International Spent Nuclear Fuel Options

Argonne Nuclear Nonproliferation Seminar:
Reactors and the Commercial Nuclear Industry

Kathryn Huff
Advanced Reactors and Fuel Cycles Group
http://arfc.github.io/pres/2017-09-21-anl.pdf

University of Illinois at Urbana-Champaign

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Outline

Nuclear Power Nations

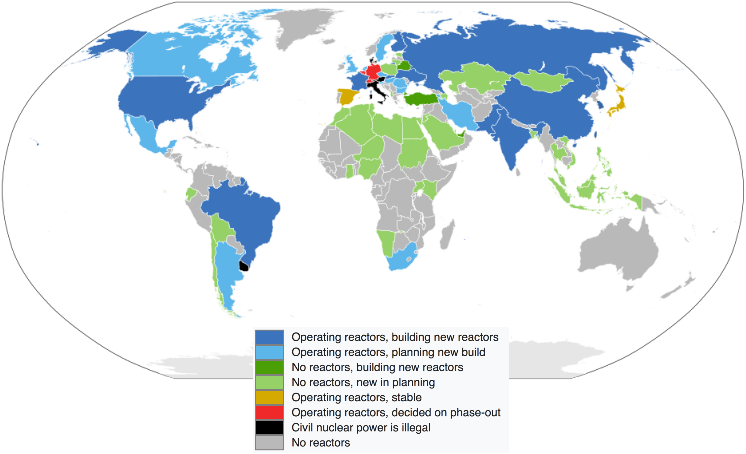


Figure 1: Nuclear power status of all nations [16].

Nuclear Weapons Nations

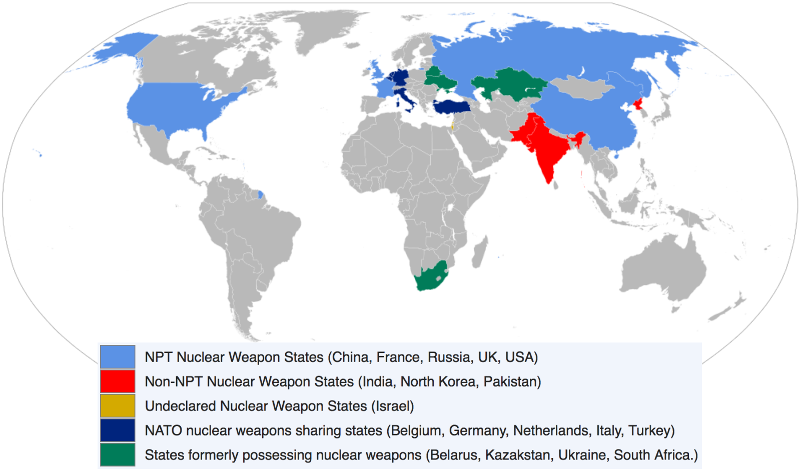
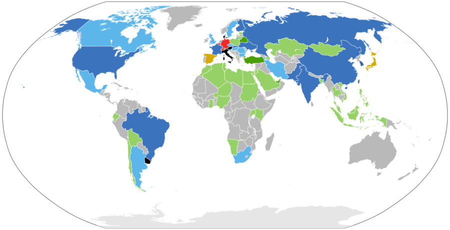
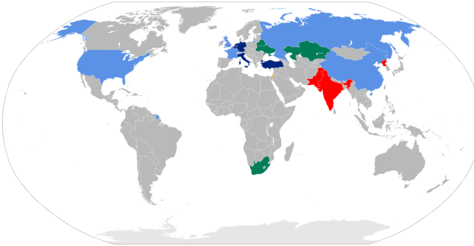


Figure 2: Nuclear power status of all nations [16].

Power vs. Weapons





International Reactors

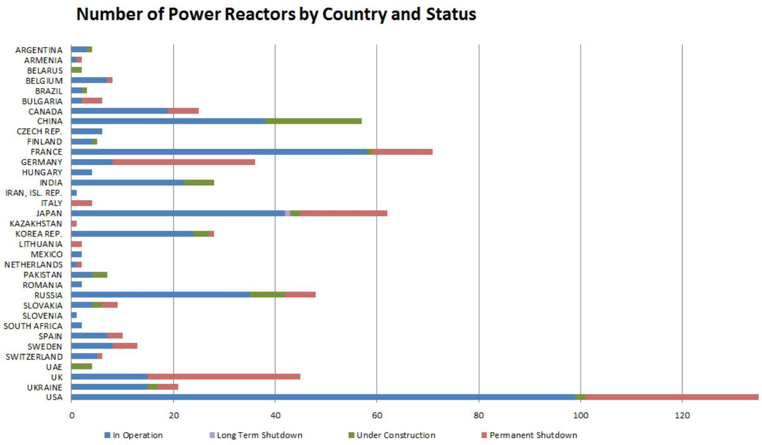


Figure 3: Nuclear reactors internationally, replicated from [12].

Nuclear Capacity

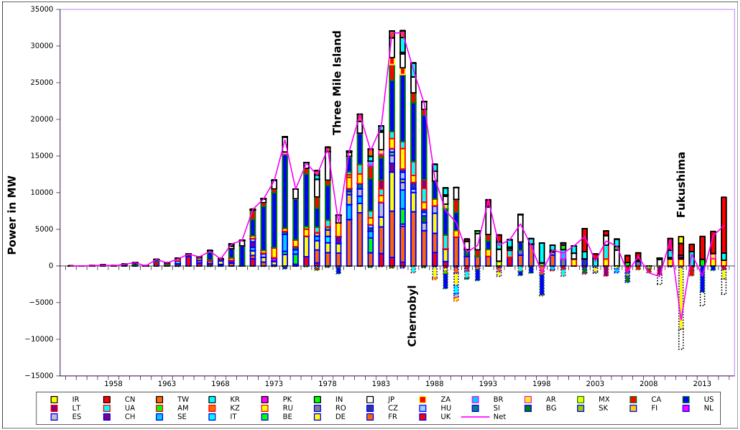


Figure 4: Nuclear power deployments as a function of time [20].

Spent Fuel Inventory

High Level Waste

- 270,000 metric tons worldwide
- 90% in storage pools
- remainder in dry casks

Spent Fuel Inventory

Radioactive Waste Volumes

Type	In storage (m^3)	In disposal (m^3)	% in disposal
VLLW	2,356,000	7,906,000	77%
LLW	3,479,000	20,451,000	85%
ILW	460,000	107,000	19%
HLW	22,000	0	0%

Table 1: Solid radioactive waste volumes worldwide, IAEA estimate 2016. [**?**]

Outline

Array of Possible Options

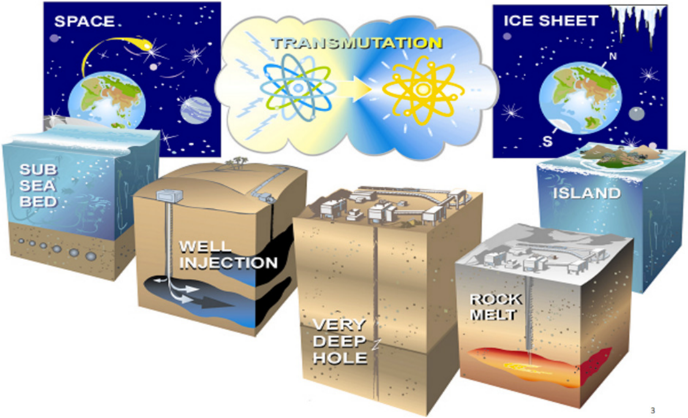


Figure 5: An array of options have been considered in the past [17].

Spent Nuclear Fuel

Figure 6: Spent nuclear fuel from conventional power reactors is in the form of uranium oxide fuel rods [?].

Other High Level Wastes

- Navy Spent Fuel
- Defense Wastes
- Reprocessing Wastes

Current Storage of SNF and HLW

Figure 7: Spent fuel pools are at reactor sites and elsewhere [?].

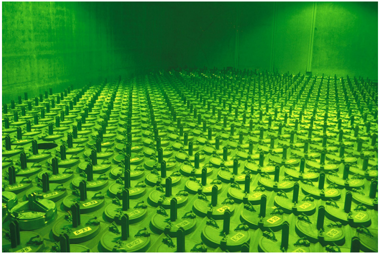


Figure 8: Vitrified glass logs at reprocessing facilities and elsewhere [8].

Current Storage of SNF and HLW

Figure 9: Dry casks at reactor sites and elsewhere [14]

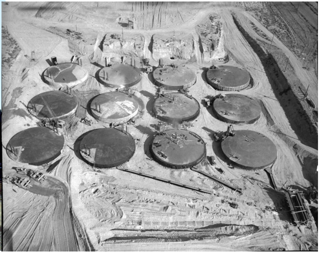


Figure 10: Liquid waste in steel or carbon steel tanks at Hanford and elsewhere[**?**].

Reprocessing Capacity

The reprocessing capacity globally is shown in Fig. 11.

	Thermal Reactor UNF	Fast Reactor UNF
Research/Pilot/Demonstration Reprocessing Facility	Japan (Tokai facility) China (at Lanzhou) France (Atalante) India (BARC, IGARC) Italy (at Rotondella) Belgium (Eurochemic facility) Germany (WAK/Karlsruhe) Russia (Khoplin, Bochvar) United Kingdom (Sellafield) United States (national laboratories)	Russia France Japan United Kingdom United States (Argonne National Laboratory and Oak Ridge National Laboratory)
Commercial Reprocessing Facility	France (Marcoule and La Hague facilities) United Kingdom (THORP and Magnox reprocessing facilities at Sellafield) Russia (RT-1 facility) United States (West Valley) India (Trombay, Tarapur, Kalpakkam)	France

Figure 11: [3].

MOX production

The MOX production globally is shown in Fig. 12.

Table II: Worldwide MOX Fuel Fabrication Capacities (tHM/yr) in 2009 and 2015

	2009	2015
France: MELOX	195	195
Japan: Tokai	10	10
Japan: Rokkasho	0	130
Russia: Mayak, Ozersk (pilot)	5	5
Russia: Zheleznogorsk (fast reactor fuel)	0	60
United Kingdom: Sellafield	40	0
Total for thermal reactors	**250**	**400**

Figure 12: [3].

Clay Disposal Environments

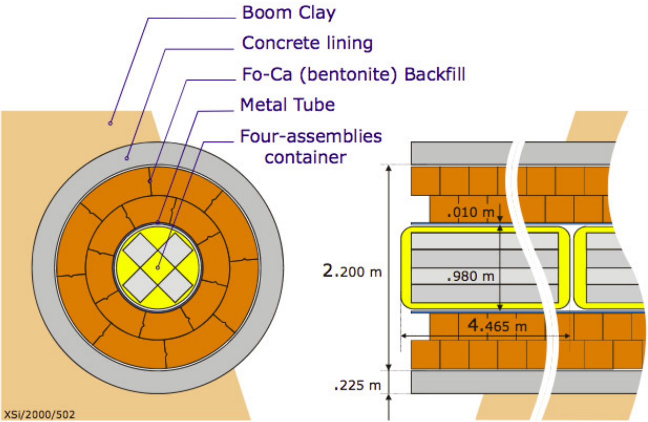


Figure 13: Belgian reference concept in Boom Clay [21].

Granite Disposal Environments

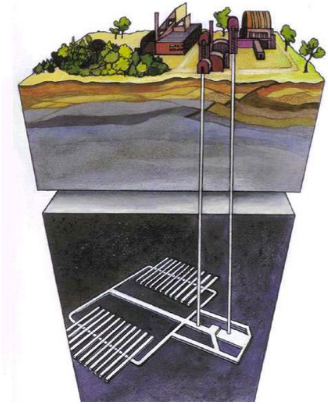


Figure 14: Czech reference concept in Granite [21].

Salt Disposal Environments

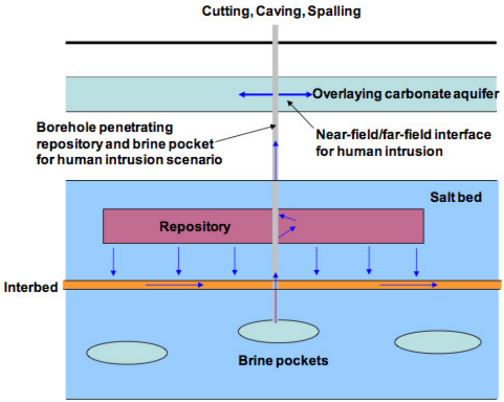


Figure 15: DOE-NE Used Fuel Disposition Campaign concept in Salt [6].

Deep Borehole Disposal Environment

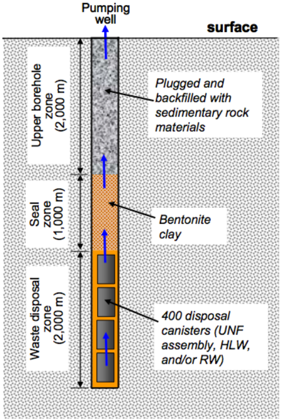
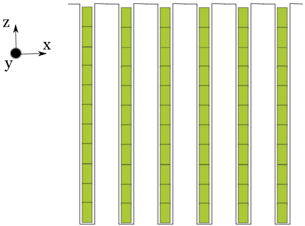


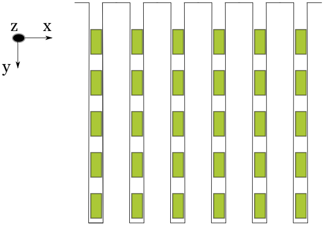
Figure 16: DOE-NE Used Fuel Disposition Campaign Deep Borehole concept [6].

Repository Layouts

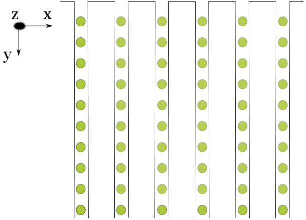
Deep Boreholes



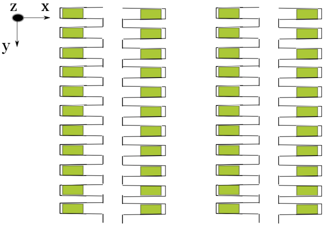
Horizontal In-Tunnel



Vertical In-Tunnel



Alcoves



All Disposal Environments

Features of Various Concepts

Feature	Clay	Granite	Salt	Deep Borehole
Hydrology				
Total Porosity [%]	34-60	0.1	0.5	0-0.5
Eff. Porosity [%]	0.5-5	0.0005	0.1	0.00005-0.01
Conductivity[m/s]	$10^{-11} - 10^{-9}$	$10^{-6} - 10^{-5}$	$10^{-12} - 10^{-10}$	$10^{-13} - 10^{-4}$
Fracturation	none	high	none	low at depth
Geochemistry				
Reducing	Near & Far Field	NF only	NF only	NF only
Oxidizing	none	Slight in FF	Slight in FF	Slight in FF
Salinity	higher at depth	higher at depth	high	high
pH	~ 7	≥ 7	≥ 7	~ 7
Design				
Waste Package	Steel, Cu	Steel, Cu	Steel	Steel,Cement
Buffer	-,Fo-Ca,Cement	Fo-Ca,Cement	Crushed Salt	-,Fo-Ca,Cement
Depth	100-500 m	100-500 m	100-500m	3-5km
Emplacement	Vert.,Horiz,Alcove	Vert.,Horiz.	Alcove	Vert.
Packages/Gallery	one, many	one, many	one, two	400
Thermal Behavior				
Buffer Limit [$^\circ C$]	100 (Fo-Ca)	100 (Fo-Ca)	180	100 (Fo-Ca)
Host Limit [$^\circ C$]	100 (alteration)	200 (cracking)	180 (brines)	none
Conductivity [$\frac{W}{m \cdot K}$]	$1 - 2$	$2 - 4$	~ 4	$2 - 4$
Coalesence	yes	no	yes	no

Repository Components

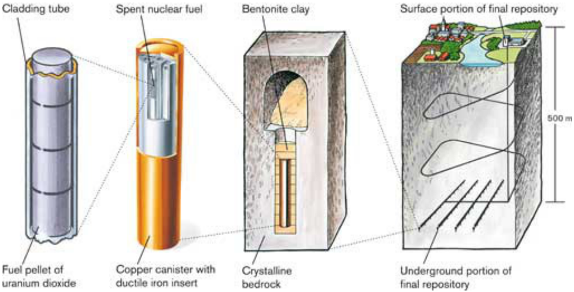


Figure 17: Geologic disposal systems typically employ engineered barrier systems as well as natural barrier systems. This is a Swedish concept in granite [1].

Engineered Barriers : Waste Forms

The first line of defense is the waste form.

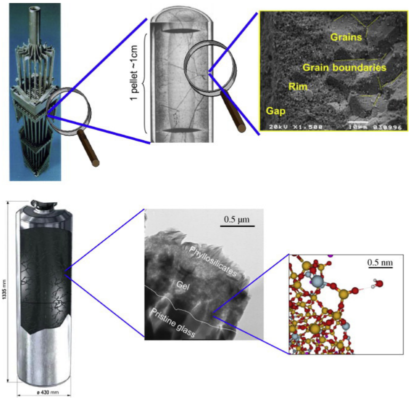


Figure 18: A comparison of uranium oxide and borosilicate glass waste forms [18].

Engineered Barriers : Waste Packages

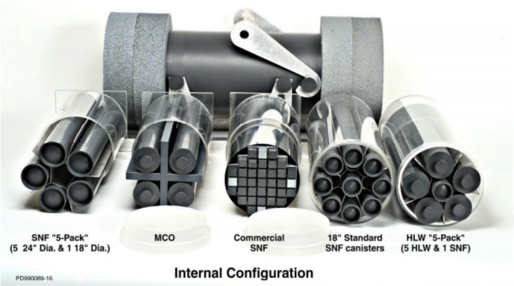


Figure 19: Conceptual mockup of waste packages around waste forms [2].

Engineered Barriers : Disposal Cask

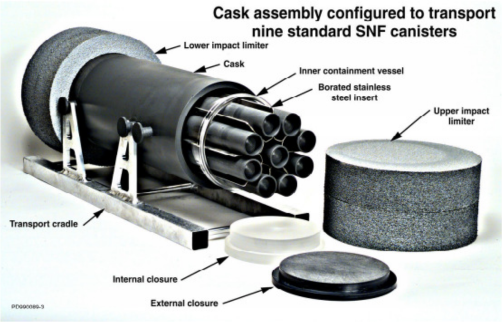
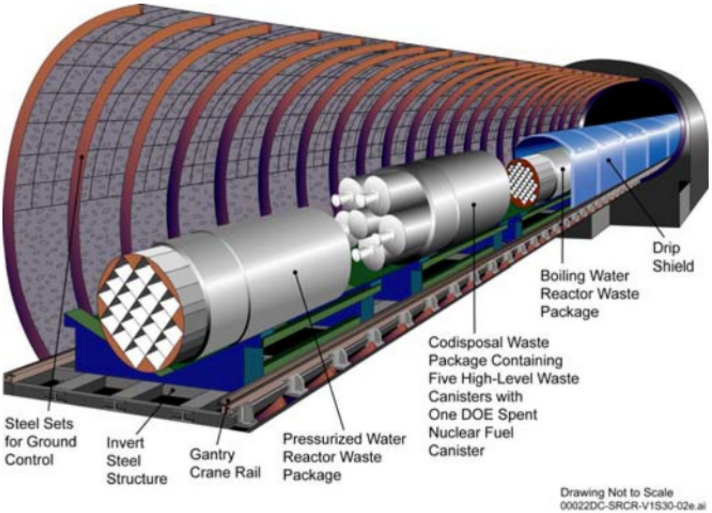


Figure 3. Conceptual design model.

Figure 20: Conceptual mockup of a transport and disposal cask [2].

Engineered Barriers : Tunnel



Natural Barrier : Geology

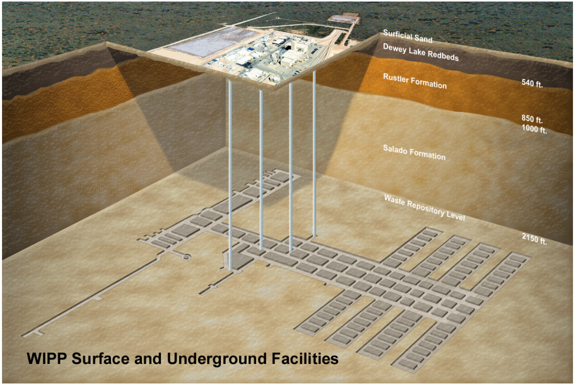
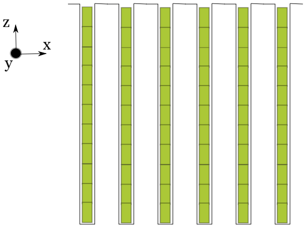


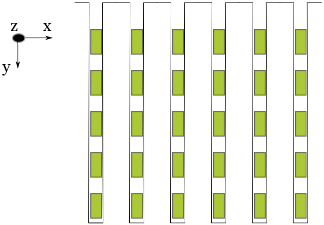
Figure 22: The Waste Isolation Pilot Plant has many geologic layers above the salt bed [7].

Repository Layouts

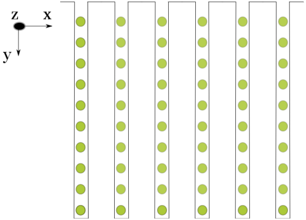
Deep Boreholes



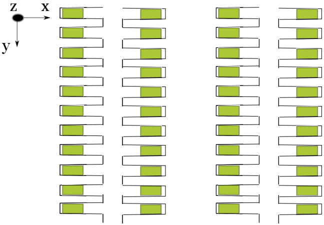
Horizontal In-Tunnel



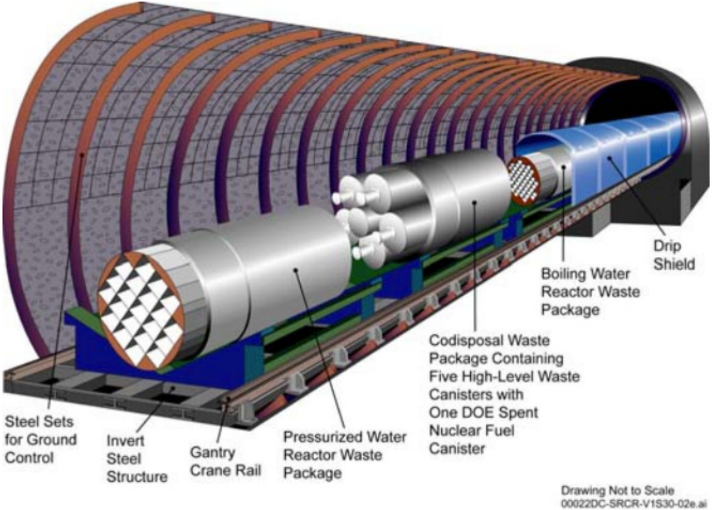
Vertical In-Tunnel



Alcoves



Unsaturated, Ventilated Concepts



Saturated , Enclosed Concepts

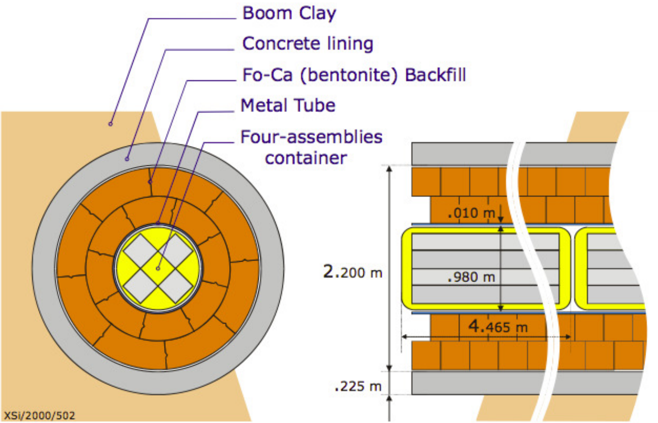


Figure 24: The Belgian reference concept in Boom Clay is backfilled very soon after waste emplacement without a ventilation period and is located below the water table [21].

Tuff (Yucca) Disposal Environments

Figure 25: Yucca Mountain is in southern Nevada [15].

Alternative Disposal Geology Options

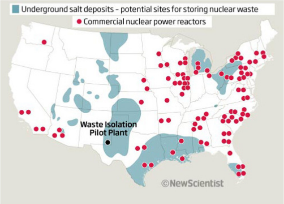


Figure 26: U.S. Salt Deposits, ref. [13].

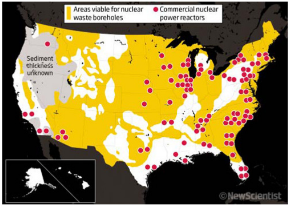


Figure 28: U.S. Crystalline Basement, ref. [13].

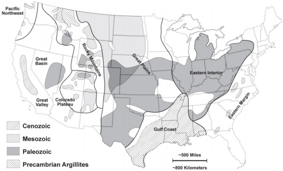


Figure 27: U.S. Clay Deposits, ref. [9].

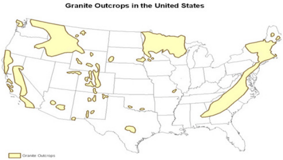


Figure 29: U.S. Granite Beds, ref. [4].

Clay Disposal Environments

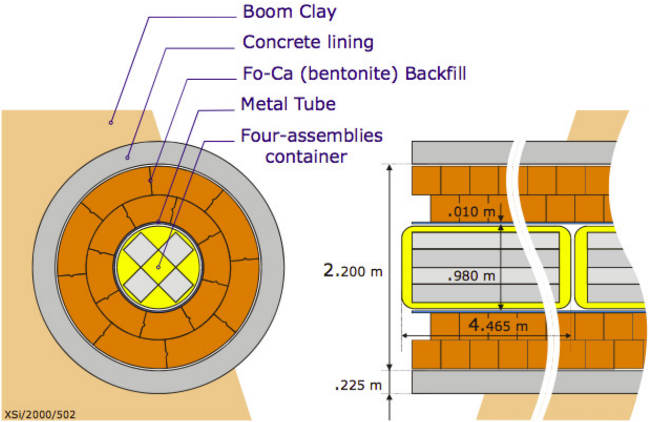


Figure 30: Belgian reference concept in Boom Clay [21].

Granite Disposal Environments

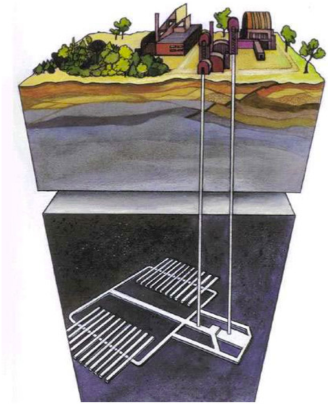


Figure 31: Czech reference concept in Granite [21].

Salt Disposal Environments

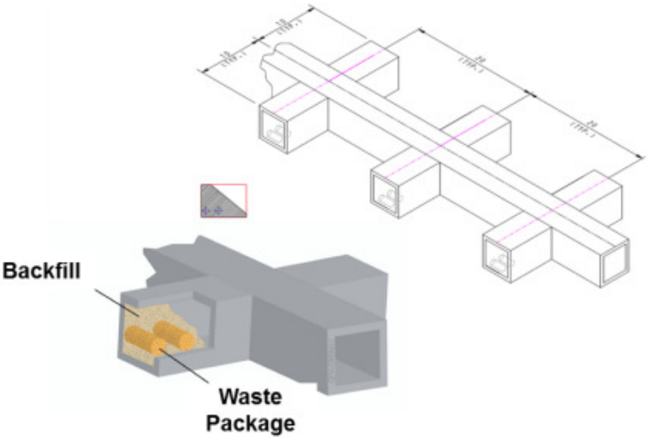


Figure 32: DOE-NE Used Fuel Disposition Campaign concept in Salt [11].

Salt Disposal Environments

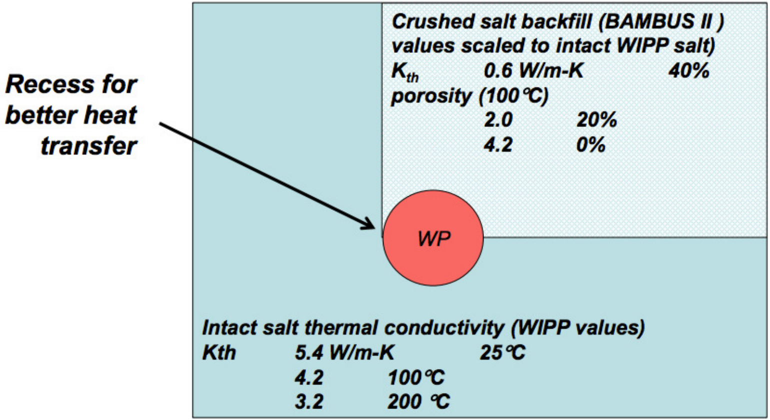


Figure 33: DOE-NE Used Fuel Disposition Campaign concept in Salt [11].

Deep Borehole Disposal Environment

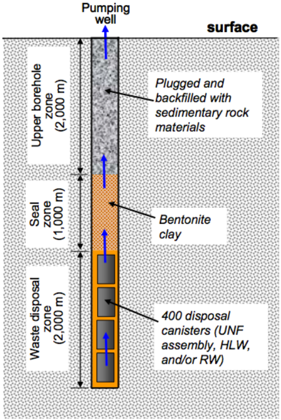


Figure 34: DOE-NE Used Fuel Disposition Campaign Deep Borehole concept [11].

Outline

Performance Metrics

- Dose
- Environmental Release
- Repository Footprint
- Cost
- ...

Thermal Capacity in Various Geologies

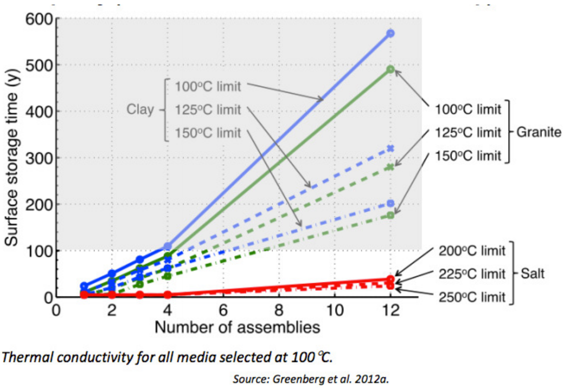


Figure 35: The varying thermal limits, thermal conductivities, and thermal diffusivities of various geologies result in differing heat capacities to similar waste [10].

Release Mechanisms

- Human Disruption
- Natural Disruption
- Barrier Dissolution
- Advection
- Diffusion
- Sorption
- Solubility Limitation
- ...

Solubility Sensitivity In A Clay Model

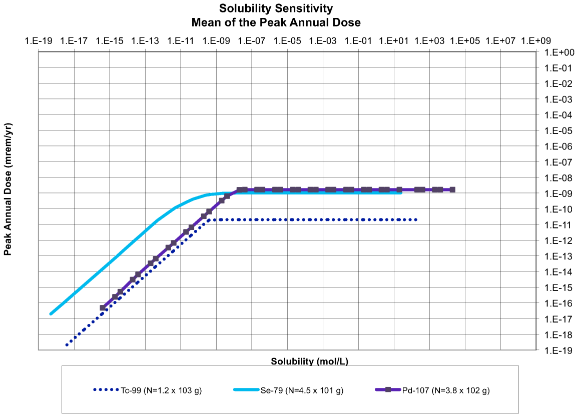


Figure 36: Solubility limit sensitivity. The peak annual dose due to an inventory, N, of each isotope.

Retardation Sensitivity In A Clay Model

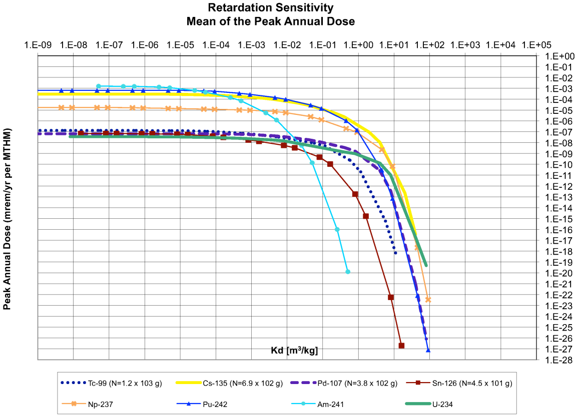


Figure 37: K_d sensitivity. The peak annual dose due to an inventory, N, of each isotope.

Example : Vertical Advective Velocity and Diffusion Coefficient

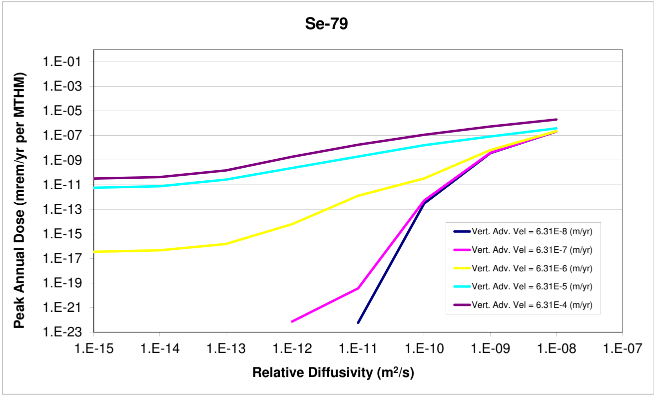


Figure 38: ${}^{79}Se$. *Se* is non sorbing, but solubility limited in clay. For low vertical advective velocity, the system is diffusion dominated.

Example : Vertical Advective Velocity and Diffusion Coefficient

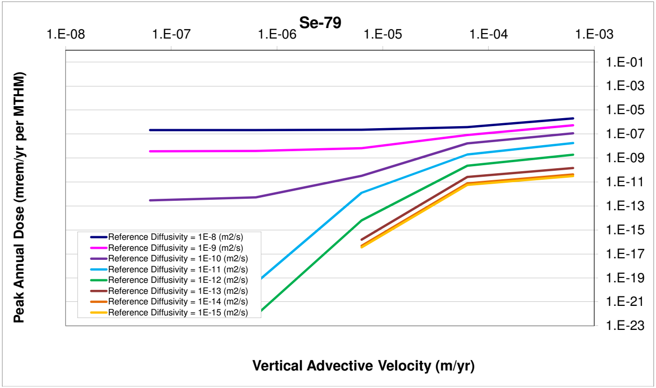


Figure 39: ^{79}Se. *Se* is non sorbing, but solubility limited in clay. For high vertical advective velocity, the diffusivity remains important even in the advective regime as spreading facilitates transport in the presence of solubility limited transport.

Heat Contributors In PWR SNF

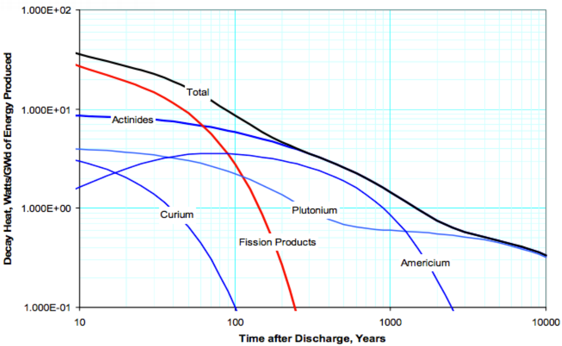


Figure 40: Heat contributors in a canonical PWR fuel[22].

Heat Contributors in PWR SNF

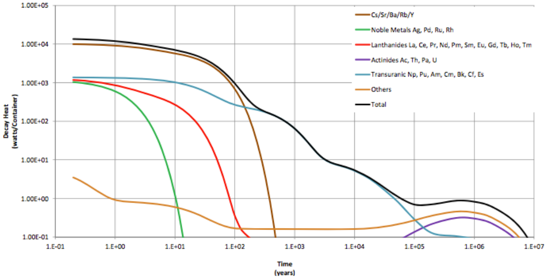


Figure 4-1 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 41: Heat contributors in the primary result of a once through PWR fuel cycle [5].

Heat Contributors in LWR Recycled MOX

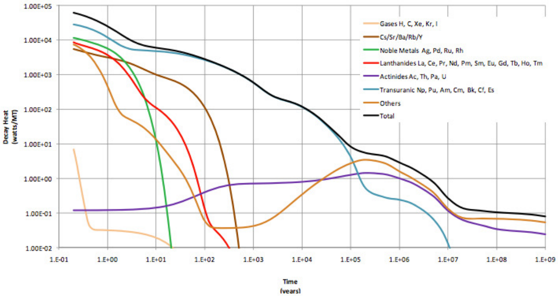


Figure 5-1 Mixed Oxide Fuel 50 GWd/MT Used Fuel Decay Heat

Figure 42: Heat contributors in the primary result of MOX recycling in an LWR [5].

Heat Contributors After NUEX Recycling

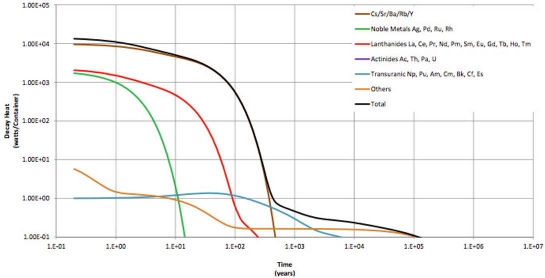


Figure 4-5 Borosilicate Glass Decay Heat Generated by New Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 43: Heat contributors in the primary result of the NUEX extraction process[5].

Heat Contributors After COEX Recycling

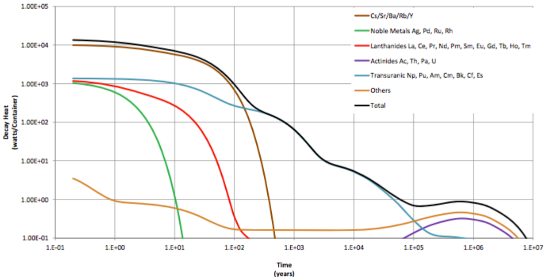


Figure 4-1 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 44: Heat contributors in the primary result of the COEX extraction process[5].

Summary: Heat Contributing Isotopes in Various Fuel Cycles

Dominant thermal contributors vary among fuel cycles.

- Recycling schemes are likely to reduce transuranics and actinides.
- Fission products such as Cs and Sr are powerful heat contributors in the first 500 years, when capacity limiting peak heat is likely to occur in many geologies.
- Transuranics, Pu, Np, Am, and Cm are dominant long term heat contributors. Some extraction processes are more successful at removing those from the waste stream.

Dose Contributors, PWR SNF In Yucca

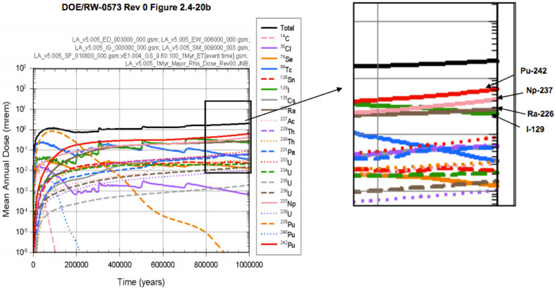
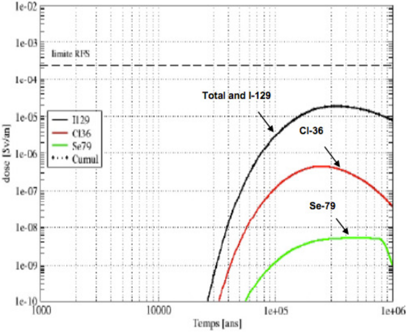


Figure 45: Dose contributors expected in the Yucca Mountain repository [19]. In the oxidizing environment at Yucca mountain, actinides such as ^{242}Pu and ^{237}Np dominate dose contribution. We also see that long-lived, highly soluble ^{129}I and highly soluble ^{226}Ra are also primary dose contributors.

Dose Contributors, PWR SNF In Clay



ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, SEN million year model, CU1 spent nuclear fuel

Figure 46: Dose contributors expected in a clay repository concept [19]. Primary contributors are highly soluble, long lived isotopes ^{129}I, ^{36}Cl, and ^{79}Se .

Dose Contributors, PWR SNF In Granite

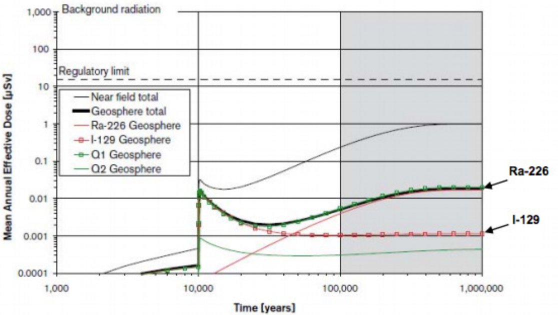


Figure 10-18. The Forsmark pinhole failure base case (geosphere total, i.e. LDF values applied to releases from the far-field model) decomposed with respect to dominant nuclides (Ra-226 and I-129) and release paths (Q1 and Q2). The effect of discarding geosphere retention is also shown (near field total, i.e. LDF applied to releases from the near field model). 10,000 realisations analytic model.

SKB 2006, *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar—a First Evaluation,* TR-06-09, Figure 10-18

Figure 47: Dose contributors expected in a granite repository concept [19]. Primary contributors in this more advective system are the most mobile products at the time of

Summary: Dose Contributing Isotopes in Various Geologies

Dominant dose contributors vary among geologies due to both **water chemistry (sorption, solubility)** and **transport regime (diffusive, advective)**.

- Long lived, highly soluble, non sorbing ^{129}I is a dominant long-term contributor in all geologies.
- In a tuff geology like Yucca Mountain, which is oxidizing with advective transport, actinides dominate in addition to ^{129}I.
- In granite, a typically reducing geology with advective release pathways, mobile ^{226}Ra may be important in addition to ^{129}I.
- In primarily diffusive salt and clay geologies, long-lived, highly soluble, non-sorbing fission and activation products (^{129}I, ^{36}Cl, ^{79}Se) dominate.

Volume

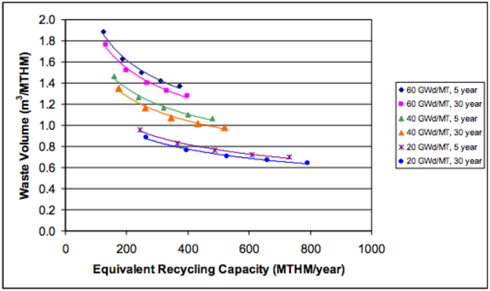


Figure 5-3 Annual Greater Than Class C Waste Volume Relative to Facility Capacity

Figure 48: Recycling strongly affects high level waste volumes[5].

Conclusion

Thanks!
Feel free to direct questions to kdhuff@illinois.edu.

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