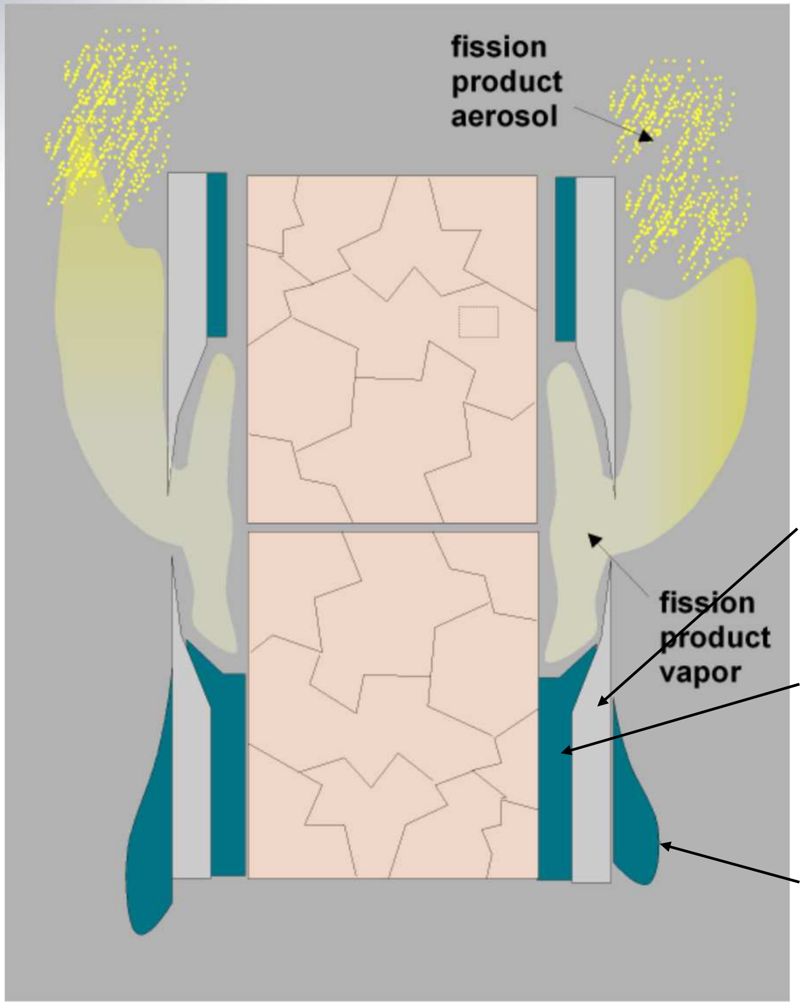
Fuel Degradation Modeling

- **Molten metallic Zr breakout temperature (2400K)**
- **Fuel rod collapse**
  - **– Time-at-temperature damage function**
  - **– Similar to MAAP model**
  - **– Eliminates single temperature criterion**



ZrO_2 oxide Shell

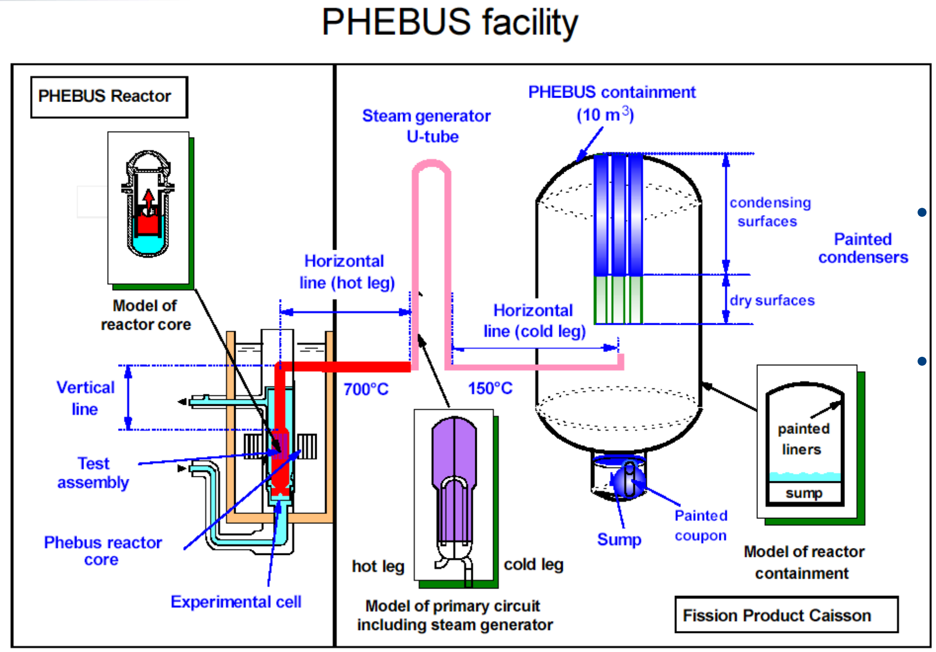
Oxidizing Zr Metal held under Oxide shell

Release of Molten Zr (2400K)

Fuel Collapse Model Implementation

- **The logic has been implemented within the code (MELCOR 2.1 & 1.8.6)**
  - **Require new input records to activate the logic (set of CFs no longer needed)**
  - **Different input format between two versions of the code**
- **Added input record: COR_ROD (CORROD in 1.8.6)**
  - **Requires two fields**
    - **(1) IRODDAMAGE: tabular function name for the residual lifetime of fuel as a function of cladding temperature (tabular function number (integer) in 1.8.6)**
    - **(2) RCLADTHICKNESS: minimum un-oxdized clad thickness under which the rod collapse model supplants the default temperature based criterion (default = 1.0E-4 m)**

The Phebus Experiment Facility



- Irradiated fuel heated in test package by Phebus driver core
  - Fuel heatup
  - Zr oxidation, H_2
  - Fission product release
- Circuit (700 C) transports FP through steam generator tube
  - Deposits in circuit and SG
- Containment receives FP gas and aerosol
  - Settling
  - Iodine chemistry

Validation of Fission Product Release Models

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    - –Phebus Facility
    - –**Validation**
    - –Vapor Pressures
    - –FPT1 Deposition
    - –Booth Parameters
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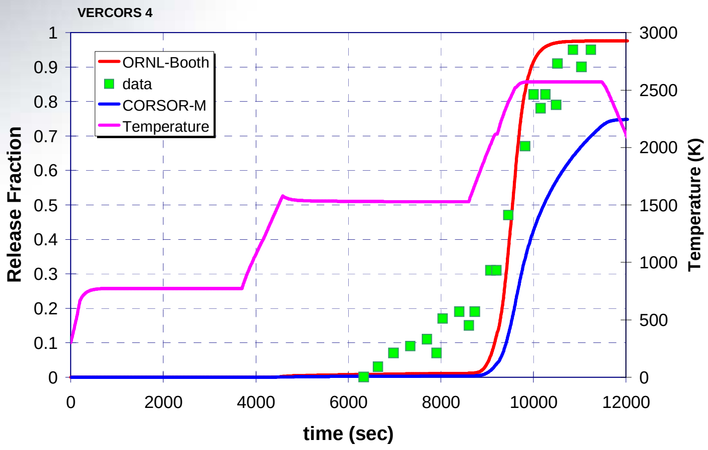
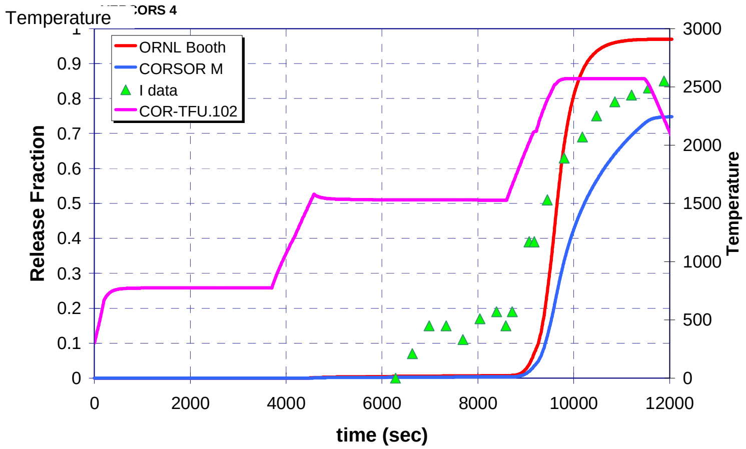
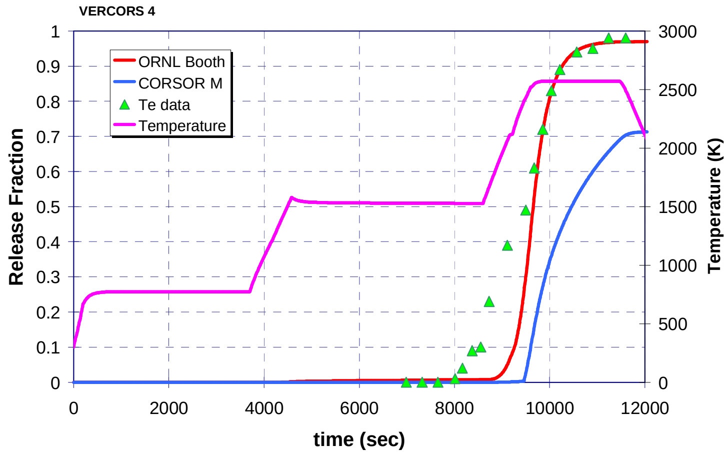
Cs Release



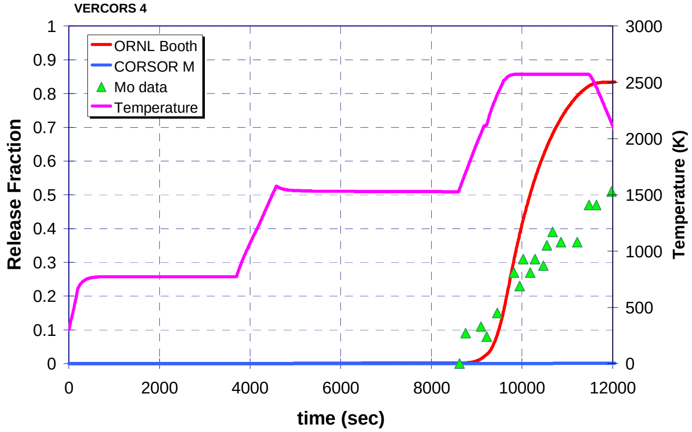
I Release



Te Release



Mo Release



Vapor Pressures of Some Important Species

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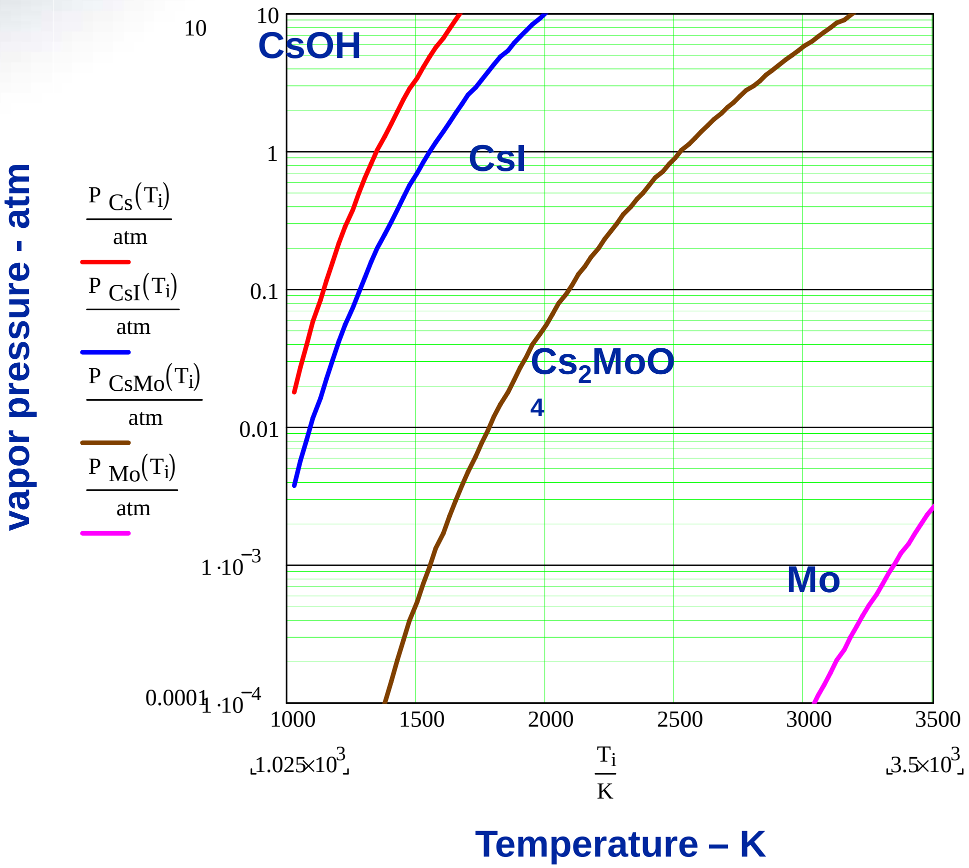
$$\dot{m}_v = \left[\frac{Nu\mathcal{D}_k}{D_{fuel}}\right]\left(\frac{P_k - 0}{RT}\right)A_{fuel}$$

Vapor transport rate



- **Molybdenum vapor pressure extremely low**
- **Cs_2MoO_4 considerably higher, but…**
- **Less volatile than CsOH or CsI**
- **MELCOR treatment**
  - **Cs and Mo treated as Cs_2MoO_4 with respect to volatility**
  - **CsI left unchanged**

FPT-1 Deposition using Modified ORNL-Booth Release Model

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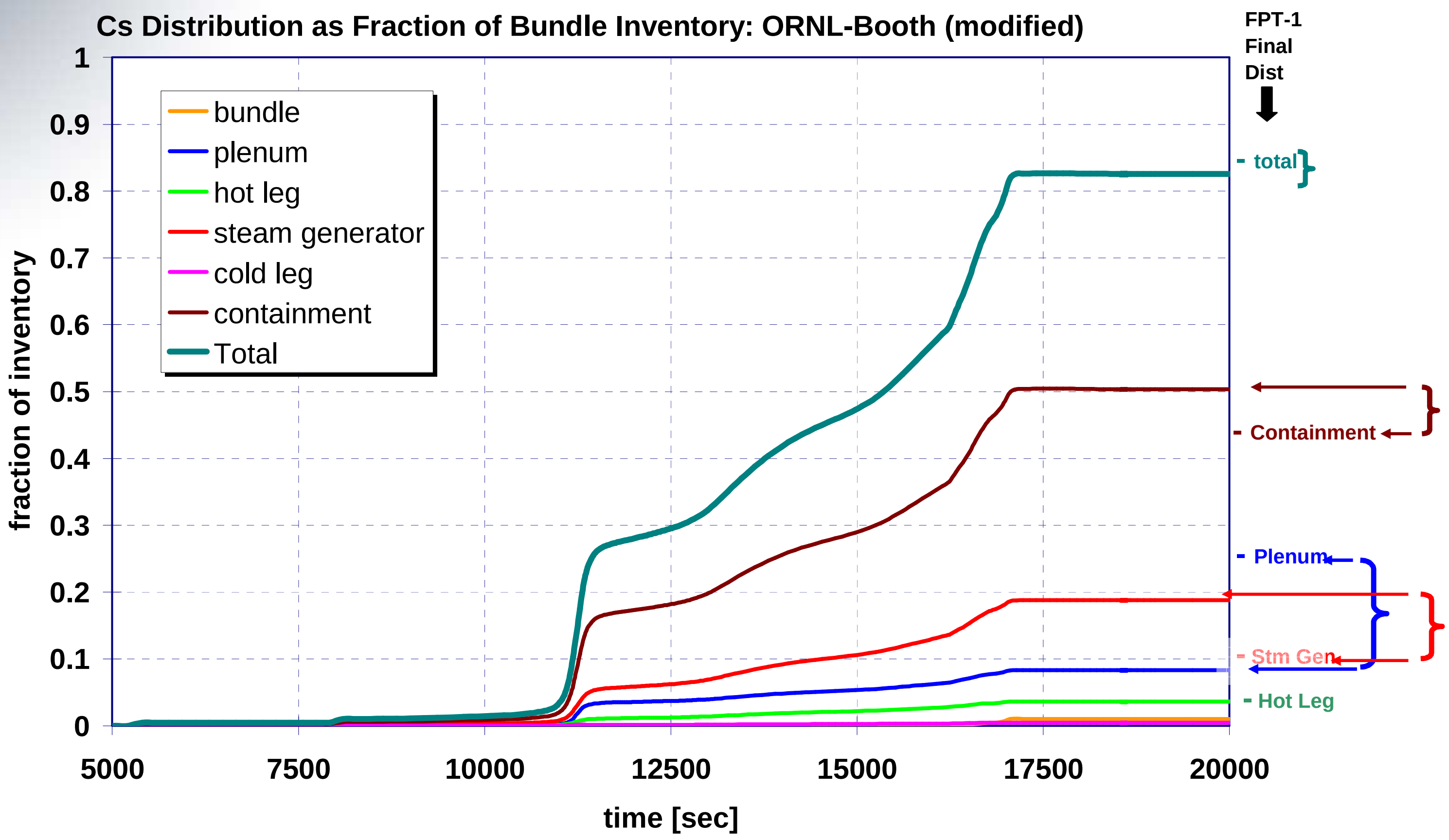

- **Distribution of transported fission products**
  - – Predictions versus experiment
  - – Performance reasonable for application

Booth Parameters for Different Data Fits

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	CORSOR-Booth	ORNL-Booth	Adjusted ORNL-Booth
Diffusion coeff. D_o	*2.5×10^{-7} m^2/sec*	*1×10^{-6} m^2/sec*	*1×10^{-6} m^2/sec*
Activation Energy Q	3.814×10^{5} joule/mole	3.814×10^{5} joule/mole	3.814×10^{5} joule/mole
Grain radius, a	6 μm	6 μm	6 μm
Class Scale Factors	---	---	---
Class 1 (Xe)	1	1	1
Class 2 (Cs)	1	1	1
Class 3 (Ba)	3.3×10^{-3}	4×10^{-4}	4×10^{-4}
Class 4 (I)	1	0.64	0.64
Class 5 (Te)	1	0.64	0.64
Class 6 (Ru)	*1×10^{-4}*	*4×10^{-4}*	*0.0025*
Class 7 (Mo)	*0.001*	*0.0625*	*0.2*
Class 8 (Ce)	3.34×10^{-5}	4×10^{-8}	4×10^{-8}
Class 9 (La)	1×10^{-4}	4×10^{-8}	4×10^{-8}
Class 10 (U)	1×10^{-4}	3.6×10^{-7}	3.2×10^{-4}
Class 11 (Cd)	0.05	0.25	.25
Class 12 (Sn)	0.05	0.16	.16

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     - Background
     - Modeling
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Release of Structural Aerosols

- **For BWRs, principal source is tin (alloy material in Zircaloy)**
  - **Approx. 70+ MT of Zircaloy in fuel clad + canister**
  - **1.45% of which is Sn**
- **Direct experimental measurements are very limited, but general observations from Phebus tests suggest:**
  - **Sn levels greatly reduced in unoxidized Zr**
  - **No Sn found in remnants of ZrO_2**
  - **Total quantity of Sn on downstream surfaces roughly half of total available mass**

Release of Structural Aerosols
-- Modeling Approach (BWRs) --

- •[Introduction]
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    - –**Modeling**
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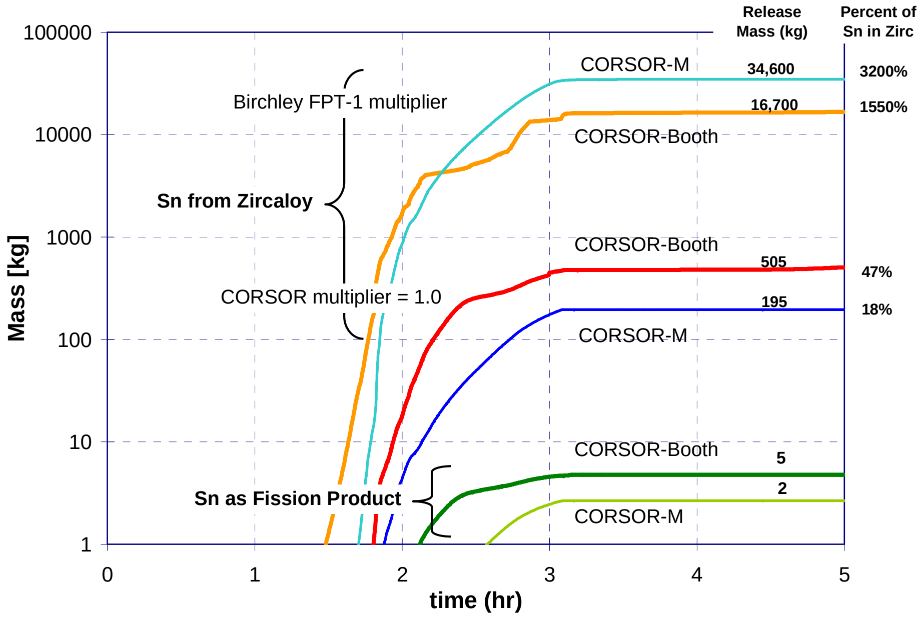
- Create special RN class to track released mass separately from fission product Sn
- Invoke ‘non-fuel’ release model in COR Package
  - Associate new RN class with releases from core components with Zr and ZrO_2
  - Release rates scaled from CORSOR model for FP Sn



- **Sensitivity calculations performed to determine appropriate release rate scalar**
  - **Results for full-scale plant model compared to similar work by Birchley at PSI**

MELCOR Aerosol Mechanics
MAEROS

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    - – **MAEROS Aerosol mechanics**
    - – Deposition
    - – Pool Scrubbing
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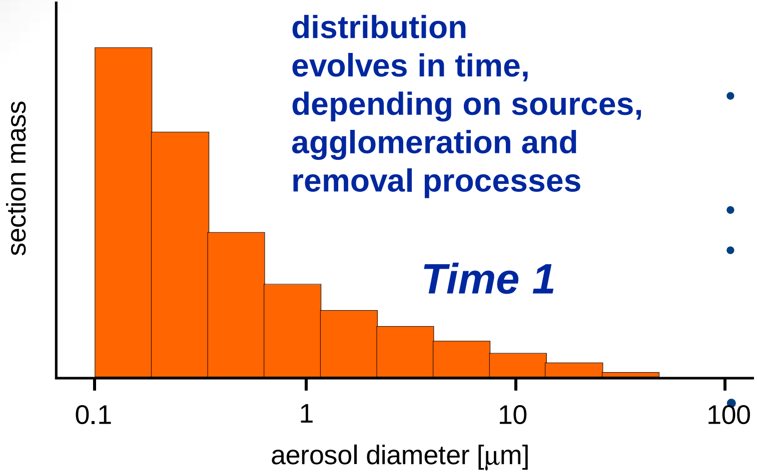
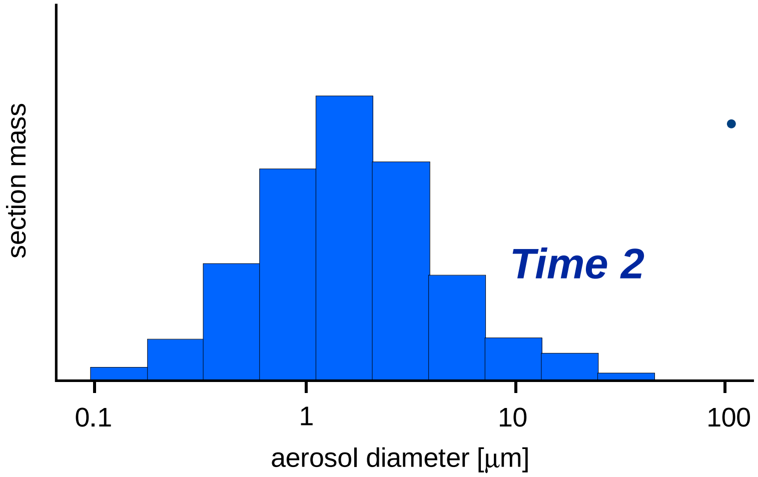


Aerosol size distribution evolves in time, depending on sources, agglomeration and removal processes



- 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
- BWR structural aerosol release (Sn) from Zr cladding and canister
  - Significant aerosol mass
  - Affects agglomeration, growth and fallout
- Cs chemisorption in RCS modeled
  - Iodine from CsI revolatilizes when reheated

Aerosol Deposition on Reactor and Containment Surfaces

- **All deposition and retention mechanisms available in MELCOR are active in all regions of plant models**
  - **Settling, phoretic processes, chemisorption, etc.**
- **Special features added to address mechanisms not captured by default models**
  - **“Filters” with filtration efficiencies designed to reflect:**
    - **Impaction losses on elbows and surfaces of long-length piping upstream of rupture location in LOCAs**
    - **Vapor scrubbing in water pools for species other than iodine**
- **Reactor, containment and auxiliary building surfaces are represented in detail**
  - **High level of nodalization: proper temperature distributions and competing transport pathways**
  - **Sub-divide complex structures into linked but separate surfaces to properly reflect orientation**

Enhanced Pool Scrubbing Model

- **Current SPARC90 pool scrubbing model**
  - **Fission product decontamination calculated**
    - **aerosol Particles**
    - **currently, Iodine is the only vapor that is scrubbed**
- **Removal of CsOH and CsI vapors**
  - **Typically enter the pool at high temperature in vapor form**
  - **Would deposit on the bubble/water surfaces and be scrubbed**
  - **Cooling offered by the pool would condense the vapor species to form aerosol particles**
  - **Treatment for the scrubbing of these vapor species now available in MELCOR 1.8.6 and 2.1**
- **Usage**
  - **MELCOR 1.8.6: IBUBT or IBUBF field on FLnnn02 must be 2**
    - **e.g., FL10002 0 0 2 2**
  - **MELCOR 2.1: ‘AllScrubbing’ (or 2) accepted as a vaild input for IBUBT or IBUBF on FL_JSW**
    - **e.g., FL_JSW 0 AllScrubbing AllScrubbing**

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Debris Mass and Composition in Lower Head

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    - –Debris mass in LH
    - –Debris & LH Temperatures
    - –Falling debris quench
    - –Stable debris in LH
    - –HT to LH
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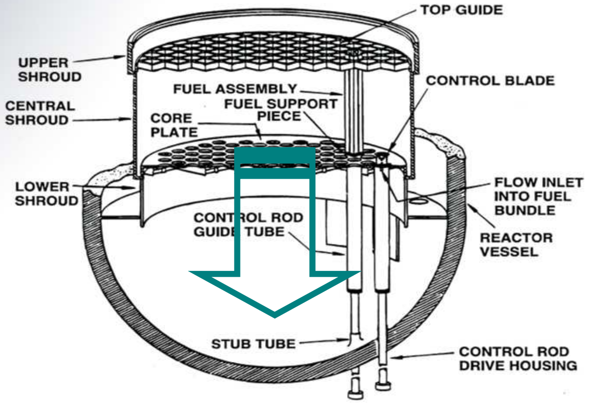
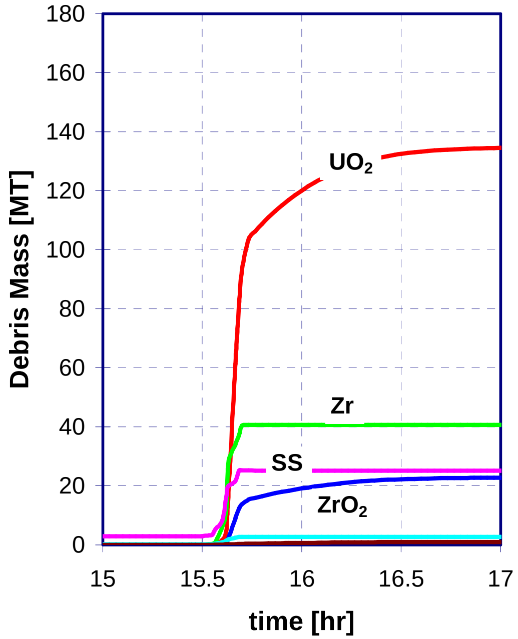
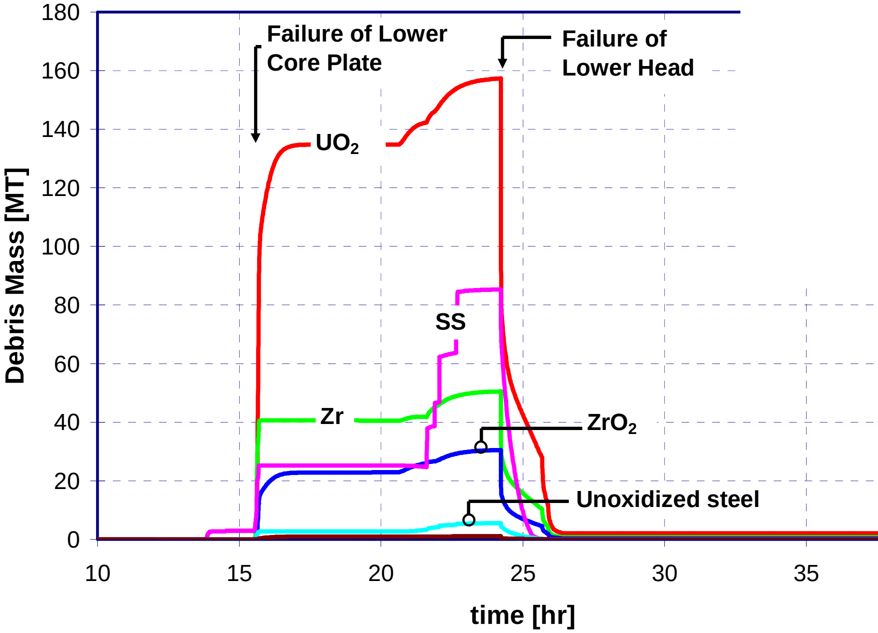
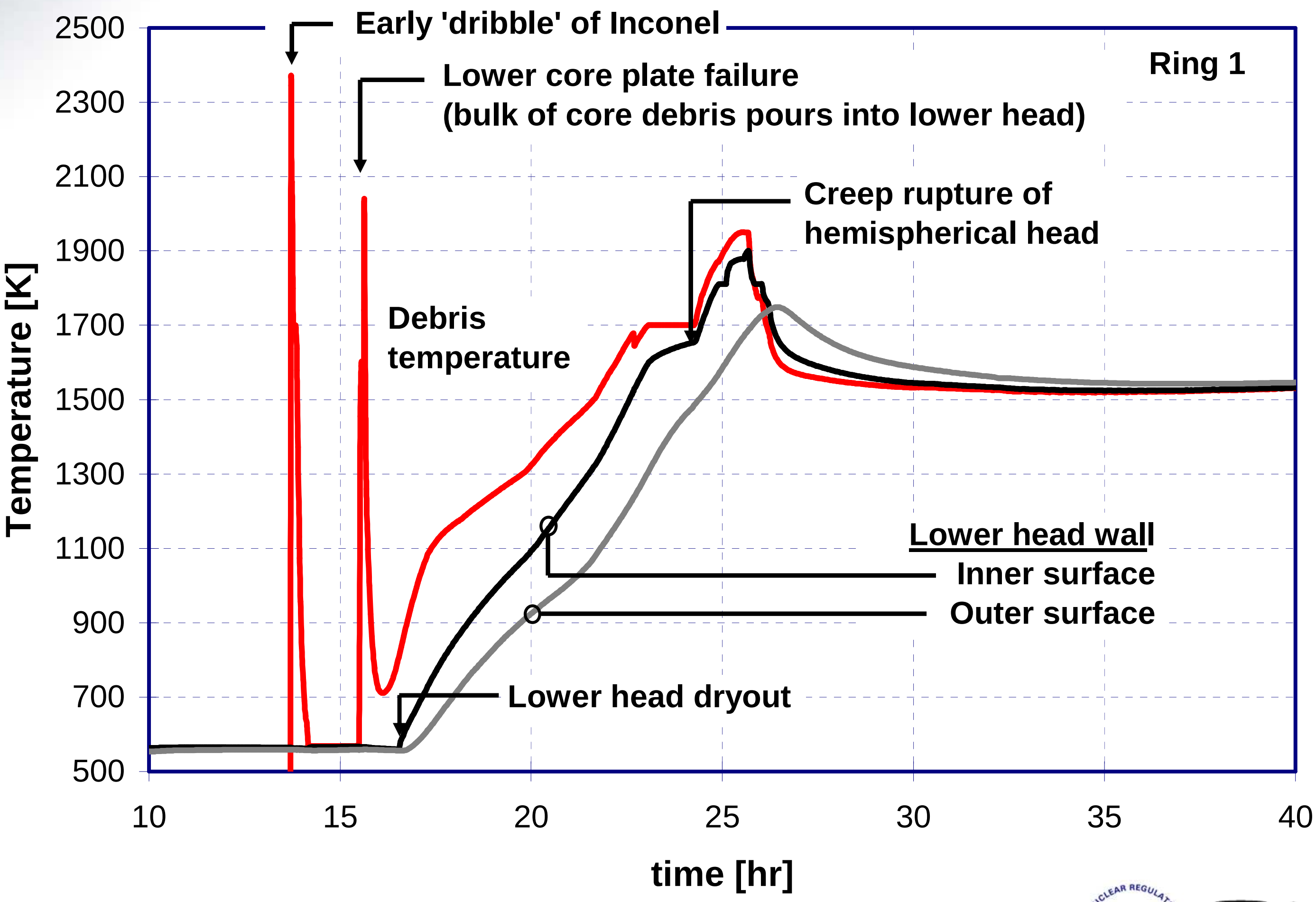






Debris and Lower Head Temperature

- •Introduction
- •BWR
  - – LTSBO
  - – Nodalization
  - 1.S/RV
  - 2.Fuel rod Failure
  - 3.Volatile FP speciation
  - 4.Structural aerosol
  - 5.Aerosol Deposition
  - 6.Debris HTF in LP
    - –Debris mass in LH
    - –Debris & LH Temperatures
    - –Falling debris quench
    - –Stable debris in LH
    - –HT to LH
  - 7.RPV failure with penetrations
  - 8.H2 combustion
  - 9.Debris Spreading (Cavity)
  - 10.MCCI
- •PWR
- •Other Best Practices



MELCOR Framework for Debris-Coolant Heat Transfer in Lower Head

- Introduction
- BWR
  - LTSBO
  - Nodalization
  - 1.S/RV
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- PWR
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- **Step 1: “Falling Debris Quench”**
  - **Parametric model of fragmentation and cooling of a molten jet pouring into pool of water**
  - **Free parameters**
    - **V_{fall} (effective fall velocity)**
    - **Heat transfer coefficient**
    - **D_{part} (D_h of final particles)**
  - **D_{part} and HTC developed from FARO data**
  - **V_{fall} selected to mimic end-state temperature of debris in deep-pool FARO tests.**

MELCOR Framework (continued)

- [Introduction](#)
- [BWR](#)
  - – [LTSBO](#)
  - – [Nodalization](#)
  - 1.[S/RV](#)
  - 2.[Fuel rod Failure](#)
  - 3.[Volatile FP speciation](#)
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    - –[Debris & LH Temperatures](#)
    - –[Falling debris quench](#)
    - –Stable debris in LH
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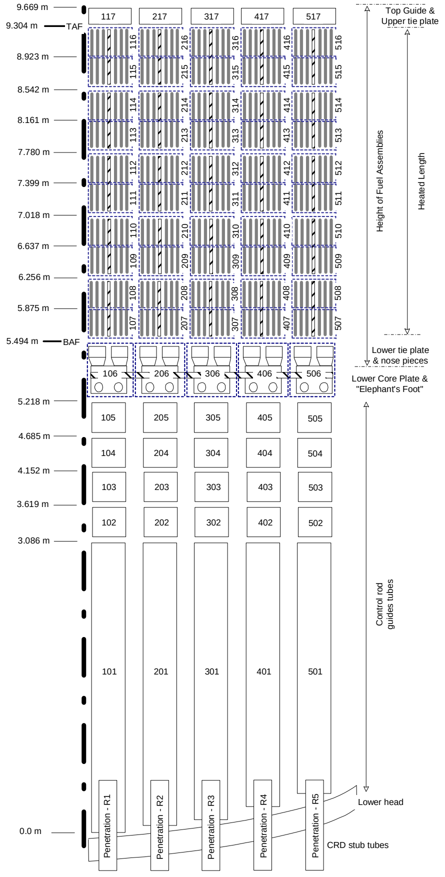
  - 7.[RPV failure with penetrations](#)
  - 8.[H2 combustion](#)
  - 9.[Debris Spreading (Cavity)](#)
  - 10.[MCCI](#)
- [PWR](#)
- [Other Best Practices](#)

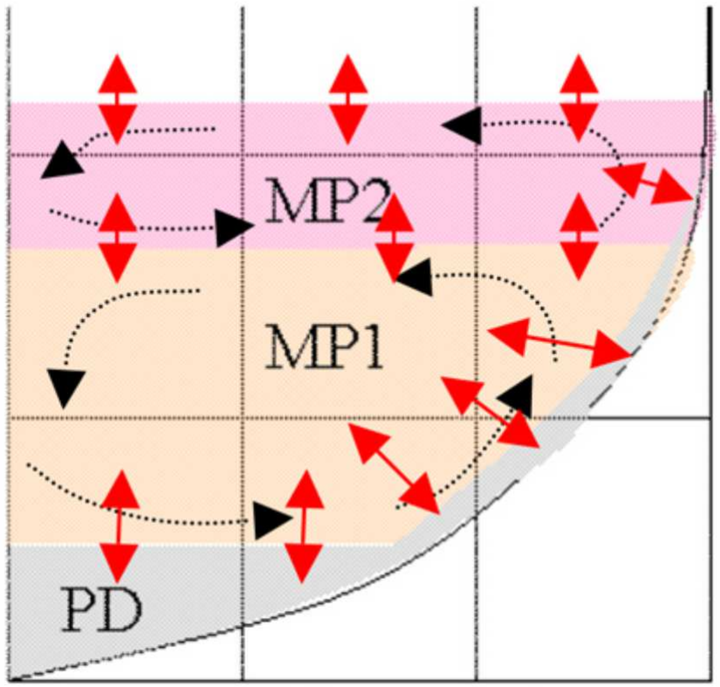
- **Step 2: Stable Debris Bed Heat Transfer**
  - – **Stable debris bed cooling limited by 1-D Lipinsky CCFL correlation**
    - **Historically limited heat transfer to uppermost region of debris bed**
      - – **Coarse nodalization required to expose entire debris bed to water**
    - **Proposed approach: restore detailed nodalization and disable1-D CCFL to reflect lateral in-flow of water from adjacent ‘rings’ of the debris bed.**
      - – **Permits calculation of debris temperature distribution**
      - – **Permits more accurate representation of heat transfer to control rod guide tubes**



BWR/4 Core Nodalization

MELCOR Framework (concluded)

- **Step 3: Heat Transfer to (and failure of) Lower Head**
  - **New 2-D curved head model in MELCOR 1.8.6**
  - **Solid debris heat conduction to vessel wall**
  - **Heat transfer coefficient between debris & head sensitive to debris temperature and morphology**
  - **Creep rupture of hemispherical head based on Larson-Miller parameter and life-fraction rule applied to a 1-D mechanical model**



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    - –Modeling
    - –Justification
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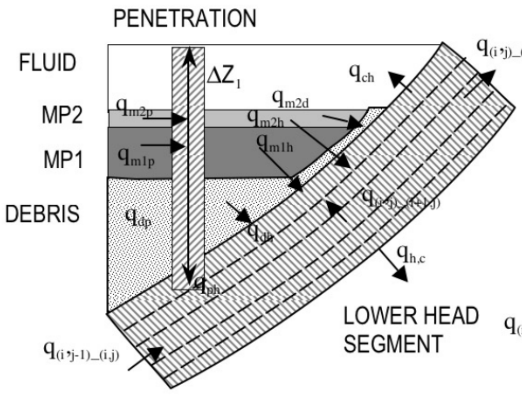
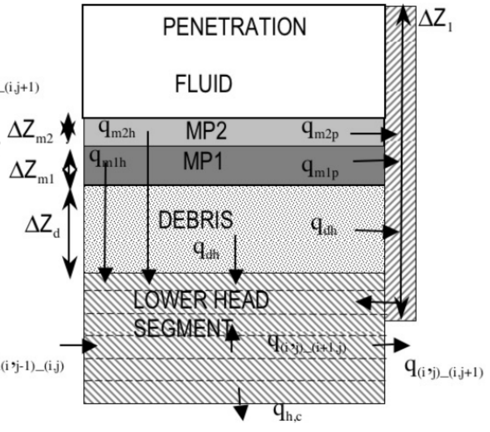
  - 10.MCCI
- PWR
- Other Best Practices

Effect of Penetrations on Failure Criteria

- **Penetration failure can be represented with the following tools:**
  - **Failure criteria specified via user-defined control function**
  - **Distinct temperature of lumped parameter steel mass in contact with debris and inner surface of lower head**



Curved Lower Head



Cylindrical Lower Head

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  – LTSBO
  – Nodalization
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  5.Aerosol Deposition
  6.Debris HTF in LP
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    –Modeling
    –Justification
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  10.MCCI
•PWR
•Other Best Practices

Baseline Analyses will Not Exercise Penetration Failure Model

- **Reasons:**
  - **Experimental/analytical work for BWR penetrations does not conclusively demonstrate high probability of failure at a time that significantly precedes creep rupture of the head**
  - **Melt penetration into penetration/stub tube structure does not necessarily result in debris ejection from RPV**
  - **Lumped-parameter penetration model in MELCOR does not account for complexities of melt penetration into structure and local changes in debris state**
  - **MELCOR sensitivity studies with active model (using reasonable range of penetration masses) indicate penetration failure has small impact on event chronology**

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  - 6.Debris HTF in LP
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  - 8.H2 combustion
  - 9.Debris Spreading (Cavity)
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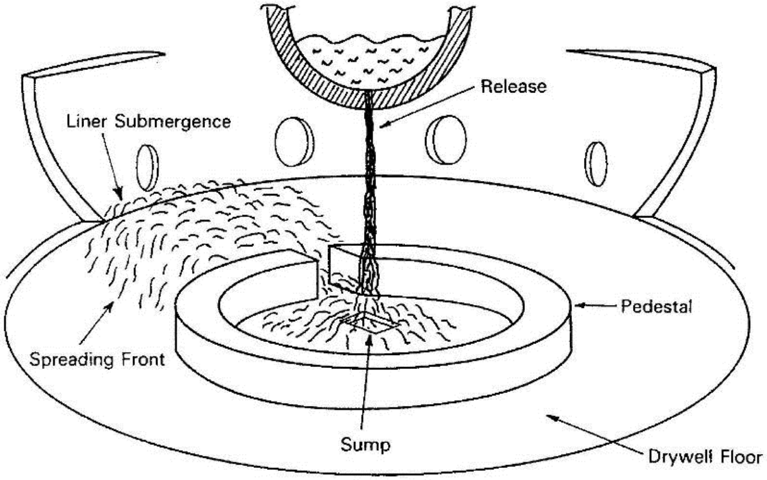
- PWR
- Other Best Practices

Hydrogen Combustion & Ignition

- **MELCOR (HECTR) combustion models will be active in all calculations**
  - **Apply default criteria for steam inerting, combustion efficiency, flame speed, etc.**
  - **One non-default option:**
    - **Time required for a flame to propagate to neighboring control volume specified on an individual CV basis**
- **Ignition criteria**
  - **Use default for sequences with well-defined ignition sources (generally all cases with active ac power)**
  - **Defer ignition until vessel breach for total loss of power scenarios.**

Lateral Debris Spreading in Mark I Drywell

- **Potential for early drywell failure often dominated by drywell shell melt-through in Mark I containment**
  - **Not a factor in some Mark I plants due to deep sumps or curbs**
- **Modeling approach follows basic conclusions of NRC issue resolution**
  - **Potential for failure dominated by lateral debris mobility**



Debris Spreading / Shell Melt-through Criteria

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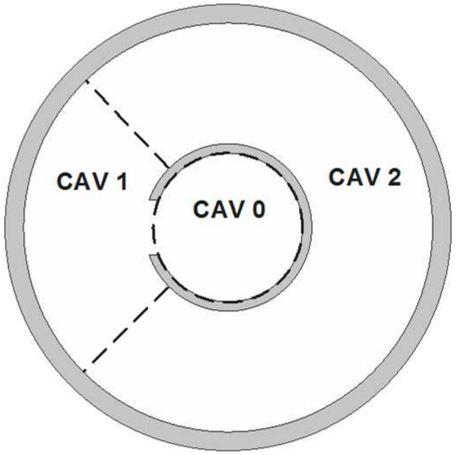
  8. H2 combustion
  9. Debris Spreading (Cavity)
     - Mark I drywell
     - Debris spreading
     - Contact with drywell liner
  10. MCCI
- PWR
- Other Best Practices

- **Debris mobility tied to debris temperature and static head (height differential between neighboring areas):**
  - **Overflow not allowed if $T_{debris} < T_{solidus}$**
  - **Above solidus:**
    - **CAV0 to CAV1: 0.5 m when $T_{debris} > T_{solidus}$**
      0.15 m when $T_{debris} = T_{liquidus}$
    - **CAV1 to CAV2: 0.5 m when $T_{debris} > T_{solidus}$**
      0.10 m when $T_{debris} = T_{liquidus}$
- **Spreading rate expressed in terms of transit time across single CAV**
  - **When $T_{debris} = T_{liquidus}$: 10 min for CAV1**
    30 min for CAV2
  - **When $T_{debris} = T_{solidus}$: infinite**
- **5 min delay to shell failure after debris contact with T > 1811 K**



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    - –Debris spreading
    - –Contact with drywell liner
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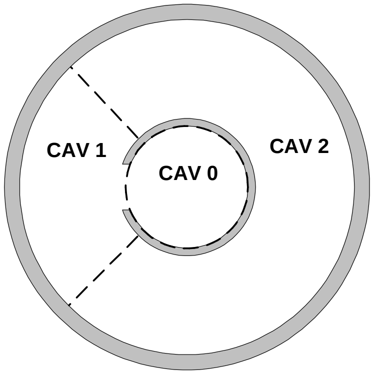
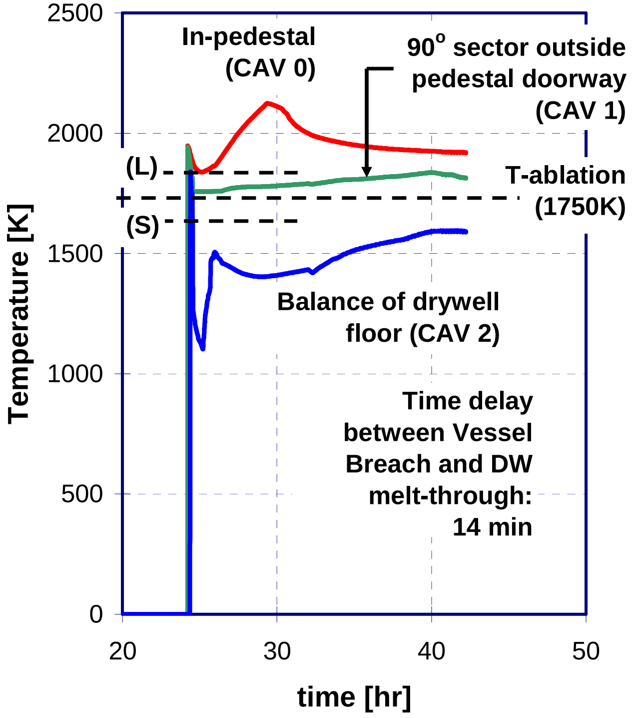
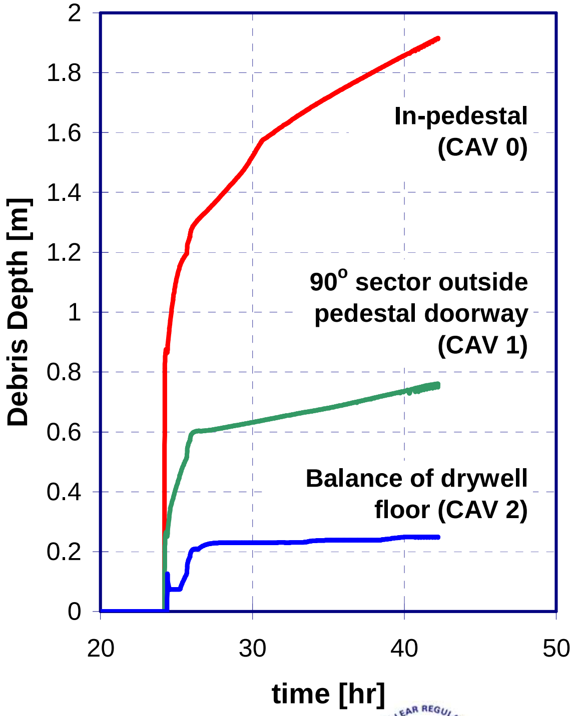
- PWR
- Other Best Practices

Debris Spreading & Contact with DW Liner





Time delay between Vessel Breach and DW melt-through: 14 min



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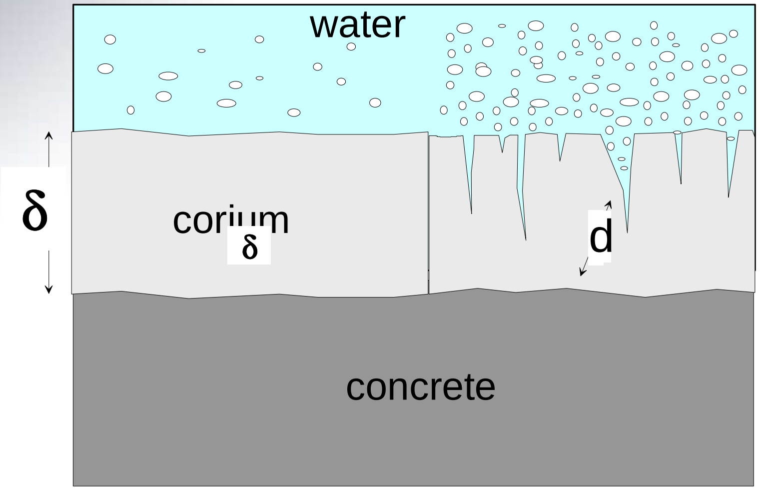
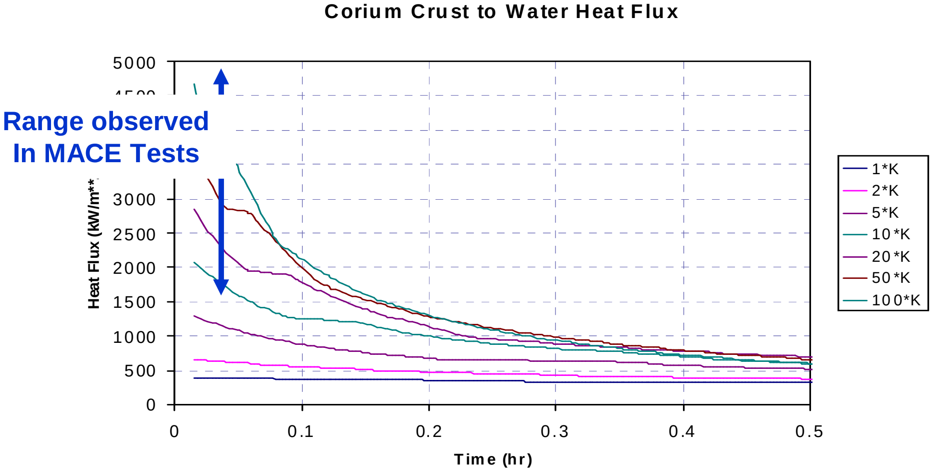
MCCI Modeling




Corium Crust to Water Heat Flux

Range observed In MACE Tests

- Corium assumed to be well mixed (default)
- Enhanced effective corium thermal conductivity (10x)
  - produces 1 to 5 MW/m^2 heat flux
  - Accounts for cracks and fissures and crust failure
  - Consistent with interpretation of MACE tests

NUCLEAR ENERGY & GLOBAL SECURITY TECHNOLOGIES

Summary of Main Points for PWR Discussion

- Introduction
- BWR
- **PWR**
  - Nodalization
  - SBO
  1. Pump seals
  2. RCS natural circulation
  3. Core plate failure
- Other Best Practices

Issues Specific to PWR reactors

- **Pump seal leakage and blowout**
- **RCS natural circulation treatment**
- **Core plate failure**

Issues Previously discussed (Treated the Same as for BWR reactors)

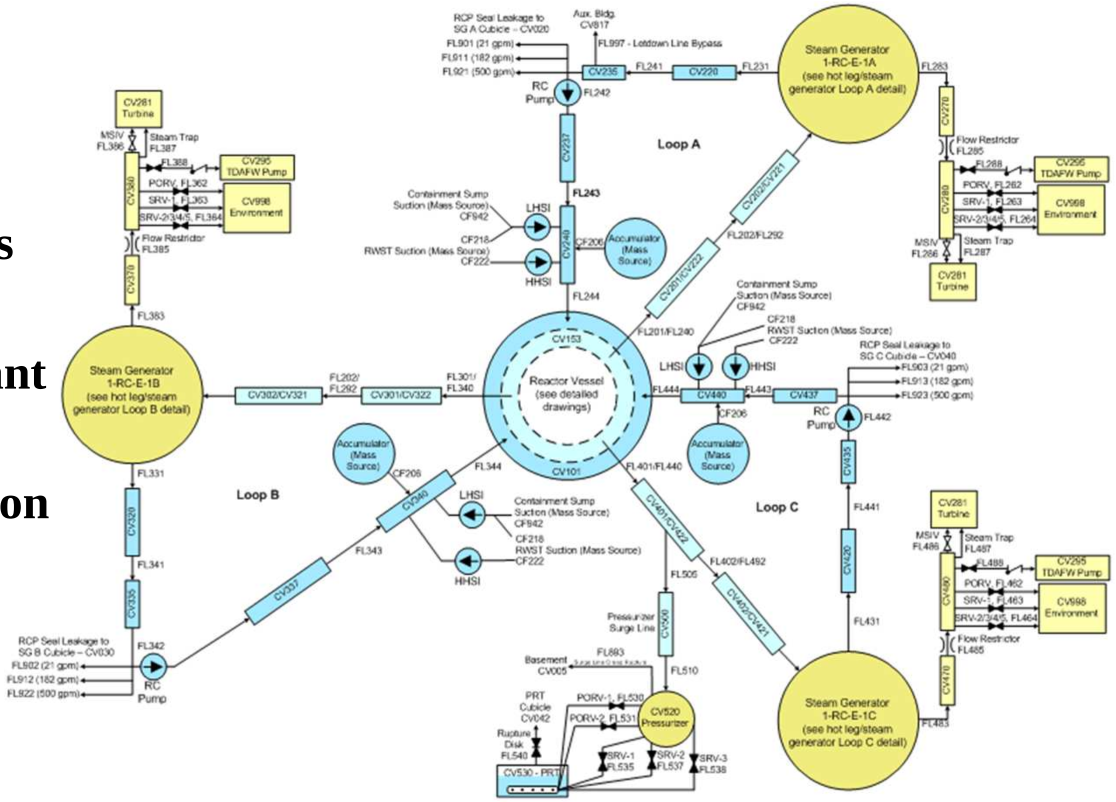
- **Safety relief valve cycling and failure**
- **Fission product release, speciation, and volatility**
- **Fuel degradation and relocation treatment**
- **Debris/coolant heat transfer**
- **Vessel head failure and debris ejection**
- **Hydrogen combustion**
- **MCCI**

Sandia National Laboratories

Plant and NSS Nodalizations

- •Introduction
- •BWR
- •PWR
  - – Nodalization
  - – SBO
  - 1.Pump seals
  - 2.RCS natural circulation
  - 3.Core plate failure
- •Other Best Practices

- Plant Buildings
  - Containment
    - Elevation View
    - Aerial view
  - Other Buildings
- Detailed nodalizations of RCS and Core
  - Capture important 2-D effects
  - Natural circulation patterns
    - Core
    - RCS
    - Steam generators
    - Loop seals



- Introduction
- BWR
- PWR
  - Nodalization
  - SBO
    - SBO definition
    - Initiation to SG dryout
    - SG dryout
    - SG dryout to pump seal failure
    - Core uncovery to hotleg failure
    - Core Waterlevel
  1. Pump seals
  2. RCS natural circulation
  3. Core plate failure
- Other Best Practices

Walkthrough of Station Blackout Accident in a PWR

- **Short term station blackout**
- **Loss of ac power**
- **No feedwater injection**
- **No ECCS**
- **Leaking pump seals**
- **Key modeling issues identified in walkthrough**

Station Blackout
High Pressure PWR Sequence
Accident Initiation – SG dryout

- Introduction
- BWR
- PWR
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  - SBO
    - SBO definition
    - Initiation to SG dryout
    - SG dryout
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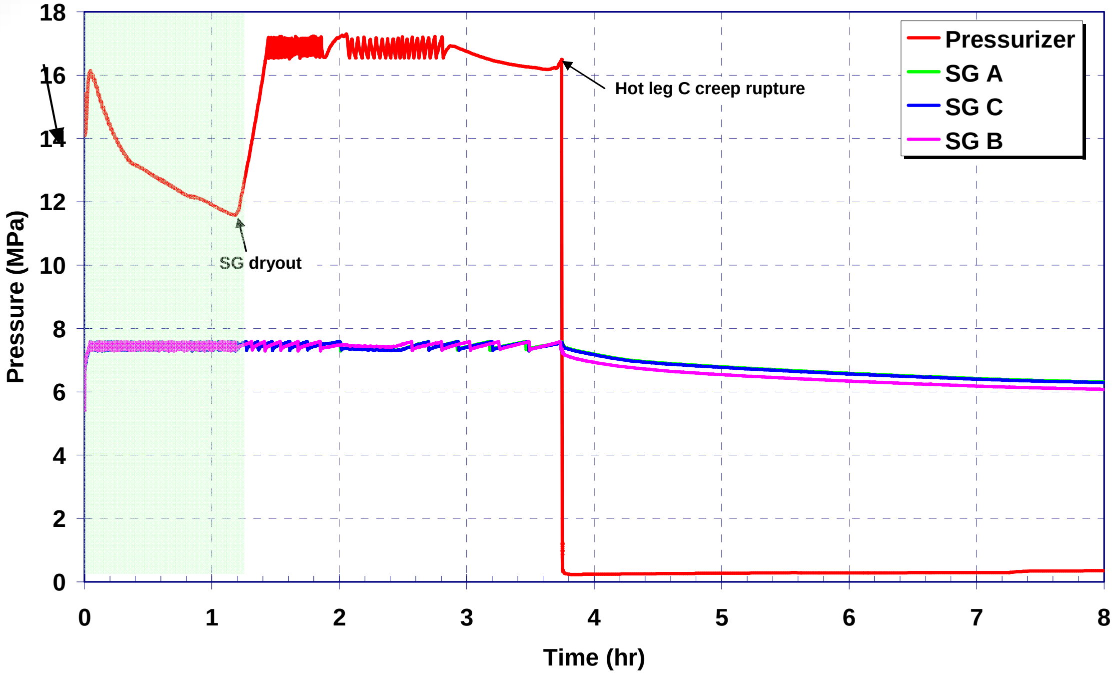
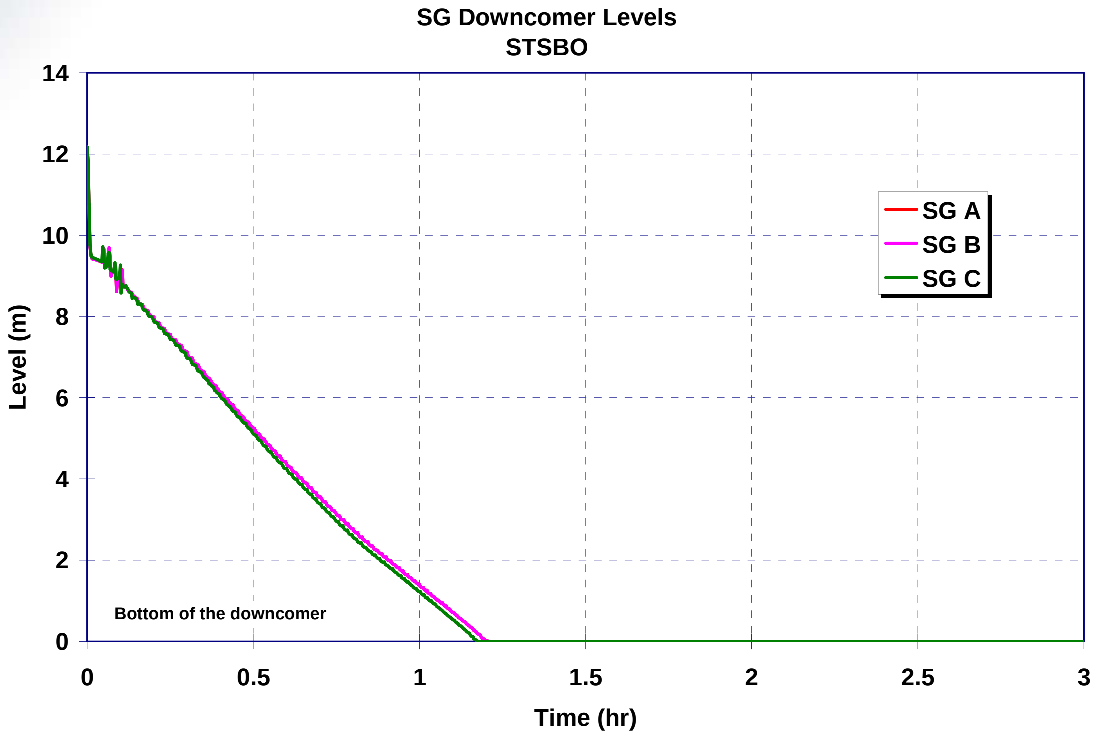


- **Initial full loop RCS water circulation removes energy**
- **Main coolant pump seals leak water**
- **Pressurizer safety valve cycling stops**

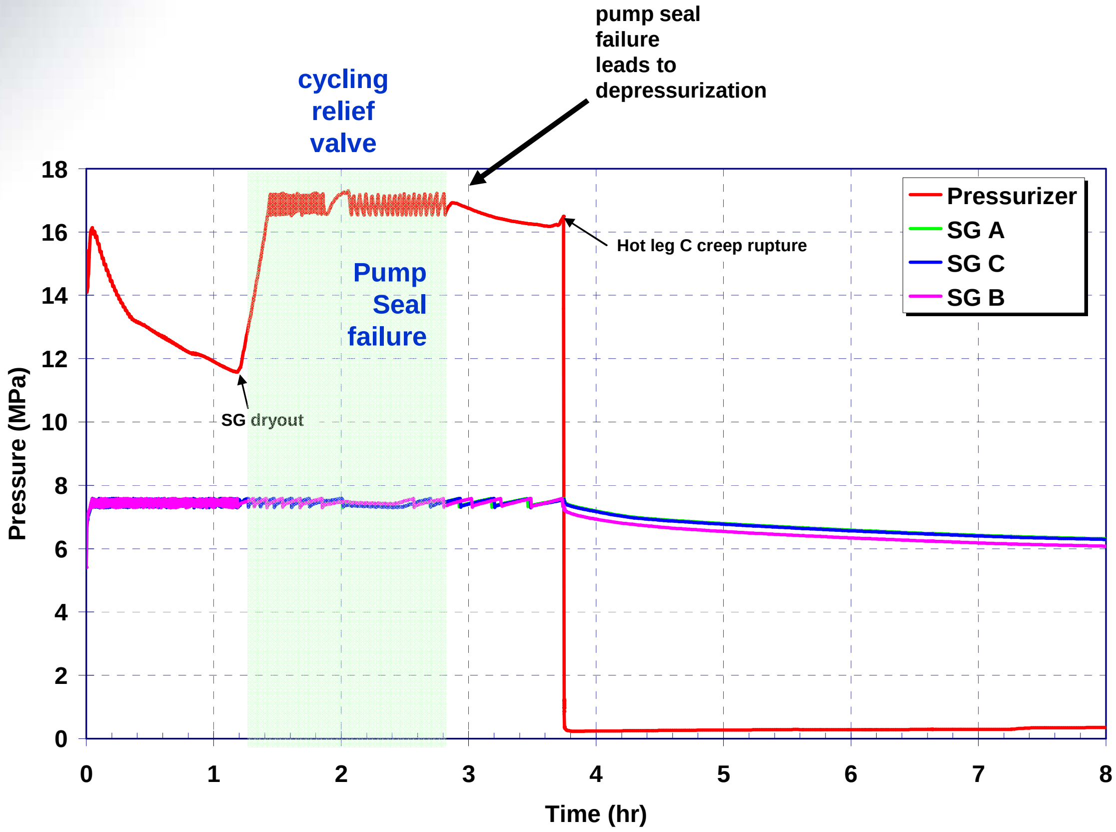
Steam Generator Secondary Water Accident Initiation – SG dryout



- Full loop RCS natural circulation period
- Good decay heat removal
- Secondary dry at ~1.2 hr
- Primary RCS pressurization follows

Station Blackout
High Pressure PWR Sequence
SG dryout – Pump Seal Failure

- •[Introduction]
- •[BWR]
- •[PWR]
  - – [Nodalization]
  - – [SBO]
    - • SBO definition
    - • Initiation to SG dryout
    - • SG dryout
    - • SG dryout to pump seal failure
    - • Core uncovery to hotleg failure
    - • Core Waterlevel
  - 1. Pump seals
  - 2. RCS natural circulation
  - 3. Core plate failure
- •Other Best Practices



- SG dryout starts RCS re-pressurization to relief valve setpoint
- RCS becomes steam-filled challenging pump seals
  - – Seal blowout at 2.8 hrs
- Seal failure increases coolant mass loss rate
- Cycling relief valve
  - – Same treatment as BWR SRV

Station Blackout
High Pressure PWR Sequence
Core Uncovery – Hotleg failure

- Introduction
- BWR
- PWR
  - Nodalization
  - SBO
    - SBO definition
    - Initiation to SG dryout
    - SG dryout
    - SG dryout to pump seal failure
    - Core uncovery to hotleg failure
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  1. Pump seals
  2. RCS natural circulation
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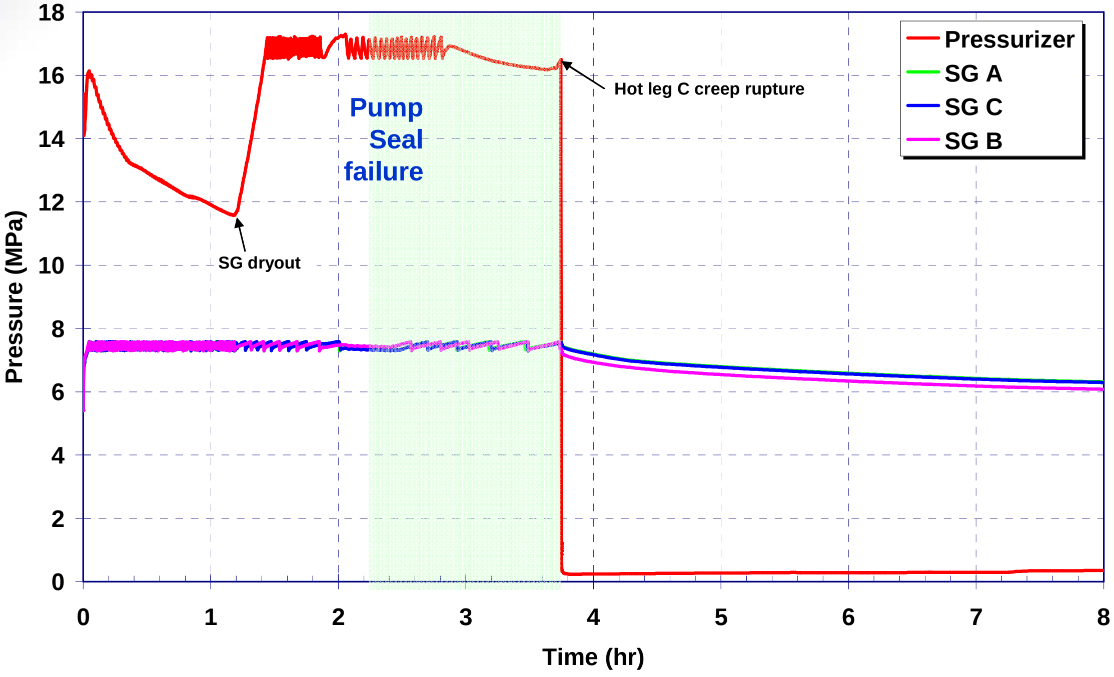

pump seal failure leads to depressurization

- Coolant loss and low core water level leads to RCS depressurization
- Core damage phase
- PWR valves less susceptible to high temperature conditions

Core Water Level

- •Introduction
- •BWR
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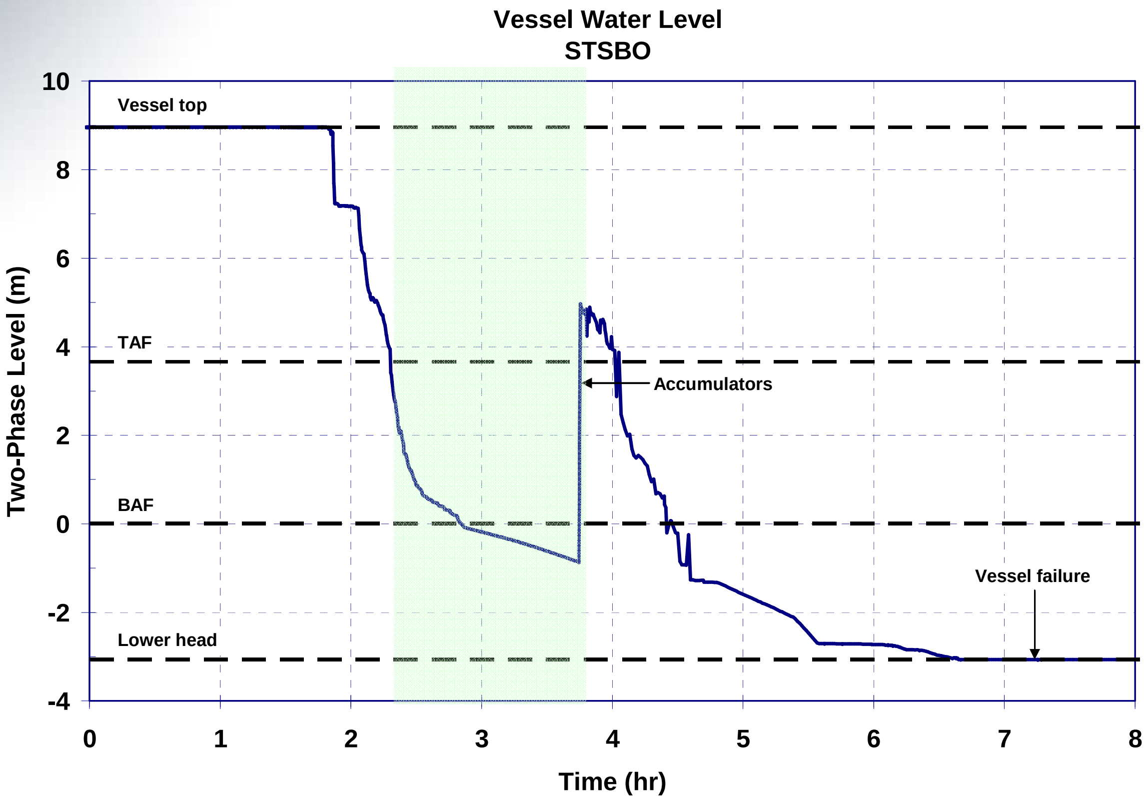
Vessel Water Level
STSBO



- Hot leg and SG natural circulation
- Hot leg failure depressurizes vessel
  - Accumulators dump
- Partial core quench and second vessel boildown
- Core damage and hydrogen generation as water in core falls

Pump Seal Leakage

- •Introduction
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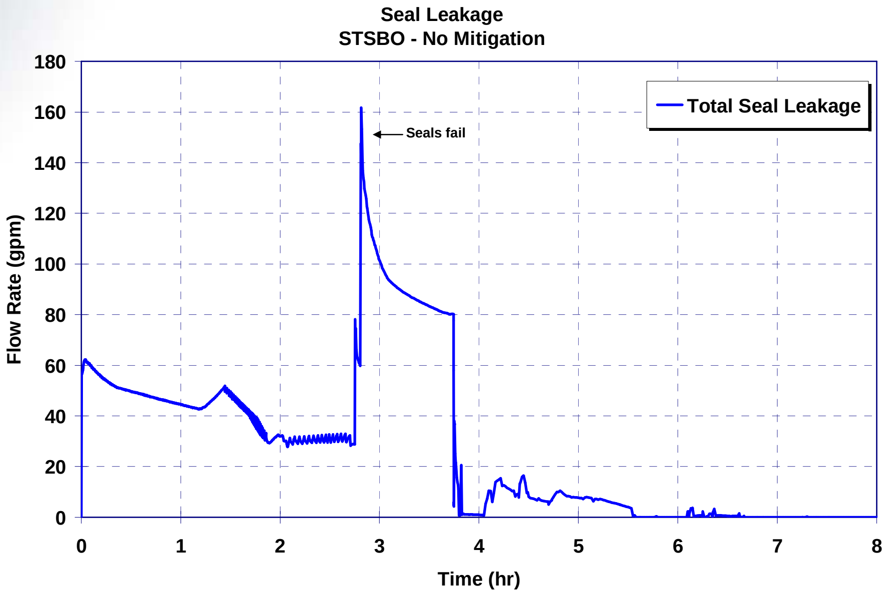
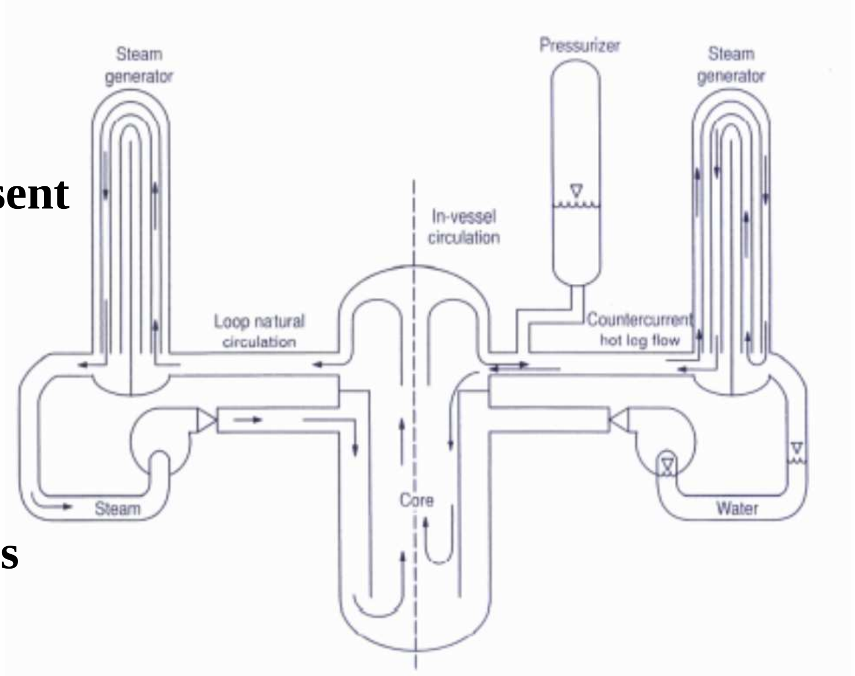


- Model based on Rhodes analysis of leakage and likelihood and degree of seal failure
  - – Seals initially leak on loss of site power and back pressure
    - 21 GPM
  - – Saturation conditions in RCS (high temperature) produces seal failure
    - Failure can range between 170 and 250 GPM
- Assume:
  - – 21 GPM initially
  - – 170 GPM at saturation

Natural Circulation Modeling

- **SCDAP/RELAP5 Studies from mid-1980’s to present**
- **COMMIX CFD, 1987**
- **1/7th-Scale Westinghouse Test, 1989-1993**
- **Fluent CFD Work, 2003 to present**
  - **Numerical CFD extends work**
    - **1/7th-scale**
    - **Full-scale**
    - **Westinghouse designs**
    - **CE designs**
- **SCDAP/RELAP5 SGTI analysis**
  - **FLUENT support**



Natural Circulation Modeling
MELCOR Approach

- Introduction
- BWR
- PWR
  - – Nodalization
  - – SBO
  - 1.Pump seals
  - 2.RCS natural circulation
    - 1.Background
    - 2.Assessment
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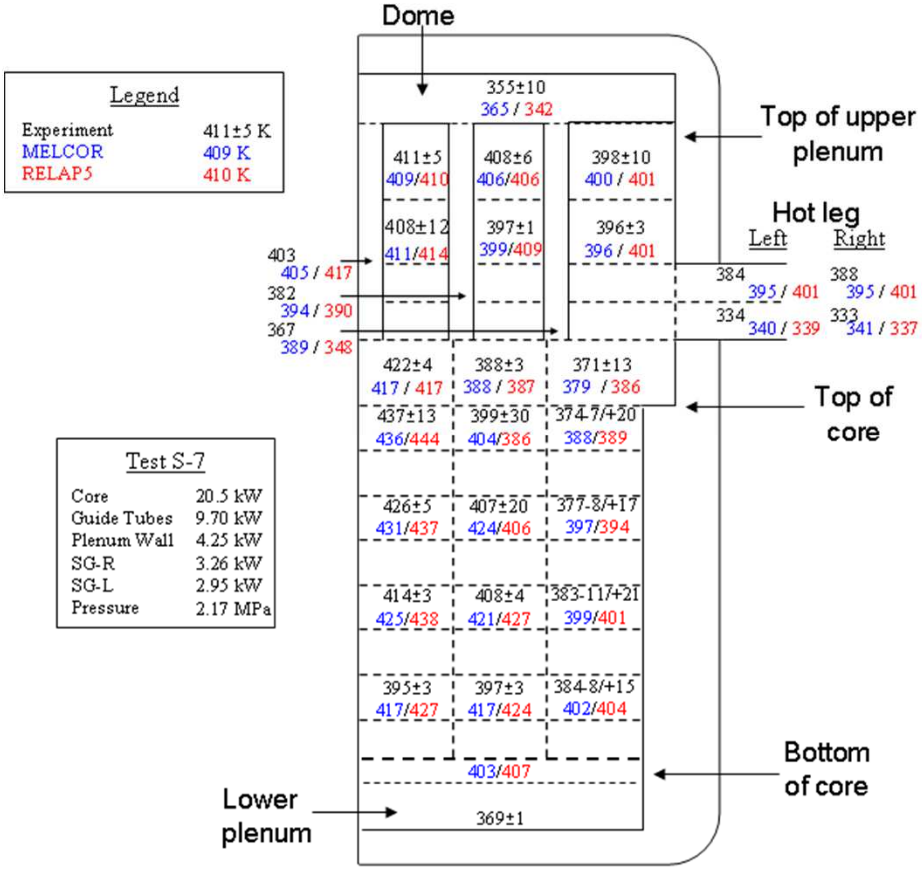
    - 4.Hotleg modeling
    - 5.Tube flow modeling
    - 6.Other modeling considerations
  - 3.Core plate failure
- Other Best Practices

- **1/7th Westinghouse Assessment**
  - **Steady state tests**
  - **Safety valve cycles**
  - **Hot leg fission product heating**
  - **Hydrogen binding**
- **Comparison to experiment and SCDAP/RELAP5 (where available)**
  - **In-vessel**
  - **Hot leg**
  - **Steam generator**



Legend

Experiment	411±5 K
MELCOR	409 K
RELAP5	410 K

Test S-7

Core	20.5 kW
Guide Tubes	9.70 kW
Plenum Wall	4.25 kW
SG-R	3.26 kW
SG-L	2.95 kW
Pressure	2.17 MPa

Natural Circulation Modeling
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•Other Best Practices

- **MELCOR vessel and RCS models developed from SCDAP/RELAP5 natural circulation models**
  - **5 ring vessel with 2-D core and upper plenum**
  - **Geometry and loss factors from RCS**
  - **Zion, Surry, and Calvert Cliffs SCDAP/RELAP5 models**
  - **New modeling approach to hot leg and steam generator natural circulation flows**
- **SCDAP/RELAP5 renodalizes model when natural circulation conditions are expected**
  - **Special 2-D hot leg and steam generator model**
- **Application of MELCOR includes calculation of source term beyond RCS failure**
  - **S/R5 used to predict timing and location of creep rupture failure and not subsequent events**

Natural Circulation Modeling
MELCOR Approach

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•Other Best Practices

- **Hot leg counter-current natural circulation tuned to a Froude Number correlation using results from FLUENT CFD analysis**

$$Q = C_D \left[g \left(\Delta\rho / \rho \right) D^5 \right]^{1/2}$$

where

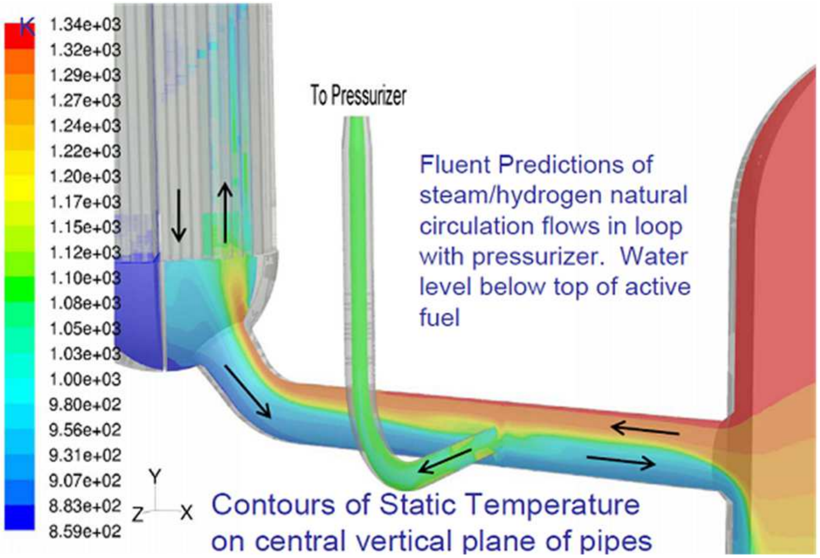
g acceleration due to gravity.

Q volumetric flow rate in a horizontal duct

ρ average fluid density (ρ)

Δρ density difference between the two fluids

C_D hot leg discharge coefficient



Fluent Predictions of steam/hydrogen natural circulation flows in loop with pressurizer. Water level below top of active fuel

Contours of Static Temperature on central vertical plane of pipes

Natural Circulation Modeling
MELCOR Approach

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    6.Other modeling considerations
  3.Core plate failure
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- **Steam generator tube to hot leg flow ratio tuned results from the FLUENT CFD analysis**
- **Inlet plenum subdivided into 3 regions for hot, mixed, and cold regions from plume analyses**
- **Steam generator mixing fractions based on FLUENT CFD analysis**
  - **M-ratio(steam generator tube to hot leg flow ratio) = 2**

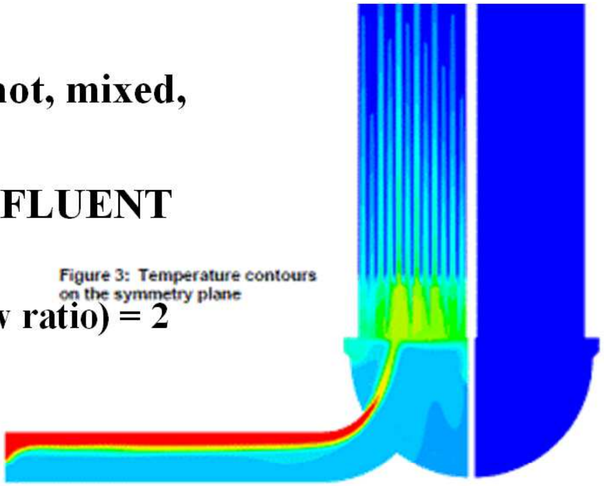
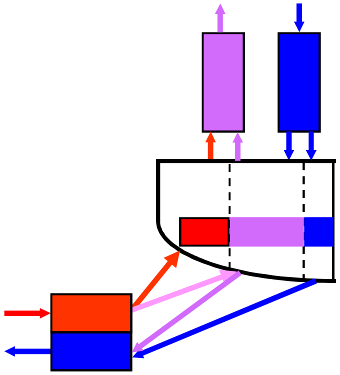


Figure 3: Temperature contours on the symmetry plane



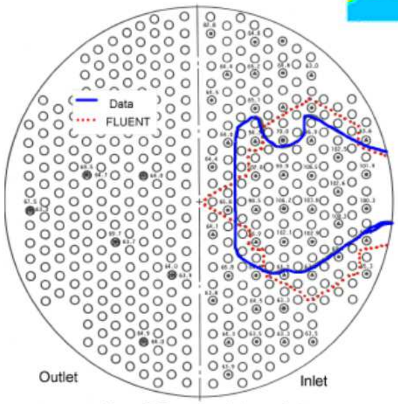


Figure 5: Boundary between hot (rising, enclosed by the curves) and cool (falling) flows at the tube sheet

④

Natural Circulation Modeling
MELCOR Approach

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  3. Core plate failure
- **Other Best Practices**

- **Explicit modeling of structures in hot leg and steam generator**
  - **Convective heat transfer**
    - **Augmented in hot leg based on FLUENT turbulence evaluations**
  - **Gas to structure radiative exchange in the hot leg and steam generator**
  - **Ambient heat loss through the piping and insulation**
- **Individual modeling of relief valves**
  - **When the valves are lumped, it creates a very large flow that non-physically disrupts natural circulation flow patterns and the timing of the valve openings**
- **Creep rupture modeling**
  - **Hot leg nozzle carbon safe zone**
  - **Hot leg piping**
  - **Surge line**
  - **Steam generator inlet tubes**

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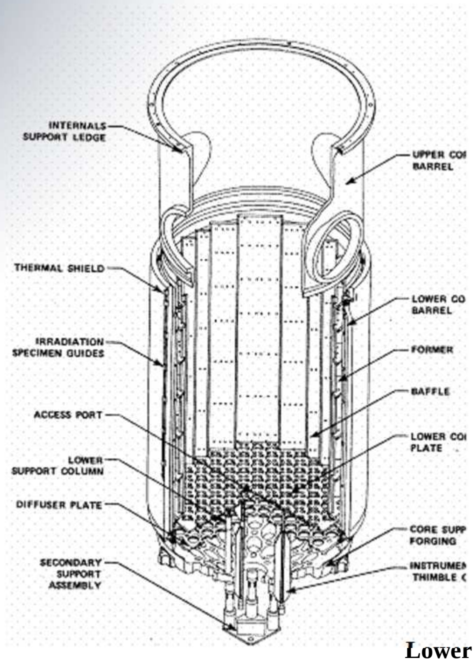
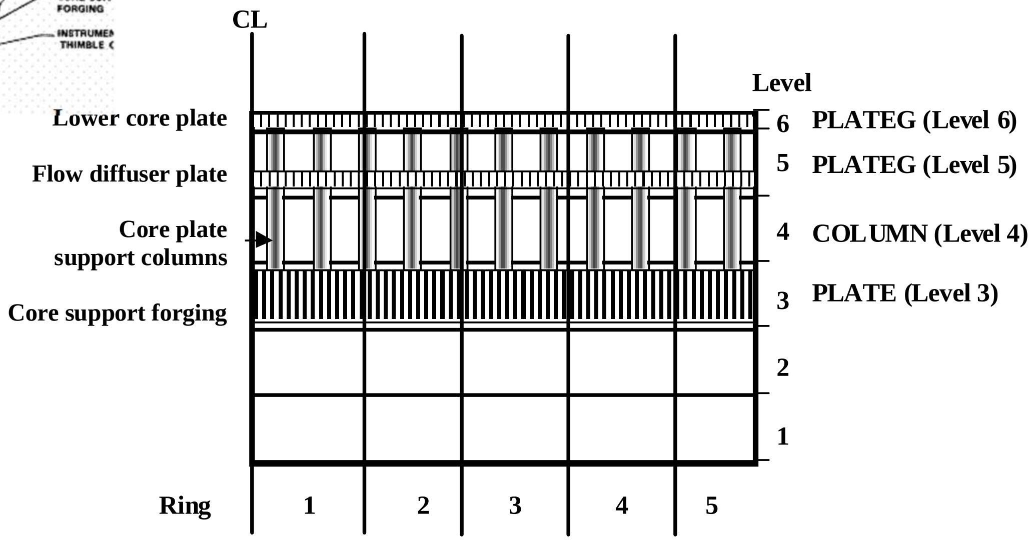
Westinghouse PWR Core Plate



- **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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Other MELCOR Best Practices

- **Some standardize some non-default input**
  - **Porosity of particulate debris**
    - **CORZjj01 PORDP 0.4**
- **Some Numeric in Nature**
  - **SC-4401(3); Maximum number of iterations permitted before solution is repeated with a decreased (subcycle) timestep.**
- **Some enable some previously non-default models**
  - **RN1002 – enable Hygroscopic model**
  - **FLnnnFF – KFLSH=1 enables flashing model**
- **Some new models activated**
  - **FLnnn02 IBUBF & IBUBT**
    - **-1 Vapor heat transfer in pools for RCS FLs**
    - **+2 SPARC scrubbing in pools for spargers, quencher, vents, and BWR downcomers.**

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- New defaults enabled automatically in 2.1
- M1.8.6 defaults enabled as follows:

```
! The following records
updates the default by
individual package
COR_DFT 1.86
CAV_DFT 1.86
RN1_DFT 1.86
HS_DFT  1.86
CVH_DFT 1.86

! This record restore
original defaults all at
once
EXEC_GLOBAL_DFT  1.86
```

- New defaults disabled automatically in 1.8.6
- M2.1 defaults enabled as follows:

```
! The following records
updates the default by
individual package
CORDEFAULT 2.0
CAVDEFAULT 2.0
RN1DEFAULT 2.0
HSDEFAULT  2.0
CVHDEFAULT 2.0

! This record restore
updates the default all
at once
DEFAULT  2.0
```

Note: See User Guide for list of those default items changed in M2.0 default template

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1.	**BUR000**	**IACTV**	**0 (Active)**	**Burn package activation**
2.	**BUR1xx** **(xx = CV)**	**IGNTR**	**86 for CVs where ignition is to be prohibited.**	**Apply to RCS control volumes to preclude combustion.**
3.	**BUR1xx** **(xx = CV)**	**TFRAC**	**1.0**	**Time fraction of burn before propagation to neighboring CV is allowed. Value of 1.0 means a flame must travel the radius of the control volume before propagating to its neighbor.**
4.	**FLnnn0T**	**ZBJT0,** **ZTJT0**	**ZTJT0 = ZBJT0 + Δz** **(For axial containment flow paths only)**	**To insure that MELCOR properly estimates vertical burn propagation in containment, drywell, reactor building, and auxiliary building, it is necessary to define "vertical" flow path "from" and "to" elevations with a small dZ. If the "from" and "to" elevations are set equal (which has been historical practice to ensure complete vertical pool drainage), the MELCOR burn package uses criteria for horizontal burn propagation.**
5.	**FLnnnFF**	**KFLSH**	**1**	**Calculate superheated pool flashing for all liquid LOCA connections to initially dry containment regions. KFLSH activates the model. Activate RN1Ikkk as needed for impact into specified heat structures.**
6.	**FLnnn02**	**IBUBF & IBUBT**	**-1** **+2**	**Vapor heat transfer in pools for RCS FLs.** **SPARC scrubbing in pools for spargers, quencher, vents, and BWR downcomers.**
7.	**RN2FLTXX00**	**FPVAPOR**	**Various geometric values**	**MELCOR SPARC pool scrubbing model was modified to scrub all gaseous RN classes for**
8.	**COR00001**	**DRGAP**	**0.0**	**Thickness of gas gap between fuel pellets and cladding set 0.0 to account for swelling of operating fuel.**
9.	**COR00001A**	**ILHTYP** **ILHTRN**	**0** **BWR =0, PWR =1**	**Lower head is a hemisphere** **Transition is at RCOR (BWR)** **or RVES (PWR)**

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Item	Record	Field	Value(s)	Description
10.	**COR00009**	**HDBPN** **HDBLH** **MDHMPO** **MDHMPM** **TPFAIL** **CDISPN**	**100 W/m^2-K** **100 W/m^2-K** **‘MODEL’** **‘MODEL’** **9999 K** **1.0**	**This record activates the internal molten pool to lower head heat transfer models and provides reasonable solid debris to lower head heat transfer coefficient.**
11.	**COR00012**	**HDBH2O** **VFALL**	**2000 W/m^2-K** **0.01 m/s**	**HTC in-vessel falling debris to pool (W/m^2-K)** **Velocity of falling debris (m/s).). Perhaps not correct for shallow pools and not necessary in deep pools since adoption of no 1-D CCFL limitation via the one-dimensional Lipinski model.**
12.	**CORCR0**	**IAICON**	**2**	**For PWRs only** **Activate control rod release model, 2 = Model is active, vaporization is allowed from both candling material and conglomerate.**
13.	**CORZjj01**	**PORDP**	**0.4**	**Porosity of particulate debris**
14.	**CORijj04**	**DHYPD**	**Core - 0.01 m** **LP - 0.002 m**	**Particulate debris equivalent diameter (LP values for DHYPD, HDBH2O, VFALL tuned to get appropriate end-of-pour debris temperature. 2mm based on FAERO fragmented debris size). Perhaps not correct for shallow pools.**
15.	**CORZjjNS**	**TNSMAX**	**1520 K** **1700 K**	**Control blades failure temperature (BWR)** **Core top guide failure temperature (BWR)**

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16.	**CORijjDX**	**FBYXSS**	**Calculated.**	**For BWRs only. Fraction of lower head COR cells normally displaced by control rod guide tubes should be 'excluded' from volume available to particulate debris. Volume recovered when tubes (as supporting structure) fails.**
17.	**SC-1131(2)**	**TRDFAI**	**2800 K**	**Fuel rod collapse temperature (addressed with CORijjFCL records)**
18.	**SC-1141 (2)**	**GAMBRK**	**0.20 kg/m-s**	**Molten Zr breakout flowrate parameter to yield 2 mm/s as evidenced in CORA experiments**
19.	**SC-1701 (1)**		**0.01**	**Open volume fraction for subnode blockage criterion. This is the default setting.**
20.	**SC-4401(3)**	**XPASMX**	**15**	**Maximum number of iterations permitted before solution is repeated with a decreased (subcycle) timestep.**
21.	**DCHNEMnn00**	**ELMNAM** **ELMMAS**	**Use ORIGEN results for core, if available.**	**Elemental fission product mass at shutdown for calculation of decay heat.**

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22.	**DCHNEMnnmm**	**DCHEAT**	**Use pre-combined methodology for Cs, I, and Mo**	**Elemental fission product decay heat per unit mass (based on shutdown RN inventory).** **•Define specific decay heat for CsI (Class 16) as 0.51155 of value for Class 2 (Cs) plus 0.48845 of value for Class 4 (I).** **•Define specific decay heat for Cs_2MoO_4 (Class 17) as 0.7348 of value for Class 2 (Cs) plus 0.2652 of value for Class 7 (Mo).** **If ORIGEN results are not available for the core, perform an input deck with BE burn-up and cycle history. Redistribute RN mass as follows,** **•Class 2 initial mass represents the NUREG-1465 Cs gap mass not already included in Class 16.** **•Class 4 initial mass is empty (10^{-6} kg)** **•Class 7 initial mass is remaining Mo mass not included in Class 17.** **•Class 16 has all I and an appropriate amount of Cs mass for CsI stoichiometry.** **•Class 17 has the remaining Cs not included in Classes 2 and 16 plus Mo for Cs_2MoO_4 stoichiometry.**
23.	**DCHCLSnnn0,** **DCHCLSnnnm**	**RDCNAM,** **CLSELM**	**New RN definitions for Classes 1-12, 16-18**	**If ORIGEN results are available, synthesize ORIGEN data to define a single representative element for each class with decay heat data that reflects decay heat for all elements within the class (DCHNEMxxxx input.) Redefine each class to include only the representative element.**

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Item	Record	Field	Value(s)	Description
24.	**DCHDEFCLS0**	**DEFCLS**	**13, 14, 15**	**Specifies that MELCOR DCH default classes are to be used.**
25.	**DCHCLNORM**	**CLSNRM**	**'No' when ORIGEN results are available.** **'Yes' when MELCOR is used to estimate initial inventories.**	**New ORIGEN input for elements/classes defines the total core decay heat.** **Otherwise, let MELCOR normalize the elemental decay heats to the rated power.** **Do not use RN1DCHNORM. Default behavior normalizes Class 10 (Uranium).**
26.	**HSccccc400 &** **HSccccc600**	**CPFPL** **CPFAL**	**See discussion**	**Minimum value of CVH pool fraction such that heat transfer is calculated to Pool/Atmosphere. For heat structures within the RPV, use 0.9. For PWR SG Tubes, use 0.1. All other structures modeled use default value of 0.5.**
27.	**HSccccc401** **HSccccc601**	**EMISWL** **RMODL** **PATHL**	**0.27** **EQUIV-BAND** **0.1 m**	**Mean emissivity of SS type 316** **Equivalent band radiation model.** **Nominal optical distance in steam (m).** **For SS heat structures within the reactor vessel and those being monitored for creep-rupture failure.**
28.	**HSDGccccc0**	**ISRCHS** **ISDIST** **GASNAM**	**HS #** **1** **SS**	**Heat structure for application of degas model.** **Degassing model requires 1 mesh.** **Name of released gas.** **For SS boundary structures modeled with the HS package that are coupled to the core.**

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29.	**HSDGccccc1**	**RHOSRC** **HTRSRC** **TEMPL** **TEMPU**	**7930 kg/m^3** **2.68x10^5 J/kg** **1695 K** **1705 K**	**Gas source density.** **Gas source heat of reaction.** **Lower temperature for degassing.** **Upper temperature for degassing.** **For SS boundary structures modeled with the HS package that are coupled to the core.**
30.	**MPMATxxxx**	**MLT**	**2800 K** **2800 K**	**Uranium-dioxide** **Zirconium-oxide** **Because of the interactions between materials, liquefaction can occur at temperatures significantly below the melt point. The interaction between ZrO_2 and UO_2 results in a mixture that is fluid at above about 2800 K (compared to the melting temperatures of 3113 K and 2990 K, respectively, for the pure materials). Similarly, although pure B4C melts at 2620 K, interaction with steel produces a mixture that is fluid at above about 1700 K.**
31.	**RN1001**	**NUMSEC** **NUMCMP** **NUMCLS**	**10** **2** **20 (PWR)** **18 (BWR)**	**Default** **Default** **For BWR & PWR: 16 = CsI, 17 = Cs_2MoO_4** **Now Class 17 includes default settings for Cs_2MoO_4.**

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32.	**BWR structural tin release RN/DCH data for RN Class 18**			**For BWR: RN Class 18 = SnO_2 (non-radioactive)** **<u>Define SnO_2 (DCHCLSnnn0)</u>** **18 = 'SnO2'** **<u>SnO_2 decay heats (DCHNEMnn00)</u>** **0 W/kg (no decay heat)** **<u>SC(7110) vapor pressures</u>** **SnO_2: $\log_{10}$(P(mm Hg)) = 15400/T + 8.15** **<u>SC(7111) diffusion coefficients</u>** **SnO_2: Sigma = 3.617, E/K = 97** **<u>SC(7120) elem./compound molecular weights</u>** **Sn: MW = 150.7 kg/kg-mole**

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33.	**PWR control rod RN data for RN Classes 18, 19, and 20**			**For PWR RN Class 18 = Ag, 19 = In, 20 = Cd** **<u>Define Ag, In, Cd (DCHCLSnnn0)</u>** **18 = ‘Ag-CR’, 19 = ‘In-CR’, 20 = ‘Cd-CR’** **<u>Ag, In, Cd decay heats (DCHNEMnn00)</u>** **0 W/kg (no decay heat)** **<u>SC(7110) vapor pressures</u>** **Ag: $\log_{10}$(P(mm Hg)) = 1000/T + 1.26×10^4 + 7.989** **In: $\log_{10}$(P(mm Hg)) = 400/T + 1.27×10^5 + 8.284** **Cd: $\log_{10}$(P(mm Hg)) = 500/T + 5.31×10^3 + 7.99** **<u>SC(7111) diffusion coefficients</u>** **Ag: Sigma = 3.48, E/K = 1300** **In: Sigma = 3.61, E/K = 2160** **Cd: Sigma = 3.46, E/K = 1760** **<u>SC(7120) elem./compound molecular weights</u>** **Ag: MW = 107.8 kg/kg-mole** **In: MW = 114.8 kg/kg-mole** **Cd: MW = 112.4 kg/kg-mole**
34.	**RNCA100**	**ICAON**	**1 (Active)**	**Chemisorption model is active (default).**
35.	**RN1002**	**IHYGRO**	**1 (Active)**	**Hygroscopic model activation. (RNACOND set to default, 0 = condensation of water onto all aerosols.)**

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36.	**RNCRCLxx** **SC7100**	**ICRMT / ICLSS / FRAC** **(2) Zr** **(3) ZrO2** **(4) steel** **(5) steel ox.** **(6) B4C**	**2 / 18 / 0.0145** **3 / 18 / 0.0145** **0.1** **1.0** **0.0** **0.0** **0.0**	**For BWRs, apply the non-fuel release model. Assign aerosol generated from Zr and ZrO$_2$ to RN Class 18 (SnO$_2$). The mass will be added as a non-radioactive mass to this class. The fraction of material mass available for release as an aerosol from these materials is 0.0145 (Sn fraction in Zirc-2 and -4.)** **Note: must also add input for the release rate (SC7103) for RN Class 18. Values should be identical to those used (default) for Class 12 (fission product Sn).** **Multipliers for various structural material types**
37.	**RNFPNijjXX**	**NINP** **RINP1** **RINP2**	**Use ORIGEN results, if available.**	**NINP = RN Class, RINP1 = mass, RINP2 = axial peaking factor. Distributes mass based on distribution developed with ORIGEN.** **If ORIGEN results are unavailable, NINP = 0, RINP1 = axial peaking factor, RINP1 = radial peaking factor. Where,** **$\Sigma_i\Sigma_j$ RINP1 * RINP2 = 1.**

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38.	**RNGAPijjnn**	**NINP** **RINP1** **RINP2**	**1 (Xe) = 0.05** **2 (Cs) = 1.00** **3 (Ba) = 0.01** **5 (Te) = 0.05** **16 (CsI) = 0.05**	**Where, NUREG-1465 recommends the following gap quantities,** **•Xe = 5%** **•Cs = 5%** **•Ba = 1%** **•Te = 5%**
39.	**RN2FLTXX00**	**FPVAPOR**	**Various geometric values**	**For all flow paths entering pools via quenchers or spargers, specify the flow path to scrub all gaseous RN classes.**