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Spent Nuclear Fuel Management Options and Technology

The Energy*Solutions*' View

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Overview of the Options for Managing SNF

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- Once-Through-and-Store at the individual Reactor Sites
  - Current default arrangement - the "Open Cycle"
- Once-Through-and-Store at one or more Consolidated Used Fuel Storage Facilities
  - Open Cycle again
- Once-Through-and-Store in one or more National Repositories
- The Modified Open Cycle
  - as identified in the DOE Fuel Cycle R&D Roadmap
  - Recycle of certain SNF components, with limited or no separations
- Full Recycle
  - Separation of bulk uranium, uranium+plutonium, actinides and fission products
  - Recycle of the uranium and plutonium as nuclear fuel
  - 'Burning' of the actinides – conversion to lower atomic weight shorter-lived species

Once Through and Store at the Reactor Sites

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Advantages

- Established, workable system using dry cask storage
- Requires only modest amounts of, (but challenging), development work
  - Need to demonstrate maintenance of satisfactory fuel and cask condition over extended periods (maybe 100s of years)

Disadvantages

- Storage of SNF at 104 reactor sites presents an increasing security cost
- As reactors are closed, more ‘orphan sites’ will exacerbate this cost
- ‘Self protection’ from FP activity will decline over ~100+ years
- Does not satisfy power utilities – they retain ownership of the SNF
- Utilities are incentivized to store SNF in larger casks - may not be transportable
- Is not a permanent solution
  - So plays into the hands of the anti-nuclear lobby
  - Is a disincentive to new nuclear build
- Does not extract the energy in the SNF

Once Through and Store at Consolidated Storage Facilities

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Commentary

- Energy*Solutions* supports this, at least as an interim measure
- We support the BRC's recommendations that:
  - sites must be voluntary
  - that funding should be from waste fund via a new public-private body ('FEDCOR')

Advantages

- Consolidates SNF: minimizing security costs
- Enables a consistent single standard of surveillance, care and maintenance to be applied
- Helps satisfy nuclear utilities by taking SNF ownership off them
- Recommended by the Blue Ribbon Commission

Disadvantages

- Still not a permanent solution
  - So plays into the hands of the anti-nuclear lobby
  - Is a disincentive to new nuclear build
- Does not extract the energy in the SNF

Once Through and Store at National Repository

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Advantages

- Consolidates SNF – minimizing security costs
- Enables a consistent single standard of surveillance, care and maintenance to be applied
- Helps satisfy nuclear utilities by taking SNF ownership off them
- Can be seen as "solving" the SNF problem
  - removes ammunition from the anti-nuclear lobby

Disadvantages

- Declared Yucca Mtn capacity was ~70,000 tons SNF
  - so current SNF backlog would use this up immediately
  - multiple repositories would be needed to support new nuclear build
- Bulk uranium and fuel cladding take up and waste space in the repository
- Presence of heat-generating actinides:
  - forces greater spacing of SNF elements, wasting more space
  - requires repository to remain intact for millions of years
- SNF elements are not a fully robust waste form
- Does not extract the energy in the SNF

Modified Open Cycle

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Commentary

- MOC may have no separations (eg Traveling Wave Reactor) or limited separations (eg remove only FP gases, or remove only partially the FPs)

Advantages

- Potential to eliminate or simplify separation processes
- Does not separate pure fissionable material – potential non-proliferation advantage
- Enables recycle of uranium, plutonium and minor actinides

Disadvantages

- Technology is immature – and 'devil will be in the detail'
- Limited separations seriously complicate fuel manufacture
  - significant radioactivity of feed materials will force glovebox or hot-cell use
- Limited separations seriously complicate reactor fuel loading
- Limited separations will produce 'poisoned' fuel that may require higher neutron efficiency reactors

Full Recycle

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Commentary

- Energy*Solutions* supports SNF recycle in conjunction with an initial move of SNF to Consolidated Storage Facilities
- Recycle can support LWRs solely or it can be part of a transition to the use of Fast Reactors in the longer term

Advantages

- Enables full recycle of uranium and plutonium – extracting maximum energy
- Enables minor actinides to be 'burned' in Fast Reactors, HWRs and LWRs
  - Separation of the minor actinides requires further development
- Enables 'troublesome' FPs (eg Tc, Np) to be separately dealt with
- Produces a robust, compact vitrified FP wasteform - containing >99% of activity
  - Up to 13-fold smaller volume than the SNF assemblies – taking into account smaller volume and increased packing density achievable

Disadvantages

- Seen by some as a proliferation risk
  - Because early recycling facilities produced pure plutonium
- Seen by some as producing too much secondary waste
  - Because early recycling facilities were built to maximize Pu production, not to minimize wastes

Conclusions from this Analysis

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- It is not sensible to leave SNF at reactor sites indefinitely
  - 'Self-protection' from FPs will decrease with time
  - Each site will require increasing levels of security
- One or more Consolidated Storage Facilities are a sensible interim measure
  - This is not 'kicking the can down the road'
  - It simplifies and reduces costs of security
  - It requires already-robust transportation methods to be developed further
  - But it doesn't offer a permanent solution
- A national repository will be needed no matter what is done with SNF
  - But treating the SNF will significantly reduce the volume of HL waste to be stored
- The Modified Open Cycle is worthy of further R&D
  - But at the moment it seems to pose large problems for fuel manufacture & handling
- Full SNF Recycling has been unjustly demonized in the US
  - It is successful and economic in Europe, using 3rd generation technology
  - It significantly reduces the volume of HL waste to be stored
  - The robust vitrified waste form opens up other repository options e.g salt domes

Recycling of Spent Nuclear Fuel

Why isn't the US Recycling SNF?

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- One or more closed cycle "Consolidated Fuel Recycling Centers" were planned to be built in the USA, starting in 2009, under GNEP
- Recycling of SNF is routinely done in the UK (Sellafield) and France (La Hague)
  - Typical facility capacity 800-1000 tons/year
- However, four objections have so far discouraged recycling in the US:
  - Suitable technology for recycling has not been developed
  - Recycling is a proliferation risk because it separates pure plutonium
  - Recycling discharges radioactive waste to the environment in unacceptable amounts
  - Recycling is un-economic

Energy*Solutions*' NUEX, & other 4th generation recycling processes, answer all these objections

The Four Generations of Recycling Facilities

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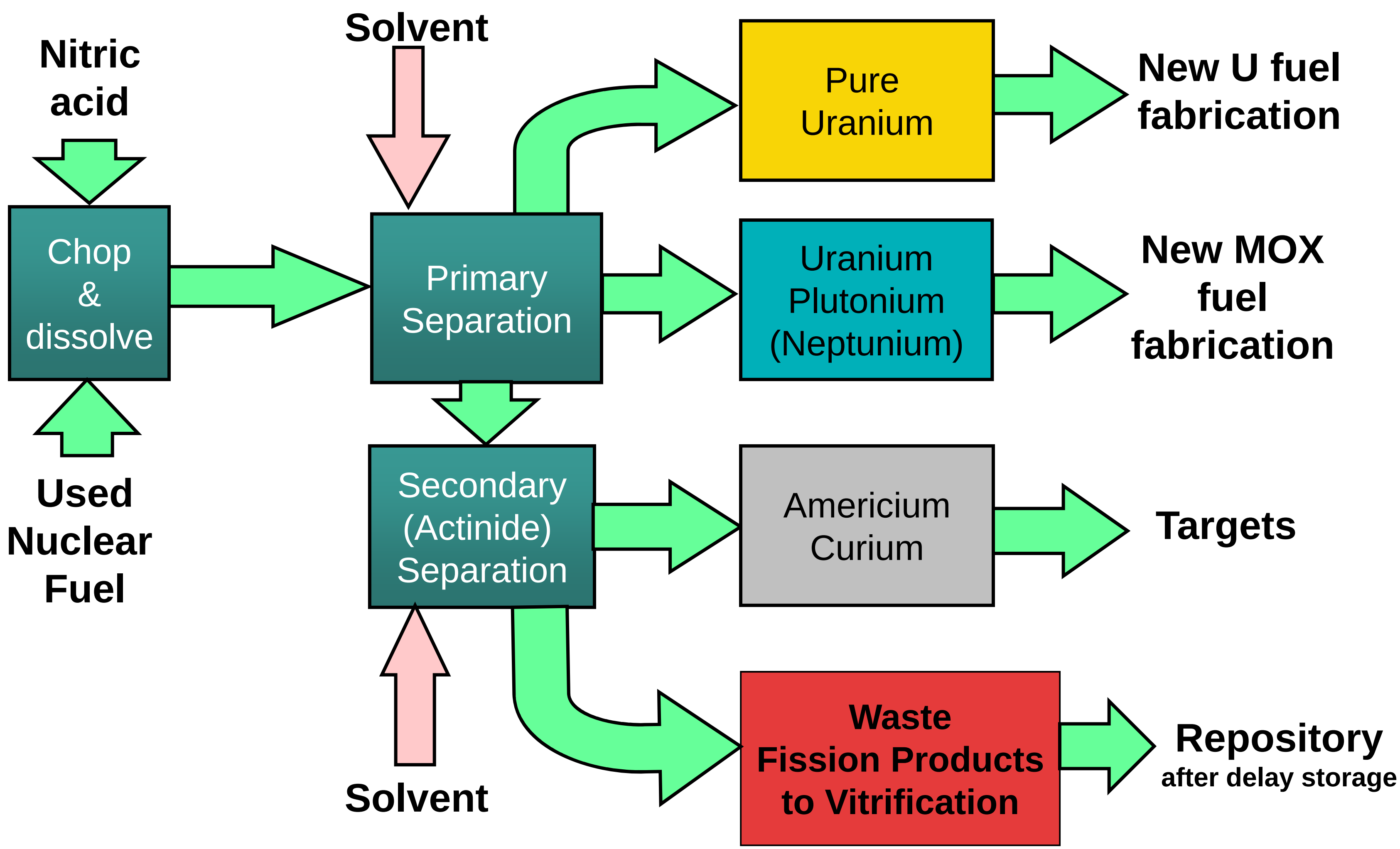
All (except 1) based on solvent extraction using tri-butyl phosphate in kerosene diluent

- First Generation (1940-50)
  - Hanford, Savannah River in the USA
  - Sellafield Butex in England
- Second Generation (1960s)
  - Sellafield Magnox in England
  - Marcoule in France
  - Tokai-Mura in Japan
  - Mayak in Russia
- Third Generation (1980-2000)
  - Sellafield THORP in England
  - La Hague UP3 and UP2 800 in France
  - Rokkasho-mura in Japan
- Fourth Generation (2020s?)
  - Energy*Solutions*' NUEX Facility
  - AREVA's COEX process
  - US National Laboratories' UREX process

- Steadily improved technology
- Decreasing liquid and gaseous waste discharges
- Improved solid waste treatments

- No separated plutonium
- Near-zero liquid & gaseous waste discharges
- >99% of waste radioactivity in the SNF goes to vitrified waste

Energy*Solutions*' NUEX 4th Generation Recycling Process



How Mature are These Recycling Processes?

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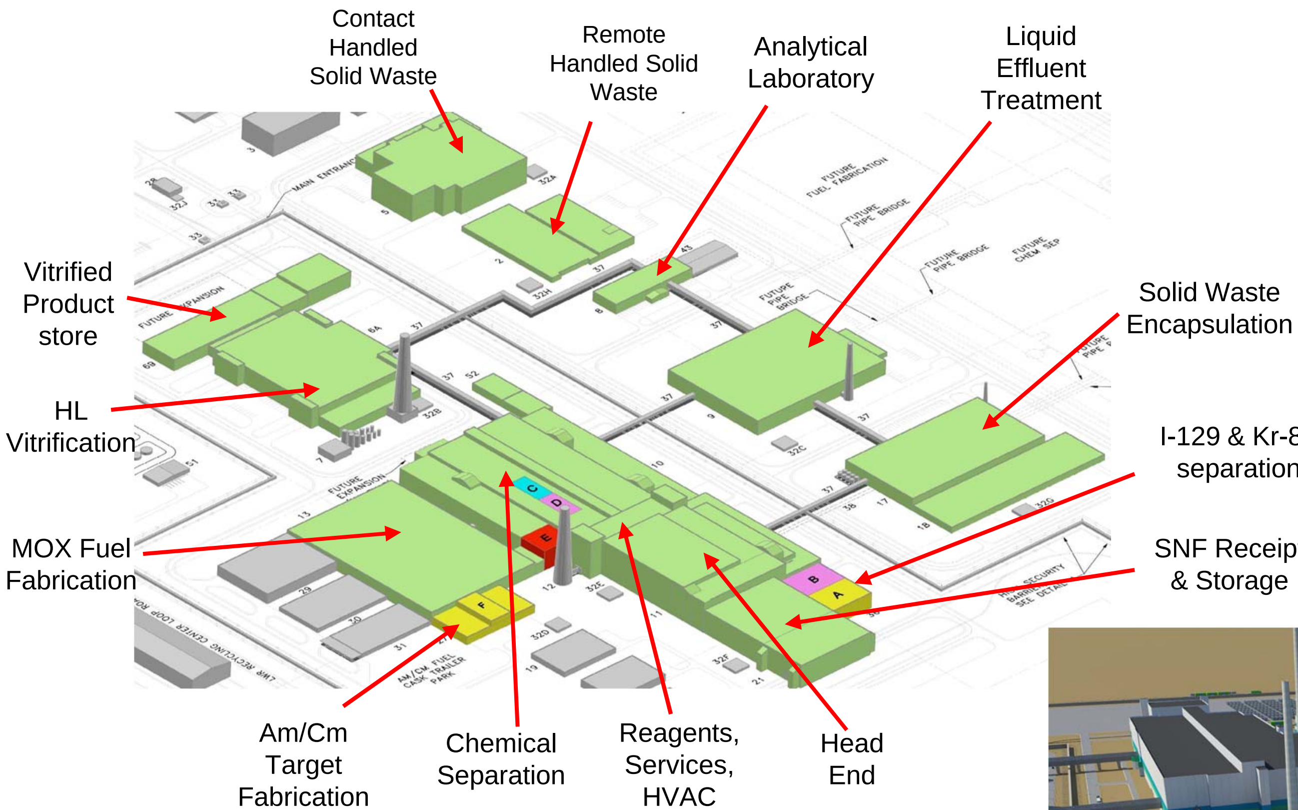
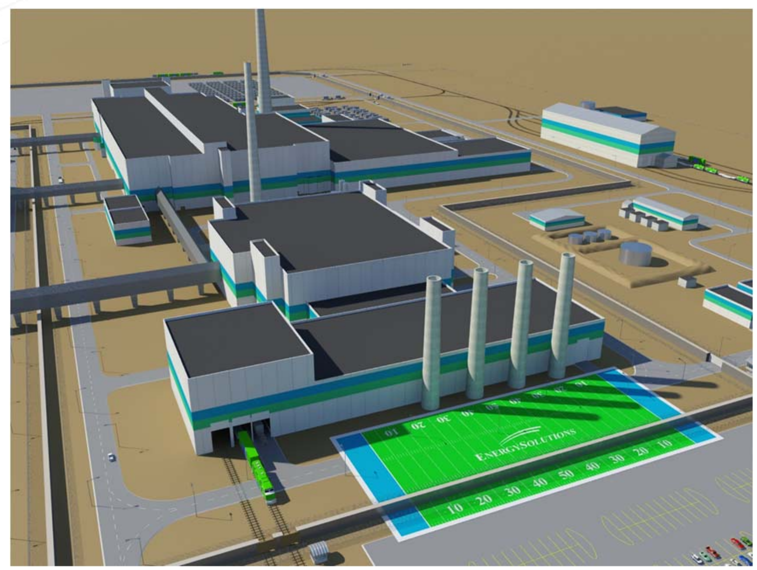
Conceptual Design for a 1500 ton/year Recycling Facility with Vitrification, MOX Production, MA Target Production, Wastes Handling



TRL 8 or 9



- Over 90% of the technology is ready to deploy
Process equipment is proven in industrial use
- Chemistry enhancements are needed to provide new separations and improve environmental performance
- Detailed design could start immediately

How does NUEX fit into an Overall Recycling Scheme?

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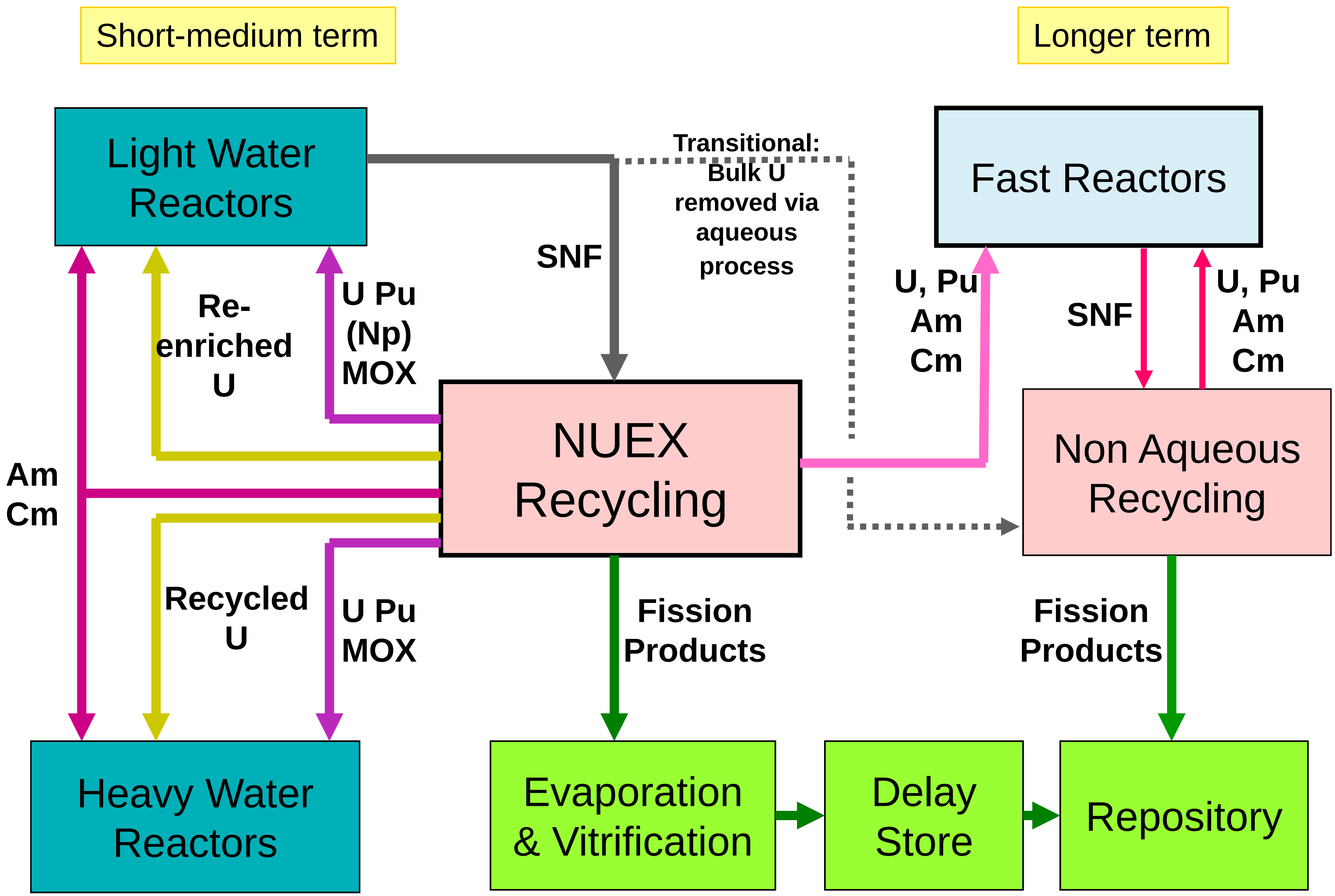

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But….What about the Wastes?

Typical Waste Volumes and Activities from an Industrial Scale SNF Recycling Plant

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Basis: 1 ton of SNF as fuel elements occupying a volume of about $2.5m^3$

Waste Stream	Final Conditioned Volume m^3/ton SNF	Alpha Activity Ci/ton SNF	Beta-gamma Activity Ci/ton SNF	% of Total Activity in the original SNF
Vitrified high active waste	0.07	1593	270,000	99.04
Compacted RH & CH TRU waste: GTCC (mainly fuel hulls & ends)	0.24	5.94	2646	0.95
Encapsulated Class A LL Wastes	6.95	0.084	4.32	0.0016
Recycled or encapsulated low level liquid waste (for H-3 capture)		0.001	0.0095	0.000004

Vitrified product volume reduction from SNF is apparently ~36-fold
However, this is reduced in practice by (i) volume of the vitrified product containers and (ii) heat-related packing restrictions in the repository

HLW and GTCC Waste Volume Reduction Achieved by Recycling

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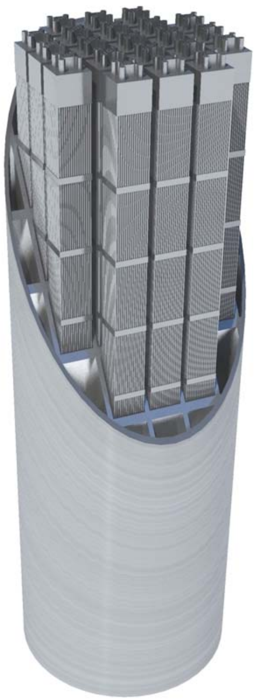
Radioactivity: 100%



Used fuel in one disposal container (MPC) 10.9m^3

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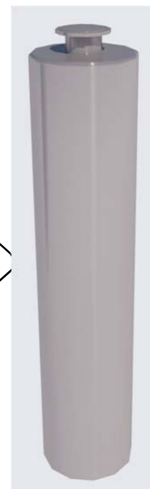
Radioactivity: 99%



One Vitrified HLW Disposal Canister 0.8m^3

+

Radioactivity: 1%

2.5 GTCC LL waste (RH72 B) Canisters 2.3m^3

(Mainly compacted fuel cladding)

5 GTCC LL CH Drums of I-129 Waste 1.6m^3

Vitrified product volume reduction from SNF is here shown to be about 13-fold. This allows for vitrified product containers Depending on heat-related packing factors that are assumed, this factor can fall to about 6-fold

Economics of Recycling

The Business Case for Recycling

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Business model developed by Booz Allen Hamilton

- The bulk recycled uranium from Recycling can be sold as fuel to reactor operators:
  - It can be used in existing LWRs following re-enrichment
    - It is competitive with “fresh” enriched uranium given a minimum uranium market price (typically somewhat greater than $80/pound, depending on assumptions)
  - It can be used in HWRs reactors without re-enrichment
    - It is competitive now and electricity utilities in China are already testing its use
- The mixed uranium-plutonium stream can be made into MOX fuel for LWRs
  - Use of MOX fuel is already well established in Europe
  - It is competitive now with standard uranium fuels (at ~10% discount)
- Use of the existing and going-forward US waste fund adds to these product sales incomes to provide the balance of funding
  - US Utilities have been paying into this fund at 0.1 cent per kwhr of electricity generated
- Detailed design of a recycling facility could start immediately, leading to an operational facility in about ~17-20 years

Does the NUEX Facility resolve the US Objections to Recycling?

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- "Suitable technology for recycling has not been developed"
  - Suitable 3rd generation technology has been developed in Europe over the last 50 years and could readily be advanced to 4th generation for use in the US
- "Recycling is a proliferation risk because it separates pure plutonium"
  - 4th generation recycling does not separate pure plutonium at any point in the process
  - Modern accountancy methods allow accurate measurement of fissile material content at any point in the process – allowing any unauthorized diversion to be quickly detected. Full IAEA approval for this already exists in Europe
  - Recycling ultimately reduces the fissile material circulating in the fuel cycle
- "Recycling discharges radioactive waste to the environment in unacceptable amounts"
  - 4th generation recycling discharges trivial or indeed no radioactivity to the environment
  - Over 99% of the SNF radioactivity goes to glass encapsulation
- "Recycling is uneconomic"
  - A coherant business case has been produced
  - This does requires access to the Waste Fund – and a minimum price for fresh uranium

Conclusions

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- Energy*Solutions* supports the BRC's recommendation that a new public-private body ('FEDCOR') should be set up to control the Waste Fund and manage the treatment of SNF
- Energy*Solutions* supports the BRC's recommendation for one of more Consolidated SNF Storage Facilities
  - Volunteer sites should be sought
- We think this should be seen as an interim step on the road to full SNF recycling
- SNF recycling:
  - reduces HL waste volume
  - produces a robust HL waste form containing >99% of the radioactivity
  - allows maximum energy to be extracted from nuclear fuel
  - is environmentally friendly
- We believe that the US should build a pilot recycling facility to demonstrate these advantages

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How are these Advances Achieved?

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- The NUEX process builds on the industrially proven world recycling facilities (England (THORP), France, Japan)
- Flexible flowsheet: ability to make products with differing proportions of uranium, plutonium and neptunium
- Separation of pure plutonium is avoided by adjustments to solvent extraction separation chemistry. Typical products are:
  - **Bulk uranium oxide (“RU”) for use in HWRs and LWRs**
  - **Mixed uranium, plutonium, neptunium oxides**
    - Proportions of U, Pu, Np can be varied by altering redox reagents, acidities, conditioning temps
    - Np can be separated if required for separate treatment or storage
    - Tc can be separated if required for separate treatment or storage
  - **Americium, curium produced for target burning in HWRs, LWRs & fast reactors**
- Uses improved “salt-free” reagents
  - **Nearly all wastes can be vitrified: >99% of the radioactivity in the SNF**
- Zero or near-zero liquid discharges
  - **Recycle of nearly all process water as reagent make-up**
  - **Purge water is cement-encapsulated**
- Gaseous tritium (H-3), krypton-85, iodine-129, carbon-14 captured
  - **Economics of krypton-85 capture under continued review**
  - **Necessity for tritium capture under continued review**