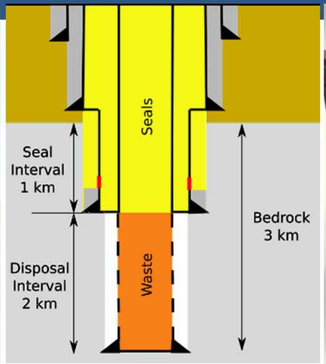
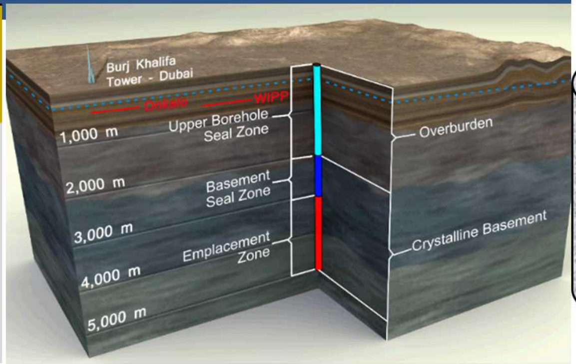
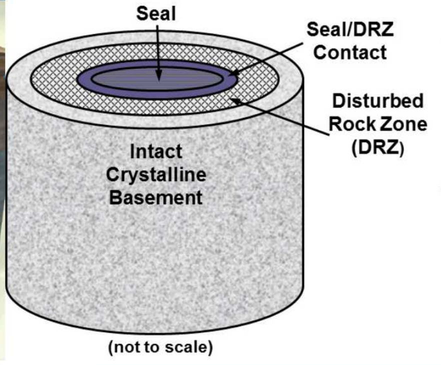
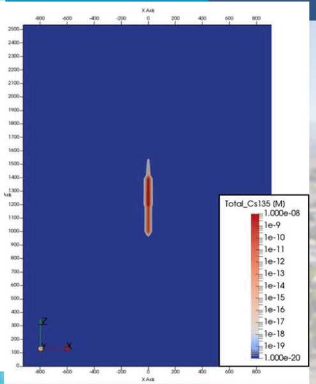
SAND2018-10790C

Thermo-Hydro-Mechanical Evaluation of Critical Mass in Repository Far-Field









PRESENTED BY

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OECD/NEA 15th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Manchester, UK, 3 October 2018

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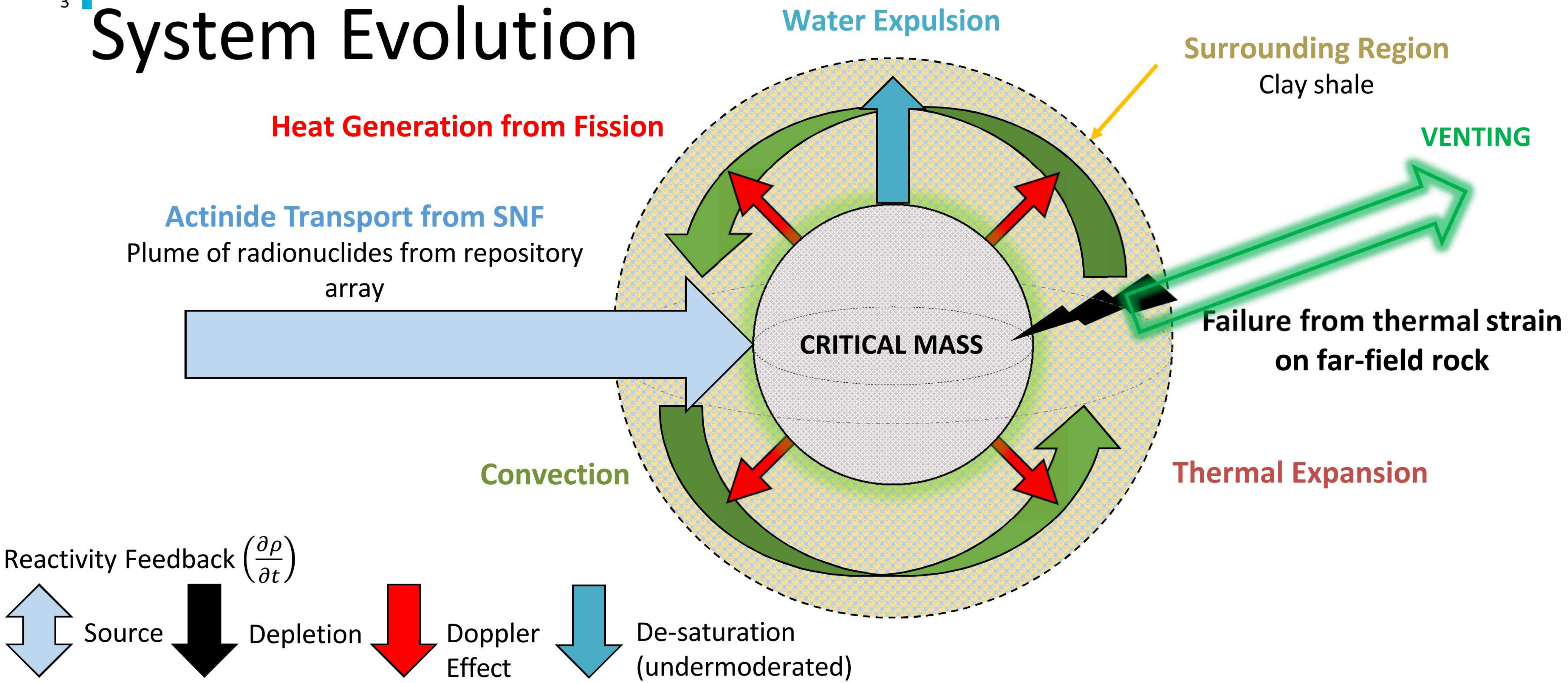
SAND2018-XXXX PE

Objective

What are the long-term consequences of a heat-emitting critical mass deposited in the far-field of a repository?

System Evolution



Water Expulsion

Surrounding Region
Clay shale

Heat Generation from Fission

VENTING

Actinide Transport from SNF
Plume of radionuclides from repository array

CRITICAL MASS

Failure from thermal strain on far-field rock

Convection

Thermal Expansion

Reactivity Feedback $\left(\frac{\partial\rho}{\partial t}\right)$

Source

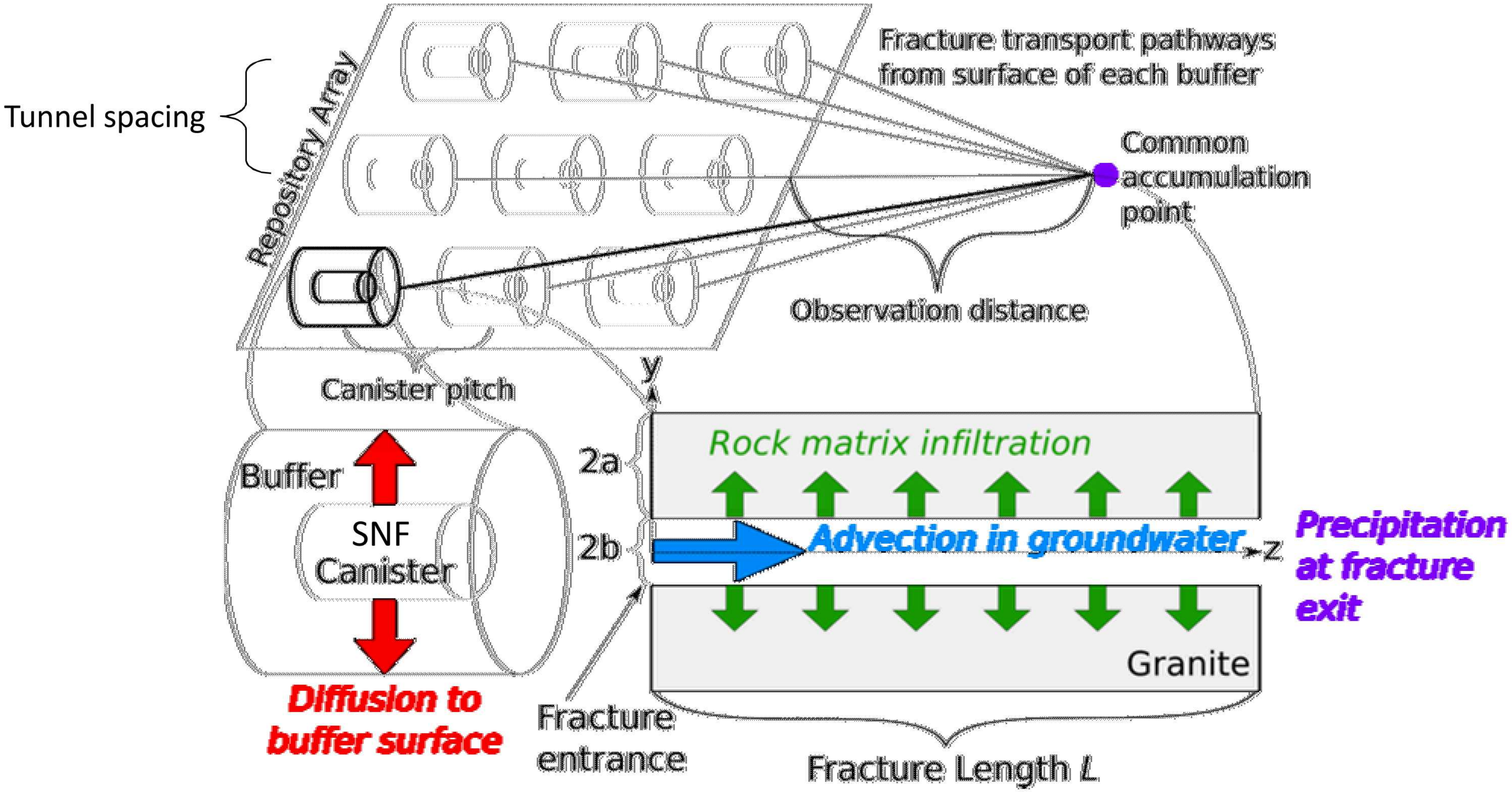
Depletion

Doppler Effect

De-saturation (undermoderated)

Critical mass in the far-field with hypothesized effects on reactivity

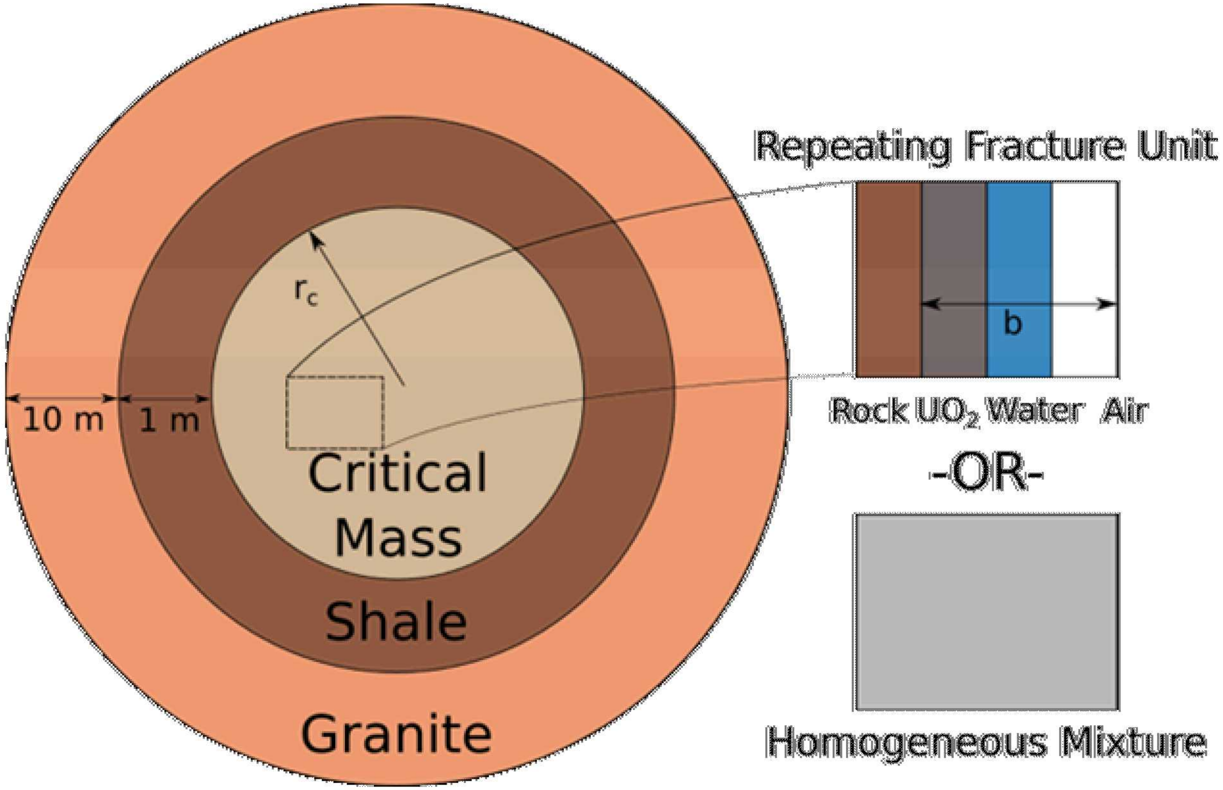
Radionuclide Transport



Borrowed from A. Salazar (2018), "Criticality in the far-field of a granitic repository for used nuclear fuel," University of California, Berkeley, Berkeley, CA.

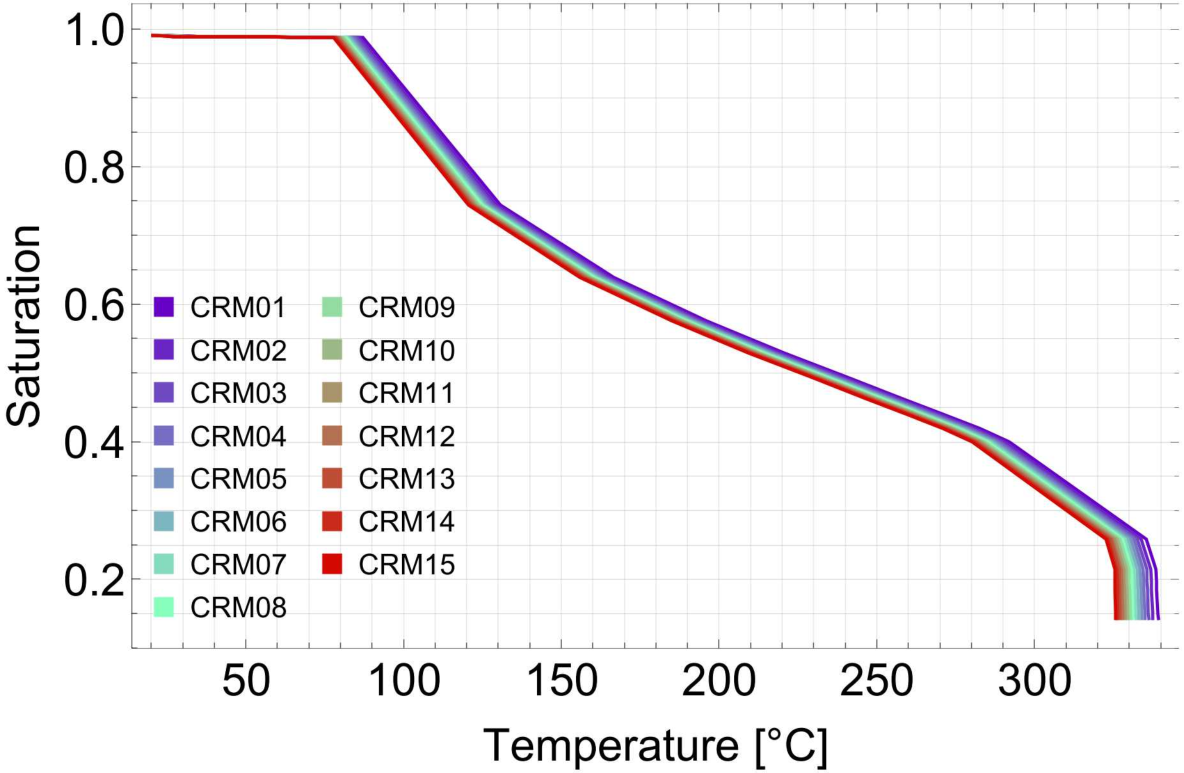
Criticality

- Far-field precipitate is modeled as a sphere in a homogeneous or fractured geometry
- Shale serves as reducing sedimentary rock
- A parametric study based on the saturated porosity (VVF) and volume fraction of UO_2 (HMVF) was performed to determine critical radius using MCNP6.1



Unsaturated Heat and Mass Transfer

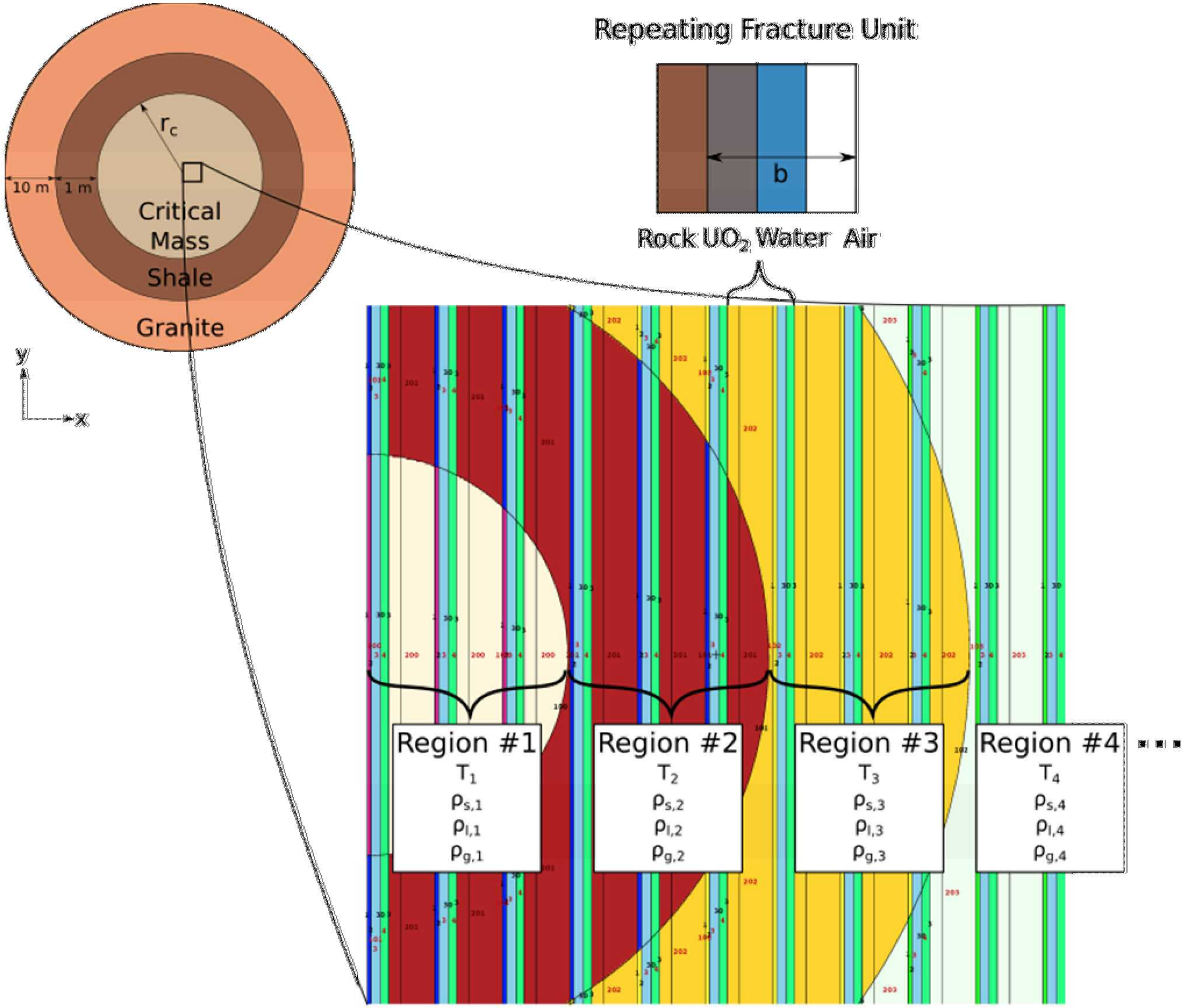
- The TOUGH2 code is used to evaluate the evolution of saturation and temperature in the critical deposition
- Van Genuchten-Mualem models are employed for capillary pressure and relative conductivity of pore fluid [1]
- Fission power distributions calculated by CINDER are employed as source terms



The behavior of saturation with temperature for each discrete region of the 5 MTU 2 wt% homogeneous critical mass (“CRM”) as steady-state is reached for a dry environment at 0.1% saturation. The regions are numbered from the core outwards.

Modification of MCNP cell densities

- The average temperature, saturation, and fluid densities from the TOUGH2 simulation are applied to discrete spherical shells of critical mass
- Saturation is varied in fractured geometry by modifying the volume of the air region in the repeating unit



Temperature Evaluation at Quasi-Steady-State

- Quasi-steady-state (QSS) approach assumes fission power generation and heat dissipation from the critical system are in a relative steady state

$$\phi N_A \sum_{i\in TFM} E_{f,i}\sigma_{f,i}n_i(t) = MC_p\frac{d\Delta T}{dt} - hA\Delta T$$

- System remains critical until competing reactivity feedback mechanisms result in subcriticality

$$\alpha_T(T)\frac{\partial \Delta T}{\partial t} + \alpha_{25}\left(n_{25} - n_{25}^{0}\right)\frac{\partial n_{25}}{\partial t} + \alpha_{28}\frac{\partial n_{28}}{\partial t}$$
$$+\alpha_R(\varDelta T)f_R(\varDelta T)\frac{\partial \varDelta T(t)}{\partial t} = 0$$

Nuclide inventories

- Fissile material

$$\dot{n}_{25}(t) = \dot{S}_{25} + \lambda_{49} n_{49}(t) + \phi(t)\left[-\sigma_c^{25} n_{25}(t) - \sigma_f^{25} n_{25}(t)\right]$$

$$\dot{n}_{49}(t) = \dot{S}_{49} - \lambda_{49} n_{49}(t) + \phi(t)\left[\sigma_c^{28} n_{28}(t) - \sigma_c^{49} n_{49}(t) - \sigma_f^{49} n_{49}(t)\right]$$

- Fertile material

$$\dot{n}_{28}(t) = \dot{S}_{28} - \sigma_c^{28} n_{28}(t)\phi(t)$$

Mechanical Failure Metric

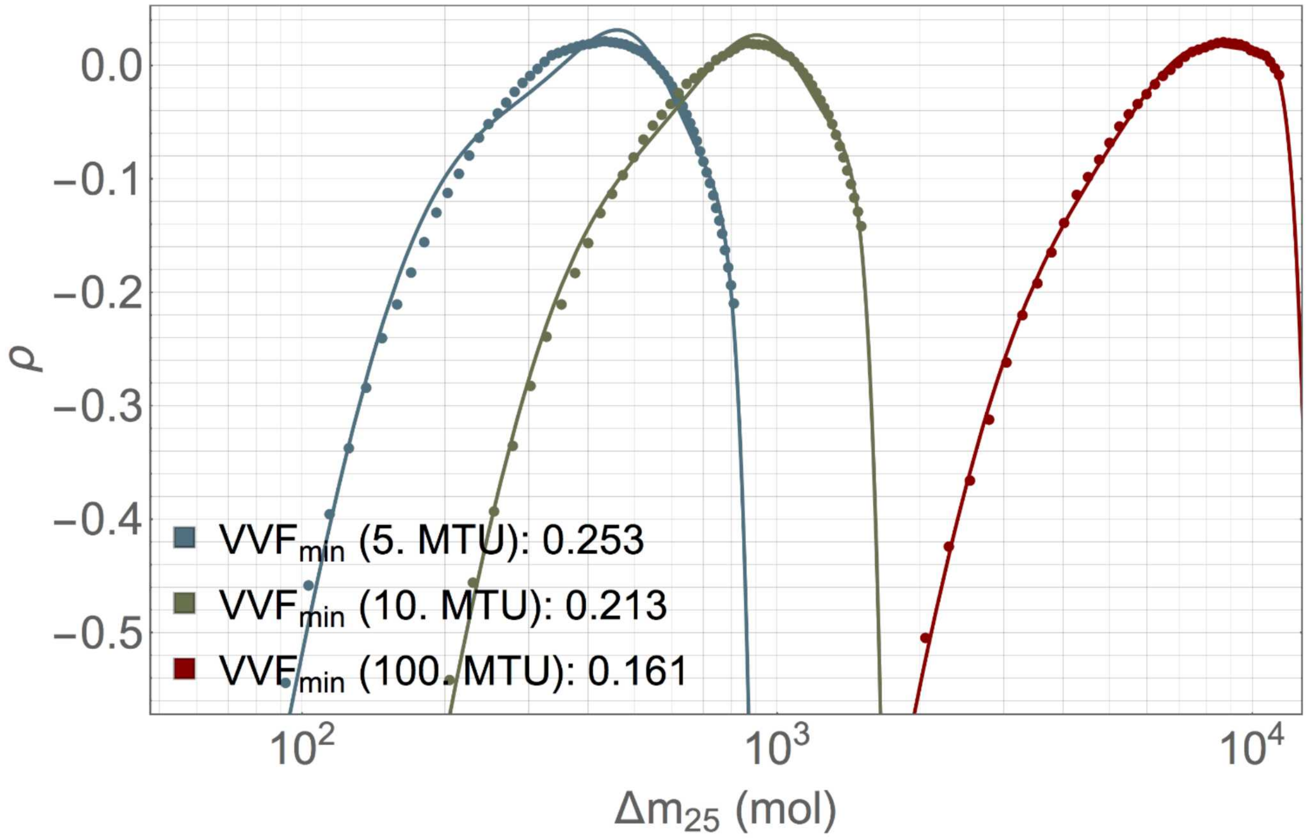
- The bedrock is assumed to fail via a steady-state thermal creep, which is governed by a power law relationship:

$$\epsilon = \begin{cases} \int_0^t A\left(\frac{\sigma}{G}\right)^n e^{-Q/R[T(\tau)+273.15]} d\tau & 150°C \leq T < 1250°C \\ 0 & T < 150°C \end{cases}$$

- The total strain is obtained through numerical integration over time using $T(t)$ results of QSS model, where a 1.5% failure metric is employed

Positive Feedback from U-235 is Limited

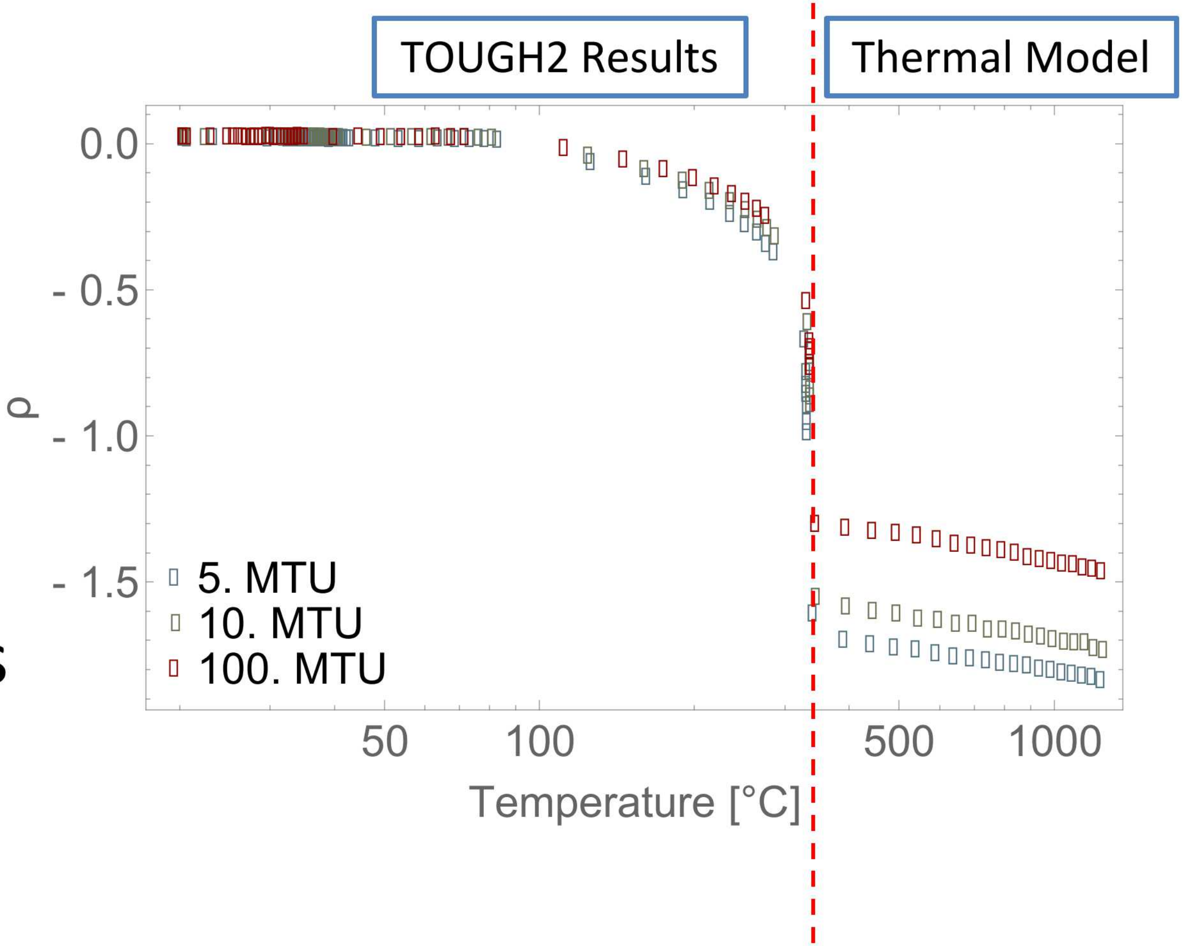
- After criticality is reached, the continued arrival of U-235 from the repository plume has limited positive reactivity (ρ) feedback
- At some point, the system becomes undermoderated



Reactivity effect of displacing water with 2 wt%-enriched uranium in the void space of minimum critical masses, expressed in terms of moles of U-235. Shown with polynomial fit curves.

Doppler Effect

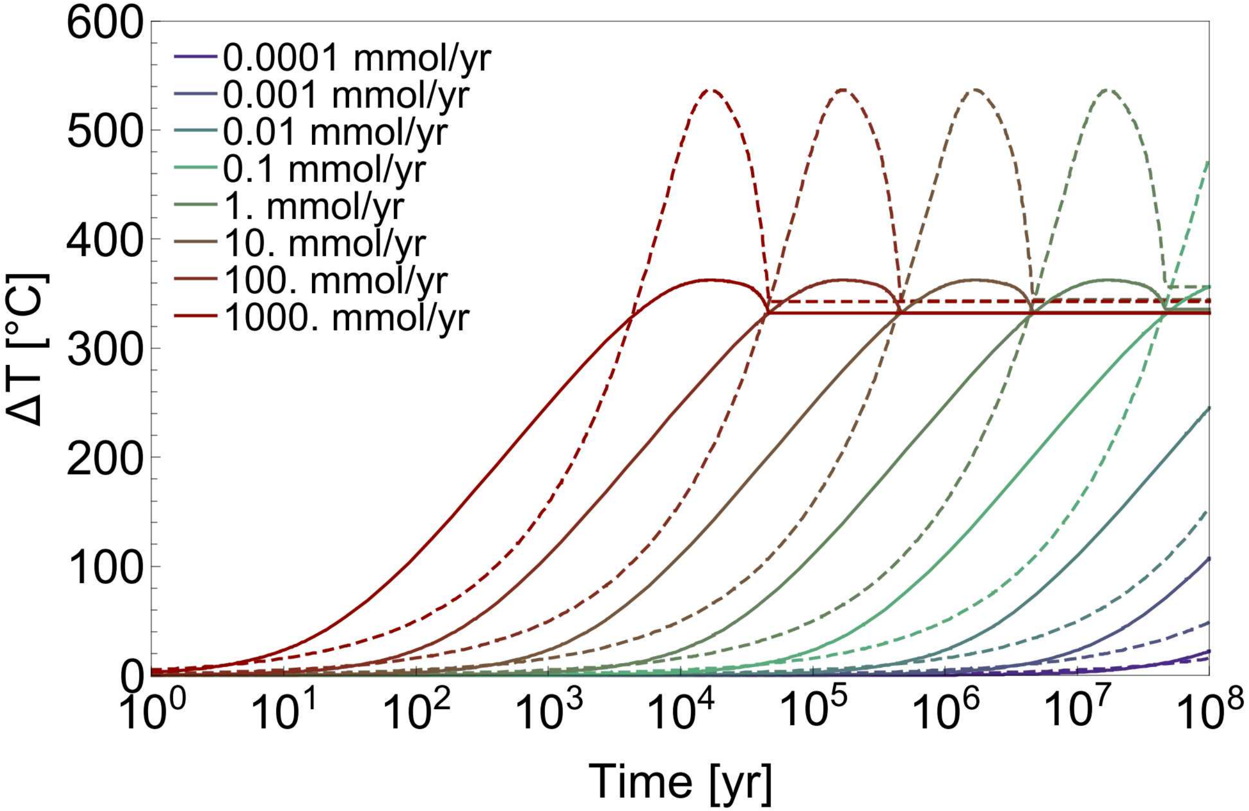
- Cross sections are modified based on average cell temperatures using the On-the-Fly Doppler Broadening code [2]
- Thermal resistance model extrapolates system temperatures to rock melting point (≈1250°C)
- Regression is performed for temperature feedback coefficient



Reactivity feedback for fractured geometry at various critical masses of 2 wt% enrichment in the fractured configuration

Lumped System Temperature

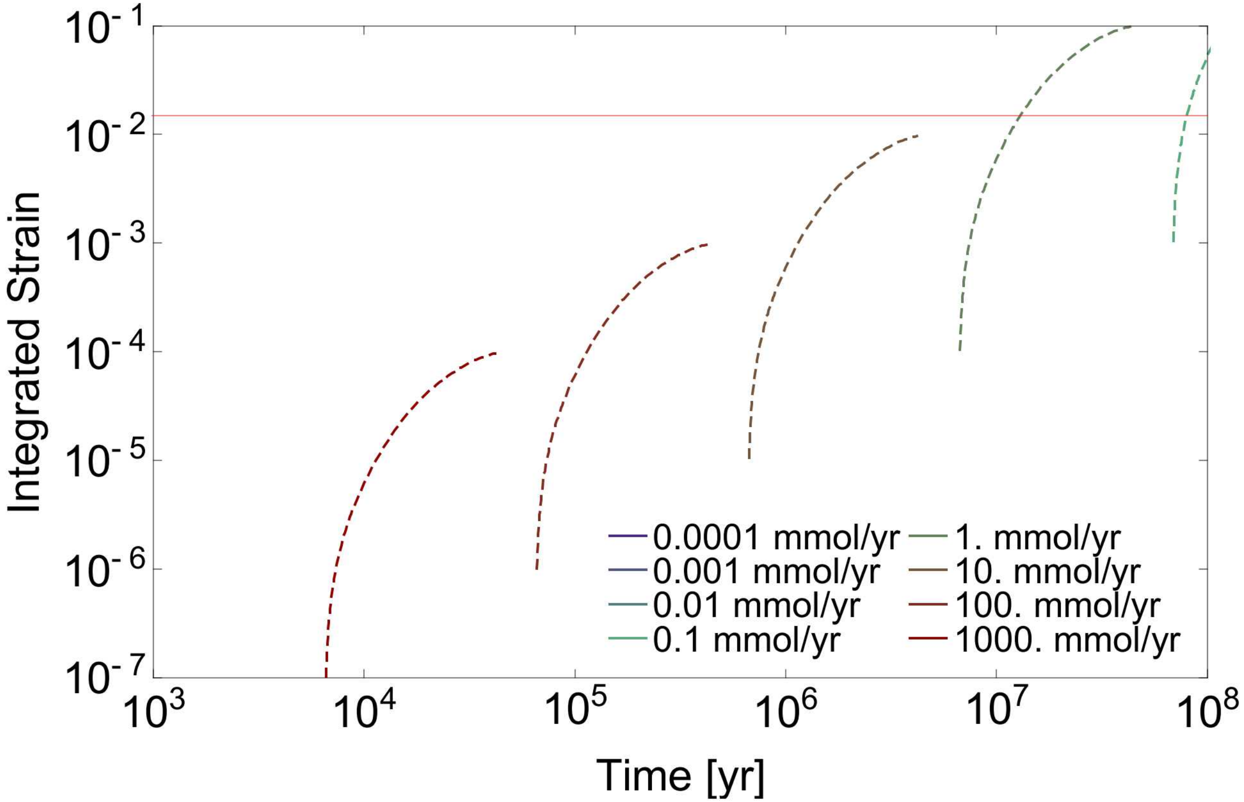
- A maximum ΔT can be achieved before uranium fills the pore space, with a minimum uranium influx of 1 mmol/yr from the repository
- For reference, the Nopal I deposit at Peña Blanca (welded tuff) has dissolution rates of ~2 mmol/m^3/yr within fractured zones [3]



The temperature change over time in the 5 MTU 2 wt% homogeneous critical mass as parametrized by the source term of uranium (in mmol/yr) for piecewise (solid) and Gaussian (dashed) fits of α_T.

Strain of Far-field Host Rock

- The time- and temperature-dependent creep relationship only allows for certain influxes to meet the failure metric
- The 1 mmol/yr source term allows for excessive strain to be reach at about **10^7** years post-formation
- Compare to 0.055 mmol/yr value observed in very conservative transport analysis [4]



The integrated creep strain over time in the 5 MTU 2 wt% homogeneous critical mass as parametrized by the source term of uranium (in mmol/yr) for a Gaussian fit of α_T.

Discussion

- The time scale needed for excessive plastic deformation from thermal creep exceeds a million years
- This comes with amplified source terms of heavy metal not likely to be observed in a reducing, water-saturated host rock even with heavily conservative assumptions
- This conservatism is compounded with the small window of applicability for creep strain to take place

Conclusions

- The failure of natural barriers from a long-term, sustained criticality event is considered to be highly implausible for direct disposal
- Although steady-state creep was isolated as the performance metric of interest, previous studies with high-energy, explosive events were also considered to be very improbable, even with more enriched materials [5]

Acknowledgments

- The presenting author would like to acknowledge the support of the U.S. Nuclear Regulatory Commission (NRC) Fellowship

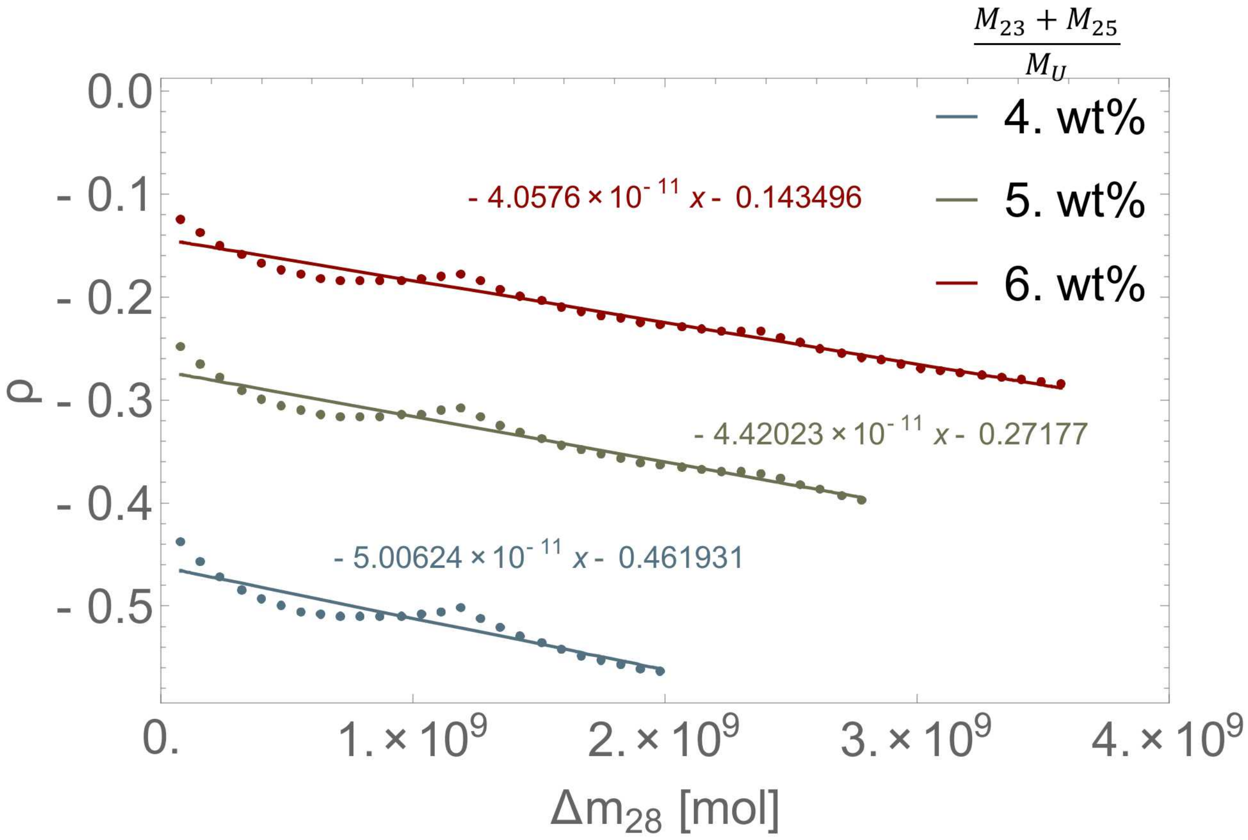
References

- [1] M. T. Van Genuchten (1980), “A closed-form equation for predicting the hydraulic conductivity of unsaturated soils,” Soil Sci. Soc. Am. J., 44[5], pp. 892–898.
- [2] F. B. Brown, W. R. Martin, G. Yesilyurt, and S. Wilderman (2012), “On-the-Fly Neutron Doppler Broadening for MCNP,” Los Alamos Natl. Lab.
- [3] S. J. Goldstein et al. (2010), “Uranium-Series Constraints on Radionuclide Transport and Groundwater Flow at the Nopal I Uranium Deposit, Sierra Peña Blanca, Mexico,” Env. Sci. & Technol., 44[5], pp. 1579-1586.
- [4] A. Salazar (2018), “Criticality in the far-field of a granitic repository for used nuclear fuel,” University of California, Berkeley, Berkeley, CA.
- [5] Kastenberg, et al (1996), “Considerations of Autocatalytic Criticality of Fissile Materials in Geologic Respositories”, J. Nuc. Tec, 115[3], pp. 298-310.

BACKUP

Effect from U-238 in the Plume

- Data for higher-enriched precipitates were interpolated to probe effect of U-238 influx
- The proportion of U-238 in the superposed uranium plume eventually becomes dominant and constitutes a negative reactivity feedback mechanism



Reactivity effect of displacing water with pure U-238 in the void space of precipitates at different initial enrichments, expressed in terms of moles of U-238. The heavy metals are assumed to be instantaneously mixed. Shown with linear best-fit curve.

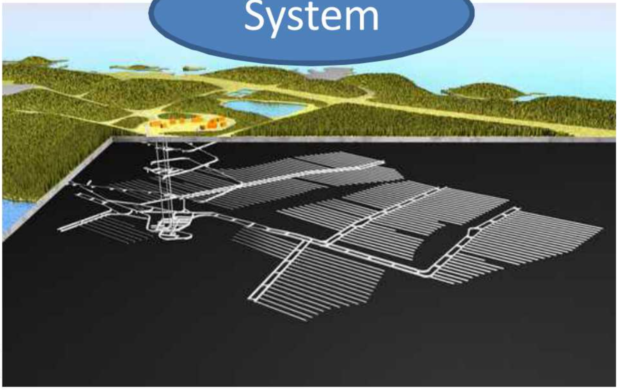
Integrated Modeling Approach

Source

[NRC]

Characterization of UNF source term in the United States

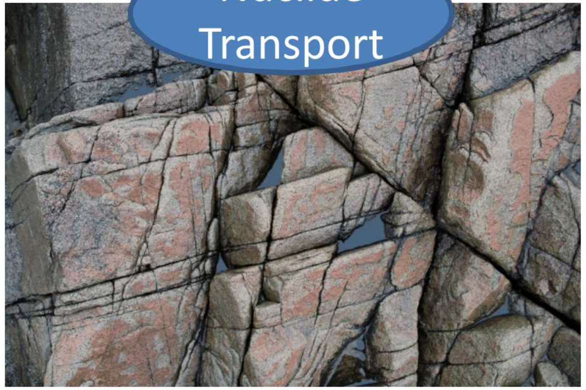
System



[POSIVA]

Canister and repository configuration

Nuclide Transport



Dissolution of UO_2 fuel and transport in granitic fractures

Criticality

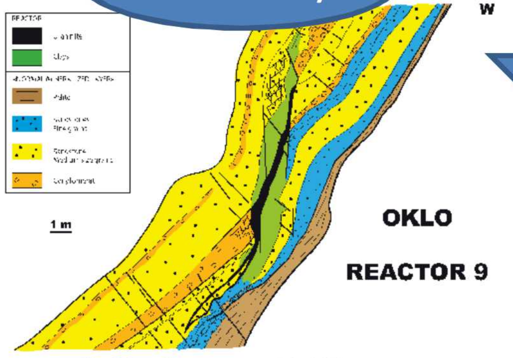
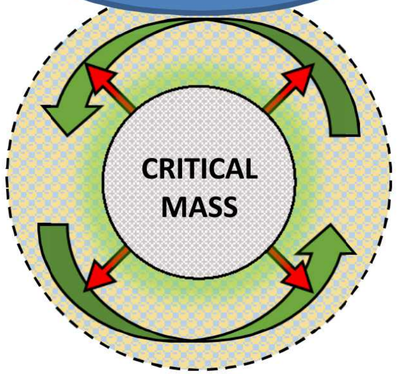


Fig. 2 East-West outcrop of the RZ9 reactor area

Re-concentration of fissile material in reducing region of the far-field

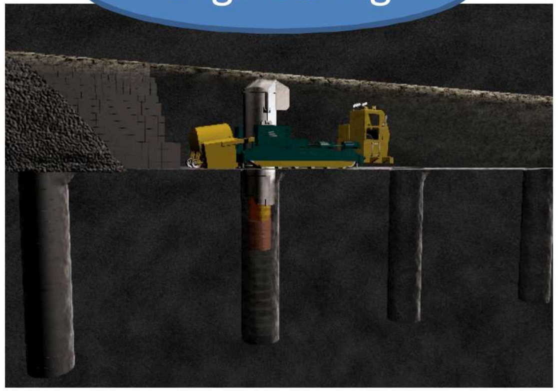
[Bentridi et al, 2011]

Dynamics



Dynamic evaluation of heat and mass transfer with sustained criticality

Engineering

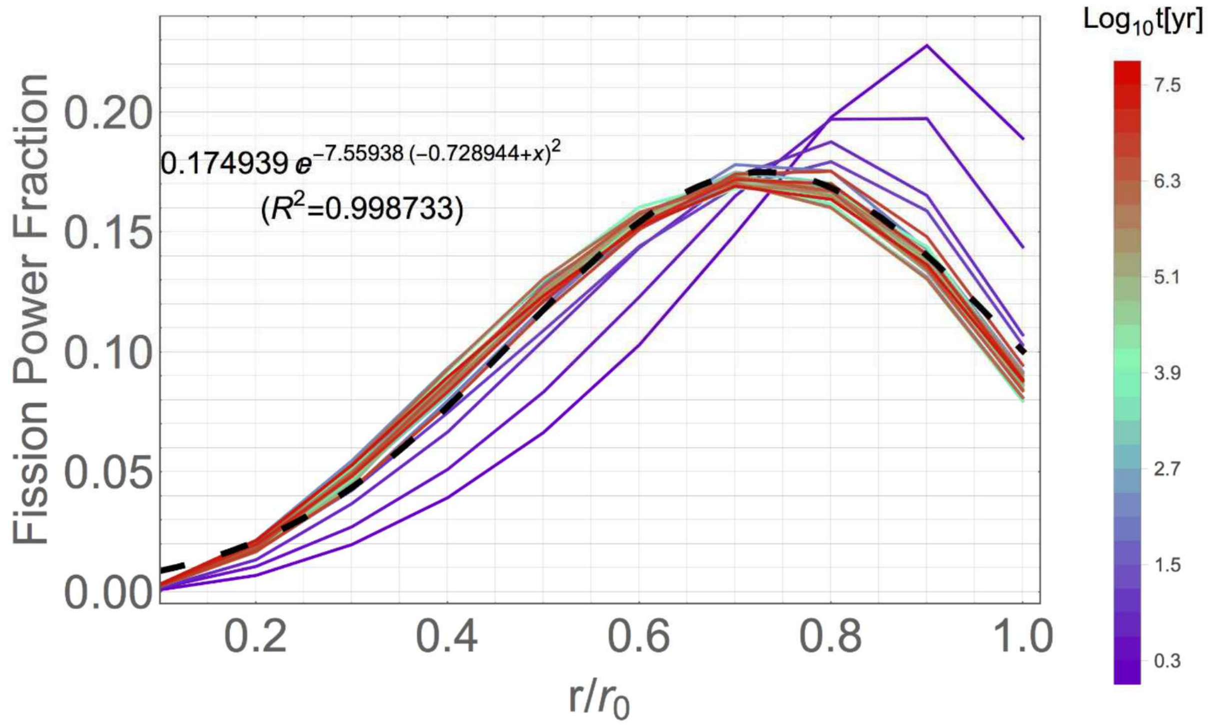


[POSIVA]

Expanded view of criticality safety criteria for repository loading

Fission Power in Precipitate Varies Radially

- CINDER module in MCNP6.1 employed for depletion to probe the spatial distribution of fission reactions
- Gradual time steps leading up to 10^8 years
- Peaked fission power distribution from shale reflector



Fission power distribution in the critical mass for 100 MT Fractured geometry at 10 kW_t output for 2.25 wt% enriched precipitate