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Insights from Safety Assessments for Mined Repositories in Crystalline Rock

DRAFT 1

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U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Outline

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- Goals of the discussion
  - First order insights into what factors may influence crystalline repository performance
  - Integrating safety assessment results with the R&D programme
- Examples of Safety Assessment Results
  - Preliminary US modeling of a generic crystalline repository
  - Canadian generic safety assessment
  - Swedish Forsmark Safety Assessment
- Observations about potentially important components and processes
- Integrating Iterative Safety Assessments with R&D
- Discussion

Generic Crystalline Repository Performance

Example from Current US DOE Analyses

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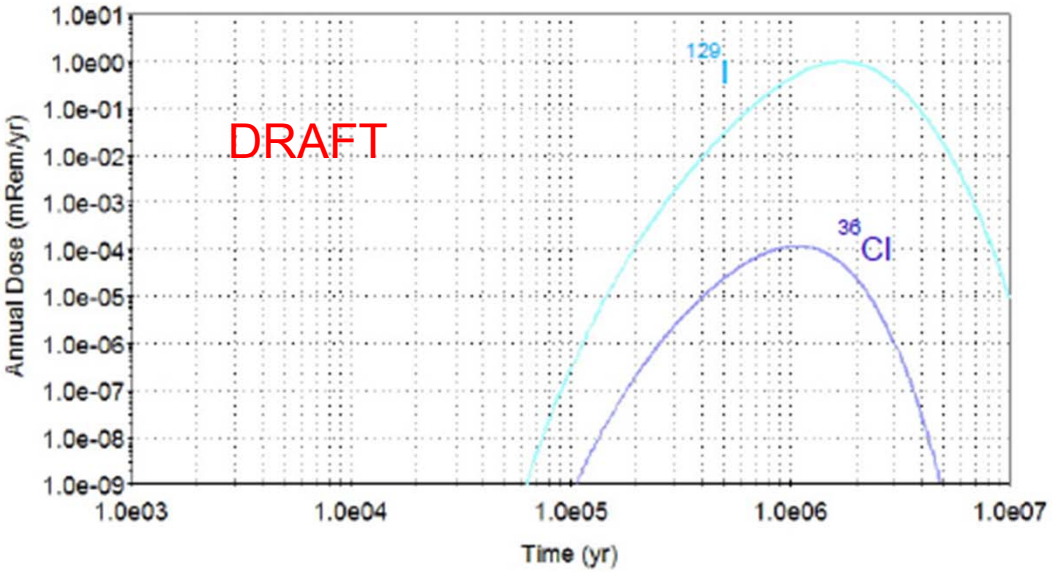
Key assumptions in this analysis

- Uncertainties treated deterministically for simplicity
- Waste packages and cladding fail immediately
- Used fuel degrades relatively rapidly (fractional degradation rate = 2×10^{-5}/yr)
- Bentonite buffer remains intact (0.36 m thick)
- 1 % of radionuclides released from the waste form pass through the buffer and enter a fracture network
- Early releases from gap and grain boundaries are not modeled
- No disruptive events or human intrusion

Nominal Performance



Estimated peak dose is 0.0095 mSv/yr at 1.7 Myr, from I-129

Generic Crystalline Repository Performance

Example from Current US DOE Analyses (cont.)

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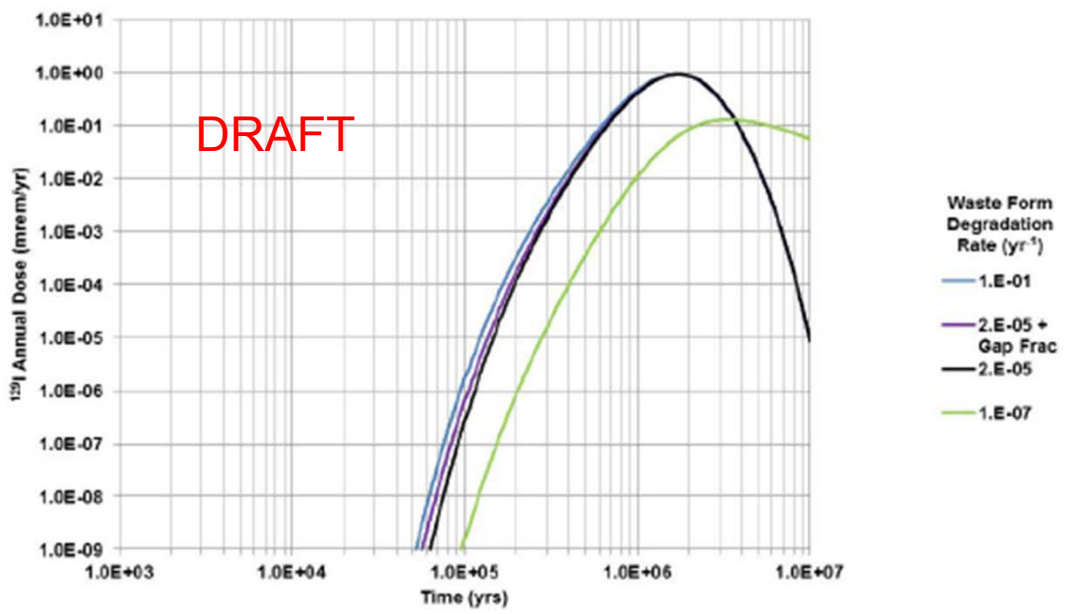
Key observations from this analysis

- Because base case was run with relatively rapid degradation, faster waste form degradation has little effect on performance
- Effects of early release fraction are not significant when compared to the base case
- Significantly slower waste form degradation rates result in smaller doses occurring at later times

Sensitivity to Waste Form Degradation Rate



Generic Crystalline Repository Performance

Example from Current US DOE Analyses (cont.)

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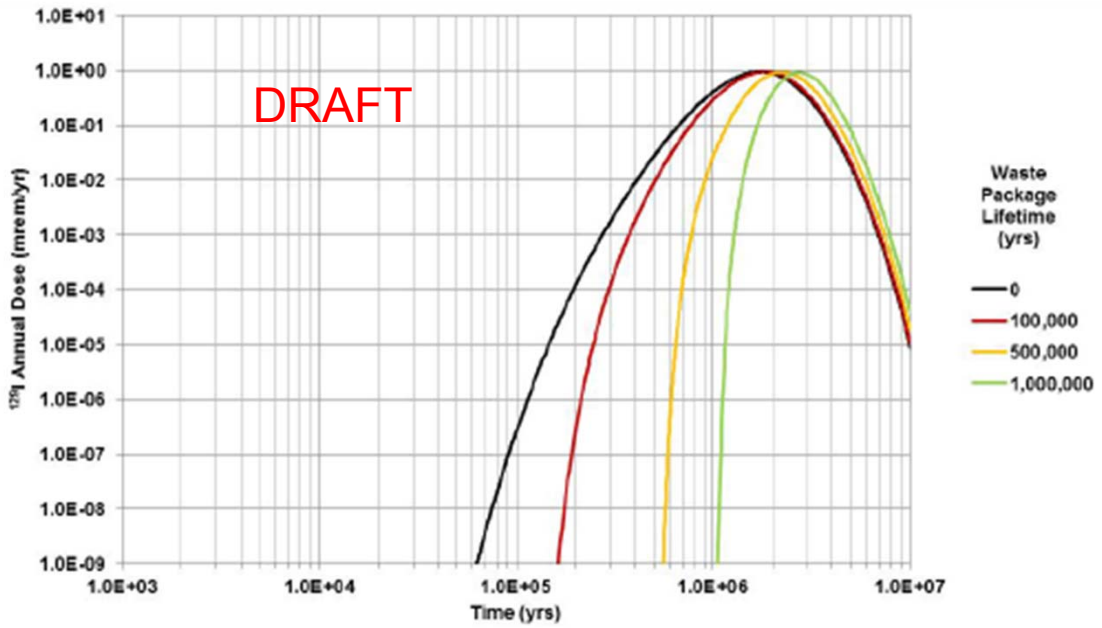
Key observations from this analysis

- Longer waste package lifetime results in doses occurring later in time.
- Because of the long half-life of I-129, there is no perceptible impact on the magnitude of the estimated dose

Sensitivity to Waste Package Lifetime



Generic Crystalline Repository Performance

Example from Current US DOE Analyses (cont.)

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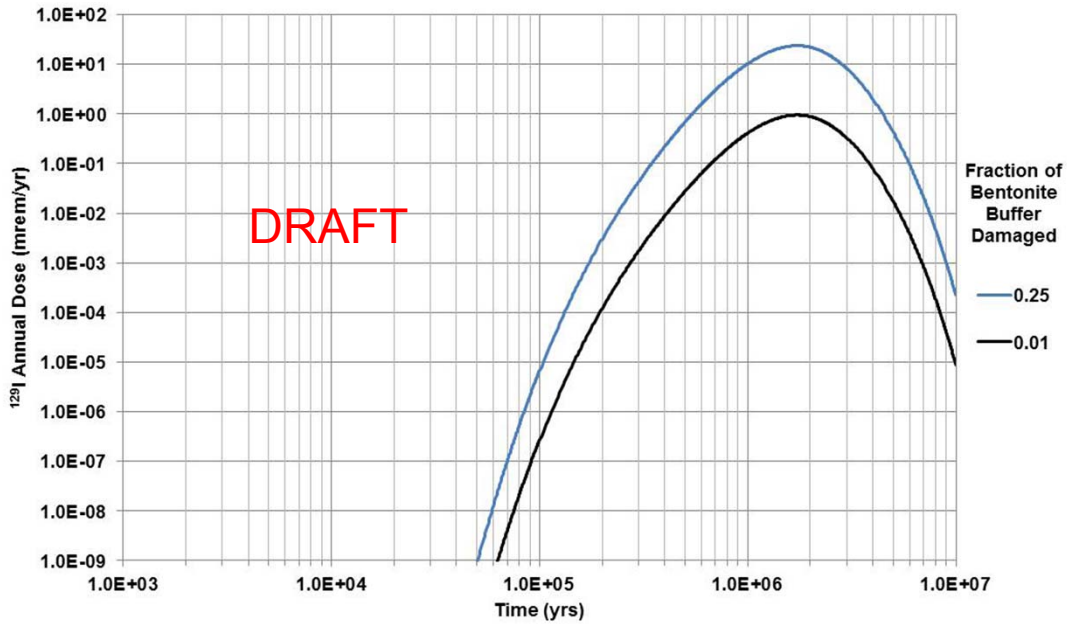
Key observation from this analysis

For the assumptions used here, the magnitude of the estimated dose increases linearly with the increase in the fraction of radionuclides passing through the bentonite buffer and entering fractures in the granite

Sensitivity to Buffer Integrity



Generic Crystalline Repository Performance

Example from Current US DOE Analyses (cont.)

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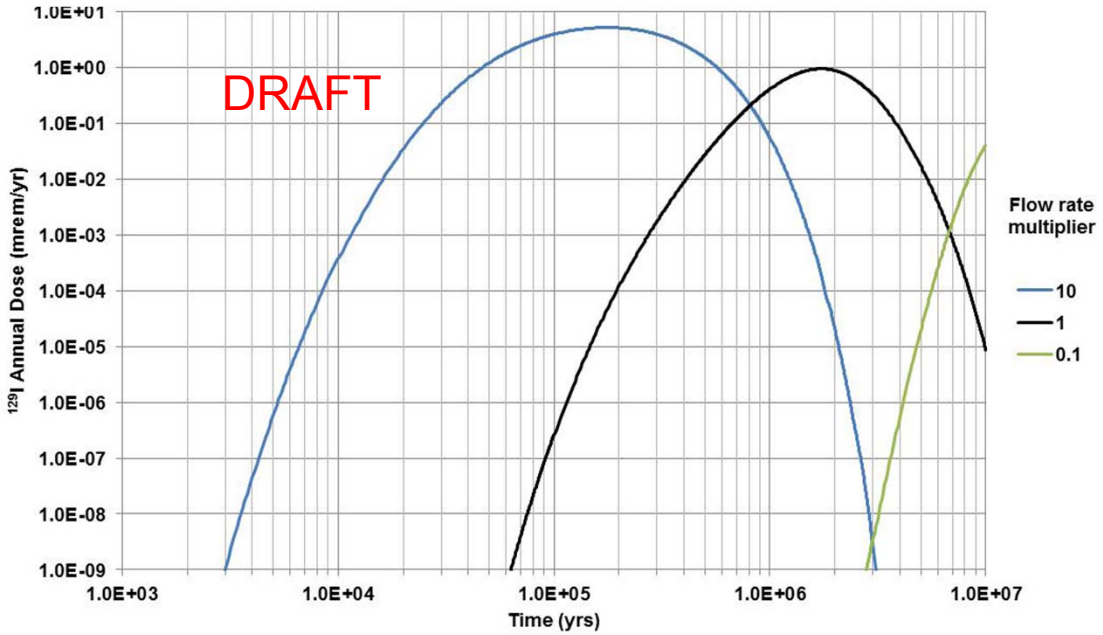
Key observation from this analysis

- For the assumptions used here, the time of peak dose is strongly sensitive to the flow rate in fractures
- Magnitude of estimated dose is less sensitive to fracture flow rate

Sensitivity to Fracture Flow Rate



Generic Crystalline Repository Performance

Example from the Canadian Fourth Case Study

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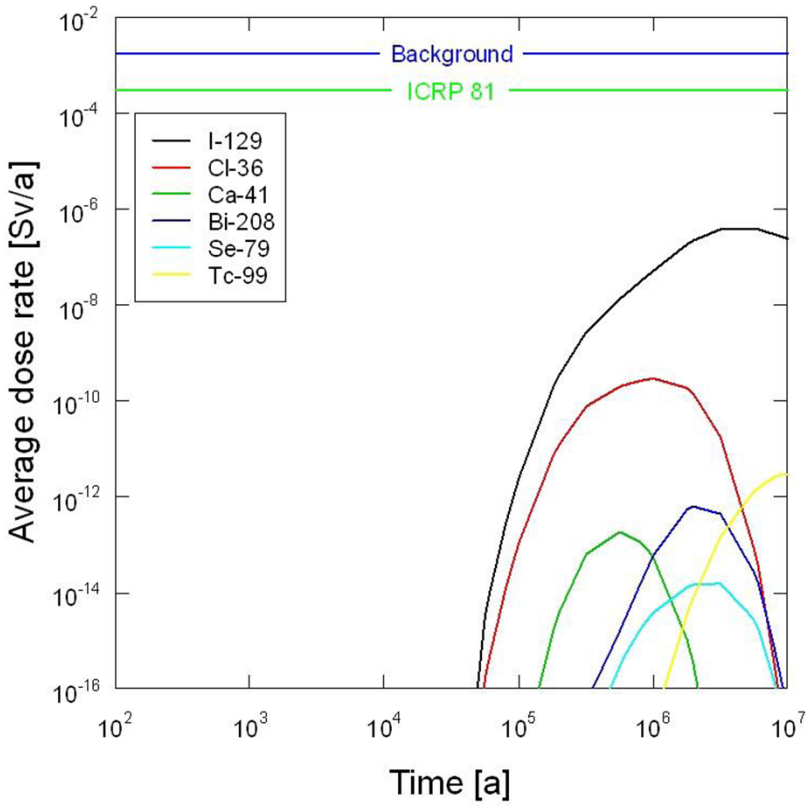
Key assumptions for this analysis

- Waste package failures treated probabilistically, expected value of 2 failures per repository
- Very low permeability for unfractured granite ($8.3\times10^{-20}m^2$)
- Relatively high permeability in fractures ($4.1\times10^{-14}m^2$), but fractures do not directly intersect the disposal region
- Slow degradation of the uranium oxide spent fuel in a reducing environment

Average Dose Rates



Source: Kremer et al., 2011, "Postclosure Safety Assessment of a Deep Geological Repository for Canada's Used Nuclear Fuel", Proceedings of the International High-Level Radioactive Waste Management Conference 2011, Albuquerque, NM USA, April 10 -14, 2011.

Generic Crystalline Repository Performance

Example from the Canadian Fourth Case Study (cont.)

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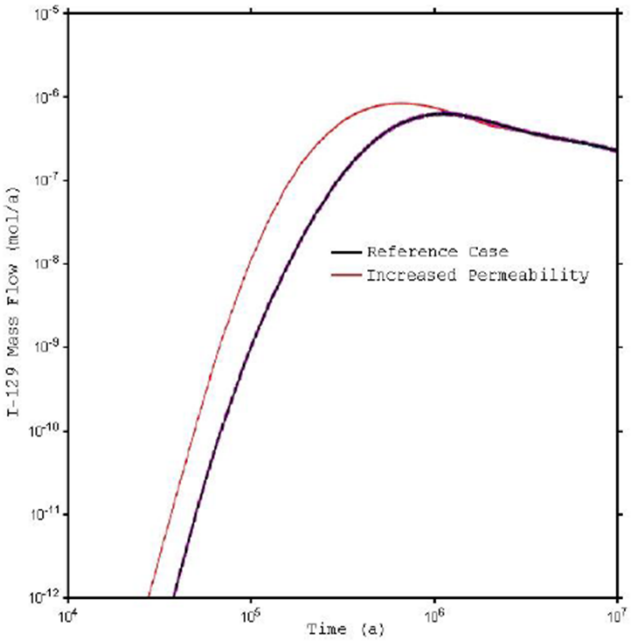
Deterministic sensitivity analyses



5-fold increase in geosphere permeability causes earlier I-129 release to biosphere

TABLE I. Comparison of dose rate sensitivities

Case Description	Peak Dose (Sv/a)	Peak Time (a)
Reference Case	9.7×10^{-8}	1.1×10^{6}
10 × Fuel Dissolution Rate	5.5×10^{-7}	8.6×10^{5}
10 × Container Defect Radius	1.4×10^{-7}	5.8×10^{5}
Geosphere Sorption set to zero	1.0×10^{-7}	1.1×10^{6}
All Containers Fail after 100,000 years	9.4×10^{-5}	3.4×10^{6}

Source: Kremer et al., 2011, "Postclosure Safety Assessment of a Deep Geological Repository for Canada's Used Nuclear Fuel", Proceedings of the International High-Level Radioactive Waste Management Conference 2011, Albuquerque, NM USA, April 10 -14, 2011.

Generic Crystalline Repository Performance

Example from the Swedish Forsmark SR-Site (2011)

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Probabilistic Calculation of the "Central Corrosion Case"

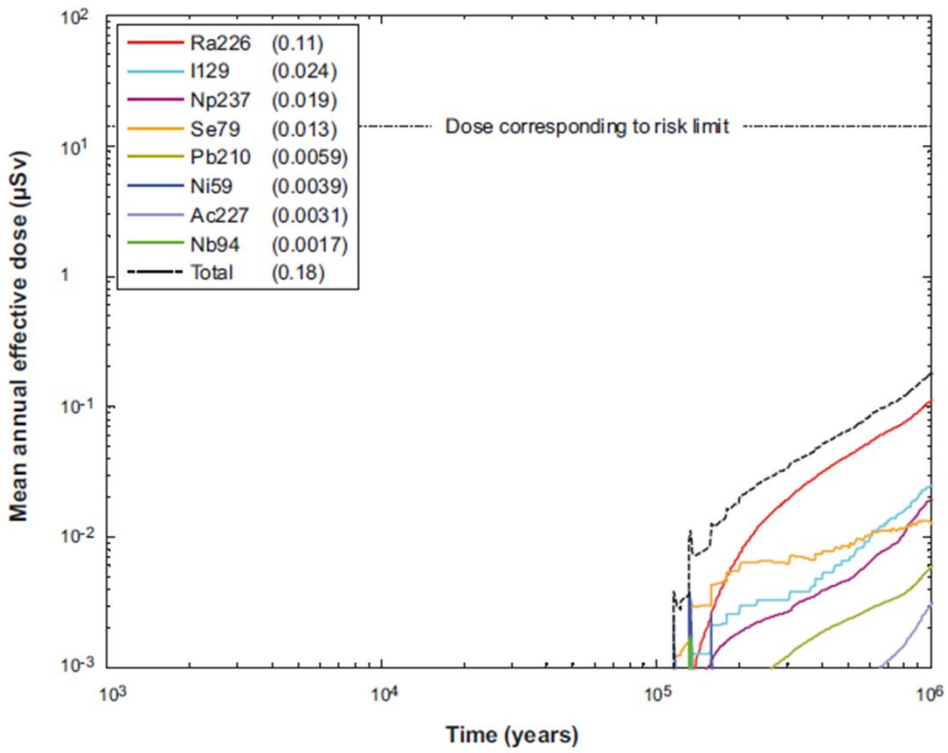
Key assumptions:

- Waste package failures treated probabilistically, expected value of 0.12 failures per repository, first failures occur at 114,000 years
- Failed waste packages assumed to be intersected by highly transmissive fractures
- Slow degradation of the uranium oxide spent fuel in a reducing environment

Key Observation

- Total dose is dominated by Ra-226, due to relatively rapid transport in fractures
- Ra-226 $t_{1/2}$ = 1601 yr

Mean Dose Rates
peak values shown in μSv



Source: SKB Technical Report TR-11-01, Figure 13-18

Generic Crystalline Repository Performance

Example from the Swedish Forsmark SR-Site (2011)

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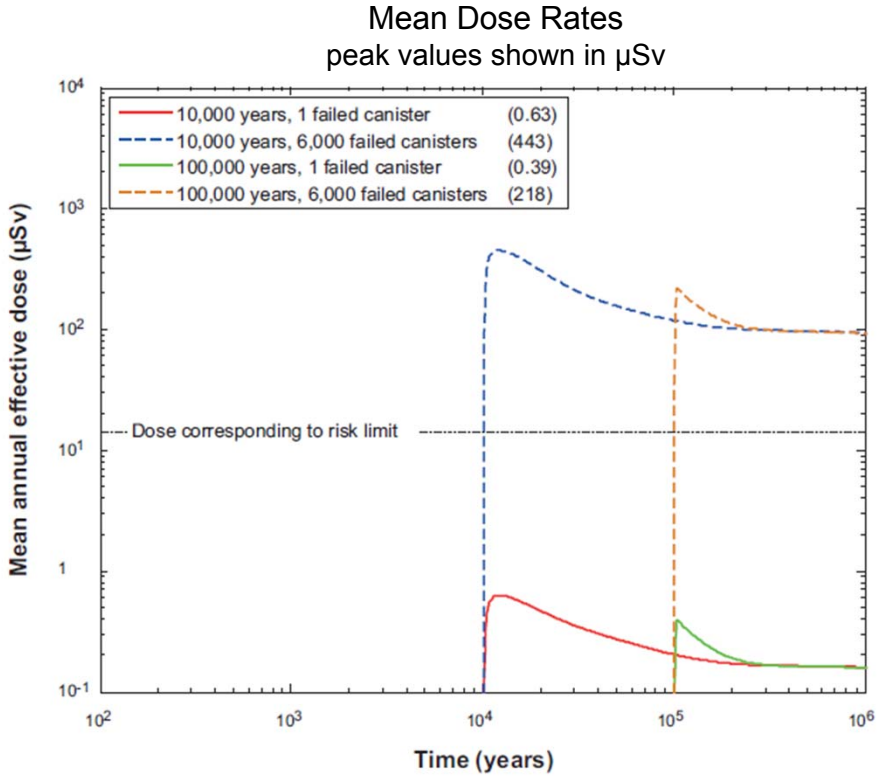
Hypothetical Deterministic Failure of Waste Packages

Key assumptions:

- Waste packages assumed to fail by unspecified mechanism, and to provide no further waste isolation capacity
- Geosphere functions as expected

Key Observation

- Total estimated dose varies linearly with the number of failed waste packages



Source: SKB Technical Report TR-11-01, Figure 13-53

Generic Crystalline Repository Performance

Example from the Swedish Forsmark SR-Can (2006)

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Sensitivity to spent fuel degradation rate

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 (corresponds to 10,000 yr)

Uncertainty in fuel dissolution rate is potentially an important contributor to overall uncertainty in modeled total dose estimates

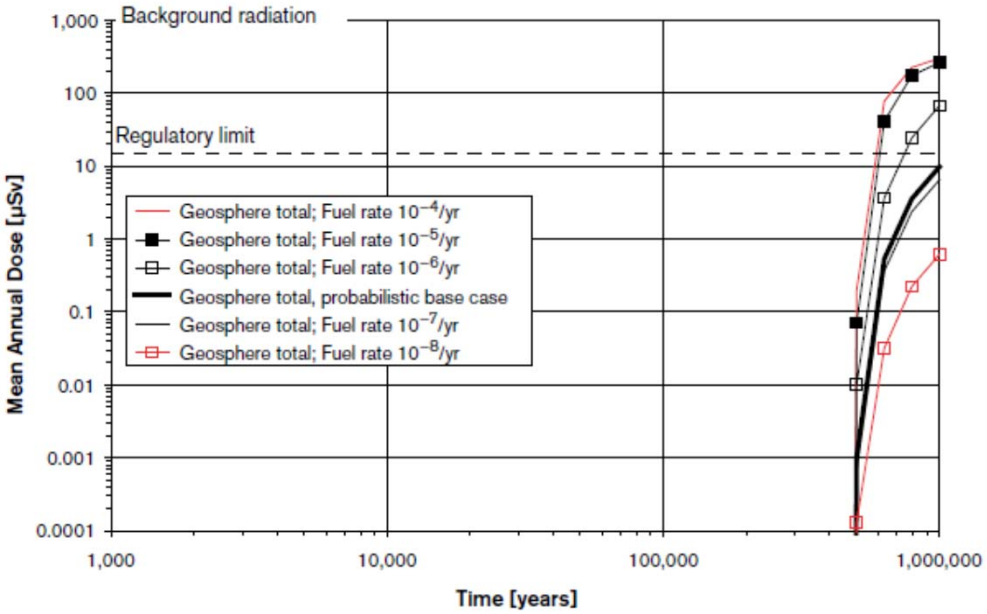
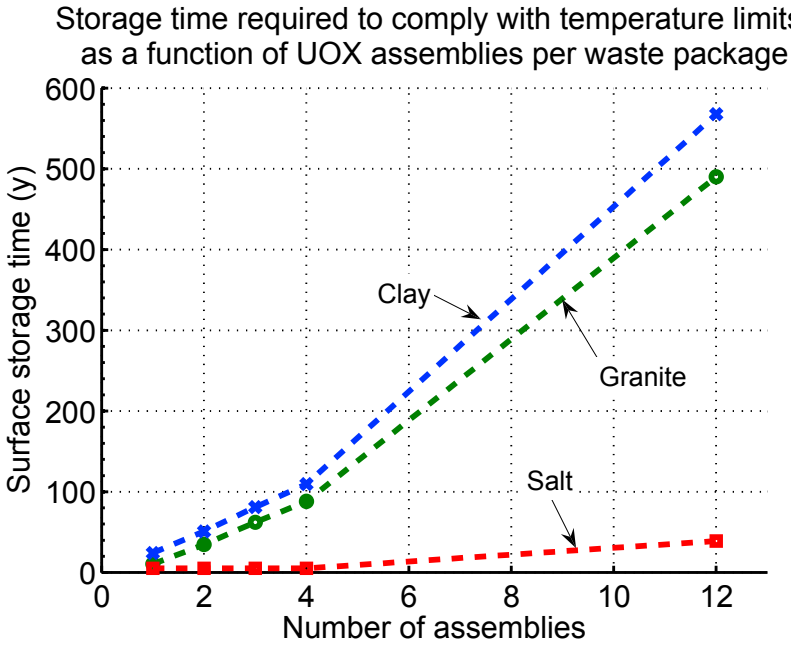


Figure 10-44. Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydro-geological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.

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

Thermal Constraints for Representative Disposal Concepts



Notes:
1. *These results are based on assumed temperature limits on the waste package surface of 100°C in clay and granite and 200°C in salt*
2. *Thermal constraints are one of many considerations for waste packaging, storage and disposal.*

Source: Hardin et al., 2011, Generic Repository Design Concepts and Thermal Analysis (FY11), FCRD-USED-2011-000143

Options for Meeting Thermal Constraints Include:

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

Summary of First Order Observations from Existing Crystalline Repository Safety Assessments

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- Crystalline repositories have the potential to provide excellent long-term isolation for used nuclear fuel and high-level radioactive waste
- Components (or parameters) important to building confidence in performance estimates are likely to include
  - Waste package lifetime
  - Waste form lifetime (UO_2 dissolution rate)
  - Connection to transmissive fractures (including rock properties and buffer integrity)
  - Rate of advective transport in the geosphere
- Thermal load management issues are likely to favor relatively smaller waste packages in crystalline repositories

Integrating Iterative Safety Assessments with Research and Development

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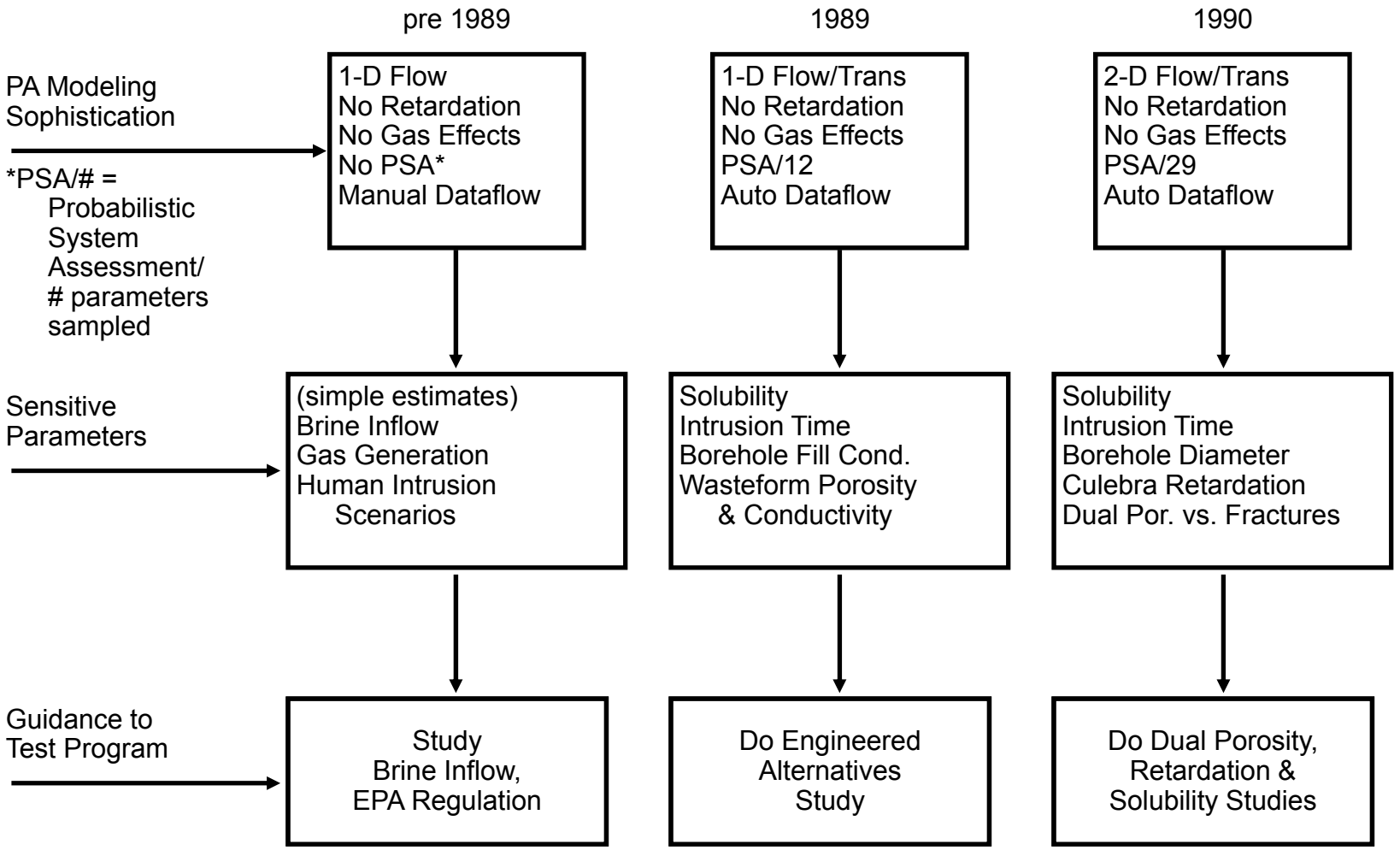
An Example from the Waste Isolation Pilot Plant (page 1)



Integrating Iterative Safety Assessments with Research and Development (cont.)

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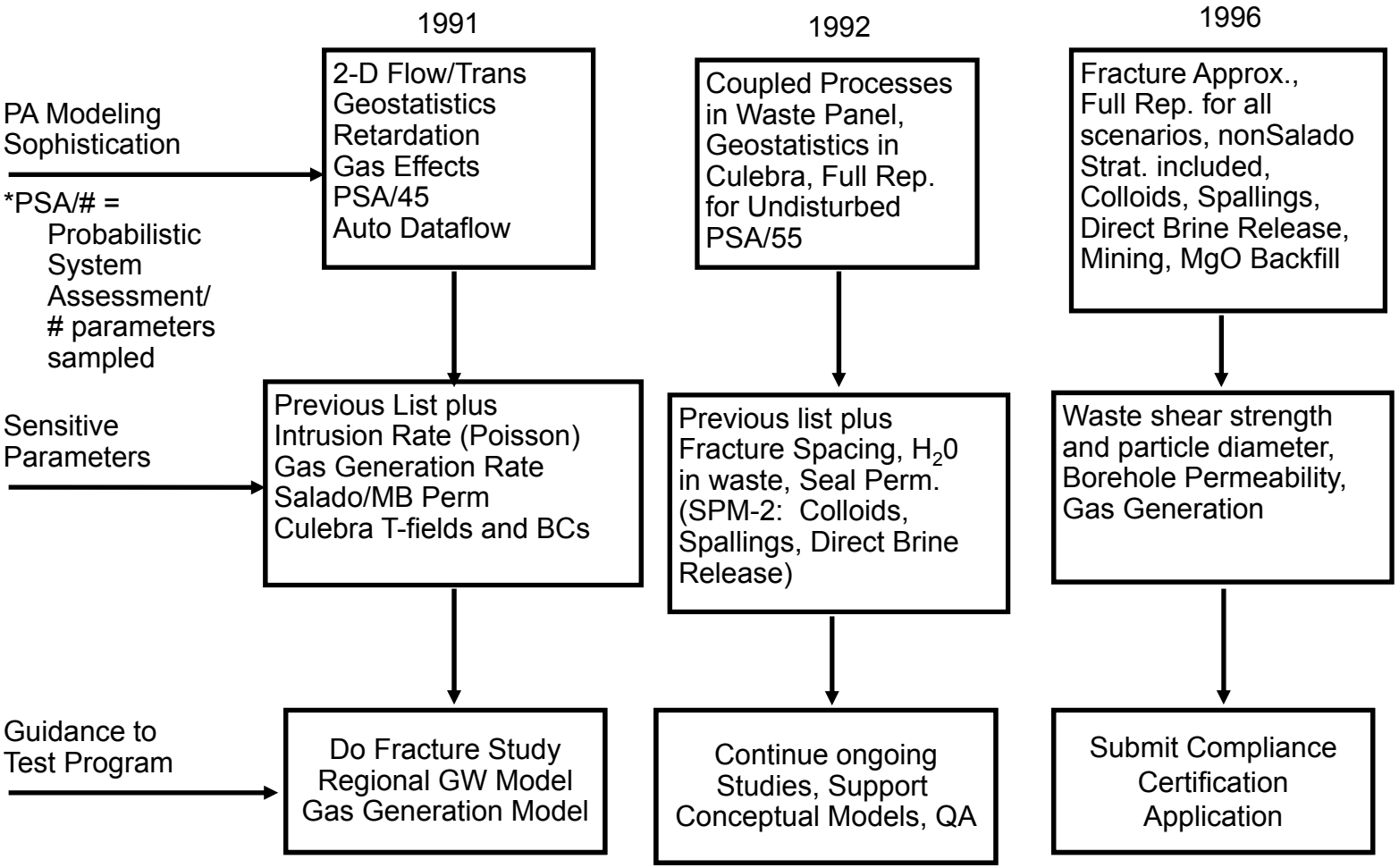
An Example from the Waste Isolation Pilot Plant (page 2)



Integrating Iterative Safety Assessments with Research and Development

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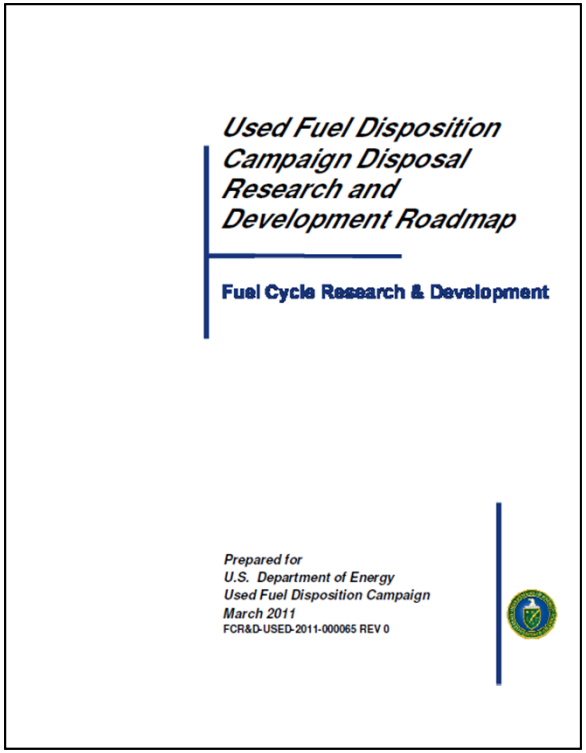
An Example from the Current US Program



- *Used Fuel Disposition Campaign Disposal Research and Development Roadmap*
  - "an initial evaluation of prioritization of R&D opportunities that could be pursued by the campaign"
  - Completed March 2011
  - Used to inform prioritization decisions for disposal research in FY12 and beyond
- Update in progress

http://www.ne.doe.gov/FuelCycle/neFuelCycle_UsedNuclearFuelDispositionReports.html

Used Fuel Disposition Campaign R&D Roadmap

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- Objective: identify and prioritize disposal R&D opportunities to inform allocation of limited resources
- Approach
  - Engage technical staff in the evaluation
  - Use the catalog of Features, Events, and Processes to identify potentially relevant issues
  - Recognition that evaluations will be subjective and scores will be qualitative
  - Consider timeliness of the R&D:
    - Does it support generic concept evaluations?
    - Does it support site screening or selection?
    - Does it support site-specific design or licensing decisions?
  - Evaluate issues based on
    - Importance to the safety assessment
    - Importance to design/construction/operation of a facility
    - Importance overall confidence in the safety case
  - Take existing state of knowledge into account
    - i.e., something may be both very important and sufficiently well understood

Used Fuel Disposition Campaign R&D Roadmap (cont.)

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- Categories used in scoring state of knowledge
  - Well Understood: representation well developed, has a strong technical basis, and is defensible. Additional R&D would add little to the current understanding
  - Fundamental Gaps in Method: the representation of an issue (conceptual and/or mathematical, experimental) is lacking
  - Fundamental Data Needs: the data or parameters used to represent an issue (process) is lacking
  - Fundamental Gaps in Method, Fundamental Data Needs: Both
  - Improved Representation: The representation of an issue may be technically defensible, but improved representation would be beneficial (i.e., lead to more realistic representation).
  - Improved Confidence: Methods and data exist, and the representation is technically defensible but there is not widely-agreed upon confidence in the representation (scientific community and other stakeholders).
  - Improved Defensibility: Related to confidence, but focuses on improving the technical basis, and defensibility, of how an issue (process) is represented
- Importance and adequacy with respect to decision points: how much do we need to know and when?
  - Importance—additional information may be essential for a given decision, supportive, or useful but not needed
  - Adequacy—existing information may be adequate for a given decision, partially sufficient, or insufficient

Used Fuel Disposition Campaign R&D Roadmap (cont.)

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- For R&D activities proposed for each topic, additional information is needed to support prioritization
  - Decision point supported by the R&D: i.e., generic concept evaluations, site selection, site characterization and repository design, licensing
  - Time required to complete the R&D
  - Cost
- Evaluation results compiled and organized using the structure of the FEP catalog

Example of the Prioritization Information Matrix

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Objective	Feature	Process (Issue)			Ability to Address through Generic R&D		Importance of Issue/Process to Safety Case				State of the Art Relative to Issue/Process	
		UFD FEP ID	UFD FEP Title	Process/Issue Description	Yes/No/Partial	Discussion	Performance (Safety Analysis)	Design, Construction, Operations	Overall Confidence	Discussion	Status	Discussion
Containment, Limited Release - Engineered Barriers	Engineered Barriers	2.1.07.10	Mechanical Degradation of EBS	- Floor buckling - Fault displacement - Initial damage from excavation / construction - Consolidation of EBS components - Degradation of waste package support structure - Alteration of EBS flow pathways [see also Mechanical Effects from Preclosure in 1.1.02.02, Evolution of Flow Pathways in EBS in 2.1.08.08, Drift Collapse in 2.1.07.02, Degradation in 2.1.04.01, 2.1.05.01, and 2.1.06.01, and Mechanical Effects on Host Rock in 2.2.07.01]	No	"Broad" mechanical degradation of the EBS is media specific and site specific. R&D on generic systems cannot address this topic.						
		2.1.08.00	1.08. HYDROLOGIC PROCESSES									
Limited Release - Engineered Barriers	Engineered Barriers	2.1.08.01	Flow Through the EBS	- Saturated / Unsaturated flow - Preferential flow pathways - Density effects on flow - Initial hydrologic conditions - Flow pathways out of EBS [see also Open Boreholes in 1.1.01.01, Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Flow in Waste Packages in 2.1.08.02, Flow in Backfill in 2.1.08.03, Flow through Seals 2.1.08.04, Flow through Liner in 2.1.08.05, Thermal Effects on Flow in 2.1.11.10, Effects of Gas on Flow in 2.1.12.02]	Partial - Site Specific, Design Specific	Generic R&D captured in flow through individual EBS components above and issues below.	"Broad" Flow through the EBS cannot be assessed through generic R&D. EBS flow processes through specific barrier components/materials addressed below.					
Limited Release - Engineered Barriers	Waste Packaging	2.1.08.02	Flow In and Through Waste Packages	- Saturated/ Unsaturated flow - Movement as thin films or droplets	Yes	Methods and Properties/Parameters	Medium	Low	Medium	Medium Safety Analysis - affects source term from breached waste packages Low - Design/Construction/Operation - Materials will be selected primarily for containment purposes, however understanding of the flow characteristics through waste package performance is important and understanding would preclude the use of conservative models [ie., entire waste package degraded] Overall Confidence medium - part of EBS and its performance	Improved Representation	Typically conservative models applied to flow through perforated waste packages.
Limited Release - Engineered Barriers	Backfill/Buffer	2.1.08.03	Flow in Backfill	- Fracture / Matrix flow	Yes	Methods and Properties/Parameters	High	Medium	High	May be of high importance for performance in certain environments - governs "source term" release upon failure of waste packages for certain designs in certain environments. Medium importance for design - could effect backfill/buffer design and emplacement techniques High importance for overall confidence - secondary isolation barrier.	Fundamental Gaps in Method	Other countries have evaluated flow through buffer/backfill materials Improved models of flow through breaches could increase understanding of releases from the engineered barriers.
Limited Release - Engineered Barriers	Seals	2.1.08.04	Flow Through Seals	- Fracture / Matrix flow - Gas transport	Partial - Site Specific, Design Specific	Also media specific. Specific R&D would require establishment of seal design and selection of material - compatible with site/media. Generic R&D could be conducted on seal materials independent of design and site/media - method and parameter development.	High	High	High	May be of high importance for performance in certain environments - Could provide preferential pathways for release. High importance for design/construction - could be key part of isolation system High importance for overall confidence - potential isolation barrier.	Fundamental Gaps in Method, Fundamental Data Needs	Improved models of flow through breaches could increase understanding of releases from the engineered barriers. For cementitious barriers, reactive transport models need to be developed to assess barrier seal performance from processes such as carbonation, sulfate attack, and coupled phenomena influencing gas transport.
Limited Release - Engineered Barriers	Other Engineered Features	2.1.08.05	Flow Through Liner / Rock Reinforcement Materials in EBS		Partial - Site Specific, Design Specific	Also media specific. Specific R&D would require establishment of sub-surface design and selection of materials - compatible with site/media. Generic R&D could be conducted to develop/improve methods and properties/parameters independent of design and site/media. Methods and Properties/Parameters	Low	High	Medium	Expected to be of low direct importance to long-term performance. Could be of high importance to repository design and construction. Estimated at medium importance for overall confidence	Fundamental Gaps in Method, Fundamental Data Needs	Reactive transport models need to be developed to assess barrier seal performance and interactions with fluids at barrier interfaces that could influence gas generation and transport.

From Appendix A of the UFD Disposal R&D Roadmap:
www.nuclear.energy.gov/FuelCycle/neFuelCycle_UsedNuclearFuelDispositionReports.html

Example of the Prioritization Information Matrix

2.1.08.03	Flow in Backfill	- Fracture / Matrix flow	May be of high importance for performance in certain environments - governs "source term" release upon failure of waste packages for certain designs in certain environments. Medium importance for design - could effect backfill/buffer design and emplacement techniques High importance for overall confidence - secondary isolation barrier.	Fundamental Gaps in Method	Other countries have evaluated flow through buffer/backfill materials. Improved models of flow through breaches could increase understanding of releases from the engineered barriers.
2.1.08.04	Flow Through Seals	- Frac - Gas	May be of high importance for performance in certain environments - Could provide preferential pathways for release. High importance for design/construction - could be key part of isolation system High importance for overall confidence - potential isolation barrier.	Fundamental Gaps in Method, Fundamental Data Needs	Improved models of flow through breaches could increase understanding of releases from the engineered barriers. For cementitious barriers, reactive transport models need to be developed to assess barrier seal performance from processes such as carbonation, sulftate attack, and coupled phenomena influencing gas transport.

Enlargements of portions of the previous page
Full table is 56 pages long

From Appendix A of the UFD Disposal R&D Roadmap:
www.nuclear.energy.gov/FuelCycle/neFuelCycle_UsedNuclearFuelDispositionReports.html

Used Fuel Disposition Campaign R&D Roadmap (cont.)

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Using Evaluation Results to Support Prioritization

- Scores and weights assigned by program management for each issue and R&D topic
- Basic principles applied in scoring
  - Overall priority is a function of
    - Importance to safety case
    - Importance at each programmatic decision point
    - Adequacy of existing information
  - Importance to the safety case is relevant at all decision points
  - Importance to near-term decisions is of higher priority
  - Where current information is adequate, priority for R&D is lower
  - Where scores differ for different concepts or media, priorities are media-specific

Used Fuel Disposition Campaign R&D Roadmap (cont.)

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Summary of Natural System Results

- **Highest ranked issues**
  - Flow and transport pathways in crystalline media
  - Excavation disturbed zone for borehole disposal and shale media
  - Hydrologic processes for salt media
  - Chemical processes for shale media
  - Thermal processes for shale

GEOSPHERE →	Crystalline	Borehole	Salt	Shale
1.2.01. LONG-TERM PROCESSES (tectonic activity)	Low	Low	Low	Low
1.2.03. SEISMIC ACTIVITY				
- Effects on EBS	High	High	High	High
- Effects on NS	Low	Low	Low	Low
1.3.01. CLIMATIC PROCESSES AND EFFECTS	Low	Low	Low	Low
2.2.01. EXCAVATION DISTURBED ZONE (EDZ)	Medium	High	Medium	High
2.2.02 HOST ROCK (properties)	High	High	High	High
2.2.03 OTHER GEOLOGIC UNITS (properties)	Medium	Medium	Medium	Medium
2.2.05. FLOW AND TRANSPORT PATHWAYS	Medium	Medium	Medium	Medium
2.2.07. MECHANICAL PROCESSES	Low	Low	Medium	Medium
2.2.08. HYDROLOGIC PROCESSES	Low	Medium	High	Medium
2.2.09. CHEMICAL PROCESSES - CHEMISTRY	Low	Medium - High	Low - Medium	Medium - High
2.2.09. CHEMICAL PROCESSES - TRANSPORT	Medium	Medium - High	Medium - High	Medium
2.2.10. BIOLOGICAL PROCESSES	Low	Low	Low	Low
2.2.11. THERMAL PROCESSES	Low	Medium	Low	Medium
2.2.12. GAS SOURCES AND EFFECTS	Low	Low	Low	Low
2.2.14. NUCLEAR CRITICALITY	Low	Low	Low	Low

Notes:
1. Shading indicates that research has been undertaken in other geologic disposal programs
2. FEP numbers lists include all FEPs beneath the 3rd level

Used Fuel Disposition Campaign R&D Roadmap (cont.)

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Summary of Engineered System Results

- **Highest ranked issues: Overall higher ranking for Waste Form, Waste Package, and Buffer/Backfill materials**
  - Waste Materials: Waste form issues ranked higher than those for inventory
  - Waste Package Materials: Waste container issues and chemical processes generally ranked higher than those for specific processes such as hydrologic and biologic.
  - Buffer and Backfill Materials: Issues related to chemical processes generally ranked higher than others.
  - Seal and Liner Materials: Issues related to chemical, mechanical, and thermal processes generally ranked higher than those for radiation or nuclear criticality effects.
  - Other Engineered Barrier Materials: Issues related to chemical processes and radionuclide speciation / solubility ranked slightly higher than issues related to thermal, mechanical, and hydrological processes.
  - Overall, chemical processes in the considered EBS components ranked higher than others but these are strongly coupled to thermal, hydrological, and even mechanical processes within the EBS

Observations Regarding the Integration of Safety Assessments and Design of an R&D Program

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- Safety assessments provide a primary source of information about the importance of R&D topics
  - Safety assessments provide the best means of identifying those topics for which uncertainty has a large impact on estimates of long-term performance
- Safety assessments mature throughout the life of a project, and help inform R&D choices at each step of the way
- R&D decisions also take into account a broad range of qualitative programmatic considerations
  - Overall confidence in the safety case
  - State of knowledge in the international community
  - Cost, schedule, and integration with phased decision-making

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Discussion