Sandia National Laboratories

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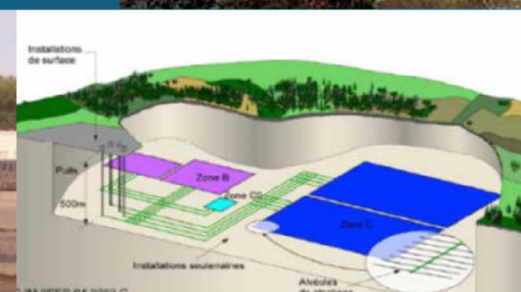
Impacts of Nuclear Fuel Cycle Choices on Permanent Disposal of High-Activity Radioactive Wastes



PRESENTED BY

Peter Swift and David Sassani

International Atomic Energy Agency International Conference on the Management of Spent Fuel from Nuclear Power Reactors

24-28 June 2019, Vienna, Austria

SWIFT AND SASSANI 2019 IAEA SPENT FUEL MANAGEMENT CONFERENCE CN-272-185

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Outline

Disposal concepts

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

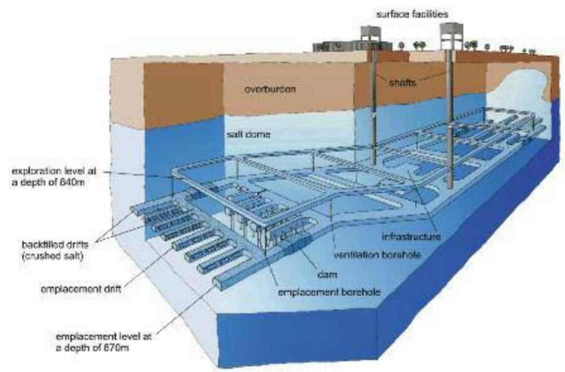
Deep Geological Disposal for Spent Nuclear Fuel and High-Level Radioactive Waste

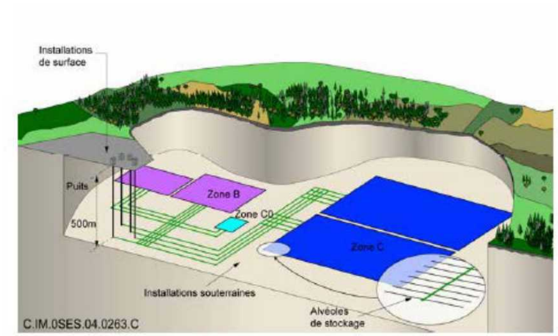
"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."

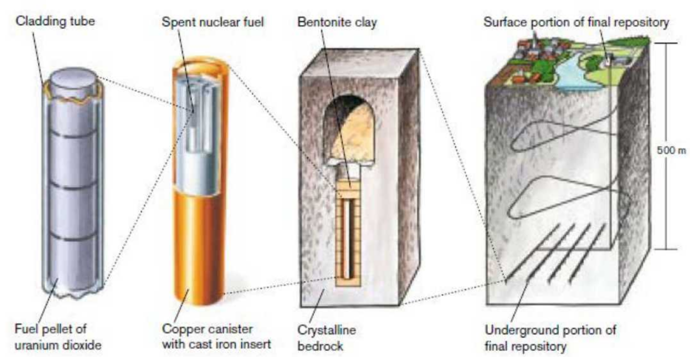
"Geological disposal remains the only long-term solution available."

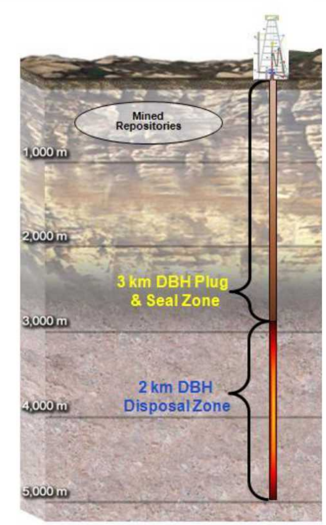
National Research Council, 2001

Deep geologic disposal has been planned since the 1950s









Status of Deep Geologic Disposal Programs World-Wide

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Operations application to be submitted in 2020
Sweden	Granite	License application submitted 2011
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended
Others: Belgium (clay), Korea (granite), Japan (sedimentary rock, granite), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), all nations with nuclear power. Source: Information from Faybishenko et al., 2016		

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

Time (radioactive decay)

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

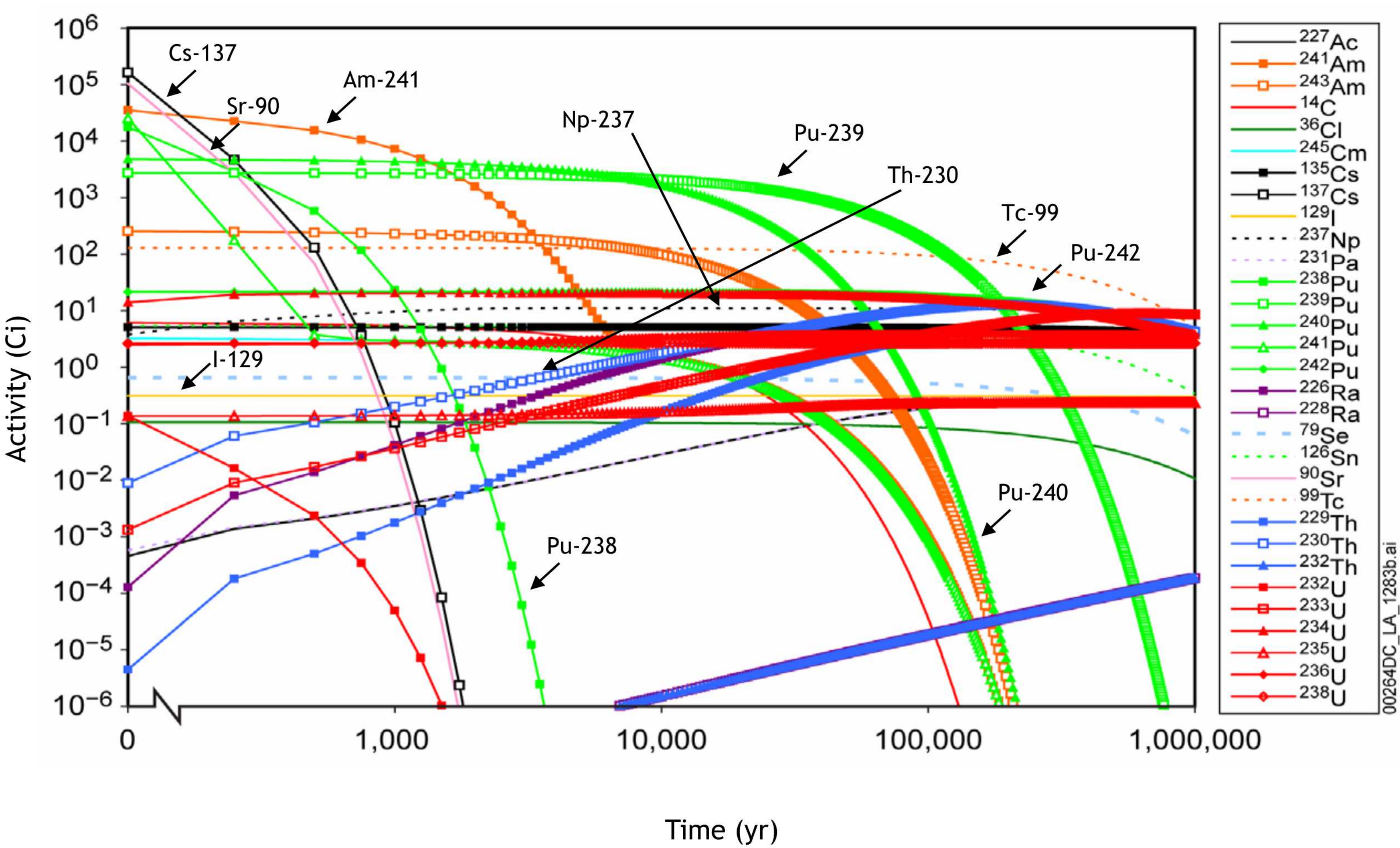
Isolation mechanisms may differ for different nuclides in different disposal concepts

How Might Alternative Nuclear Fuel Cycles Impact Geological Disposal?

- For a given amount of electric power, alternative fission-based nuclear fuel cycles may result in
  - Changes in the radionuclide inventory
    - *Reprocessing 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 repository safety
  - How will these changes impact repository cost and efficiency

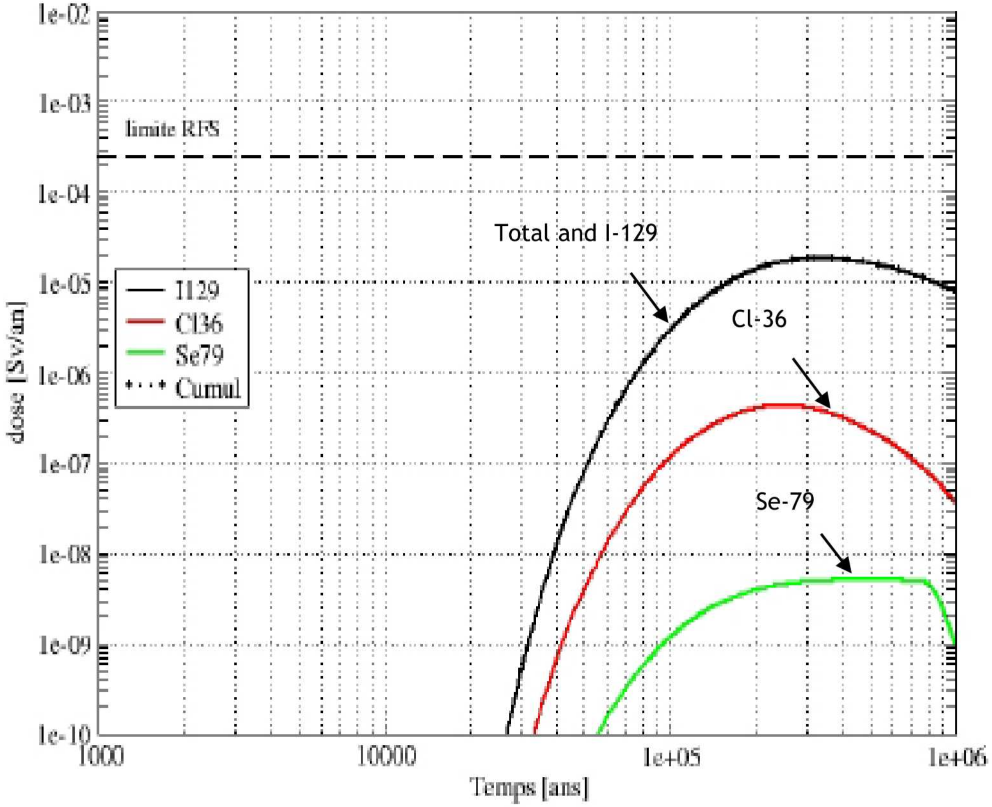
Light-Water Reactor Spent Nuclear Fuel Decay

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.

Contributors to Total Dose: Meuse / Haute Marne Site (France)

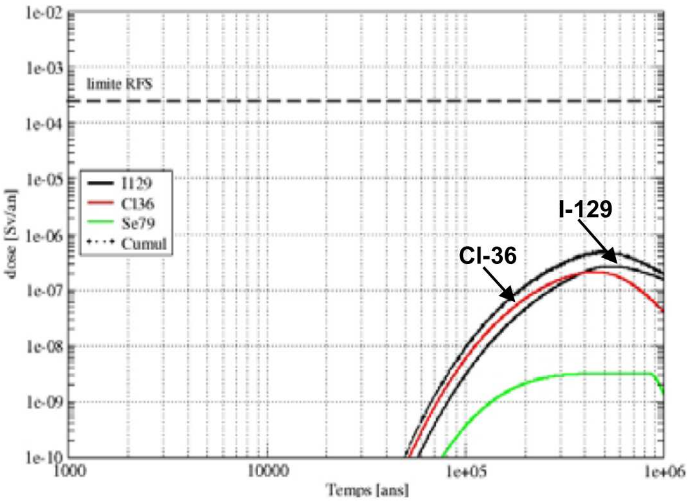


ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, million year model for spent nuclear fuel disposal and Figure 5.5-22, million year model for vitrified waste disposal

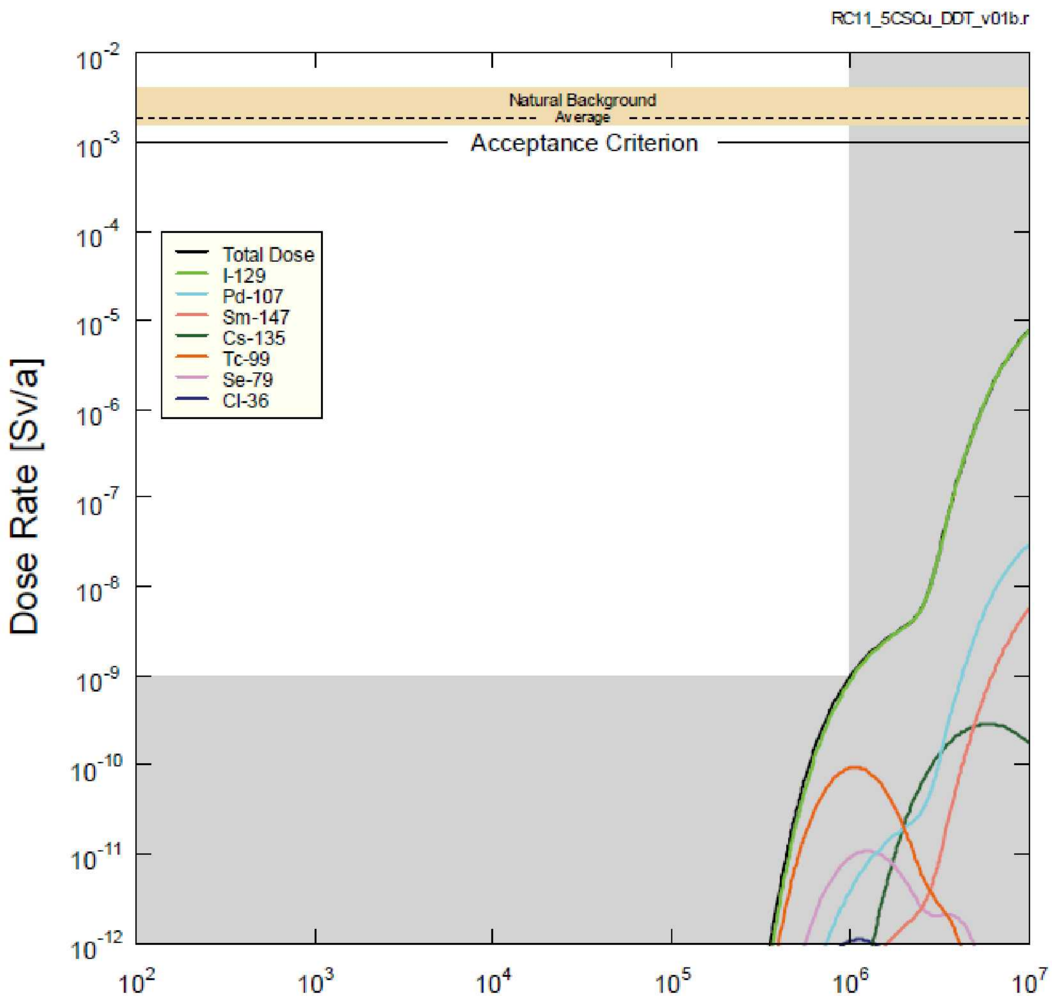
Diffusion-dominated disposal concept: Argillite

I-129 is the dominant contributor at peak dose

Examples shown for direct disposal of spent fuel (left) and vitrified waste (below)



Contributors to Total Dose: Hypothetical Site (Canada)



NWMO 2013, Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07, Figure 7-96.

Diffusion-dominated disposal concept: spent fuel disposal in unfractured carbonate host rock

Long-lived copper waste packages and long diffusive transport path

All waste packages assumed to fail at 60,000 years for this simulation; primary barriers are slow dissolution of SNF and long diffusion paths

Major contributor to peak dose is I-129

Contributors to Total Dose: Forsmark site (Sweden)

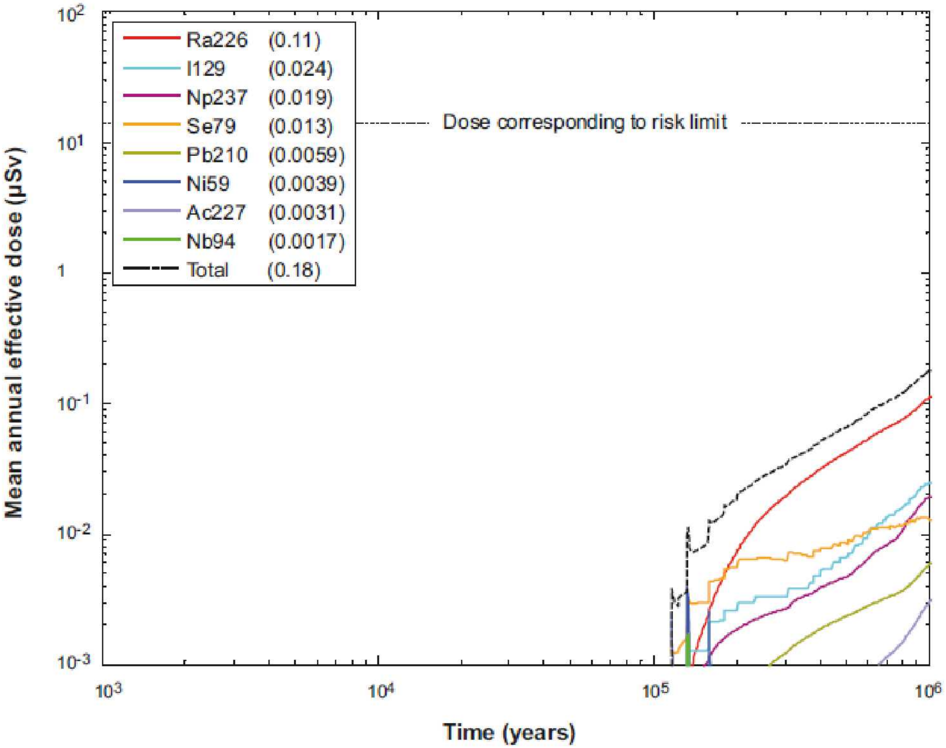


Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).

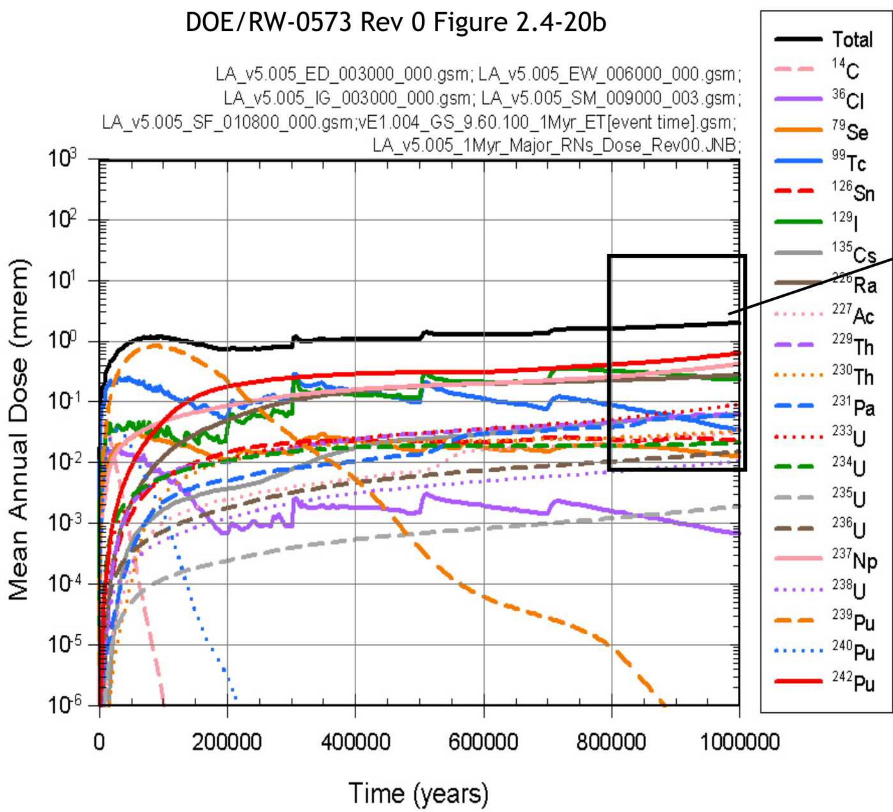
SKB 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01

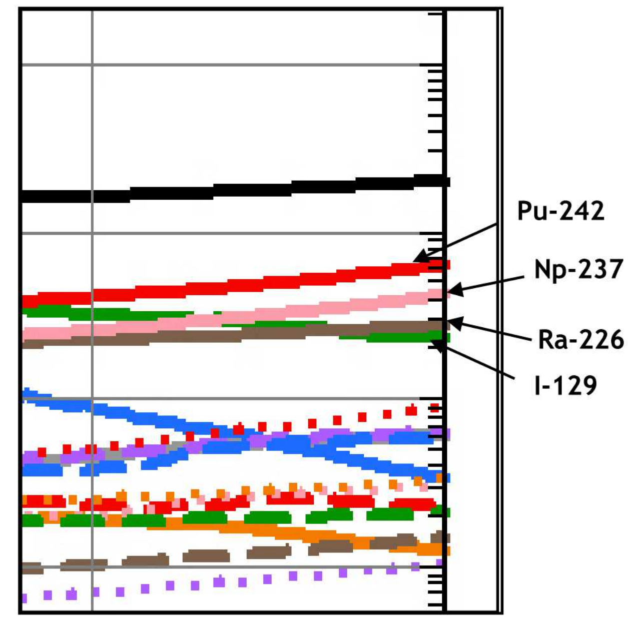
Disposal concept with advective fracture transport in the far-field: Granite

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

Contributors to Total Dose: Yucca Mountain (USA)





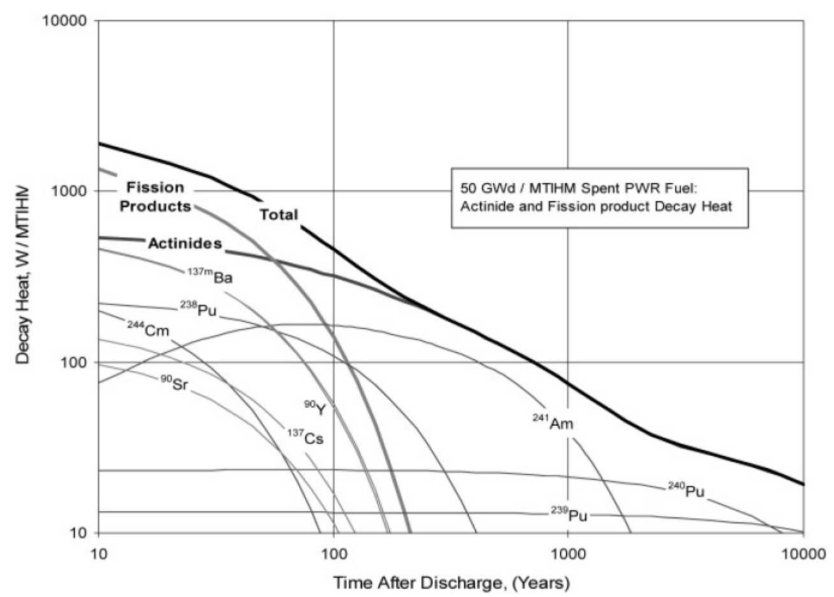
Disposal concept with an oxidizing environment and advective transport in the far-field: Fractured Tuff

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

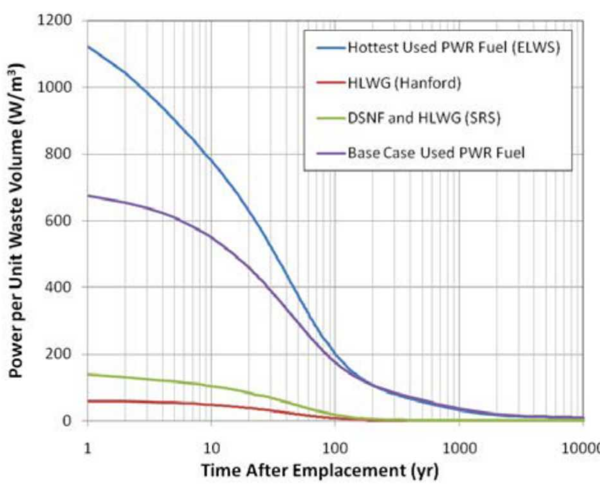
Waste Volume and Thermal Power Considerations

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 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 inversely to volume without separation of heat-generating radionuclides

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: Meuse / Haute Marne Site

HLW

- Base case model: glass "release periods on the order of a few hundred thousand years" (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, modest increase in magnitude of modeled peak dose
  - **For rapid degradation case, modeled releases are controlled by diffusive transport time in clay**

	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 Examples: Forsmark Site

Used fuel

- 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
- Uncertainty in fuel dissolution rate can be a dominant contributor to uncertainty in modeled total dose estimates for sites with relatively rapid transport

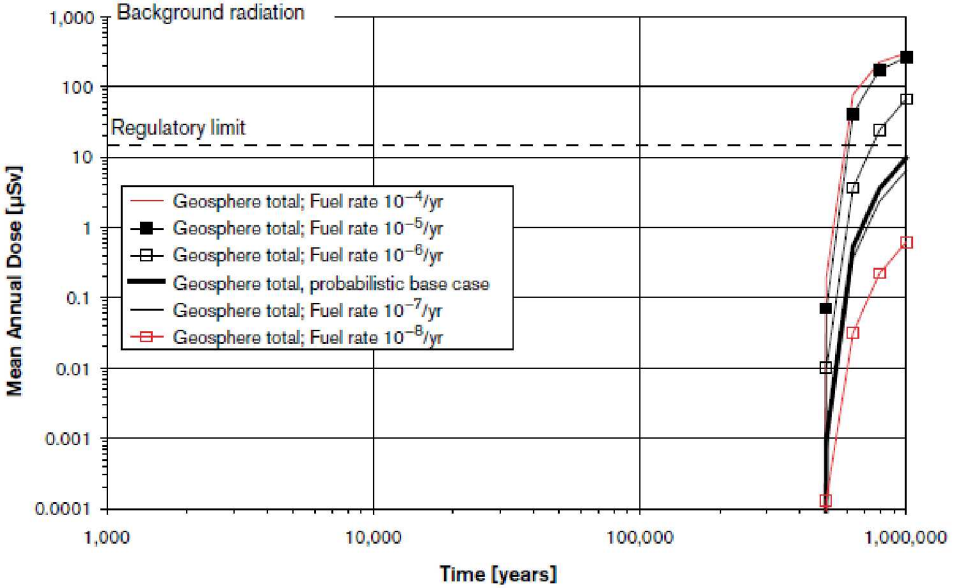


Figure 10-44. Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.

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 operational costs and benefits

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 little impact 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

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

References

ANDRA (Agence nationale pour la gestion des déchets radioactifs), 2005. Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository (English translation: original documentation written in French remains ultimately the reference documentation).

Faybishenko, B., Birkholzer, J., Sassani, D., and Swift, P., 2016. International Approaches for Deep Geological Disposal of Nuclear Waste: Geological Challenges in Radioactive Waste Isolation, Fifth Worldwide Review, LBNL-1006984, Lawrence Berkeley National Laboratory.

NAGRA (Nationale Genossenschaft für die Lagerung Radioactiver Abfälle [National Cooperative for the Disposal of Radioactive Waste]), 2002, *Project Opalinus Clay Safety Report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis),* Technical Report 02-05.

National Research Council / National Academies, 2001. Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges, Washington, DC, National Academy Press.

NWMO (Nuclear Waste Management Organization), 2013. Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07.

Posiva Oy, 2012, Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto—Synthesis 2012, POSIVA 2012-12.

SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2006. Long-Term Safety KBS-3 Repositories at Forsmark and Laxemar—a First Evaluatin, TR-06-09.

SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2006. Fuel and Canister Process Report for the Safety Assessment SR-Can, TR-06-22.

SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2011. Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark: Main Report of the SR-Site Project, Technical Report TR-11-01.

Swift, P.N., and W.M. Nutt, 2010. "Applying Insights from Repository Safety Assessments to Evaluating Impacts of Partitionin g and Transmutation," Proceedings of the 11th OECD-NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, CA, November 1-4, 2010.

Swift, P.N., C.W. Hansen, E. Hardin, R.J. MacKinnon, D. Sassani, S. D. Sevougian, 2010. "Potential Impacts of Alternative Wa ste Forms on Long-Term Performance of Geological Repositories for Radioactive Waste." Proceedings of PSAM-10, June 7-11, 2010, Seattle, WA.

US DOE (United States Department of Energy) 2008. Yucca Mountain Repository License Application, DOE/RW -0573, Rev. 1.

von Lensa, W., R. Rabbi, M. Rossbach, 2008, *RED-IMPACT: Impact of Partitioning, transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal, Synthesis Report*, Forschungszentrum Jülich GmbH. 178 p.

Wigeland, R.A., T.H. Fanning, and E.E. Morris, 2006, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," *Nuclear Technology* v. 154.