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Ceramic and TRISO fuel recycle options

Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and Waste Aspects of Advanced Nuclear Reactors

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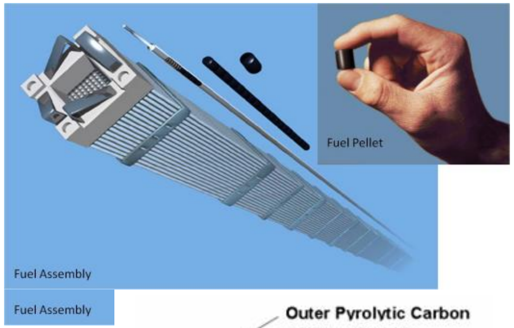
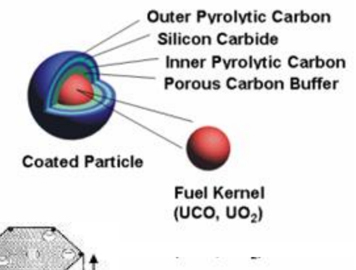
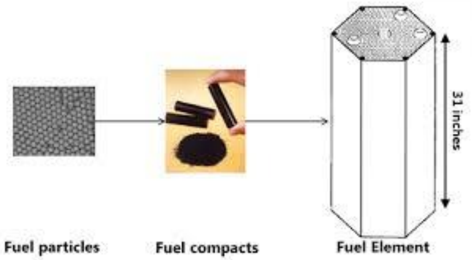
Advanced Reactor Fuels

- Current LWR fuel is <5% enriched UO_2 pellets inside Zircalloy Tubing
  - Accident tolerant fuels may have slightly higher enrichment and used coated zircalloy or other cladding materials
- Proposed advanced reactors use different fuels
  - MOx ceramic fuel
  - Tri-structural Isotropic particle fuel (TRISO)
    - UO_2 or UCO fuel
    - In compacts or pebbles
  - Metallic fuel
  - Molten salt fuel
- Many advanced reactor fuels utilize HALEU (uranium enriched up to 19.75%)
- Of these fuel types, MOx and TRISO are the most amenable to recycle by aqueous processing

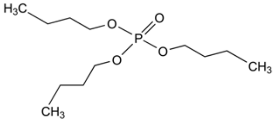




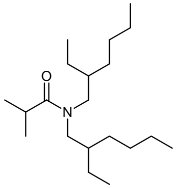


Aqueous uranium recovery/recycle approaches

- There have been a number of technologies demonstrated for recovery of uranium and/or plutonium
  - Solvent extraction, ion exchange/extraction chromatography, precipitation
  - All these techniques have been studied for over 60 years for processing used nuclear fuel
  - Of these, only solvent extraction has been used to recover fissile material from used fuel at industrial-scale for more than 70 years
    - The most widely used method is the PUREX process (plutonium uranium reduction extraction)
    - Variations of the PUREX process have also been demonstrated (e.g. UREX to recovery only U not Pu)
    - Other solvent extraction processes have been developed that use different extractants than PUREX (e.g. monoamides)

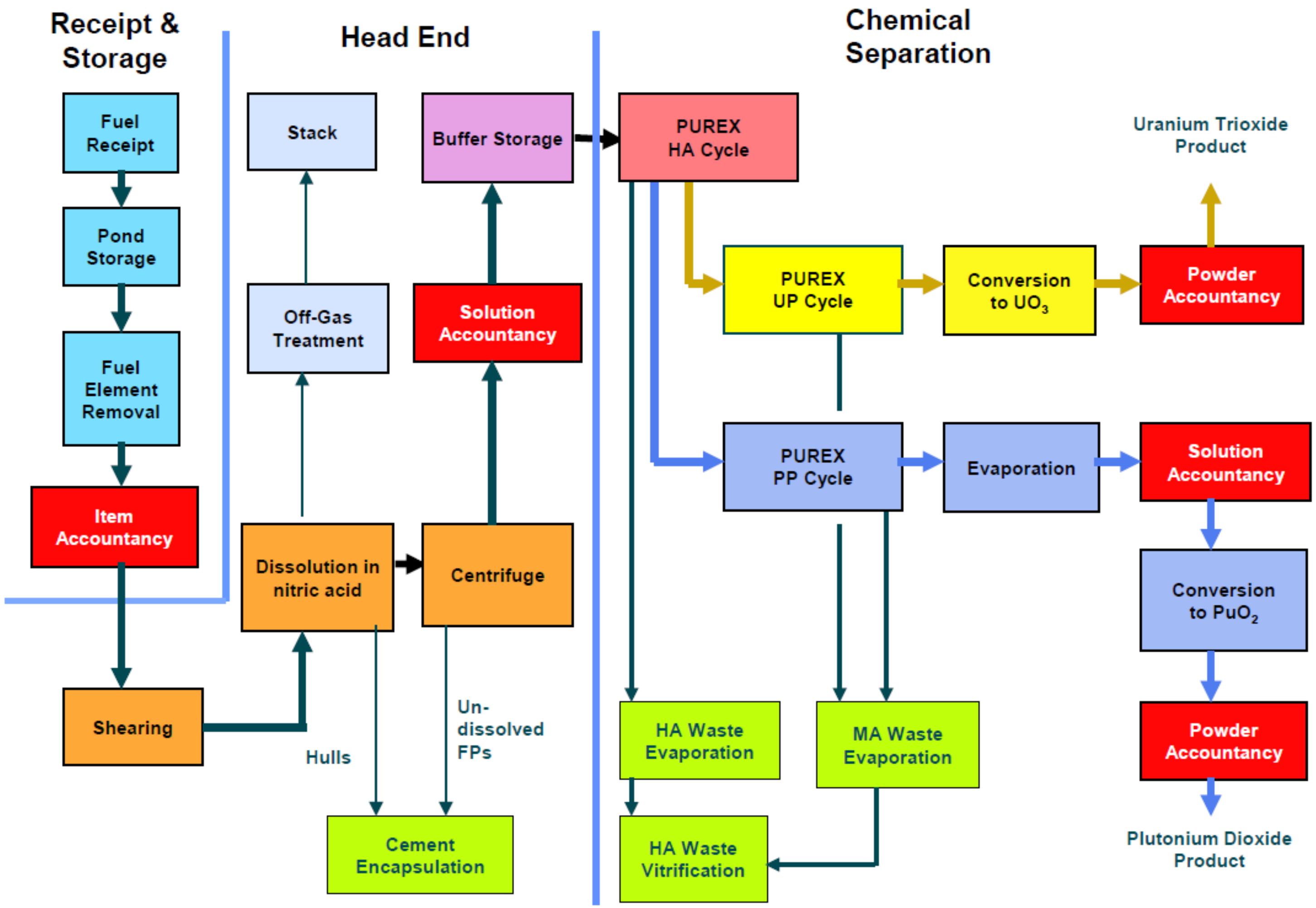


TBP



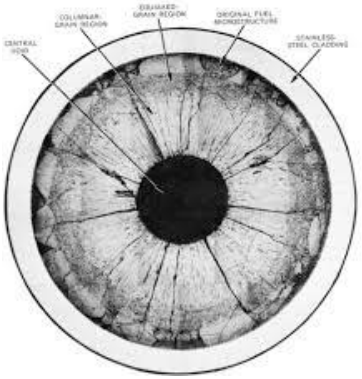
DEHiBA

Typical Commercial LWR PUREX Operations



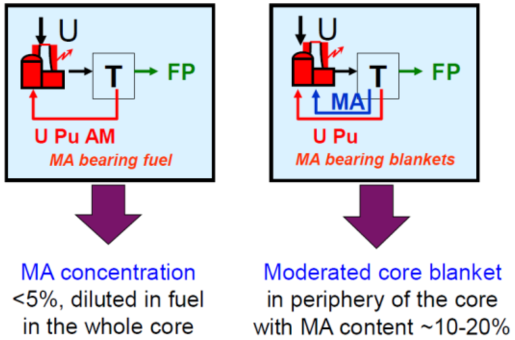
MOx fuel

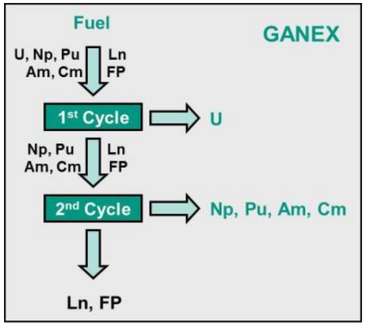
- MOx fuel (mixed oxide) is a ceramic fuel containing both UO_2 and PuO_2
- Because of Pu isotopics, MOx fuel is typically only burned once in a thermal (LWR) reactor
  - LWR MO_X typically has about 7-10% PuO_2 and the remainder UO_2
- Recycled Pu can be burned indefinitely in a fast reactor over several cycles
  - Fast reactor MO_X can have as much as 30% PuO_2
- Processing MO_X fuels is similar to processing LWR fuels with a few exceptions
  - The fuel is higher burnup and dissolving the fuel is more difficult
  - The extraction process has to be adjusted to account for the higher amounts of Pu
- ~70 MT of MOx fuel has been processed at the La Hague reprocessing facility in France

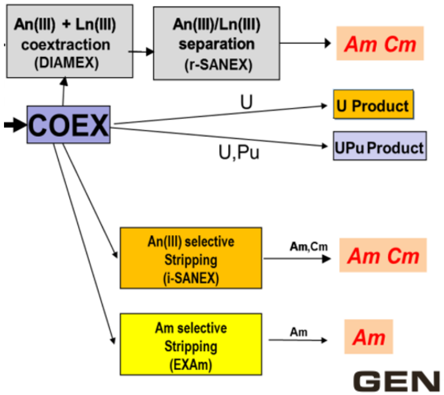


Processing Advanced Reactor Fuels

- **MOx Fuel** (for fast reactor recycle)
  - European approach (heterogeneous or homogeneous recycle)
  - GANEX (group actinide extraction for homogeneous recycle)
    - Two step process
      - Separate U using DEHiBA extractant
      - Separate Np, Pu, Am, Cm using Euro-GANEX process
  - SANEX (selective actinide extraction for heterogeneous recycle)
    - Multiple approaches
    - Similar approaches internationally (e.g. ALSEP process in US, SELECT process in Japan, etc.)
      - Most based on TODGA ligand or derivative







GENIORS

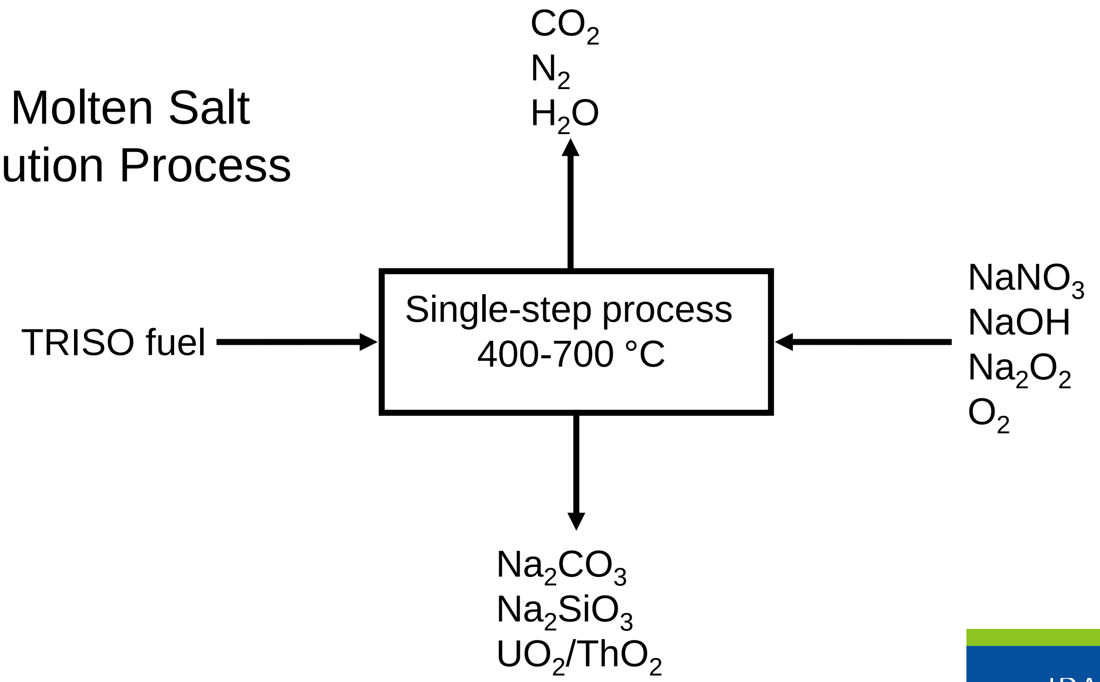
Processing Advanced Reactor Fuels

- **TRISO Fuel**
  - It is challenging to destroy the outer coatings of TRISO particles to access the uranium
  - Historically, a grinding, burning and leaching approach was developed, but burning the graphite releases C-14
  - Besides the carbon coating of the particles, there is a very large mass of contaminated graphite in the compacts, prisms or pebbles that will require disposal
  - Methods that need developed are:
    - Separation of TRISO particles from graphite material
    - Accessing the uranium inside the TRISO particle
      - SRNL molten nitrate salt (US patent # 9,793,019)
      - Electrochemical method
      - Sonication
      - Others ?

Processing Advanced Reactor Fuels

- **TRISO Fuel continued**
  - Once the TRISO particle is breached, the fuel can be easily leached out and conventional solvent extraction processes employed
  - Graphite waste disposal and possible waste forms have not been addressed sufficiently
    - Addressed only for direct disposal in Yucca Mt.

SRNL Molten Salt Dissolution Process



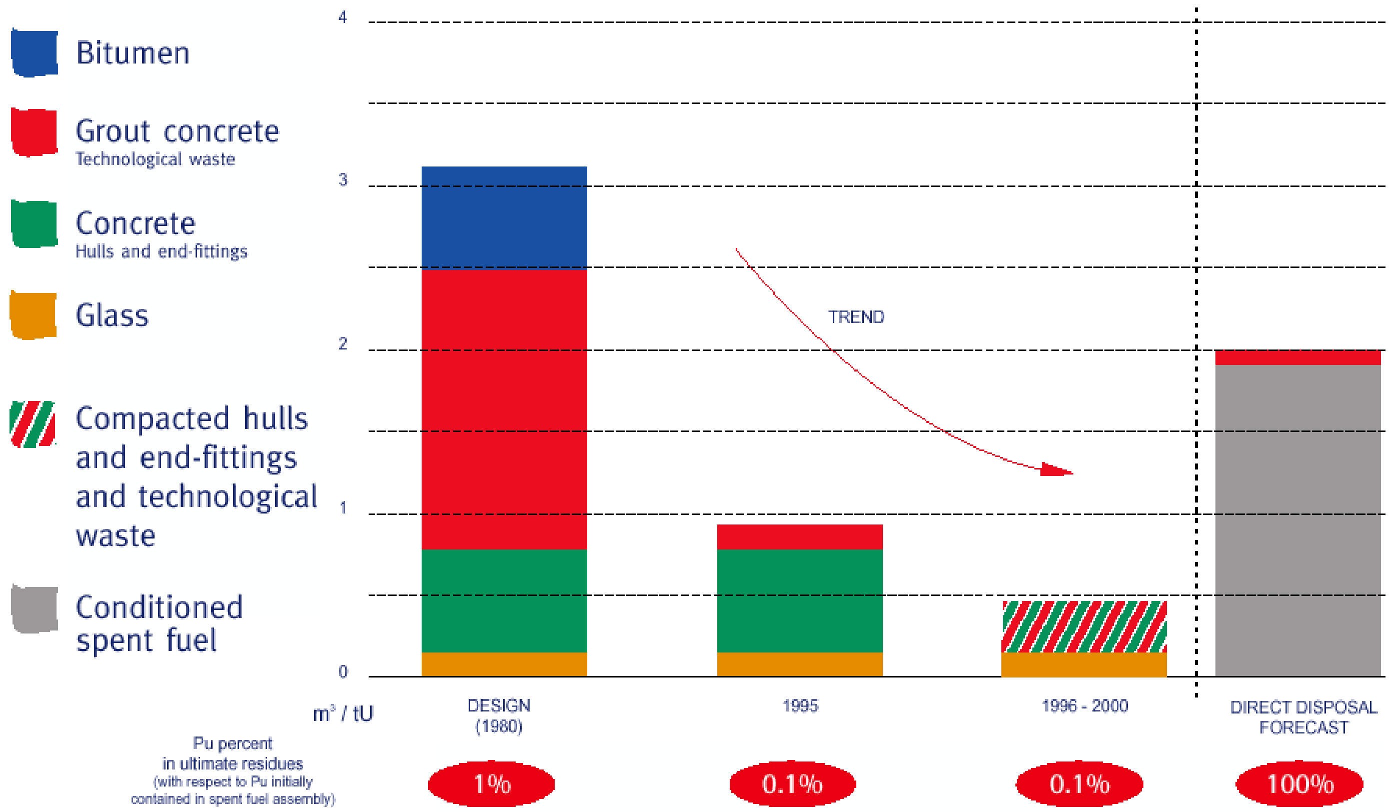
Waste Products of PUREX process

- PUREX processing produces two primary waste streams
  - High level waste
    - Liquid raffinate containing all fission products, inert metals, minor actinides (Np, Am, Cm)
      - This stream is converted to a stable waste form such as glass or ceramic for eventual geologic disposal
    - The fuel cladding is considered HLW in the US (Intermediate Level Waste in most other countries)
  - Low level waste
    - Any contaminated by-product of running the process or facility
      - Does not require disposal in geologic repository
      - Some LLWs are encased in cement, others directly disposed
  - Wastes from the capture and immobilization of volatile off-gas constituents (these wastes would be either HLW or LLW depending on their characteristics and regulations)

Waste Products of PUREX process

Volumes of final residues conditioned in La Hague UP3

(High level and long-lived waste after conditioning)



Courtesy AREVA (now Orano)

Does recycle make sense for advanced reactor fuels?

- The US is currently not utilizing MOx for either thermal or fast reactors
  - Recycle of U and Pu from LWRs for MOx would require a significant investment in new infrastructure based around Gen-III reactors
  - Reprocessed uranium (1% enriched) is less attractive than natural uranium at current market prices
  - US fast reactor designs employ either metal or molten salt fuel
- TRISO fuels will require a new headend system for processing
  - Significant waste volume benefit from recycle
  - HALEU fuels make uranium recycle more attractive
- Currently there are no commercial sources of HALEU for advanced reactors
  - Recycle of existing HEU fuels may help fill the need, until commercial HALEU enrichment is available

Potential research areas that could be impactful for advanced reactor fuel cycles

- Headend processes
  - Advanced methods to remove cladding that would enable it to be disposed as LLW rather than HLW
    - For oxide fuels, this could be Zr or SS volatility
    - For TRISO fuel separation of fuel particles from graphite
  - Advanced separation processes
    - Simplification for waste minimization
      - Can we go from 2 or 3 extraction cycles to one cycle and significantly reduce facility size and operational costs?
  - Advanced waste forms
    - Advanced waste forms have the potential to increase waste loading (reduce volume) and be more durable than borosilicate glass
  - Volatile off-gas capture/immobilization
    - Enabling technologies for all processing methods

Summary

- Advanced reactor fuels have differences from current LWR fuels that create new challenges
  - Headend processing to access fissile material
  - Waste management
  - HALEU
- Aqueous processing is a mature technology with over 70 years of industrial-scale experience (and a lot of lessons learned)
- There are a number of research opportunities that could make advancements in aqueous processing and waste management
  - These advancements could reduce waste generation, improve operational effectiveness and reduce cost