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Postclosure Transient Criticality Analysis for a Dual-Purpose Canister

Fuel Storage, Transportation, and Disposal: I

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Objective

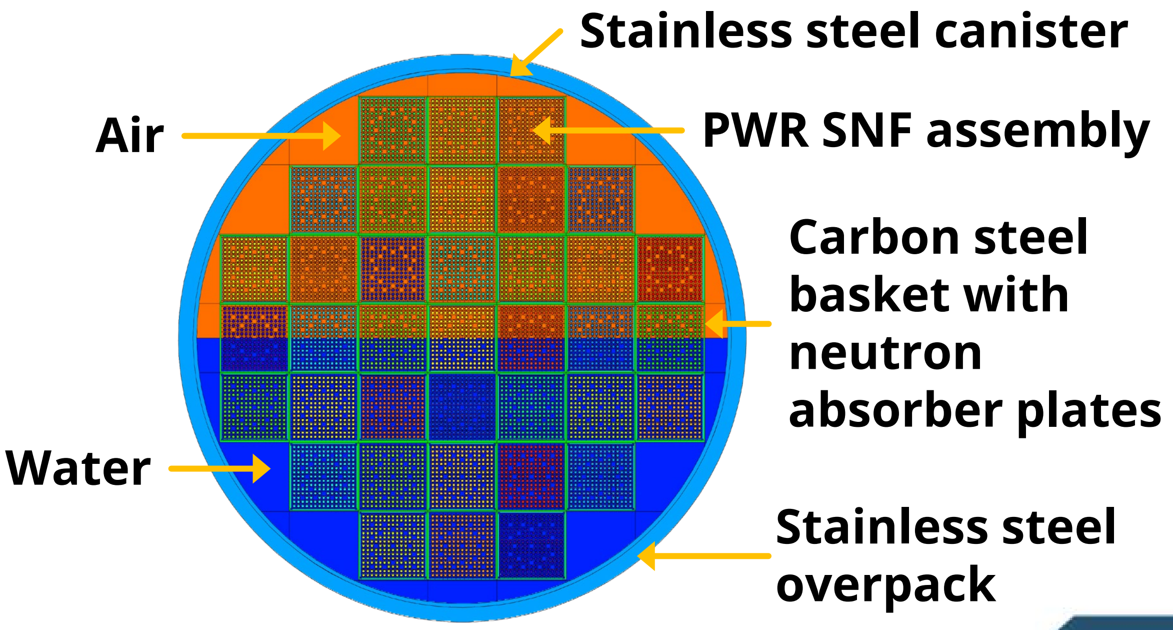
Evaluate the behavior of potential transient criticality events in a Dual-Purpose Canister (DPC) disposed in an unsaturated repository to further the understanding of neutronic, kinetic, and thermal hydraulic characteristics that could be used in evaluating the extent of potential adverse impacts on repository performance.

Methodology

- A reactor kinetics calculation with the RAZORBACK code (D. Talley, 2017) can illuminate the pulse characteristics given the thermal properties of the spent nuclear fuel and infiltrated water along with the reactivity insertion characteristics.
- For unsaturated alluvium, the evolution of reactivity as water infiltrates a breached canister and degrades neutron absorbers is investigated as a necessary precursor to the kinetics analysis.
- Reactivity insertion is modeled via a series of a steady-state calculations with MCNP (T. Goorley, 2014).

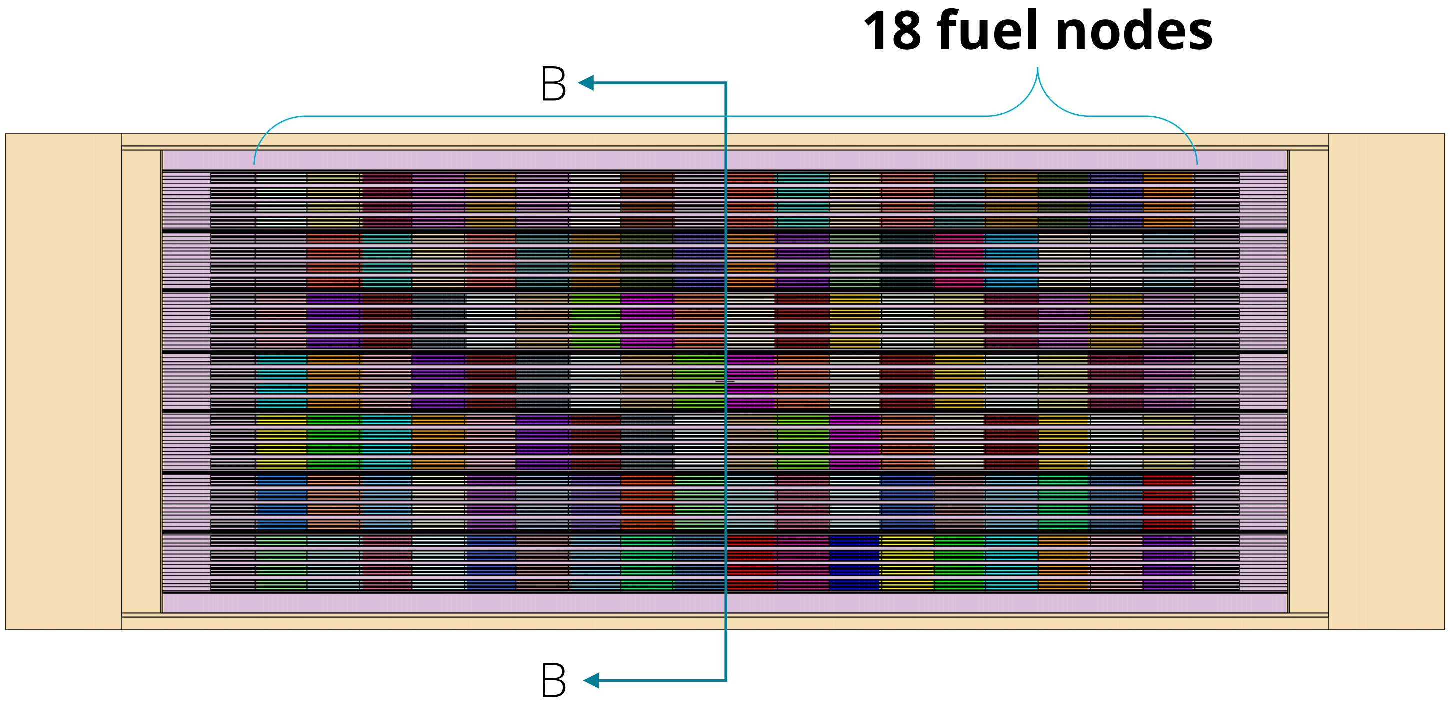
Modeling Process

- MCNP model has been developed for a 37-PWR DPC with the as-loaded configuration of spent nuclear fuel (SNF) from the Zion commercial nuclear power station (L. Price *et al.*, 2021).
- Unsaturated conditions are modeled with air and various levels of water after canister is breached. There is no backfill gas remaining.
- MCNP 6.1.1 used to evaluate neutron multiplication (k_{eff}) using cross sections from Evaluated Nuclear Data File Version B - Rev. 7.1 library at 20.45 °C.
- Perl scripts are used to configure evolving geometries and material compositions for MCNP input.



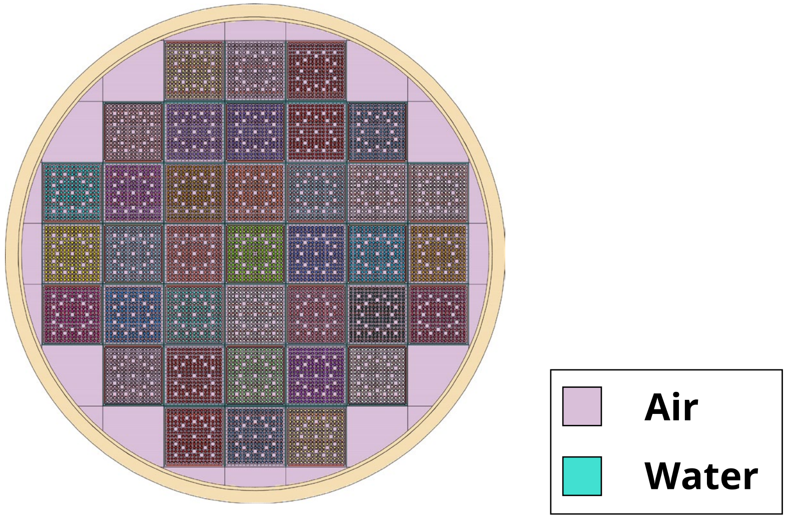
MCNP model accommodates arbitrary water level

37-PWR DPC with SNF inventories* from Zion power plant (t = 22,000 y)



VIEW A: YZ

Nuclide inventory is axially discretized on assembly basis. Fuel rods are prototypic length and include plenum regions.



VIEW B: XY

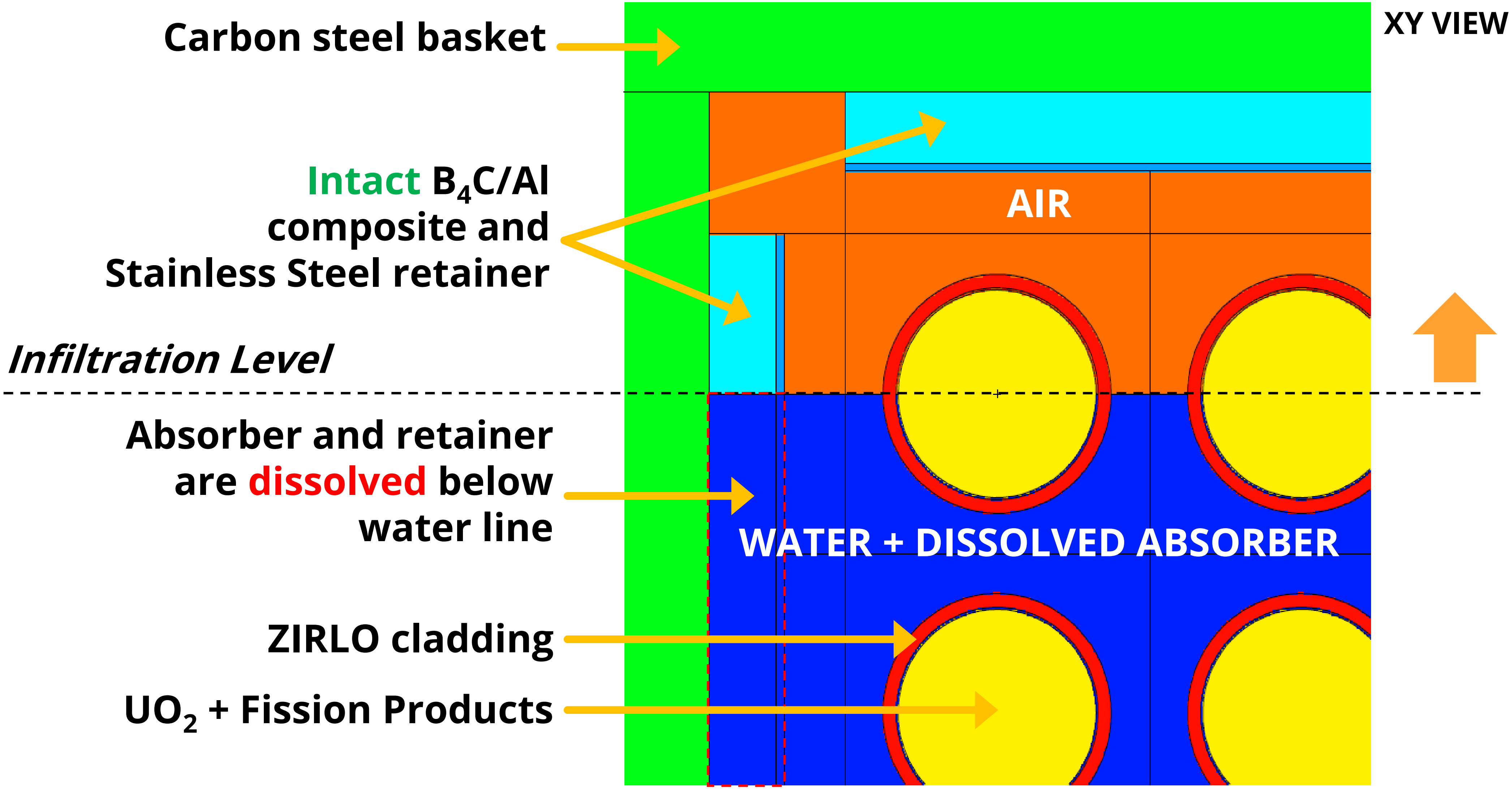
As-loaded configuration of 15×15 PWR assemblies with stratified air+H_2O extending across void space of canister, basket, and fuel rods

* From UNF-ST&DARDS and SCALE, courtesy of K. Banerjee (PNNL)

Scenario for reactivity insertion

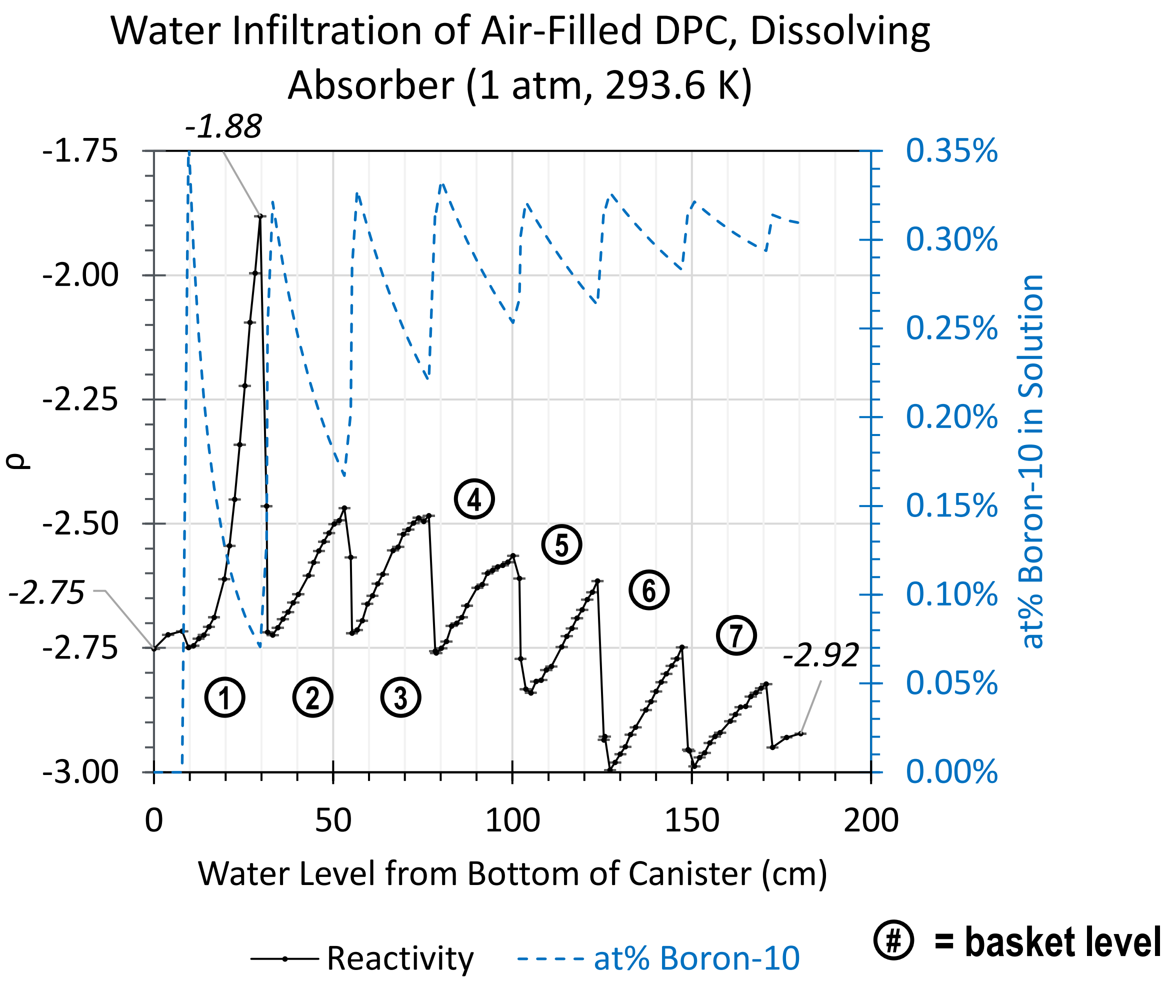
1. The breached canister is filled with atmospheric air and pure water infiltrates in increments.
2. Per given water level, the wetted portion of the neutron absorber plate is dissolved and the boron content of the water is modified.
3. Water infiltrates until the canister is full and all absorber plates have dissolved homogeneously into solution.
4. The dissolved absorber components precipitate outside of the fuel in the basket, leaving the SNF exposed to fresh water and resulting in a critical state.
5. The water level in the canister is decreased via heat emitted from criticality until a subcritical state is attained.

Neutron absorber plates are dissolved as water infiltrates



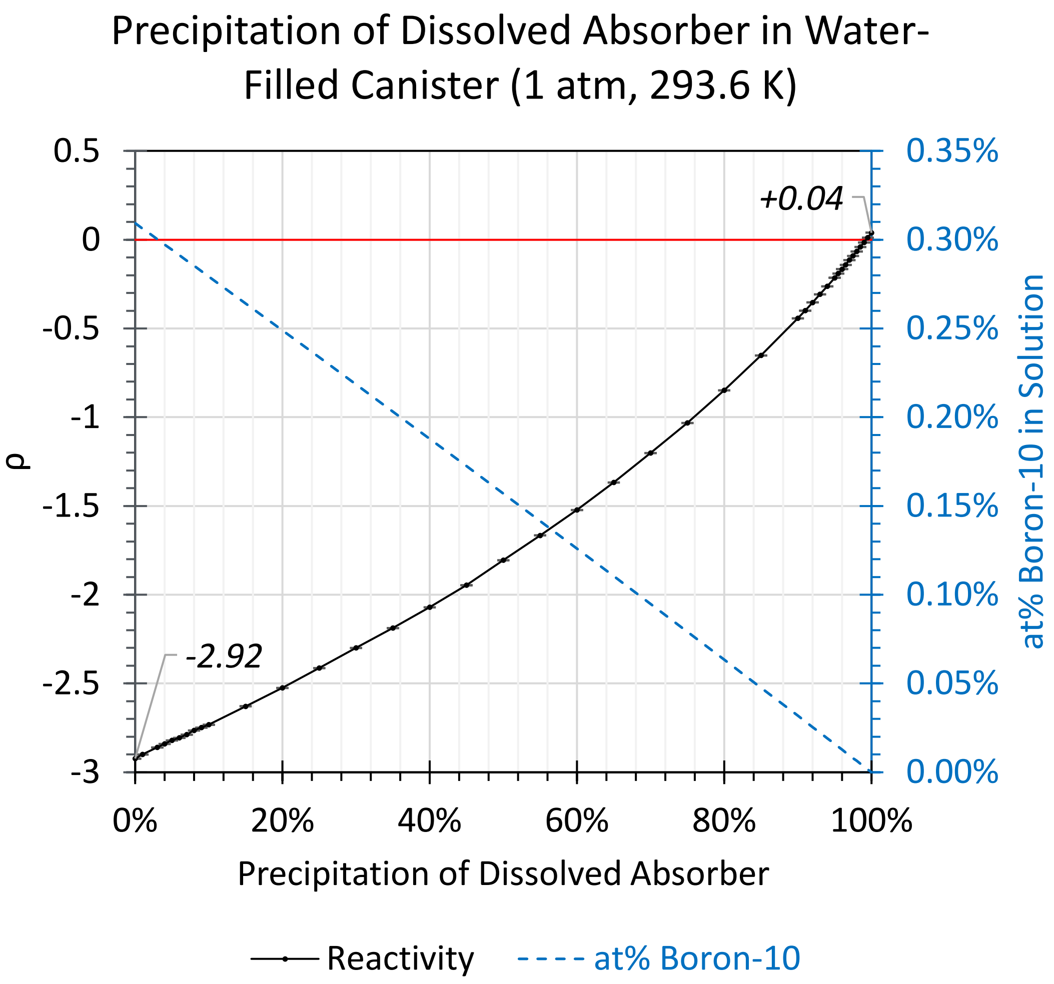
Dissolution of absorber offsets reactivity effects from water

- Infiltration of water leads to an increase in reactivity (ρ), but this effect is offset with the addition of boron from the absorber plates.
- There is a net *decrease* in reactivity (-2.75 → -2.92) when the canister is full and all the absorber plates have dissolved into solution.
- If the absorbers remained *intact*, k_{eff} would rise to 0.87 at the full water level.



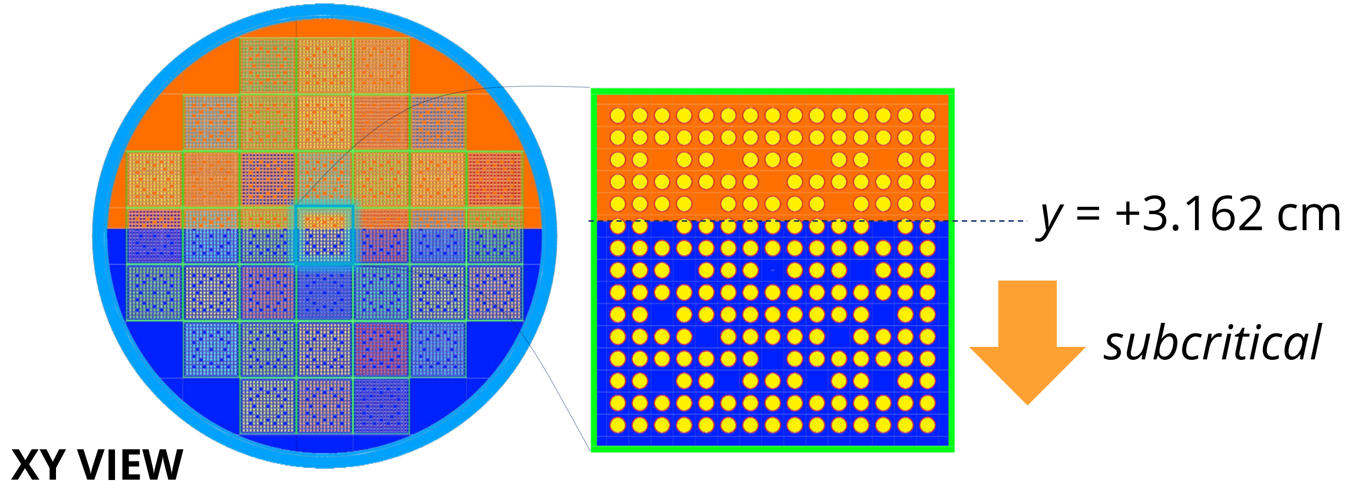
Loss of dissolved absorber to precipitation leads to criticality

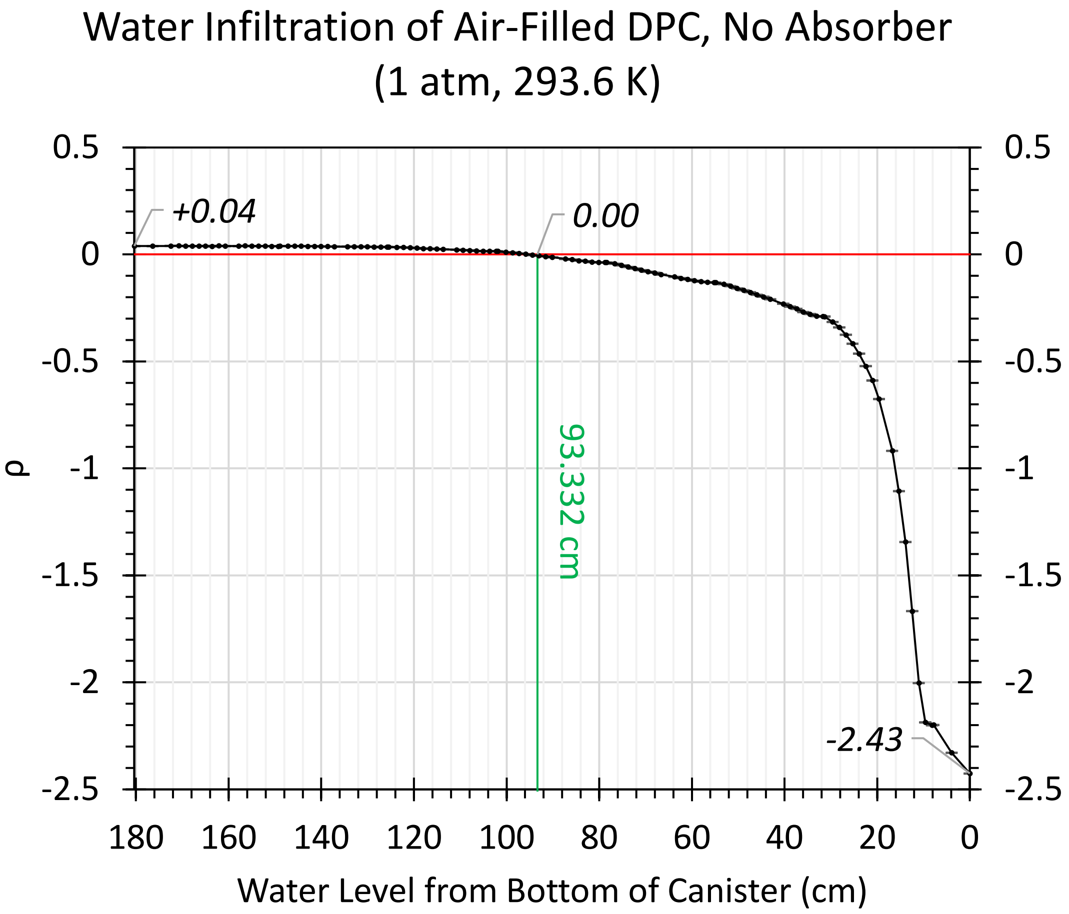
- After the canister has filled and the neutron absorber plates have dissolved, boron precipitates outside of the fuel regions.
- As more boron precipitates, the reactivity in the DPC rises.
- System is critical (ρ = 0) when 99.3% of absorber has precipitated and is prompt critical (ρ = $1) shortly thereafter.
- Maximum reactivity of $6.67



Drop in water level from heating leads to subcriticality

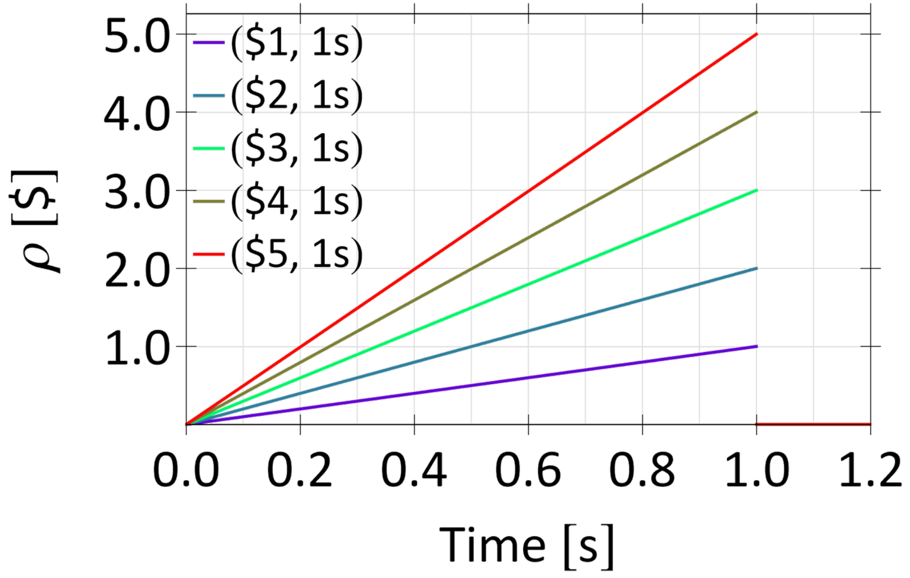
- With no absorbers remaining in the basket, the reactivity of the system drops as the water level decreases from the heat of criticality.
- Baseline critical water level is found using the bisection method
  - 93.332 cm from bottom of canister
  - 3.162 cm above the midplane





Implementation in RAZORBACK

- Reactivity points for ≥ 90% B_4C precipitation are fitted and employed in RAZORBACK as series of time-dependent piecewise curves ρ(t) [$] beginning at ρ = $0.
- Kinetics analysis conducted for reactivity insertions from $1 to $5 and insertion periods between 0.01 s and 10 s.
- Feedback coefficients are obtained from steady-state calculations with MCNP that isolate particular effects.

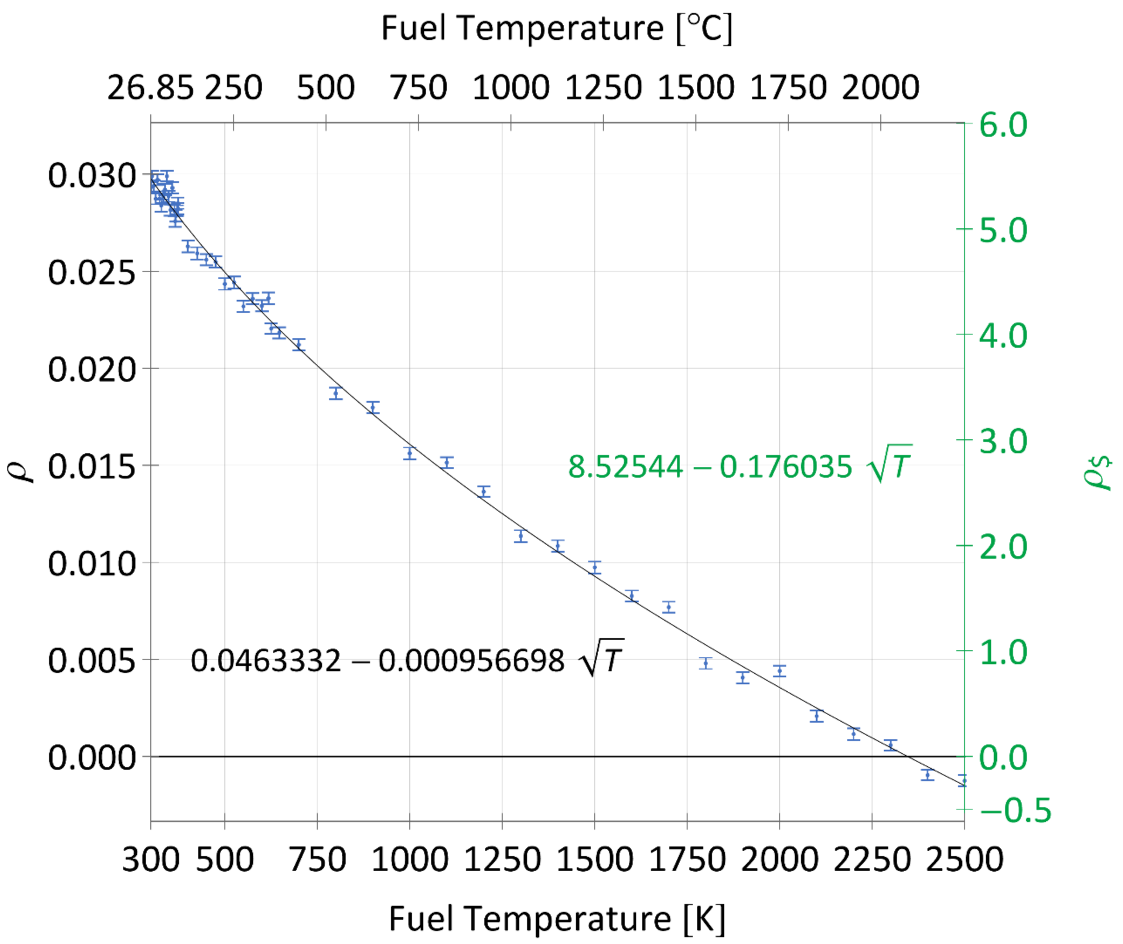


Piecewise ρ(t) curves for 1 second insertions.

Mechanism	Feedback Coefficient	Units
Doppler broadening in fuel	$\partial\rho_\$/\partial T_F = -0.088/\sqrt{T}$	$/K
Coolant density reduction	$\partial\rho_\$/\partial(\%\varrho) = -0.260$	$/(%ϱ)
Coolant temperature	$\partial\rho_\$/\partial T_W = -0.009$	$/K
Fuel thermal expansion: $R_{F,o}$	$\partial\rho_\$/\partial R_{F,o} = -41.822$	$/cm
Fuel density changes: ϱ_F	$\partial\rho_\$/\partial\varrho_F = +0.981$	$/(g/cm^3)
Cladding thermal expansion: $R_{C,o}$	$\partial\rho_\$/\partial R_{C,o} = -56.471$	$/cm
Cladding thermal expansion: $R_{C,i}$	$\partial\rho_\$/\partial R_{C,i} = +36.071$	$/cm
Cladding density changes: ϱ_C	$\partial\rho_\$/\partial\varrho_C = +0.351$	$/(g/cm^3)

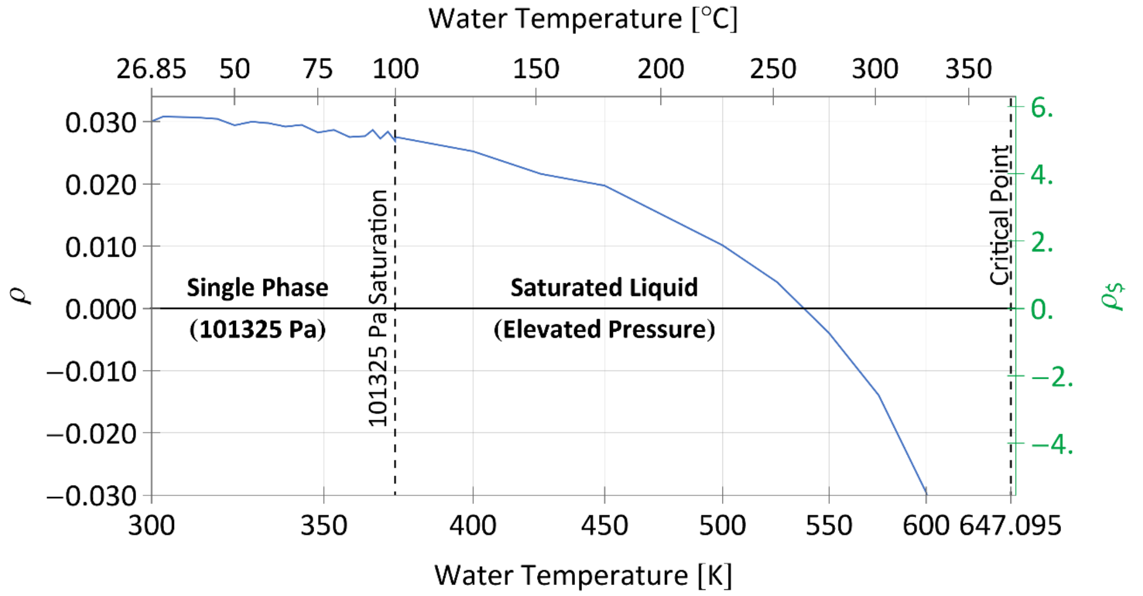
Doppler Broadening in the Fuel

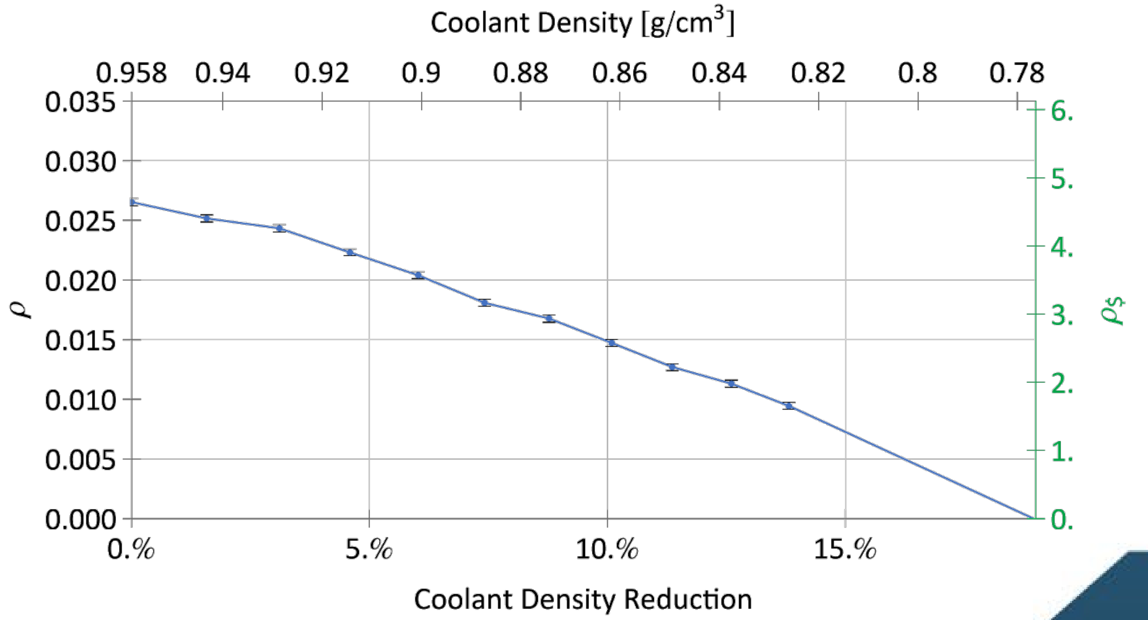
- ENDF/B-7.1 cross sections are modified with the On-the-fly Doppler Broadening (OTFDB) code for evolving UO_2 temperature (W. Martin, 2012).
- When collision is scored in the fuel, 8th-order interpolations are made on an energy grid from 300 K – 2500 K using the Cullen & Weisbin broadening equation.
- Results from MCNP are then fit to a $T^{1/2}$ curve.



Temperature Feedback in the Coolant

- Reactivity effects are analyzed and fitted for infiltrated groundwater given
  - rising temperature, and
  - voiding in the saturated state.
- Temperature feedback limited to liquid state at 1 atm, and the gas phase transition is ignored.
- Coolant voiding has substantial effect on reactivity. Only results for 20% coolant density reduction are applied to the reactivity fit.





Kinetics Results

- Results indicate that peak fuel temperatures do not rise to an extent where the SNF is damaged.
- Refinement needed to complete calculations with fast insertions.
- Heat generation may result in localized boiling but may not expel the full volume of infiltrated water in the DPC.
- Doppler broadening is dominant feedback mechanism for fast insertions, while slow insertions show additional effects from moderator heating and voiding.

P: Power (W)
E: Energy (J)
(shaded): Simulation did not complete

MF: Max. Fuel Temperature (°C)
MZ: Max. Zircaloy Temperature (°C)
MW: Max. Water Temperature (°C)

t (s)	$1	$2	$3
0.01	P: 4.59E+12 W E: 5.66E+09 J MF: 1645.81 °C MZ: 72.064 °C MW: 64.96 °C	P: 4.81E+12 W E: 3.72E+09 J MF: 1023.37 °C MZ: 68.955 °C MW: 64.96 °C	P: 2.62E+12 W E: 1.77E+09 J MF: 505.19 °C MZ: 66.830 °C MW: 64.96 °C
0.1	P: 6.77E+09 W E: 6.08E+08 J MF: 268.76 °C MZ: 103.641 °C MW: 80.20 °C	P: 1.71E+11 W E: 1.06E+09 J MF: 331.53 °C MZ: 67.658 °C MW: 64.96 °C	P: 1.47E+12 W E: 5.37E+09 J MF: 1649.42 °C MZ: 77.458 °C MW: 64.96 °C
0.5	P: 2.71E+10 W E: 1.80E+09 J MF: 634.16 °C MZ: 138.656 °C MW: 103.81 °C	P: 1.42E+11 W E: 5.32E+09 J MF: 1633.33 °C MZ: 274.278 °C MW: 96.78 °C	P: 2.72E+11 W E: 3.65E+09 J MF: 1182.88 °C MZ: 78.570 °C MW: 64.96 °C
1	P: 1.78E+08 W E: 6.27E+07 J MF: 85.33 °C MZ: 75.866 °C MW: 67.47 °C	P: 2.27E+10 W E: 1.56E+09 J MF: 563.98 °C MZ: 135.016 °C MW: 99.74 °C	P: 7.76E+10 W E: 3.70E+09 J MF: 1188.93 °C MZ: 184.107 °C MW: 113.51 °C
5	P: 2.42E+06 W E: 3.84E+07 J MF: 79.82 °C MZ: 75.697 °C MW: 68.29 °C	P: 4.95E+06 W E: 2.16E+07 J MF: 69.07 °C MZ: 67.829 °C MW: 66.07 °C	P: 1.21E+07 W E: 2.19E+07 J MF: 140.94 °C MZ: 94.133 °C MW: 74.31 °C
10	P: 4.97E+06 W E: 1.05E+08 J MF: 67.09 °C MZ: 66.258 °C MW: 65.60 °C	P: 2.42E+06 W E: 3.82E+07 J MF: 79.67 °C MZ: 75.599 °C MW: 68.28 °C	P: 3.39E+06 W E: 3.24E+07 J MF: 87.02 °C MZ: 78.555 °C MW: 69.13 °C

Continuing Work

- The modeling framework is being expanded to an 89-BWR DPC with various assembly geometries (8×8, 9×9, and 10×10) for as-loaded configurations.
- Results will be compared with those from SIMULATE-3K in the related study for fully-saturated geology.
- A solid mechanics analysis is being devised with SNL software SIERRA and CTH to investigate the effects of the transient criticality energy release on the stress field of the canister and surrounding materials.
- Work will refine understanding of reactivity insertion locations, rates, and magnitudes.

References

- D. G. Talley (2017), *RAZORBACK – A Research Reactor Transient Analysis Code v. 1.0 vol. 1: User's Manual*, SAND2017-10561, Sandia National Laboratories, Albuquerque, NM.
- T. Goorley (2014), *MCNP6.1.1-Beta Release Notes*, LA-UR-14-24680, Los Alamos National Laboratory, Los Alamos, NM.
- L. Price *et al.* (2021), *Repository-Scale Performance Assessment Incorporating Postclosure Criticality*, Spent Fuel and Waste Disposition M2SF-21SN01030506, SAND2022-7932 R, Sandia National Laboratories, Albuquerque, NM.
- W. Martin (2012), "Implementation of On-the-Fly Doppler Broadening in MCNP5 for Multiphysics Simulation of Nuclear Reactors," *NEUP 10-897*, Battelle Energy Alliance, Ann Arbor, MI.