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

September 21, 2017

Outline

1. Introduction
   - Nuclear Nations
   - Spent Fuel Inventory
2. Spent Fuel Options
   - Long-Term Storage
   - Reprocessing
   - Deep Geologic Disposal
3. International Progress
   - International Discussion
   - Finland
   - Sweden
4. Challenges
   - Challenge: Financial
   - Challenge: Political
   - Challenge: Security
   - Challenge: Geological

Nuclear Power Nations

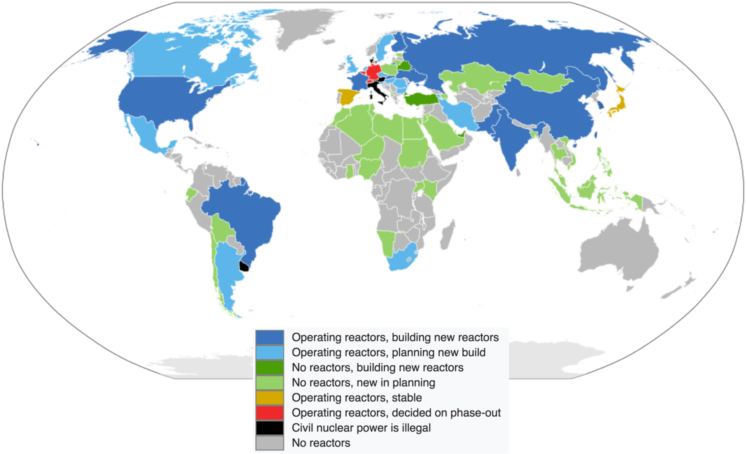


Figure 1: Nuclear power status of all nations [14].

Nuclear Weapons Nations

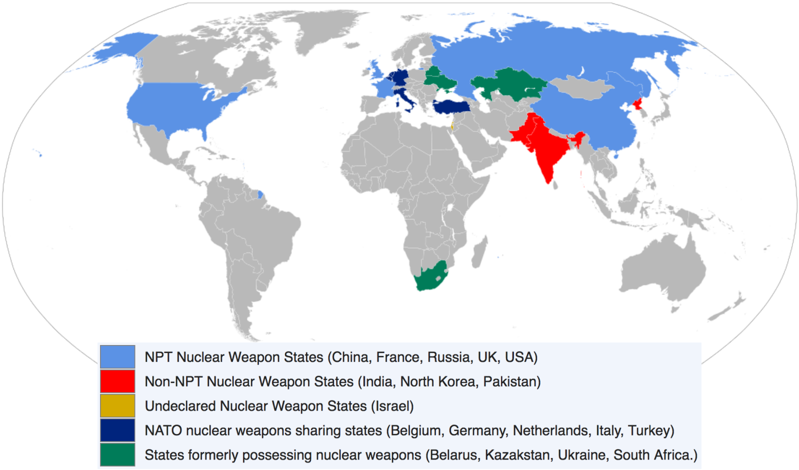
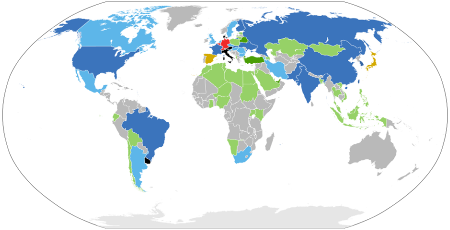
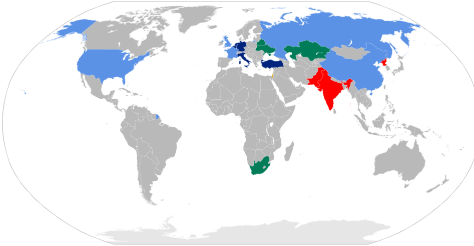


Figure 2: Nuclear weapons status of all nations [14].

Power vs. Weapons





International Reactors

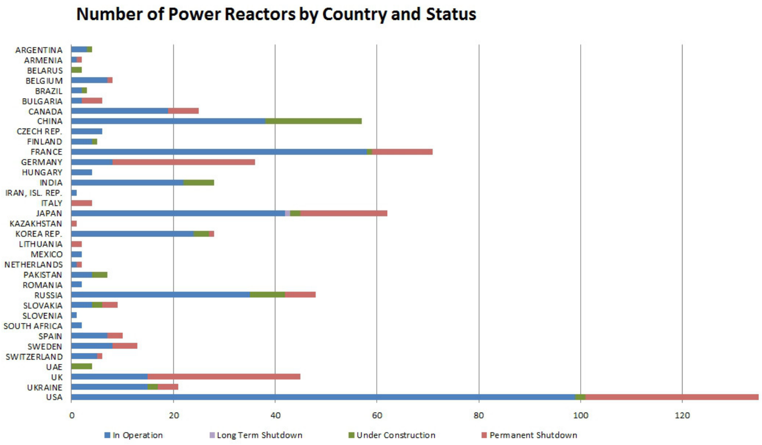


Figure 3: Nuclear reactors internationally, replicated from [10].

Nuclear Capacity

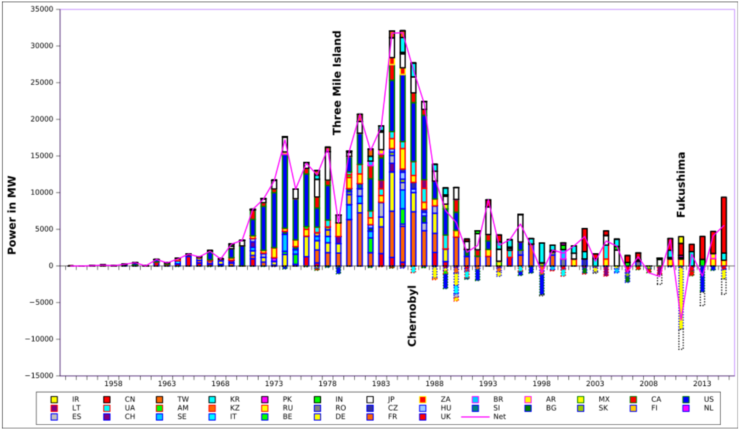


Figure 4: Nuclear power deployments as a function of time [18].

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. [**?**]

VLLW, LLW, ILW

Liquid

Must be solidified or, must be packed in absorbant package 2x liquid volume. (i.e. decontamination solutions, liquid scintillators, ion-exchange fluids, etc.)

Wet Solid

Greater than 1% liquid, but primarily solid (i.e. filters).

Dry Solid

Less than 1% liquid (i.e. trash, swipes, clothes, tools, etc.)

Spent Fuel Inventory

Figure 5: Spent nuclear fuel from conventional power reactors is in the form of uranium oxide fuel rods [?].

Spent Fuel

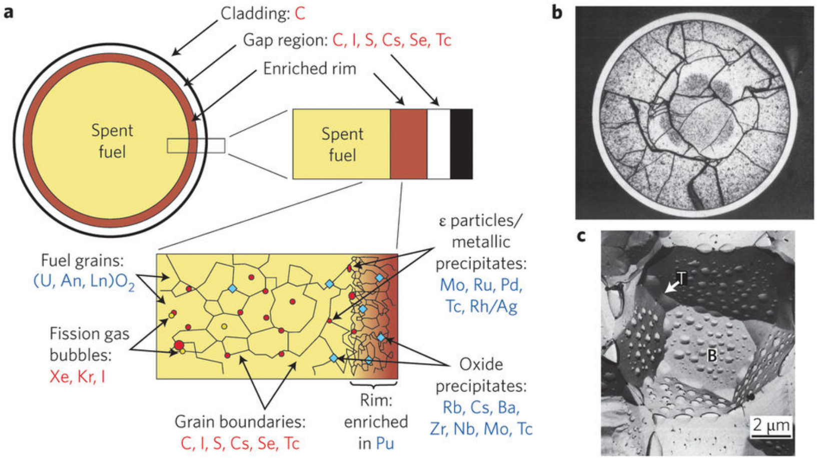


Figure 6: Microstructure of spent fuel and the distribution of fission products and actinides after irradiation in a reactor. From [?].

Spent Fuel Inventory

High Level Waste

- 300,000 metric tons worldwide [?]
- 90% in storage pools
- remainder in dry casks

Outline

1 Introduction
   Nuclear Nations
   Spent Fuel Inventory

2 Spent Fuel Options
   Long-Term Storage
   Reprocessing
   Deep Geologic Disposal

3 International Progress
   International Discussion
   Finland
   Sweden

4 Challenges
   Challenge: Financial
   Challenge: Political
   Challenge: Security
   Challenge: Geological

Array of Possible Options

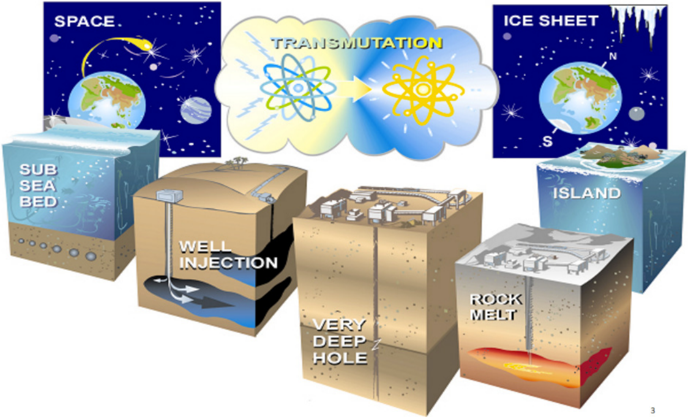


Figure 7: An array of options have been considered in the past [15].

Spent Nuclear Fuel

Figure 8: Spent nuclear fuel from conventional power reactors is in the form of uranium oxide fuel rods [?].

VLLW, LLW, ILW

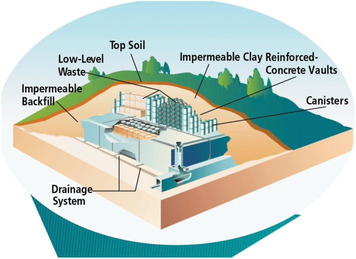


Figure 9: Design of a LLW repository.

Figure 10: Waste Control Specialists Low Level Waste Repository in Andrews County, Tx.

Spent Fuel Inventory

Figure 11: Spent nuclear fuel from conventional power reactors is in the form of uranium oxide fuel rods [?].

Spent Fuel

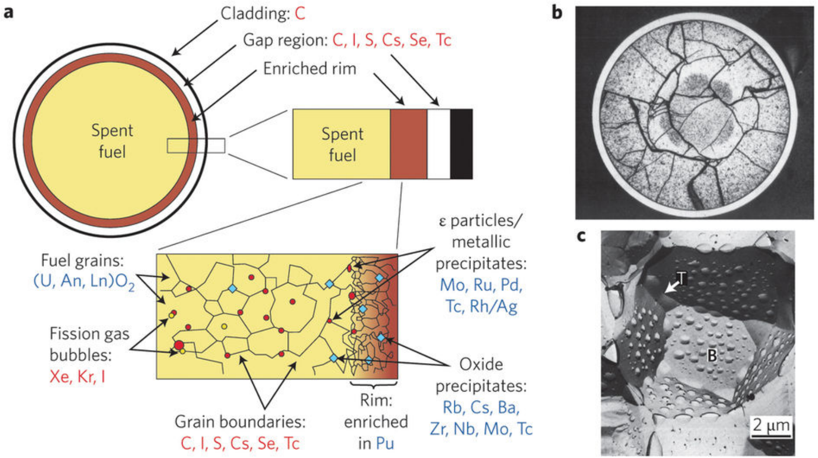


Figure 12: Microstructure of spent fuel and the distribution of fission products and actinides after irradiation in a reactor. From [?].

Spent Fuel Inventory

Figure 13: Spent fuel pools are at reactor sites and elsewhere [?].

Figure 14: Dry casks at reactor sites and elsewhere [12]

Reprocessing Waste

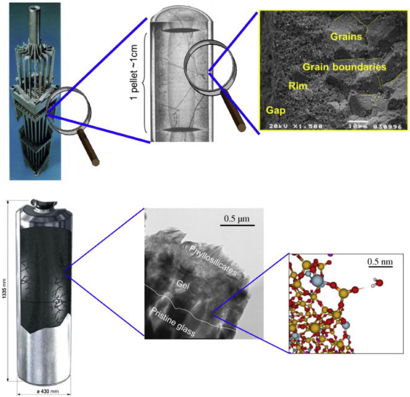


Figure 15: A comparison of uranium oxide and borosilicate glass waste forms [16].

Reprocessing Waste

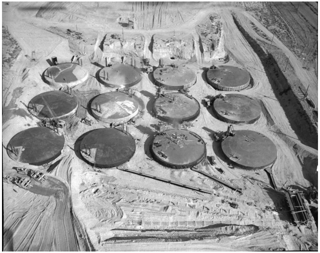


Figure 16: Liquid waste in steel or carbon steel tanks at Hanford and elsewhere[**?**].

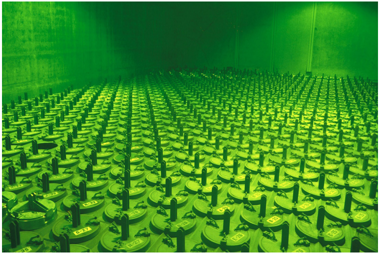


Figure 17: Vitrified glass logs at reprocessing facilities and elsewhere [6].

Reprocessing Capacity

Global reprocessing capacity is shown in Fig. 18.

	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-I facility) United States (West Valley) India (Trombay, Tarapur, Kalpakkam)	France

Figure 18: [2].

MOX production

Global MOX production is shown in Fig. 19.

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 19: [2].

Clay Disposal Environments

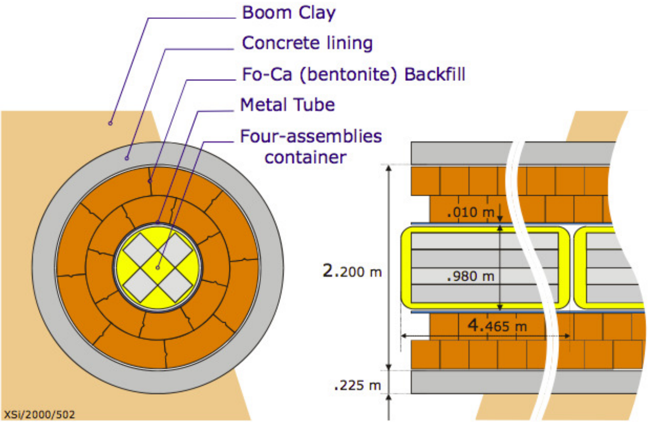


Figure 20: Belgian reference concept in Boom Clay [19].

Granite Disposal Environments

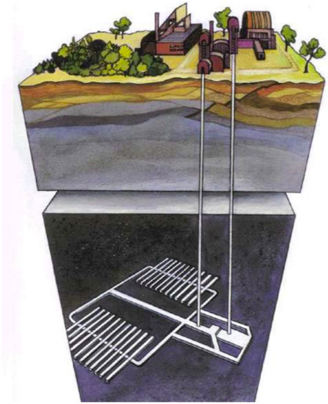


Figure 21: Czech reference concept in Granite [19].

Salt Disposal Environments

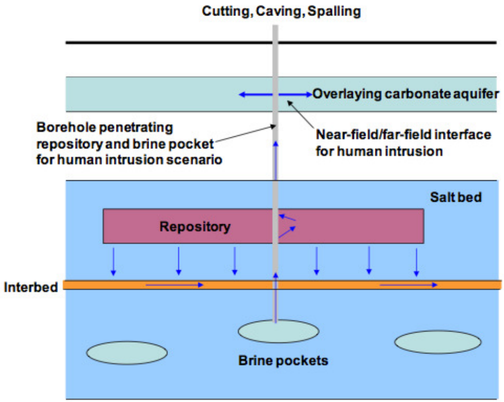


Figure 22: DOE-NE Used Fuel Disposition Campaign concept in Salt [5].

Deep Borehole Disposal Environment

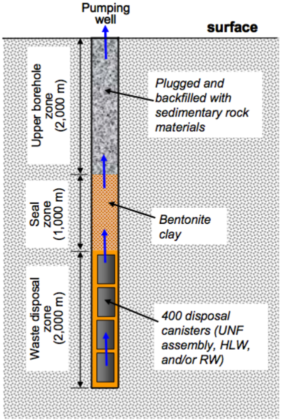
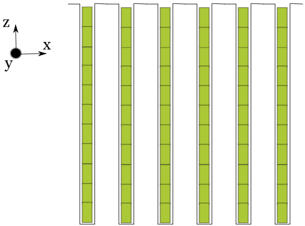


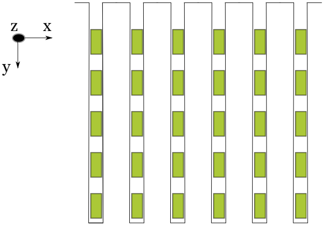
Figure 23: DOE-NE Used Fuel Disposition Campaign Deep Borehole concept [5].

Repository Layouts

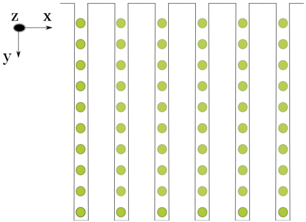
Deep Boreholes



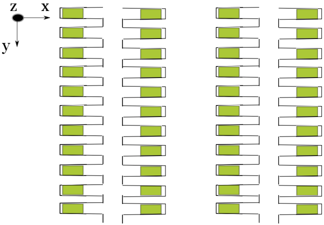
Horizontal In-Tunnel



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

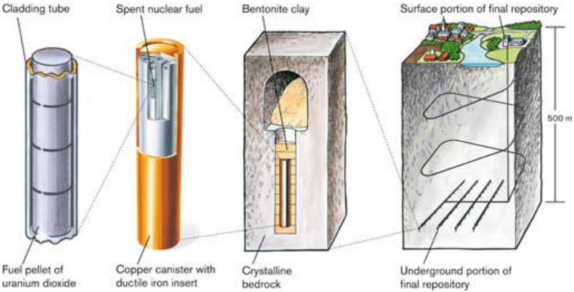
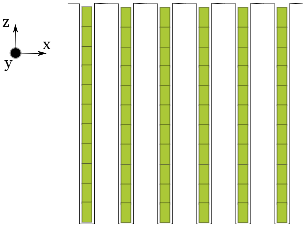


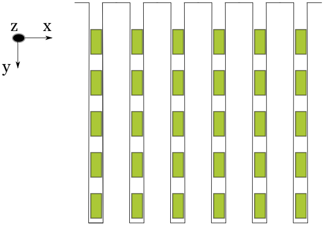
Figure 24: Geologic disposal systems typically employ engineered barrier systems as well as natural barrier systems. This is a Swedish concept in granite [1].

Repository Layouts

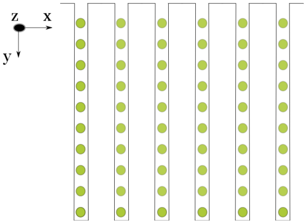
Deep Boreholes



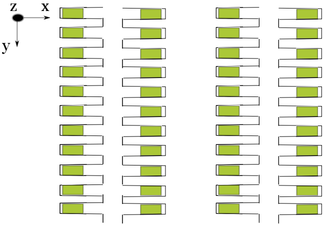
Horizontal In-Tunnel



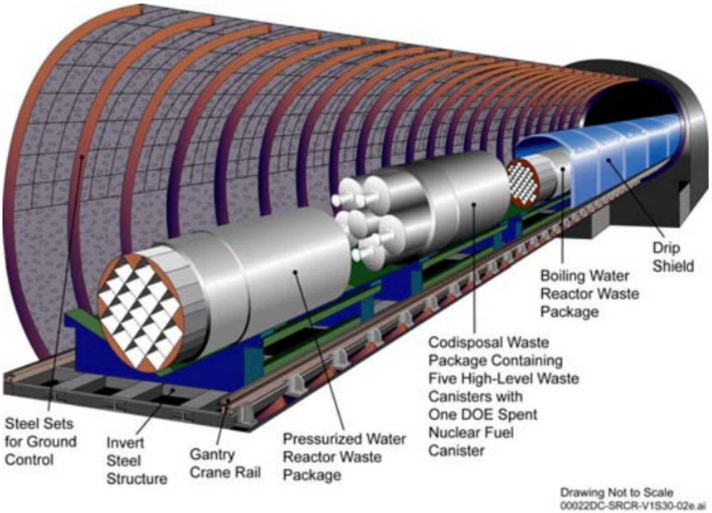
Vertical In-Tunnel



Alcoves



Unsaturated, Ventilated Concepts



Saturated , Enclosed Concepts

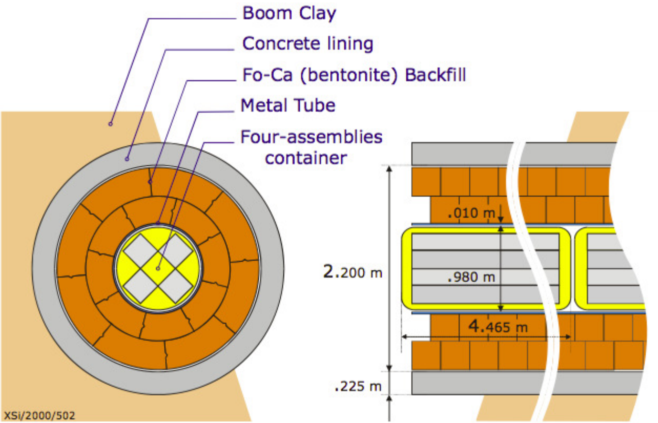


Figure 26: The Belgian reference concept in Boom Clay is backfilled very soon after waste emplacement without a ventilation period and is located below the water table [19].

Tuff (Yucca) Disposal Environments

Figure 27: Yucca Mountain is in southern Nevada [13].

Alternative Disposal Geology Options

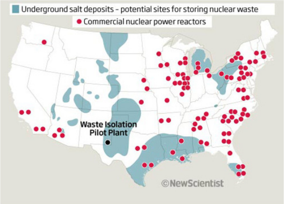


Figure 28: U.S. Salt Deposits, ref. [11].

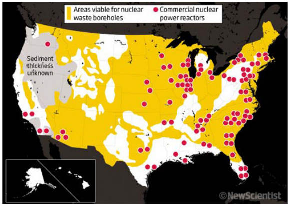


Figure 30: U.S. Crystalline Basement, ref. [11].

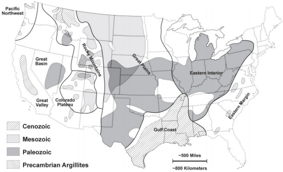


Figure 29: U.S. Clay Deposits, ref. [7].

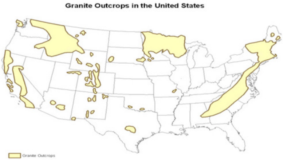


Figure 31: U.S. Granite Beds, ref. [3].

Clay Disposal Environments

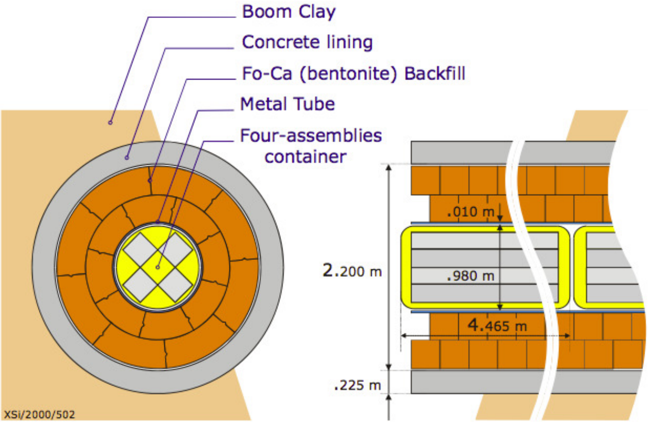


Figure 32: Belgian reference concept in Boom Clay [19].

Granite Disposal Environments

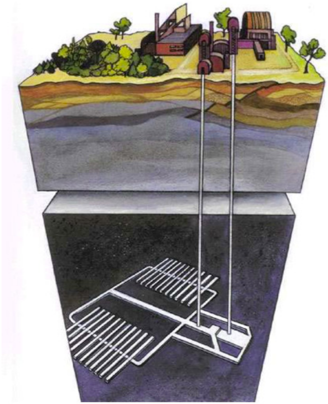


Figure 33: Czech reference concept in Granite [19].

Salt Disposal Environments

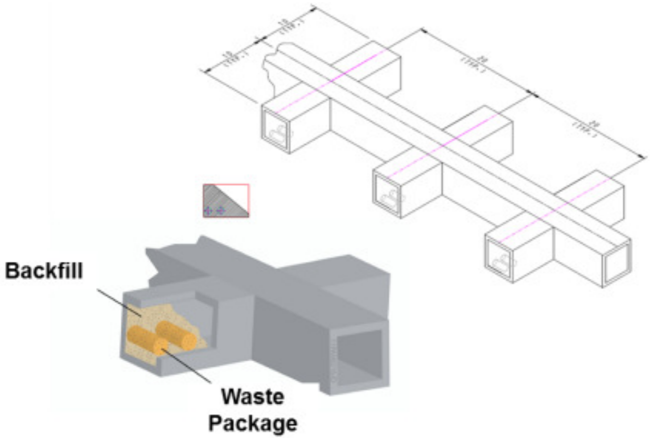


Figure 34: DOE-NE Used Fuel Disposition Campaign concept in Salt [9].

Salt Disposal Environments

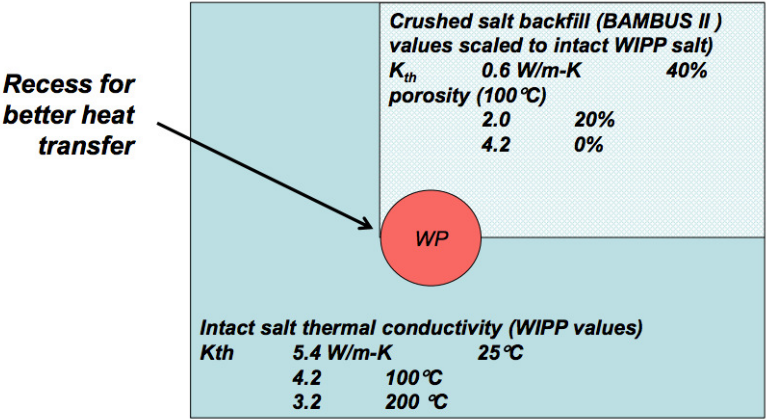


Figure 35: DOE-NE Used Fuel Disposition Campaign concept in Salt [9].

Deep Borehole Disposal Environment

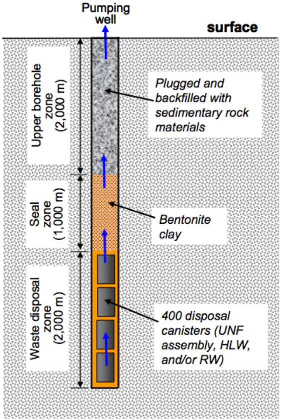


Figure 36: DOE-NE Used Fuel Disposition Campaign Deep Borehole concept [9].

Outline

1. Introduction
   - Nuclear Nations
   - Spent Fuel Inventory
2. Spent Fuel Options
   - Long-Term Storage
   - Reprocessing
   - Deep Geologic Disposal
3. International Progress
   - International Discussion
   - Finland
   - Sweden
4. Challenges
   - Challenge: Financial
   - Challenge: Political
   - Challenge: Security
   - Challenge: Geological

Finland: Posvia

2001 Parliament ratified decision-in-principle siting Olkiluoto, Eurajoki

2012 Construction licence application submitted

2015 Construction licence granted.

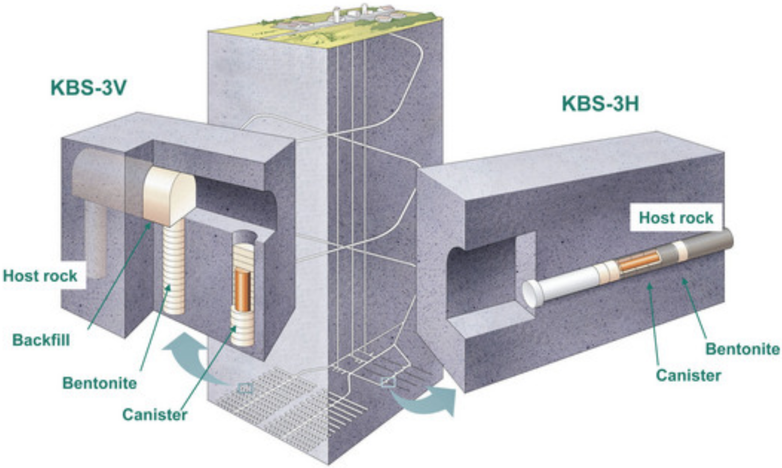
2020 Operation licence application to be submitted.

2020+ Final disposal begins.

Finland: Posiva

[?]

Finland: Posvia: KBS-3V Concept



Courtesy of SKB, Illustrator: Jan Rojmar

Finland: Posvia: KBS-3V Concept

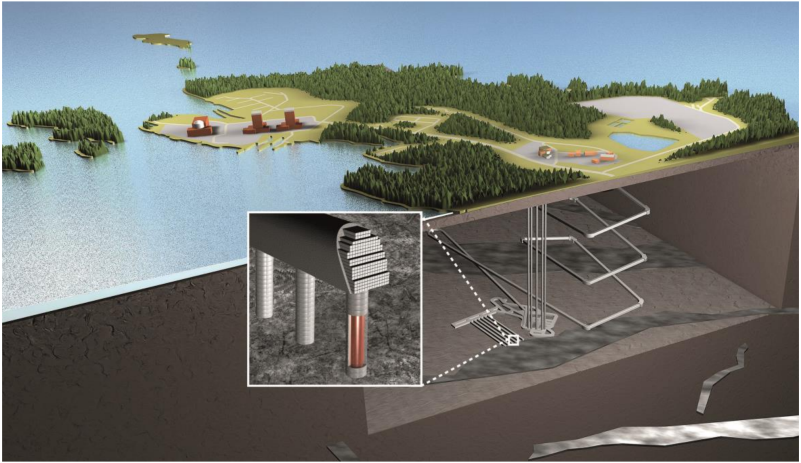
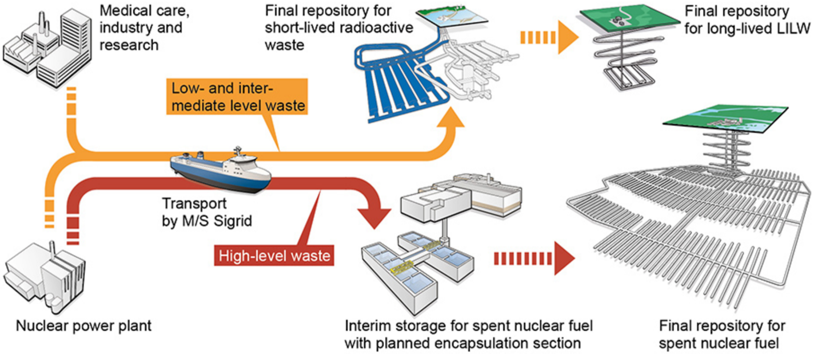


Figure 1-1. *Schematic illustration of the KBS-3V repository design.*

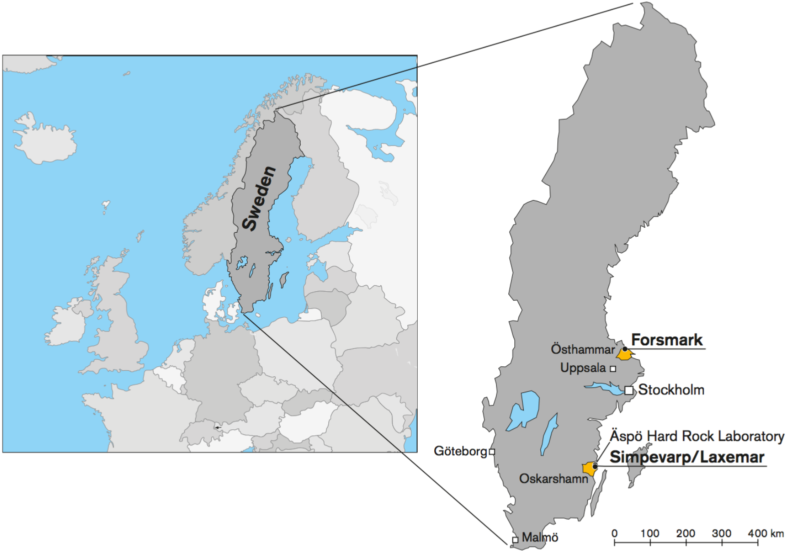
Sweden: SKB

[?]



This is what the system for dealing with Sweden´s **radioactive waste** looks like. The facilities that still have to be constructed are indicated by dotted arrows.

Sweden: Site


Sweden
Forsmark
Östhammar
Uppsala
Stockholm
Äspö Hard Rock Laboratory
Simpevarp/Laxemar
Göteborg
Oskarshamn
Malmö
0
100
200
300
400 km

Sweden: Clab

Clab - the Central Interim Storage Facility for Spent Nuclear Fuel is located at Simpevarp about 25 kilometres north of Oskarshamn. This is where all the spent nuclear fuel from Swedish nuclear power plants is kept while waiting for the final repository to begin operating.

Sweden: Short-Lived Radioactive Waste

SKBs Final Repository for Short-Lived Radioactive Waste is located At Forsmark in the municipality of Östhammar. The facility started operating in 1988 and was then the first of its kind in the world.

tional start 1988

Capacity Approx. 63,000 cubic metres

g capacity Approx. 600 cubic metres per year

nance staff Approx. 30

ve ground Offices and workshops, terminal building, ventilation plant

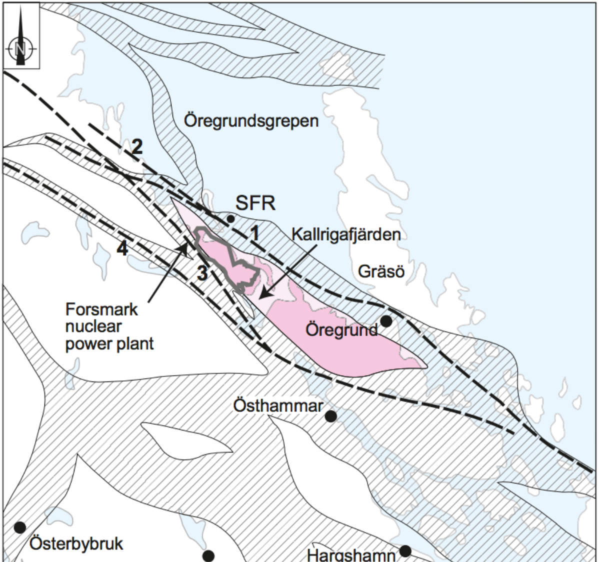
derground Four rock vaults, one silo, control room

ating costs Approx. SEK 40 million per year

The SFR is situated 50 metres below the bottom of the Baltic and comprises four 160-metre long rock vaults and a chamber in the bedrock with a 50-metre high concrete silo for the most radioactive waste. Two parallel kilometre-long access tunnels link the facility to the surface.

Sweden: SKB

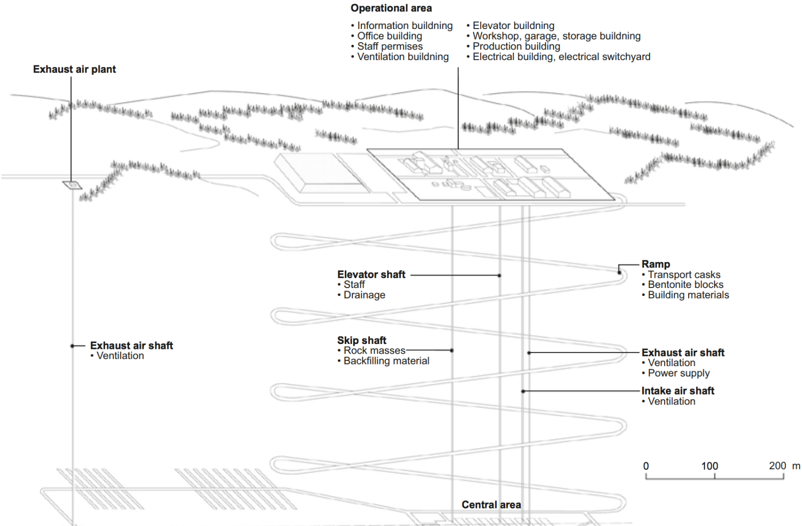
Sweden: Final Disposal



Sweden: Final Disposal

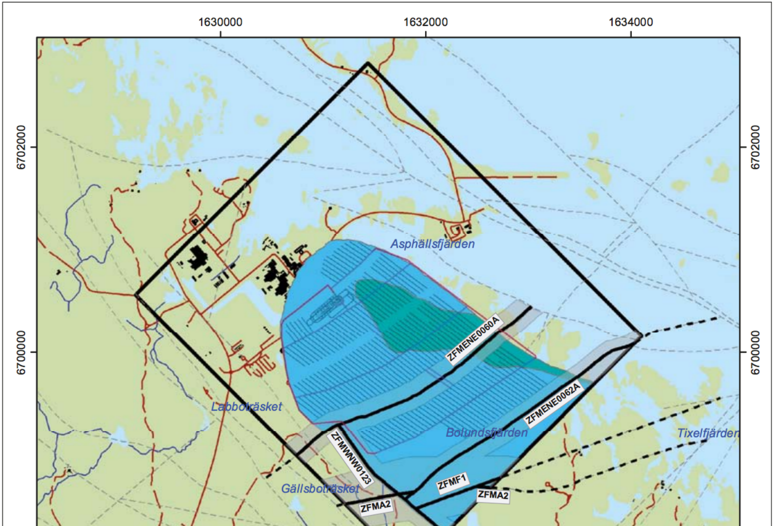
Sweden: Final Disposal

sweden-forsmark-design.png



Sweden: Final Disposal

sweden-forsmark-fractures.png



Sweden: Transport By Sea

Sigrid,

Sweden: Transport By Sea

gth overall	99.5 metres
mary cargo	Radioactive waste and spent nuclear fuel
o capacity	12 transport casks or 40 freight containers
Draught	4.5 metres
nt tonnage	1,600 tonnes

Outline

1. Introduction
   - Nuclear Nations
   - Spent Fuel Inventory
2. Spent Fuel Options
   - Long-Term Storage
   - Reprocessing
   - Deep Geologic Disposal
3. International Progress
   - International Discussion
   - Finland
   - Sweden
4. Challenges
   - Challenge: Financial
   - Challenge: Political
   - Challenge: Security
   - Challenge: Geological

Performance Metrics

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

Thermal Capacity in Various Geologies

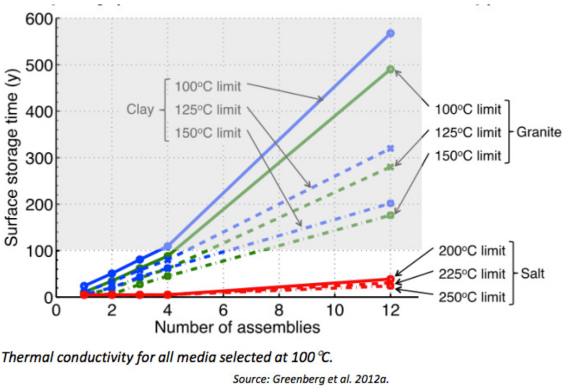


Figure 37: The varying thermal limits, thermal conductivities, and thermal diffusivities of various geologies result in differing heat capacities to similar waste [8].

Release Mechanisms

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

Solubility Sensitivity In A Clay Model

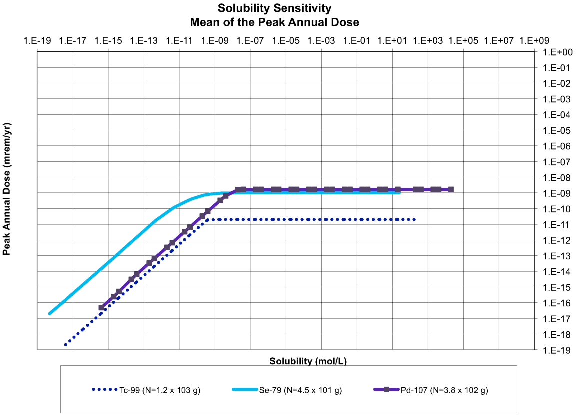


Figure 38: Solubility limit sensitivity. The peak annual dose due to an inventory, N, of each isotope.

Retardation Sensitivity In A Clay Model

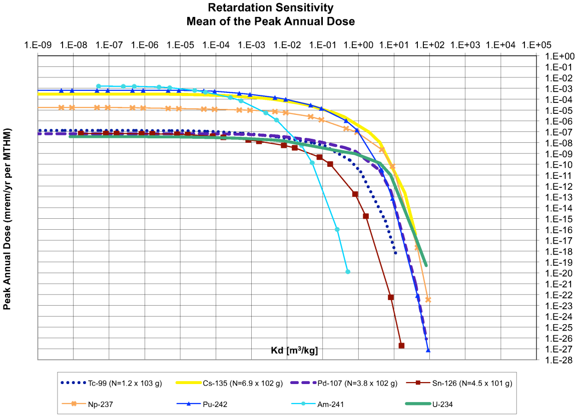


Figure 39: K_d sensitivity. The peak annual dose due to an inventory, N, of each isotope.

Example : Vertical Advective Velocity and Diffusion Coefficient

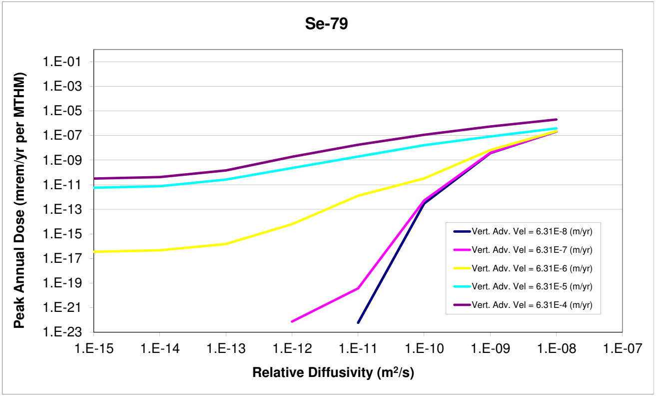


Figure 40: ^{79}Se. *Se* is non sorbing, but solubility limited in clay. For low vertical advective velocity, the system is diffusion dominated.

Example : Vertical Advective Velocity and Diffusion Coefficient

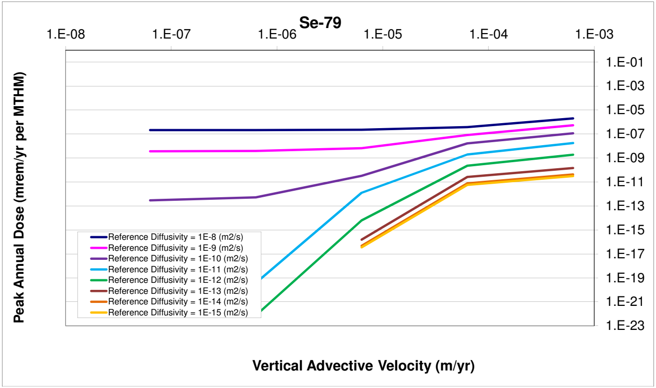


Figure 41: ^{79}Se. *Se* is non sorbing, but solubility limited in clay. For high vertical advective velocity, the diffusivity remains important even in the advective regime as spreading facilitates transport in the presence of solubility limited transport.

Heat Contributors In PWR SNF

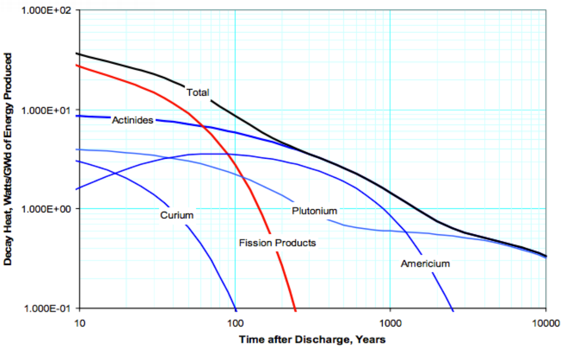


Figure 42: Heat contributors in a canonical PWR fuel[20].

Heat Contributors in PWR SNF

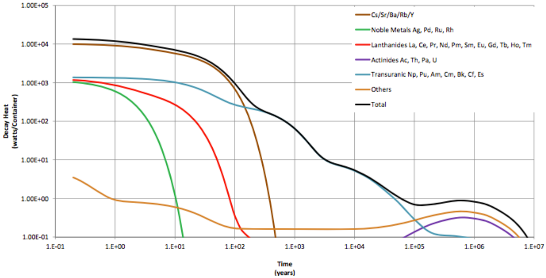


Figure 4-1 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 43: Heat contributors in the primary result of a once through PWR fuel cycle [4].

Heat Contributors in LWR Recycled MOX

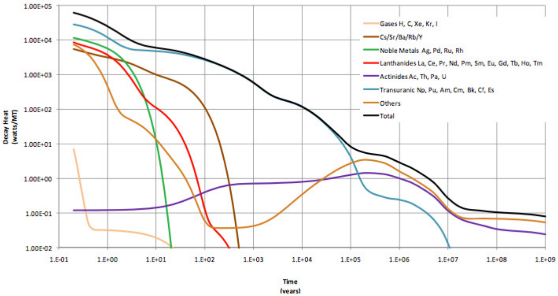


Figure 5-1 Mixed Oxide Fuel 50 GWd/MT Used Fuel Decay Heat

Figure 44: Heat contributors in the primary result of MOX recycling in an LWR [4].

Heat Contributors After NUEX Recycling

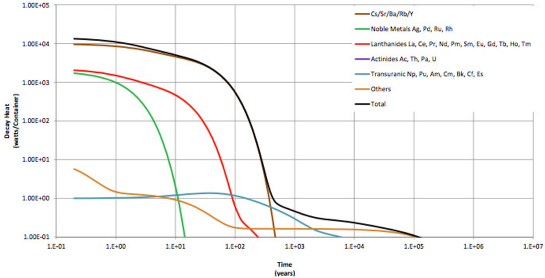


Figure 4-5 Borosilicate Glass Decay Heat Generated by New Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 45: Heat contributors in the primary result of the NUEX extraction process[4].

Heat Contributors After COEX Recycling

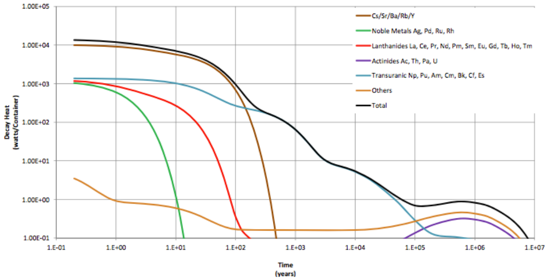


Figure 4-1 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GWd/MT 5 Year Cooled PWR Fuel

Figure 46: Heat contributors in the primary result of the COEX extraction process[4].

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

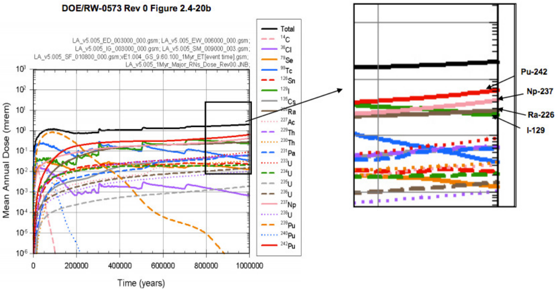
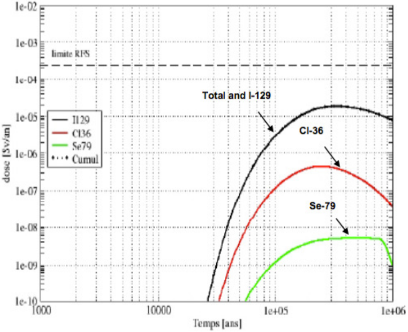


Figure 47: Dose contributors expected in the Yucca Mountain repository [17]. In the oxidizing environment at Yucca mountain, actinides such as ^{242}Pu and ^{237}Np dominate dose contribution. We also see that long-lived, highly soluble ^{129}I and highly soluble ^{226}Ra are also primary dose contributors.

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 48: Dose contributors expected in a clay repository concept [17]. Primary contributors are highly soluble, long lived isotopes ^{129}I, ^{36}Cl, and ^{79}Se .

Dose Contributors, PWR SNF In Granite

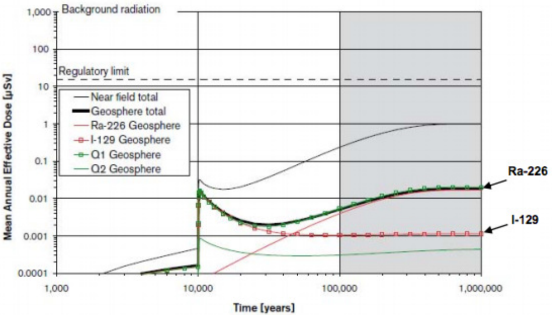


Figure 10-18. The Forsmark pinhole failure base case (geosphere total, i.e. LDF values applied to releases from the far-field model) decomposed with respect to dominant nuclides (Ra-226 and I-129) and release paths (Q1 and Q2). The effect of discarding geosphere retention is also shown (near field total, 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 49: Dose contributors expected in a granite repository concept [17]. 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

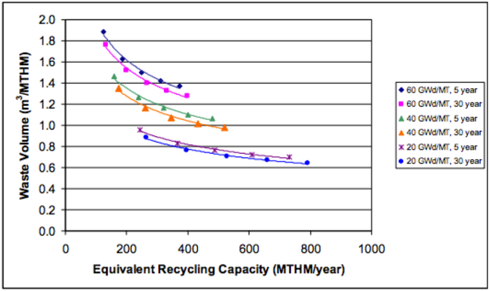


Figure 5-3 Annual Greater Than Class C Waste Volume Relative to Facility Capacity

Figure 50: Recycling strongly affects high level waste volumes[4].

Conclusion

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

References I

[1] Svensk karnbranslehantering AB.
Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar-a First Evaluation: Main Report of the SR-Can Project.
SKB, November 2006.

[2] Melvin R. Buckner and William E. Burchill.
The case for nuclear fuel recycling.
Nuclear News, 2016.

[3] J. B. Bush.
Economic and Technical Feasibility Study of Compressed Air Storage.
Report ERDA, pages 76–76, 1976.

[4] Joe Carter, Robert Jones, and Alan Luptak.
US Radioactive Waste Inventory and Characteristics Related to Potential Future Nuclear Energy Systems.
Technical Report FCRD-USED-2011-000068, Rev 2, May 2011.

References II

[5] Daniel Clayton, Geoff Freeze, Ernest Hardin, W. Mark Nutt, Jens Birkholzer, H.H. Liu, and Shaoping Chu.
Generic Disposal System Modeling - Fiscal Year 2011 Progress Report.
Technical Report FCRD-USED-2011-000184, U.S. Department of Energy, Sandia, NM, August 2011.

[6] Peter Essick.
Photographing the Infinity Room - Timing is Everything, April 2012.

[7] Serge Gonzales and Kenneth Sutherland Johnson.
Shales and other argillaceous strata in the United States.
Technical report, Earth Resource Associates, Inc., Athens, GA (USA), 1985.

[8] Harris Greenberg, James Blink, Massimiliano Fratoni, Mark Sutton, and Amber Ross.
Application of Analytical Heat Transfer Models of Multi-layered Natural and Engineered Barriers in Potential High-Level Nuclear Waste Repositories.
In *WM2012*, Phoenix, AZ, March 2012.
LLNL-CONF-511672.

References III

[9] Ernest Hardin, James Blink, Harris Greenberg, Mark Sutton, Massimo Fratoni, Joe Carter, Mark Dupont, and Rob Howard.
Generic Repository Design Concepts and Thermal Analysis - 8.8.2011 Draft.
Technical Report FCRD-USED-2011-000143, Department of Energy Office of Used Fuel Disposition, Sandia, August 2011.

[10] IAEA.
Country Nuclear Power Profiles.
2015.

[11] NewScientist.
Where should the US store its nuclear waste?
NewScientist, April 2011.

[12] NRC.
Dry cask storage., January 2008.

[13] OMB.
Yucca Mountain 2.jpg, August 2006.

References IV

[14] Ichabod Paleogene and Krzysztof Kori.
File:Nuclear power station.svg, 2017.
https://en.wikipedia.org/wiki/File:Nuclear_power_station.svg.

[15] Mark Peters.
What's Next for Used Nuclear Fuel and Nuclear Waste Management Policy?, January 2013.

[16] Christophe Poinssot and Stéphane Gin.
Long-term Behavior Science: The cornerstone approach for reliably assessing the long-term performance of nuclear waste.
Journal of Nuclear Materials, 420(1–3):182–192, January 2012.

[17] Peter Swift and Mark Nutt.
Applying insights from repository safety assessments.
In *Proceedings of 11th Information Exchange Meeting on Partitioning and Transmutation*, San Francisco, CA, October 2010. OECD-NEA.

[18] Torsch.
Global status of nuclear deployment as of 2017, February 2013.
https://commons.wikimedia.org/wiki/File:Nuclear_Energy_by_Year.svg.

References V

[19] W. von Lensa, R. Nabbi, and M. Rossbach.
RED-IMPACT Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal.
Forschungszentrum Julich, 2008.

[20] Roald Wigeland.
Relationship between Geologic Disposal Characteristics and Advanced Nuclear Fuel Cycles with Partitioning and Transmutation, November 2010.