Impacts of Nuclear Fuel Cycle Choices on Permanent Disposal of High-Activity Radioactive Waste

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Study of the "Merits and Viability of Different Nuclear Fuel Cycles and
Technology Options and the Waste Aspects of Advanced Nuclear Reactors"

Outline

- How geologic disposal concepts work
- How alternative nuclear fuel cycles might change waste forms requiring deep geologic disposal
- How existing safety assessments inform observations about the impacts of such changes on repository performance (examples from multiple programs)
- Conclusions
  - Are there specific waste forms that might facilitate or complicate disposal?

Much of the content of this presentation is derived from Swift, P. N., and D.C. Sassani, 2020, "Impacts of nuclear fuel cycle choices on permanent disposal of high-activity radioactive wastes," proceedings of the *International Conference on Management of Spent Fuel from Nuclear Power Reactors: Learning from the Past, Enabling the Future,* Vienna, Austria, 24-28 June, 2019, IAEA-CN-272-185. https://inis.iaea.org/search/search.aspx?orig_q=RN:51081645

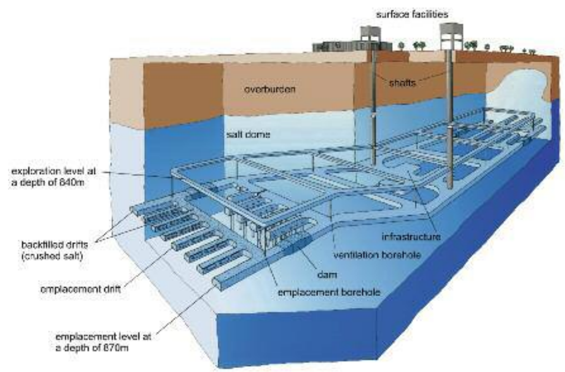
Deep Geological Disposal for Spent Nuclear Fuel and High-Level Radioactive Waste

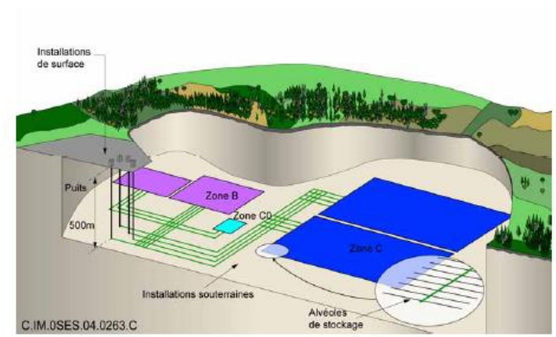
"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."

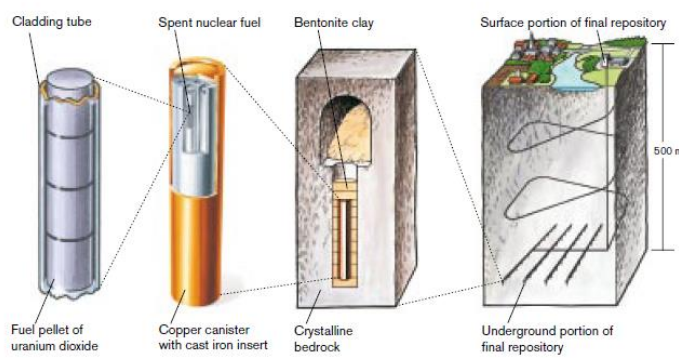
"Geological disposal remains the only long-term solution available."

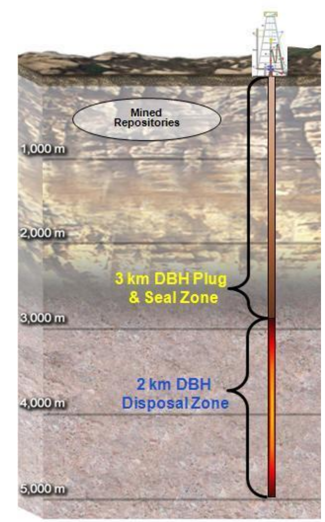
National Research Council, 2001

Deep geologic disposal has been planned since the 1950s









How Repositories Work

Natural barriers prevent or delay water from reaching waste form

Engineered barriers prevent or delay water from reaching waste form

Slow degradation of waste form limits exposure to water

Near Field: water chemistry limits aqueous concentrations

Natural and engineered barriers prevent or delay transport of radionuclides to the human environment

Overall performance relies on multiple components; different disposal concepts emphasize different barriers

Time (radioactive decay)

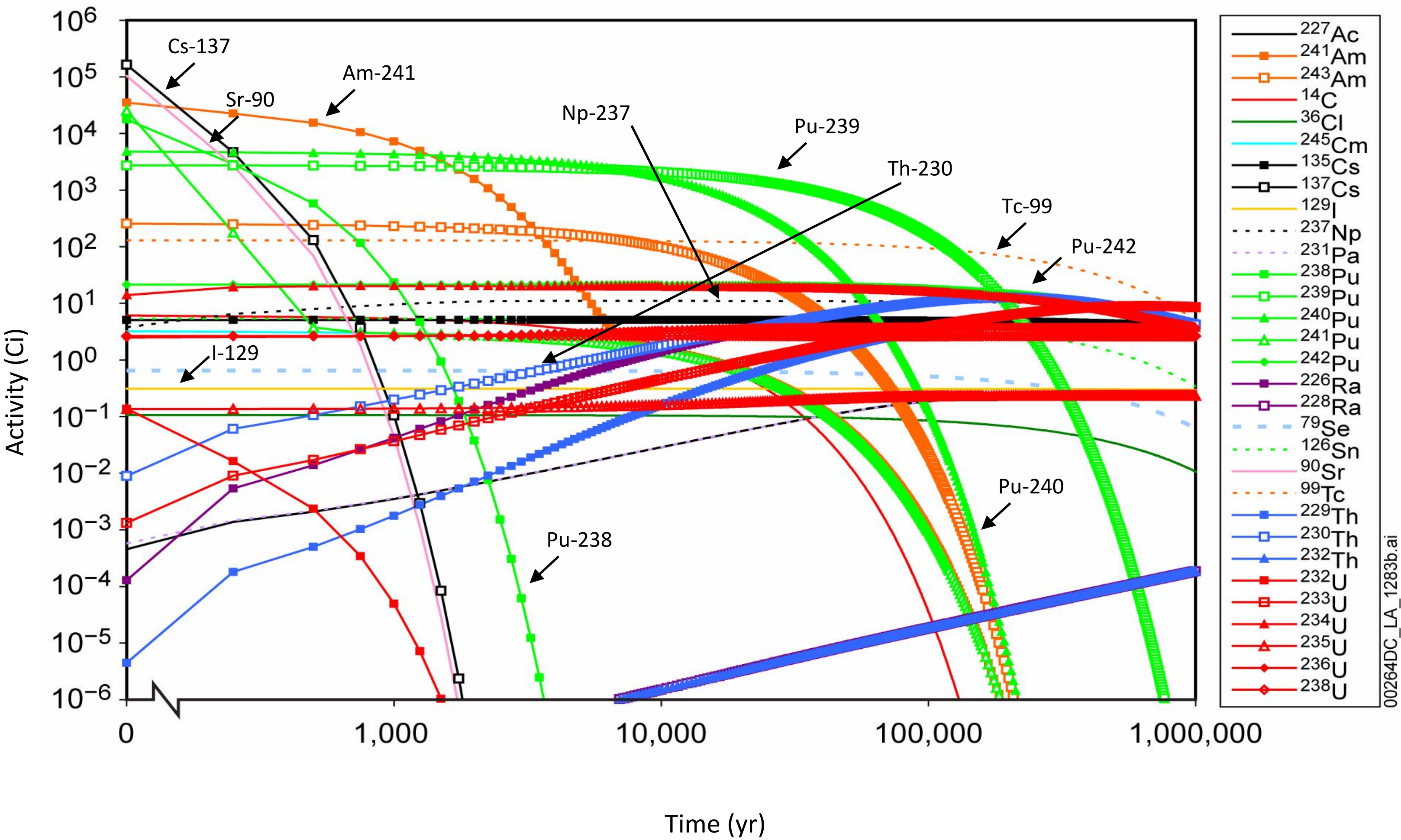
Isolation mechanisms may differ for different nuclides in different disposal concepts

How Might Alternative Nuclear Fuel Cycles Impact Geologic Disposal?

- For a given amount of electric power, alternative fission-based nuclear fuel cycles may result in
  - Changes in the radionuclide inventory
    - *Reprocessing and higher burnup can reduce actinide content of final waste product*
  - Changes in the volume of waste
    - *Reprocessing can reduce the volume of waste requiring deep geologic disposal*
  - Changes in the thermal power of the waste
    - *Separation of minor actinides can reduce thermal power of the final waste form*
  - Changes in the durability of the waste in repository environments
    - *Treatment of waste streams can create more durable waste forms*
- For each potential change, consider
  - How will these changes impact disposal system safety
  - How will these changes impact disposal system cost and efficiency

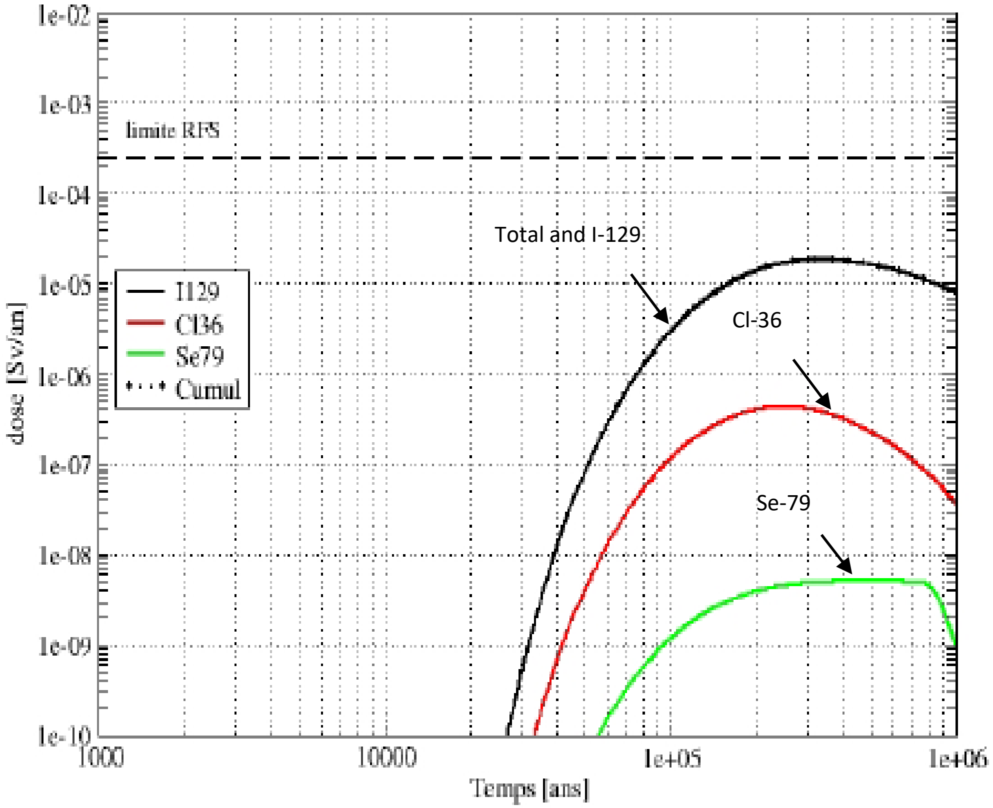
Light-Water Reactor Spent Nuclear Fuel Composition through Time

Example from US Program



DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for a single representative Yucca Mountain spent fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Estimated Long-term Dose: Meuse/Haute Marne Site (France)

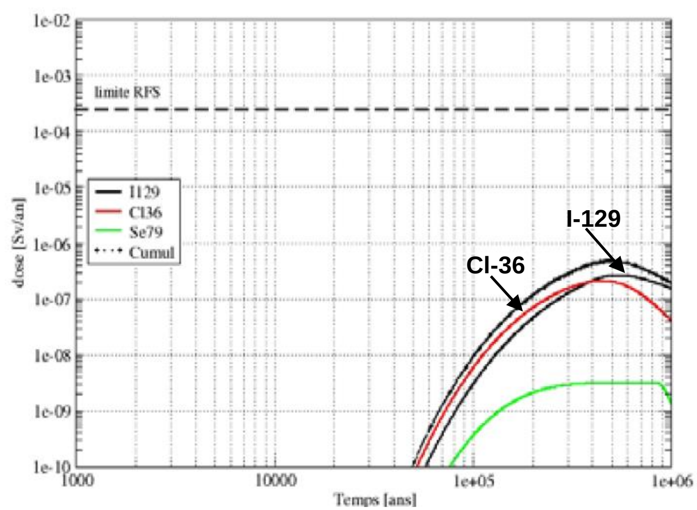


ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, million year model for spent nuclear fuel disposal and Figure 5.5-22, million year model for vitrified waste disposal

Diffusion-dominated disposal concept: Argillite

I-129 is the dominant contributor at peak dose

Examples shown for disposal of SNF (left) and HLW glass (below)



Estimated Long-term Dose: SNF, Forsmark Site (Sweden)

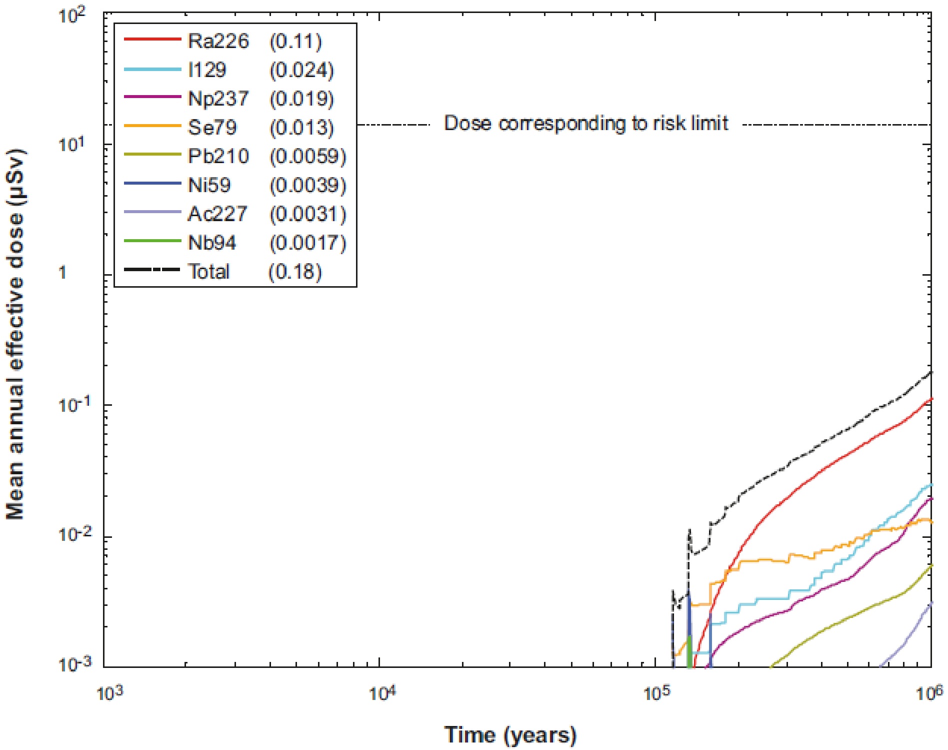


Figure 13-18. *Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).*

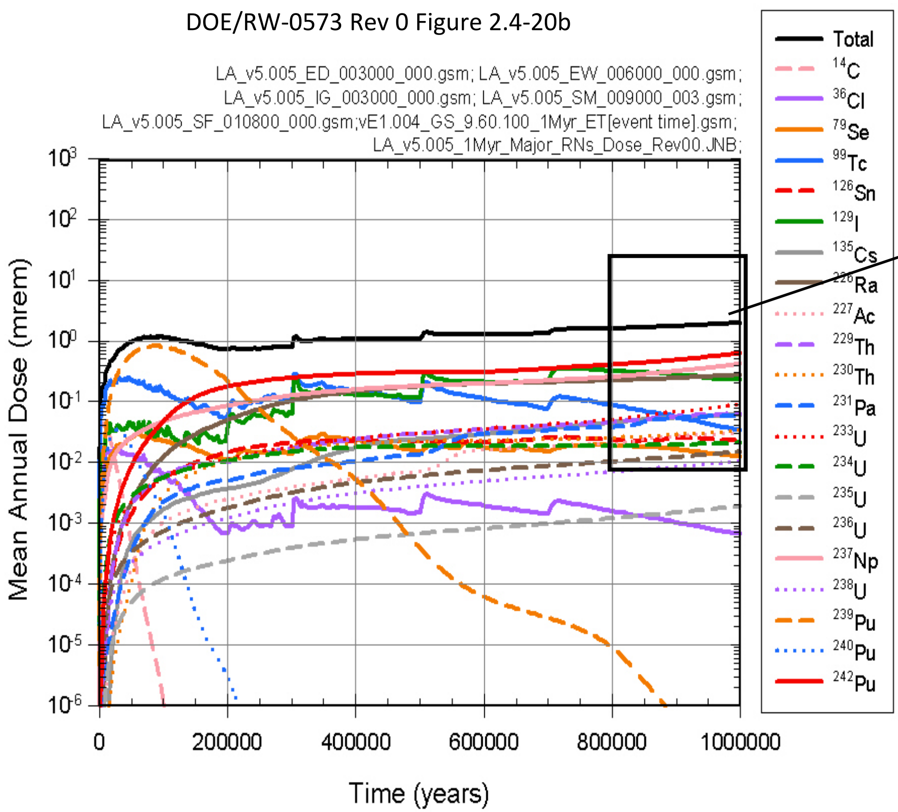
SKB 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01

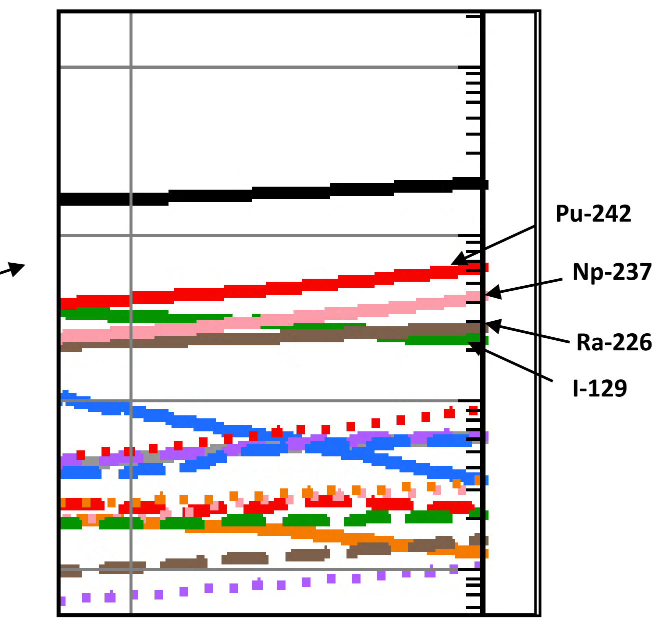
Disposal concept with advective fracture transport in the far-field: Granite

Long-term peak dose dominated by Ra-226

Once corrosion failure occurs, dose is primarily controlled by fuel dissolution and diffusion through buffer rather than far-field retardation

Estimated Long-term Dose: proposed Yucca Mountain Site (USA)





Disposal concept with an oxidizing environment and advective transport in the far-field: Fractured Tuff

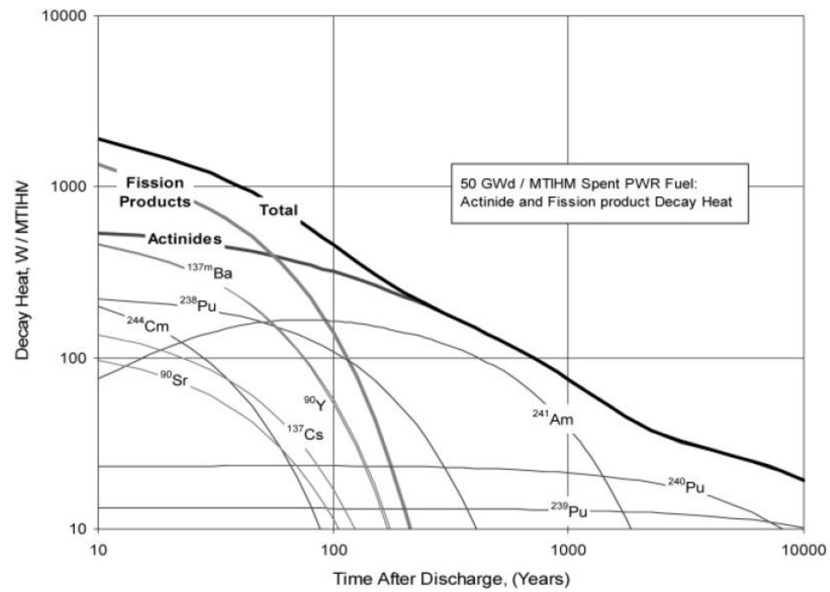
Actinides are significant contributors to dose; I-129 is approx. 1/10th of total

Waste Volume and Thermal Power Considerations

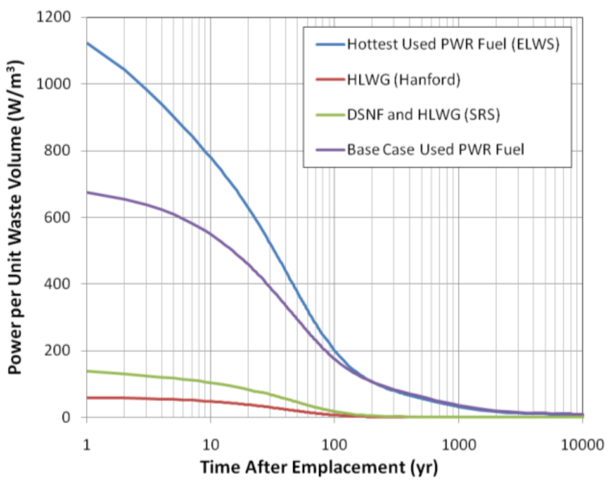
Repository thermal constraints are design-specific

Options for meeting thermal constraints include

- Design choices including size and spacing of waste packages
- Operational practices including aging and ventilation
- Modifications to waste forms



Thermal decay of light water reactor spent nuclear fuel (from Wigeland et al., 2006, Figure 1)



Calculated thermal power density vs. time for representative Yucca Mountain waste forms (from Swift et al., 2010, figure 1)

Selection of optimal volume and thermal loading criteria will depend on multiple factors evaluated across entire fuel cycle, including cost and operational efficiency

Waste Volume and Thermal Power Considerations (cont.)

- To a first approximation, waste volume and thermal power density have an inverse correlation
  - All other factors held constant, reductions in volume increase thermal power density
  - Relevant metric is disposal volume, i.e., the excavated volume needed per unit volume of waste, which is a function of repository design as well as waste properties
- Volume of HLW is process-dependent
  - Existing processes can achieve substantial reductions in disposal volume
    - 30-40% of disposal volume relative to spent fuel (including packaging)
    - Up to 8% of fuel disposal volume with 100-yr aging period (van Lensa et al., 2010, table 7.1)
  - Advanced processes may achieve lower volumes of HLW
- Thermal power density of HLW can be engineered over a wide range
  - Thermal power correlates to fission-product loading at early times
- Waste volume does not correlate to long-term performance
  - It does affect cost (excavated volume and, ultimately, total number of repositories)
  - Volume of low-level waste also contributes to total cost

Waste Form Lifetime Example: HLW Meuse/Haute Marne Site

Base case model: glass "release periods on the order of a few hundred thousand years" (Model assumes degradation rate decreases when surrounding medium is saturated in silica: Andra 2005, p. 221)

Sensitivity analysis assuming rapid degradation (100s to 1000s of yr) accelerates peak concentrations at outlet by ~200 kyr, with only a modest increase in magnitude of modeled peak dose

Conclusion: Slow diffusive transport is more important to the modeled performance of this system than waste form lifetime.

	Maximum molar flow exiting Callovo-Oxfordian (mol/yr) and maximum dates (yrs.)	
	Reference	Sensitivity
^{129}I	$8.6.10^{-4}$ 460,000 yrs	$9.1.10^{-4}$ 250,000 yrs
^{36}Cl	$2.2.10^{-4}$ 380,000 yrs	$3.8.10^{-4}$ 190,000 yrs

Table 5.5-24 SEN - Attenuation ^{129}I and ^{36}Cl – C1+C2 – comparison between the models $V_0.S$ (sensitivity) and the model $V_0.S \rightarrow V_r$

Impact of changes in HLW glass degradation rate on modeled radionuclide concentrations in groundwater, ANDRA 2005 Table 5.5-24

Waste Form Lifetime Example: Spent Nuclear Fuel, Forsmark Site (2006 analysis)

- Fractional dissolution rate range 10^{-6}/yr to 10^{-8}/yr
  - Corresponding fuel lifetimes: ~ 1 Myr to 100 Myr
  - Dissolution rates for oxidizing conditions (not anticipated), up to 10^{-4}/yr
- Conclusion: Uncertainty in fuel dissolution rate can be a dominant contributor to uncertainty in modeled performance of sites with relatively rapid transport

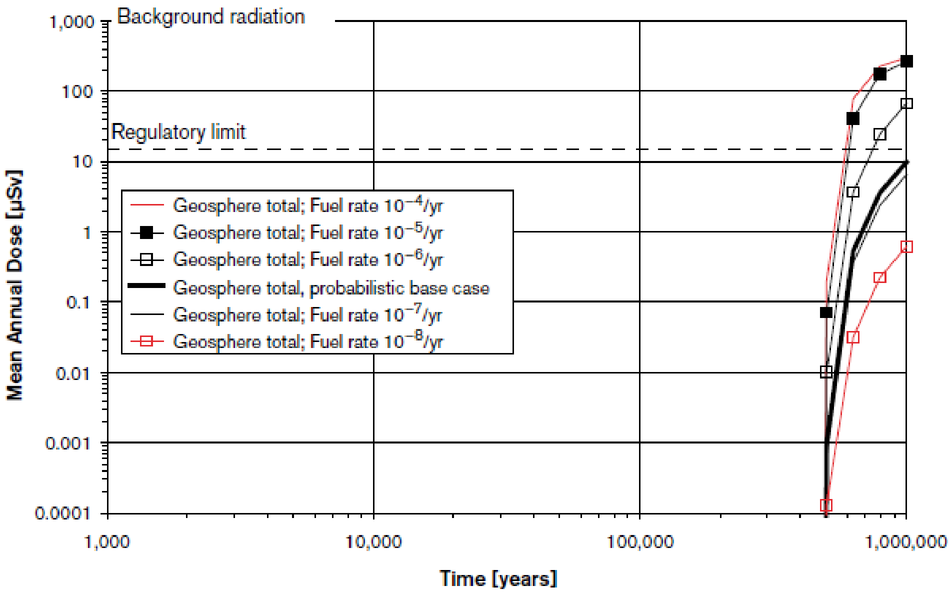


Figure 10-44. *Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.*

Source: SKB 2006, *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar—a First Evaluation,* TR-06-09, section 10.6.5

Also, SKB 2006, *Fuel and Canister Process Report for the Safety Assessment SR-Can,* TR-06-22, section 2.5.5

Conclusions

- For all disposal concepts, potential benefits of alternative fuel cycle choices will be considered in the context of system-level costs and benefits, including operations as well as disposal
- Alternative fuel cycle choices can reduce waste volume
    - Without century-scale surface aging of fission products, reductions in disposal volume may be limited to 30-40% of the disposal volume of the unprocessed fuel
- Alternative fuel cycle choices will have modest impacts on thermal load management without century-scale aging of fission products
    - Fission products may need geologic disposal regardless, depending on regulatory criteria
- The impact of long-lived waste forms on repository performance varies with disposal concept
    - For some disposal concepts, long-lived waste forms can be important
- Most alternative fuel cycle choices will have little impact on estimates of long-term repository performance
    - Long-term dose estimates in most geologic settings are dominated by mobile species, primarily I-129

Conclusions (cont.)

- Are there specific waste forms that might facilitate or complicate permanent disposal?
  - System-level operational cost, safety, and safeguards are essential considerations
    - Operational considerations must include secondary waste streams
  - Potentially beneficial long-term safety attributes include
    - Waste form durability/reductions in chemical reactivity
    - Reductions in nuclear reactivity
  - Potentially detrimental long-term safety attributes include
    - Increases in chemical reactivity (e.g., pyrophoricity, corrosivity)
    - Increases in total mass of problematic waste forms
  - Essentially all proposed future waste forms have analogs that exist today, at least in small quantities and in prototype forms, and have been considered in published assessments (e.g., DOE 2008)
    - Existing geologic disposal concepts can accommodate all existing waste forms without further treatment, except sodium-bonded fuels, which may require treatment prior to disposal (SNL 2014)

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