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Advanced Nuclear Fuel Cycles

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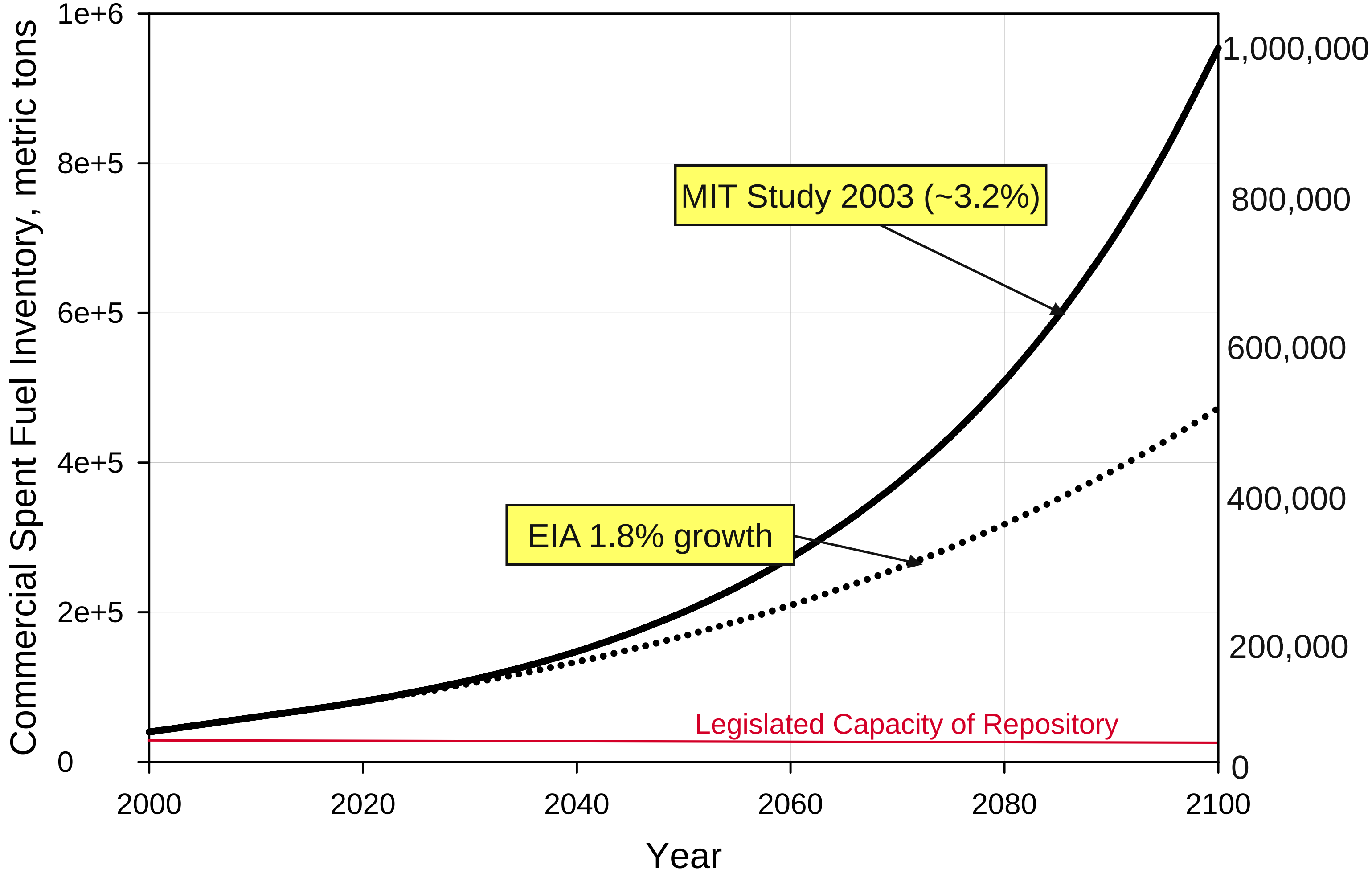
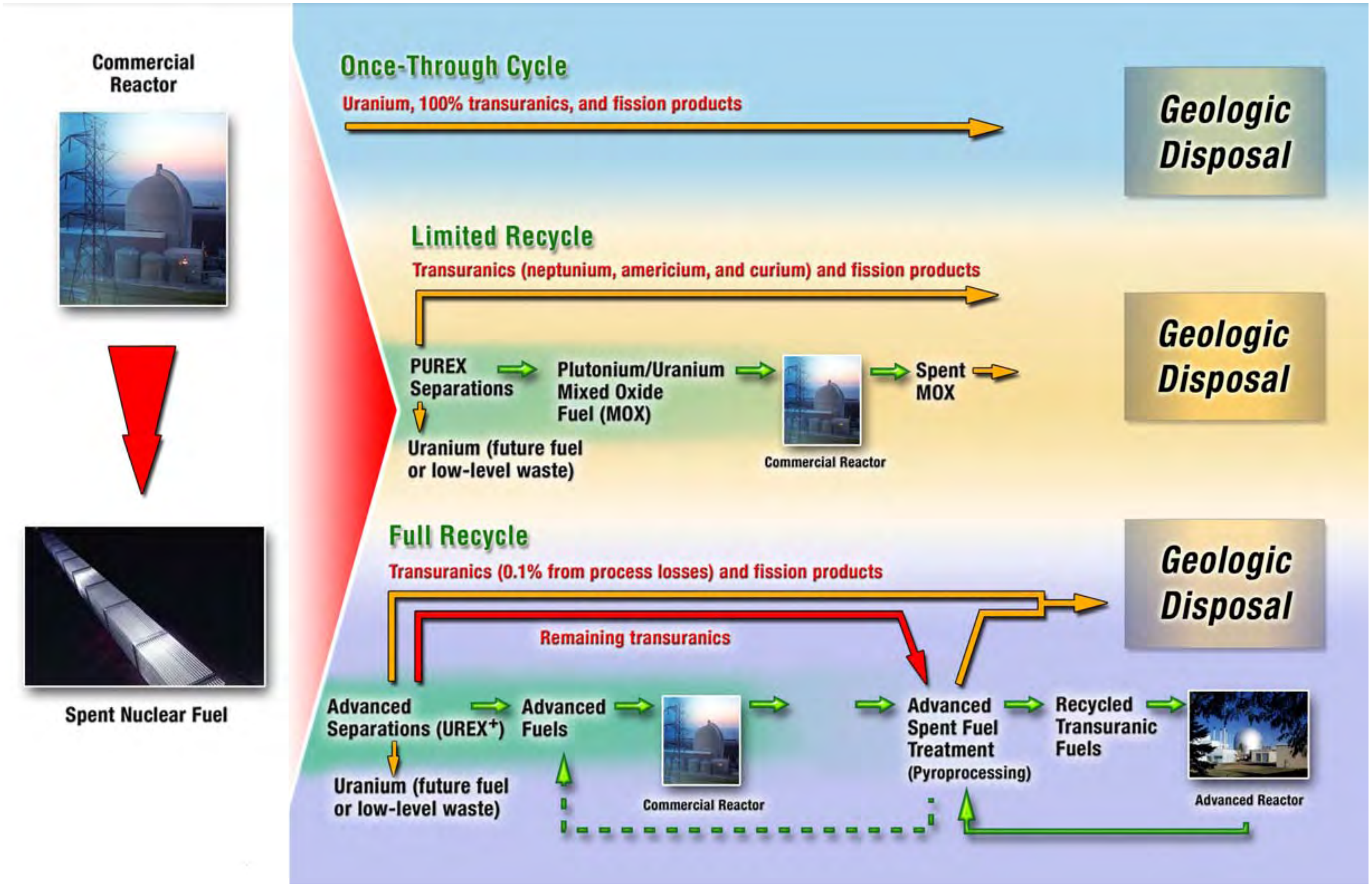
Sustainable Nuclear Energy

- **Nuclear power is a reliable energy source.**
- **Nuclear energy will be a critical resource for the future, especially as total energy needs increase and other energy sources need to be displaced.**
- **The essential, sustainable future for nuclear energy warrants an integrated, comprehensive approach to nuclear waste management in which fuel fabrication, reactor design and performance, separations, transmutation, and geologic disposal work in an integrated manner to provide abundant, sustainable nuclear energy.**
- **A comprehensive vision for expanded, sustainable nuclear energy must include:**
  - Safe and secure fuel cycle technologies
  - Closed fuel cycle for waste and resource management

Projected Spent Fuel Accumulation without Recycling



Spent Nuclear Fuel Management Options

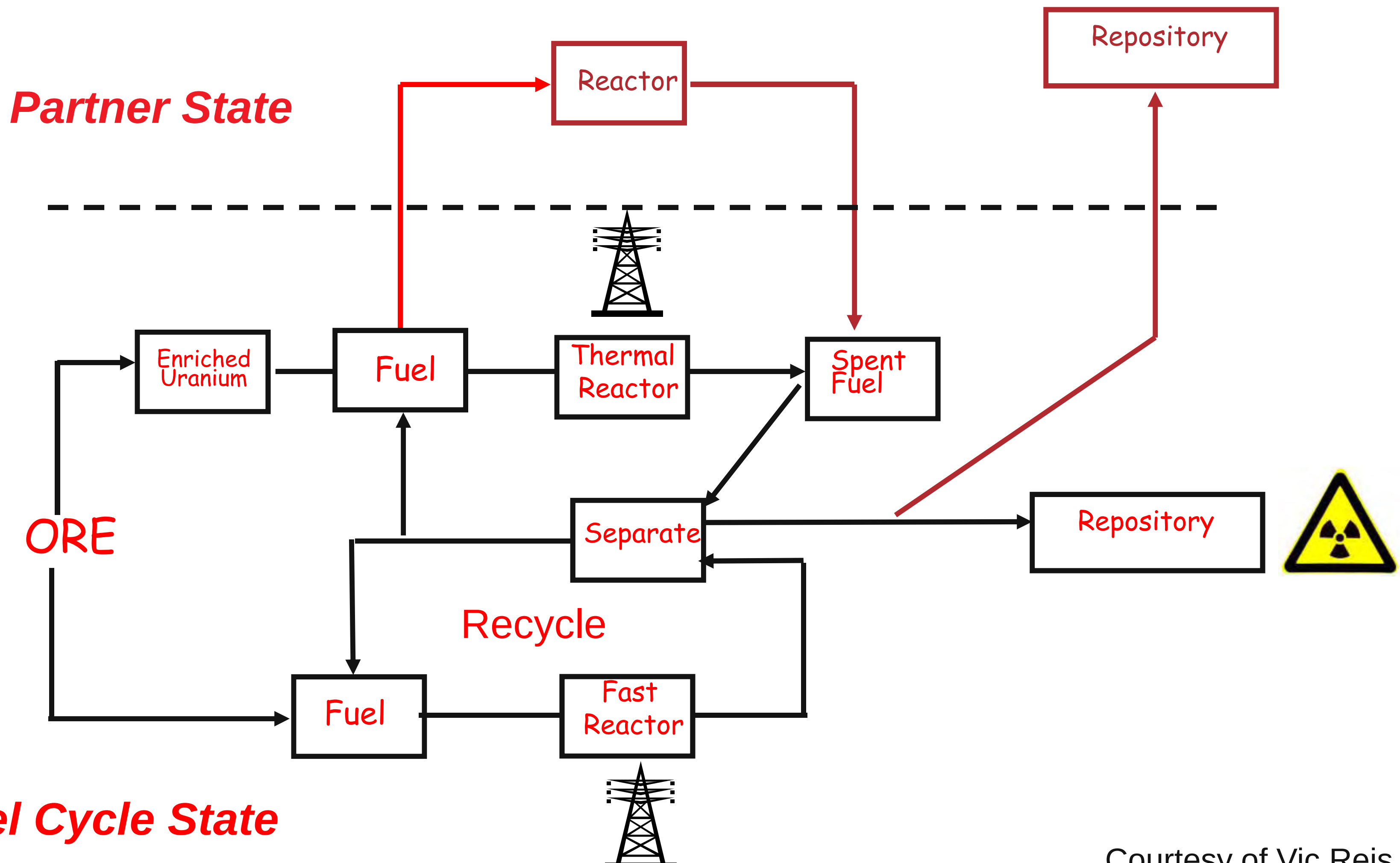


Potential Benefits of Closed Fuel Cycle: Uranium Supply and Economics

- **A closed fuel cycle can effectively multiply uranium resources by a factor of ~100**

- **Current known uranium resources are sufficient for nuclear energy production for several decades, but there are other considerations**
  - Energy independence is a factor because much of the uranium resources are non-U.S.
  - The additional costs of a closed fuel cycle are high enough that uranium supply and demand cannot be the sole economic driver for a closed fuel cycle.
  - This will be the case for several decades – the tipping point could be as soon as 2050.

Potential Benefits of Closed Fuel Cycle: Nonproliferation



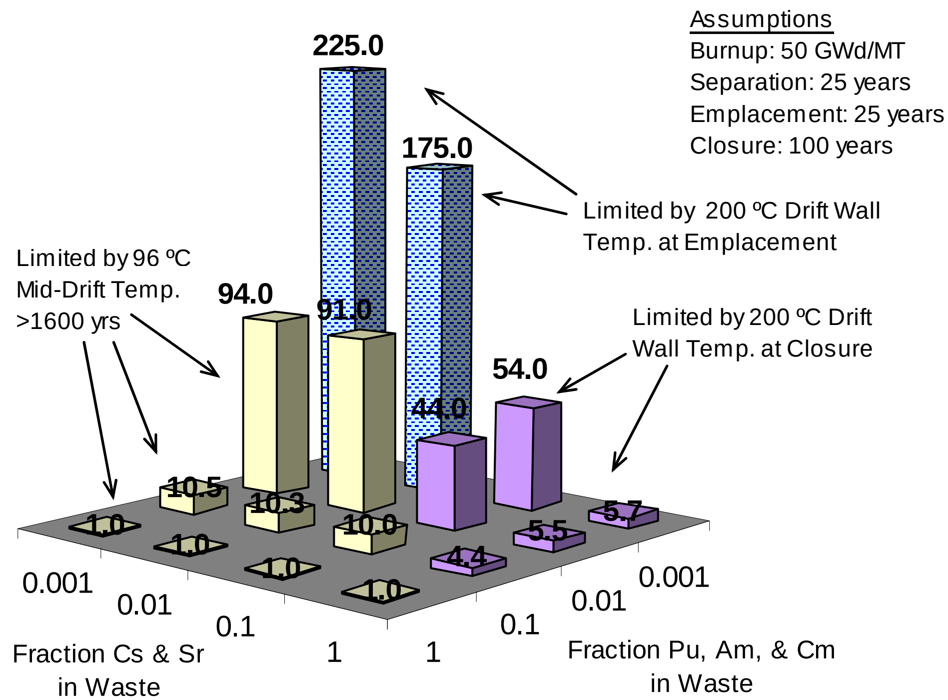
Courtesy of Vic Reis

Potential Benefits of Closed Fuel Cycle: Waste Management

- **With the processing of spent PWR fuel to remove the elements responsible for the decay heat that cause temperature limits to be reached, large gains in utilization of repository space are possible**
  - Only considers thermal performance, not dose rate

- **Pu, Am, Cs, Sr, & Cm are the dominant elements**
  - The recovered elements must be treated
    - *Separate storage of Cs & Sr for 200-300 years*

- **Recycling of Pu, Am, & Cm for transmutation and/or fission**
  - Irradiation in reactors



Advanced Fuel Cycle Requirements

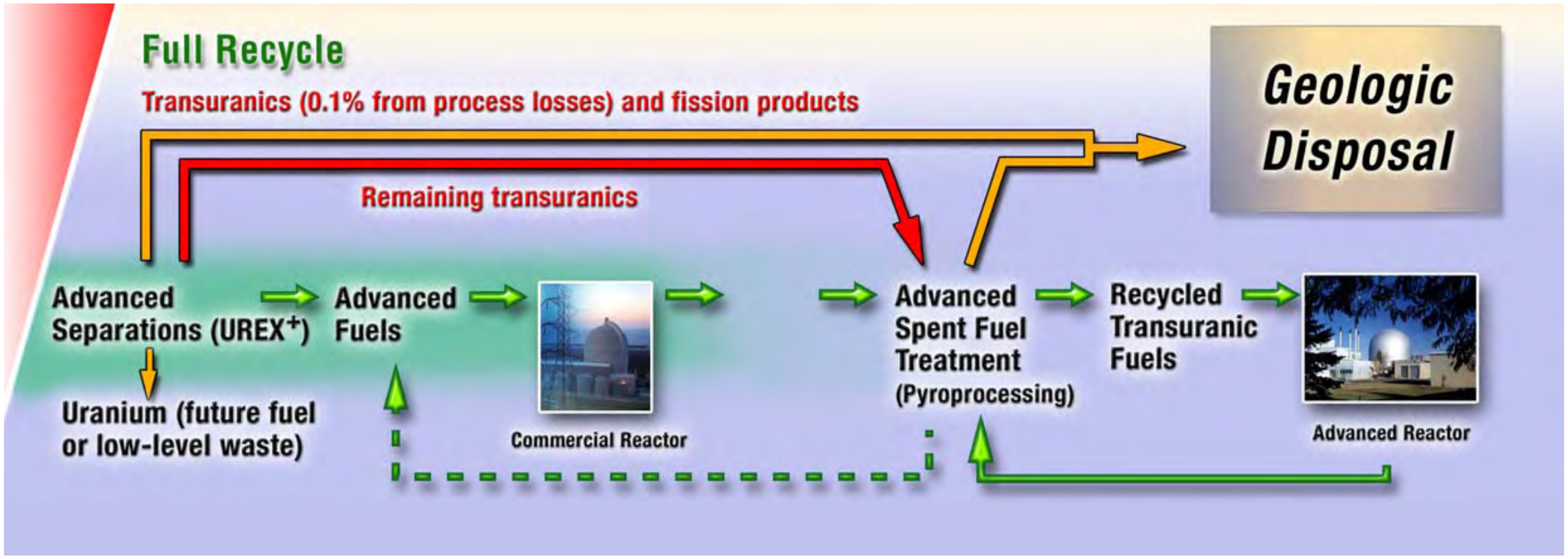
- **The objective of increasing energy production, while reducing the global proliferation risk and environmental impacts, could be achieved with a combination of Light Water Reactors (LWR) and Fast Reactors**

- **Technology choices must be made for:**
  - LWR fuels and LWR fuel separations technologies (if LWR recycle is contemplated)
  - Fast reactor technologies, fast reactor fuels, and fast reactor fuel separations technologies

- **The fuel cycle must be designed as a system, taking into account the following constraints:**
  - Compatibility between technologies
  - Safety of each component
  - Security of each component
  - Feasibility of each component
  - Suitability of waste forms for geologic disposal
  - Cost reduction
  - Infrastructure distribution

Current Developments for Advanced Fuel Cycle Technologies

- **Several nations are proposing a closed fuel cycle that effectively manages spent nuclear fuel to support continued and/or expanding nuclear energy production.**
- **The selection of technologies needed to meet this objective include**
  - Advanced separations for spent fuel (UREX+ and others)
  - Advanced spent fuel treatment (e.g., pyrochemical processing)
  - Advanced reactors to burn the recycled transuranics (burner reactors)



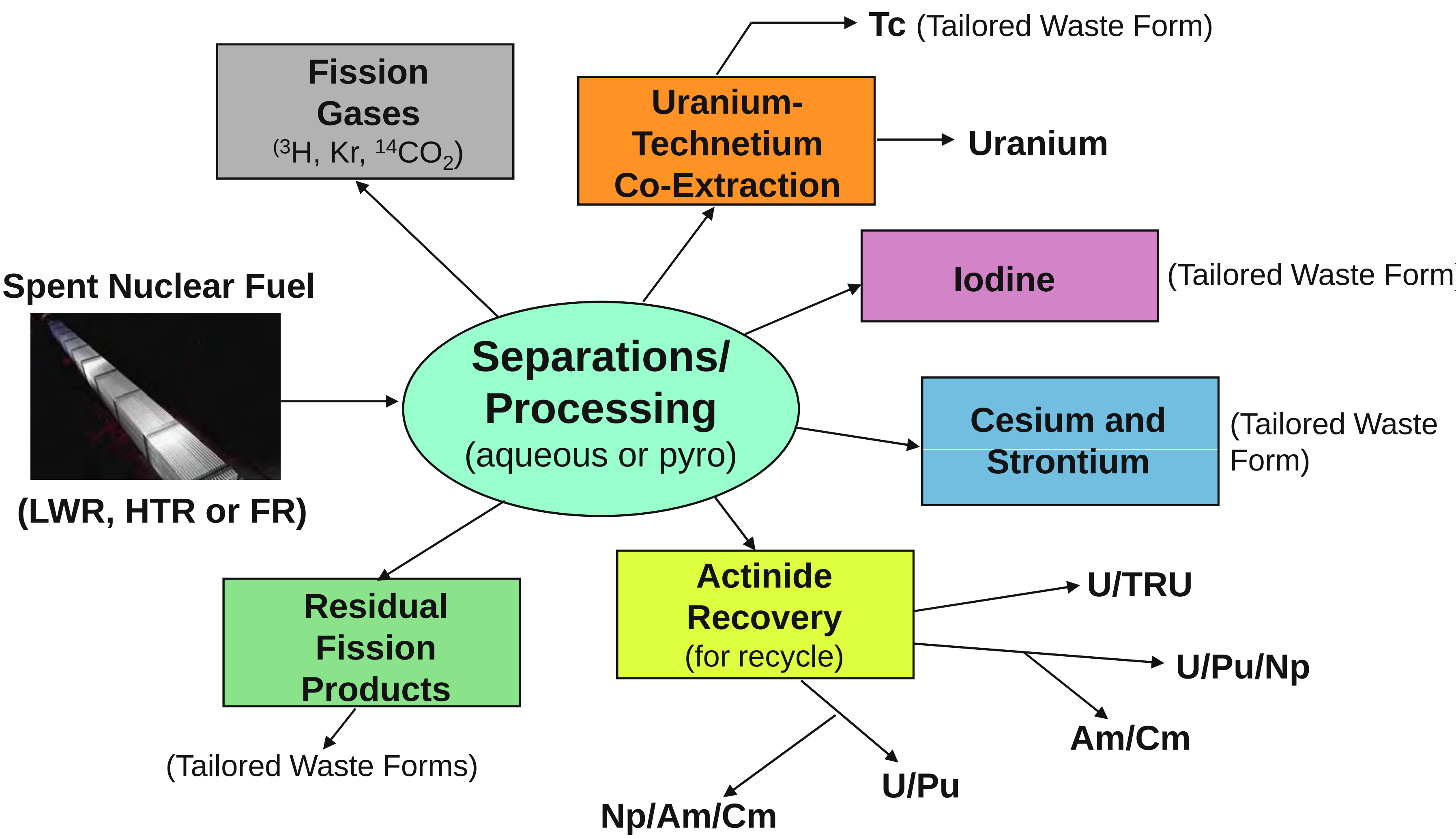
Major Technical Challenges

- **The challenges in developing advanced fuel cycle technologies include:**
  - **Separations**
    - ***Process losses, waste forms, and cost reduction***
  - **Advanced spent fuel treatment**
    - ***Process losses, fuel fabrication, fuel performance, and waste forms***
  - **Burner reactors**
    - ***Cost reduction***
  - **Scale-up is needed to discover and solve industrial issues**

- **A robust basic and applied R&D program is required to improve performance and develop next-generation technologies**

- **Advanced modeling and simulation can transform the design process for advanced nuclear energy systems**

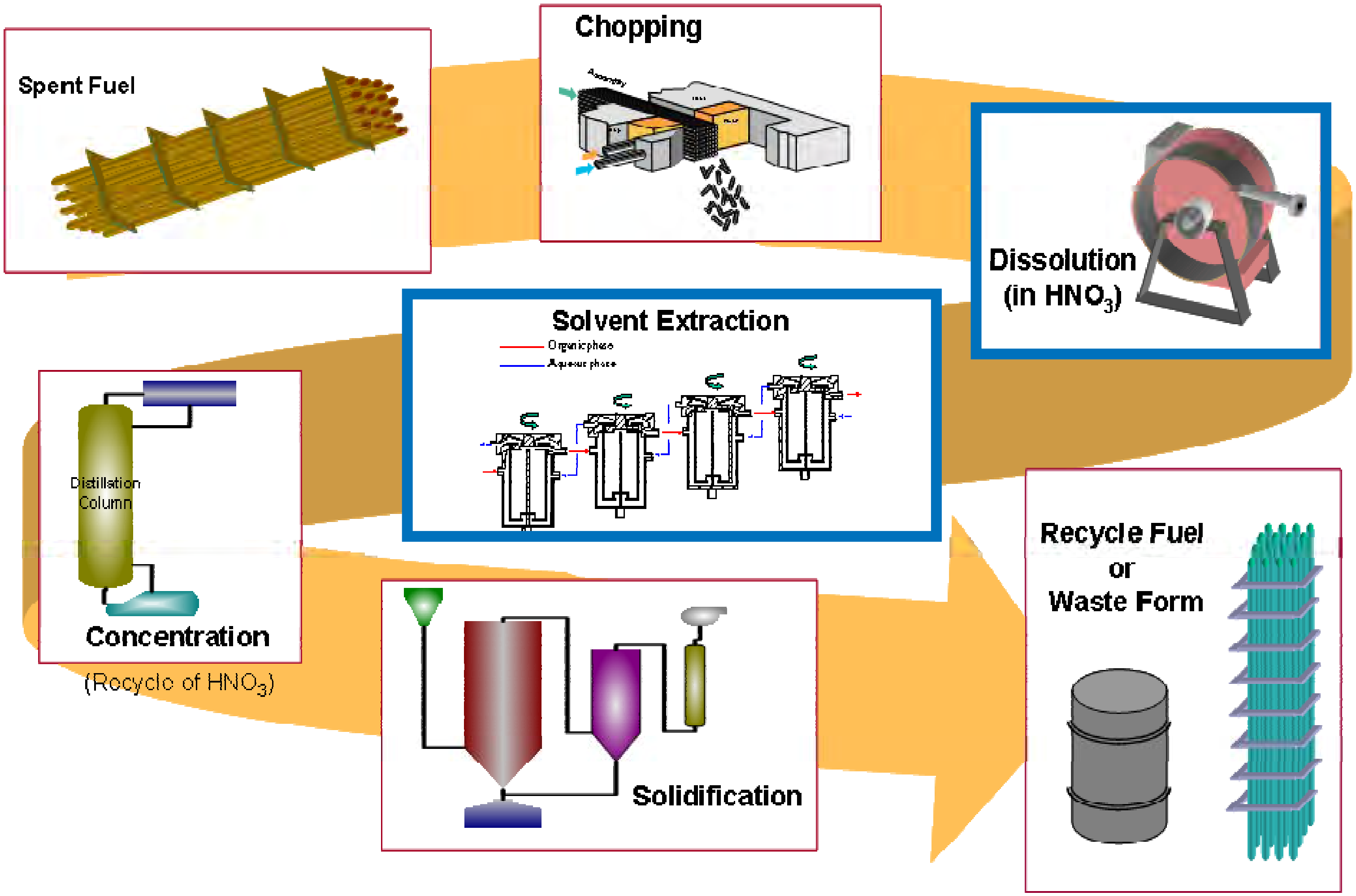
Spent Fuel Processing System Design



Aqueous vs. Pyrochemical Processing

- Pyrochemical processing is the preferred technology for use in processing metallic fast reactor spent fuel; both pyro and aqueous are capable of FR oxide fuel treatment
- Aqueous processing is a relatively mature technology for treatment of LWR spent oxide fuel
  - Pyrochemical processing requires the reduction of oxide fuel to the metallic state, a technology that is at an earlier stage of development
  - Pyrochemical processing is more practical for small-scale collocated plants
- Either process could be applied to HTGR spent fuels
- Hybrid aqueous/pyrochemical processes are being considered
- Aqueous processing of LWR spent fuel has the advantage of providing a diversity of partitioning options

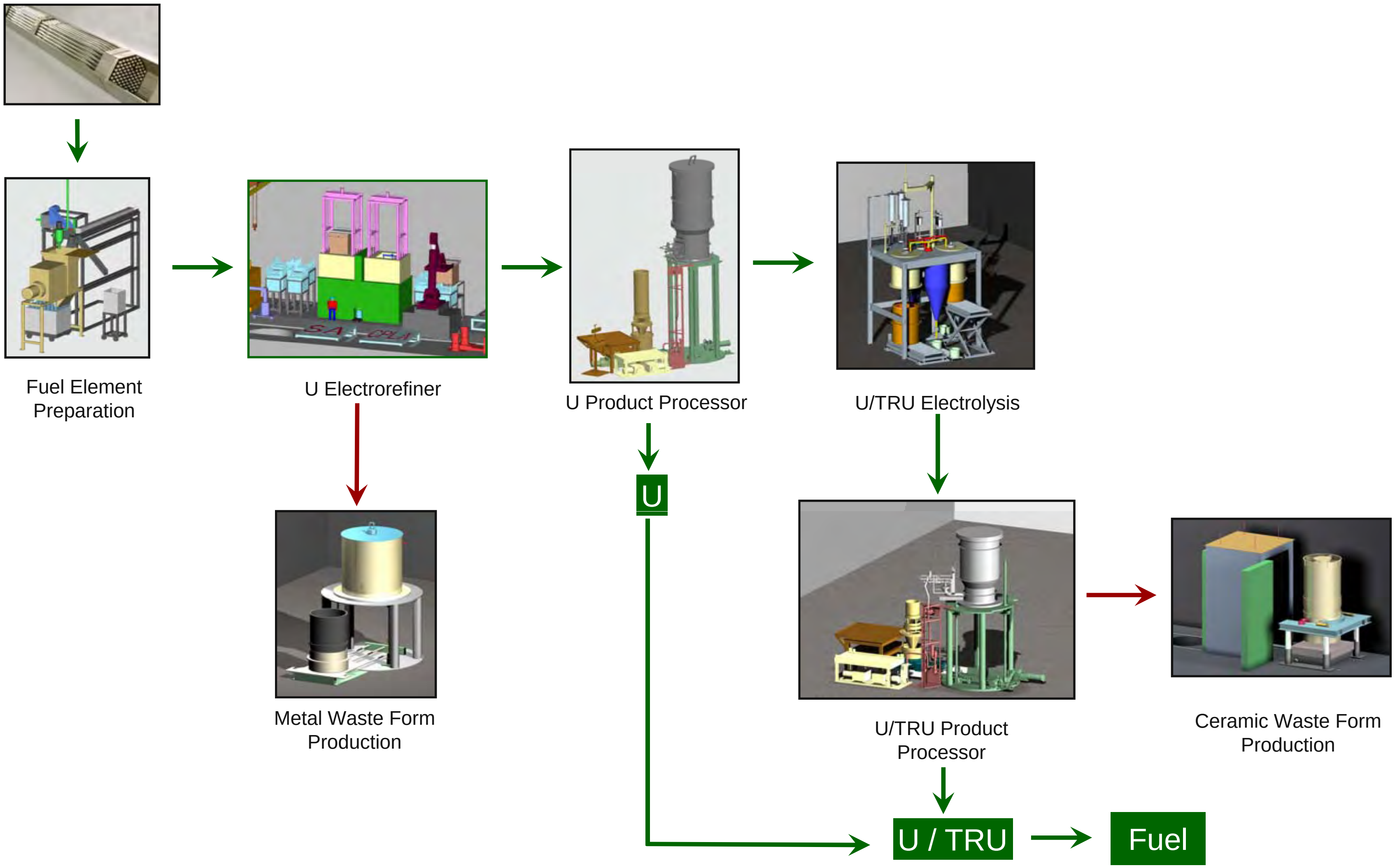
Aqueous Spent Fuel Treatment (UREX+)



Advanced Separations:
Aqueous Spent Fuel Treatment (UREX+)

Process	*1st Product*	*2nd Product*	*3rd Product*	*4th Product*	*5th Product*	*6th Product*	*7th Product*
UREX+1a	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**TRU (group extraction)**		
UREX+2	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**Other FPs**	**Pu+Np (for FR recycle fuel)**	**Am+Cm+Ln (temp. storage)**	
UREX+3a	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**Pu+Np (for FR recycle fuel)**	**Am+Cm (heterogeneous targets)**	
UREX+3b	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**U+Pu+Np (for FR recycle fuel)**	**Am+Cm (heterogeneous targets)**	
UREX+3c	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**U+Pu (for thermal recycle fuel)**	**Am+Np+Cm (heterogeneous targets)**	
UREX+4a	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**U+Pu+Np (for FR recycle fuel)**	**Am (heterogeneous targets)**	**Cm (storage)**
UREX+4b	**U (highly purified)**	**Tc, I (LLFPs, dose issue)**	**Cs,Sr (short-term heat mgmt.)**	**FPs (including lanthanides)**	**U+Pu (for thermal recycle fuel)**	**Am+Np (heterogeneous targets)**	**Cm (storage)**

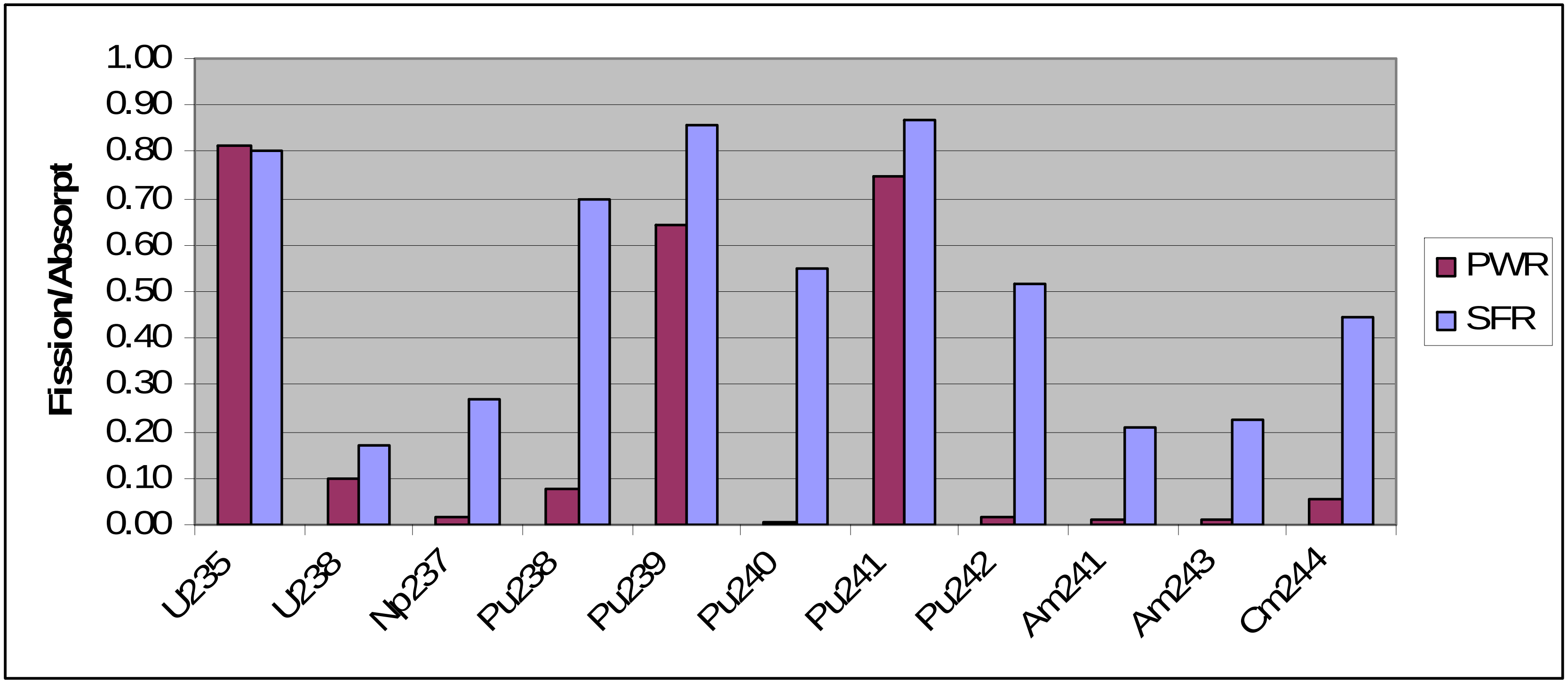
Advanced Separations:
Fast Reactor Fuel Fabrication and Recycle - Pyroprocessing



Actinide Recycling and Transmutation

- Once the desired chemical elements have been recovered, they must be recycled in a suitable reactor for transmutation of hazardous into relatively non-hazardous elements
  - Goal: consumption of these elements by fission into short-lived fission products
- Studies in DOE/AFCI have examined the potential for transmutation in both the thermal and fast neutron spectrum
  - Thermal reactors (today's LWRs) can only effectively fission certain isotopes
    - *Lower neutron energy results in a high probability of neutron capture, causing transmutation into higher actinide elements, some of which are more hazardous*
    - *Thermal reactors can be effectively used for treating plutonium that contains a substantial fraction of fissionable isotopes*
    - *Extensive use of recycle in thermal reactors will require more uranium resources*
  - Fast neutron reactors have a more favorable ratio of fission-to-capture
    - *Much lower probability of neutron capture in favor of fission, where even the higher actinide elements can be effectively fissioned; resolves the waste management issue*
    - *No uranium resource issue*
- Overall result is that fast reactors are best suited for transmutation of most actinide elements

Transmutation Impact of Energy Spectrum



- 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
  - One of the key factors is the behavior of Pu-240

Net result is less higher actinide generation in a fast reactor

Candidate Future Systems
(Generation IV International Forum)

System	Neutron Spectrum	Fuel Cycle	Size	Applications	R&D
Very High Temp. Gas Reactor (VHTR)	*Thermal*	*Open*	*Med*	*Electricity, Hydrogen Production, Process Heat*	*Fuels, Materials, H_2 production*
Supercritical Water Reactor (SCWR)	*Thermal, Fast*	*Open, Closed*	*Large*	*Electricity*	*Materials, Safety*
Gas-Cooled Fast Reactor (GFR)	*Fast*	*Closed*	*Med to Large*	*Electricity, Hydrogen, Actinide Management*	*Fuels, Materials, Safety*
Lead-alloy Cooled Fast Reactor (LFR)	*Fast*	*Closed*	*Small*	*Electricity, Hydrogen Production*	*Fuels, Materials compatibility*
Sodium Cooled Fast Reactor (SFR)	*Fast*	*Closed*	*Med to Large*	*Electricity, Actinide Management*	*Advanced Recycle*
Molten Salt Reactor (MSR)	*Thermal*	*Closed*	*Large*	*Electricity, Hydrogen, Actinide Management*	*Fuel, Fuel treatment, Materials, Safety and Reliability*

Fast Reactor Experience

U.S. Experience

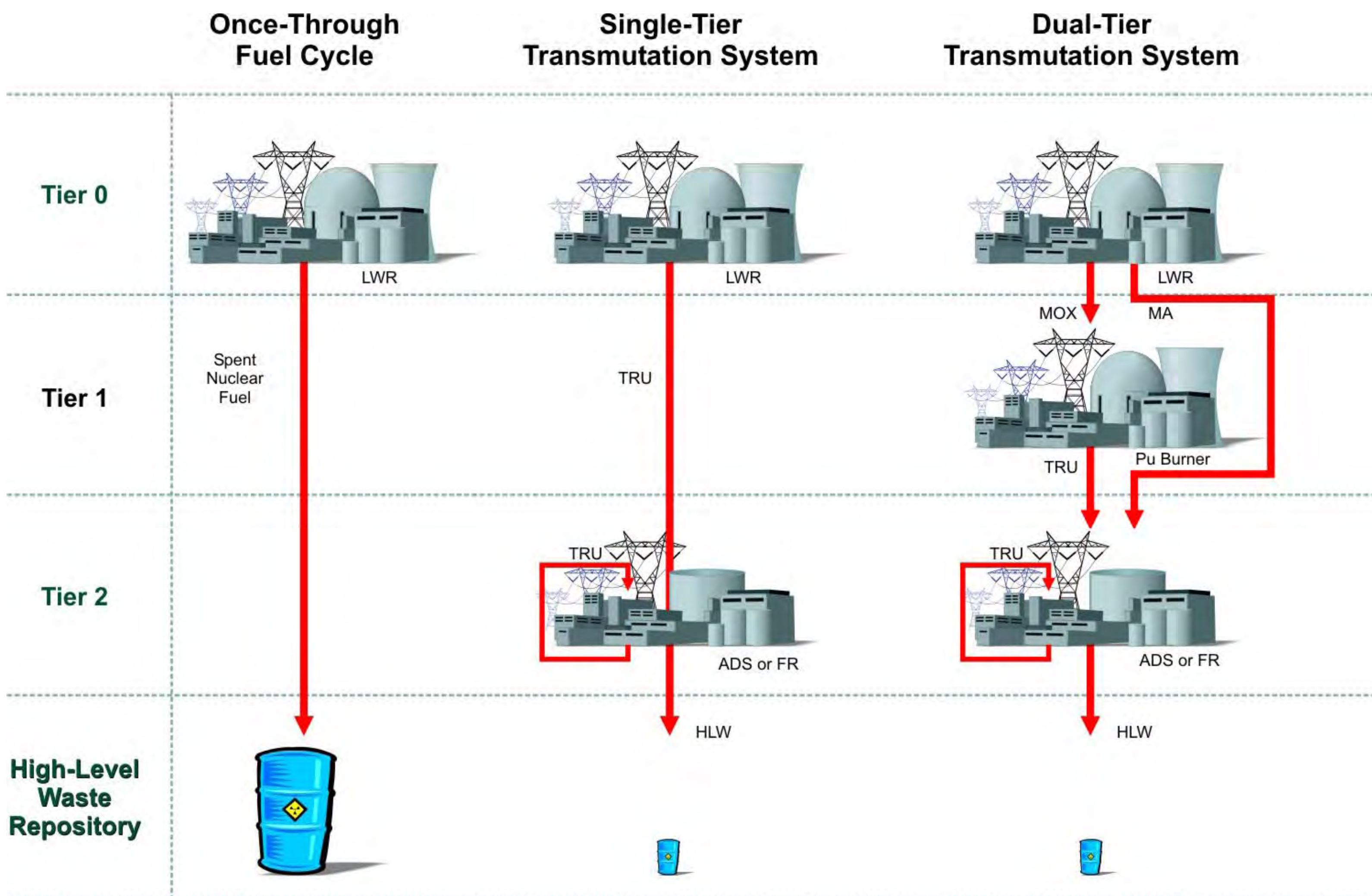
- First usable nuclear electricity generated by a fast reactor – EBR-I in 1951
- EBR-II (20 MWe) operated at Idaho site from 1963 to 1994
  - *Closed fuel cycle demonstration*
  - *Passive safety tests*
- Fast Flux Test Facility (400 MWt) operated 1980–1992

International Experience

- BN-600 power reactor since 1980 at 75% capacity factor
- Operating test reactors: PHENIX (France), BOR-60 (Russia), JOYO (Japan)
- Most recent construction was MONJU (280 MWe) in 1990

Sodium-cooled fast reactor technology has been demonstrated

AFCI Transmutation System Approach



Advanced Fuel Cycles and Integrated Waste Management

- **Only with proper integration can the waste management system be optimized, coordinating separations and processing needs with disposal requirements**
  - Introduction of processing and recycling creates other waste streams not present in the ‘once-through’ approach
    - *Production of other classes of radioactive waste from the operation and maintenance of the facilities*
  - Processing of spent LWR and fast reactor fuel can have a significant favorable impact on the amount of high-level waste produced for a given total energy production
  - Disposal of low-level waste must also be considered in evaluating the overall waste management impact
    - *Processing and recycling will increase the amount of low-level waste compared to the ‘once-through’ approach*
      - Amount of lower level waste needs to be carefully controlled to avoid negative impact on the waste management system
    - *Must ensure that appropriate disposal waste forms and disposal paths exist with sufficient capacity*

Geologic Disposal

- **There is scientific consensus that the disposal of spent nuclear fuel and high-level radioactive waste in deep geologic formations is potentially safe and feasible**
  - Provided that sites are chosen and characterized well, and
  - Provided that the combination of engineered and natural barriers is designed appropriately

- **Geologic systems are considered suitable for radioactive waste disposal because of:**
  - Their stability over long time periods,
  - Their ability to physically and chemically isolate the waste canisters,
  - Their property to limit or significantly retard the release of radionuclides, and
  - Their relative inaccessibility, preventing unintentional or malevolent interventions

Potential World-Wide Geologic Repository Environments

Hydrologic Environment	Rock Type	Key Features	Countries Considering this Option
Unsaturated	Ash-flow tuff	Limited seepage, fluid flow predominantly in fractures, zeolitic units have high sorptivity, oxidizing environment	USA
Saturated	Crystalline rock	Low porosity and permeability, fluid flow predominantly in fractures, reducing environment	Canada, Finland, France, Germany Hungary, Russia, Sweden, S. Korea, Spain, Switzerland,
	Clay	Low permeability, high sorptivity, reducing environment	Belgium, France, Germany, Hungary, Russia, Spain, Switzerland
	Salt	Low-permeability, self-sealing, reducing environment	Germany, USA

The Grand Challenge for Nuclear Waste Disposal

- **Need to understand and predict with sufficient confidence flow and transport processes and performance of materials (engineered and geologic) over geological time scales (at least to a million years), with long-term climate changes and the impact of extreme (disruptive) events (e.g., seismic and volcanic events) taken into account**
  - The longevity of engineered barrier components depends on the quantity and chemistry of fluids in the surrounding natural system

- **Finally, there is a need to establish a sound foundation for model abstraction and stochastic approaches used for performance assessment**

Advanced Fuel Cycles and Geologic Repositories

- **An advanced fuel cycle could allow for an evolution in the designs and operational concepts of geologic repositories**
  - Such a change could simplify the demonstration of repository safety and the requirements for engineered barrier system materials

- **Optimization of a repository design depends on several factors, including**
  - Physical extent of host rock
  - Characteristics of the host rock
  - Inventory and types of wastes that will be disposed
  - Thermal management
  - Waste form volume
  - Long-term repository performance
  - Cost

- **These factors are interdependent with varying levels of significance to repository design optimization**

Advanced Fuel Cycles and Geologic Repositories (cont.)

- **A global nuclear energy enterprise provides the opportunity to address the challenges of geologic repository development and waste management at an unprecedented level**

- **Efforts can explore many challenging aspects of waste management in more detail including**
  - Regional repositories
  - Take-back

A Science-Based Engineering Approach to Understanding Waste Form Durability and Repository Performance

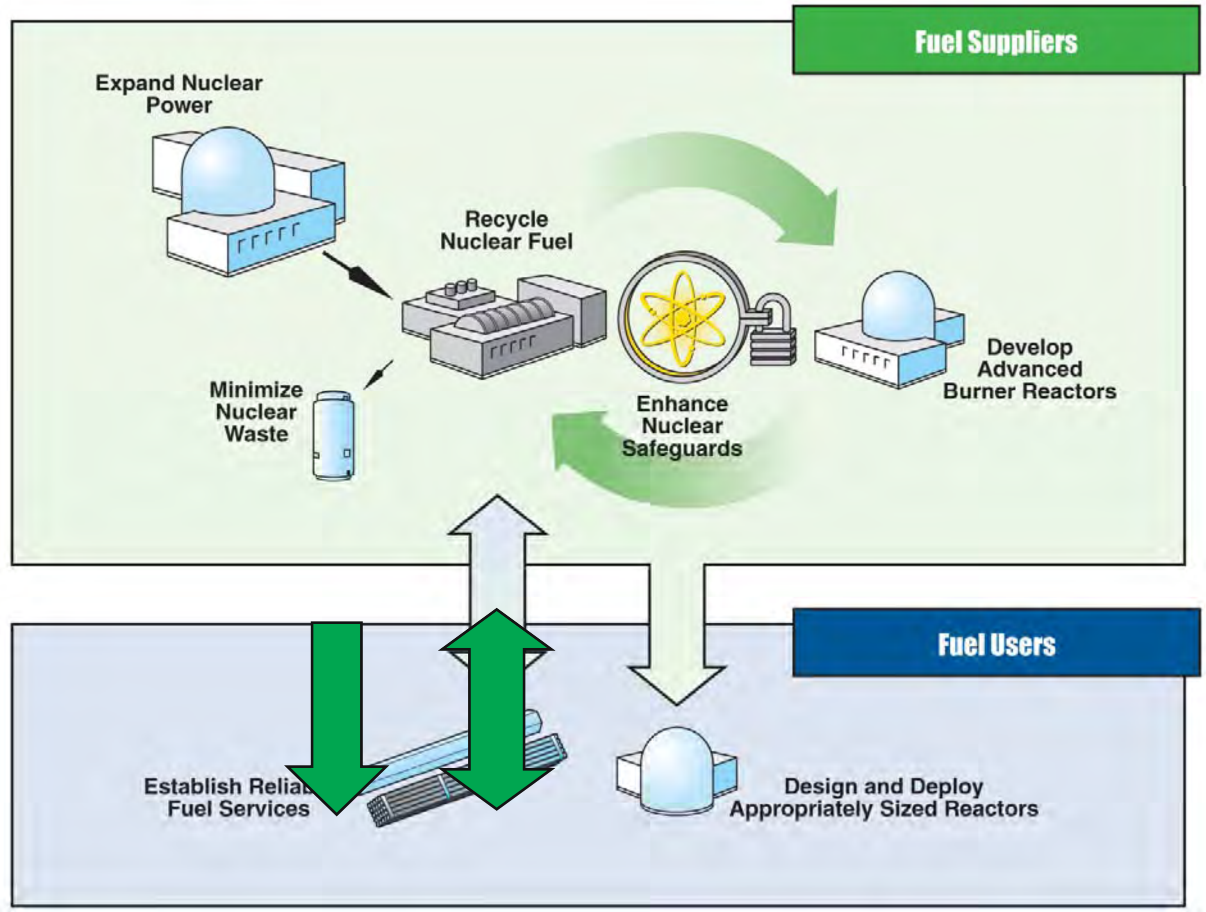
- **An integrated science and technology program – systems analyses, experiments, modeling and simulation**

- **Future Directions**
  - Development of advanced, more durable, tailored waste forms
  - Enhanced understanding of geologic repository performance
  - Systems optimization of repository design
  - Systems-level optimization of advanced fuel cycles
  - Development of advanced geologic disposal concepts in a range of geologic settings and geochemical environments

Questions and Discussion

Backup

An International Fuel Service is an Essential Part of Reducing Proliferation Risk

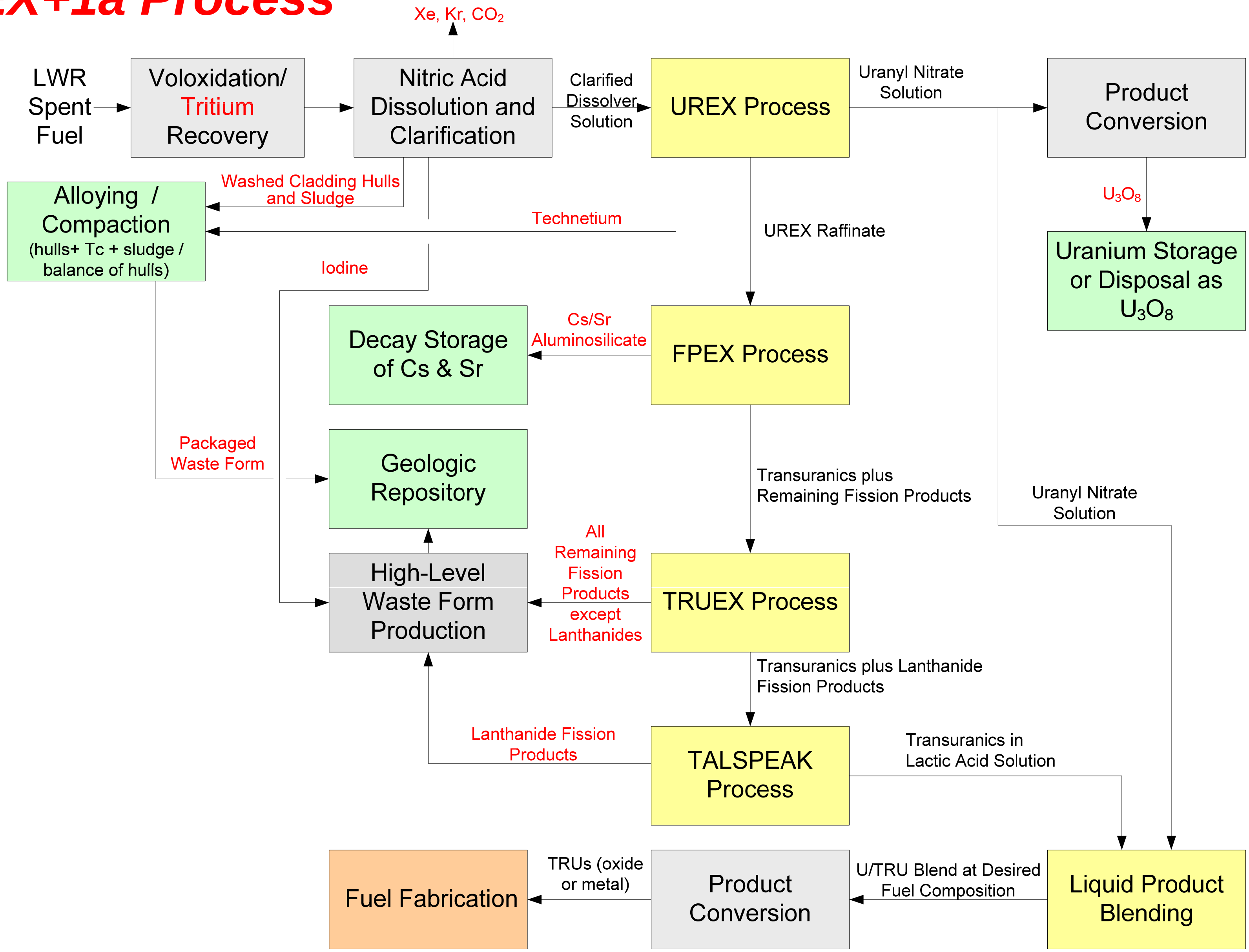


- **<u>Fuel Suppliers</u>**: operate reactors and fuel cycle facilities, including fast reactors to transmute the actinides from spent fuel into less toxic materials

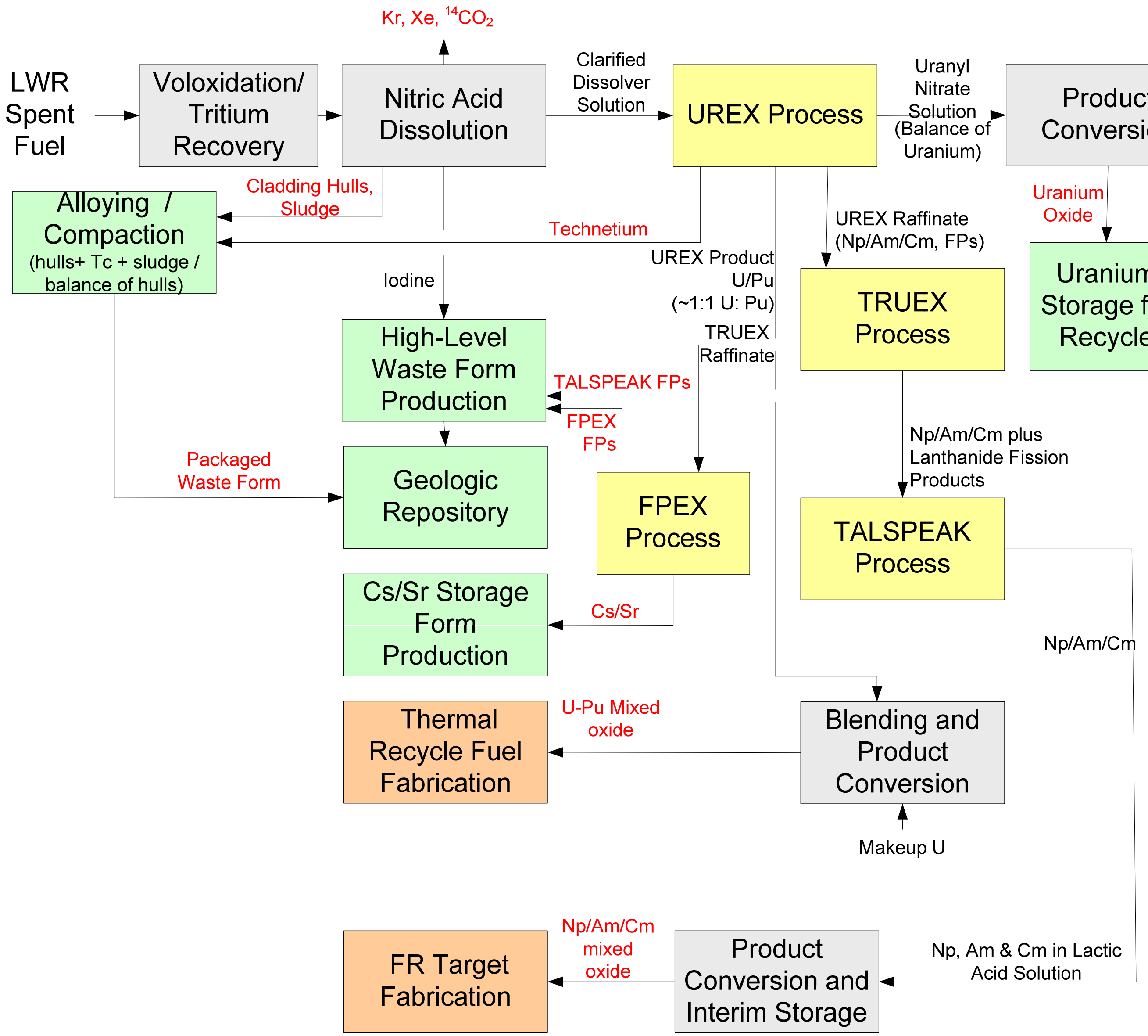
- **<u>Fuel Users</u>**: operate reactors, lease and return fuel

- **<u>IAEA</u>**: provide safeguards and fuel assurances, backed up with a reserve of nuclear fuel for states that do not pursue enrichment and reprocessing

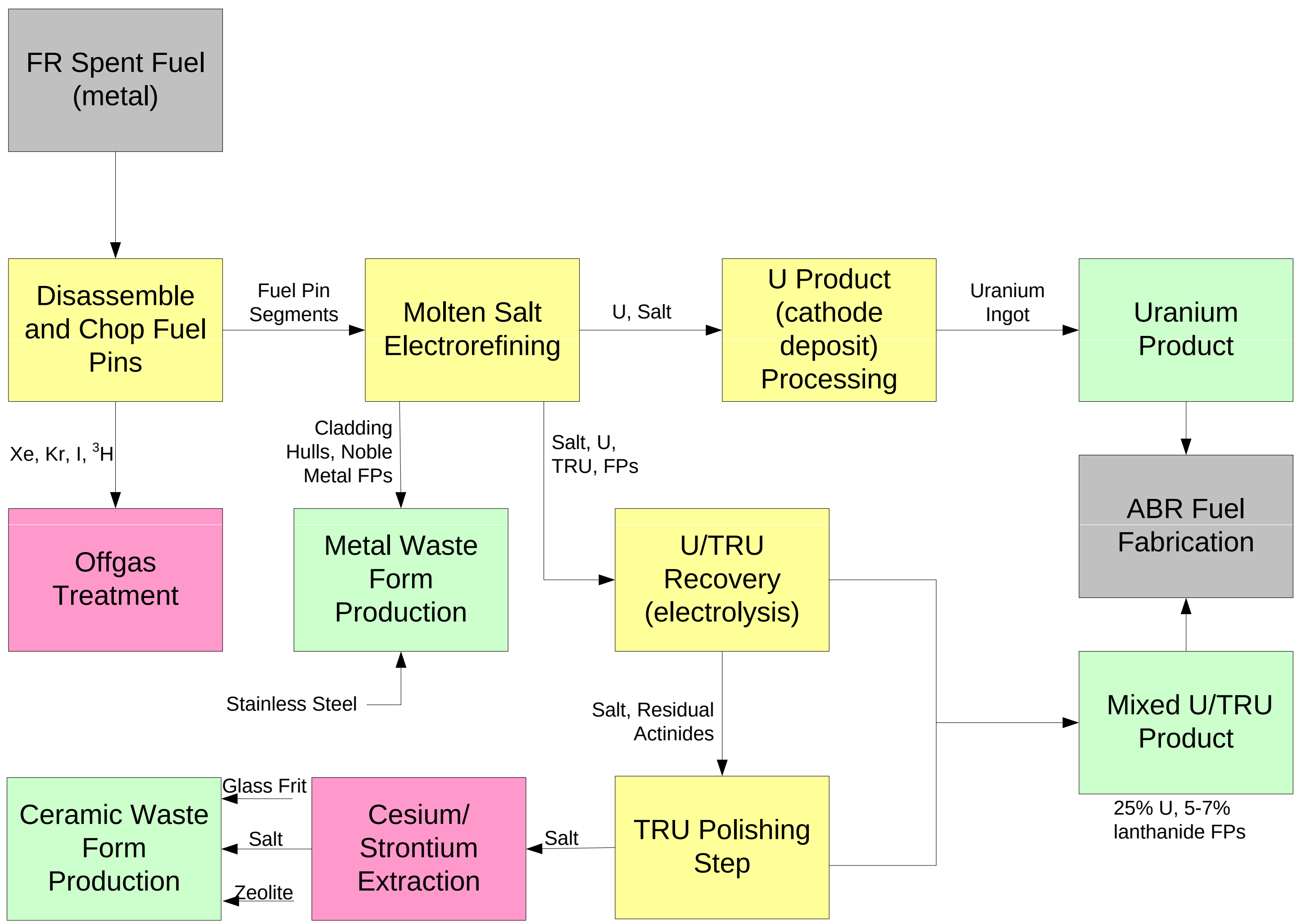
UREX+1a Process



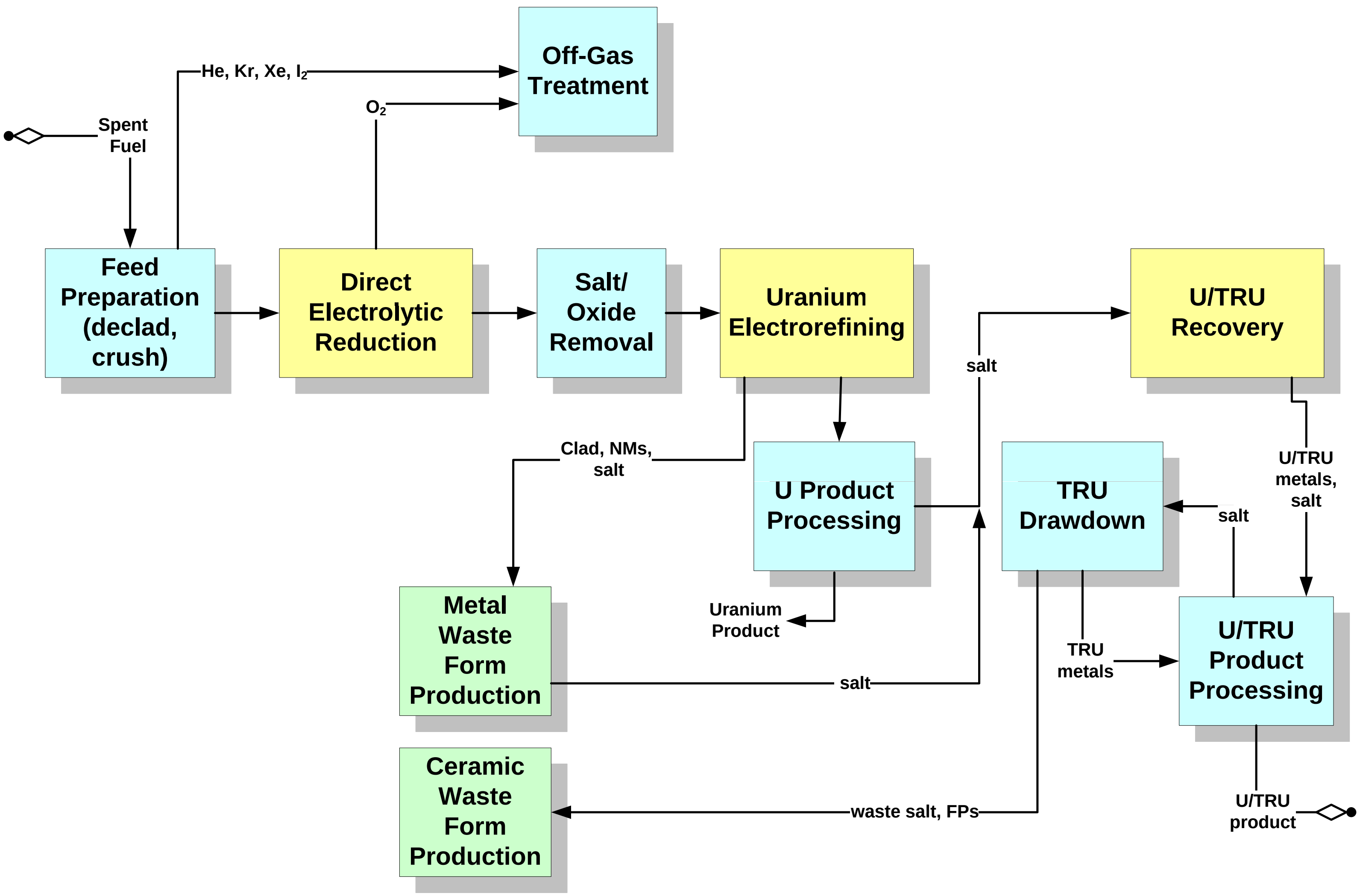
UREX+3c Process



Pyrochemical Processing of FR Metal Fuel



PYROX Flowsheet for Oxide Fuel



Reactor Characteristics

	VHTR	SCWR	GFR	LFR	SFR
Power, MW_{th}	600-600 (block) ~300 (pebble)	~2000-3600	600, 2400	25-400	600-3500
Power Density, W/cm^3	≤ 6.5	≤ 70	100 (50-200)	25-100	200-400
Primary Coolant (T_{outlet}, °C)	He (1000) Molten Salt?	SC H_2O (450-500)	He (800-850) SC CO_2	Pb (500-800) Pb-Bi (500-550)	Na (510-550)
Fuel Material	UO_2, $UC_{0.5}O_{1.5}$	UO_2	(U,TRU) carbide, nitride, oxide	(U,TRU) nitride	(U,TRU) oxide, metal alloy
Fuel Form	Triso particle	solid pellet	CerCer dispersion, solid solution, coated particle	solid pellet	pellet or slug
Fuel Element/ Assembly	hex block, pebble	LWR or ACR type pin bundle	hex block, plate, pin, or particle	triangular pitch pin bundle	triangular pitch pin bundle w/duct
Moderator	graphite	water rods (PV) D_2O (PT)	None	None	None
Core Structural Material	graphite	F-M SS, Ni alloy	SiC matrix or cladding, TiN, ODS steel	F-M SS, SiC/SiC composite	ODS ferritic steel

Transmutation Implications of Thermal vs. Fast Physics

- Fast systems are more “efficient” in destroying actinides because fewer neutrons lost to capture reactions
  - Superior neutron balance for actinide destruction
  - Less generation of higher actinides
- However, fissile reactions are favored at thermal energies
  - Pu239f/U238c ratio is ~100 in thermal, 8 in fast
  - Despite an inferior neutron balance for the individual isotopes, *thermal reactors can operate on much lower enrichment fuel*
- Based on these differences, thermal reactors are typically configured for LEU utilization in once-through (open) fuel cycle
  - Improved behavior by high thermal efficiency and burnup
- Conversely, fast reactors are typically intended for closed fuel cycle with uranium conversion and resource extension
  - Alternate TRU burners designs have been developed

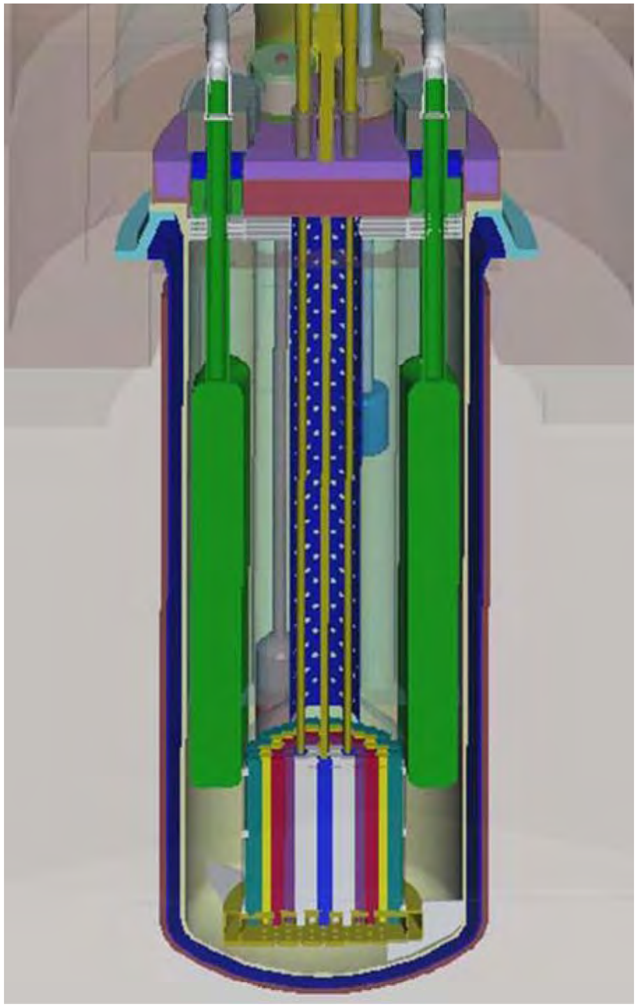
Multi-recycle in LWRs

- Significant research on multi-recycle in conventional LWRs has been conducted recently both in AFCI and internationally (e.g., CEA)
- Continuous recycle can be achieved within <u>two</u> important constraints:
  - An external fissile "support" feed is required
    - Neutron balance of TRU not sufficient to sustain criticality
    - Standard 5% LEU pins or fuel mix can provide support
  - A technique to manage higher actinide buildup is required
    - Initial recycles may be possible, but neutron source from very high actinides (e.g., Cf-252) becomes fuel handling problem
    - Long cooling time approach can mitigate
    - Separation/storage of curium prevents higher actinide generation
- Safety impact of TRU containing fuels must also be considered
  - May limit fraction of core loading, particularly for current LWRs
- Thermal recycle will be limited by practical constraints related to fuel handling that get progressively more difficult each recycle
- Fast reactors provide a more attractive alternative

Fast Reactor with Closed Fuel Cycle Was Key to Conception of Nuclear Power

Fermi	**The vision to "close" the fuel cycle**
1950s	**First electricity-generating reactor: EBR-I with a vision to "close" the fuel cycle for resource extension**
1960s-1970s	**Expected uranium scarcity – significant fast reactor programs**
1980s	**Decline of nuclear – uranium plentiful – two paths:** – USA (and others): once through cycle and repository – France, Japan (and others): limited recycle to mitigate and delay waste disposal
Late 1990s	**Rebirth of closed cycle research and development for improved waste management (USA)**
Now	**Long-term energy security and the role of nuclear**

Advanced Reactor: Sodium-cooled Fast Burner



- Basic viability of sodium-cooled fast reactor technology has been demonstrated
- Low pressure primary coolant
  - Outlet temperature of 500-550^{o}C
- Pool configuration
  - Pumps and heat exchangers contained
  - Loop configurations favored by Japan
- Heat exchanged to secondary coolant for energy conversion system
  - Rankine steam generator or supercritical CO_2 Brayton
- High power density core
  - 250 kW/l (vs. 75 kW/l for LWR)
  - High fuel enrichment (>20% fissile)
- Passive decay heat removal
  - Either from pool heat exchangers or air cooling of reactor vessel
- Favorable inherent safety behavior

Science-Based Engineering

- **We must continue to address the challenges of public perception and acceptance and economics to enable sustainable nuclear energy. Again, these challenges include:**
    - Reactor safety
    - Domestic nuclear waste disposal
    - International nonproliferation
    - The role of nuclear energy in addressing global warming

- **We should be adopting a modern science and simulation-based engineering approach**
  – Nuclear engineering must transition to a modern science and computations-based discipline
    - High fidelity (science-based) integrated simulations must form the core of the design efforts and allow for rapid prototyping
    - Science-based, validated modeling at both the detailed (small-scale) and systems-level must be part of the core capabilities
    - The field must generate internal technical excitement to attract the “best and the brightest”
    - The National Laboratories must establish long-term partnerships with industry in order to translate present and future advances in science-based simulations to industrial practice

Science-Based Engineering (cont.)
Thermal-Hydraulics, Neutronics, and Coupling