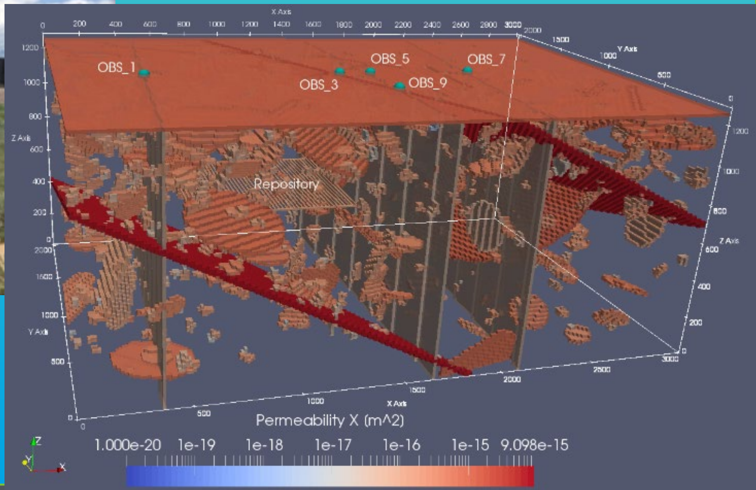
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

Clean. Reliable. Nuclear.



Repository-Scale Performance Assessment Incorporating Postclosure Criticality

Laura Price, Sandia National Laboratories

NWTRB Winter 2022 Board Meeting
March 1-2, 2022
Online Virtual Meeting

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND2022-1823 PE

Disclaimer

This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Acknowledgements

- Alex Salazar (Sandia National Laboratories)
- Eddie Basurto (Sandia National Laboratories)
- Halim Alsaed (EnviroNuclear)
- Jeff Cardoni (Sandia National Laboratories)
- Fred Gelbard (Sandia National Laboratories)
- Michael Nole (Sandia National Laboratories)
- Jeralyn Prouty (Nuclear & Regulatory Support Services)
- Charlotta Sanders (University of Nevada – Las Vegas)
- Greg Davidson (Oak Ridge National Laboratory)
- Scott Painter (Oak Ridge National Laboratory)
- Mathew Swinney (Oak Ridge National Laboratory)
- Santosh Bhatt (Oak Ridge National Laboratory)
- Evan Gonzalez (University of Michigan)
- Brian Kiedrowski (University of Michigan)
- Kaushik Banerjee (Pacific Northwest National Laboratory)

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

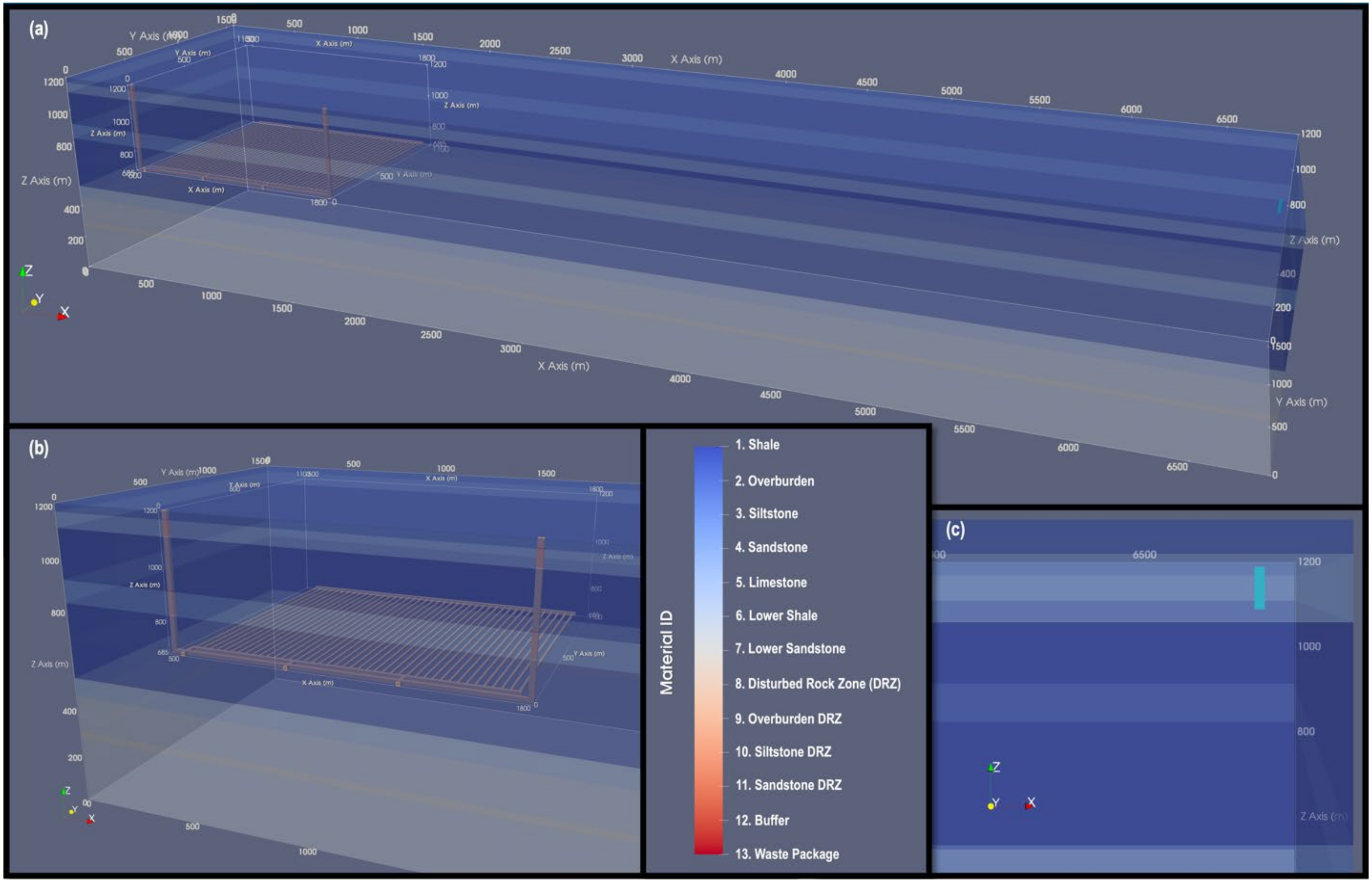
Objectives and Scope

- 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

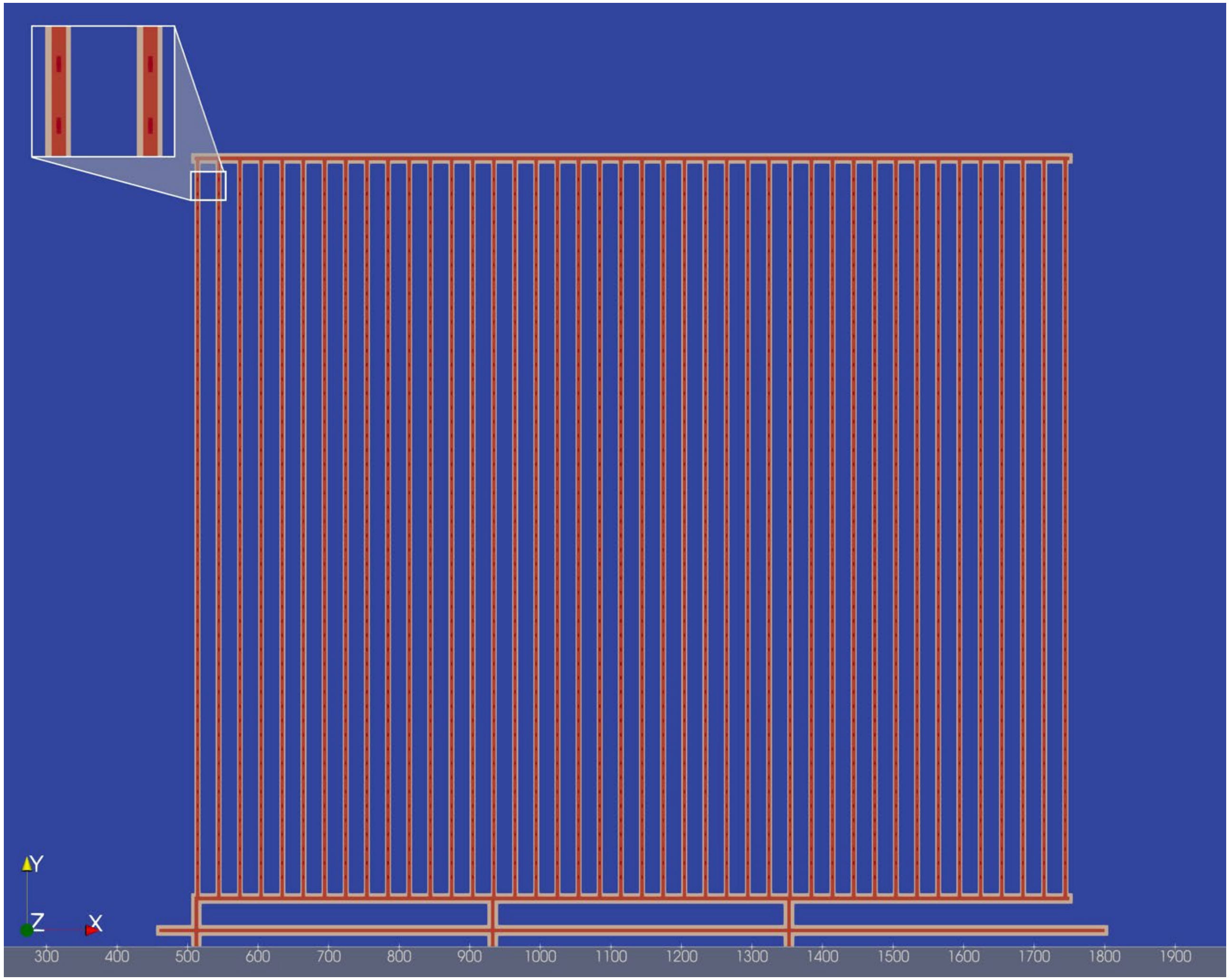
Repository Concepts, Postclosure Scenarios, and Assumptions

- 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



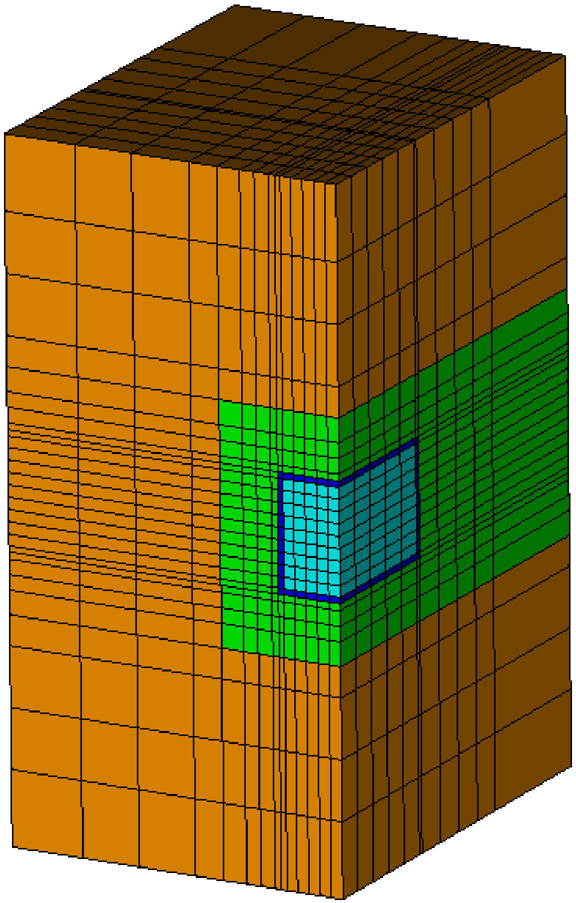
Horizontal Slice Through Hypothetical Saturated Shale Model Domain



Repository Concepts, Postclosure Scenarios, and Assumptions (cont'd)

- 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



Repository Concepts, Postclosure Scenarios, and Assumptions (cont'd)

- 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

Repository Concepts, Postclosure Scenarios, and Assumptions (cont'd)

- 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)

Repository Concepts, Postclosure Scenarios, and Assumptions (cont'd)

- 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

Repository Concepts, Postclosure Scenarios, and Assumptions (cont'd)

- 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)

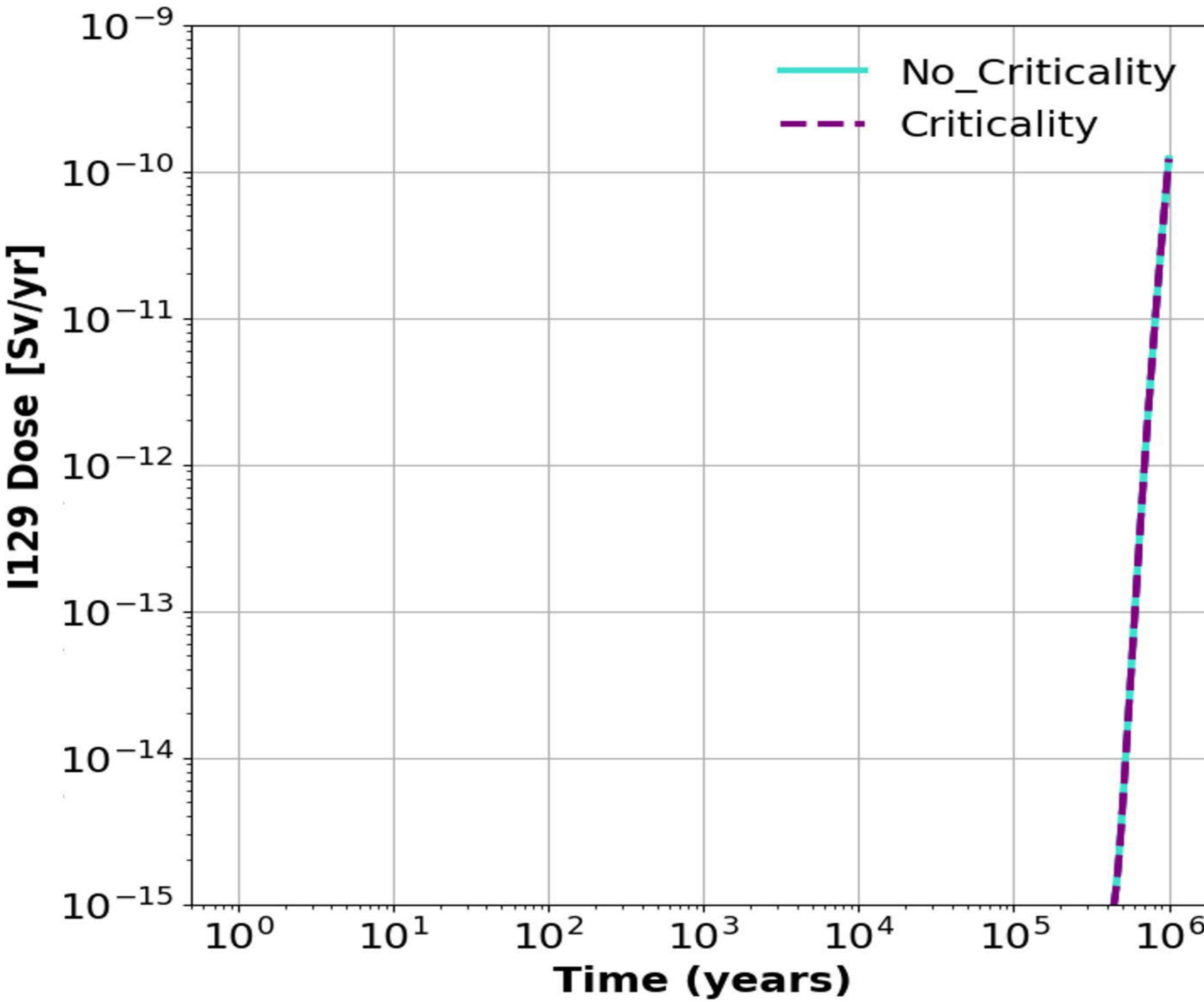
Major Accomplishments

- 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

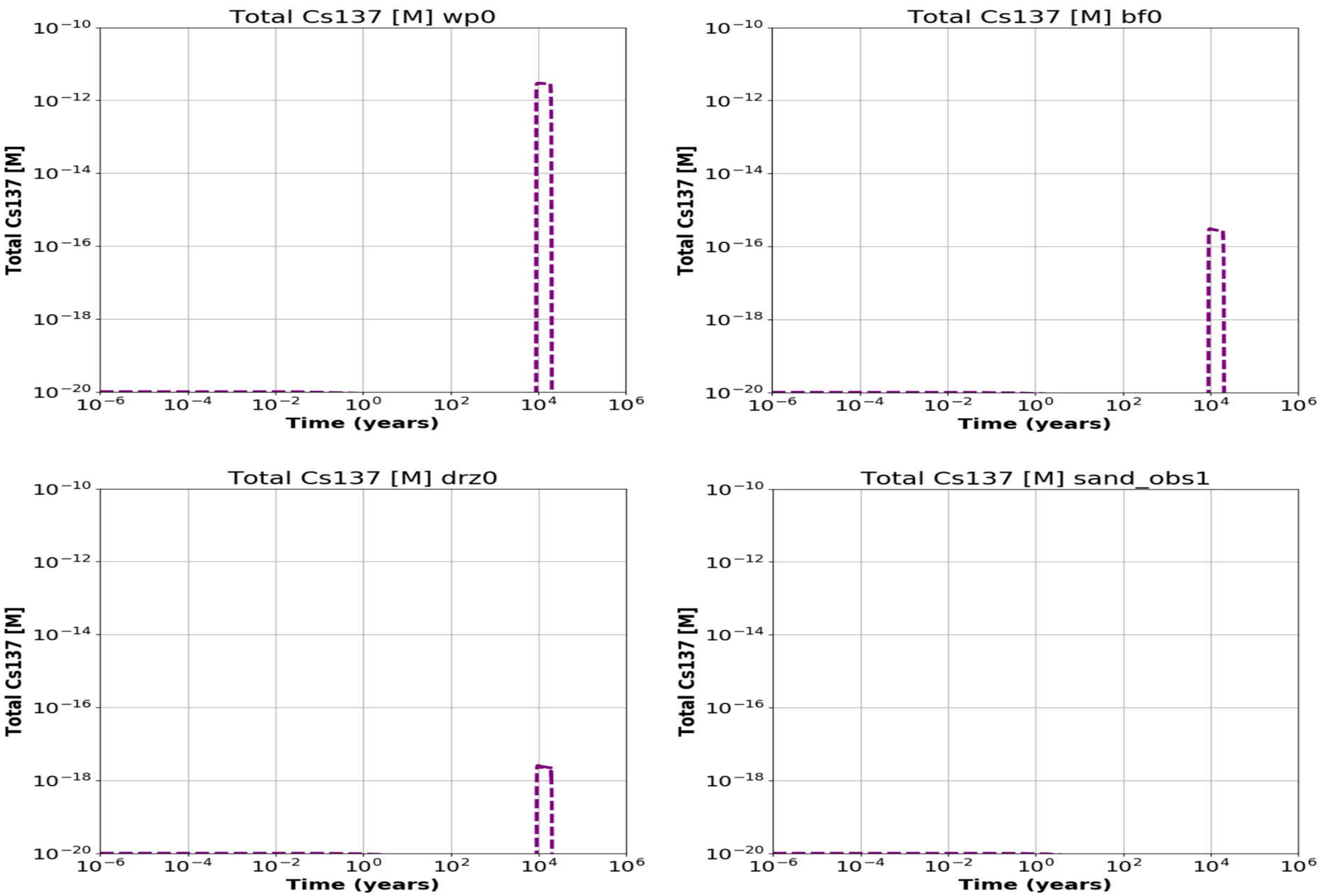
Major Accomplishments (cont'd)

- 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

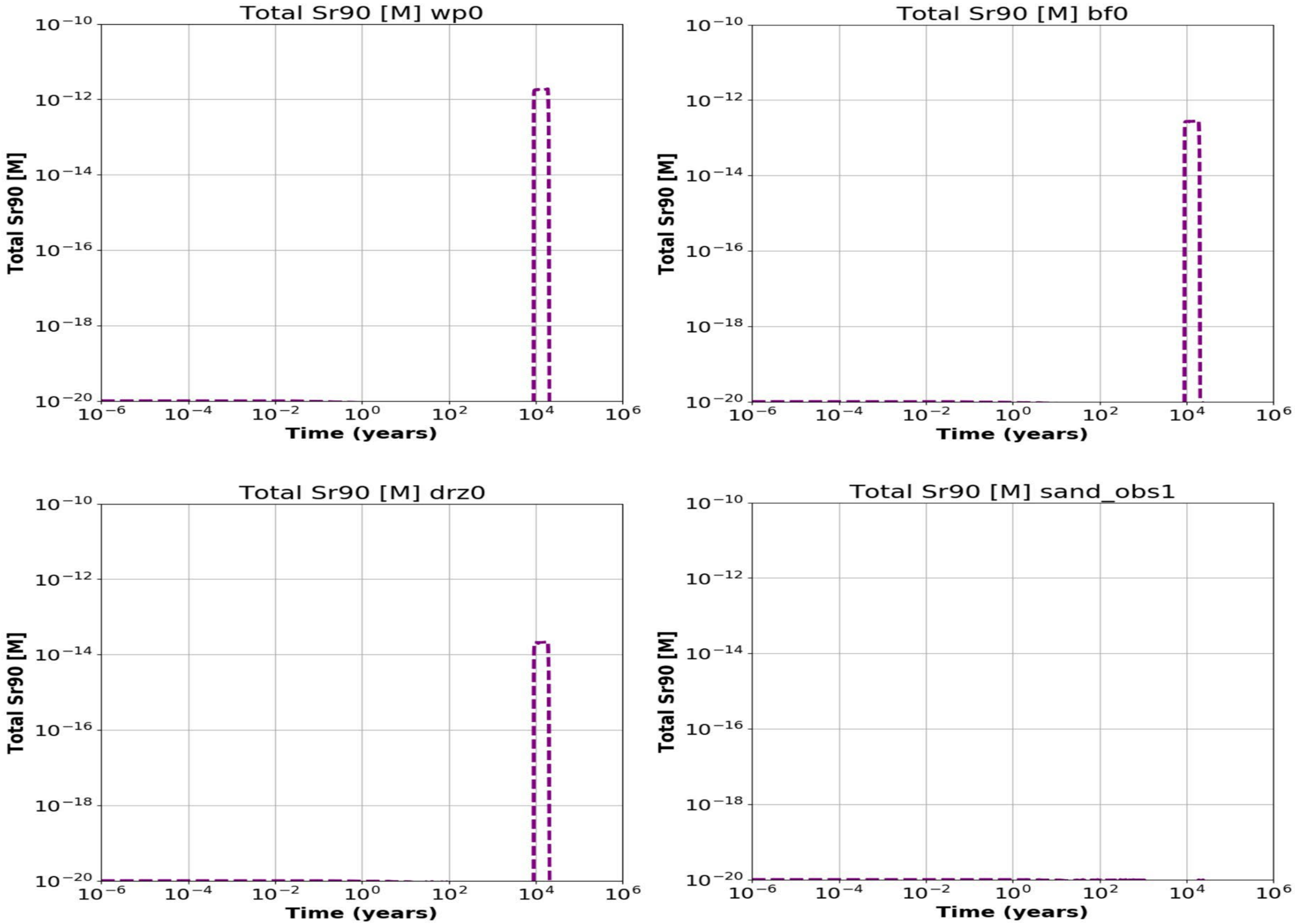
Major Accomplishments (cont'd)



Major Accomplishments (cont'd)



Major Accomplishments (cont'd)



Major Accomplishments (cont'd)

- 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%

Major Accomplishments (cont'd)

Case	Time of Criticality Event (years postclosure)	Lower Bound on Power Output (W)	Upper Bound on Power Output (W)
Reference (deep percolation = 2 mm/yr)	17,100	50	100
Deep percolation = 1 mm/yr	25,300	0	50
Deep percolation = 10 mm/yr	10,600	300	400
Partial breach (2 mm/yr)	22,600	100	200

Major Accomplishments (cont'd)

- 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

Hardin, E. and E. Kalinina. 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts*. SAND2016-0235. Albuquerque, NM: Sandia National Laboratories.

Mariner, P.E., E.R. Stein, J.M Frederick, S.D. Sevougian, and G.E. Hammond. 2017. *Advances in Geologic Disposal System Modeling and Shale Reference Case*. SFWD-SFWST-2017-000044; SAND2017-10304R. Albuquerque, NM: Sandia National Laboratories.

Mariner, P.E., E.R. Stein, S.D. Sevougian, L.J. Cunningham, J.M Frederick, G.E. Hammond, T.S. Lowry, S. Jordan, and E. Basurto. 2018. *Advances in Geologic Disposal Safety Assessment and an Unsaturated Alluvium Reference Case*. SFWD-SFWST-2018-000509; SAND2018-11858R. Albuquerque, NM: Sandia National Laboratories.

Sevougian, S.D., E.R. Stein, T. LaForce, F.V. Perry, T.S. Lowry, L. Cunningham, M. Nole, C.B. Haukwa, K.W. Chang, and P.E. Mariner. 2019. *GDSA Repository Systems Analysis Progress Report*. M2SF-19SNO10304051; SAND2019-5189R. Albuquerque, NM: Sandia National Laboratories.

YMP (Yucca Mountain Project). 2003. *Disposal Criticality Analysis Methodology Topical Report.* YMP/TR-004Q, Rev. 2. Las Vegas, NV: Yucca Mountain Site Characterization Office.

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?