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Fuel Cycle Research and Development

Consideration of Transformational Approaches for Nuclide Transmutation

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Background: Fission Fuel Cycles

- **Nuclear energy is a significant contributor to U.S. and international electricity production**
  - 16% world, 20% U.S., 78% France
- **Given concern over carbon emissions, nuclear utilization might grow significantly worldwide**
- **Once-through fuel cycle has been employed to-date in U.S.**
  - Large quantities of spent fuel stored at reactor sites
  - Final waste disposal is not secured
- **With nuclear expansion, this is not a sustainable approach; thus, advanced fuel cycles being explored – two key goals**
  - Waste management
  - Resource utilization

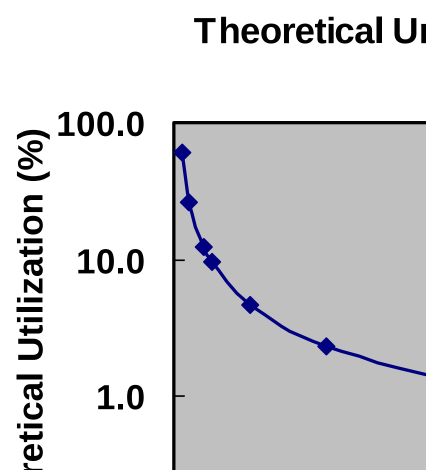
Why Consider Transformational Approaches for Transmutation

- **Effective resource utilization**
- **Better waste management – transuranic elements (TRU) and fission products (FP)**
- **Improved repository capacity**
- **Transformation of repository sequestration of radionuclides from hundreds of thousands of years (geologic time scale) to hundreds of years (engineered time scale)**
  - Might require transmutation of long-lived fission products
- **Reduced proliferation risk**
  - By utilization of fissile materials

Resource Utilization

- **Natural uranium is significantly under-utilized by current and innovative advanced <u>once-through</u> nuclear systems**
  - LWR utilization less than 1%
  - Utilization in advanced once-through systems less than 2%
- **Any system that requires enriched uranium fuel will have low uranium utilization**

Theoretical Uranium Utilization
(assuming complete fuel burnup)



- **Any transformational approach should enable high uranium consumption – at least greater than 98%**

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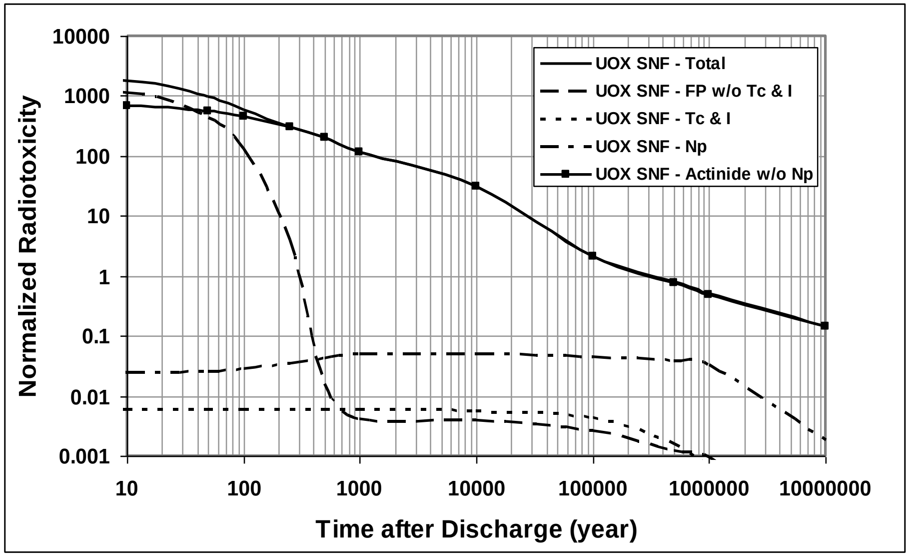
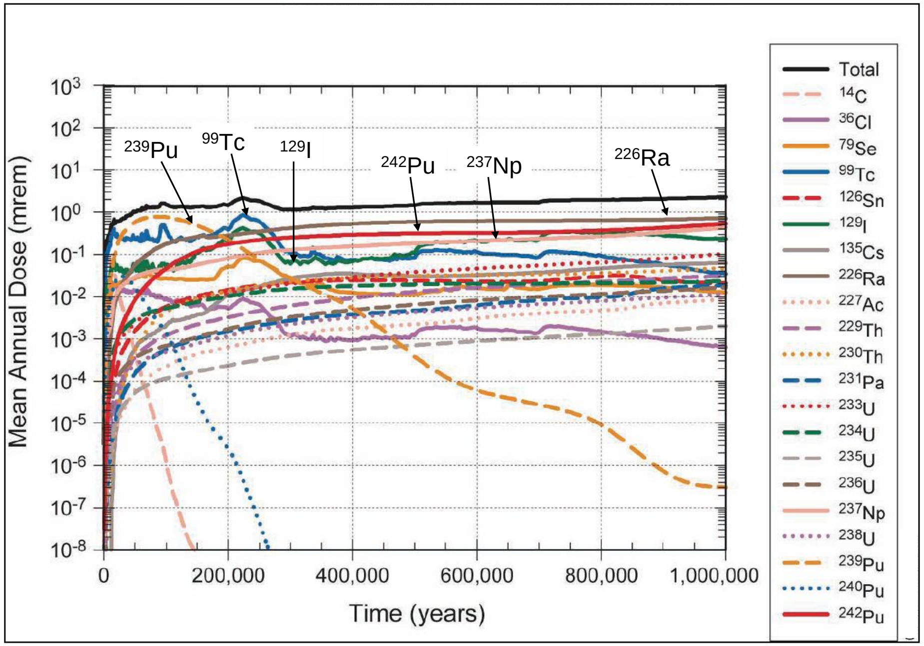
Waste Hazard and Risk Measures

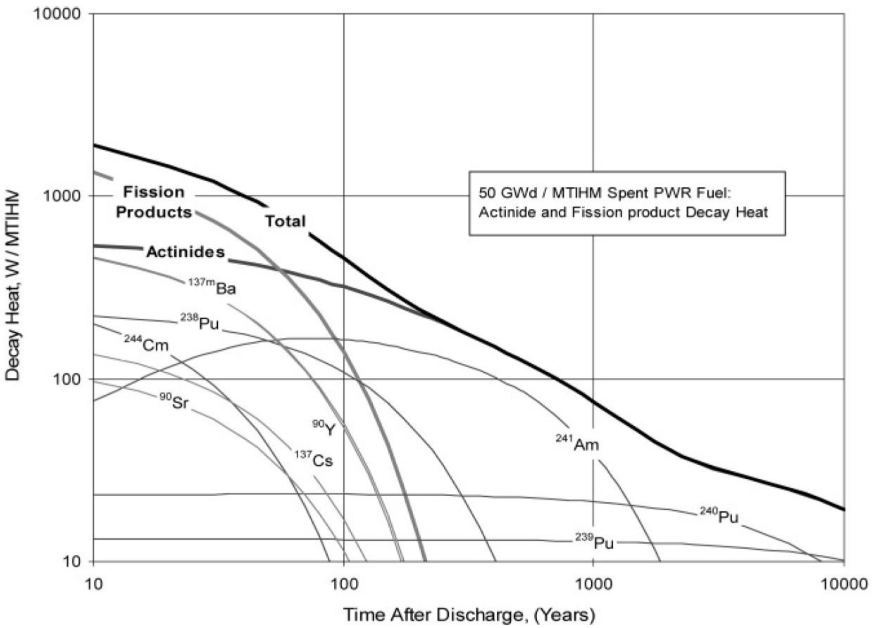
- **Radiotoxicity reflects the hazard of the source materials**
  - TRU dominate after about a 100 years; FPs contribution to radiotoxicity small after 100 years
- **Radiotoxicity alone does not provide any indication of how a geologic repository may perform**
  - Engineered and natural barriers serve to isolate wastes or control release of radionuclides

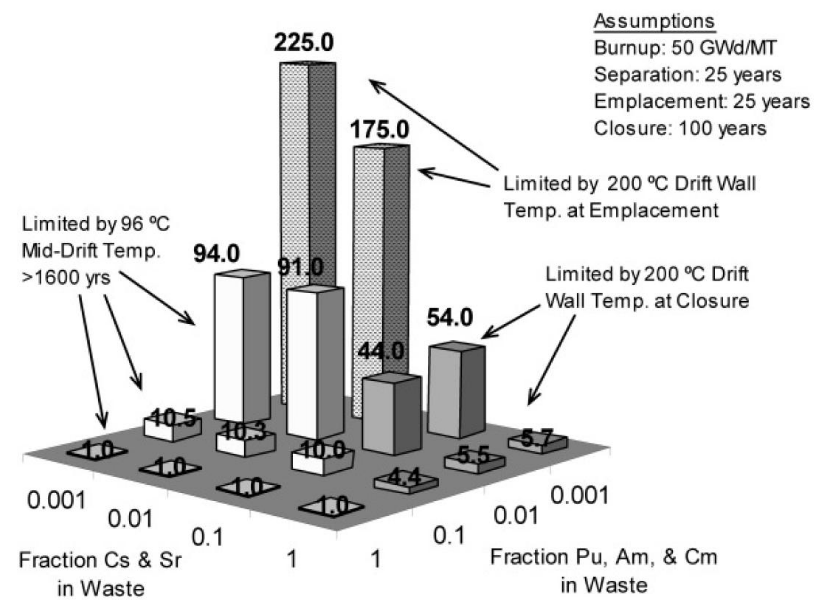




Advanced Nuclear Fuel Cycle – Potential Benefits

- Cs/Sr (and decay products), Cm, and Pu dominate "early" decay heat
- Am dominates "later" decay heat
- Removal of decay heat producers would allow for increased utilization of repository space

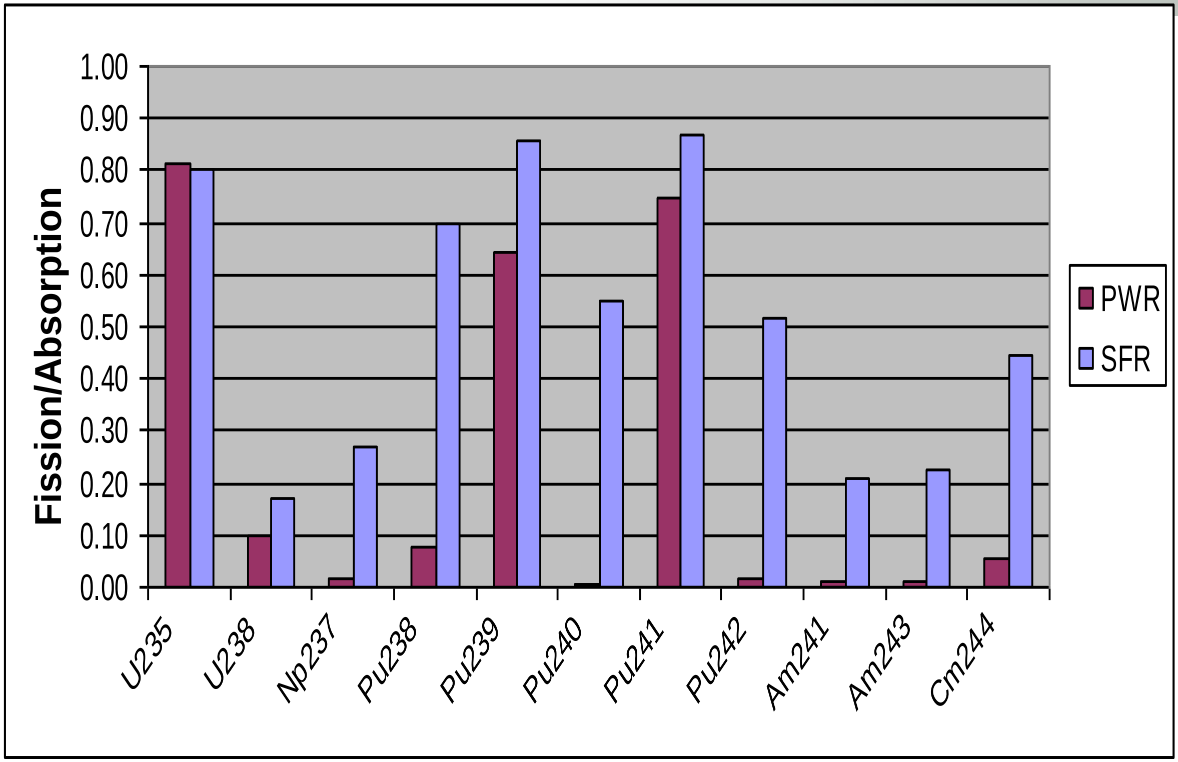




Proliferation Risk

- **Proliferation of nuclear material is a major concern**
  - Effective safeguards is most practical approach to ensure no material diversion and theft
- **Uranium enrichment less than 20% (LEU) is tolerated for commercial and research reactor operations**
  - Internationally, there is interest to limit uranium enrichment facilities
- **Fuel reprocessing has been discouraged in U.S. in the past**
  - Reprocessing considered to enable diversion of plutonium
  - Advanced separations systems now part of FCR&D (AFCI)
- **Transformational approach should minimize use of enrichment and reprocessing facilities**

Impact of Energy Spectrum on Fuel Cycle (Transmutation) Performance



- **Fissile isotopes are likely to fission in both thermal/fast spectrum**
  - Fission fraction is higher in fast spectrum
- **Significant (up to 50%) fission of fertile isotopes in fast spectrum**

Net result is more excess neutrons and less higher actinide generation in FR

Transformational Approaches for Transmutation – Neutron-based Reactors

- **Continuous recycle of fuel material in advanced reactors is transformational as it would allow ~99% uranium utilization and eliminate need for uranium enrichment, and drastically improve repository utilization**
  - Conversion ratio must be greater than 1
  - Fast reactors ideal for this purpose
- **Reactors have operated for over 60 years and are matured**
- **Low cost fast reactors being developed**
- **High cross sections and flux are attractive for nuclide consumption**
- **Achievable neutron flux level limited**
  - Limits transmutation level achievable for most radionuclides, particularly fission products
  - Transmutation of all fission products impractical
- **Once-through near-complete consumption physically impossible**

Transformational Approaches for Transmutation – Driven Subcritical Systems

- **Subcritical systems require further technology development**
  - Fusion-fission hybrids
  - Accelerator-driven fission systems
- **Neutrons still used for transmutation**
  - Typically, fission blanket (core) produces bulk of neutrons for transmutation
  - Waste characteristics similar to reactors
- **System cost will be nearly twice or so that of reactors**
  - Necessitates continuous power production to recover cost of facility
  - Systems safety issues different but must be resolved
- **Workable advanced systems could be truly transformational**
  - Could provide external neutrons – better if surplus neutrons
  - Driver system must be nearly self-sustainable to be practical
  - Once-through, near complete burnup concept requires advanced fuel-pin materials – radiation damage and time at high temperature are concerns
  - Can consume depleted, natural, reactor-grade uranium and TRU, and thorium and FPs

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Transformational Approaches for Transmutation – Non-Neutron-based

- **Non-neutron elementary particles have been considered**
- **Charged particle systems – protons, electrons, ions, etc., to directly impact materials to be transmuted**
- **Photon-based (high-energy) systems to induce photo-nuclear reactions**
  - New sources of mono-energetic photons may enable transmutation of select isotopes that are difficult to treat with other processes
- **Electromagnetic radiation (EM)-based systems**
  - Directly transmute individual isotopes by exciting nuclei with intense narrow-band EM radiation to pre-defined energy levels prompting enhanced β-decay to more stable, less hazardous or stable elements
  - Source of EM radiation can be lasers and rf-fields

Transformational Approaches for Transmutation – Non-Neutron-based – Gammas

- **Conceptually possible to use gammas for transmutation of TRU to stable or shorter-lived nuclides by inducing fission, or raising nucleus to an energy level that then *decays* via neutron or beta emission**
- **High photon energies (several MeV) required to initiate these reactions**
- **Currently, photons generally produced with an electron accelerator via Brehmstraulung on a heavy metal target, resulting in a continuous photon energy spectrum**
  - Most of photons are produced below desired MeV range, which when coupled with relatively low interaction probability results in a low transmutation rate
- **Technologies capable of producing high flux, mono-energetic photons required, and if development is successful might overcome deficiencies described above**

Transformational Approaches for Transmutation – Non-Neutron-based – Protons

- **Transmutation based on direct nuclide interaction with protons does not appear to offer any advantages relative to neutron-based systems**
- **Likely not cost-effective, as it requires high-energy/high-current proton accelerator (1-2GeV, 100s of mA) to overcome Coulomb barrier and needs sufficiently high proton flux for effective transmutation**
- **Energy required to produce high-power proton beams would make these systems net user rather than generators of power**
- **High gas production in any actinide-containing targets and associated embrittlement of cladding/structural materials introduces addition complexities that need to be addressed**
- **High-power proton beam would also generate neutrons in irradiated material via spallation**
  - Is bulk of transmutation neutron or proton based?
  - If neutrons, why not use ADS?

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Transformational Approaches for Transmutation – Non-Neutron-based – Closing Thoughts

- **Significant research and development required before these approaches can be practically used for transmutation mission**
- **Non-neutron systems for nuclear power production are currently ineffective due to fundamental physics limitations**
  - Low intensity and production-efficiency of particles
  - High system cost
- **Advanced materials required for significant nuclide consumption**
- **Energy balance is important**
  - Electric power required for transmutation might be more than power generated while producing nuclides
  - Systems would be impractical for power production, and could be relegated to use as scientific instruments where efficiency is not relevant