Can advanced fuel cycles really reduce the waste burden for nuclear energy?

IAEA Technical Meeting on Advanced Fuel Cycles for Waste Burden Minimization

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Waste Burden Minimization - past discussion

- For the past few decades nuclear scientists and engineers have tried to justify advanced fuel cycles on the basis of waste minimization but have been largely unsuccessful (particularly in the US) - Why?
  - We often tend to focus only on high level waste
  - We often tend to focus only on the back-end of the fuel cycle
    - wastes from processing and/or disposal of used nuclear fuel
  - Sadly, we sometimes use or quote information incorrectly
    - For example, radiotoxicity

- If we are going to evaluate and discuss waste burden minimization, we must consider the following:
  - Include the impacts of the entire fuel cycle - mining to disposal
  - Include the impacts of all waste streams from all parts of the fuel cycle
  - Be realistic, accurate and transparent about our calculations and results
  - Realize that there is no “one size fits all” approach. Different approaches for different nations or regions may make sense
A couple examples: HLW minimization attempts

- **US Hanford “Clean Option”**
  - Goal was to minimize HLW from treatment of 210 million liters of high level waste stored in 177 underground storage tanks
  - Over 10,000 HLW glass canisters (1.5 M$^3$ glass each) would be produced with minimal pretreatment
  - The “Clean Option” was a plan to perform extensive separations in order to reduce the HLW canisters to <1000
  - Determined to be excessively expensive and generate significantly more total waste than for minimal pretreatment

- **US GNEP UREX**
  - Up to 5 or 6 sequential separation steps to remove U/Pu, Np, Cs and Sr, Tc, Am and Cm
  - Goal to create “taylored waste forms” with high waste loadings
  - Found to be far too complex and costly
  - Separation, treatment and decay storage of Cs/Sr waste forms was one of the biggest cost drivers
  - Program evolved to one in which separations is greatly simplified
The large number of separation and waste/product solidification steps, besides being operationally complex beyond any existing experience, were excessively expensive and generated a substantial amount of waste.
Waste Burden Minimization

• Some believe it is better to leave the nuclear waste problem to future generations in hopes they will have better technical solutions

• Many feel that it is our responsibility to reduce the waste burden to future generations

• “The better is the enemy of the good” (Voltaire)
  – This is the argument being used in the US on why we should not license and open the Yucca Mt. Repository, i.e. that we can do better, even though the safety analysis has shown it to be safe
Reduce the waste burden - RECYCLE

• Recycle combined with fast neutron reactors can significantly reduce the waste burden
  – Minimize the amount of uranium that needs to be mined
  – Minimizes or potentially eliminates the need for uranium enrichment, reducing uranium disposal by >1000 times
  – Increases the overall uranium utilization by >100 times - from 0.7% (once through) to 0.9% with mono-recycle, and >70% for multi-recycle
  – Reduces the mass of HLW requiring geologic disposal by ~10 times (and volume by a similar amount)

• These benefits are substantial and essentially make nuclear energy a sustainable energy source
  – But, they still require research and development to make them a reality
  – The full benefits are not completely realized until a steady-state is achieved, which may be >100 years from now
The current U.S. fuel cycle is a once-through fuel cycle using enriched uranium fuel in LWRs.

The fuel cycle is not yet complete:
- Disposal paths for spent fuel and depleted uranium are not currently implemented.
The current U.S. fuel cycle generates two major waste streams requiring geologic disposal or similar isolation, along with LLW:

- 2,000 MT per year of spent fuel – planned disposal path: geologic repository
- 16,000 MT per year of depleted uranium – no disposal path identified at this time, but will also require long-term isolation due to buildup of radioactive decay products
Uranium utilization

The US situation

- A recent US study (Wigland, et al.) concluded that based on substantial improvements in reduction of the amount of waste generated and fuel resources needed that the most promising fuel cycles involved the continuous (multi) recycle of U/Pu or U/TRU
  - The benefits of recycling U/TRU over U/Pu are mostly in the area of waste management (heat load in the repository), but come at a higher cost and technical risk (i.e. needs more R&D prior to implementation)
  - All continuous recycle options utilized fast neutron reactors
  - The US is developing advanced separation methods for U/Pu and U/TRU recovery as well as looking at possible means to reduce the cost of fast reactors

https://inlportal.inl.gov/portal/server.pt/community/nuclear_science_and_technology/337/nuclear_fuel_cycle_evaluation_and_screening_final_report/11118
The US situation (Reactors)

- While recycle and fast reactors are being studied in the US, for possible implementation by ~mid century, the timescale for implementation is very uncertain.

- LWR’s in the US are facing economic challenges due to market inequalities:
  - 4 recently shutdown
  - 6 more announcing early shutdowns in 2017-2018

- A large number of LWRs will begin to shutdown in the 2030s and 2040s due to end of 60 yr life (80 yrs may still be possible, but no reactors have had license extensions beyond 60 yr so far).

- So, the issue facing the US is whether fast reactors will be available and economically attractive by this time to begin replacing LWRs.

- If not, then more LWRs will likely be built with 60+ year lifetimes, pushing continuous recycle implementation back several years.
The US situation (UNF)

- By 2050, the US will have nearly 150,000 metric tons of used nuclear fuel (assuming a constant number of LWRs ~100)
- To meet climate goals, it has been suggested that nuclear will need to double by 2050, this would result in 180,000 metric tons of UNF by 2050
- Current US policy is that the first ~70,000 MT of UNF will be directly disposed in a repository (that would open after 2048)
- That means that any UNF generated after 2015 would be available for recycle, if US policy changes
- Don’t forget, if all LWRs, the amount of DU in 2050 would be an enormous 18,000,000 MT – currently without a disposal path
The US situation (Recycle)

• The US is currently focused on metal fuel for fast reactors
• There is a need to recycle LWR fuel to recover U/Pu or U/TRU for use in the fast reactors
  • This will likely be aqueous-based recycle technologies as the processing throughput will be very large and for fast reactor startup only U/Pu recycle will be preferred, which is beyond current electrochemical processing capabilities
• Recycle of U/TRU from fast reactors will likely be electrochemical-based technology, but aqueous technology may also be considered due to possible product purity issues (Ln) and potential future throughput issues (full fleet of FR)
  • Presently, only research of electrochemical recycle of metal fuel is supported
Current Focus of US Separations R&D

• The current goal of the US research program is to develop a simplified, robust method for actinide separations
• The two primary approaches being investigated involve selective complexation of An(III) over the Lns, and the oxidation of Am(VI) to enable a group actinide separation
• Both “GANEX” and “SANEX” approaches are supported by these approaches, in a much simplified system from the UREX+ approach

Note: The GANEX approach involving Am (VI) extraction does not extract Cm
ALSEP – Actinide Lanthanide Separation Process

Preferred ALSEP solvent extracts An(III)+ Ln from >1 M HNO₃; HEDTA strips An(III) from Ln at pH 3–4  

\[ SF \ (An/Ln) \sim 21 \text{ to } 25 \]

**Extraction (left):** 0.75 M HEH[EHP]/0.05 M T2EHDGA in dodecane  
**Stripping (right) with:** 0.125 M HEDTA/0.2 M citrate

\[ T2EHDGA \]

\[ R = CH₂CH(CH₂CH₃)CH₂CH₂CH₃ \]

\[ \text{HEHEHP} \]
Americium (VI) Extraction

Am(VI) can be extracted from Ln(III) and Cm(III)

Diamylamylphosphonate extracts Am(VI) - similar results with DEHBA
Ce(IV) coextracts
Am(VI) selectively stripped with hydrogen peroxide

Extractions from Bismuthate-treated Simulant

Simulated Co-extraction process raffinate

1 M DAAP/dodecane
Electrochemical R&D in the US

- U/TRU Co-deposition Studies with kg-scale evaluation process using uranium and TRU surrogates (Ln)
- U/TRU Co-deposition Studies with g-scale process using Mk-IV electrorefiner salt with uranium and TRU

Studies and tests to address key data gaps in Case Study mass balance

The majority of the electrochemical R&D effort in the US is currently the Joint Fuel Cycle Studies program with the Republic of Korea
**Zirconium Recovery from Cladding**

- **Can cladding be recycled or decontaminated enough to be LLW?**
- **Cladding is ~25% (wt.) of UNF mass, representing large volume fraction of waste that currently requires disposal in a geologic repository**
- **Value of hafnium-free zirconium is high ($40-50/kg)**
- **Zirconium in UNF cladding contains only one radioisotope, $^{93}$Zr, with 1.5 million-year half-life and weak beta emission**
- **Challenge is to remove other radioactive elements, U, TRUs, fission products, and activation products**
Summary - a US perspective

- There may be more than one approach that makes sense, based on regional or national situations
- Significant waste minimization benefits can be realized if multi-recycle and fast reactors are employed
  - Greatly reduce uranium mining
  - Reduce or eliminate uranium enrichment
  - Use current DU inventories to feed fast reactors rather than dispose of as waste
  - Maximize uranium utilization - from 0.7% to >70%
  - Reduce mass and volume of HLW that requires geologic repository (note: the US believes all fuel cycles will need a geologic repository)
  - Potentially recycle other valuable components of UNF (Zr or other strategic metals)
- But, there is much R&D required before we are ready to implement such a fuel cycle, so let’s get busy!!!!