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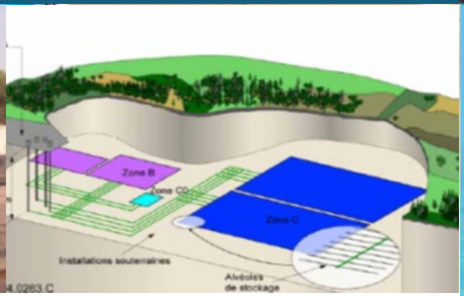
Geologic Disposal Considerations for Potential Waste Streams from Advanced Reactors



PRESENTED BY

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45th Scientific Basis for Nuclear Waste Management Symposium

October 26, 2021. Virtual Conference

SASSANI ET AL., 2021: 45TH SCIENTIFIC BASIS FOR NUCLEAR WASTE MANAGEMENT SYMPOSIUM

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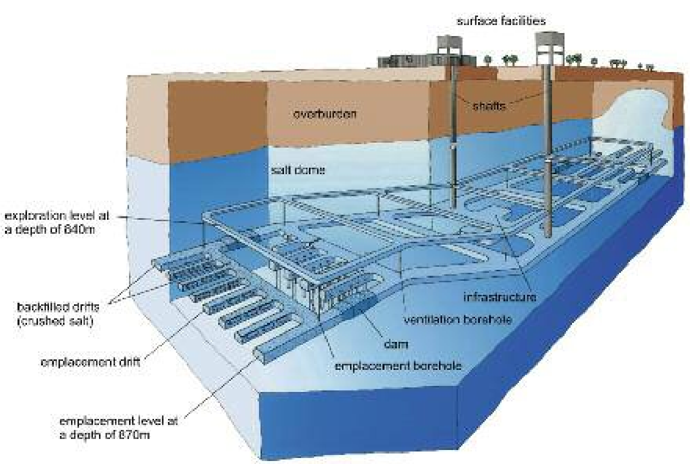
Outline

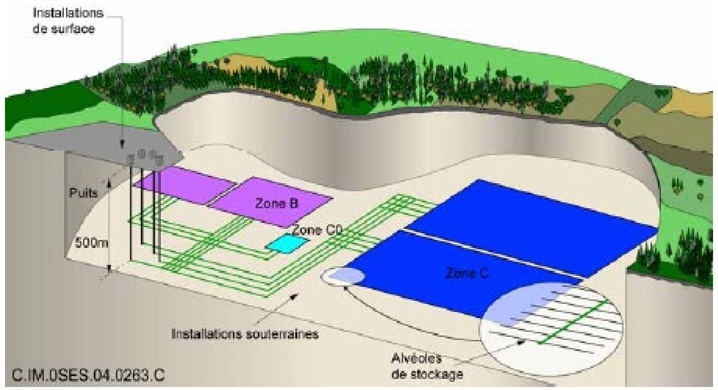
- Disposal concepts
- Waste characteristics affecting disposal and considerations for potential waste forms from advanced reactors (AR)
- How alternative nuclear fuel cycles might affect waste forms for deep geologic disposal
- How existing safety assessments inform observations about the impacts of such changes on repository performance (examples from multiple programs)
- Conclusions

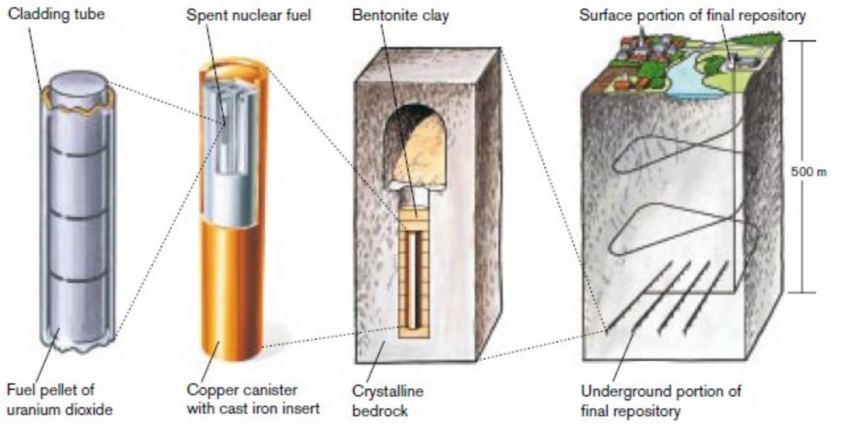
Deep Geological Disposal for Spent Nuclear Fuel and High-Level Radioactive Waste

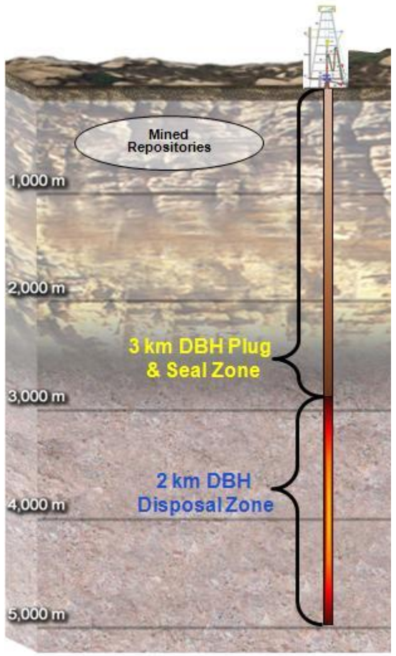
> "There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."
>
> "Geological disposal remains the only long-term solution available."
>
> National Research Council, 2001

Deep geologic disposal has been evaluated/planned since the 1950s









SASSANI ET AL., 2021; 45TH SBNWM SYMPOSIUM

Status of Deep Geologic Disposal Programs World-Wide

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Start of final disposal planned for mid -2020s
Sweden	Granite	License application submitted 2011 Local municipalities gave approval Oct. 2020 Construction planned to start in mid-2020s
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
Japan	TBD	Candidate sites being identified
Korea	TBD	Candidate sites being identified

Others: Belgium (clay), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), all nations with nuclear power.

Sources: Faybishenko et al. 2016; World Nuclear News 2020; Posiva Oy 2019; ABC News 2020; Wiley Online Library 2020

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

Technical Characteristics/Properties of Waste Forms to be Considered for Disposal Strategy

- In general, waste forms (WF) should be disposable in any of the possible generic geologic disposal concepts
  - Not striving to optimize waste forms for disposal geologies
- Waste form degradation rate (slow vs. very fast - e.g., salt wastes)
  - Reliance on WF performance varies by disposal concept
  - Deep borehole disposal may accommodate less robust WF – i.e., DBH does not rely very much on WF performance for postclosure safety
- Potential for criticality over repository time scales (e.g., dual purpose canisters; DPC)
  - Current SNF dry storage canisters are designed to prevent criticality over timescales commensurate with storage and transportation
  - DOE investigating
    - *Consequences of postclosure criticality on repository performance*
    - *Development of advanced neutron absorbers*
    - *Filler material addition to DPC*

Technical Characteristics/Properties of Waste Forms to be Considered for Disposal Strategy (cont'd)

- Thermal output per waste package (e.g., CSNF in DPC)
  - Thermal limits per waste package vary by repository concept: geologic media and repository design
  - Options include repackaging, long-term above-ground storage, spacing of waste packages and drifts
- Whether the WF is vigorously reactive to water (e.g., Na-bonded spent fuel)
  - Does WF produce aggressive/deleterious chemistry to engineered system?
- Chemical effects such as rate of gas generation (e.g., fluoride-based salt from molten salt reactors)

Disposal Options Considerations for Potential Waste Forms from Advanced Reactors (AR)

- Some existing DOE SNF are similar to potential advanced reactor fuels and have been included in US disposal program (DOE, 2008; SNL, 2014)
  - Only very minor component of disposal inventory
  - Included with very conservative instantaneous degradation rate
  - Some not included without treatment (e.g., Na-bonded SNF–not directly disposable)
- Use experience with DOE SNF from prior similar reactors for strategies
  - TRISO fuels – e.g., Fort St. Vrain
    - *Potential slow degradation rates (Sassani and Gelbard, 2019)*
    - *Possibly directly disposable with consideration of any specific differences: enrichment, etc.*
  - Metallic Na-bonded fuels – e.g., EBR-II, Fermi
    - *Need treatment to remove metallic sodium*
    - *Electrometallurgical treatment (EMT) makes metallic WF, salt waste*
  - ORNL molten salt reactor experiment – final waste form(s) not yet defined

Disposal Options Considerations for Potential Waste Forms from Advanced Reactors (AR) (cont'd)

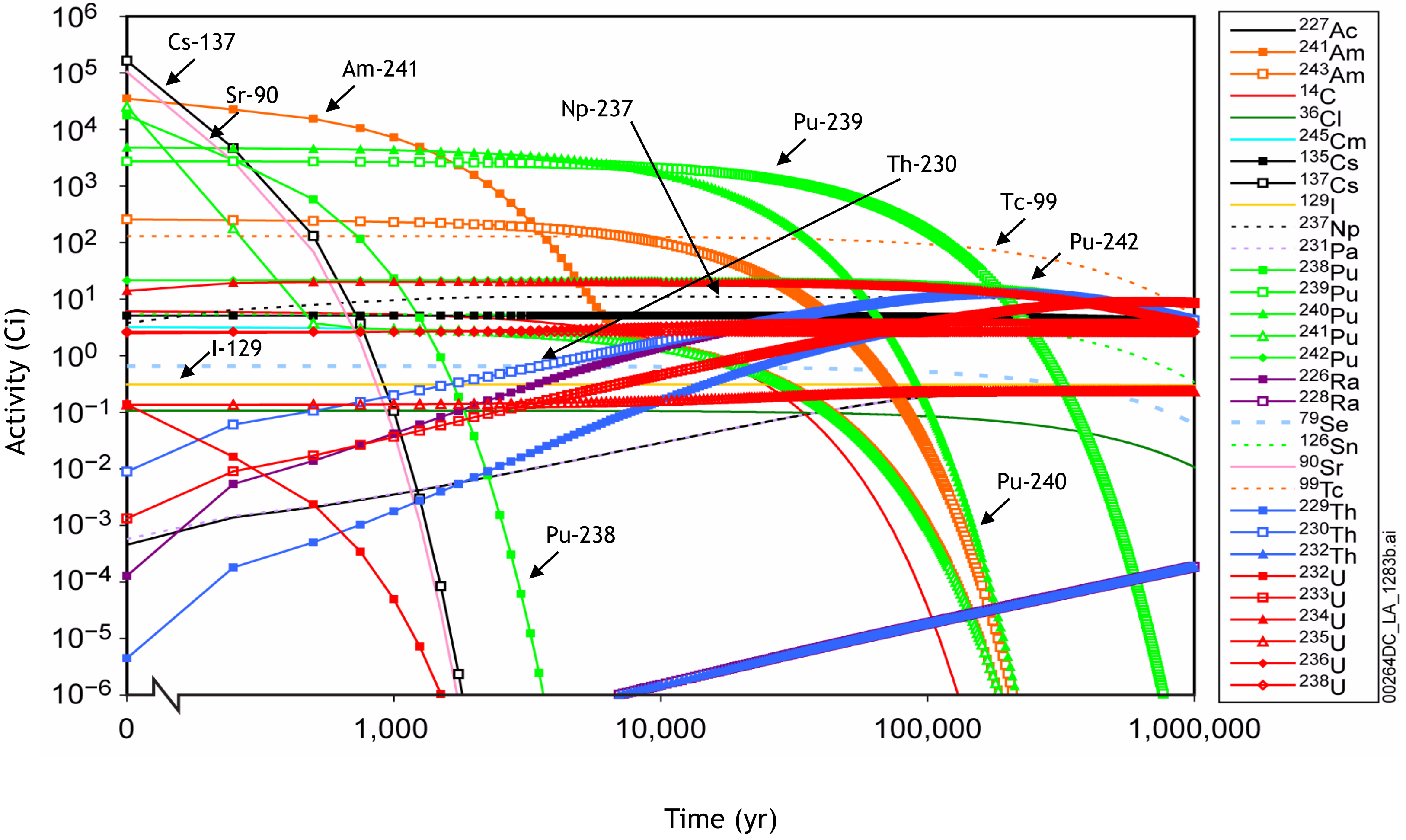
- For AR WF unique characteristics consider
  - Degradation rate behavior constraints are essential for primary disposal inventory
    - Ancillary chemical impacts should be evaluated
  - Potential for criticality over repository time scales needs to assess
    - *Enrichment*
    - *Burn-up specifics*
    - *Packaging (neutron absorbers)*
  - Thermal output per waste package is dependent on
    - *Fission product content*
    - *Packaging size*
    - *Aging and storage*
  - Secondary waste streams from operations and treatment

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 and materials
    - *Reprocessing can reduce actinide content of final waste product*
    - *Different materials for AR than in a typical LWR (e.g., graphite, chloride salts)*
  - Changes in the volume of waste
    - *Reprocessing can reduce the volume of waste requiring deep geologic disposal*
    - *Defining final waste form volumes needed for some AR*
  - Changes in the thermal power of the waste
    - *Separation of minor actinides can reduce thermal power of the final waste form*
    - *Higher enrichment/burnup AR fuels*
  - 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

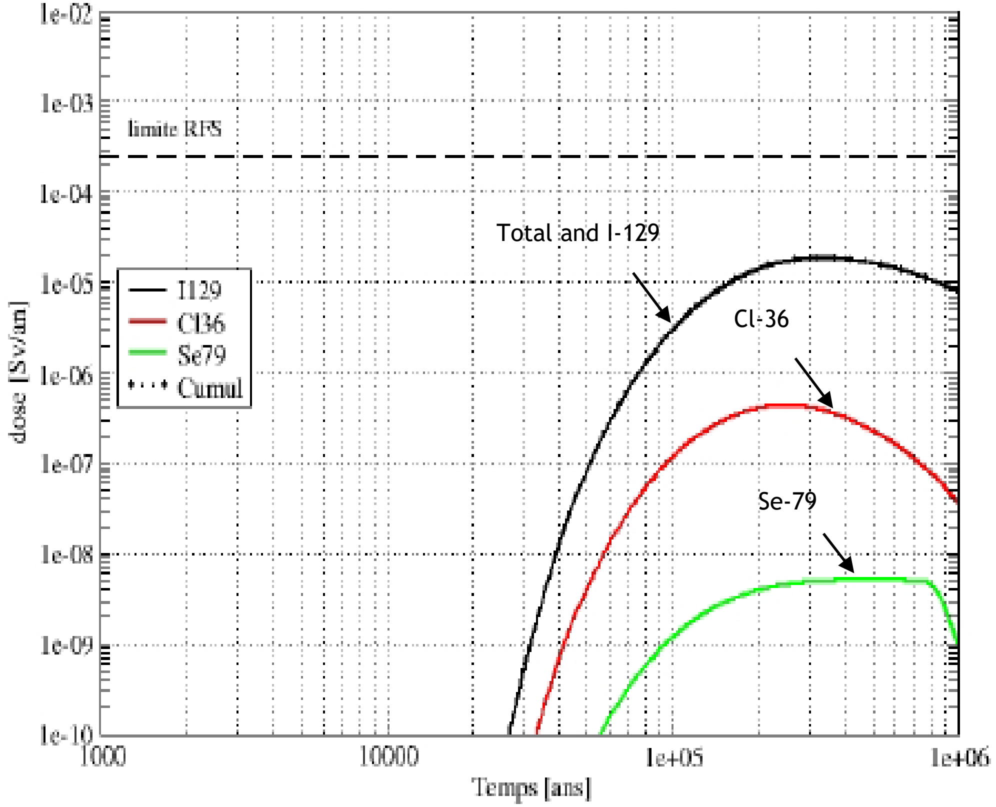
Light-Water Reactor Spent Nuclear Fuel Decay

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)

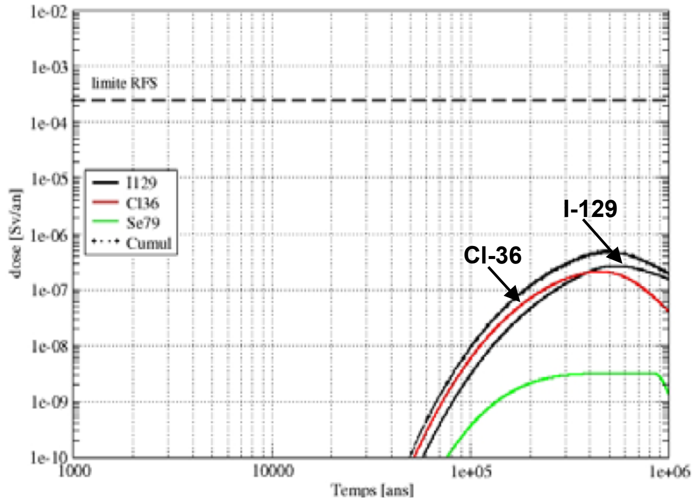


ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, million year model for spent nuclear fuel disposal and Figure 5.5-22, million year model for vitrified waste disposal

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: Forsmark site (Sweden)

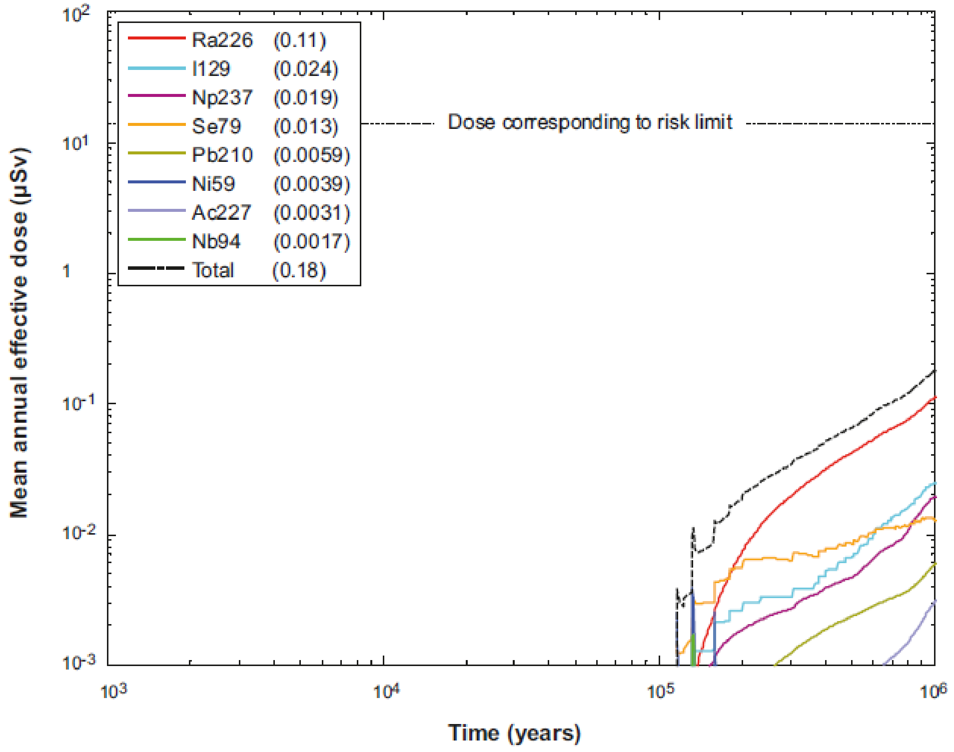


Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in μSv).

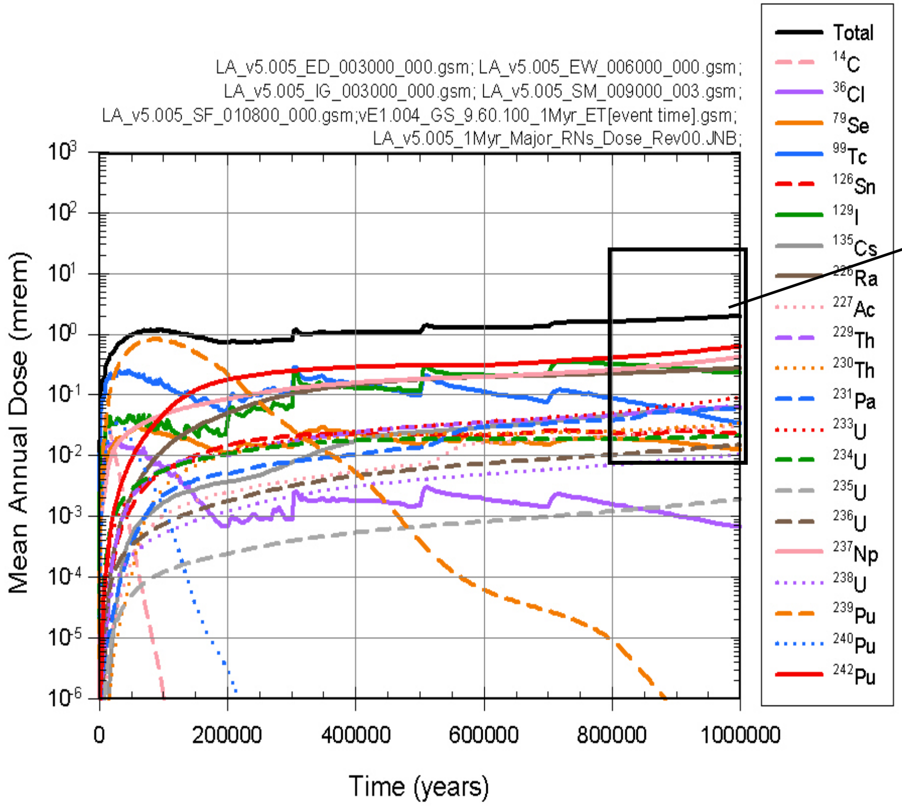
SKB 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01

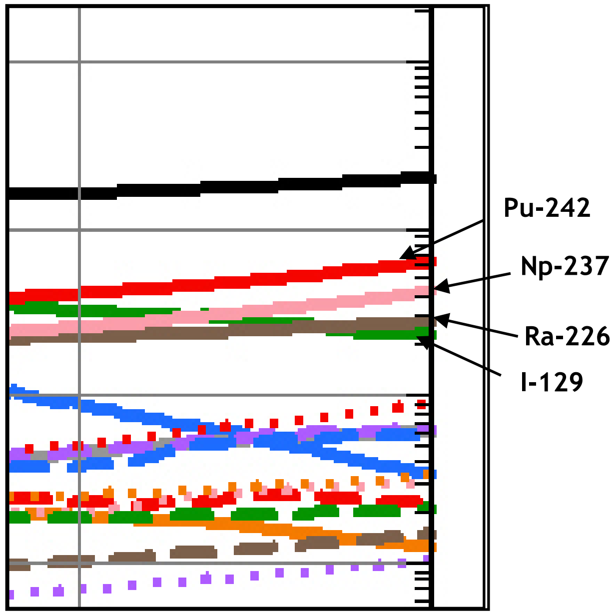
Disposal concept with advective fracture transport in the far-field: Granite

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)





DOE/RW-0573 Rev 0 Figure 2.4-20b

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

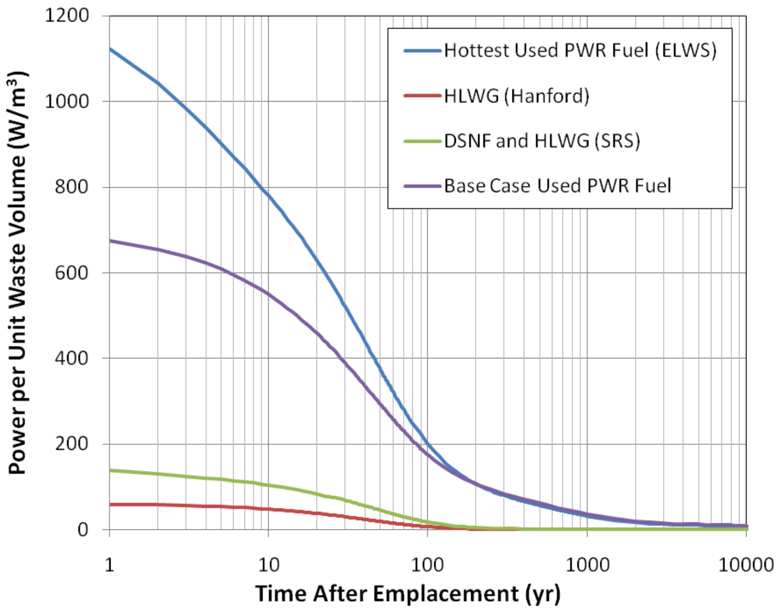
Actinides are significant contributors to dose; I-129 is approx. 1/10th of total

Waste Volume and Thermal Power Considerations

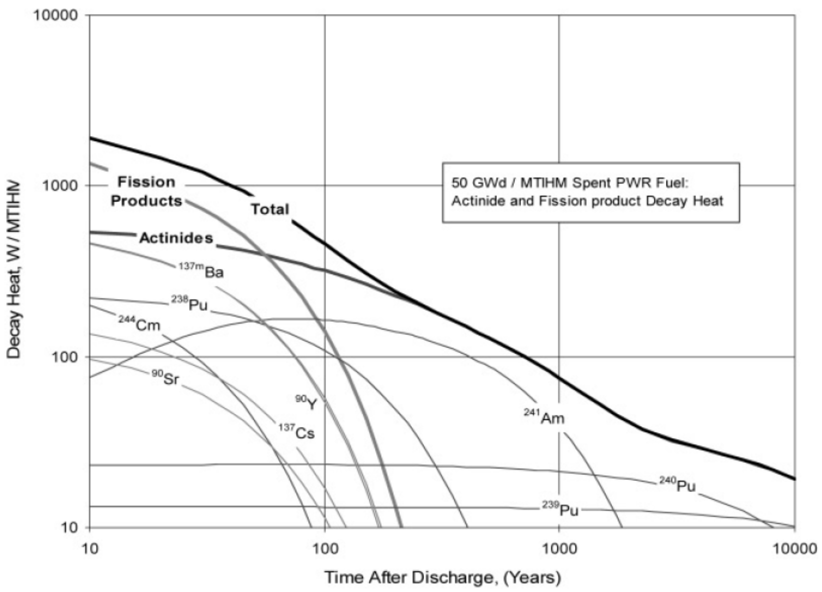
Repository thermal constraints are design-specific

Options for meeting thermal constraints include

- Design choices: e.g. waste package size and spacing
- Operational practices: e.g. aging and ventilation
- Modifications to waste forms



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



Thermal decay of light water reactor spent nuclear fuel (from Wigeland et al., 2006, 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 without separation of heat-generating radionuclides
  - 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
- 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

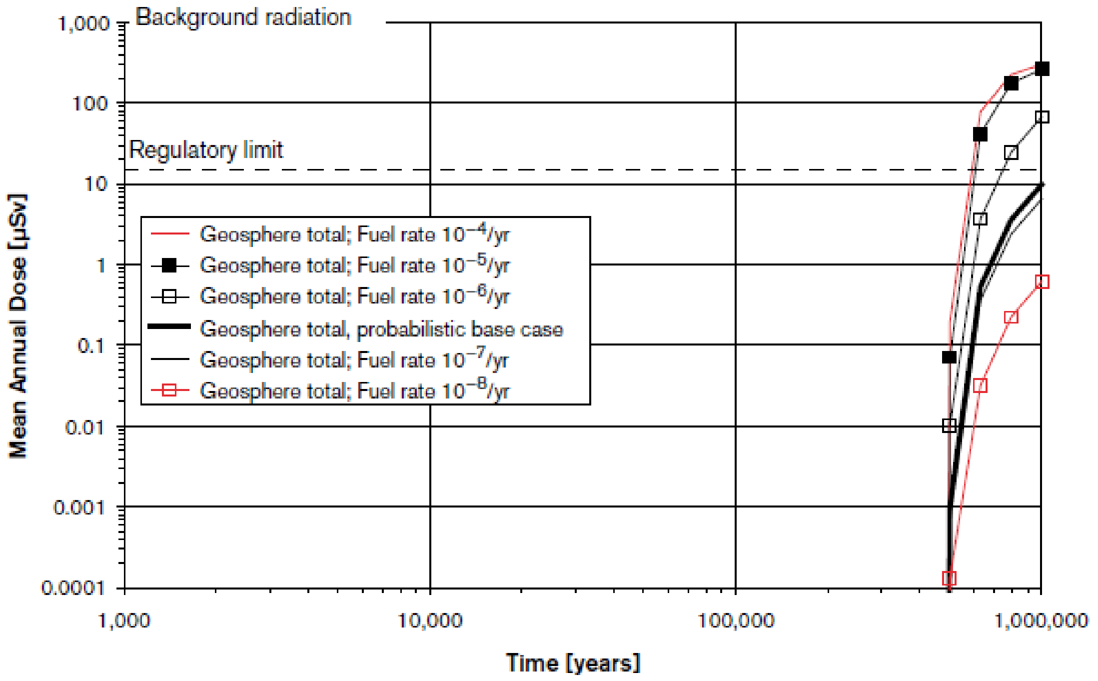


***Figure 10-44.** Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.*

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/AR choices will be considered in the context of operational costs and benefits
- Alternative fuel cycle/AR choices can reduce waste volume but may have little impact on thermal load management without century-scale aging of fission products
  - Without separation or surface aging of fission products, reductions in disposal volume may be limited to 30-40% of the disposal volume of the unprocessed fuel
  - Fission products may need geologic disposal regardless, depending on regulatory criteria
- Use existing DOE SNF to guide disposal options strategies for AR spent fuel/WF
  - Advantages to spent fuels that can be directly disposed without treatment
  - Specific considerations needed for AR spent fuels/WF unique attributes
- The impact of WF lifetime on repository performance varies with disposal concept
  - For some disposal concepts, long-lived waste forms can be important
  - Deep borehole concept does not rely much on waste form performance for postclosure safety
- Alternative fuel cycle/AR choices will have little impact on estimates of long-term repository performance for disposable WF
  - Long-term dose estimates in most geologic settings are dominated by mobile species, primarily I-129

References

ABC News, 2020. “2 Remote Japan towns seek to host nuclear waste storage site,” October 9, 2020. ABC News Internet Ventures.

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.

Sassani, D., and F. Gelbard, 2019, “Performance assessment model for degradation of tristructural-isotropic (TRISO) coated particle spent fuel,” Proceedings of the American Nuclear Society International High-Level Radioactive Waste Management Conference, April 14-18, 2019.

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.

SNL (Sandia National Laboratories) 2014. Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High -Level Radioactive Waste Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy. FCRD-UFD-2013-000371, Revision 1; SAND-2014-0187P; SAND-2014-0189P. Albuquerque, NM: Sandia National Laboratories.

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.

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.

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.

Wiley Online Library, 2020. “Managing spent nuclear fuel in South Korea: Heterogeneous public attitudes toward different mana gement strategies at individual and segment levels,” International Journal of Energy Research, Volume 44, Issue 10.

World Nuclear News, 2020. “Swedish municipality gives approval for fuel repository,” October 14, 2020, World Nuclear Associated, Tower House, 10 Southampton Street, London, WC2E 7HA, UK.