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Considerations for Spent Fuel Management for the Once-Through Cycle in the U.S.

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Clean. Reliable. Nuclear.

IAEA Technical Meeting on Strategies and Opportunities for the Management of Spent Fuel from Power Reactors in the Longer Timeframe

GCNEP, Bahadurgarh, India
25 – 29 November 2019

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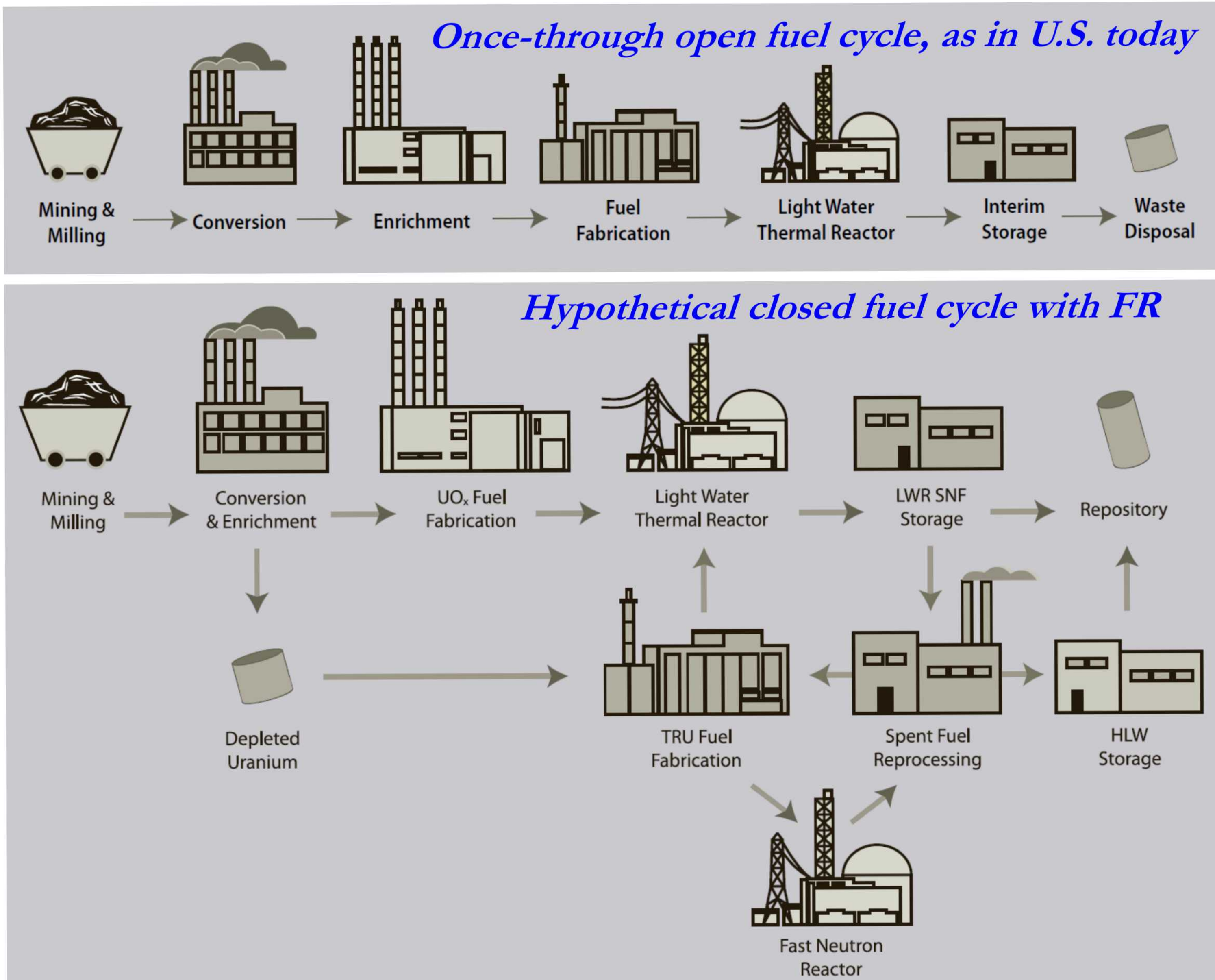
Outline

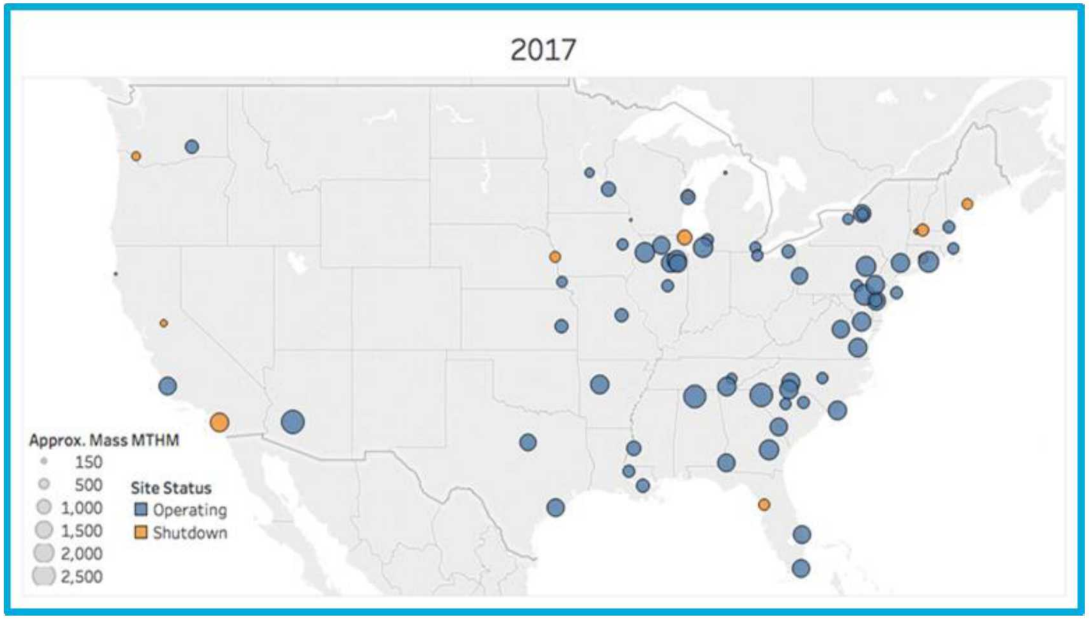
- **Once-through cycle in the U.S. and its waste burden**
- **Considerations for recycling in the U.S.**
- **Observations of various fuel cycle options studies with respect to waste management**
- **How alternative nuclear fuel cycles might affect deep geologic waste disposal**
- **How existing safety assessments inform conclusions about waste management and disposal (examples from multiple programs)**
- **Conclusions**

Once-Through vs. Recycle (from 2011 MIT Study)



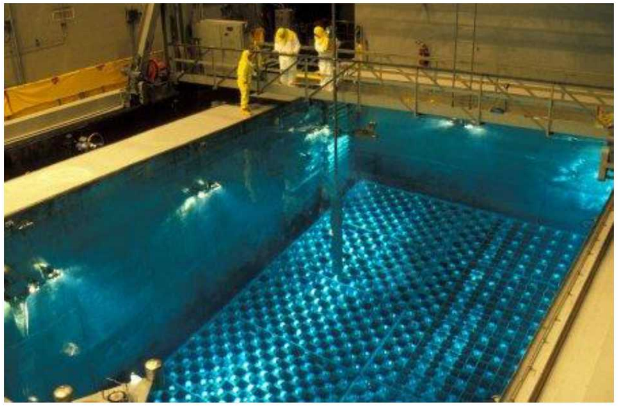
Current SNF Disposition for the Once-Through Cycle in the U.S.: The Reality

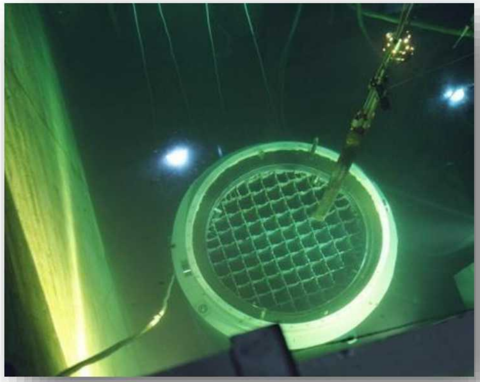
Temporary Storage at 75 commercial reactor sites in 33 States



Map of the US commercial SNF storage from Bonano et al. 2018

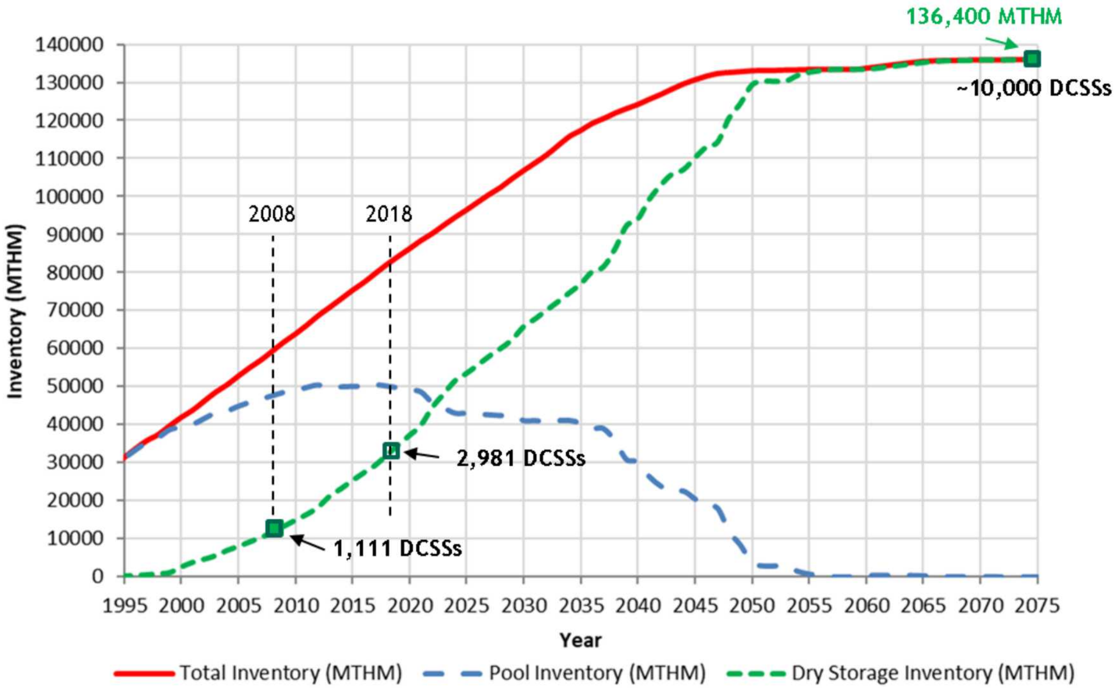
- Pool storage provides cooling and shielding of radiation
  - Primary risks for spent fuel pools are associated with loss of the cooling and shielding water
- US pools have reached capacity limits and utilities have implemented dry storage
- Some facilities have shutdown and all that remains is "stranded" fuel at an independent spent fuel storage installation (ISFSI):



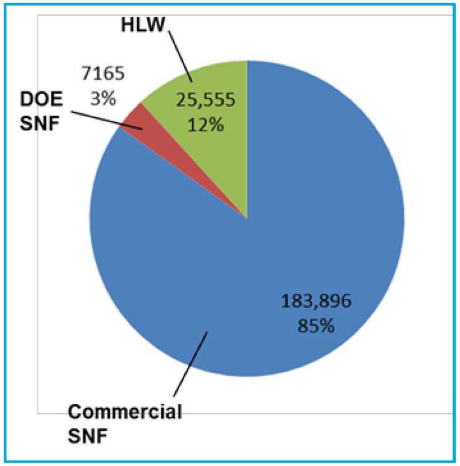


US Projections of Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW)

Projections assumes full license renewals and no new reactor construction or disposal (updated from Bonano et al., 2018)



Projected Volumes of SNF and HLW in 2048



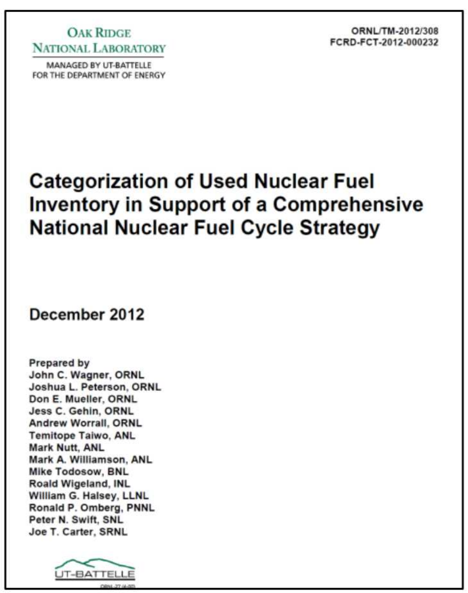
Volumes shown in m³ assuming constant rate of nuclear power generation and packaging of future commercial SNF in existing designs of dual-purpose canisters.

- Approx. 80,000 MTHM (metric tons heavy metal) of commercial SNF in storage in the US as of Dec. 2017
- 30,000 MTHM in dry storage at reactor sites, in approximately 2,981 cask/canister systems as of Dec. 2018
  - Balance in pools, mainly at reactors
- Approx. 2200 MTHM of SNF generated nationwide each year
  - Approximately 160 new dry storage canisters are loaded each year in the US

Could the U.S. Re-Process Existing Spent Nuclear Fuel and Reuse It?

- The US has no commercial reprocessing capability
  - Operations at West Valley, New York, ceased in 1972
  - Savannah River Site, South Carolina retains the capability to reprocess for defense purposes
- The US has more than 80,000 metric tons of spent fuel and generates an additional 2,200 metric tons each year
- The largest reprocessing facility in the world (Sellafield, UK) had a nominal capacity of 1,200 metric tons per year
  - La Hague in France has a capacity of about 1100 metric tons per year
- The US would need two or three of the world's largest reprocessing facilities just to keep up with current discharges

To date there has not been a viable economic model in which existing spent fuel gets reprocessed in the U.S.



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ORNL/TM-2012/308
FCRD-FCT-2012-000232

Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy

December 2012

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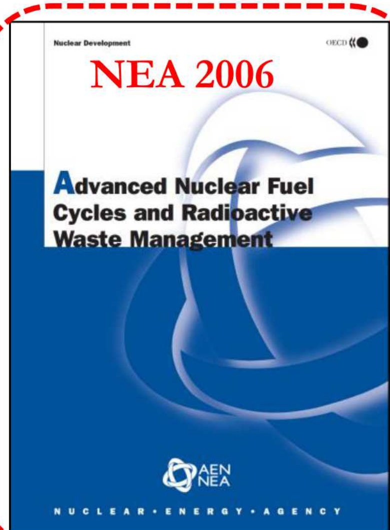
"98% of the total current U.S. inventory by mass can proceed to permanent disposal without the need to ensure retrievability for reuse or research" (Wagner et al., 2012)*

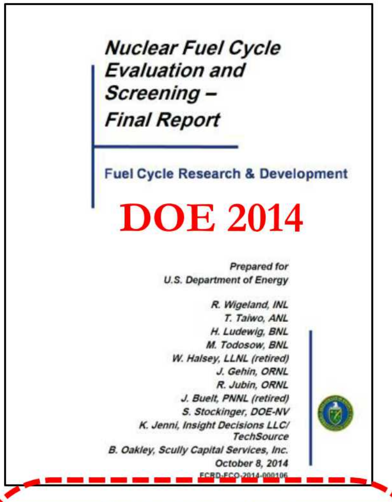
*** This assessment does not assume any decision about future fuel cycle options or preclude any potential options, including those with potential recycling of commercial UNF, since the ~2000 MTHM that is generated annually could provide the feedstock needed for deployment of alternative fuel cycles….***

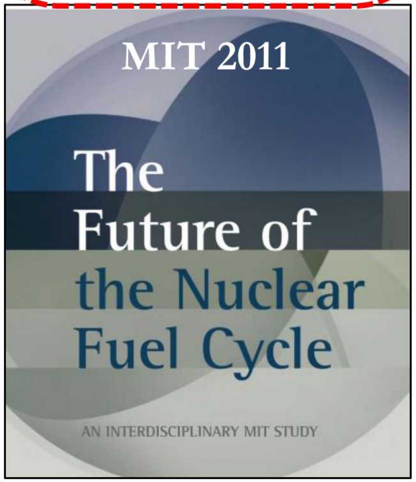
Yes, but what about various fuel cycle options studies?

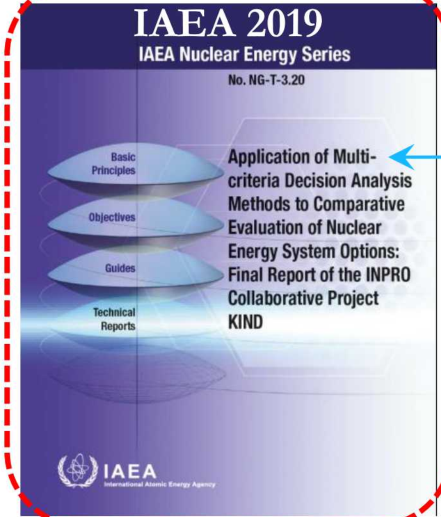
Fuel Cycle Options Studies
– Decision Analysis with Subject Matter Experts (SMEs)

- **Evaluate fuel cycles based on various criteria and metrics, including costs, waste management, U/Th resource utilization, proliferation, etc.**
- **Many such FC options studies have been conducted using various versions of <u>MCDA</u>:**



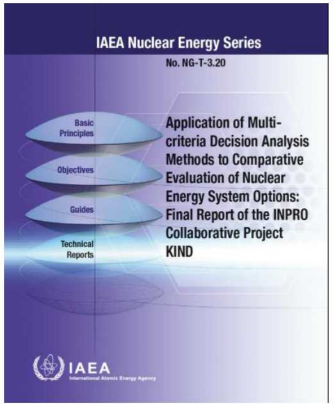


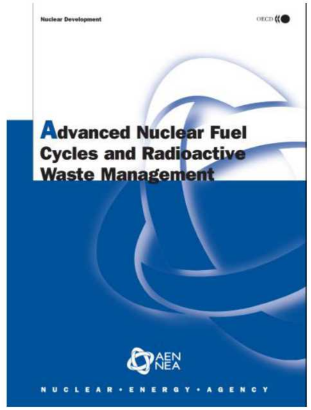




Fuel Cycle Options Studies – IAEA 2019 INPRO KIND Evaluation of 4 FCs from NEA 2006

- **Consider typical waste management criteria: volumes, activities, decay heat**





Consider the following 4 of the 12 NEA FCs:

- Scheme 1a (PWR, open cycle, UO2 fuel), reference cycle
- Scheme 1b (PWR, PUREX reprocessing, single recycling of Pu as MOX), representative of current technology
- Scheme 2a (PWR, PUREX reprocessing, multi-recycling of Pu as MOX), a partially-closed fuel cycle
- Scheme 3cV1 (GFR, pyro-reprocessing, carbide fuel), a fully-closed fuel cycle.

KIND criteria: **NEA metrics:**

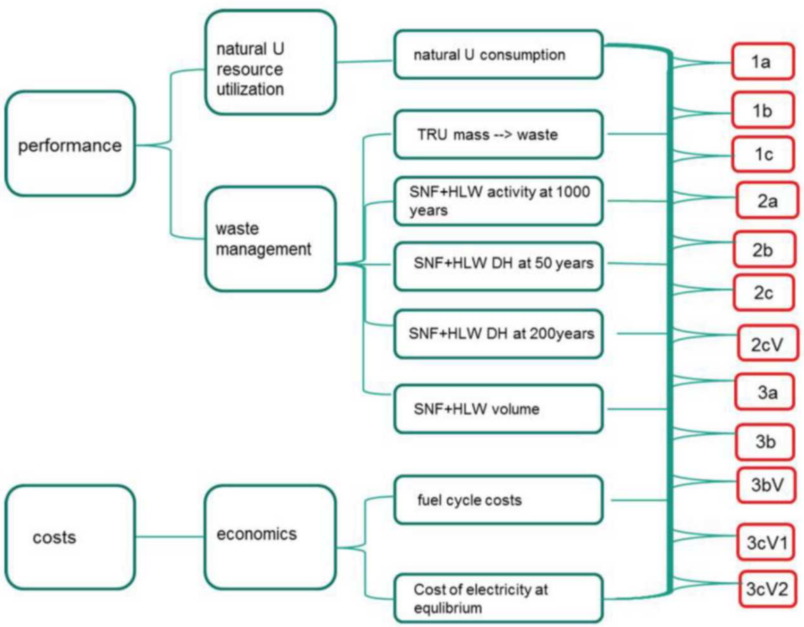
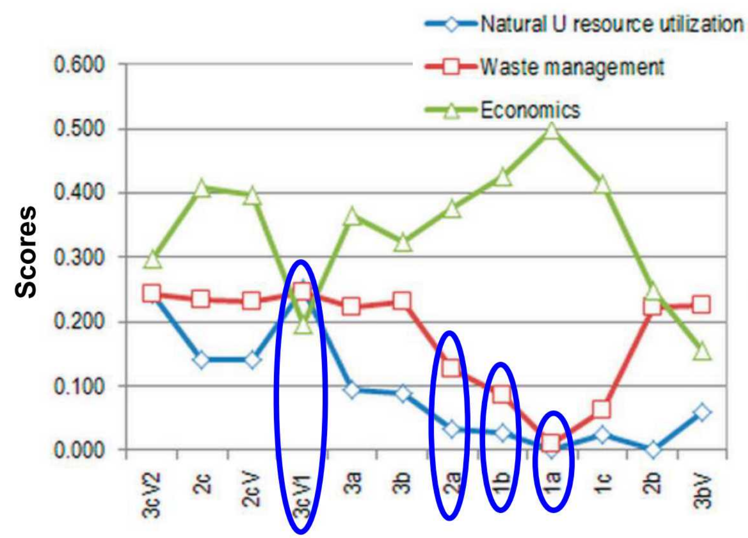


FIG. 5.59. Three level hierarchy structure.



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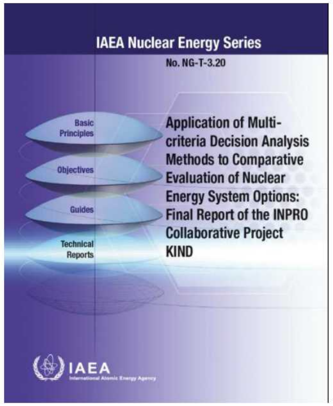

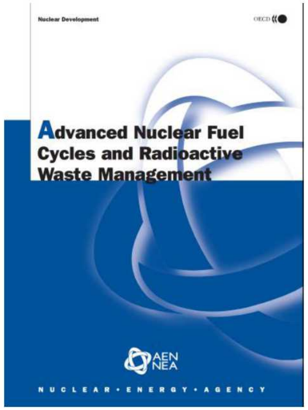

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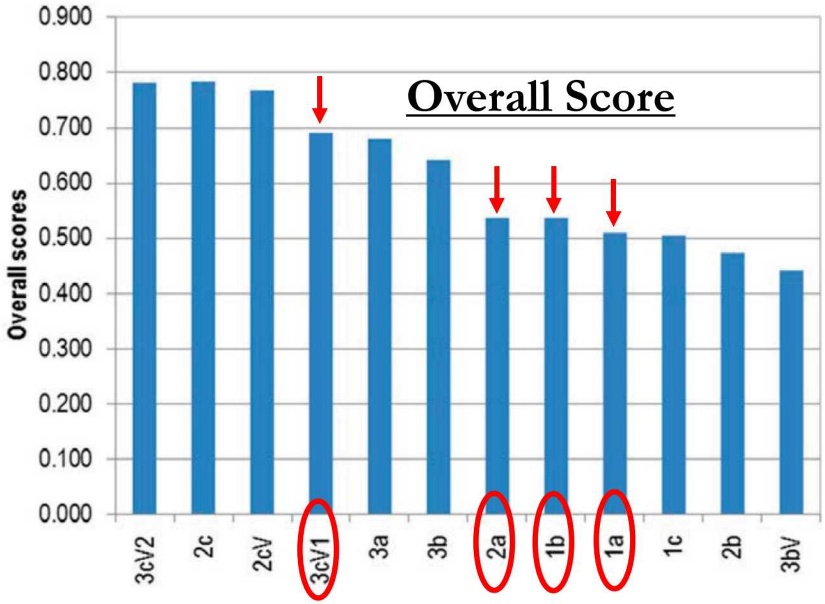
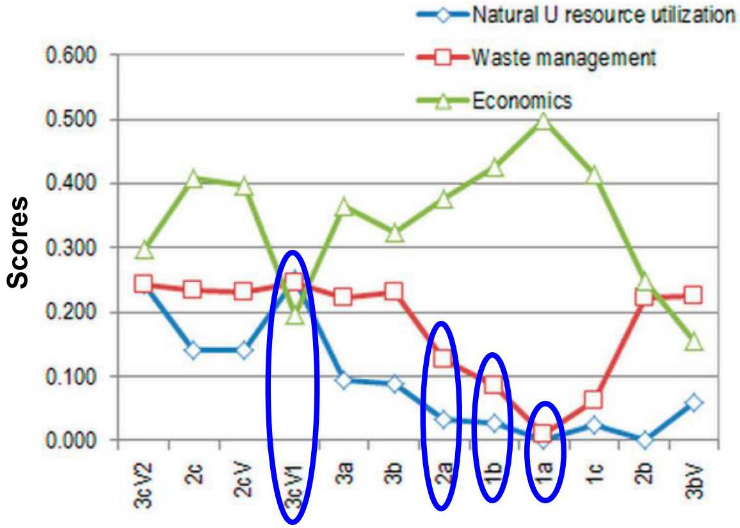
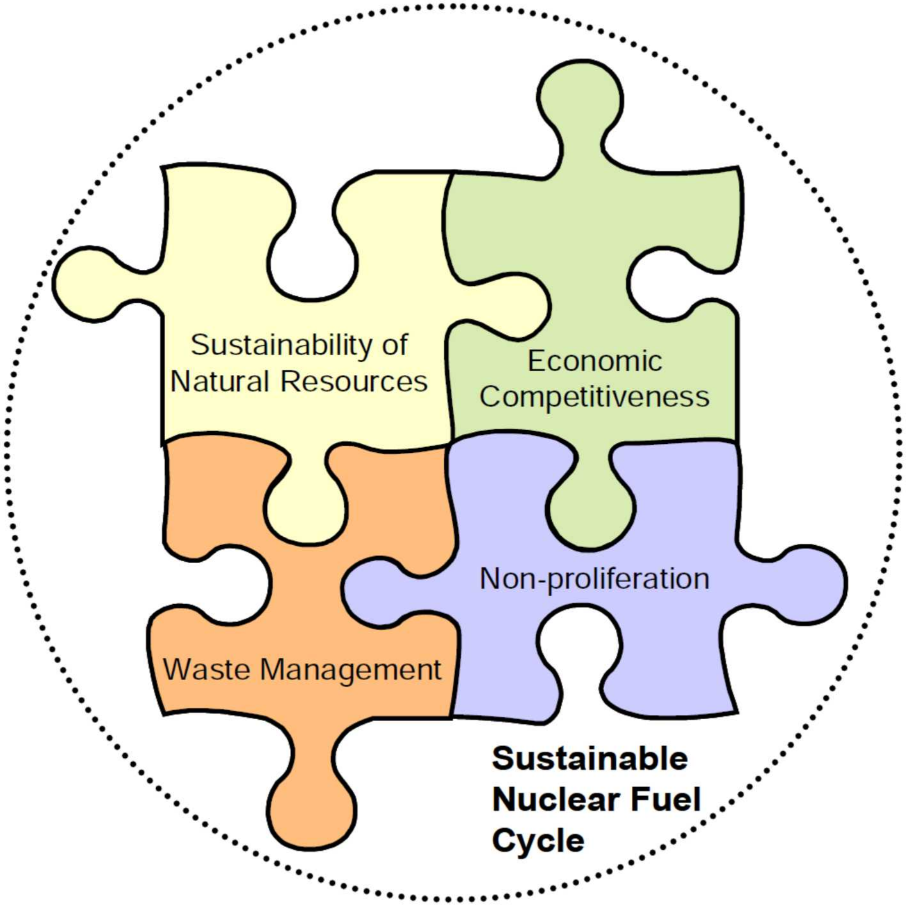


FIG. 5.62. Ranking results for three level tree with equal weights.



EPRI 2010 Advanced Nuclear Fuel Cycles Study – Another Perspective

Four Main Challenges for "Sustainability" of a Nuclear Fuel Cycle



EPRI 2010 Advanced Nuclear Fuel Cycles – Economics

"Depending on the fuel cycle chosen and on different assumptions made for the different unit costs, reactor costs represent between 80 and 90% of electricity costs, reflecting the high capital cost of constructing nuclear power plants that, alone, can represent 60% or more of the nuclear electricity costs. ***As a result, the fuel cycle choice has a relatively small impact on the overall economics of nuclear power.****"

INL 2009 study, where three cycles are evaluated:

- **Once-Through Cycle,**
- **1-Tier (LWR-UOX + FR) and**
- **2-Tier (LWR-UOX + LWR-MOX + FR).**

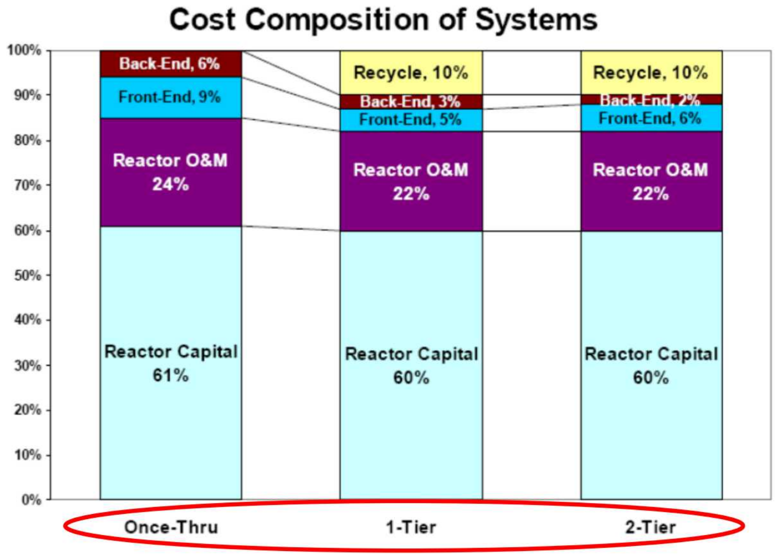


Figure 1-13
Cost Breakdown for Different Fuel Cycles (Source: INL)[15]

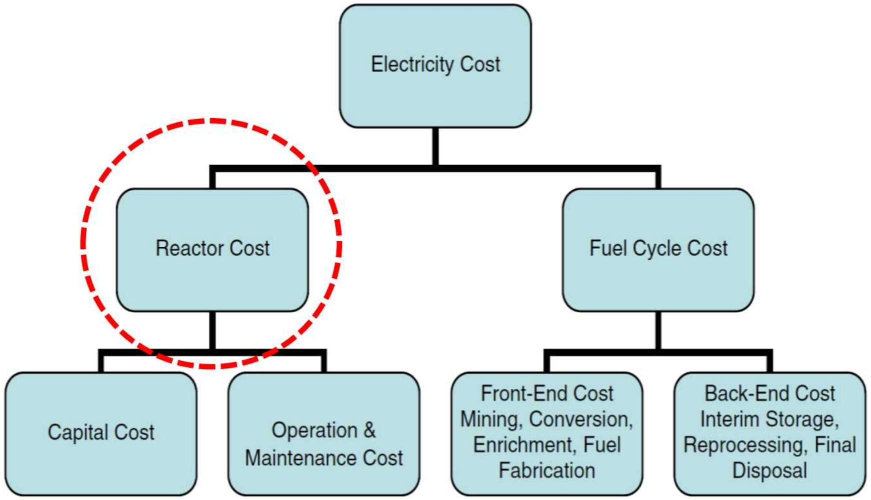


Figure 1-10
Breakdown of Nuclear Generation Electricity Cost

*However, it is important to note that once the plants are in operation, recurring fuel cycle costs become much more important, as do operation and maintenance (O&M) costs. This is especially true for plants whose capital costs have been largely amortized.

EPRI 2010 Advanced Nuclear Fuel Cycles – Waste Management

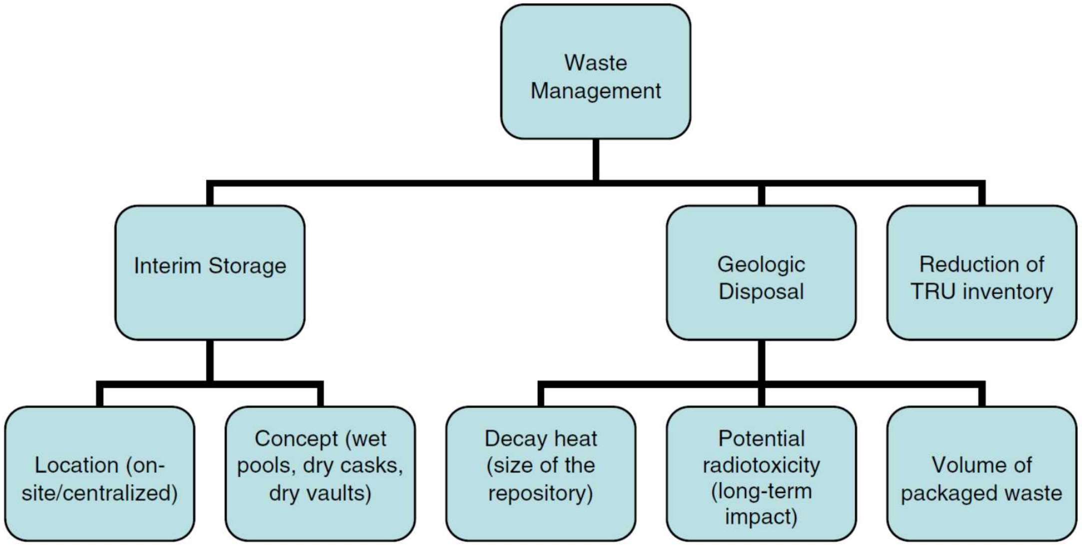


Figure 1-15
Waste Management Main Issues

"High-level waste management is a long-term concern, given the long half-lives of some radionuclides and the associated period of performance for a repository that spans tens of thousands to hundreds of thousands of years. The management of decay heat represents a more useful and objective figure-of-merit compared to waste radiotoxicity, because it more directly impacts the size, design, and performance of the geological repository. Interim storage of spent fuel and vitrified wastes is a necessary and important fuel cycle activity that should be integrated in the context of managing spent fuel/HLW for either geologic disposal or recycling. *Waste management is also an important consideration in terms of public acceptance.*"

Deep Geological Disposal for SNF and HLW – Fuel Cycle Considerations

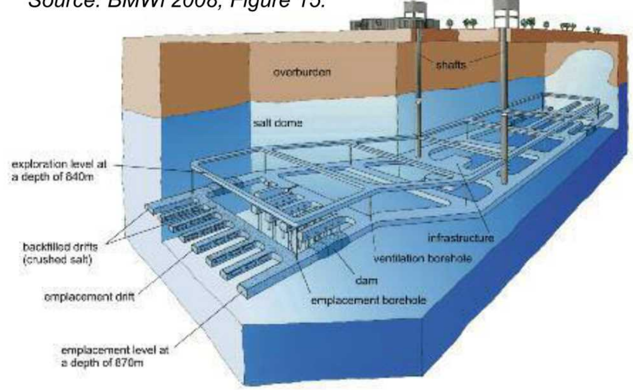
Deep geologic disposal has been planned since the 1950s:

"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."

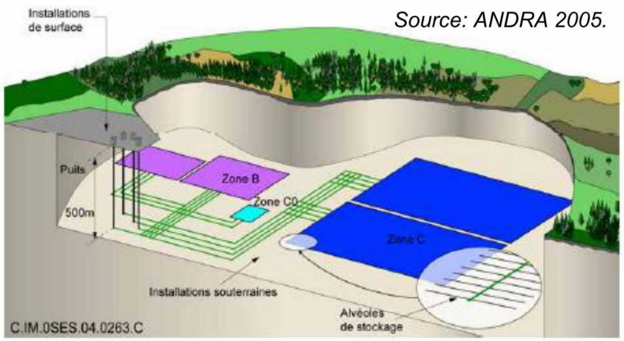
"Geological disposal remains the only long-term solution available."

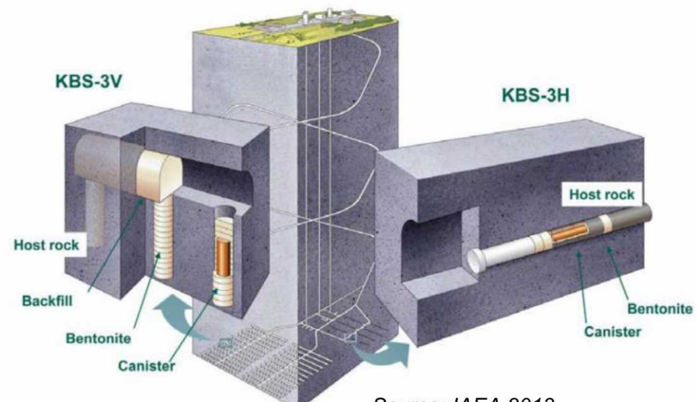
National Research Council, 2001

Source: BMWi 2008, Figure 15.



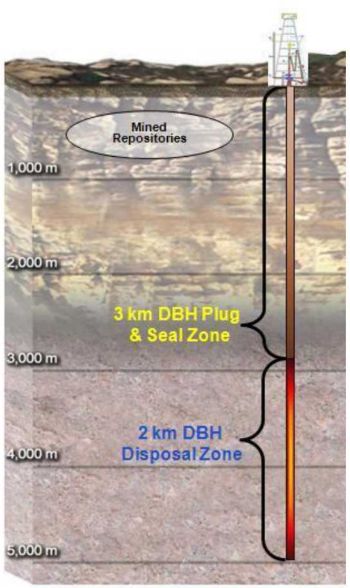
Source: ANDRA 2005.





Source: IAEA 2013

FIG. 9. The disposal facility proposed for disposal of spent fuel in copper-sheathed cast iron–steel canisters in a bentonite buffer. The disposal facility would be located at about 500 m in depth in hard metamorphic or granitic rocks. This approach will be used in Finland and Sweden. (Courtesy of POSIVA, Finland.)



How Repositories Work

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

Natural barriers isolate the waste from the biosphere

Engineered barriers provide containment by preventing or delaying 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, containment, and dilute/delay mechanisms may differ for different nuclides in different disposal concepts

Status of Deep Geologic Disposal Programs World-Wide

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Operations application to be submitted in 2020
Sweden	Granite	License application submitted 2011
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended

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

Source: Information from Faybishenko et al., 2016

Socio-Political Issues "Rule" SNF Management and Final Disposition Regardless of the Fuel Cycle

Example: Brief History of the U.S. SNF Disposal Program*

1982: Nuclear Waste Policy Act (NWPA) defines Federal responsibility for permanent disposal of spent fuel and high-level waste, and leaves responsibility for storage at reactor sites with private sector

1987: Congress amends NWPA to focus solely on disposal at Yucca Mountain, Nevada

2002: Congress overrides Nevada's veto of the site and directs the Department of Energy and the Nuclear Regulatory Commission to proceed with the licensing process

2008: DOE submits Yucca Mountain license application to the NRC

2009-10: DOE determines Yucca Mountain is "unworkable" and Congress terminates funding for the project (directed by the U.S. president, in collaboration with the Majority Leader of the U.S. Senate – a senator from Nevada)

2013: DOE proposes to "facilitate the availability of a geologic repository by 2048"

2015: NRC staff completes its Safety Evaluation Report for Yucca Mountain, concluding that "DOE has met the applicable regulatory requirements" related to safety

2016-18: Private sector applications to the NRC for consolidated interim storage of spent fuel

Present: Funding for Yucca Mountain licensing process remains suspended. Approximately 300 technical contentions remain to be adjudicated before a licensing board can reach a decision regarding construction authorization

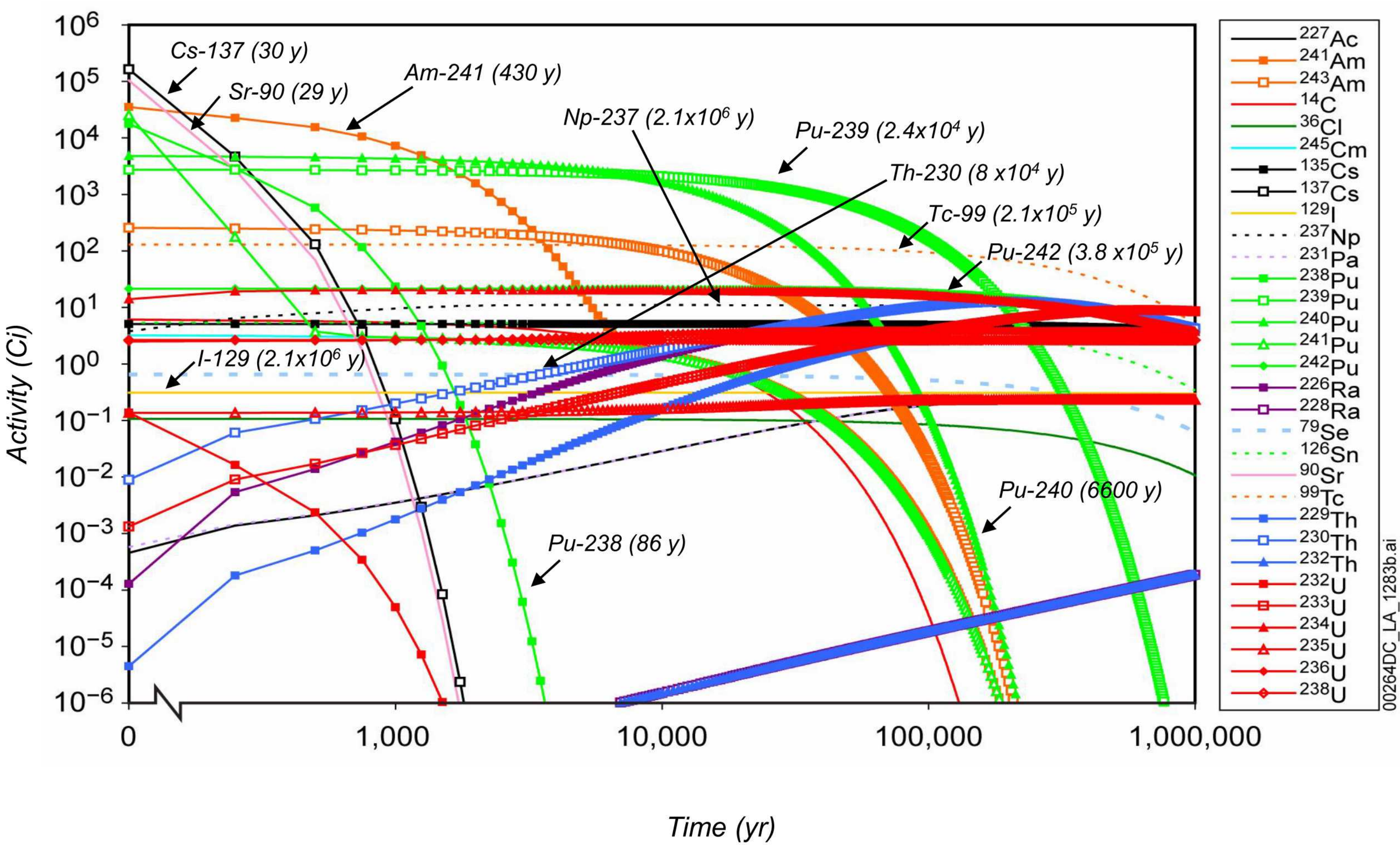
** From Swift 2017; Bonano 2019*

Technically, How Might Alternative Nuclear Fuel Cycles Impact Geological Disposal?

- **For a given amount of electric power, alternative fission-based nuclear fuel cycles may result in**
  - Changes in the radionuclide inventory
    - → *Reprocessing can reduce actinide content of final waste product*
  - Changes in the volume of waste
    - → *Reprocessing can reduce the volume of waste requiring deep geologic disposal*
  - Changes in the thermal power of the waste
    - → *Separation of minor actinides can reduce thermal power of the final waste form*
  - Changes in the durability of the waste in repository environments
    - → *Treatment of waste streams can create more durable waste forms*
- **For each potential change, consider**
  - How will these changes impact repository safety
  - How will these changes impact repository cost and efficiency

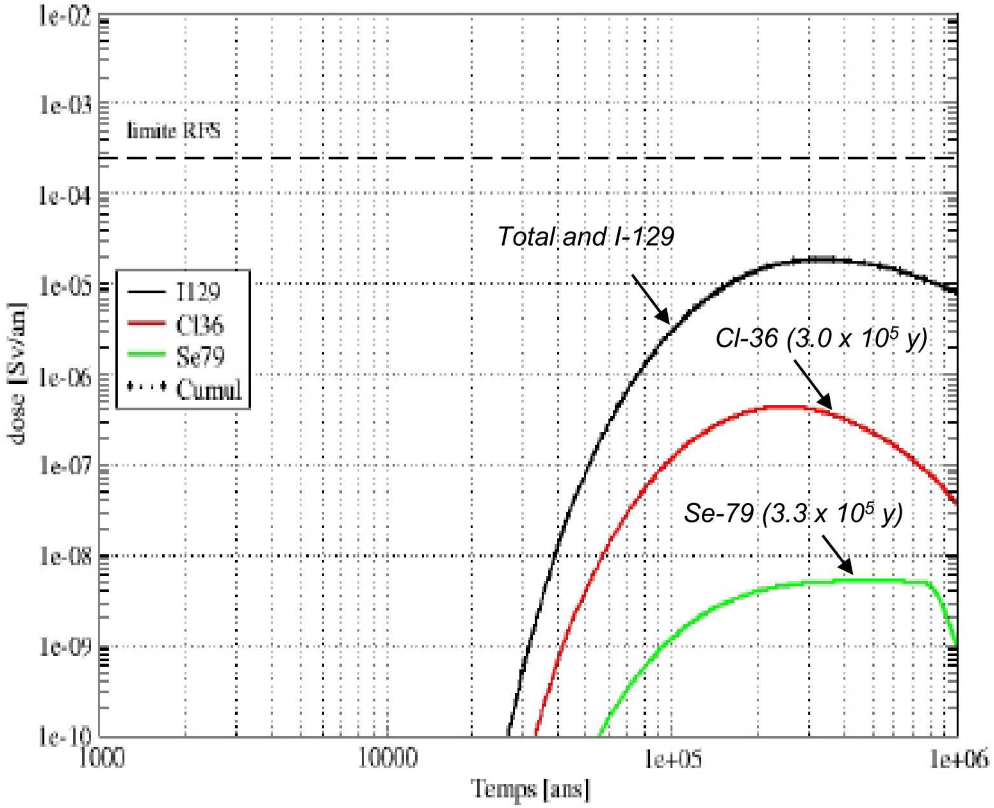
Light-Water Reactor Spent Nuclear Fuel Decay

Example from US Program



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

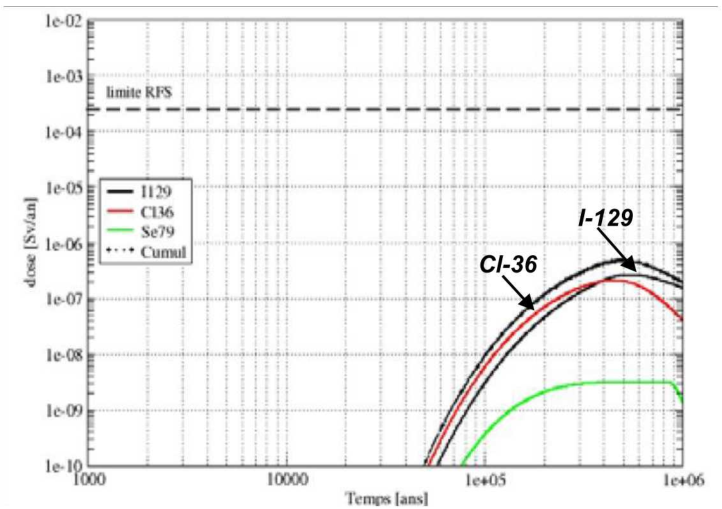
Contributors to Total Dose: Meuse / Haute Marne Site (France)



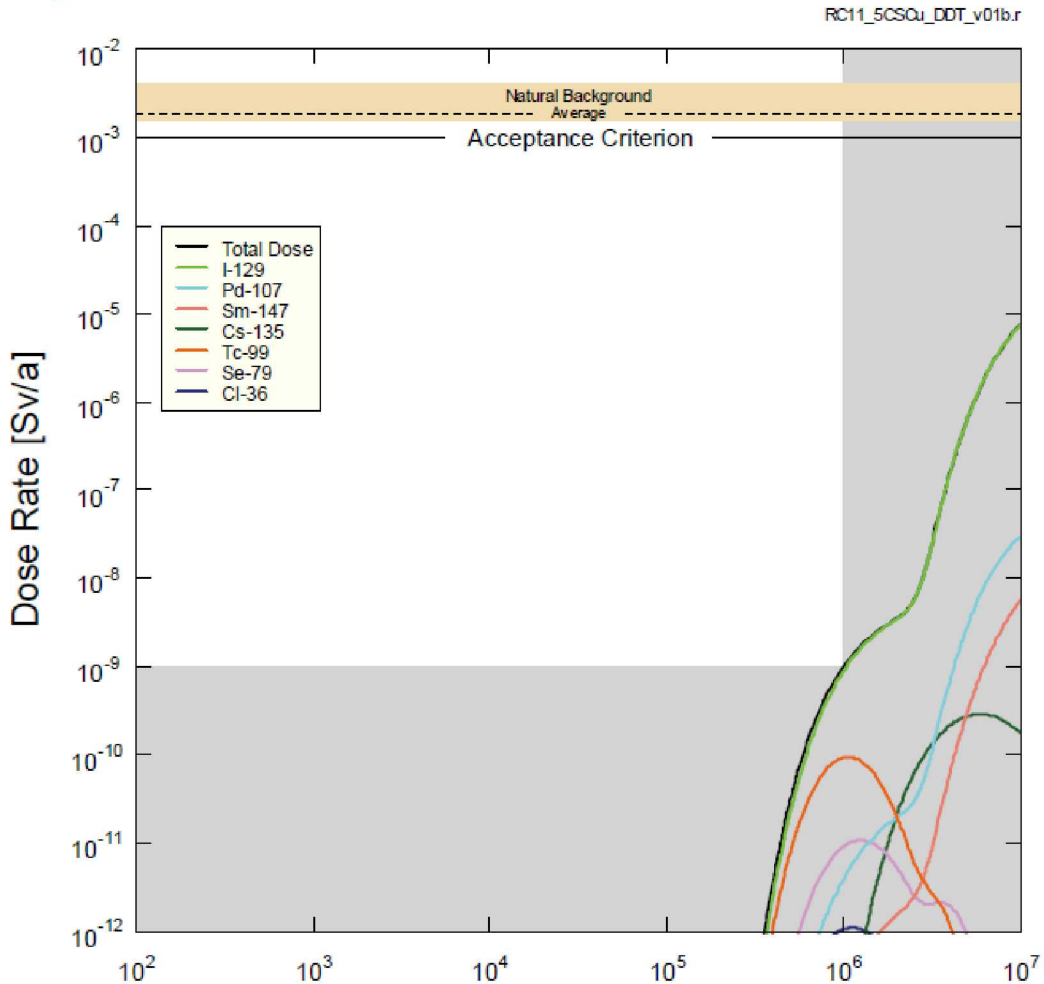
ANDRA 2005, Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation, Figure 5.5-18, million year model for spent nuclear fuel disposal and Figure 5.5-22, million year model for vitrified waste disposal

Diffusion-dominated disposal concept: Argillite

- **I-129 is the dominant contributor at peak dose**
- **Examples shown for direct disposal of spent fuel (left) and vitrified waste (below)**



Contributors to Total Dose: Hypothetical Site (Canada)



NWMO 2013, Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07, Figure 7-96.

Diffusion-dominated disposal concept: spent fuel disposal in unfractured carbonate host rock

Long-lived copper waste packages and long diffusive transport path

- **Major contributor to peak dose is I-129**
- **All waste packages assumed to fail at 60,000 years for this simulation; primary barriers are slow dissolution of SNF and long diffusion paths**

Contributors to Total Dose: Forsmark Site (Sweden)

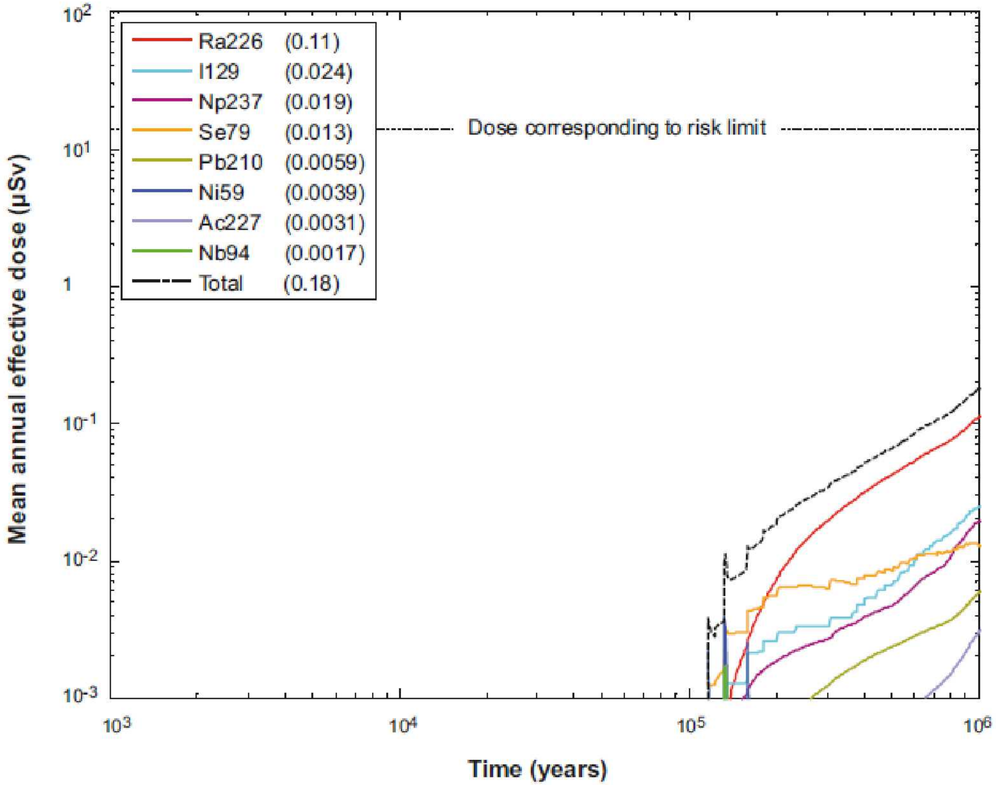


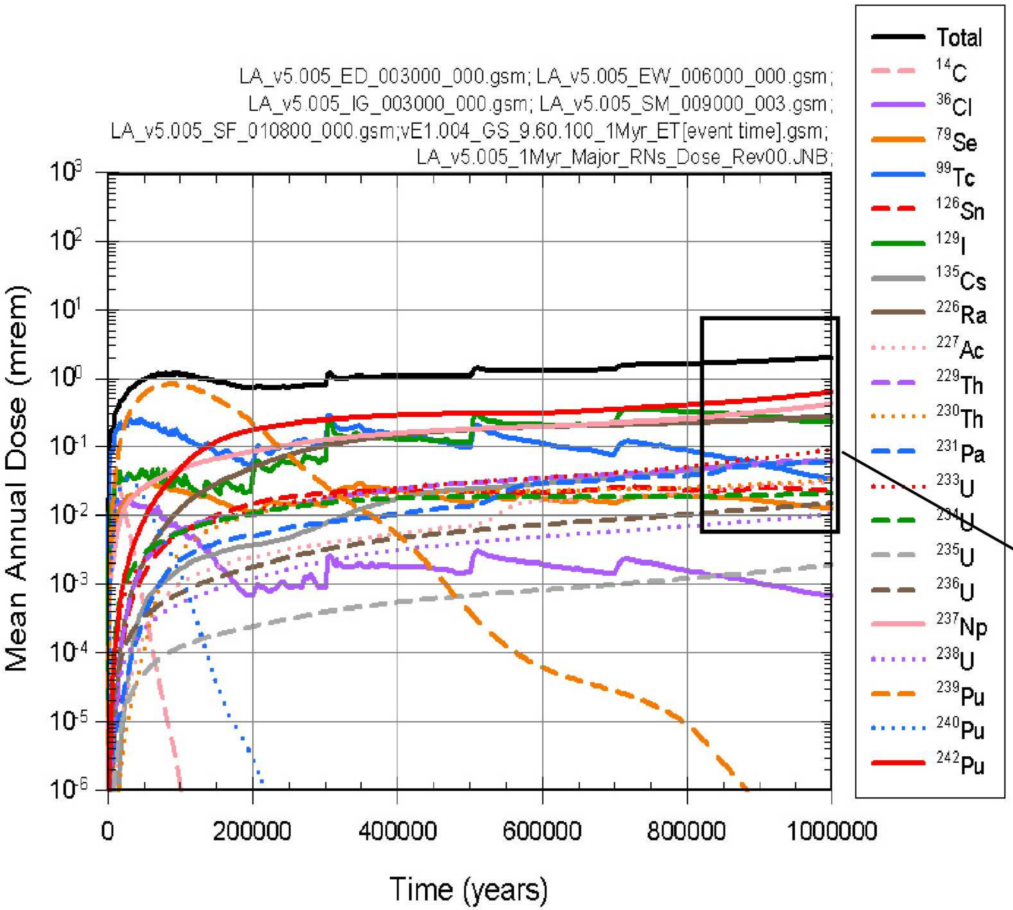
Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).

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

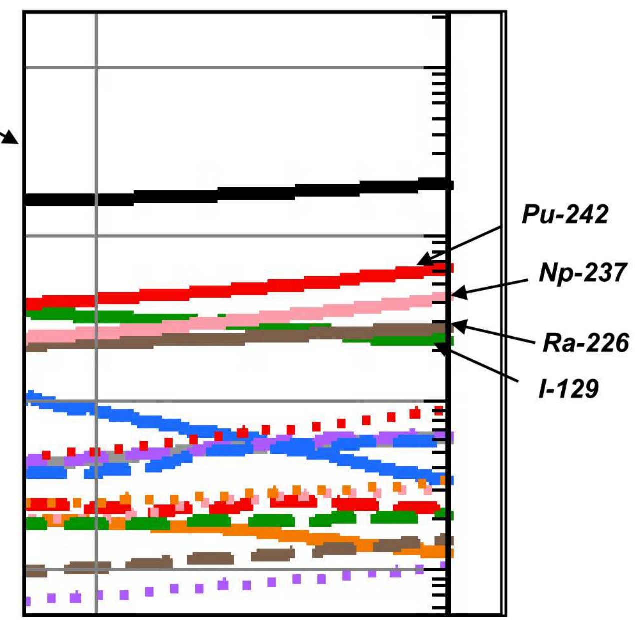
Disposal concept with <u>advective fracture transport</u> in the far-field: <u>Granite</u>

- Long-term peak dose dominated by Ra-226
- Once corrosion failure occurs, dose is primarily controlled by fuel dissolution and diffusion through buffer rather than far-field retardation

Contributors to Total Dose: Yucca Mountain (USA)



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

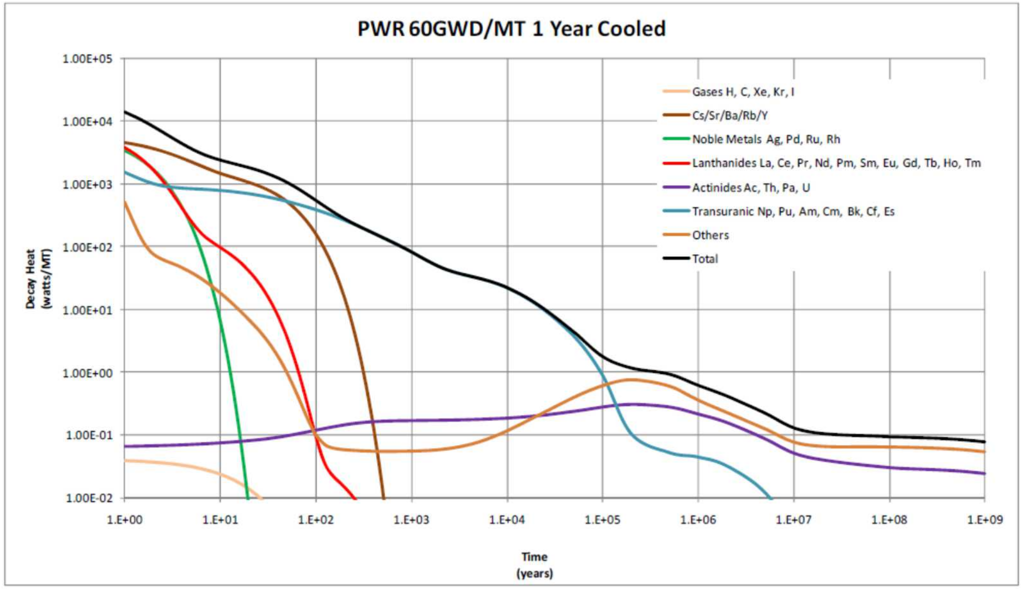


Disposal concept with an oxidizing environment and advective transport in the far-field: Fractured Volcanic Tuff

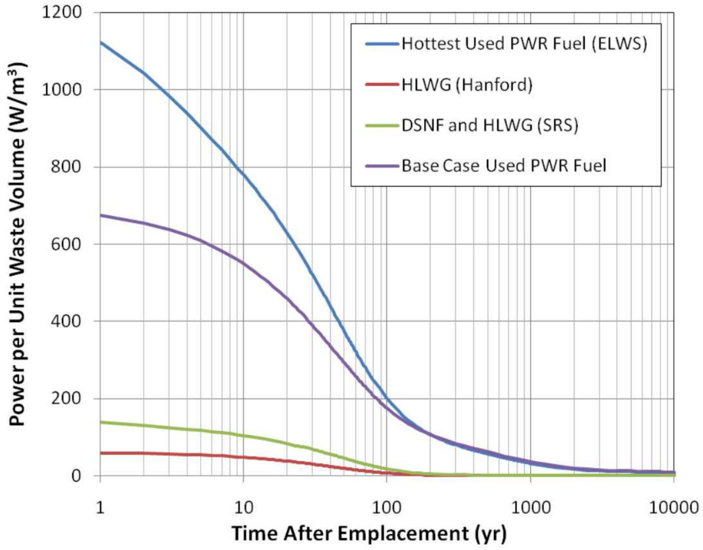
- **Actinides are significant contributors to dose; I-129 is approx 1/10th of total**

Waste Volume & Thermal Power Considerations

- **Repository thermal constraints are design-specific**
- **Options for meeting thermal constraints include**
  - Design choices including size and spacing of waste packages
  - Operational practices including aging and ventilation
  - Modifications to waste forms



Heat of decay versus time for PWR SNF (60 GWd/MT burnup) – from Carter et al. (2013) and Mariner et al. 2017, Fig. 4.2



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

Selection of optimal waste volume and thermal loading criteria will depend on multiple factors evaluated across entire fuel cycle, including cost and operational efficiency

Waste Volume & Thermal Power Considerations (cont.)

- **To a first approximation, waste volume and thermal power density have an inverse correlation without separation of heat-generating radionuclides**
  - All other factors held constant, reductions in volume increase thermal power density
  - Relevant metric is disposal volume, i.e., the excavated volume needed per unit volume of waste, which is a function of repository design as well as waste properties
- **Volume of HLW is process-dependent**
  - Existing processes can achieve substantial reductions in disposal volume
    - 30-40% of disposal volume relative to spent fuel (including packaging)
    - Up to 8% of fuel volume with 100-yr aging period (van Lensa et al., 2010, table 7.1)
  - Advanced processes may achieve lower volumes of HLW
- **Thermal power density of HLW can be engineered over a wide range**
- **Waste volume does not correlate to long-term performance**
  - It does affect cost (excavated volume and, ultimately, total number of repositories)
  - Volume of low-level waste also contributes to total cost

Waste Form Lifetime Example: Meuse / Haute Marne Site

- **High-Level Waste glass**
  - Base case model: glass "release periods on the order of a few hundred thousand years" (degradation rate decreases when surrounding medium is saturated in silica: Andra 2005, p. 221)
  - Sensitivity analysis assuming rapid degradation (100s to 1000s of yr) accelerates peak concentrations at outlet by ~200 kyr, with a modest increase in magnitude of modeled peak dose:
    - **For rapid degradation case, modeled releases are controlled by diffusive transport time in clay**

	Maximum molar flow exiting Callovo-Oxfordian (mol/yr) and maximum dates (yrs.)	
	Reference	Sensitivity
^{129}I	$8.6.10^{-4}$ 460,000 yrs	$9.1.10^{-4}$ 250,000 yrs
^{36}Cl	$2.2.10^{-4}$ 380,000 yrs	$3.8.10^{-4}$ 190,000 yrs

Table 5.5-24 SEN - Attenuation ^{129}I and ^{36}Cl – C1+C2 – comparison between the models $V_0.S$ (sensitivity) and the model $V_0.S \rightarrow V_r$

Impact of changes in HLW glass degradation rate on modeled radionuclide concentrations in groundwater, ANDRA 2005, Table 5.5-24

Waste Form Lifetime Examples: Forsmark Site

- **Used fuel**
  - Fractional dissolution rate range 10^{-6}/yr to 10^{-8}/yr
    - Corresponding fuel lifetimes: ~ 1 Myr to 100 Myr
    - Dissolution rates for oxidizing conditions (not anticipated), up to 10^{-4}/yr
  - **Uncertainty in fuel dissolution rate can be a dominant contributor to uncertainty in modeled total dose estimates for sites with relatively rapid transport**

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

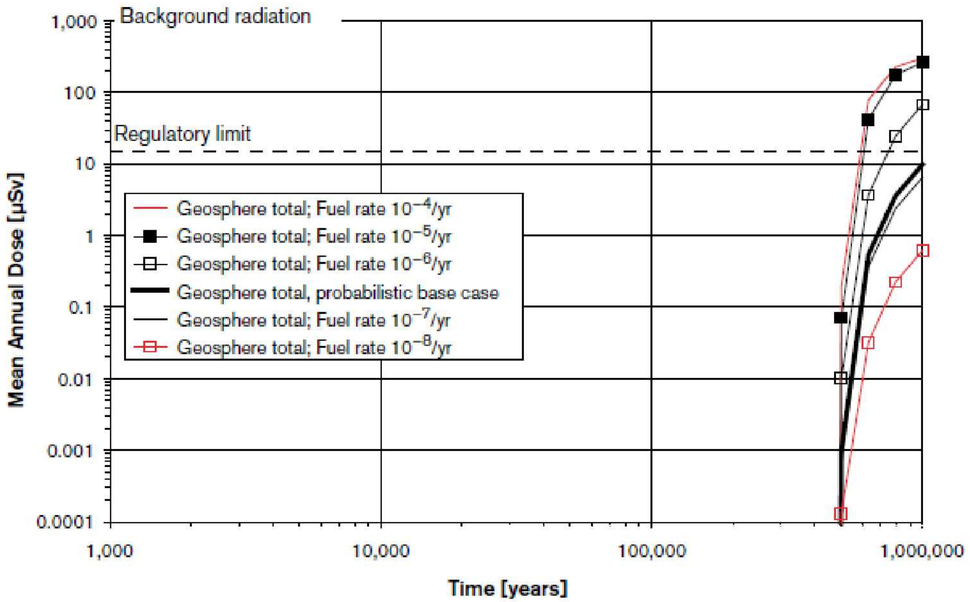


Figure 10-44. *Sensitivity of the base case result to the fuel dissolution rate. Semi-correlated hydrogeological DFN model for Forsmark. 1,000 realisations of the analytic model for each case.*

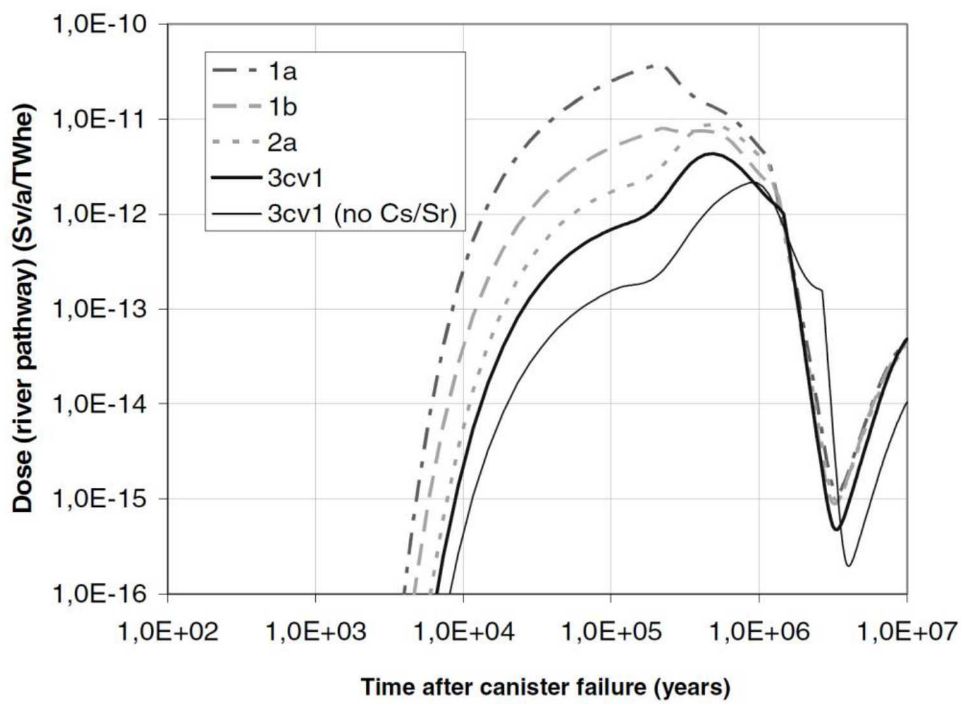
Comparison of Dose for Different Fuel Cycles: IAEA 2019 INPRO KIND Evaluation of 4 FCs from NEA 2006

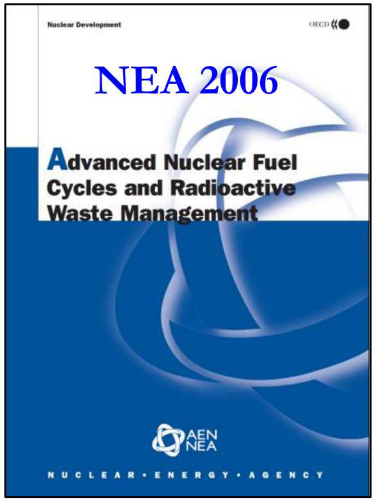
- **Clay repository host rock (SCK-CEN, SAFIR 2 Safety Assessment, Belgium)**

Consider the following 4 of 12 NEA FCs:

- **Scheme 1a** (PWR, open cycle, UO2 fuel), reference cycle
- **Scheme 1b** (PWR, PUREX reprocessing, single recycling of Pu as MOX), representative of current technology
- **Scheme 2a** (PWR, PUREX reprocessing, multi-recycling of Pu as MOX), a partially-closed fuel cycle
- **Scheme 3cV1** (GFR, pyro-reprocessing, carbide fuel), a fully-closed fuel cycle.

Figure 5.15. Total dose calculated for Schemes 1a, 1b, 2a, 3cV1 and 3cV1 with separation of Cs/Sr





"For all the repositories considered the maximum dose resulting from the disposal of HLW from the fuel cycle schemes evaluated does not change significantly. The dose reduction factor resulting from reprocessing is at most 8 and mainly results from the removal of ^{129}I from the liquid HLW during reprocessing. Should ^{129}I be captured and disposed of in the HLW repository, the doses resulting from all schemes would be about equal."

Conclusions

- **Alternative fuel cycle choices can reduce waste volume but may have little impact on thermal load management without century-scale aging of fission products**
  - Without separation or surface aging of fission products, reductions in disposal volume may be limited to 30-40% of the disposal volume of the unprocessed fuel
  - Fission products may need geologic disposal regardless, depending on regulatory criteria
- **The impact of long-lived waste forms on repository performance varies with disposal concept**
  - For some disposal concepts, long-lived waste forms can be important
- **Alternative fuel cycle choices will have little impact on estimates of long-term repository performance**
  - Long-term dose estimates in most geologic settings are dominated by mobile species, primarily I-129
- **For any disposal concept, potential benefits of alternative fuel cycle choices should be considered in the context of operational costs and benefits**

2011 MIT FC Options Study – Some of their Observations

- **"We can and should preserve our options for fuel cycle choices by continuing with the open fuel cycle, implementing a system for managed LWR spent fuel storage, developing a geological repository, and researching technology alternatives appropriate to a range of nuclear energy futures:**
  - For the next several decades, a once through fuel cycle using light water reactors (LWRs) is the preferred economic option for the U.S. Improvements in light-water reactor designs to increase the efficiency of fuel resource utilization and reduce the cost of future reactor plants should be a principal research and development focus
  - Permanent geological isolation will be required for at least some long-lived components of spent nuclear fuel, and so systematic development of a geological repository needs to be undertaken. We recommend (1) the integration of waste management with the design of the fuel cycle, and (2) a supporting R&D program in waste management to enable full coupling of fuel cycle and waste management decisions.
  - Long-term managed storage preserves future options for spent fuel utilization at little relative cost. Preservation of options for future fuel cycle choices has been undervalued in the debate about fuel cycle policy. Planning for long term managed storage of spent nuclear fuel—for about a century—should be an integral part of nuclear fuel cycle design.
  - The choices of nuclear fuel cycle (open, closed, or partially closed through limited SNF recycle) depend upon (1) the technologies we develop and (2) societal weighting of goals (safety, economics, waste management, and nonproliferation)"

References

- ANDRA (Agence nationale pour la gestion des déchets radioactifs), 2005. Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository (English translation: original documentation written in French remains ultimately the reference documentation).
- Bonano, E., Kalinina, E., and Swift, P., 2018, "The Need for Integrating the Back End of the Nuclear Fuel Cycle in the United States of America." *MRS Advances*, 1-13. doi:10.1557/adv.2018.231
- Bonano, E. 2019. "Status of the Back End of the Nuclear Fuel Cycle in the United States of America: Current R&D Program," presentation at Goldschmidt 2019 Conference, Barcelona, Spain, 18-23 August 2019, SAND2019-8432C, Sandia National Laboratories, Albuquerque, New Mexico.
- Carter, J. T., A. J. Luptak, J. Gastelum, C. Stockman and A. Miller (2013). Fuel Cycle Potential Waste Inventory for Disposition. FCRD-USED-2010-000031 Rev 6. Savannah River National Laboratory, Aiken, SC, USA.
- EPRI (Electric Power Research Institute) 2010. "Advanced Nuclear Fuel Cycles — Main Challenges and Strategic Choices," 1020307, Final Report, September 2010, Electric Power Research Institute, Palo Alto, CA, USA, www.epri.com .
- Faybishenko, B., Birkholzer, J., Sassani, D., and Swift, P., 2016. International Approaches for Deep Geological Disposal of Nuclear Waste: Geological Challenges in Radioactive Waste Isolation, Fifth Worldwide Review, LBNL-1006984, Lawrence Berkeley National Laboratory.
- IAEA (International Atomic Energy Agency) 2013. "Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes," IAEA Nuclear Energy Series No. NW-T-1.24, Vienna, 2013.
- IAEA (International Atomic Energy Agency) 2019. "Application of Multi-Criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND," IAEA Nuclear Energy Series No. NG-T-3.20, Vienna, 2019.
- INL (Idaho National Laboratory) 2009. "Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems," INL/EXT-09-15254
- Mariner, P. E., E. R. Stein, J. M. Frederick, S. D. Sevougian and G. E. Hammond (2017). Advances in Geologic Disposal System Modeling and Shale Reference Cases. SFWD-SFWST-2017-000044, SAND2017-10304 R. Sandia National Laboratories, Albuquerque, New Mexico.
- MIT (Massachusetts Institute of Technology) 2011. "The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study," ISBN 978-0-9828008-4-3.
- NAGRA (Nationale Genossenschaft für die Lagerung Radioactiver Abfälle [National Cooperative for the Disposal of Radioactive Waste]), 2002, *Project Opalinus Clay Safety Report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis),* Technical Report 02-05.
- National Research Council / National Academies, 2001. Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges, Washington, DC, National Academy Press.
- NEA (Nuclear Energy Agency) 2006. "Advanced Nuclear Fuel Cycles and Radioactive Waste Management," NEA No. 5990, Organisation for Economic Co-operation and Development, Paris, France.

References (cont.)

- NWMO (Nuclear Waste Management Organization), 2013. Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07.
- Posiva Oy, 2012, Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto—Synthesis 2012, POSIVA 2012-12.
- SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2006. Long-Term Safety KBS-3 Repositories at Forsmark and Laxemar—a First Evaluatin, TR-06-09.
- SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2006. Fuel and Canister Process Report for the Safety Assessment SR-Can, TR-06-22.
- SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2011. Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark: Main Report of the SR-Site Project, Technical Report TR-11-01.
- Swift, P.N. 2017. "Spent Fuel Management and Disposition," 2017 MeV Summer School, www.mevschool.org, SAND2017-6058PE, Sandia National Laboratories, Albuquerque, New Mexico.
- Swift, P.N., and W.M. Nutt, 2010. "Applying Insights from Repository Safety Assessments to Evaluating Impacts of Partitioning and Transmutation," Proceedings of the 11th OECD-NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, CA, November 1-4, 2010.
- Swift, P.N., C.W. Hansen, E. Hardin, R.J. MacKinnon, D. Sassani, S. D. Sevougian, 2010. "Potential Impacts of Alternative Waste Forms on Long-Term Performance of Geological Repositories for Radioactive Waste." Proceedings of PSAM-10, June 7-11, 2010, Seattle, WA.
- US DOE (United States Department of Energy) 2008. Yucca Mountain Repository License Application, DOE/RW-0573, Rev. 1.
- Wagner, J. C., J.L. Peterson, D.E. Mueller, J.C. Gehin, A. Worrall, T. Taiwo, M. Nutt, M.A. Williamson, M. Todosow, R. Wigeland, W. Halsey, R. Omberg, P.N. Swift, and J.T. Carter, 2012. "Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy," ORNL/TM-2012/308, FCRD-FCT-2012-000232, Oak Ridge National Laboratory, Oak Ridge, TN, USA, December 2012.

Back-Up Slides

EPRI 2010 Fuel Cycle Study – Some of their Observations

- **"A partially closed fuel cycle with fast reactors, in which fertile U-238 is converted into fissile Pu-239, is presently considered the most attractive advanced option. Another possibility is the thorium fuel cycle, in which fertile Th-232 is converted into fissile U-233**
- **"A nuclear fuel cycle has to be "industrially sustainable." An evolutionary and progressive pathway appears to be more realistic than a revolutionary approach that attempts to solve all the fuel cycle issues with extremely advanced technologies. Possible evolutionary pathway:**

  1. Once-through cycle.
     1a. Option: reprocessing of the used LWR fuel and single-recycling of extracted plutonium and reprocessed uranium into LWRs.
  2. Interim storage of spent UOX and spent MOX.
  3. Partial closure of the fuel cycle with multi-recycling of plutonium in fast reactors (FRs) requiring advanced reprocessing of both LWR and FR fuels.
     3a. Option: recycling of the neptunium together with the plutonium.
  4. Full closure of the fuel cycle with homogeneous multi-recycling of plutonium and minor actinides requiring group separation of the transuranic elements.
     4a. Option: Full closure of the fuel cycle with heterogeneous recycling of americium in the form of americium targets and storage of curium to allow decay into lower actinides.
  5. In all cases, disposal of fission products and of remaining actinides in a permanent geologic repository.

- **"The nuclear fuel cycle has to remain focused on efficient power generation….advocating transmutation of all the transuranics and fission products, or making nuclear materials so unattractive that they are practically unusable in the fuel cycle itself, do not represent realistic options"**