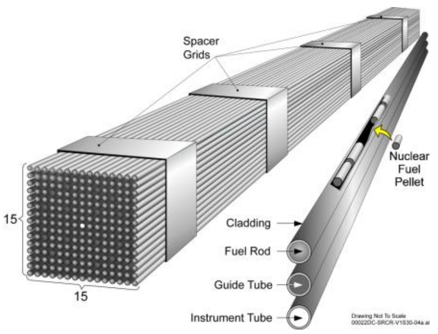
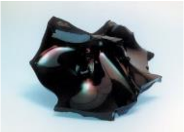


Spent Nuclear Fuel

?



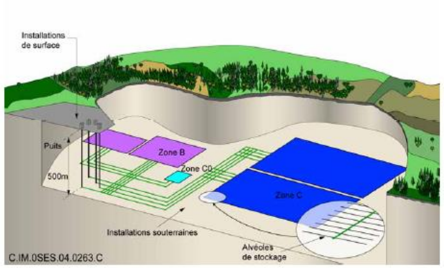
Vitrified Waste

?

Stored or Processed Fuel

?

?



Geologic Repository

How Spent Fuel Management Affects Geologic Disposal

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Sandia National Laboratories, USA

International Conference on Management of Spent Fuel from Nuclear Power Reactors
International Atomic Energy Agency, Vienna, Austria
15-19 June 2014

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A Perspective from Decades of Repository Science and Engineering

- Repository programs in multiple nations
  - Belgium, Canada, China, Czech Republic, Finland, France, Germany, Japan, Korea, Spain, Sweden, Switzerland, United Kingdom, United States …
  - International collaboration through the International Atomic Energy Agency and the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development
- Detailed safety assessments have been published for multiple disposal concepts, e.g.,
  - Switzerland: Opalinus Clay, 2002
  - France: Dossier 2005 Argile, 2005
  - USA: Yucca Mountain License Application, 2008
  - Sweden: Forsmark site in granite, 2011

First order conclusions

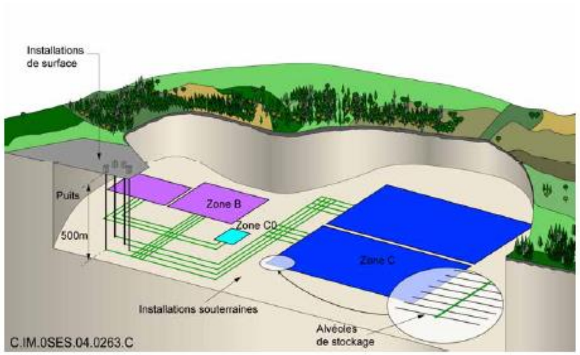
There are multiple approaches to achieving safe geologic isolation

Estimated long-term doses are very low for each of the disposal concepts that have been analyzed in detail

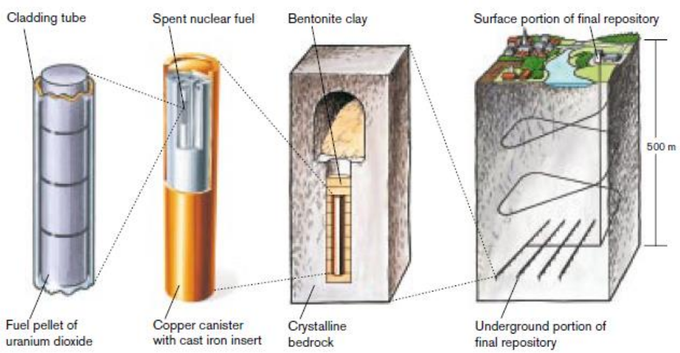
Safe isolation can be achieved for both spent fuel and HLW

Multiple Concepts for Geologic Disposal

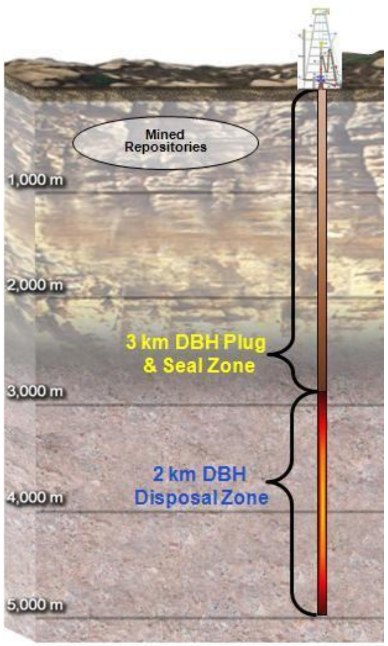
Mined repositories in various rock types

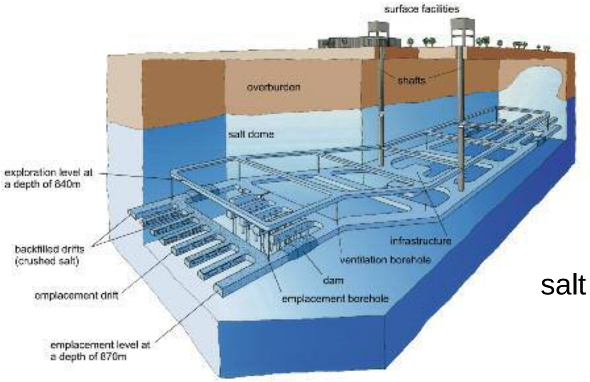


argillite



Crystalline (granitic) rock





salt

Deep borehole disposal in crystalline basement

How do Repositories Achieve Safe Isolation?

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

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)

Isolation mechanisms may differ for different nuclides in different disposal concepts

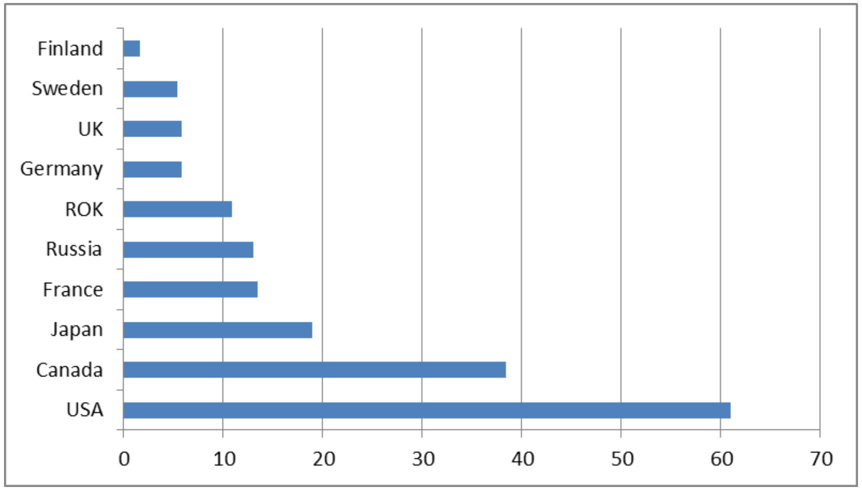
How does the Waste Form Affect the Repository?

- Repository design and operations
  - Total volume of waste
  - Size and mass of packages
  - Thermal considerations
- Impacts on estimates of long-term dose
  - Initial radionuclide inventory emplaced in the repository
  - Waste form degradation and rate of radionuclide mobilization

Waste Volume Considerations

- Volume of SNF and HLW requiring disposal is a function of the national program
  - Size of program
  - Fuel cycle choices
  - Treatment and packaging
- Volume of SNF and HLW is a factor in determining repository cost

Relative Amounts of SNF in Storage as of 2007



Data in thousands of metric tons. Source: Feiveson et al., 2011

Programmatic decisions that affect the volume of waste requiring geologic disposal vary from nation to nation

Waste Volume Considerations (cont.)

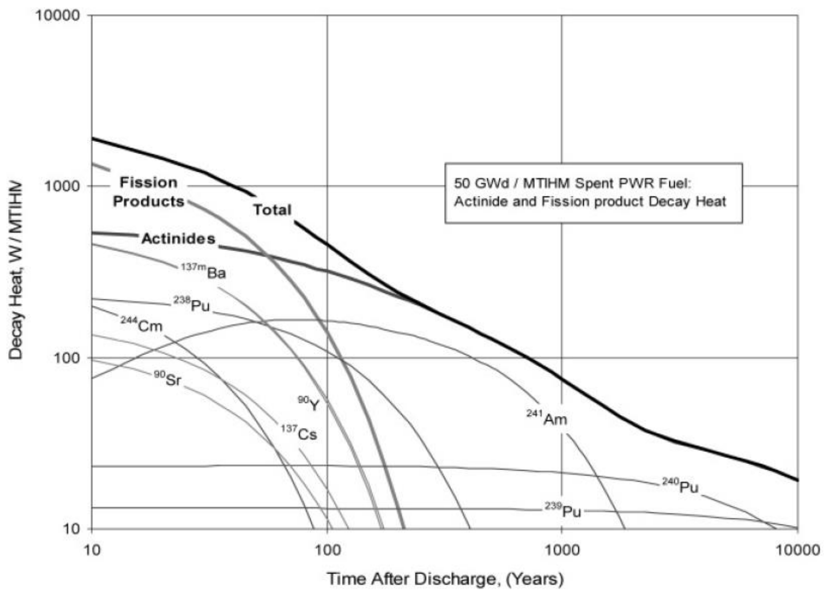
- Volume of HLW is process-dependent
  - Existing processes can achieve 3-4x reductions in disposal volume relative to used fuel, including packaging
    - up to 13 × with 100-yr aging period [van Lensa et al., 2010, table 7.1]
  - Advanced processes may achieve lower volumes of HLW
- Thermal output, rather than waste volume, determines loading density and overall repository size
  - Thermal output of HLW can be engineered over a wide range, correlates inversely to volume without separation of heat-generating radionuclides
- Reductions in the volume of waste requiring deep geologic disposal will reduce total repository cost
  - Volume of low-level waste also contributes to total cost
- Selection of optimal volume and thermal loading criteria will depend on multiple factors evaluated across entire fuel cycle

Thermal Considerations

Repository temperature constraints are design-specific and may have considerable flexibility

- For disposal concepts that rely on clay backfill/buffer
  - Peak temperatures below boiling at the waste package surface
- For salt disposal concepts
  - Peak temperatures in salt below 200° C
- For ventilated disposal concepts without backfill
  - Peak temperatures may be dictated by material properties of host rock or engineered barriers

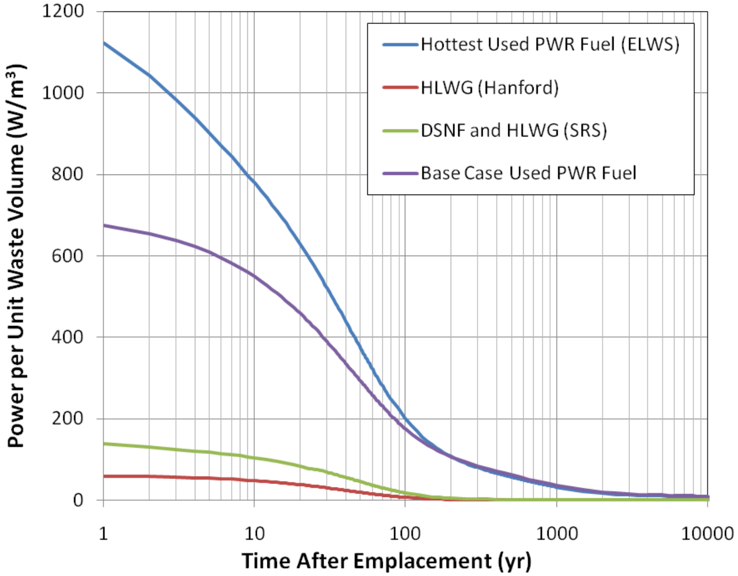
Heat Generating Nuclides



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, Figure 1

Options for Achieving Thermal Objectives

- Operational Options
  - Aging
  - Ventilation
  - Load management
- Repository Design
  - Size of waste packages
  - Spacing between packages
  - Thermal properties of engineered materials
- Modifications to Waste Forms
  - Decreasing density of fission-product and actinide loading
  - Separation of heat-generating isotopes



Calculated thermal power for representative Yucca Mountain waste forms

Example Thermal Modeling Result:

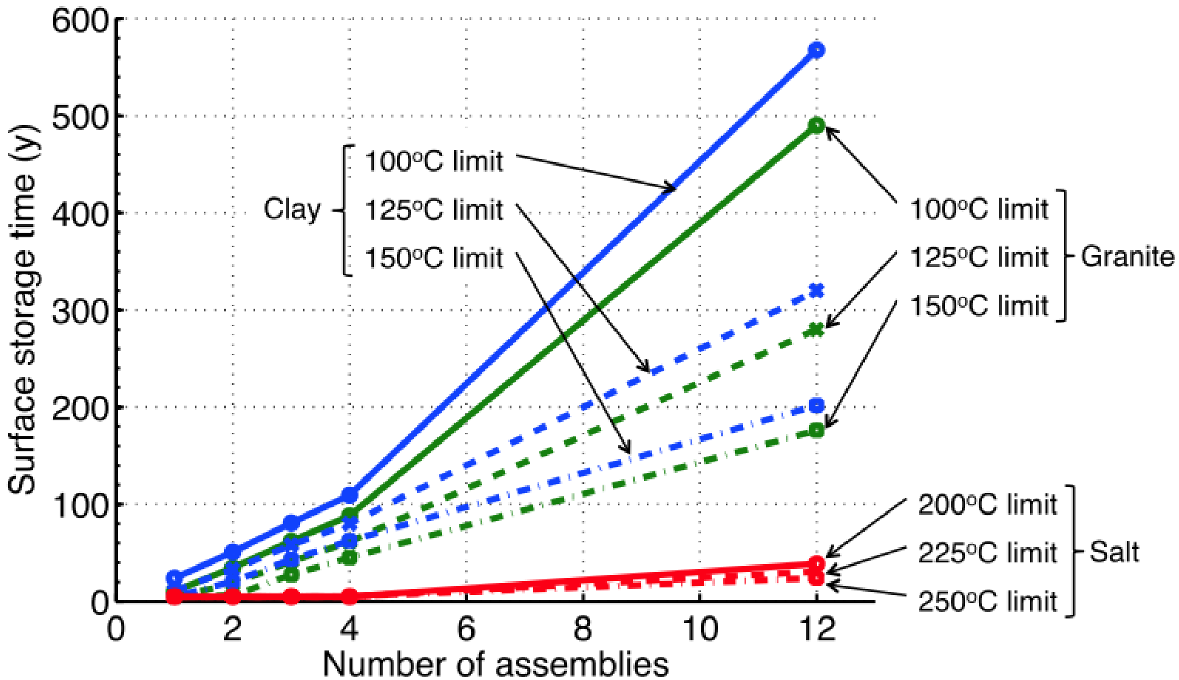
Managing Peak Temperature through Canister Size and Decay Storage

Decay Storage Needed to Meet WP Surface Temperature Limits vs. WP Size or Capacity (PWR Assemblies; 60 GWd/MT Burnup)

Temperature limits based on current international and previous U.S. concepts:

- 100°C for clay buffers and clay/shale media (e.g., SKB 2006)
- 200°C for salt (e.g., Salt Repository Project, Fluor 1986)

Final temperature constraints will be site- and design-specific



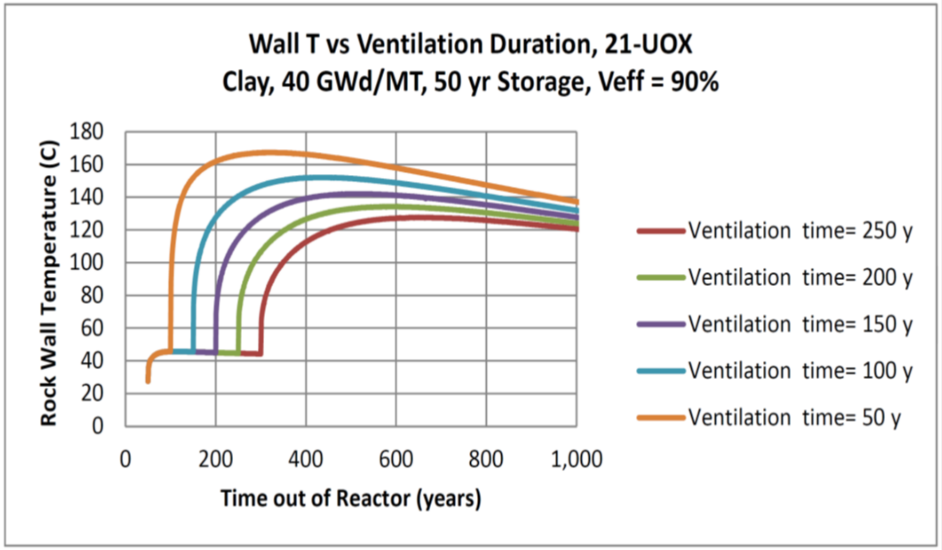
Thermal conductivity for all media selected at 100℃.

Source: Greenberg et al. 2012

Example Thermal Modeling Result:

Managing Peak Temperature through Ventilation and Spacing in Shale

- Package size 21-PWR; burnup 40 GWd/MT; V_{eff} = 90%
- Ventilation varied 50-250 yr, after 50 yr surface storage
- Drift spacing for 50-yr ventilation varied 30-50 m
- Effect from ~2X drift spacing is greater than ~3X UNF age at closure



Source: Hardin et al. 2012

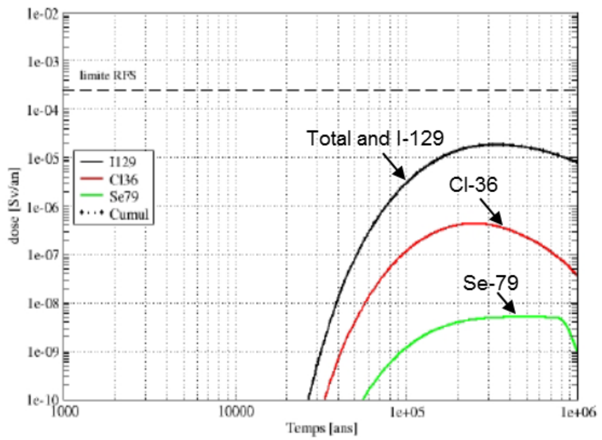
Ventilation Period (yr)	Drift Spacing (m)	Peak Rock Temp. (°C)	Peak Time (yr)
250	30	127.6	659
200	30	134.3	602
150	30	142.0	518
100	30	152.0	424
50	30	167.4	322
50	40	141.3	349
50	50	124.2	322

Impacts on Estimates of Long-Term Dose

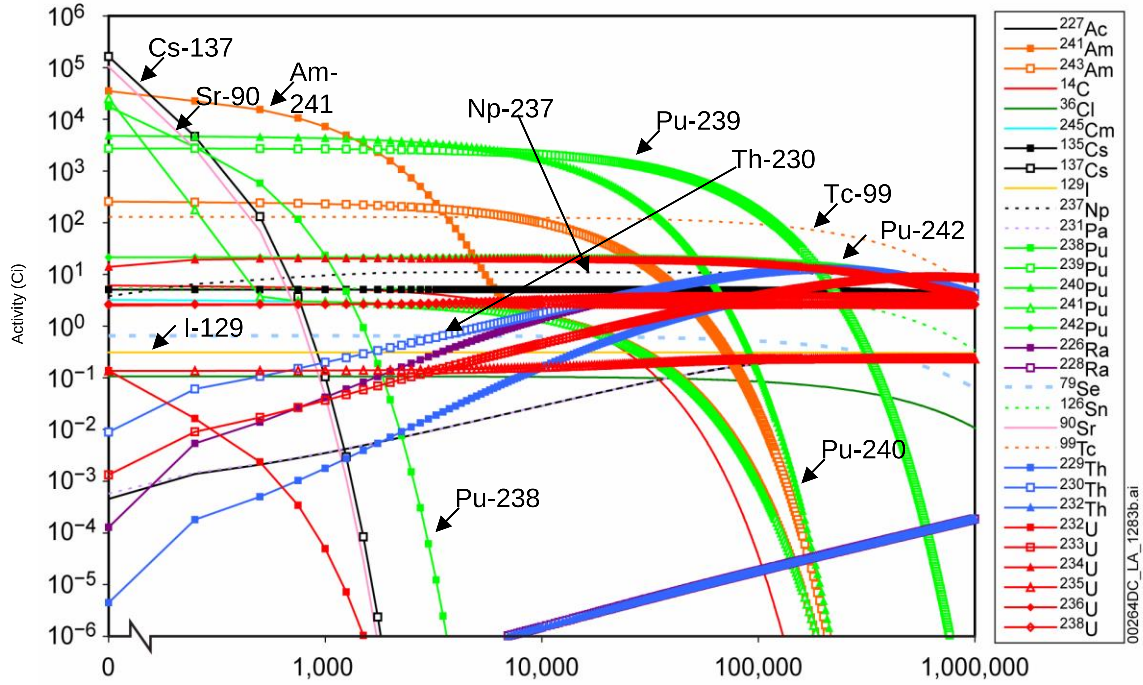
Total radioactivity of SNF is dominated by actinides and long-lived fission products

Estimates of long-term dose from repositories are dominated by those nuclides that are mobile in the disposal environment

Million-year dose estimates, French repository for SNF



Million-year radionuclide inventory for US SNF

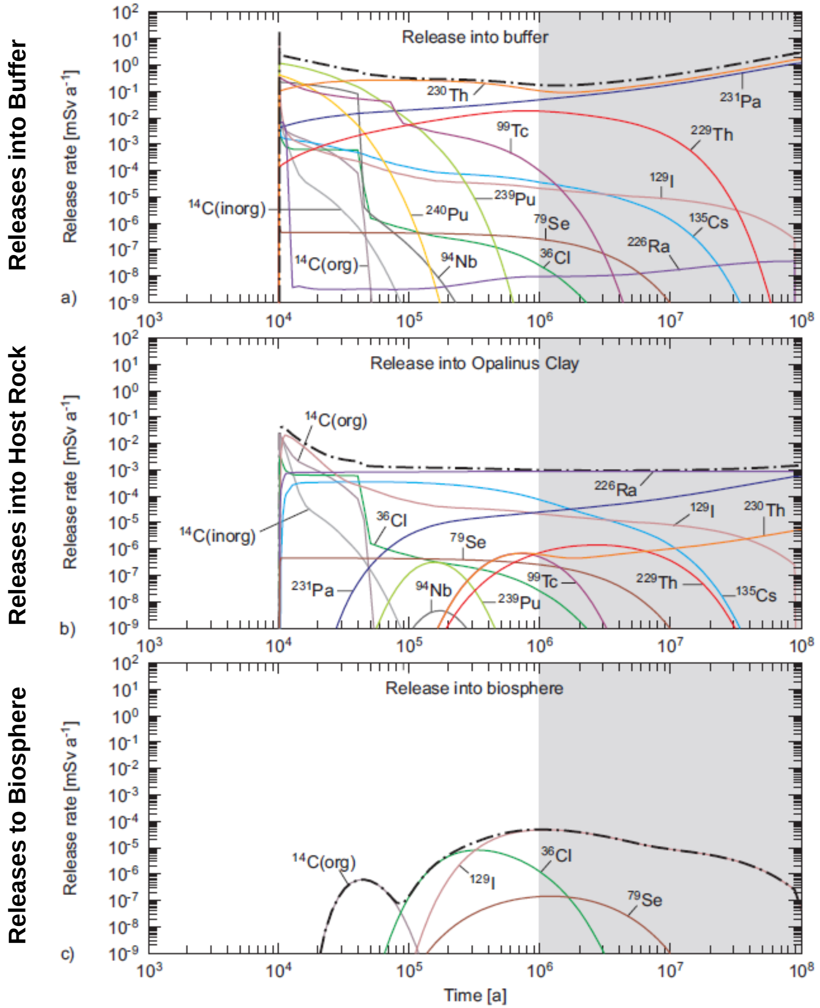


Above: DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for an single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Left: ANDRA 2005, Figure 5.5-18, SEN million year model, CU1 spent nuclear fuel and Figure 5.5-22

Contributors to Total Dose in a Diffusion-Dominated Disposal Concept

Mined Repository in Opalinus Clay (Switzerland)



Releases from spent fuel dominated by early spike of I-129 and long-lived actinides (Th-230, Pa-231)

Releases from clay buffer dominated by relatively more mobile Ra-226 and I-129

Releases to biosphere dominated by I-129, Cl-36, C-14, and Se-79

NAGRA 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, Figure 6.5-1

Contributors to Total Dose in a Disposal Concept with Advective Transport in the Far Field

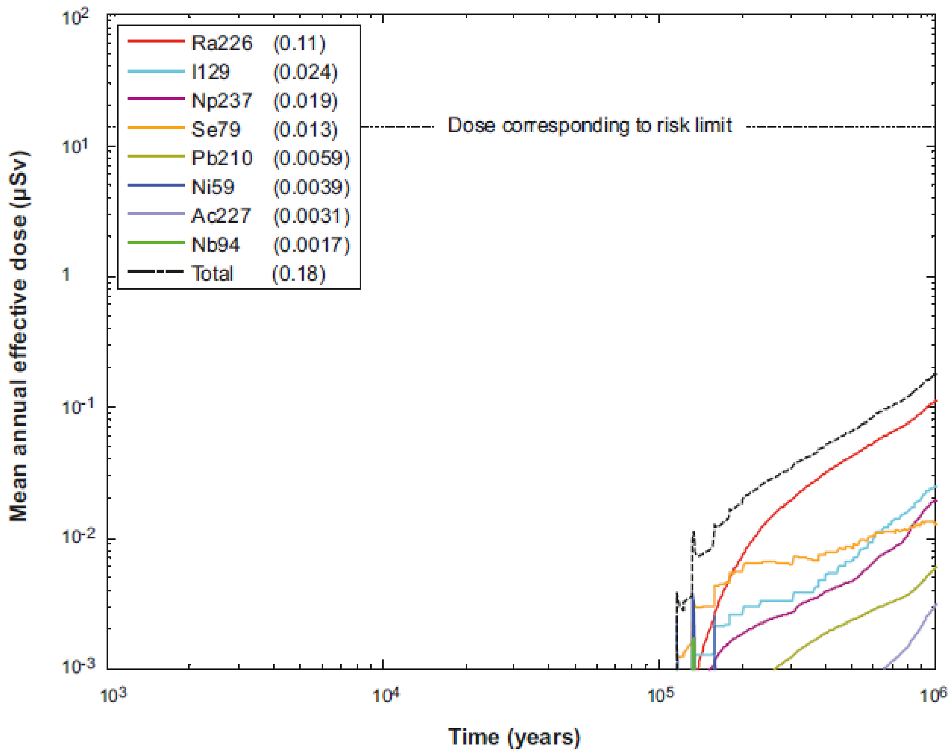


Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).

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

Disposal in fractured granite at the Forsmark Site, Sweden

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

Reduce Long-term Risk by Extending Waste Form Lifetime?

- Example from preliminary spent fuel disposal analyses at Forsmark, Sweden
  - 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 contributes to uncertainty in modeled total dose estimates

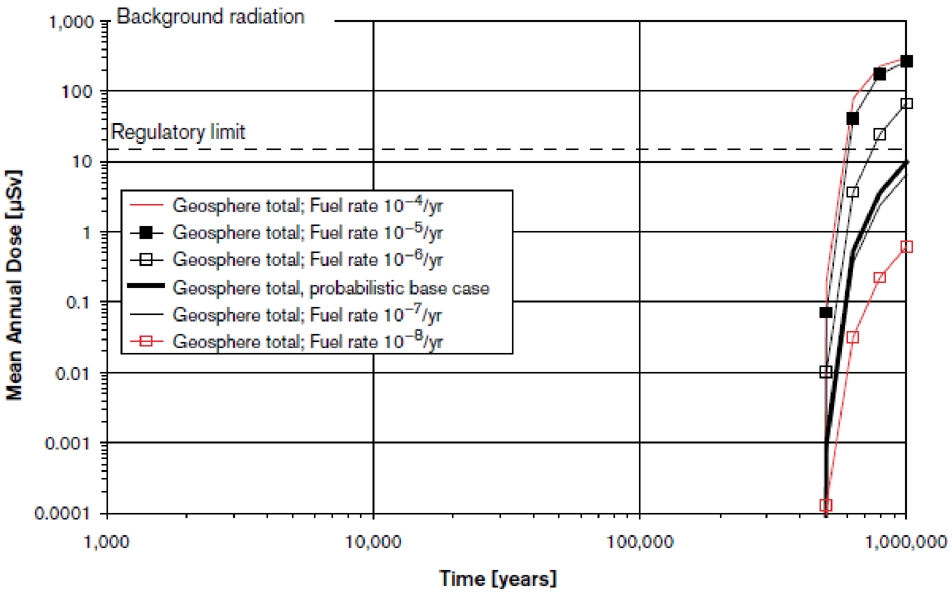


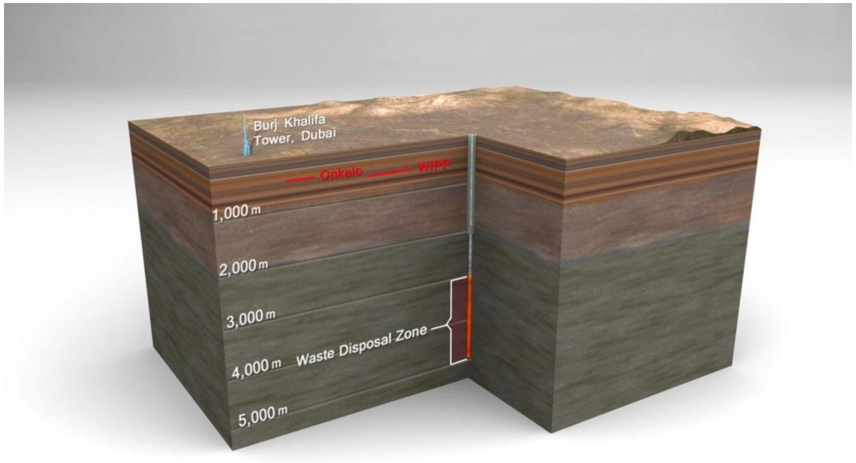
Figure 10-44. Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.

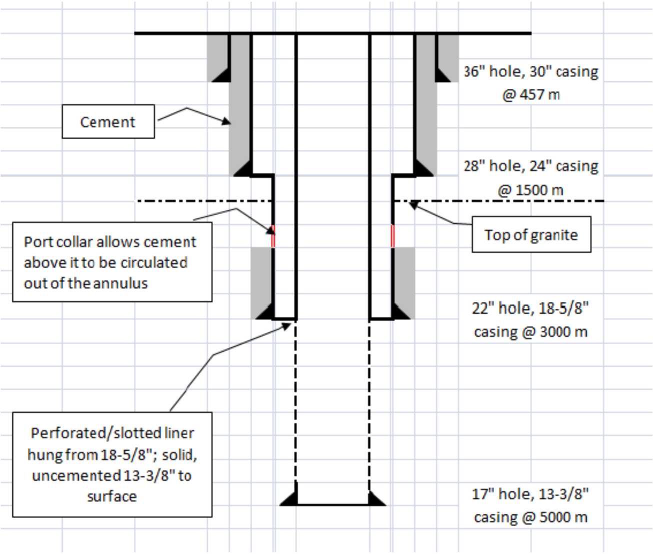
Source: SKB 2006, *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar—a First Evaluation,* TR-06-09, section 10.6.5

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

Observations on Deep Borehole Disposal

- Potential for long-term isolation is excellent, but further R&D is needed
- Primary constraints defined by borehole geometry
  - Standard drilling technology allows up to ~45 cm bottom hole diameter
    - With packaging, precludes disposal of typical intact PWR assemblies
    - Other fuel forms limited to single-assembly disposal packages
  - Thermal considerations simplified by small packaging





Deep borehole disposal may be viable for small volumes of small-diameter waste

Concept has not been demonstrated

Conclusions

- Multiple disposal concepts have the potential to achieve permanent isolation of spent nuclear fuel
  - Estimated long-term doses are very low for each of the disposal concepts that have been analyzed in detail
- Thermal load can be managed through design and operations
  - All disposal concepts call for limiting near field temperatures
- Radionuclides contributing to dose vary for different disposal concepts
  - Water chemistry (redox state) and transport mechanism (advection vs. diffusion) matter
  - Long-lived fission products (i.e., I-129) are likely to be of greatest importance
- Joint optimization of spent fuel management and disposal criteria requires consideration of multiple factors evaluated across entire fuel cycle

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