Repository-Scale Performance Assessment Incorporating Postclosure Criticality

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Topics to be Covered

- The objectives and scope of the probabilistic postclosure DPC criticality consequence analyses
- Repository concepts and postclosure scenarios considered and assumptions used in these analyses
- Recent major accomplishments and how the performance assessment results informed planned near and long-term technical activities that will be pursued
- How probabilities of events occurring and their uncertainties are being obtained and treated
Objectives and Scope

- **Objectives**
  - Further our understanding of the features, events, and processes important to modeling postclosure criticality
  - Develop tools to model the consequences of postclosure criticality
    - Couple neutronics calculations and thermal-hydraulic calculations
    - Build sub-module in PFLOTRAN to be able to model features, events, and processes associated with a postclosure critical event
  - Examine processes leading to permanent termination of critical event
  - Identify areas where further work is needed

- **Scope**
  - In-package postclosure criticality; no external postclosure criticality
  - Commercial SNF in DPCs
  - Examining consequences of criticality, not probability
Repository Concepts – Saturated and Unsaturated

- Hypothetical shale repository
  - Saturated environment
  - Depth of 500 m
  - Hydrostatic pressure is 50 bar; saturation temperature is 264°C
  - Waste emplacement drifts backfilled with bentonite
  - Waste packages have a 316SS overpack and are 5 m long
  - Waste package center-to-center spacing is 20 m
  - Centerline-to-centerline drift spacing is 30 m
  - Repository-scale model – 4,200 waste packages containing spent PWR fuel
  - Has an upper sandstone aquifer which a well intersects 5 km downstream to calculate dose to a member of the public
  - Based on GDSA Shale Reference Case (Mariner et al. 2017)
Hypothetical Shale Repository Model Domain

(a) 3D model of the repository with labeled axes and sections.

(b) Close-up view of the repository model showing material distribution.

(c) Material ID Legend:
1. Shale
2. Overburden
3. Siltstone
4. Sandstone
5. Limestone
6. Lower Shale
7. Lower Sandstone
8. Disturbed Rock Zone (DRZ)
9. Overburden DRZ
10. Siltstone DRZ
11. Sandstone DRZ
12. Buffer
13. Waste Package
Horizontal Slice Through Hypothetical Saturated Shale Model Domain
Repository Concepts – Saturated and Unsaturated

- Hypothetical alluvial repository
  - Unsaturated environment
  - Infiltration rate varies from 2 mm/yr to 10 mm/yr
  - Depth of 250 m
  - Ambient pressure; saturation temperature is about 100°C
  - Waste emplacement drifts backfilled with alluvium
  - Waste packages have a 316SS overpack and are 5 m long
  - Waste package center-to-center spacing is 40 m
  - Centerline-to-centerline drift spacing is 40 m
  - Single waste package model, top removed 9,000 after repository closure
  - Based on GDSA Alluvium Reference Case (Mariner et al. 2018; Sevougian et al 2019; Hardin and Kalinina 2016)
Computational Domain for Hypothetical Unsaturated Alluvium Model
Postclosure Scenarios – Steady State and Transient Criticality

- Steady State Criticality
  - Consistent with DOE’s Criticality Topical Report (YMP 2003), primary concerns are thermal effects and change in inventory
  - Low power (50 W to 4 kW), long duration (100’s to 1000’s of years)
  - Failed waste packages fill with water
    - Upon waste package failure for saturated repository
    - As a function of infiltration rate and power for unsaturated repository
- Criticality event begins after waste package has filled with water
- All waste packages become critical
- Power level of criticality event
  - Determined by saturation temperature for hypothetical shale repository
  - Varied to determine evaporation time, refilling time for unsaturated case
Postclosure Scenarios – Steady State and Transient Criticality

- Steady State Criticality
  - Duration
    - 10,000 years for hypothetical saturated shale repository
    - Until water evaporates for hypothetical unsaturated alluvial repository
  - Additional processes considered
    - Illitization of buffer for the hypothetical saturated case
  - Consequences
    - Dose to a member of the public for the hypothetical saturated case
    - Time required for evaporation, refilling of waste package for hypothetical unsaturated case

- Transient Criticality
  - Consistent with DOE’s Criticality Topical Report (YMP 2003), primary concern is mechanical effect on barriers and their properties
  - High power ($10^2$ MW to $10^5$ MW), short duration (0.01 to 10 seconds)
Postclosure Scenarios – Steady State and Transient Criticality

- Transient Criticality
  - Modeled reactivity insertion rates are consistent with sudden neutron absorber plate failure
  - Developed neutronic model for a single waste package, varying reactivity insertion rates and insertion period
    - Razorback for unsaturated model
    - SIMULATE3-K for saturated model
  - For a range of reactivity insertion rates and insertion periods, calculated
    - Peak power and power peaking factor
    - Total integrated energy
    - Maximum and average fuel temperature
    - Maximum and average coolant temperature
    - Time of peak power
    - Maximum reactivity
Assumptions

- Waste packages fail 9,000 years after closure and criticality occurs
- Fuel assembly configuration remain intact but cladding permits radionuclide transport
- Postclosure performance requirements are similar to those in 10 CFR 63 and 40 CFR 197
- Basket neutron absorbers have degraded prior to the initiation of criticality
- Steady-state criticality does not oscillate between being supercritical and subcritical (applicable to hypothetical unsaturated repository)
Major Accomplishments

- Identified features, events, and processes that are relevant to criticality
- Modified PFLOTRAN for steady-state case
  - Include the change in inventory and thermal output midway through the simulation
  - Develop loose coupling between neutronics, in-canister thermohydraulic processes, and rates of heat transfer out of the canister
  - Identified radionuclides that might need to be included
  - Include the temperature dependence and anisotropy of thermal conductivity
  - Include the change in buffer permeability from thermal illitization
Major Accomplishments (cont’d)

- Developed a model of grid spacer failure that leads to termination of the steady-state critical event – currently working on implementing in PFLOTRAN
- Found no difference in performance between a hypothetical saturated repository that remains subcritical and one in which a steady-state critical event occurs
  - $^{129}$I was the only radionuclide to reach the well
  - $^{90}$Sr and $^{137}$Cs decay before reaching the upper aquifer
Major Accomplishments (cont’d)
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Found that for a hypothetical unsaturated repository, the power that can be generated in a steady-state criticality is limited by the infiltration rate
  - 50 W to 100 W for 2 mm/yr
  - 300 W to 400 W for 10 mm/yr

Water evaporates from the waste package at temperatures well below 100°C

Temperatures associated with steady-state criticality event likely will not affect barrier performance

Radionuclide inventory increase would be < 1%
<table>
<thead>
<tr>
<th>Case</th>
<th>Time of Criticality Event (years postclosure)</th>
<th>Lower Bound on Power Output (W)</th>
<th>Upper Bound on Power Output (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (deep percolation = 2 mm/yr)</td>
<td>17,100</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Deep percolation = 1 mm/yr</td>
<td>25,300</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Deep percolation = 10 mm/yr</td>
<td>10,600</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Partial breach (2 mm/yr)</td>
<td>22,600</td>
<td>100</td>
<td>200</td>
</tr>
</tbody>
</table>
Used existing neutronics codes to characterize the pulse from a transient criticality event

Temperatures remain well below the melting temperature of UO$_2$
Potential Technical Activities to be Pursued

- **Neutronics-based activities**
  - Improve coupling between neutronics calculations and performance assessment calculations
  - Develop a model including spent fuel from BWRs
  - Evaluate reactivity at a variety of times greater than 9,000 years
  - Evaluate reactivity with water that is more representative of repository conditions.

- **Steady-state criticality events**
  - Expand material alteration model
  - Enable temperature-dependent radionuclide solubilities
  - Implement grid spacer degradation model
  - Examine effects of gas generation on barriers
Potential Technical Activities to be Pursued (cont’d)

- **Steady-state criticality events**
  - Examine thermal fatigue of waste package materials
  - Examine effects of criticality in one waste package on an adjacent waste package
  - Examine thermally induced stress changes in backfill

- **Transient criticality events**
  - Calculate damage to fuel, engineered barriers, and natural barriers from rapid energy production.
  - Further refine transient neutronics calculations
  - Examine the role of subcritical heating as criticality is approached
  - Examine thermal and mechanical fatigue of materials resulting from intermittent criticality
  - Examine effects of criticality in one waste package on adjacent waste packages
Potential Technical Activities to be Pursued (cont’d)

- Repository-wide sensitivities and variabilities
  - Vary how many waste packages experience criticality events, when they experience criticality events, and their location in the repository
  - Examine effects of varying hydrostatic head
  - Increase the distance from the repository to the model domain lower boundary
  - Work toward incorporating variability and uncertainty in parameter values into performance assessment calculations
Probability and Uncertainty

- Probability of occurrence of criticality is not calculated
  - Need specific site
  - Need specific waste package and repository design
- Incorporating uncertainty and variability in parameter values is on our list of activities to be pursued.
References


Acronyms

- BWR – boiling water reactor
- CFR – Code of Federal Regulations
- DOE – U.S. Department of Energy
- DPC – dual purpose canister
- GDSA – Geologic Disposal Safety Assessment
- SNF – spent nuclear fuel
Questions?