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UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

RECENT APPLICATIONS OF MELCOR

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Second European MELCOR User Group Meeting
Prague, Czech Republic
March 1, 2010

OUTLINE

- Application of MELCOR to Design Certification for New Reactors
- Development of MELCOR Fission Product Release Models for Gas Cooled Reactors
- Application of MELCOR to Evaluation of System Success Criteria
- Development and Application of MELCOR Accident Simulation Using SNAP

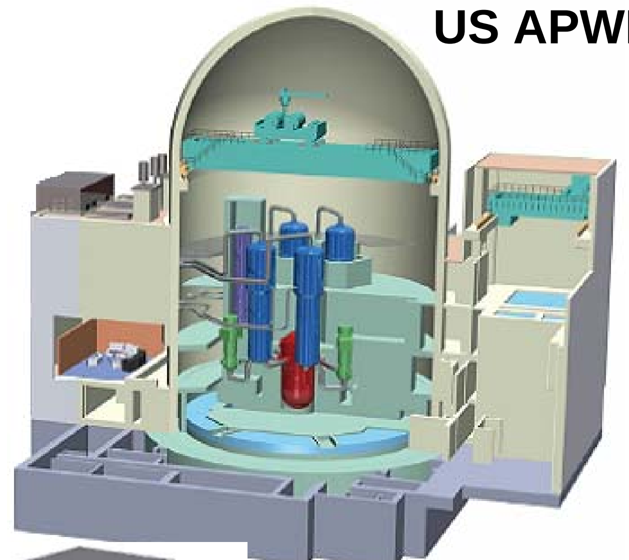
Applications of MELCOR

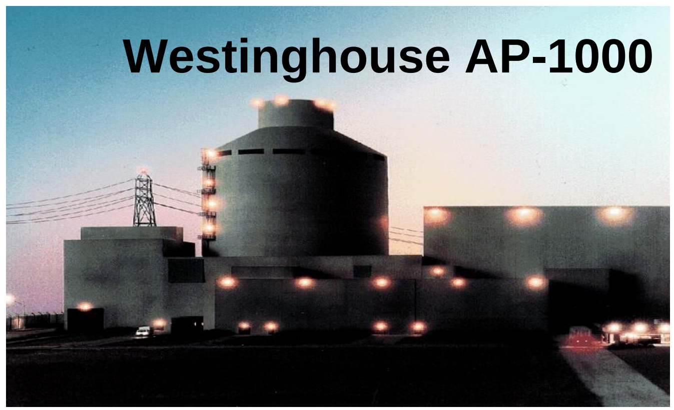
APPLICATION OF MELCOR TO DESIGN CERTIFICATION OF NEW REACTORS

Design Certification

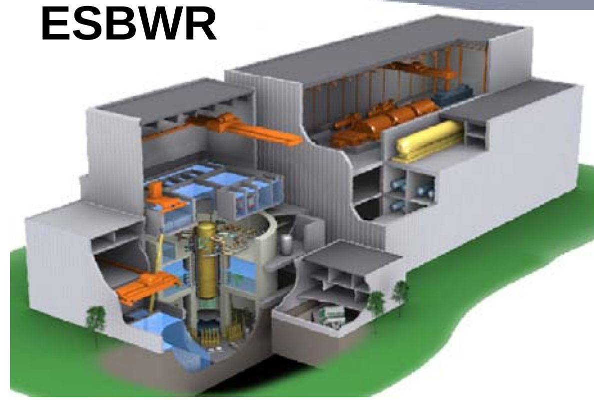
- Severe accident response and source term
- Containment response to design basis accident

US APWR





ESBWR



Design Certification

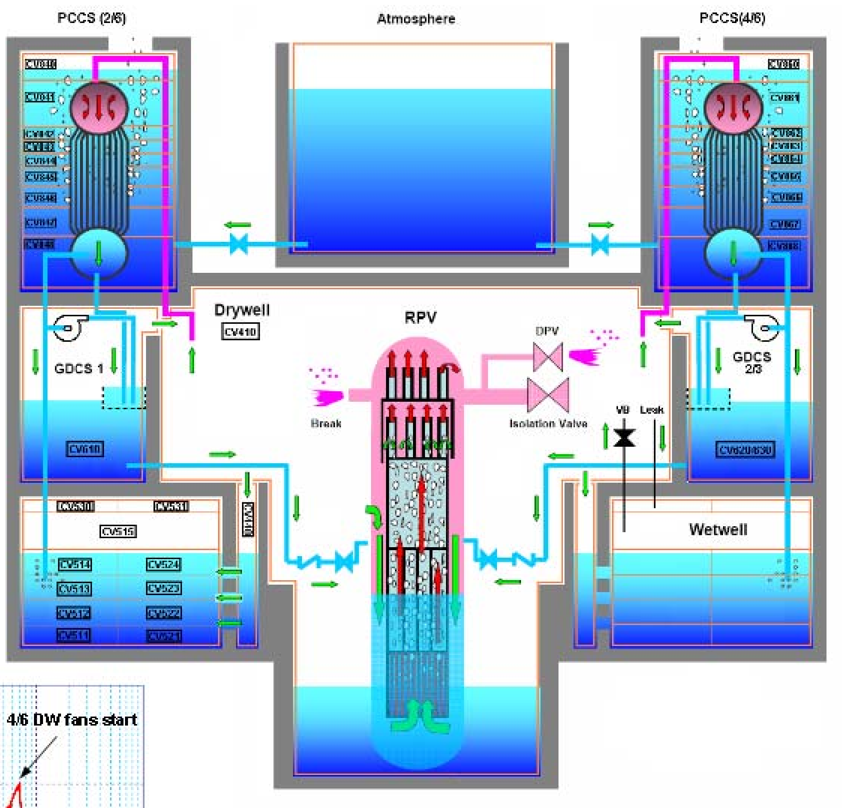
ESBWR Long Term Cooling

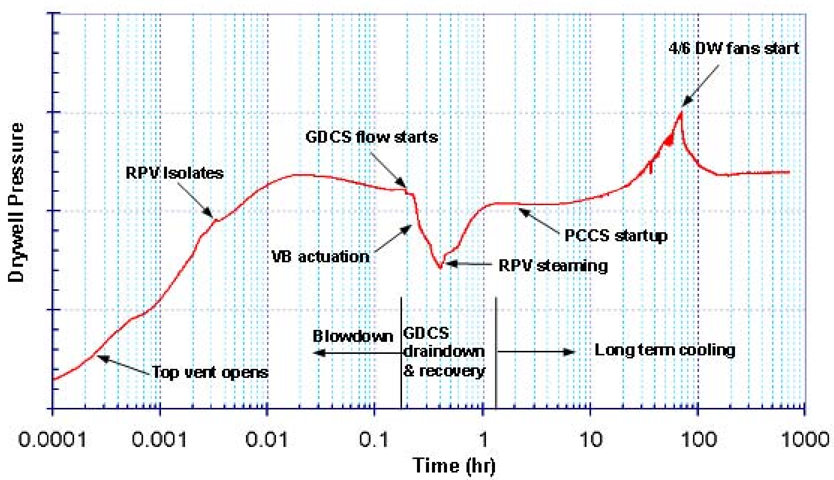
First 3 days (Passive Period)

Dominant phenomena include core radiolysis causing PCCS non-condensible gas bounding and bypass leakage of steam from drywell to wetwell

Post 3 days (Intervention Period)

- Drywell recirculation fans
- PCCS pool refill
- PARs credited





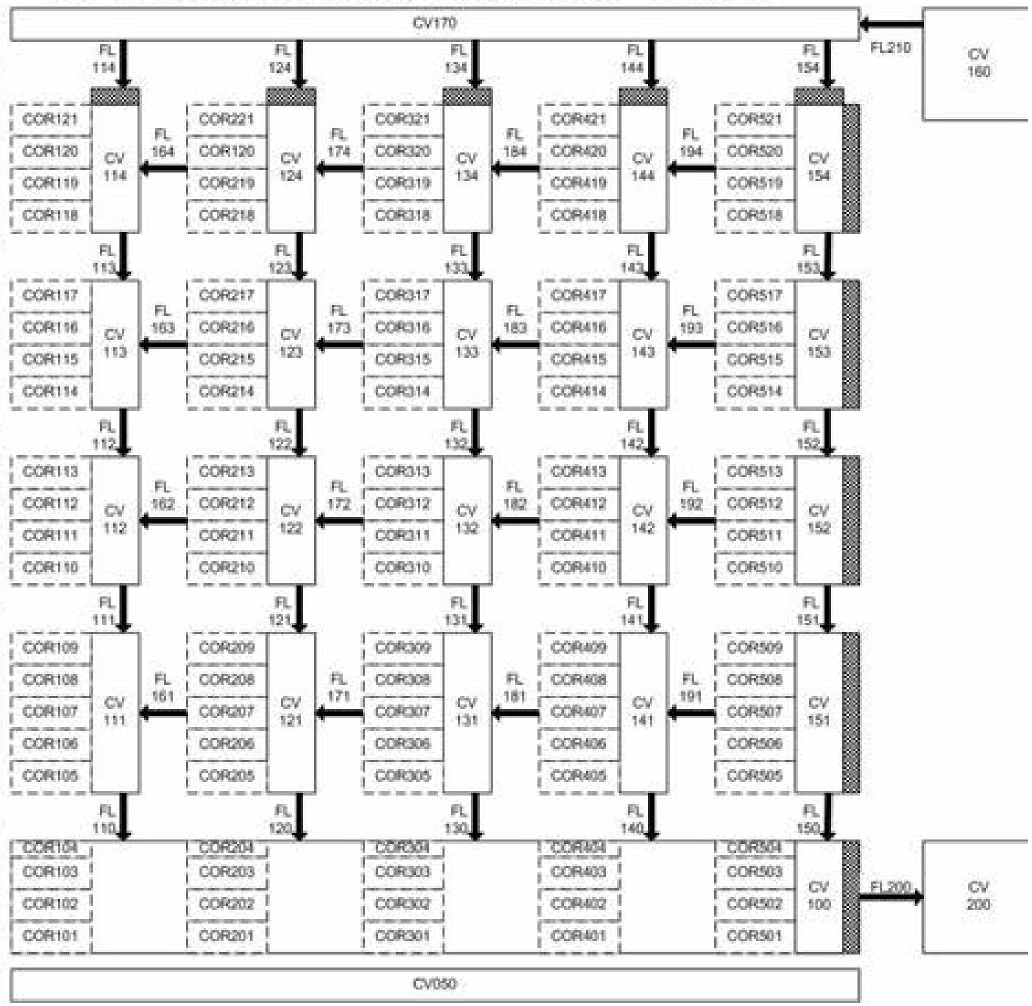
MELCOR FISSION PRODUCT MODELING APPROACH FOR HTGR

HTGR FP Release Objectives

- Develop HTGR specific fission product release and transport models for MELCOR
  - Use existing MELCOR models for fission product transport and deposition in the primary system and containment
  - Implement diffusional release models for both intact and failed TRISO fuel particles
  - Implement diffusional release model for matrix and graphite block
  - Applicable to both pebble bed and prismatic designs
  - Calculate releases for both normal operation and accident conditions
- Basic approach similar to LWRs
  - Code used for confirmatory (audit) calculations

HTGR Core Nodalization

- Detailed Core Nodalization for PMR/PBR
- Allow use of MELCOR fuel/clad components to represent HTGR fuel
- Fuel radial temperature profile provides peak and surface temperature

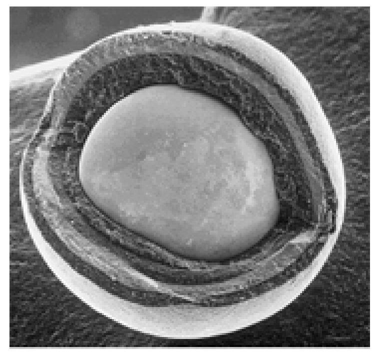


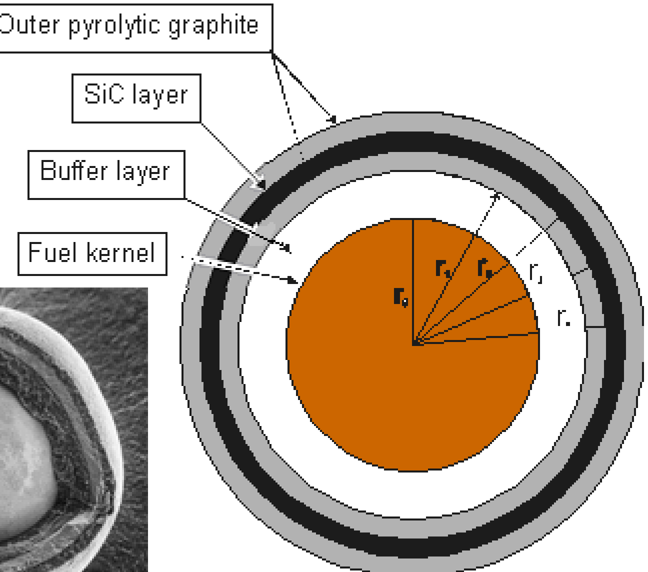
HTGR Required Input/Output

Input	Source	Output
FP inventory	ORIGEN output, Vendor	(1) Thermal hydraulic response of the primary system (core components and fluid temperatures) (2) Thermal hydraulic response of the confinement (temperature, pressures, release paths, etc.) (3) FP and dust distribution during normal operation (4) In-containment source term during accidents (**input to DBA source term analysis and for consequence analysis**)
FP diffusion coefficients	Experiments (e.g., TECDOC-978)	
Core power shape	Radial/Axial profiles (vendor, PARCS)	
Fuel particle failure rate response surface (function of temperature and burnup)	Experiments/other codes (e.g., PARFUME)	
Dust generation, lift-off, and FP adsorption on dust (impact of aerosol growth, shape factor, etc.)	Experiments & Historical data (MELCOR has models for aerosol dynamics, FP condensation/evaporation from aerosols/structures – need a lift-off model)	
FP release under accident conditions including air/water ingress	Experiments (to tune model)	
FP speciation and interaction with graphite and other structures	Experiments (to tune model) (MELCOR has models for FP chemistry including adsroption, chemisorption)	

TRISO Particle FP Release

- FP release from kernel involves both diffusion and recoil
- For failed particles, release from kernel
- For intact particles, release is controlled by SiC layer





$$\frac{\partial C}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial C}{\partial r}\right) - \lambda C + \beta$$

$$\frac{\partial C}{\partial r} = 0\,;\,(r = 0)$$

$$C = 0\,;\,(r = R)$$

C = Concentration ($1/m^3$)
D = Diffusion coefficient (m^2/s)
λ = Decay constant (1/s)
β = Generation rate ($1/m^3$-s)

Kernel generation ~ yield x power
Buffer generation due to recoil $\propto$ kernel generation

Fission Product Tracking

$$^{133}Xe \xrightarrow[5.29\,da]{\beta-} {}^{133}Cs$$

$$^{85}Kr \xrightarrow[10.7\,yr]{\beta-} {}^{85}Rb$$

$$^{137}Cs \xrightarrow[30.1\,yr]{\beta-} {}^{137}Ba$$

$$^{90}Sr \xrightarrow[28.9\,yr]{\beta-} {}^{90}Y \xrightarrow[64\,hr]{\beta-} {}^{90}Zr$$

$$^{110}Ag \xrightarrow[252\,da]{\beta-} {}^{110}Cd$$

$$^{131}I \xrightarrow[8.04\,da]{\beta-} {}^{131}Xe$$

- MELCOR lumps elements into radionuclide classes
- Additional classes will be defined to track individual isotopes of interest for gas reactors

FP Diffusion in TRISO Particles

$$D(T) = D_o e^{-Q/RT}$$

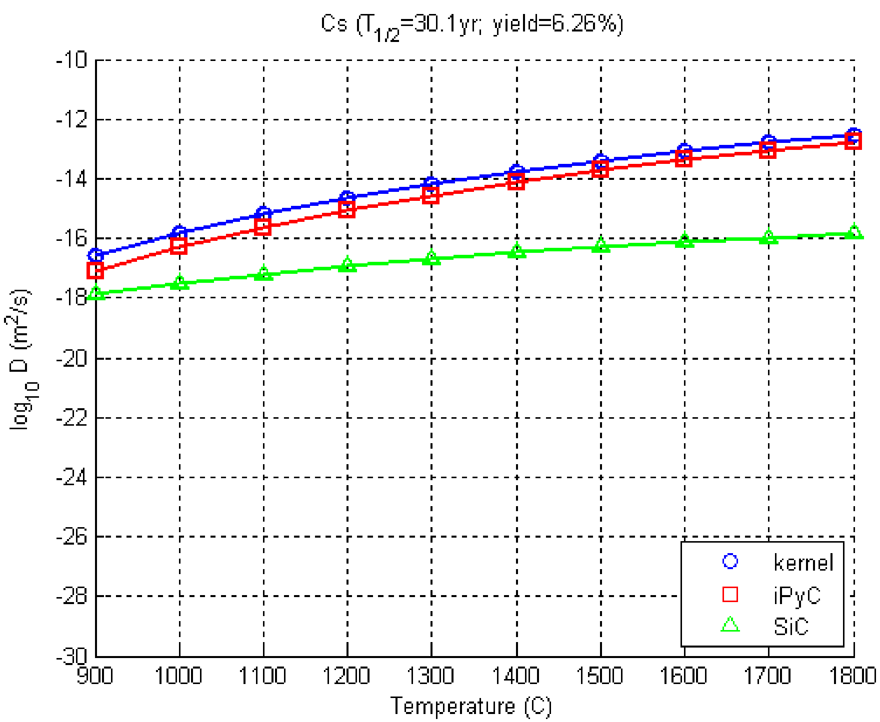
Diffusion coefficient (m^2/s)

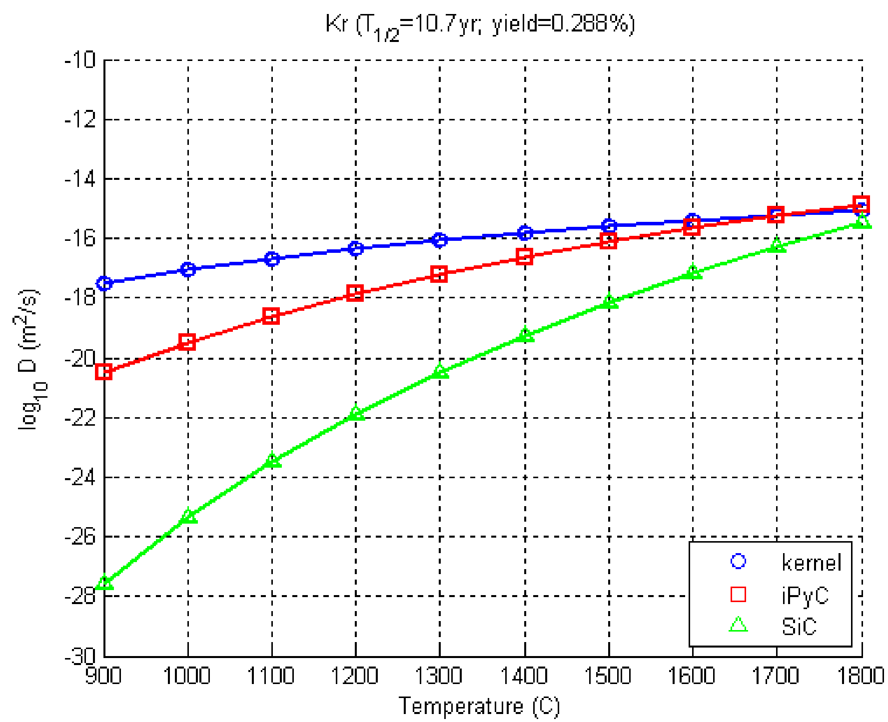
pre-exponential factor

Activation energy

Gas constant

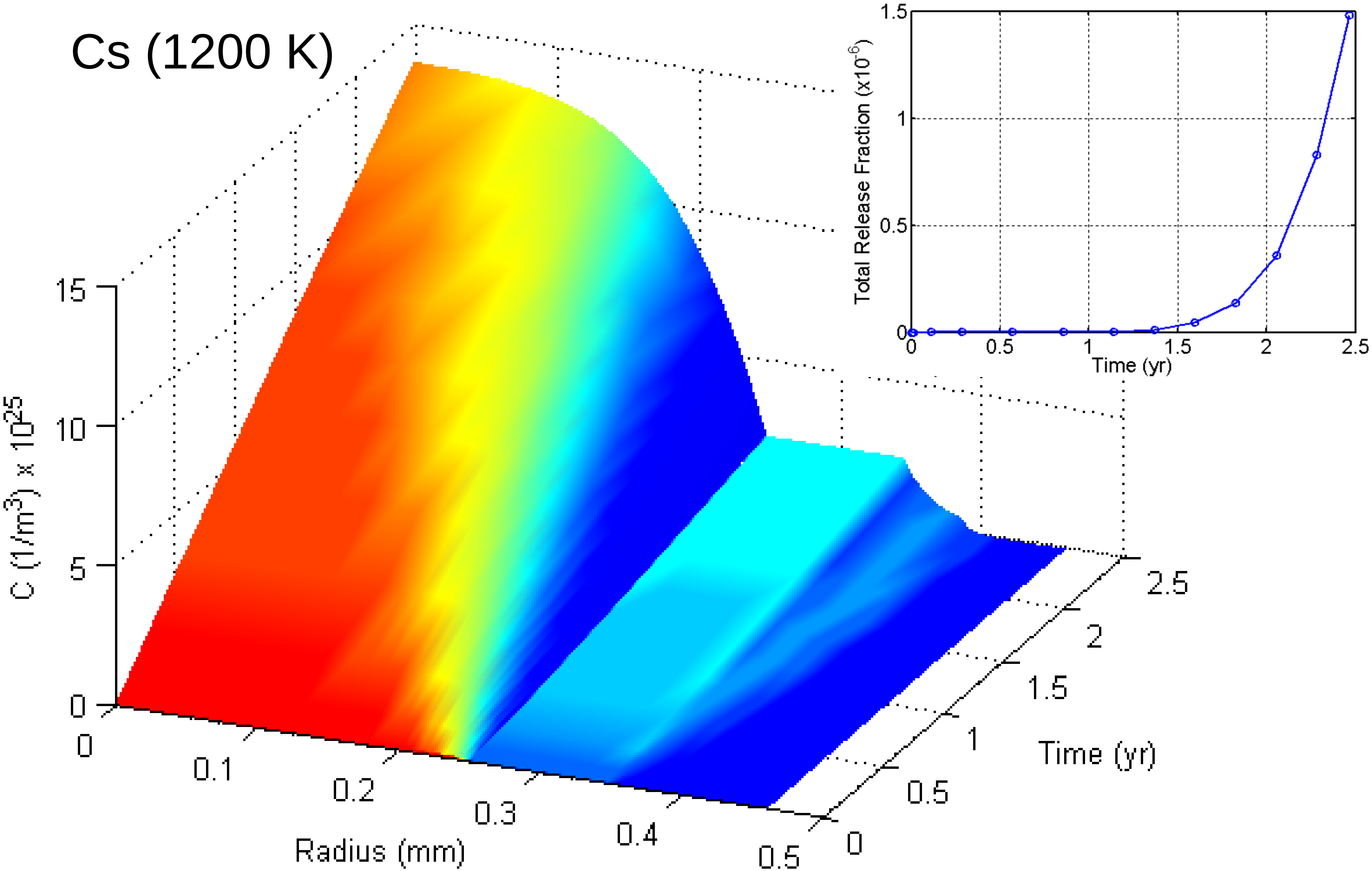
Temperature





Intact TRISO Particles

Cs (1200 K)



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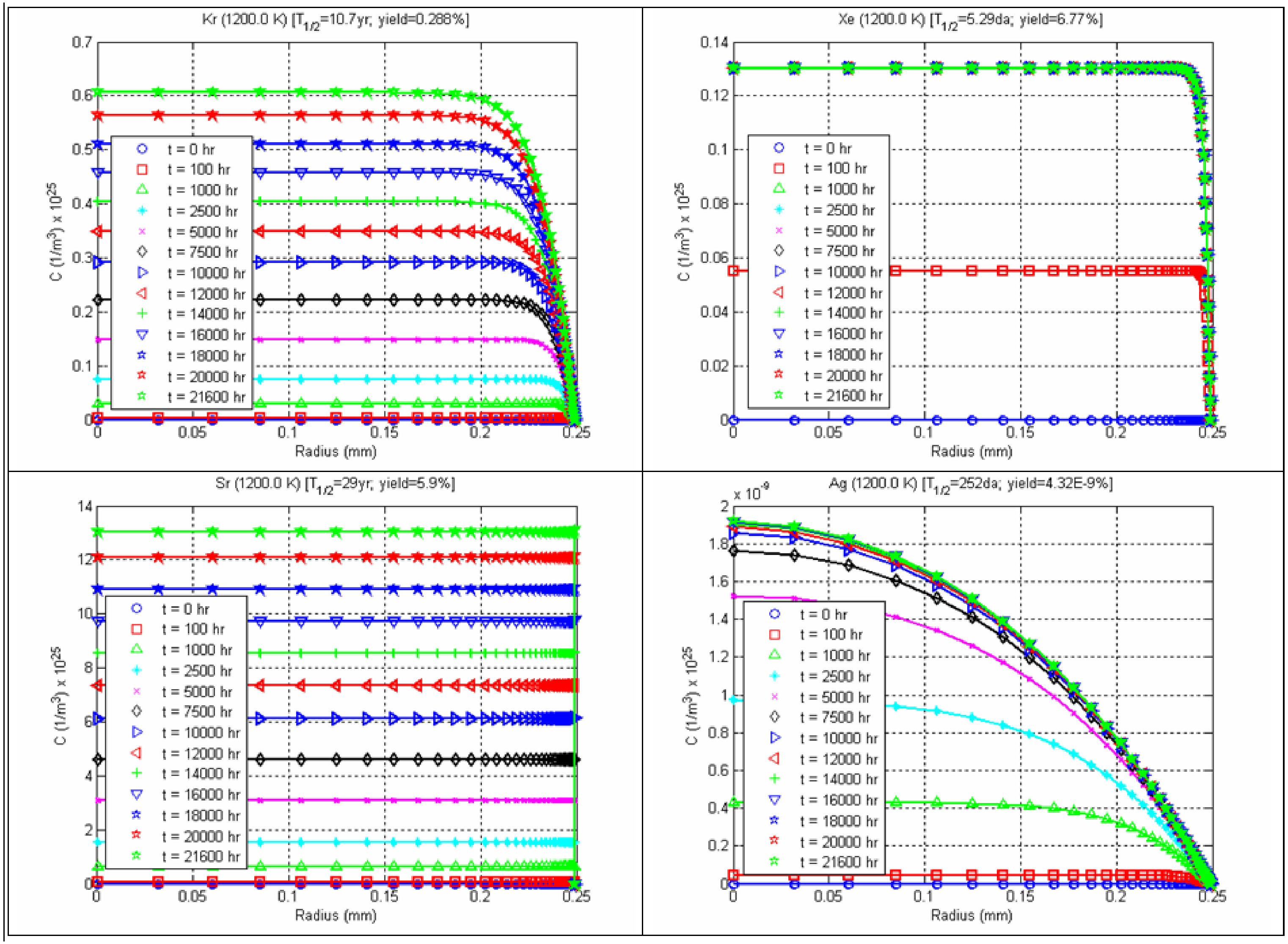
Failed TRISO Particles



FP Release to Primary System

Solve the diffusion equation in the pebble (PBR) and fuel compact and graphite block (PMR)

$$\frac{\partial C}{\partial t}=\frac{1}{r^m}\frac{\partial}{\partial r}\left(r^m D\frac{\partial C}{\partial r}\right)-\lambda C+S$$

$$m=1\ \ (cylindrical)$$
$$m=2\ \ (spherical)$$

C = Concentration (1/m^3)
D = Diffusion coefficient (m^2/s)
λ = Decay constant (1/s)
S = Source term (1/m^3-s)

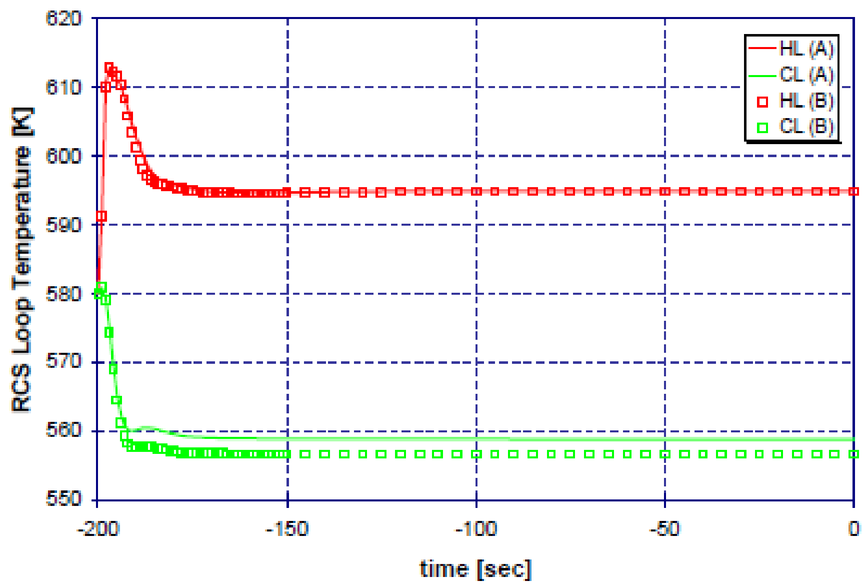
S (fuel compact or pebble) = Release from particles and U contamination

MELCOR Steady State

- Perform “Accelerated” Steady State Run with MELCOR to Get FP and Dust Distribution in the System
  - Dust and FP release during normal operation
  - Use existing models in MELCOR for FP transport and deposition on surfaces
  - Need to be run long enough to establish trends and/or equilibrium
  - Scale to desired operating time
  - Use as initial condition for accident analysis

Steady State Step 1

- Establish Thermal Steady State
  - Reduce heat capacities for core and heat structure components (reset to actual values after steady state)
  - Output is core cell component temperatures required for diffusion calculation
  - Approach is similar to LWRs



Steady State Step 2

- Solve Diffusion Equation
  - Solve the diffusion equation using core cell component temperatures (temperature dependent diffusion coefficients)
  - Finite difference solver (DIF2) integrated into MELCOR as a subroutine
  - Track both intact and initially failed particles
  - Output of the diffusion calculation is spatial distribution in the particles (kernel/buffer), graphite, and relative amounts released to the primary system (for each isotope from each core cell)
  - FP distribution and release rates are ultimately scaled using ORIGEN results for burnup (more accurate in terms of actual isotope inventory)

Steady State Step 3

- FP/Dust Distribution in Primary System
  - MELCOR run for some problem time to establish distribution rates and patterns in the primary system (input is release to the coolant from step 2)
  - Dust deposition is also done at this stage (no model available at this time – for now parametric in MELCOR)

Failed Particle (kernel) Release

- General solution to the diffusion equation in an equivalent sphere after irradiation with time-dependent diffusion coefficient

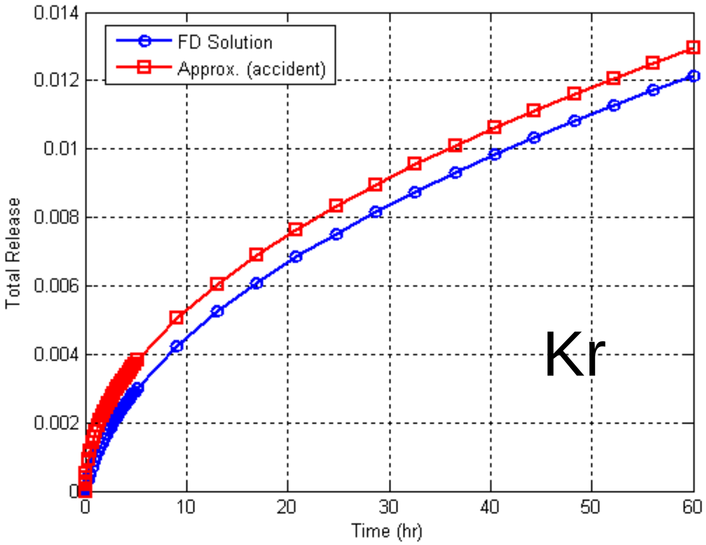
$$F(t) = 6\sum_{n=1}^{\infty} \int_0^t \exp\left[- \left(n^2\pi^2 \int_0^{\mu} D'(t')dt' + \lambda \mu \right) \right] D'(\mu)d\mu$$

$F(t)$	= Fractional release of fission product up to time t
$D'(t)$	= Reduced diffusion coefficient = $\frac{D(t)}{a^2}$
a	= Radius of equivalent sphere (m)

- Short term approximation (Booth solution)

$$F(t) = \frac{3D'}{\lambda}\left(e^{-\lambda t} - 1 + \sqrt{\frac{\lambda}{D'}} erf\sqrt{\lambda t} \right) \xrightarrow[\lambda = 0]{} F(t) = 6\sqrt{\frac{D't}{\pi}} - 3D't$$

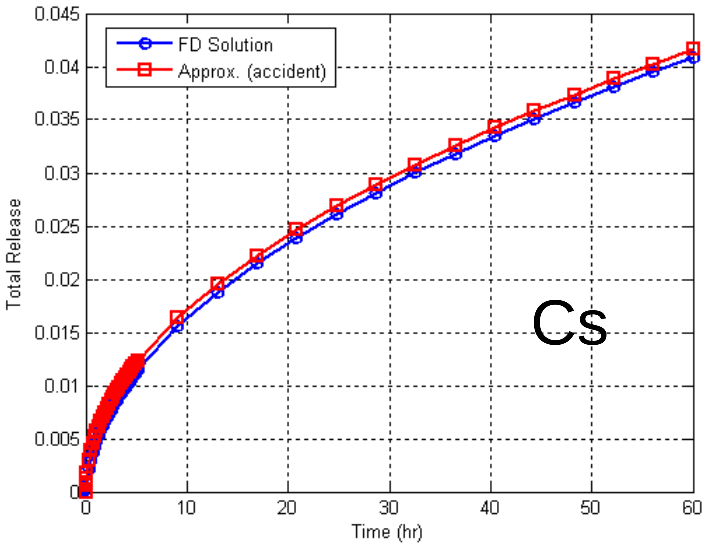
Failed Particle (kernel) Release

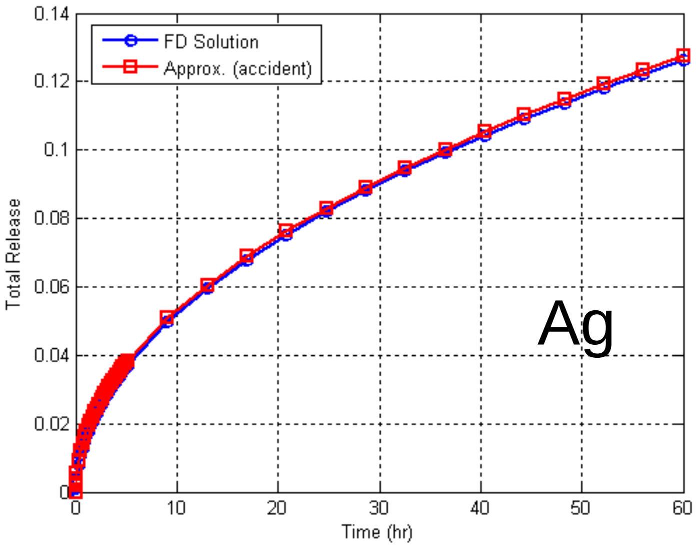


Analytic models provide reasonable agreement with more detailed finite difference solutions over transient times of interest

Easier to adjust the parameters as more experimental data become available (e.g., Booth model parameters for LWRs)

Easier to implement in combination with particle failure rate (see next slide)





TRISO Particle Failure

- Particles fail at different times during accident
- Convolution integral of release rate and failure rate

$$F_{tot}(t) = \int_0^t \frac{dF_W(\tau)}{d\tau} F_R(t-\tau)d\tau$$

- $F_W(t)$ is failure fraction at time t
- $F_R(t-\tau)$ is release fraction from a particle at time t due to failure at τ

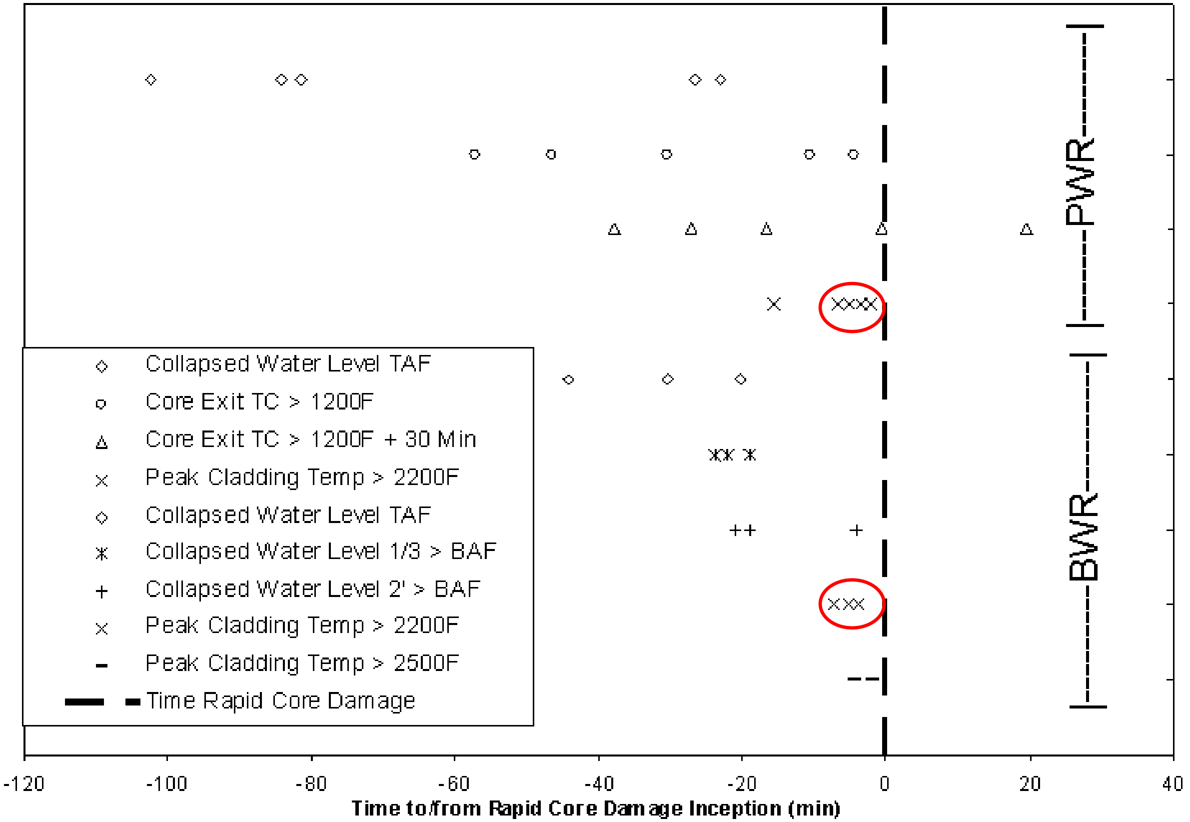
Evaluation of System Success Criteria

Success Criteria Application

- Staff has begun using MELCOR to investigate a limited set of PRA success criteria issues
- Use MELCOR for Thermal-Hydraulic Analysis
  - Surry (PWR) and Peach Bottom (BWR) models from State-of-the-art Reactor Consequence Analysis (SOARCA)
  - Definition of core damage
  - Code calculations for various scenarios to define success criteria
- Collaborative Effort
  - Project Management: Don Helton (NRC/RES/DRA)
  - Calculation Matrix: Don Dube (NRC/NRO), Rick Sherry (retired), et al.
  - Systems Analysis Support: Don Marksberry (NRC/RES/DRA), Bob Buell (INL)
  - MELCOR Analysis: Hossein Esmaili (NRC/RES/DSA)
  - SPAR Model: Pete Appignani (NRC/RES/DRA), Bob Buell (INL)

Core Damage Definition

- MELCOR analyses performed to look at various core damage surrogates
  - 2200 F (1204 C) selected based on a number of calculations for a PWR and a BWR
- Additional surrogate comparisons planned in 2010



Thermal-Hydraulic Analysis

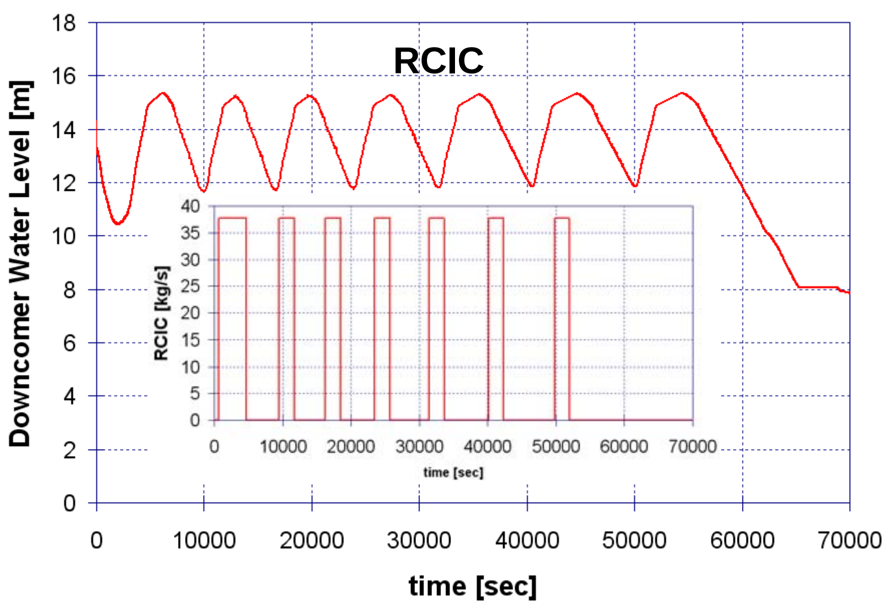
- Detailed SOARCA MELCOR 1.8.6 models for Surry and Peach Bottom used
- Many calculations intentionally assume minimal operator action and are allowed to proceed to core damage to:
  - Establish minimal equipment configurations
  - Establish timings for human error probability (HEP) evaluations
- Results are documented in an August 2009 report available in the NRC's Agencywide Document Accession and Management System (ADAMS) at accession number ML091890792
- Analyses are confirmatory in nature:
  - Detailed and insightful, but should not be viewed as licensing calculations

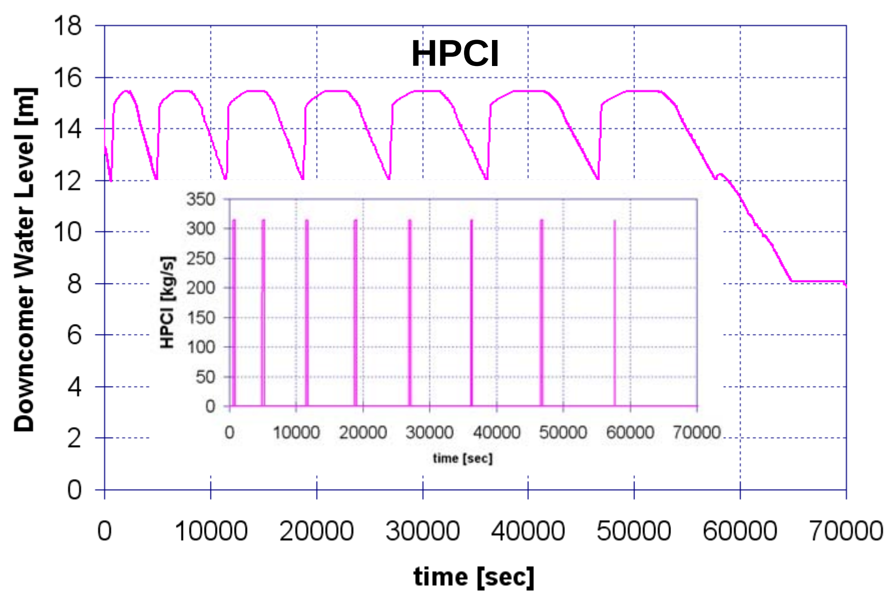
Surry Calculation Matrix

- Small LOCA dependency on sump recirculation
  - Effect of sprays on RWST depletion
  - Does the system depressurize (and how fast)?
- Feed & Bleed PORV success criteria
  - Combination of HHSI and PORVs
- Steam Generator Tube Rupture
  - Multiple tube ruptures
  - Impact of secondary cooling, HHSI, forced cooldown
- Station blackout
  - Investigating time available for A/C power recovery
  - Both small and large RCP leaks with and without TD-AFW
- Accumulator injection
  - Spectrum of LOCA sizes
  - Availability of HHSI/LHSI in conjunction with number of accumulators

Peach Bottom Calculation Matrix

- SRV/RCIC
  - Can RCIC maintain cooling until low pressure system injects?
- Station blackout (RCIC/HPCI availability)
  - Investigating time available for A/C power recovery
  - Suppression pool heatup and pump NPSH limit



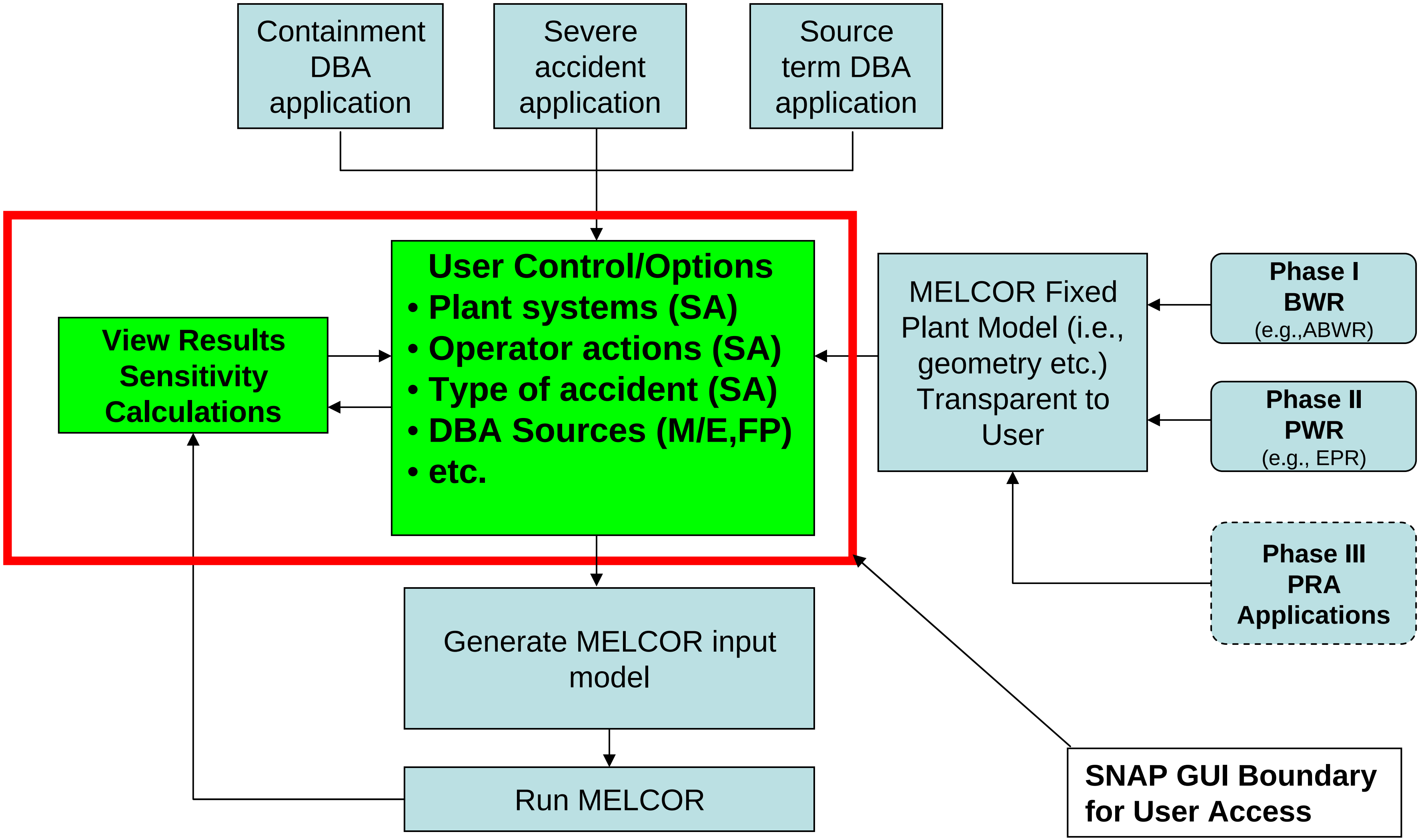


Success Criteria Summary

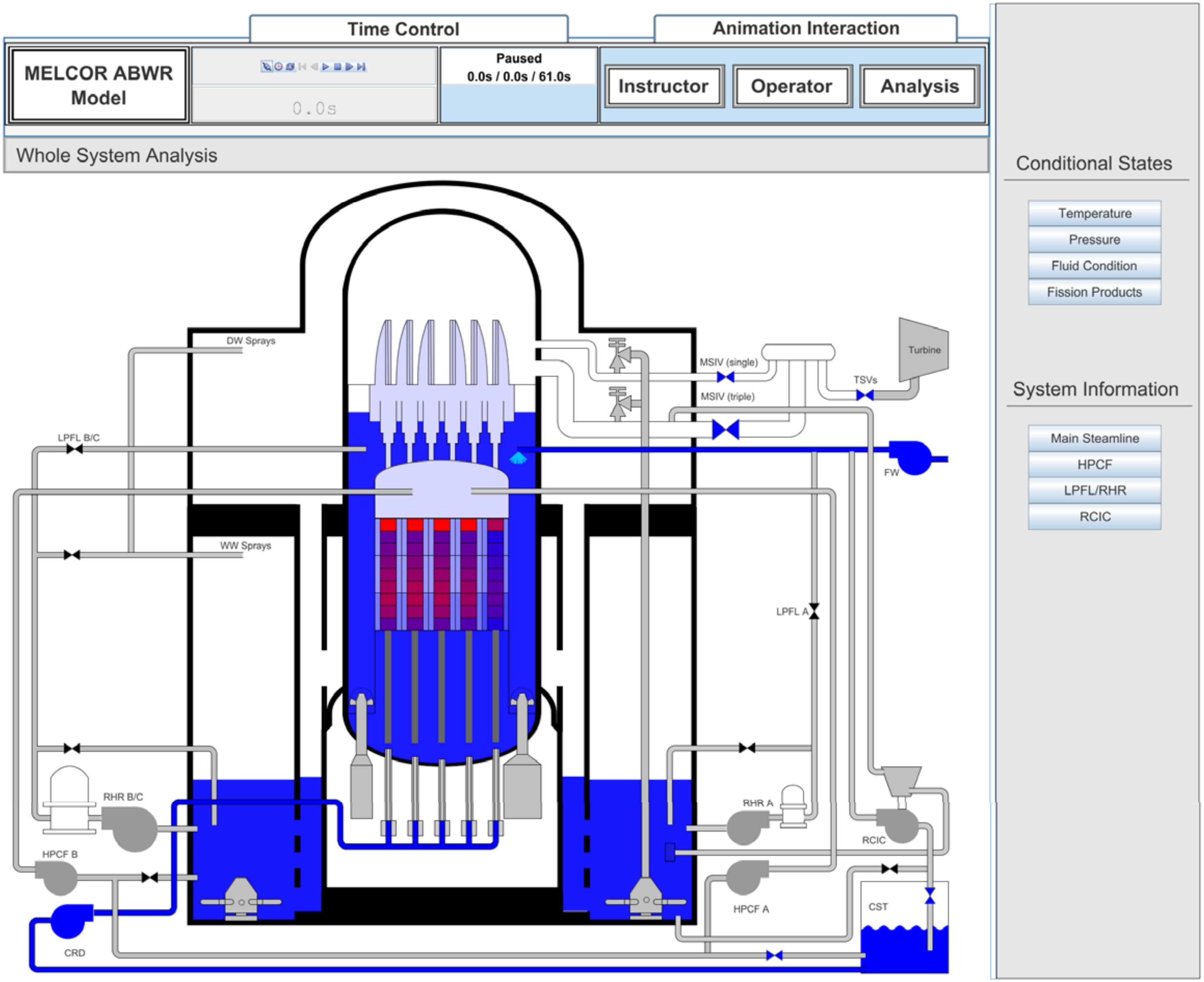
- Application of MELCOR to update basis for PRA treatment of specific operator timing and mitigation system effectiveness issues of interest
- Work underway to establish basis for SPAR model changes
- Work recently commenced at SNL to look at additional aspects (e.g., core damage surrogates)
- Extension to other plants (e.g., 4-loop large, dry)
- Possible future interactions with industry

MELCOR ACCIDENT SIMULATION USING SNAP (MASS)

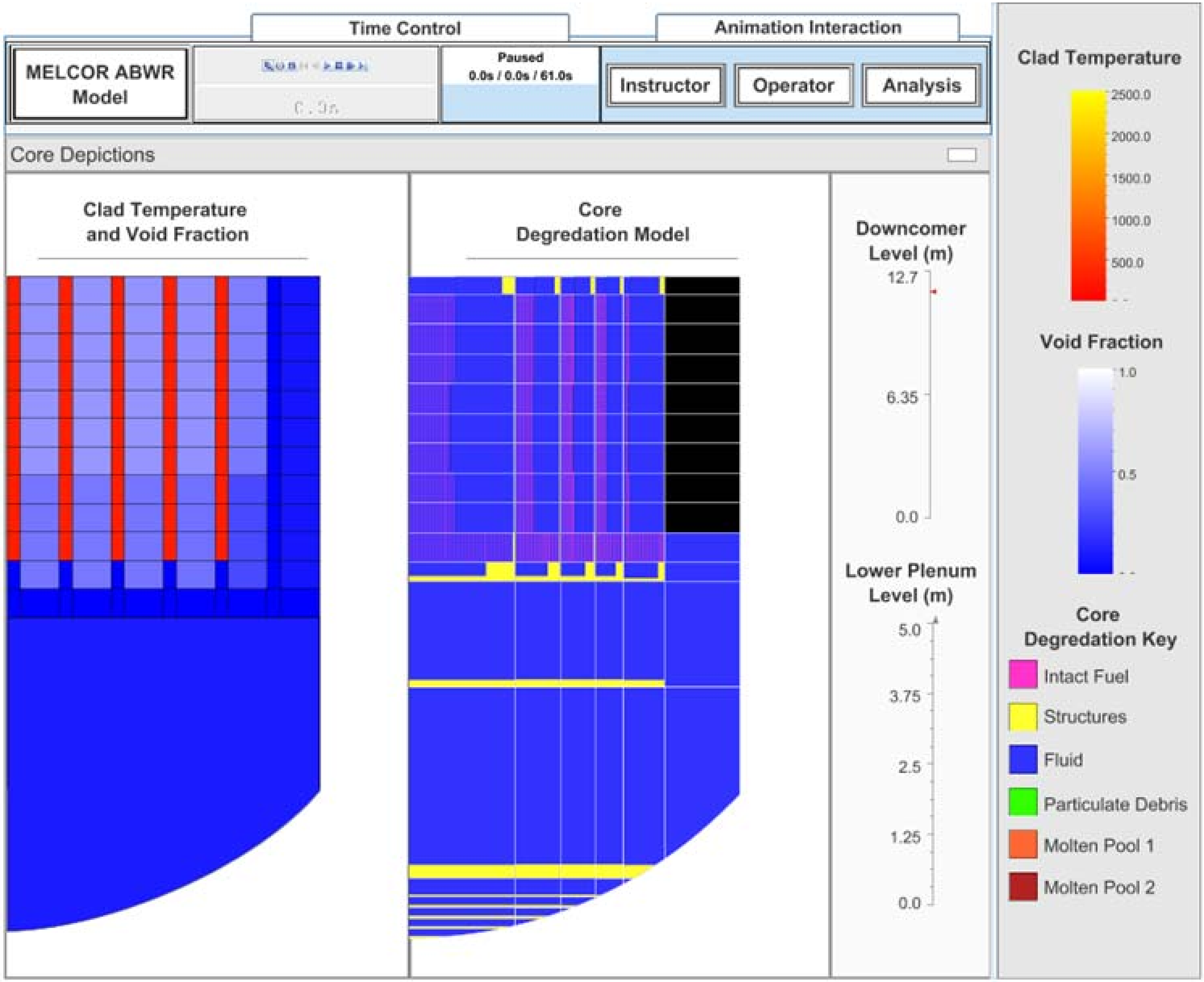
Design Concept



Accident Simulation Using SNAP



Accident Simulation Using SNAP



Accident Simulation Using SNAP