The Abdus Salam International Centre for Theoretical Physics

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Joint ICTP-IAEA School of Nuclear Energy Management

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Spent Fuel Management

Alexander V. Bychkov
IAEA, Vienna
Austria

IAEA

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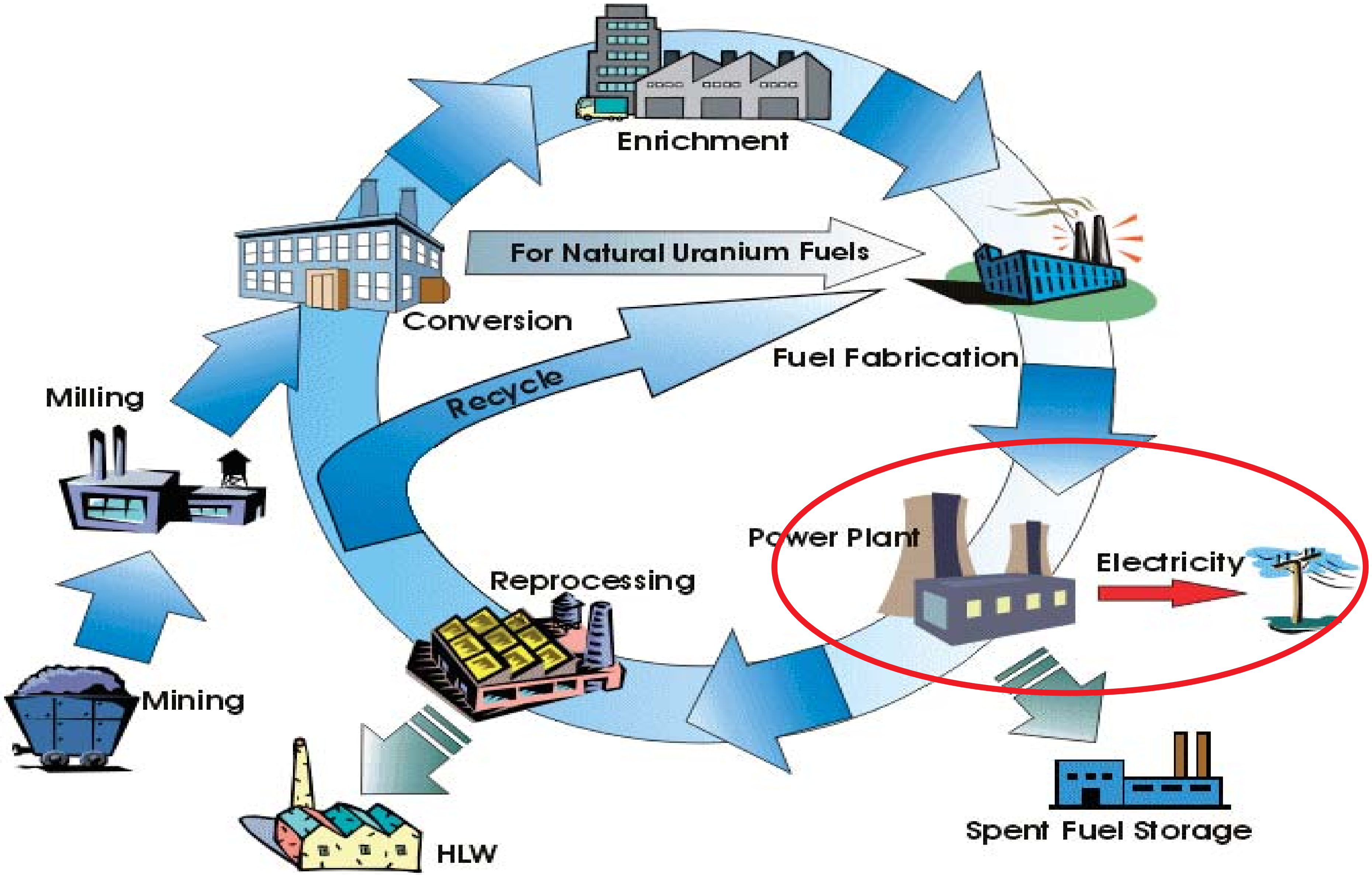
The Nuclear Fuel Cycle: Spent Fuel Management

Alexander Bychkov

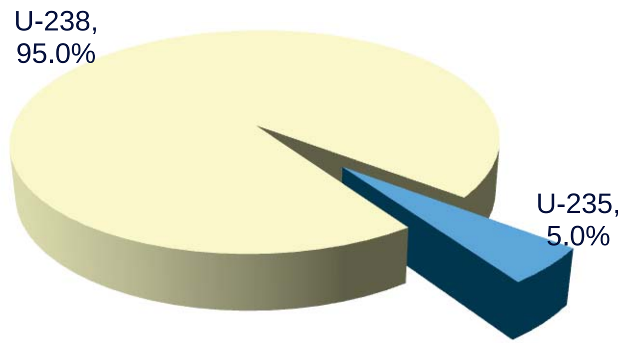
DDG-NE

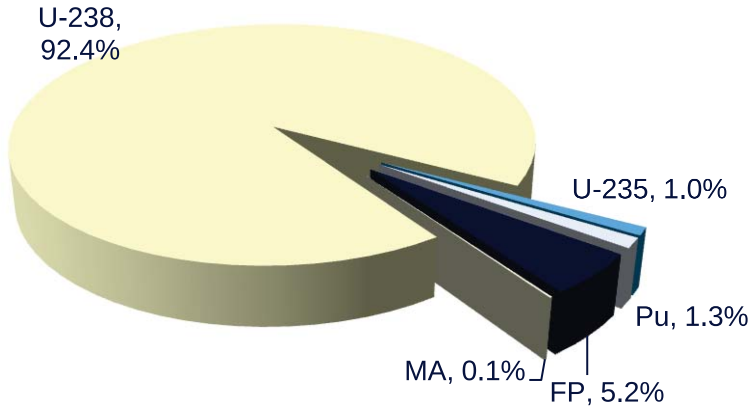
Nuclear Fuel Cycle



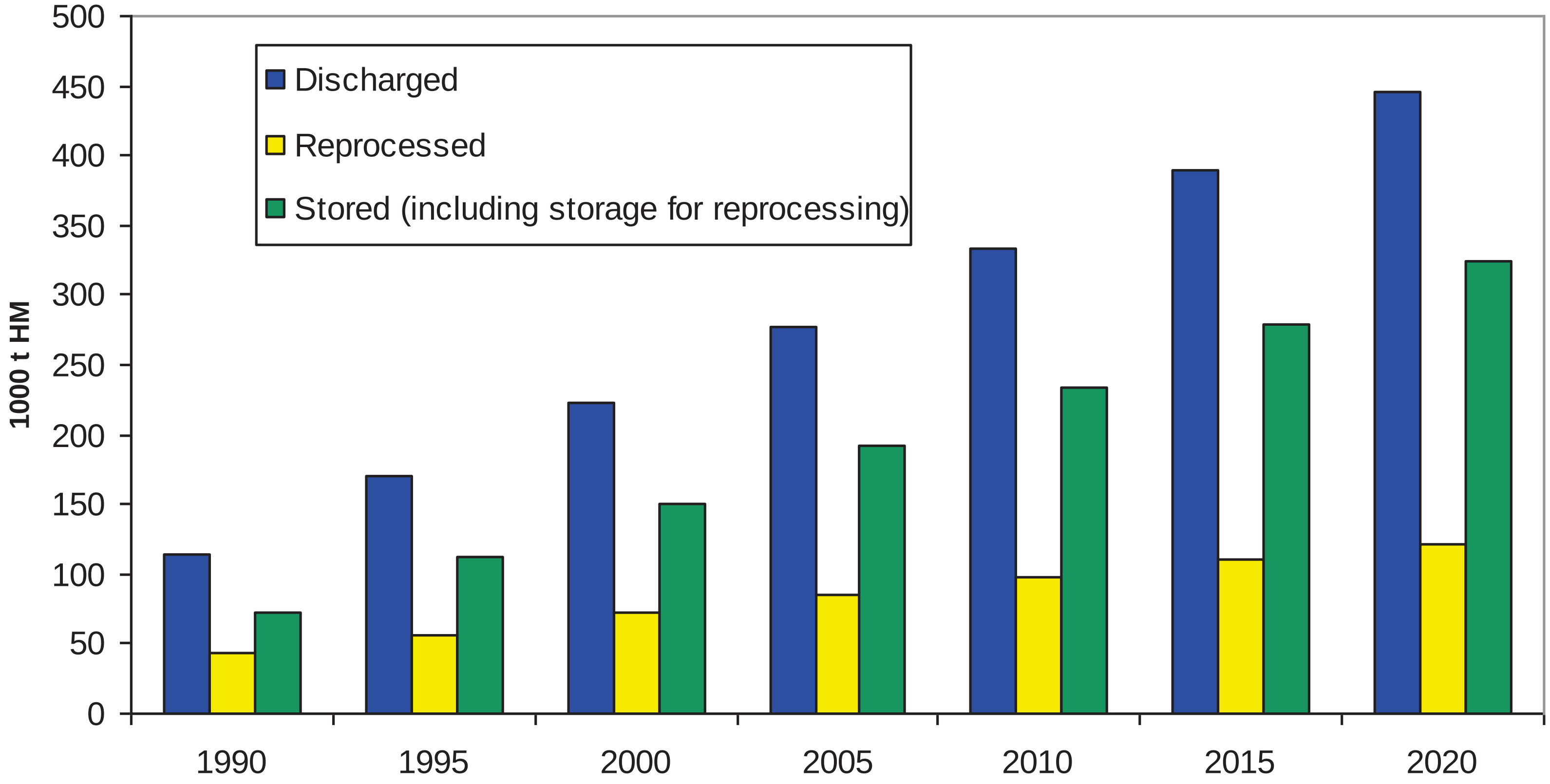
Summary of the Presentation

- Uranium Production
- Conversion
- Enrichment
- Reactor Fuel Fabrication
- In-Reactor Fission
  - (change in composition)
- **Spent Fuel Management**
- **Spent Fuel Recycle**
- **Disposal**



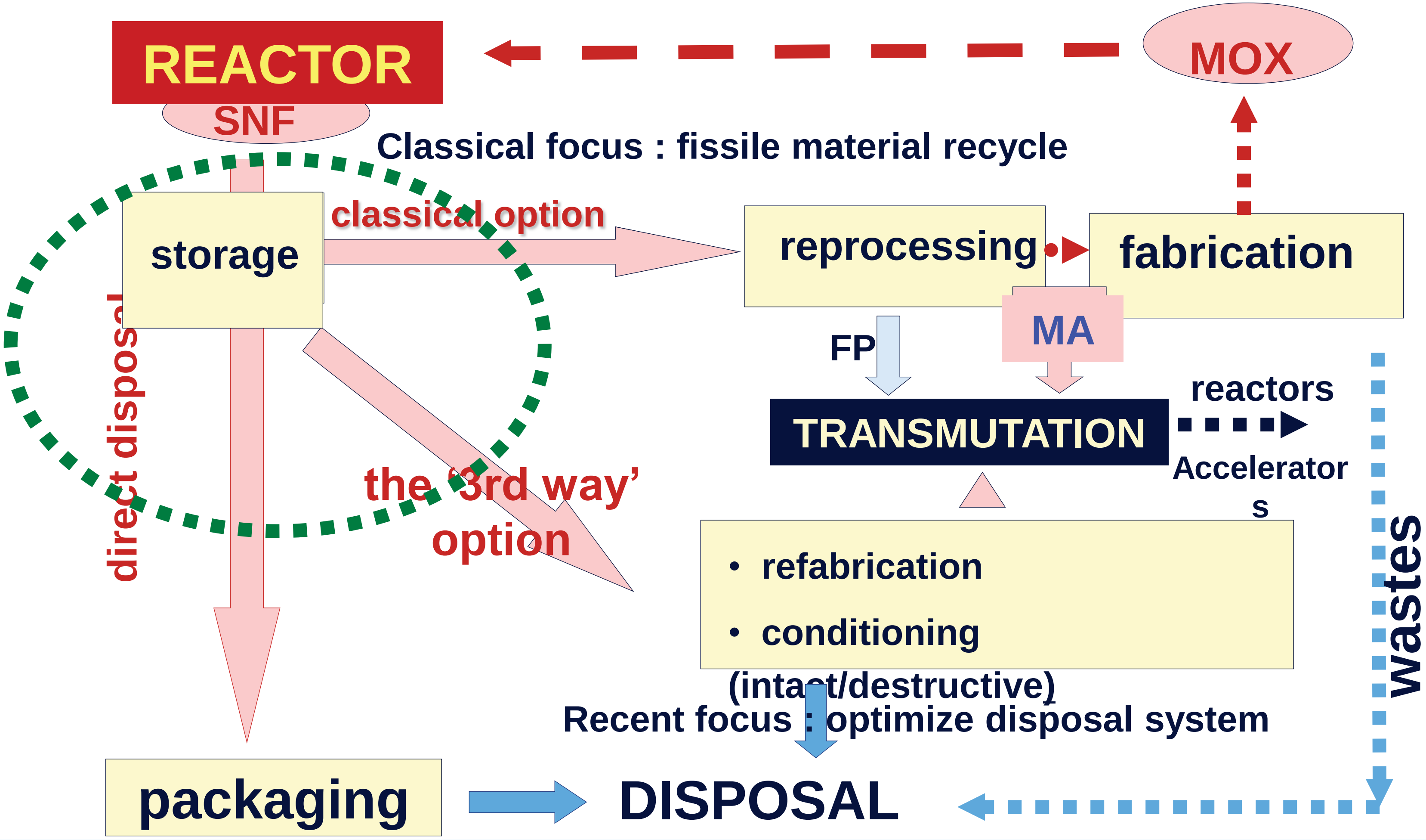


Status of Spent Nuclear Fuel



- **The total amount of spent fuel that has been discharged globally is approximately 334 500 tonnes of heavy metal (t HM).**
- **The annual discharges of spent fuel from the world's power reactors total about 10 500 tHM per year.**

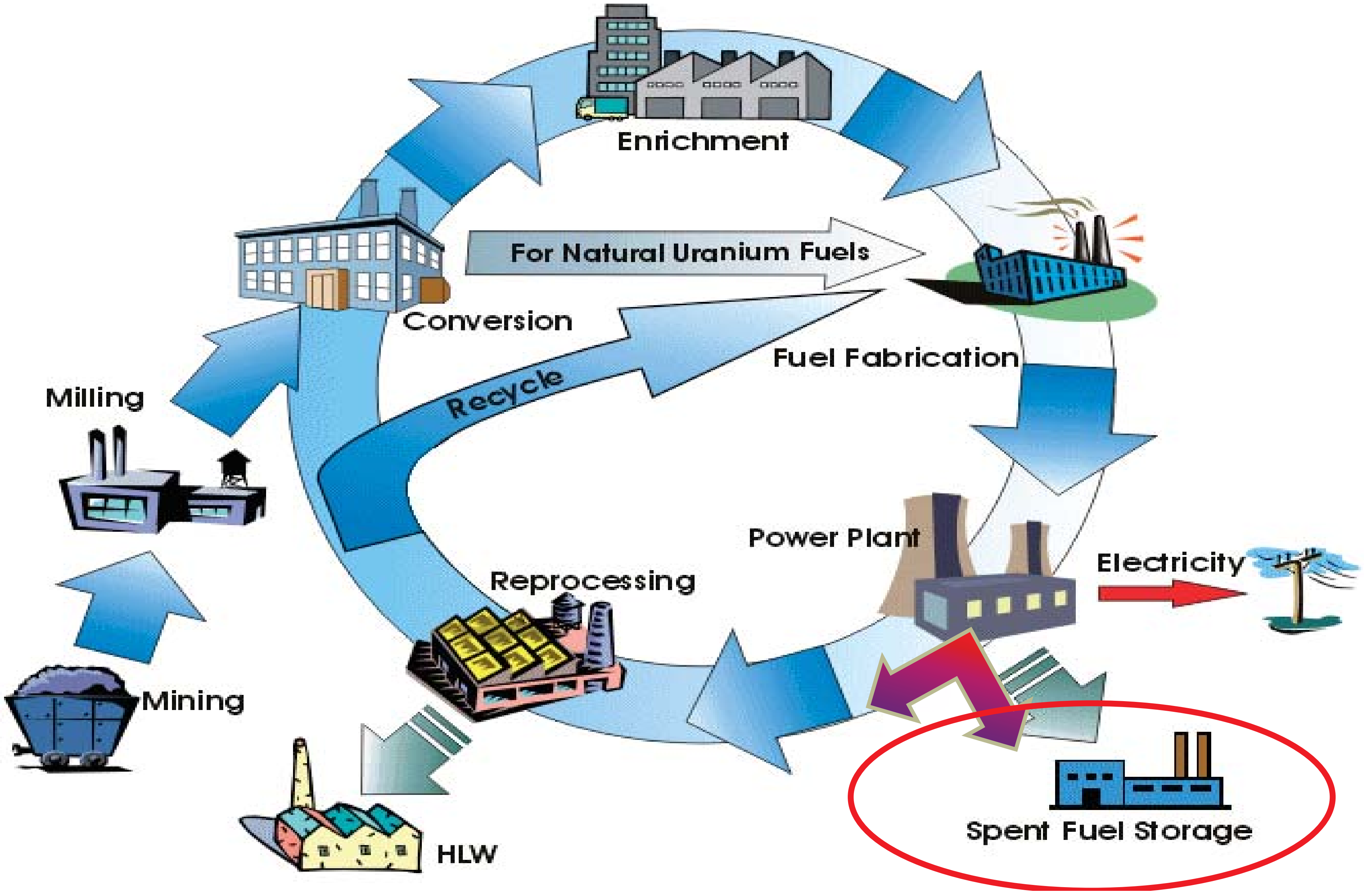
Spent Fuel Management Options



Challenges - Spent Fuel Management

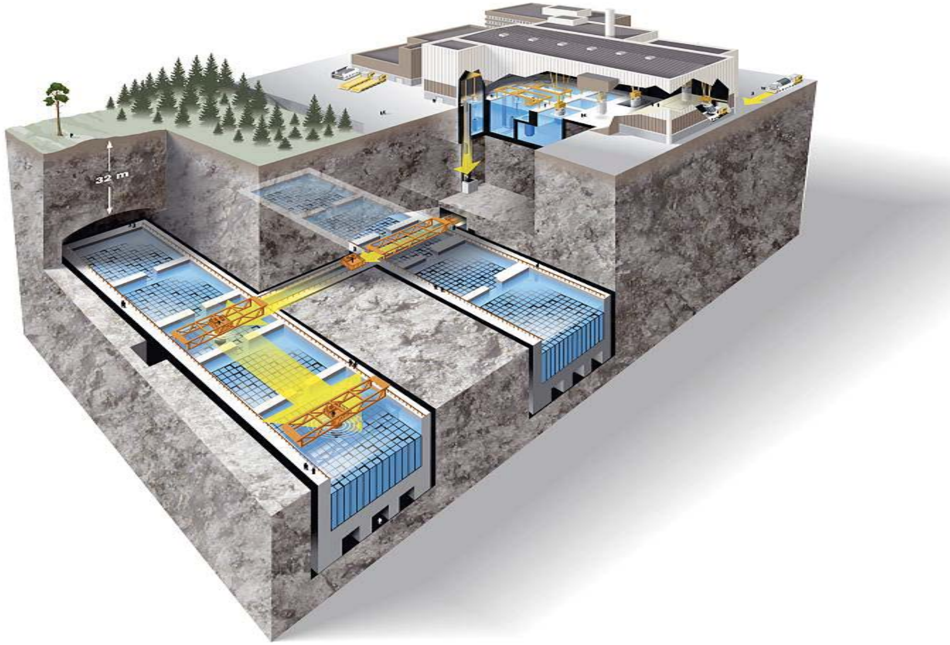
- **Strategy for spent fuel management – resource or waste;**
- **Long term storage becoming a progressive reality…storage durations up to 100 years and even beyond possible;**
- **Use of MOX and higher enrichment/burnup lead to higher decay heat levels and more brittle fuel;**
- **License extensions for existing facilities.**

Nuclear Fuel Cycle



Spent Fuel Storage

- **Wet and dry storage have provided flexibility for spent fuel management**



Wet Storage (CLAB-Sweden)

Dry Storage (Surry – USA)

Interim Storage technologies

2 technologies

Wet Interim Storage

Dry Interim Storage

- Spent fuel storage pool
- Spent fuel stored inside racks

- Metallic casks:
  - Dual-purpose casks
  - Passive system, and independent to the plant
  - Germany, Belgium, Switzerland, Spain, Japan, USA
- Canister systems:
  - The fuel is stored in a metallic canister, stored inside an overpack
  - To transport the fuel, the canister is inserted in a transport cask
  - Passive system, and independent to the plant
  - USA, Spain, Republic of Armenia

At Reactor / Away From Reactor Storage

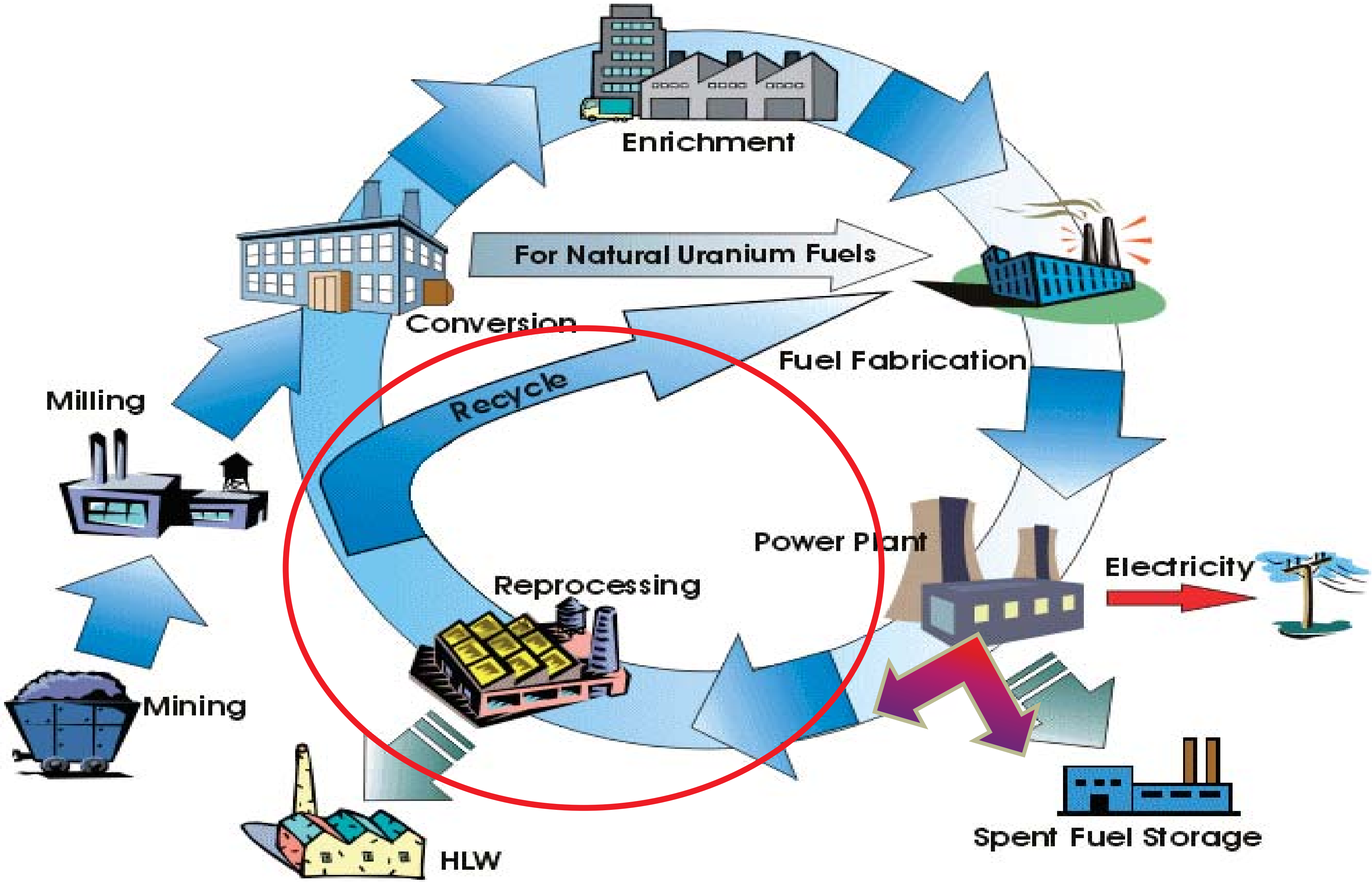
- The AR option has lower costs that the AFR one
  - For capacity below 300 tU, the AFR option is not convenient because the cost is very high
  - For capacity over 1000 tU, the AR option may not be adequate
- In the AFR option, the wet storage technologies present higher costs that the dry storage solutions
  - The dry storage solutions offer a modular approach that has a positive effect on financing costs

	AR Storage	AFR Storage
Advantages	•No additional siting •Less Transportation	•Centralized protection
Drawbacks	•Public acceptance •NPP Decommission	•Additional siting/licensing •More Transportation

Integrity of Spent Fuel in Dry Storage

- **The use of an inert atmosphere has been implemented to protect against oxidation.**
- **Creep under normal conditions of storage will not cause gross rupture of the cladding, provided that the maximum cladding temperature does not exceed 400˚C.**
- **As the combination of SCC agent and stress conditions required for crack propagation are normally absent, it can be concluded that cladding failure via SCC is not expected to occur.**
- **DHC is not expected to be an active degradation mechanism in cladding tubes, given that the cladding does not appear to have enough wall thickness to generate much tri-axial stress.**
- **Hydride re-orientation and hydrogen migration are unlikely to result in failures.**
  - the potential to impair the ability of the cladding to withstand potential mechanical challenges resulting from handling or transportation accidents.

Nuclear Fuel Cycle



Spent Fuel Recycle

When is waste not waste?

When it is valuable.

REPROCESSING AS AN OPTION FOR SFM

- **EVOLUTION OF PURPOSE**
  - ***PAST** : The classical option for spent fuel management (to recover fissile materials for recycle as MOX, especially in FBR)*
  - ***PRESENT**: A fraction of spent fuel inventory recycled to thermal reactors (mainly in LWR)*
  - ***FUTURE** : Anticipation for innovative nuclear systems, P&T,etc*

- **INDUSTRIAL MATURITY**
  - *Currently, the only industrially available option (~1/3 of global inventory of spent fuel being reprocessed)*
  - *Technical and/or infrastructural base for future applications to other futuristic options (i.e., P&T)*

The Case for Recycling

Front-End benefits
- **Uranium savings**
- **Energy security**

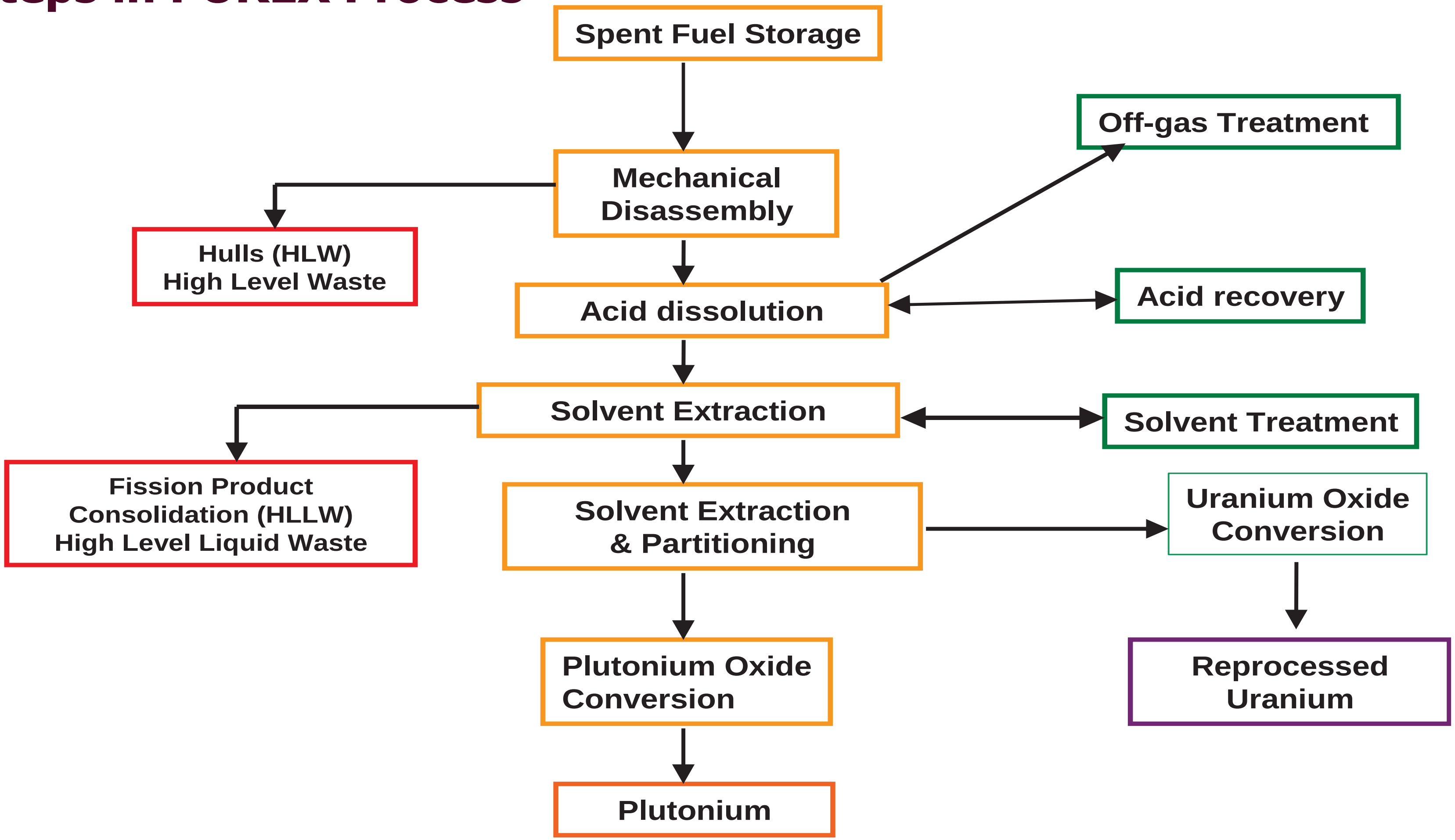
Competitive and predictable economics

Back-End benefits
- **Optimizes final repository**
  - Volume
  - Decay heat
  - Radiotoxicity
  - Standardized waste forms
- **Introduces long-term storage as a viable complement: flexibility in repository timing**

Nuclear acceptance

Spent Fuel Recycle

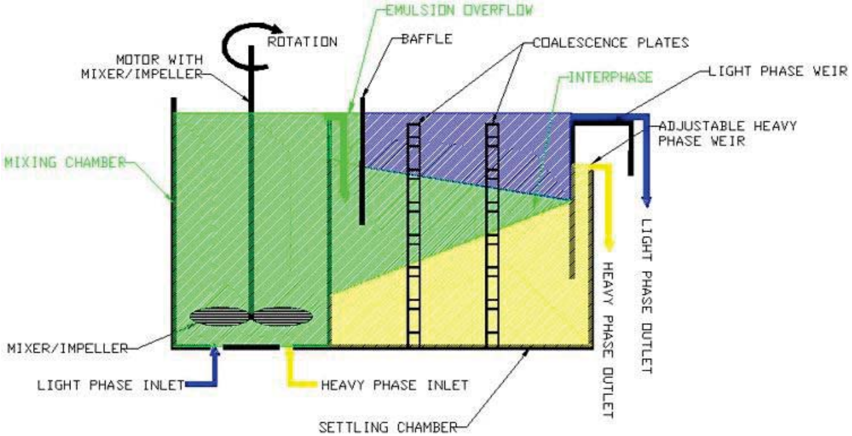
Main Steps in PUREX Process



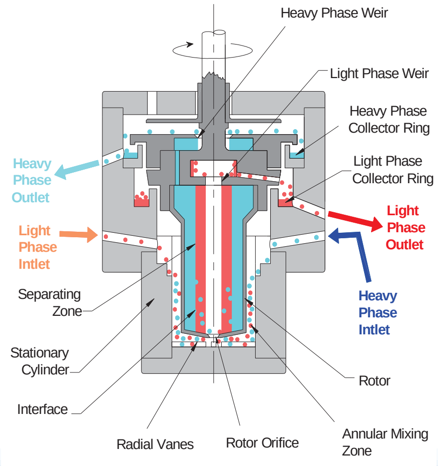
Fuel Recycle: Aqueous

- **Pulsed columns**

- **Mixer-settlers**



- **Centrifugal contactors**



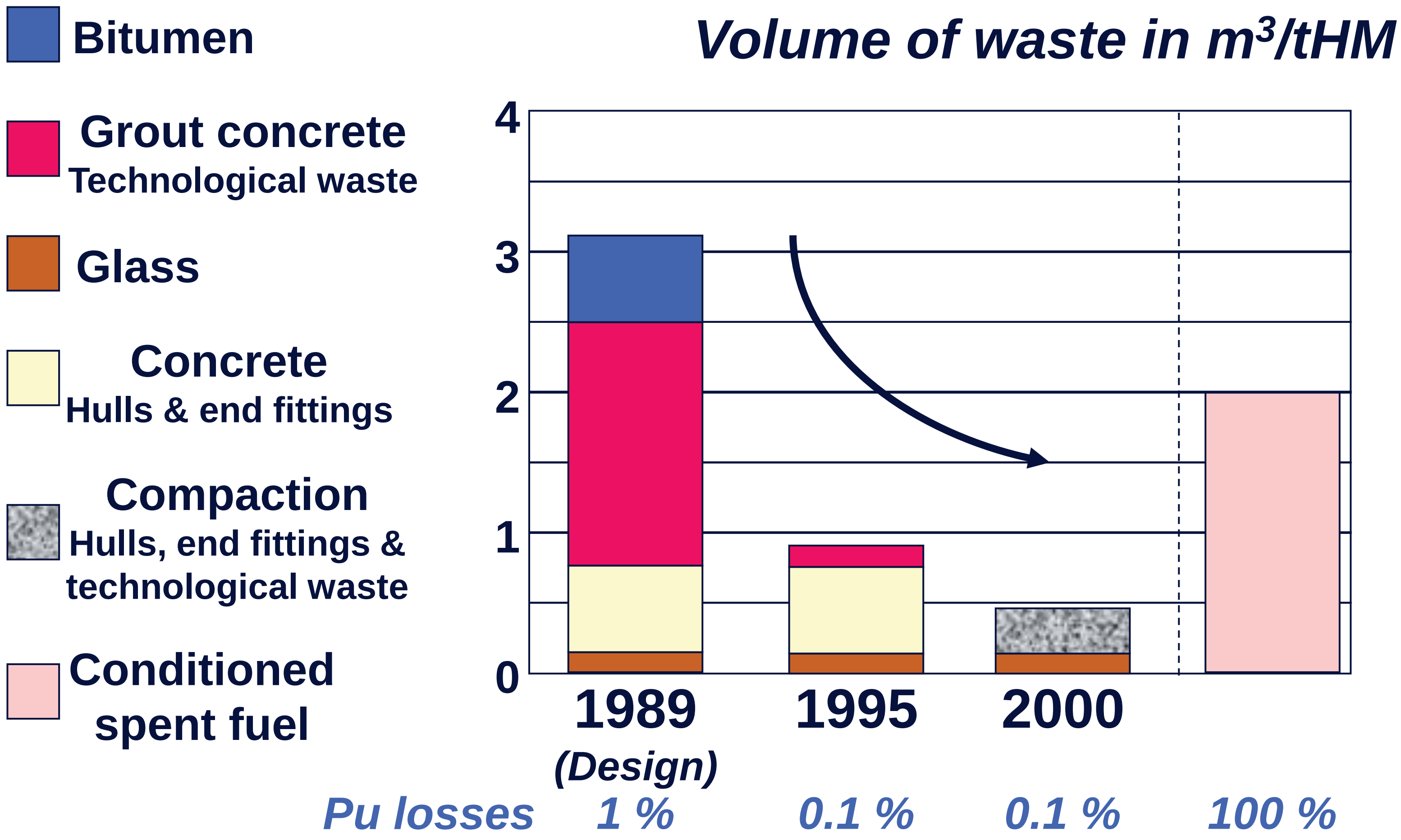
Spent Fuel Recycle

country	site	plant	Operation time	Capacity (tHM/y)	
				present	future
China	Lanzou	RPP (LWR)	2008	50	50
		CRP (LWR)	2020		800
France	La Hague	UP2-800 (LWR)	1994	800	800
	La Hague	UP3 (LWR)	1990	800	800
India	Trombay	PP Research	1964	60	60
	Tarapur	PREFRE1 (PHWR)	1974	100	100
	Kalpakkam	PREFRE2 (PHWR)	1998	100	100
	Kalpakkam	PREFRE3A (PHWR)	2005	150	150
	Tarapur	PREFRE3B (PHWR)	2005	150	150
Japan	Tokai-mura	PNC TRP (LWR)	1977	90	90
	Rokkasho-mura	RRP (LWR)	2012	800	800
Russia	Chelyabinsk	RT1 (WWER-440)	1971	400	400
	Krasnoyarsk	RT2 (WWER-1000)	2020		1500
UK	Sallafield	B205 (GCR)	1967	1500	
	Sallafield	Thorp (LWR/AGR)	1994	900	900
Total				5900	6700

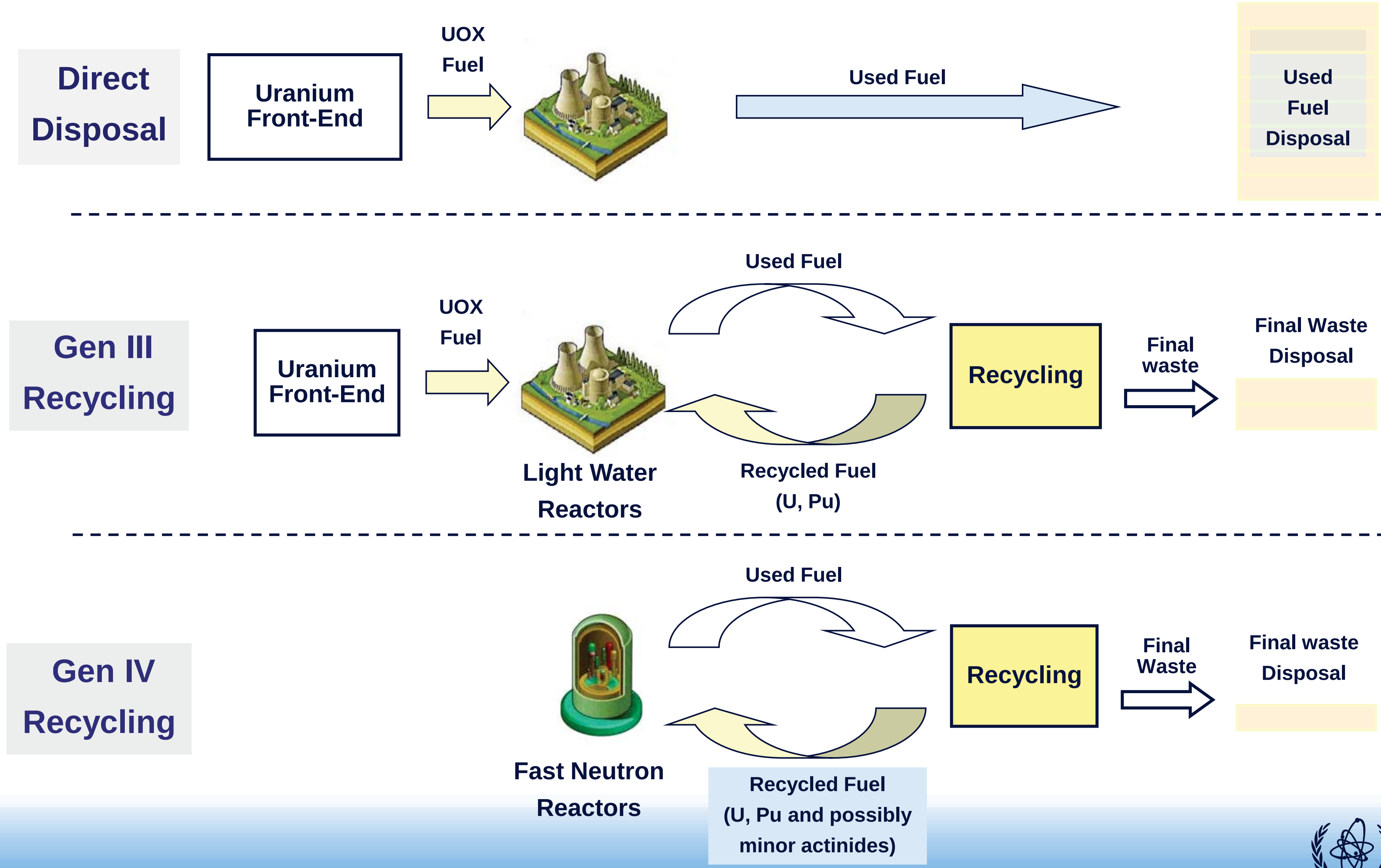
RECENT TRENDS IN SPENT FUEL REPROCESING

- Higher Burn-up of Spent Fuel
- Reduction in Dose to Plant Operator
- Reduction in Waste Volume
- Reduction in Discharge of Radioactivity to Environment
- Plant Expansion / Lifetime Extension
- Decommissioning

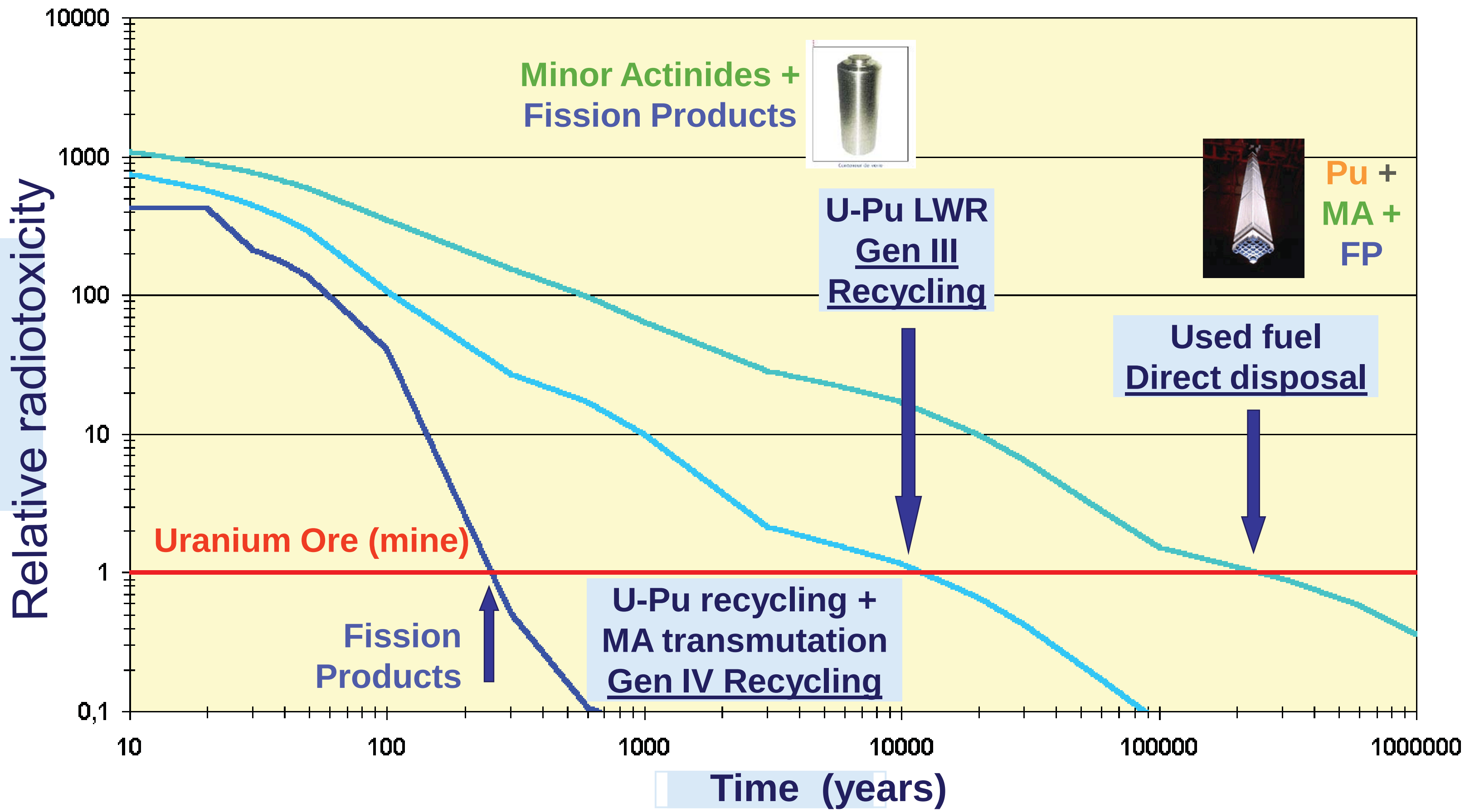
Specific waste volume for the UP3 plant



Which Recycling?



Repository Potential Radiotoxicity

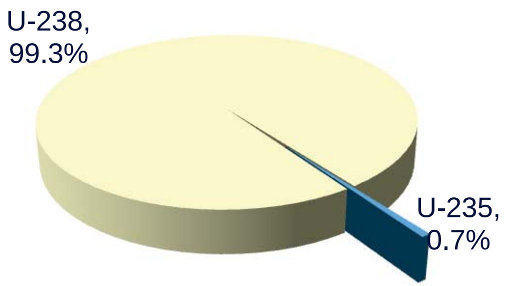


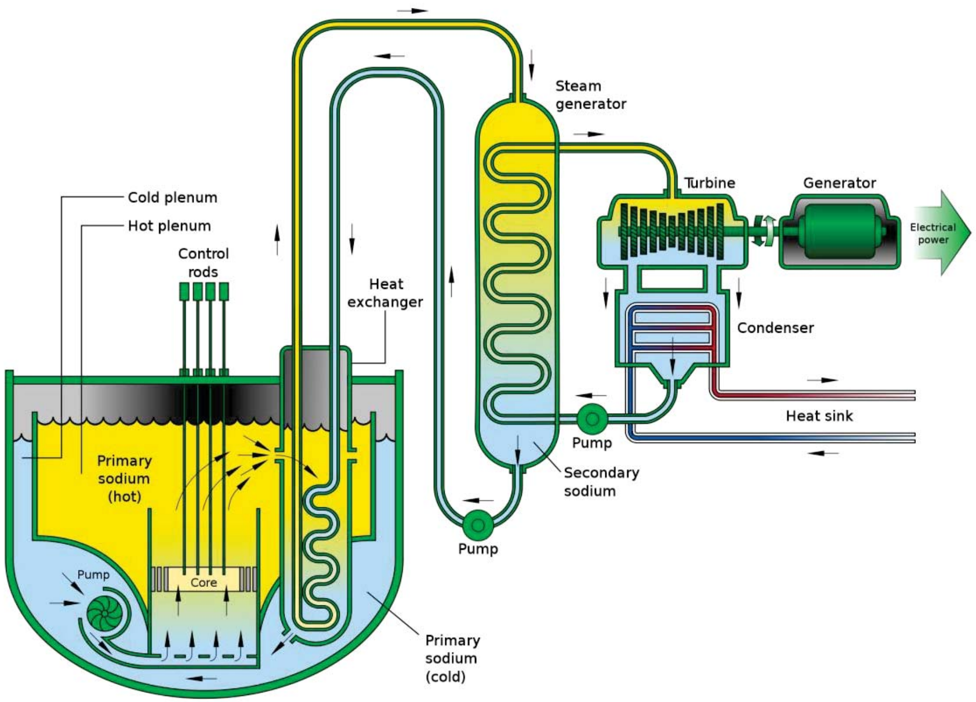
- Assuming an optimistic 100% efficiency in the partitioning and transmutation of all Minor Actinides with Gen IV recycling

Fast Reactor Fuel Cycles

Fast neutron spectrum reactors can:

- Produce more fissile material (Pu) than they consume (breeding)
- Effectively fission (transmute) long-lived minor actinides.

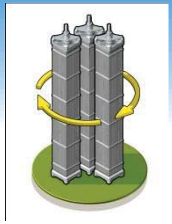




Compared Benefits of Recycling Options

- Gen IV recycling through fast neutron reactors holds great promises
  - Significant extension of the uranium resource
    - From several hundred to several thousands of years of availability of the total Uranium resource
    - Benefiting from directly available resources such as depleted Uranium
  - Much reduced radiotoxicity of the final waste

- But today's Gen III LWR recycling already starts to address those issues
  - 25% uranium savings through LWR MOX and Enriched Reprocessed uranium fuel
  - Radiotoxicity reduction by 10 compared to direct disposal
  - … using proven technologies and commercial models



Recycling Strengthens Non-proliferation

- **Recycling restricted to a few regional centers under international safeguards**
  - Offering recycling services to a wide range of customers
  - Avoiding the accumulation of used fuel in multiple storage sites worldwide
  - Returning to customers final waste not subject to IAEA safeguards
- **Plutonium recycled in MOX fuel**
  - Consumes roughly one third of the plutonium and controls overall Pu inventory
  - Significantly degrades the isotopic composition of the remaining plutonium and thus the potential attractiveness for non-peaceful usage
- **Commercial recycling facilities such as La Hague and Melox have a perfect track record with respect to fissile materials safeguards**
- **Recycling contributes to international non-proliferation initiatives**
  - Weapon-grade plutonium disposition (MOX Fuel Fabrication Facility in the US)
  - Securing « gap material »

Spent Fuel Recycle

Advanced Aqueous Partitioning Methods

GANEX

Uranium extraction followed by group extraction of all actinides

UREX +

- Separation of U & Tc by UREX
- Recovery Cs & Sr by CCD-PEG
- Recovery of Pu & Np by NPEX
- Recovery of Am, Cm and Ln by TRUEX
- Separation of Am and Cm from Ln (Cyanex 301)

DIAMEX

TODGA

Separation of MAs and Ln from HLLW

TRUEX

Transuranic element extraction from HLLW

SANEX

ARTIST

TALSPEAK

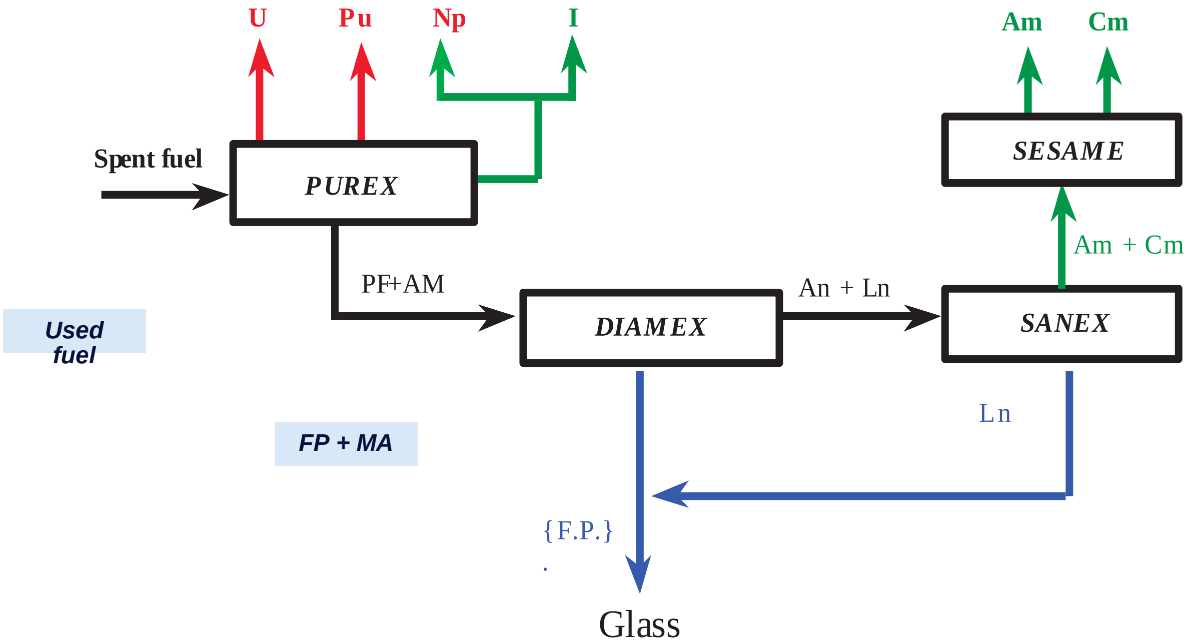
Separation of An from Ln

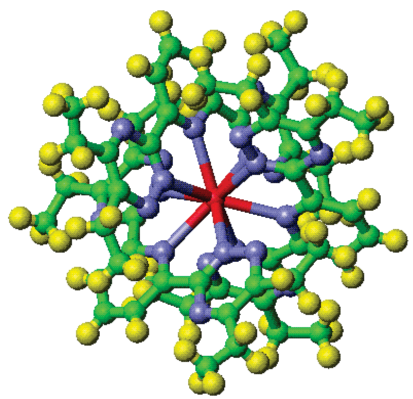
SESAME

Separation of Am from Cm

Partitioning and Transmutation

- **Scientific feasibility of the Minor Actinides partitioning, and of some of the long-lived fission products**
- **Very selective molecules have been developed and tested with performances of partitioning above 99%**





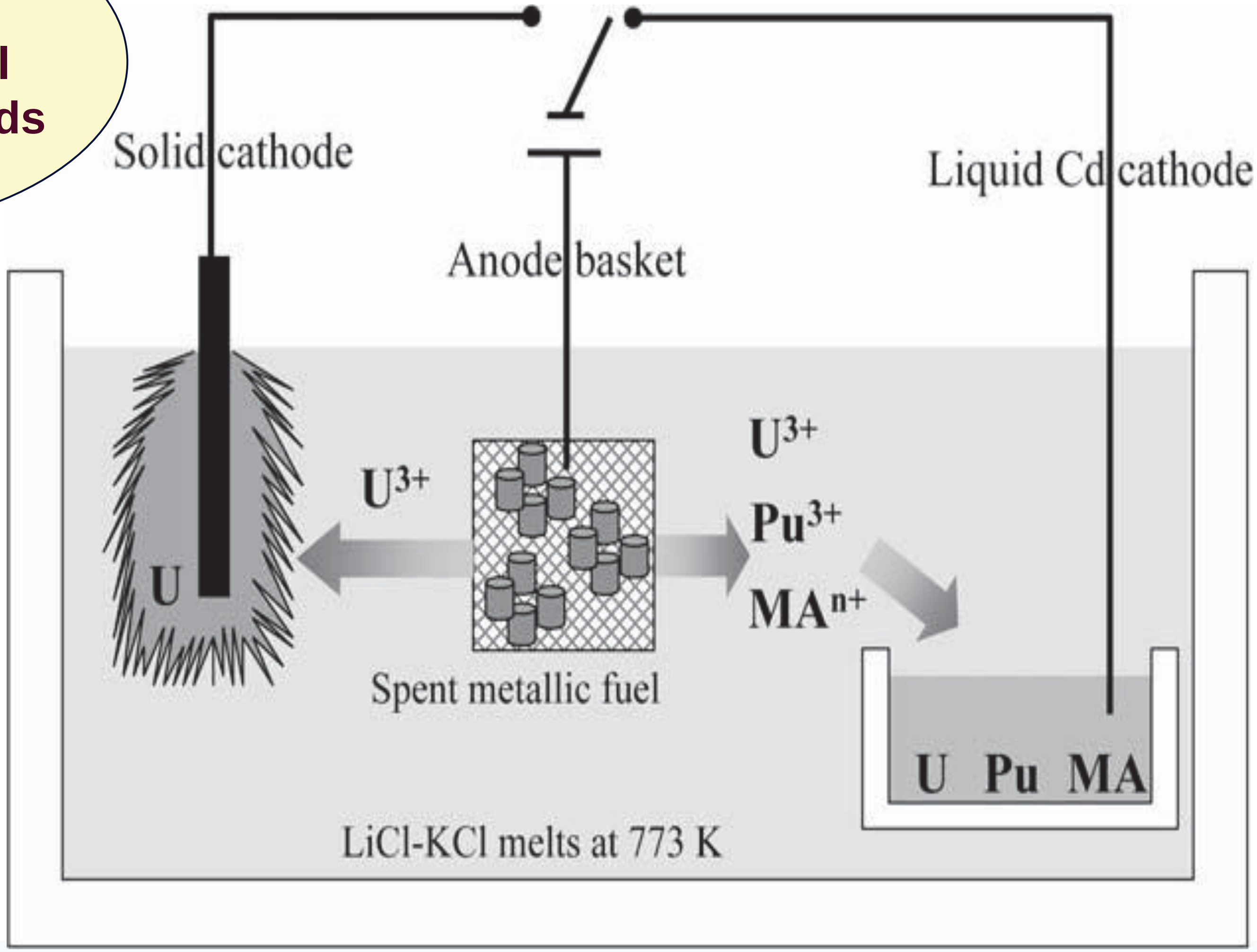
FP . Fission products

MA : Minor actinides

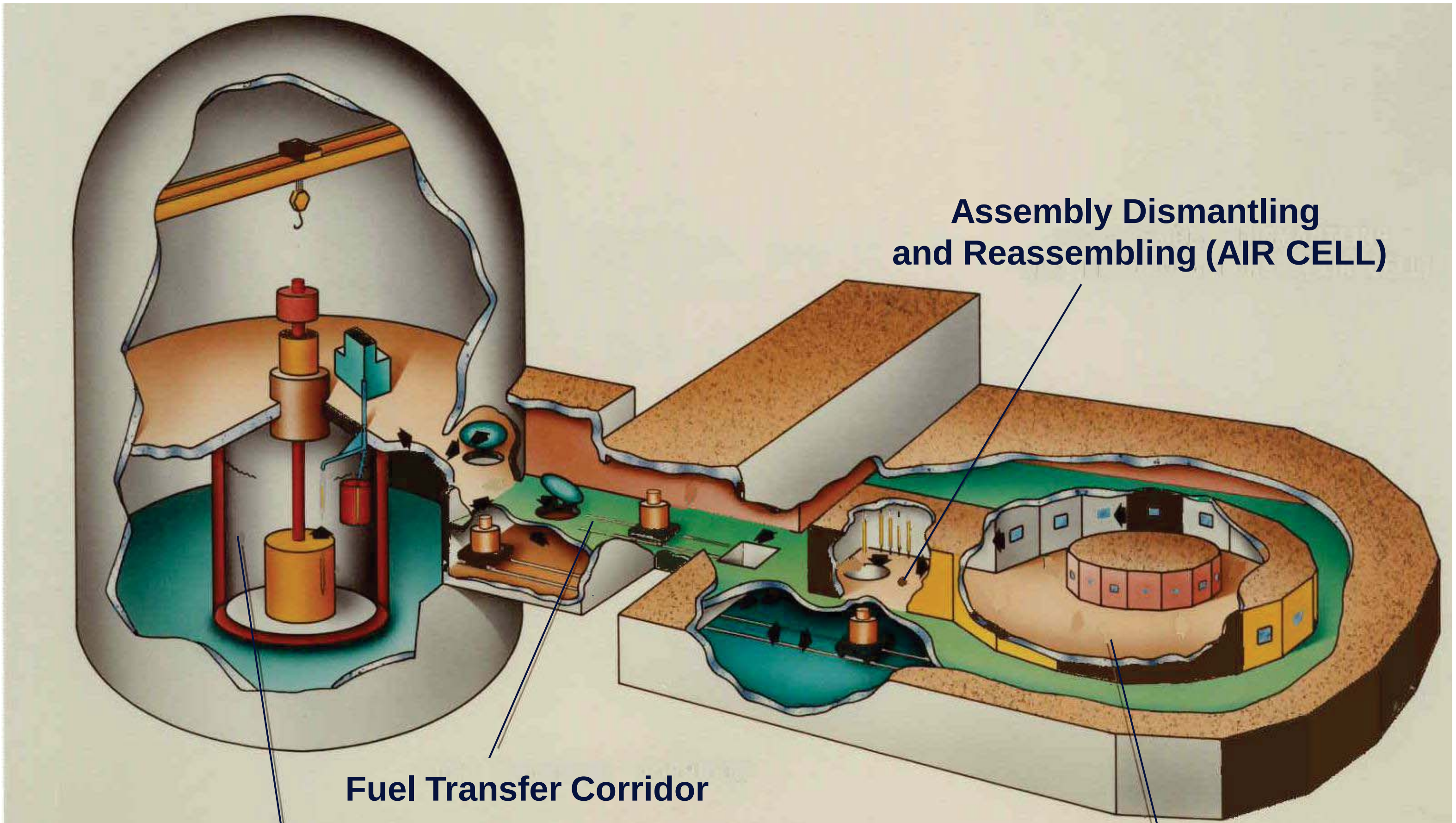
Ln : Lanthanides

Spent Fuel Recycle

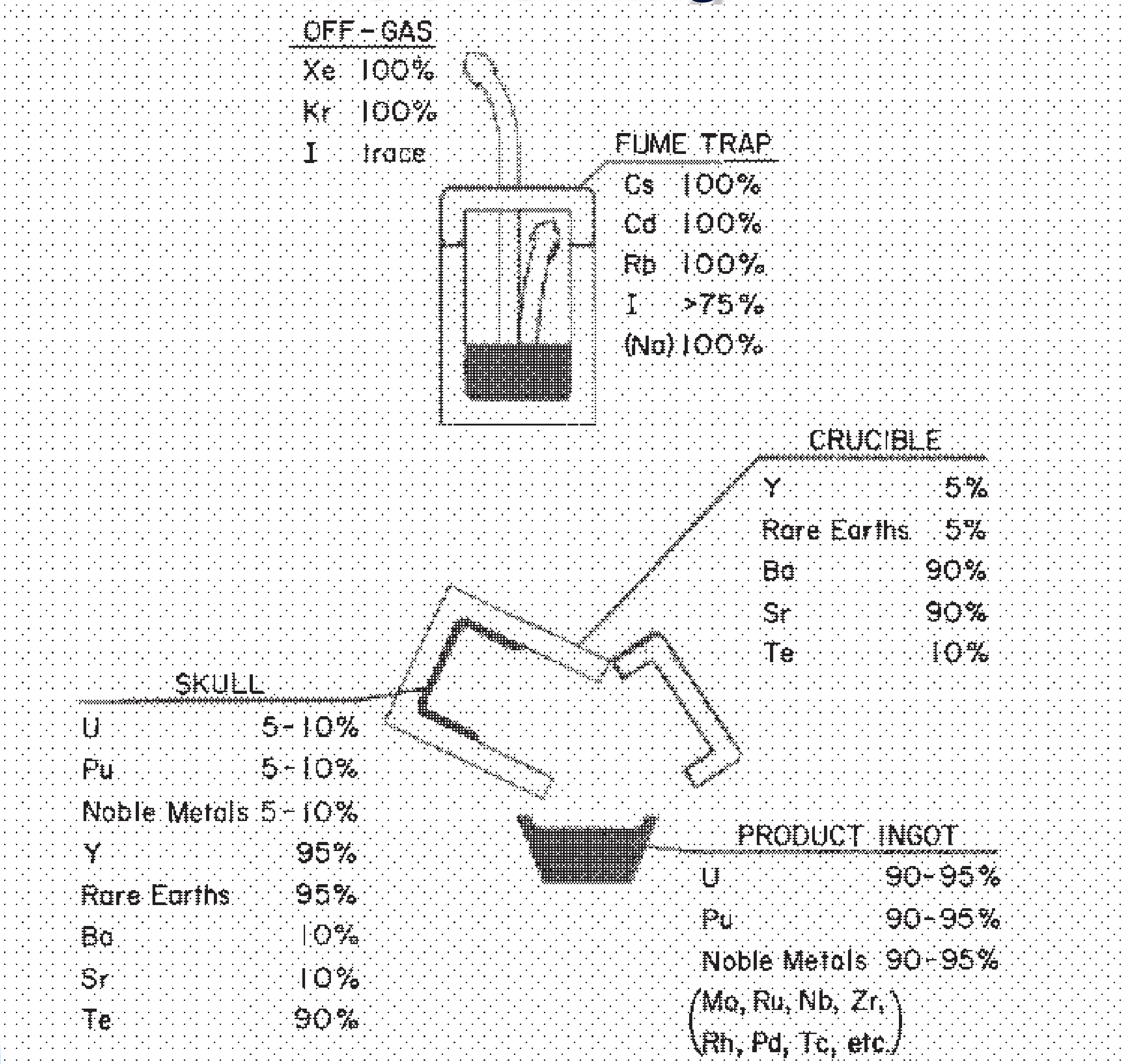
Advanced Pyro-Metallurgical Partitioning Methods

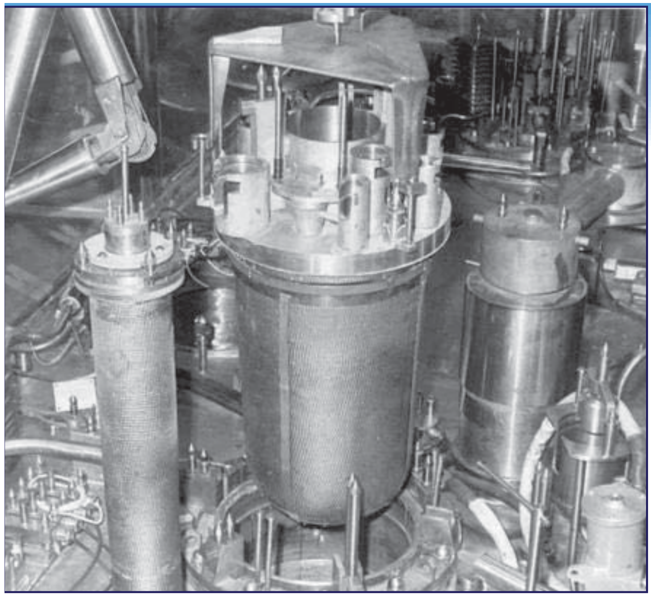


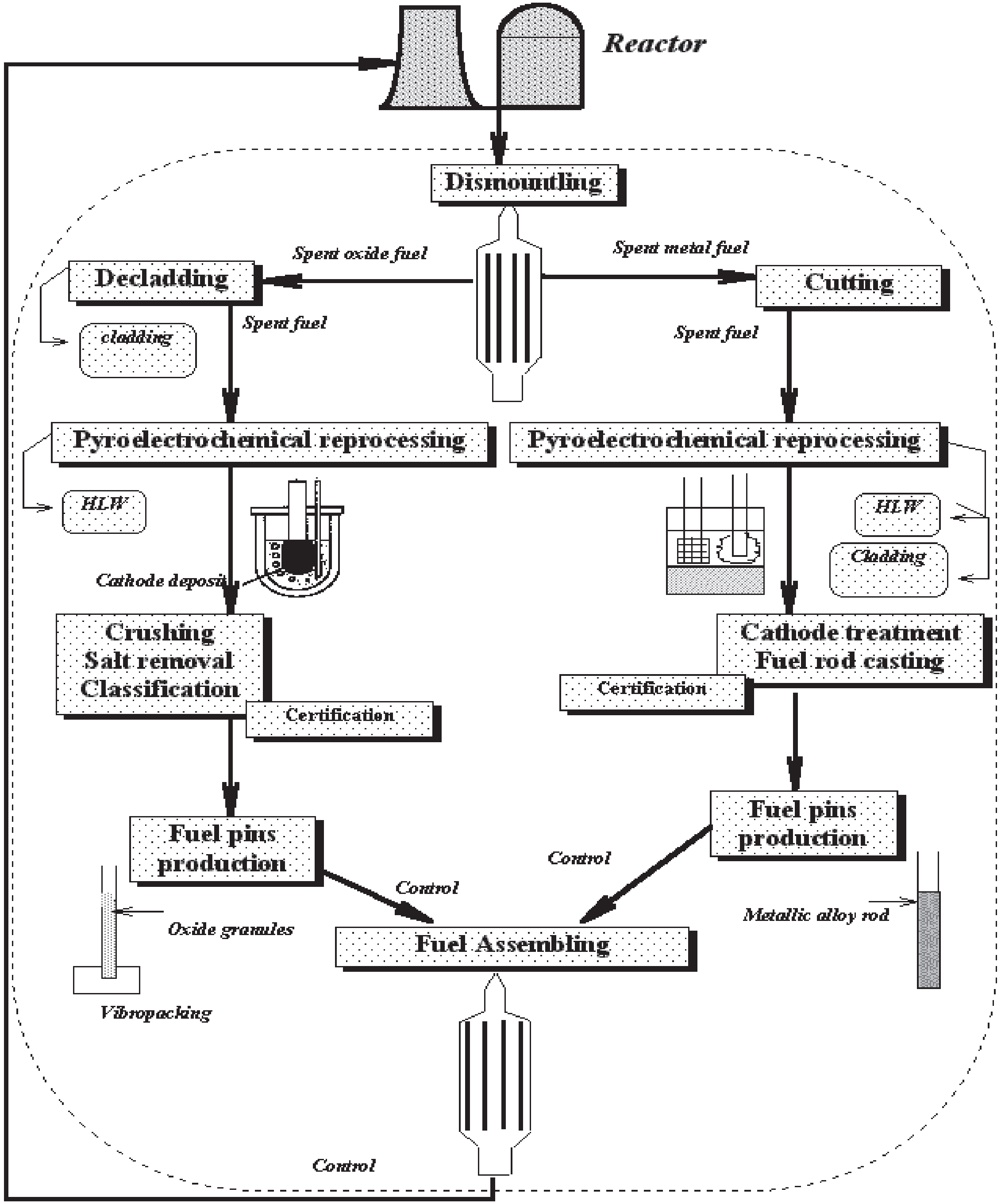
Pyroprocessing was used to demonstrate the EBR-II fuel cycle closure during 1964-69



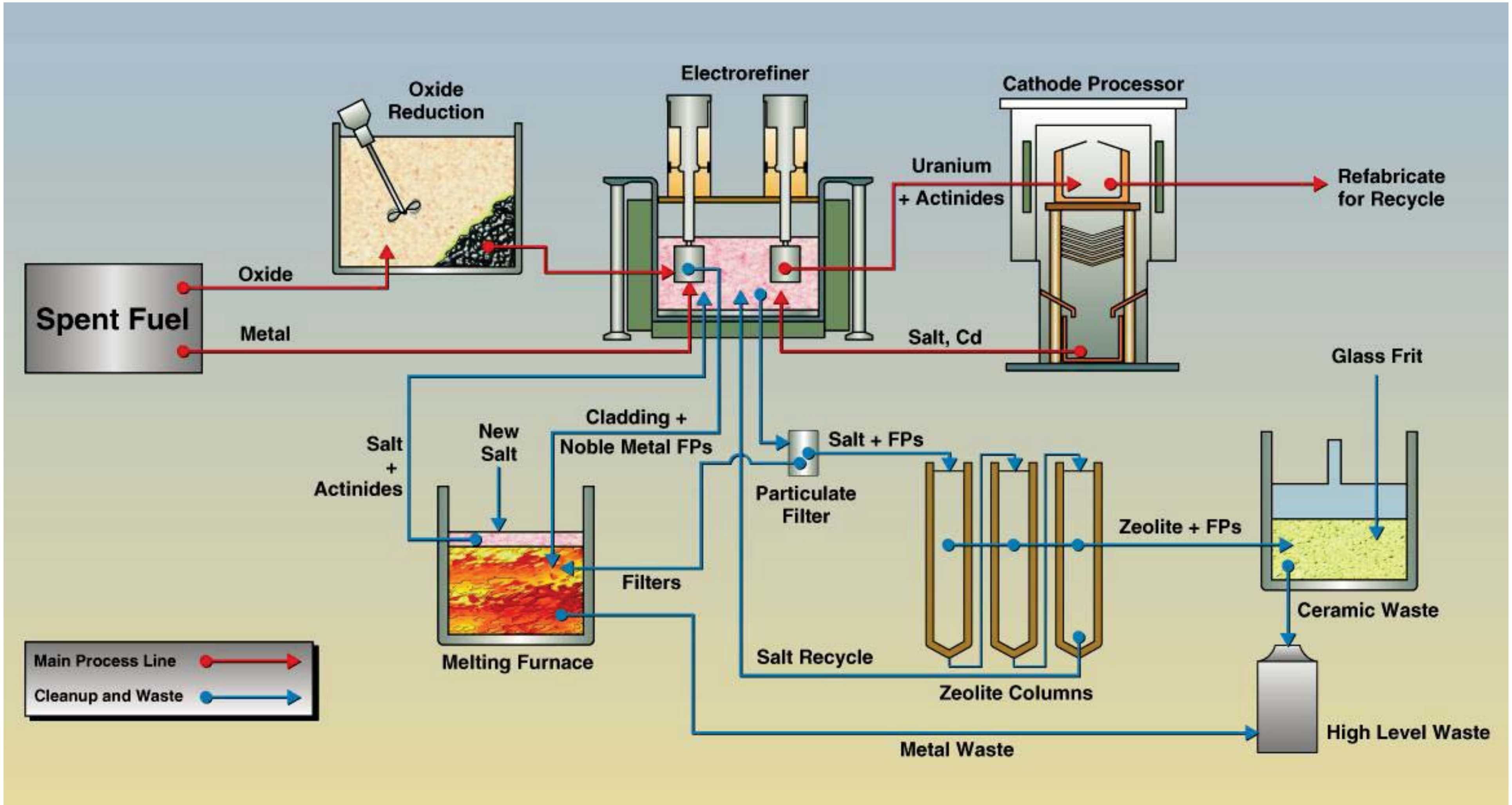
Melt Refining






Reactor
Dismountling
Spent oxide fuel
Spent metal fuel
Decladding
Cutting
Spent fuel
cladding
Spent fuel
Pyroelectrochemical reprocessing
Pyroelectrochemical reprocessing
HLW
HLW
Cladding
Cathode deposit
Crushing
Salt removal
Classification
Certification
Cathode treatment
Fuel rod casting
Certification
Fuel pins production
Fuel pins production
Control
Control
Oxide granules
Metallic alloy rod
Fuel Assembling
Vibropacking
Control

Pyroprocessing Flowsheet



Current status of pyrochemical development for oxide fuel

- **Fundamental research**

  Properties of U, Pu, Th, Np, Am have been studied. Knowledge of physical chemistry and electrochemistry of basic FP is sufficient for processes understanding and modeling. The needed research lines – study of Cm and Tc chemistry. Development of nitride fuel recycle methods is carried out.

- **Development work**

  All technological steps and equipment have been developed for the oxide fuel reprocessing and fabrication processes. The process was tested more than to 7200 kg of fresh fuel for different reactors and up to 40 kg of BN-350 and BOR-60 irradiated fuel. The essentials of technology have been elaborated and feasibility study has been completed for the BN-800 large-scale CFC plant. More than 45 000 fuel pins and more than 1000 FAs

- **Industrial implementation**

  As the readiness of technology is high, work is underway on industrial implementation of U-Pu fuel. The BOR-60 operates on vi-pack fuel. The design of the CFC facility is in progress. 30 FAs have been tested and irradiated in BN-600. These technologies are under implementation as basic for BN-800 industrial MOX fuel production.

RIAR experience in reprocessing of spent fuel of the BOR-60 and BN-350 reactors

Fuel type	Burn up ,%	Mass, kg	Period	Reactor
UO2	7,7	2,5	1972..1973	BOR–60
$(U,Pu)O_2$	4,7	4,1	1991	BN–350
(U,Pu)O2	21..24	3,5	1995	BOR–60
UO2	10	5	2000	BOR–60
(U,Pu)O2	10	12	2000…2001	BOR–60
(U,Pu)O2	16	5	2004	BOR–60

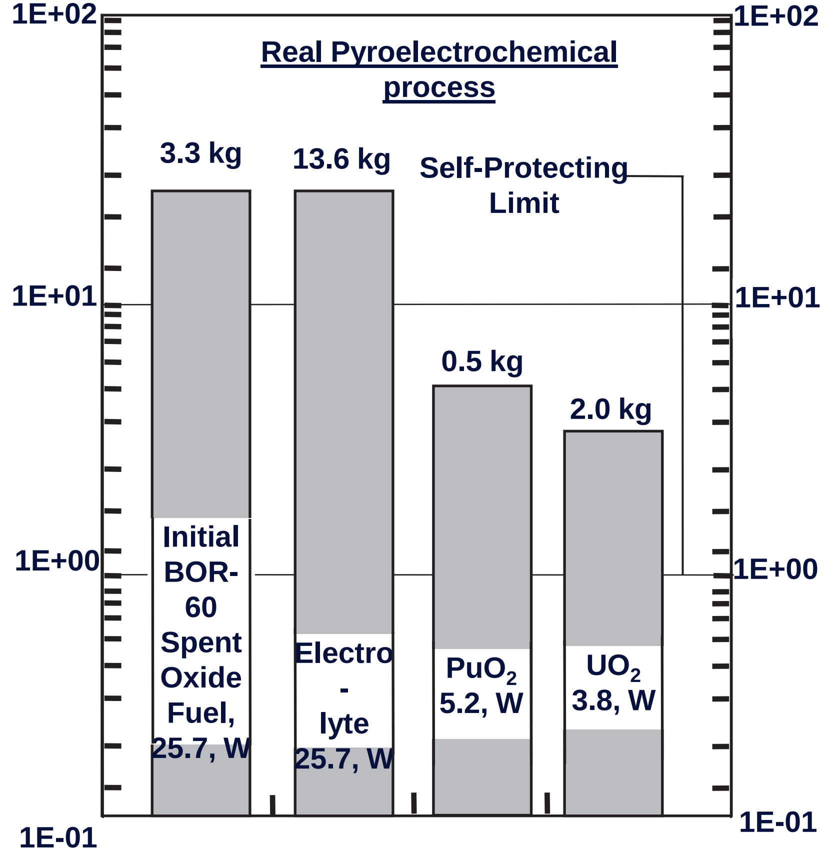
Decontamination factors (DF) from main FPs

Fuel type	Main FPs				
	Ru–Rh	Ce– Pr	Cs	Eu	Sb
PuO_2 for BN–350 (test, 1991)	50	220	> 3000	40	200
PuO_2 for BOR–60 (test, 1995)	33	40..50	4000	40..50	120
UO_2 for BOR–60 (test, 2000)	> 30	~	> 4000	> 200	~
$(U,Pu)O_2$ for BOR–60 (test, 2001)	20 – 30	25	~ 10000	> 100	~

Excluding of pure plutonium

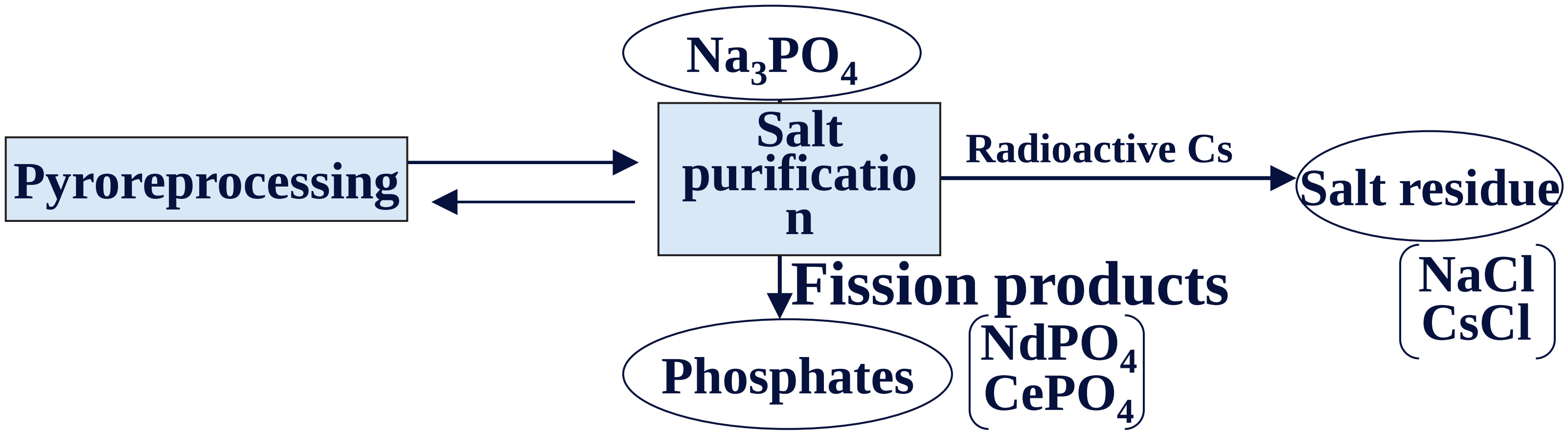
For utilization of Pu in Fast reactors:

- High DF no necessary
- Additional treatment in closed cycle of Fast reactor
- Possibility of recycle of other TRU (*Np, Am, Cm*)



Self-Protection of BOR-60 spent Fuel Reprocessing by Gamma Radiation .

Pyrochemical Wastes treatment



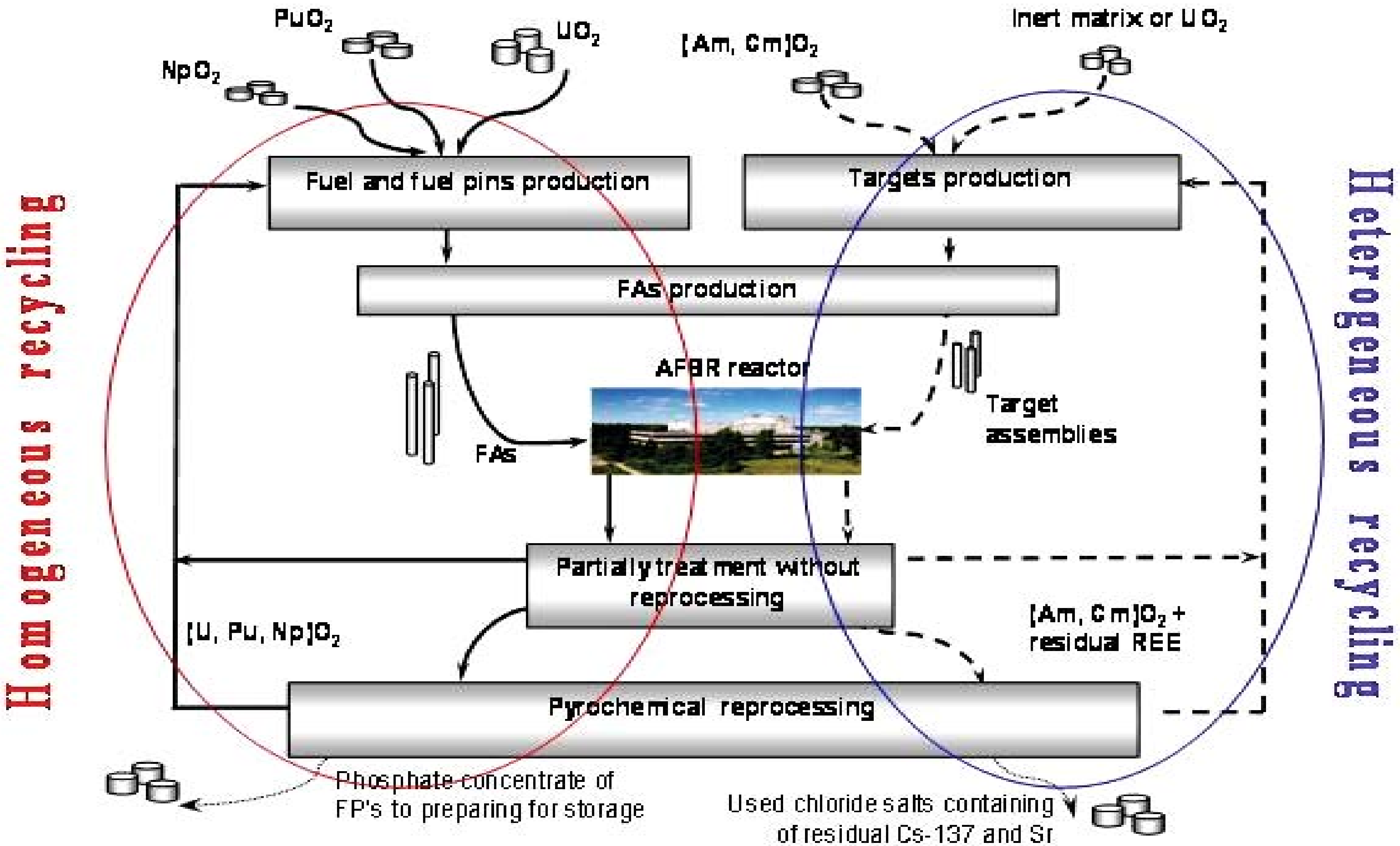
Waste	Phosphates	Salt residue
Special features	contain fission products	Alkaline metal chlorides, high activity, significant heat release
Basic elements	11 wt.% Nd 4,4 wt.% Ce	81,96 wt.% CsCl 18,04 wt.% NaCl
Quantity	<0,15 kg/kg of fast reactor SNF	<0,03 kg/kg of fast reactor SNF

Evaluations by Toshiba

Fuel Recycle Technology Options

Process Characteristics	Aqueous Processes	Pyro Processes
Process nature	Continuous, high throughput	Batch, limited throughput
Solvents	Organic; nitric acid	Molten salts; metals
Pu recovery	> 99.9%	~ 99.3%
Criticality	Requires stringent control	Less stringent
Material accounting	Continuous accounting	Batch-wise accounting
High level waste	Nitrate solutions	Chlorides; phosphates
Technical maturity	Industrially demonstrated	Pilot-scale facilities

DOVITA fuel cycle



COMMON ISSUES TO ALL OPTIONS

- **SUSTAINABILITY**
  - *Cost-effective*
  - *Proliferation-resistant*
  - *Environmentally friendly*
- **INSTITUTIONAL ISSUES**
  - *Political/economical/social stability*
  - *Information management*
- **REGIONALIZATION / INTERNATIONALIZATION**
  - *Win-win strategy (especially beneficial for small scale partners)*
  - *Difficulty of finding host to the site(s) of facilities*

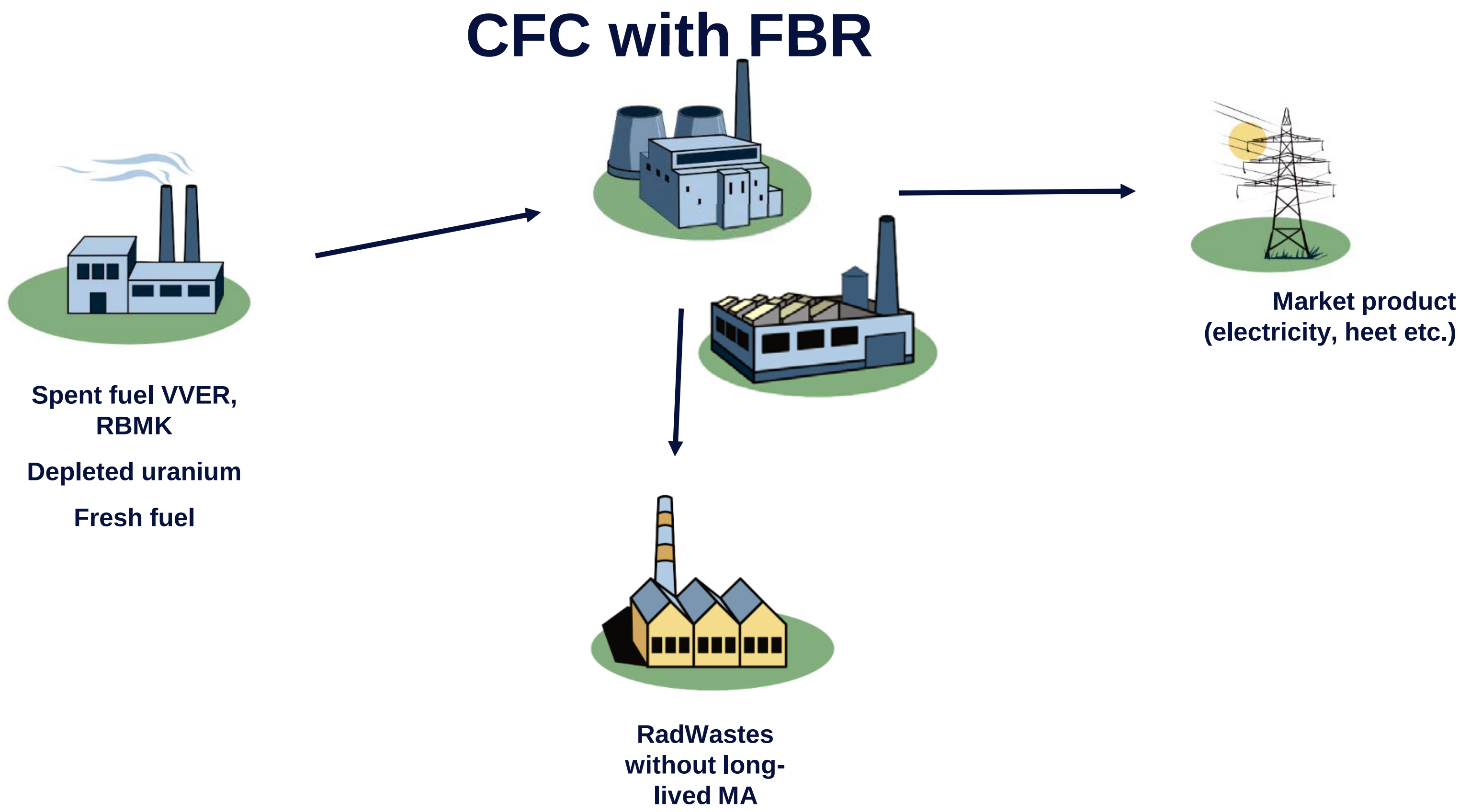
Basic approaches to SF reprocessing

- **Materials demanding for utilization**
  - **Reprocessing only in case of using of materials in fuel cycle**
  - **Excluding of recovery of basic components for stockpiles**

Partitioning and recycling instead reprocessing

- **All components must be introduced in closed fuel cycle**
- **Technologies flexibility and modules principle**
- **Criteria:**
  - **Minimization of wastes (and storage and disposal costs)**
  - **Non-proliferation (inherent barriers)**

Closed Fuel Cycle with FBR



National Policy on Spent Fuel

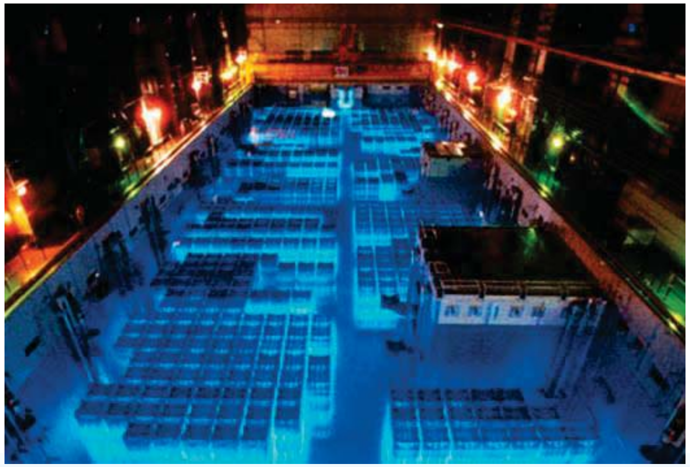
Country	NPP	Policy	Remark
USA	104	Review	AR/AFR interim storage Yucca Mt. licensing stop
Finland	4	Disposal	Olkiuoto repository (2000-2020) AR wet storage
Canada	18	Disposal	AR dry storage Repository site investigation
Sweden	10	Disposal	AFR wet storage (CLAP) Osthammar repository site (2009-2025)
Germany	17	Disposal	2005 reprocessing moratorium AFR dry storage (Ahaus, Gorleben) Gorleben repository site under investigation
Switzerland	5	Disposal	Zwilag AFR dry storage 3 repository candidate sites

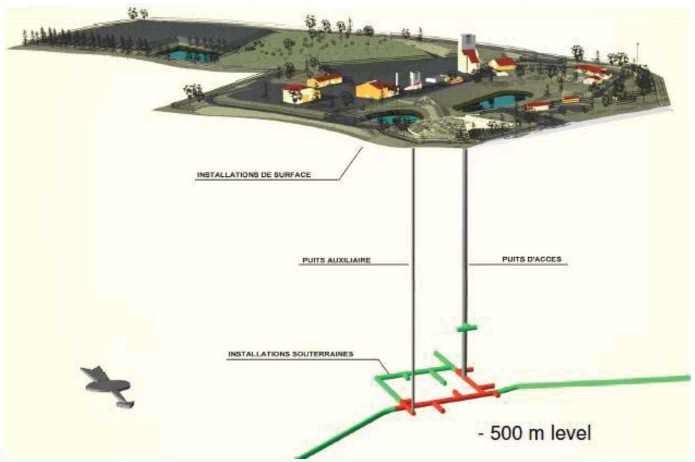
National Policy on Spent Fuel

Country	NPP	Policy	Remark
France	59	Reprocess	AFR wet storage Bure repository site under investigation
Japan	54	Reprocess	Rokkasho reprocessing plant (2012) Mutsu AFR dry storage (2015)
China	11	Reprocess	Reprocessing plant planned (800 t)
Russia	31	Reprocess	AFR wet/dry storage
UK	19	Reprocess & Disposal	Magnox reprocess – AFR wet storage LWR spent fuel disposal
India	18	Reprocess	

France

- **Most of the spent fuel is currently being reprocessed**
  - **58 NPP in operation => 1250 tons of SF every year.**
  - **La Hague: operated since 1966; current capacity=1700 t/year.**
  - **HLW repository 2025 → Bure underground laboratory**



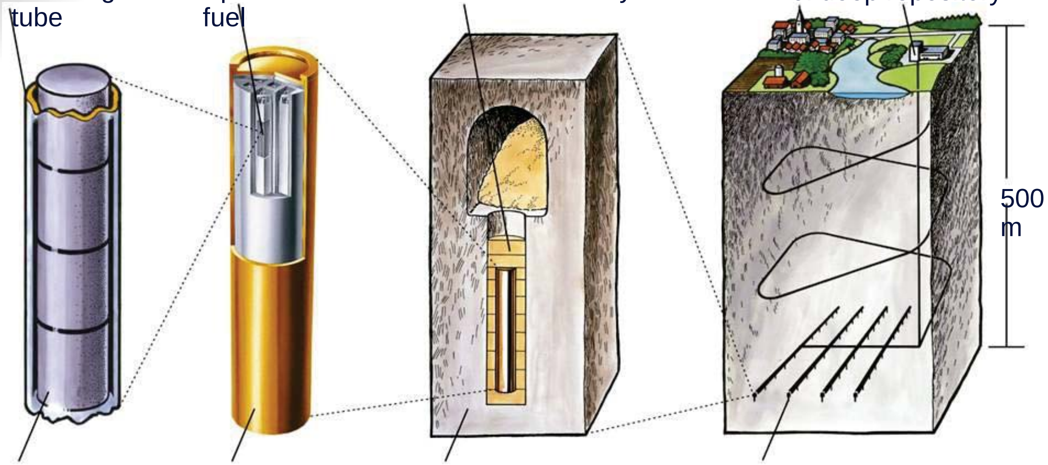


Sweden

10 reactors operation

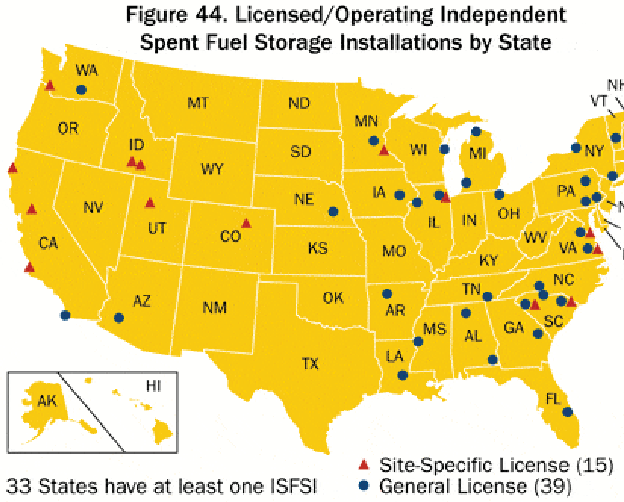
Centralized Wet Storage (Oskarshamn) 8000 tHM

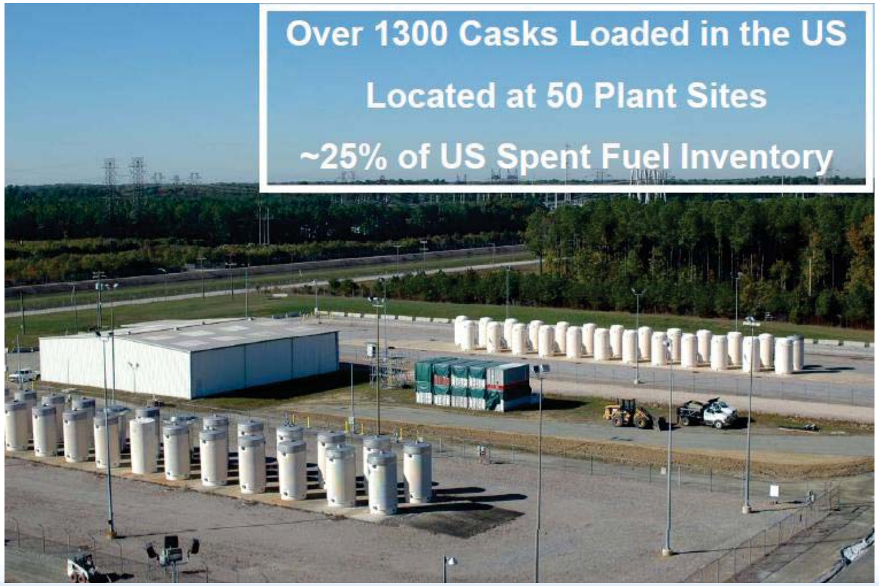
Repository Construction: 2015-2025 (Forsmark)



USA

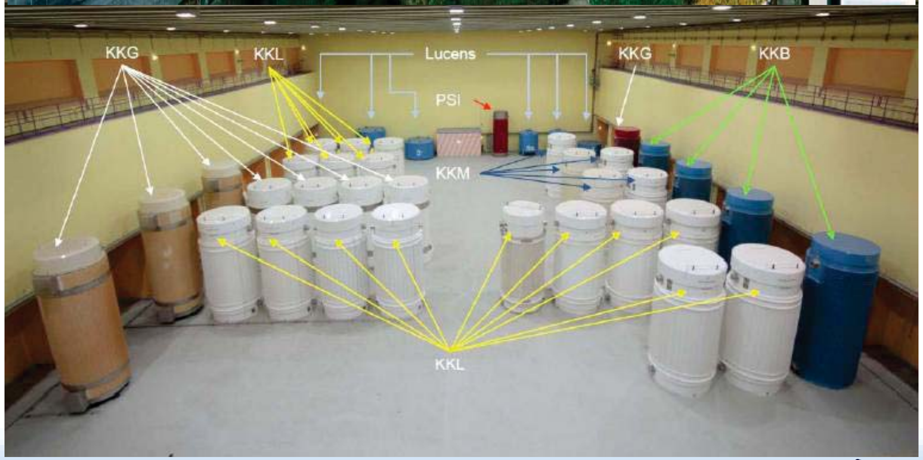
- **National totals:**
  - **Wet storage: 169,696 assemblies at >50 reactor sites**
  - **Dry storage: 1,232 casks, 51,585 assemblies in 32 states**
- **Yucca Mt. project terminated**
- **Blue ribbon commission**
- **Confidence in 60 years of storage after reactor shutdown**
- **Considering extended storage ~120 years**





Switzerland

- In Würenlingen, the Central Storage Facility for radioactive waste (ZZL) has been constructed by the utility-owned company ZWILAG (2001)
- Maximum capacity: 200 casks
- Shipment of spent fuel for reprocessing abroad is not allowed for a period of 10 years which started in July 2006. During this period, spent fuel has to be managed as radioactive waste.
- By the end of 2007, about 1’139 t of spent fuel had been shipped from the Swiss NPPs to the reprocessing facilities in France and the UK.



Germany

- **Spent Fuel Management Options**
  - 450 t annual discharge from 17 NPP
  - ~2005: Reprocessing at France, UK ~ 6,670 tHM
  - 2005~: Direct Disposal ~6,427 tHM

- **Spent Fuel Interim Storage**
  - 3,420 tHM in wet storage pool
  - 2 centralized interim storage facility (Ahaus, Gorleben)
  - 15 on-site interim storage facility

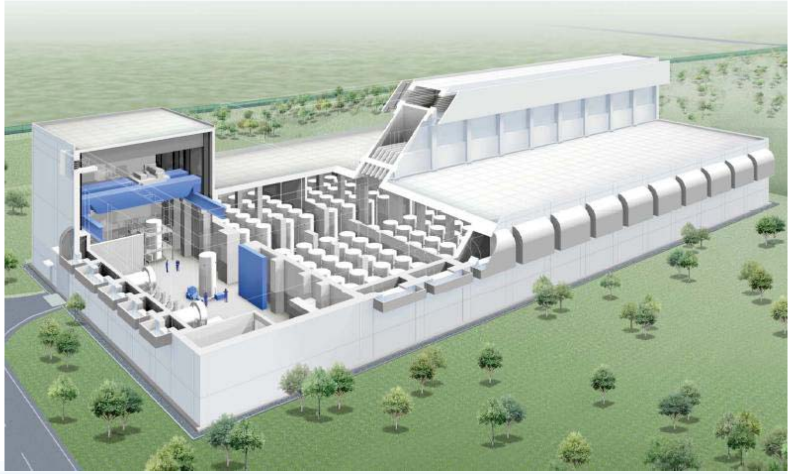
- **Final Repository**
  - Resumption of exploration work of the salt dome in Gorleben 2010 - 2015
  - Development of a site related suitability statement 2015 - 2016
  - Decision on site 2019
  - Planning of the final repository layout and plan submission from 2020
  - Finishing of the plan approval procedure 2028
  - Construction until operational start 2035

Japan

- **1,000tU of Spent Fuels arises from 54 NPPs annually.**
  - Reprocessed in Tokai 1,140 tU 1975 to 2007
  - Transported for reprocessing (France, UK) 7,130 tU 1969 to 2001
  - Transported to Rokkasho 2,926 tU 1998 and after
  - Stored in NPP sites 12,840 tU

- **Rokkasho reprocessing plant** (800tU/year, 2012)

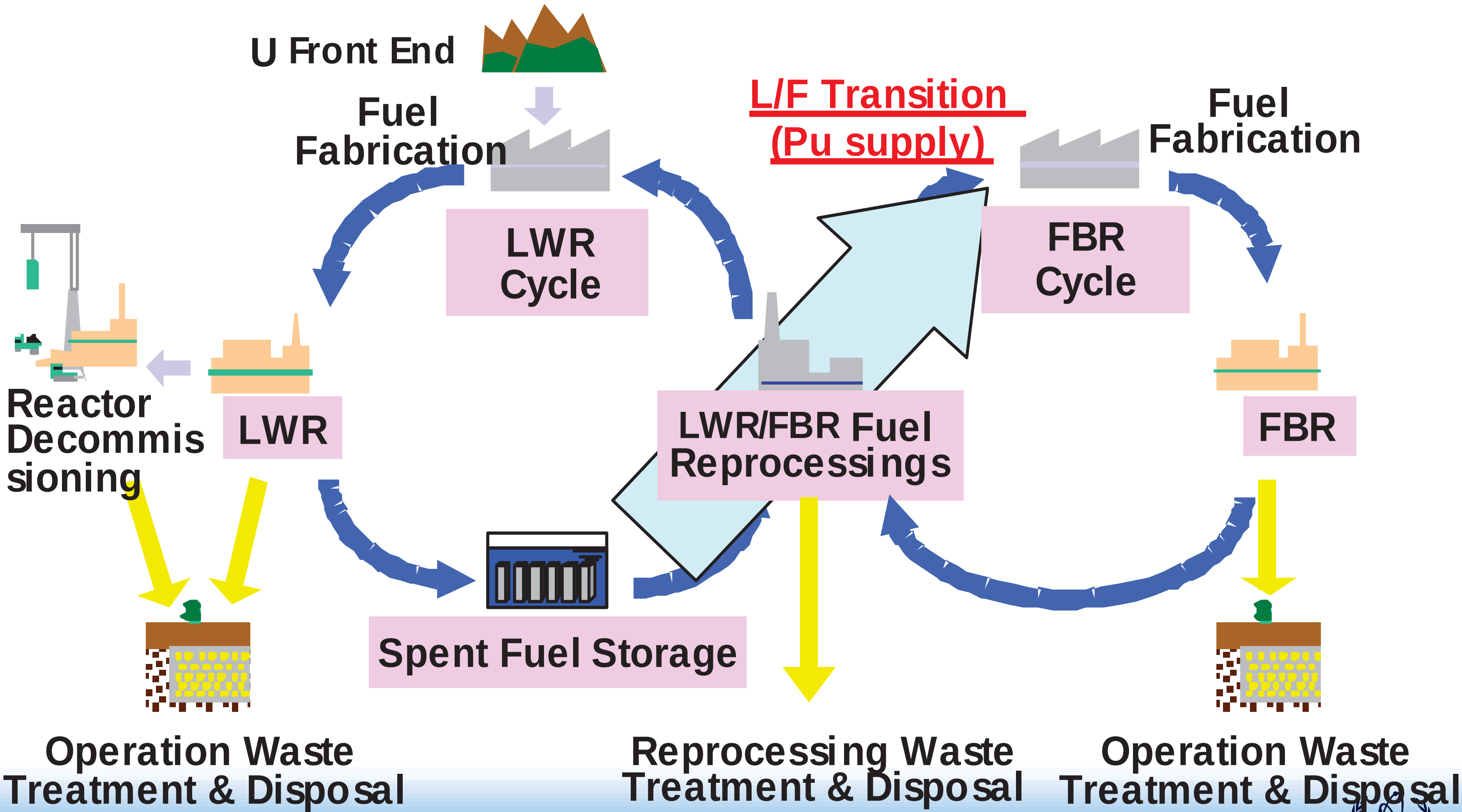
- **The 1st Away-from-reactor type Interim Storage Facility**
  - Mutsu city, Aomori prefecture (2005)
  - 3,000 tU (final 5,000 tU)
  - Dual Purpose Dry Metal Casks
  - construction started in August 2010
  - to begin operation in 2014



Japanese Reprocessing Plant

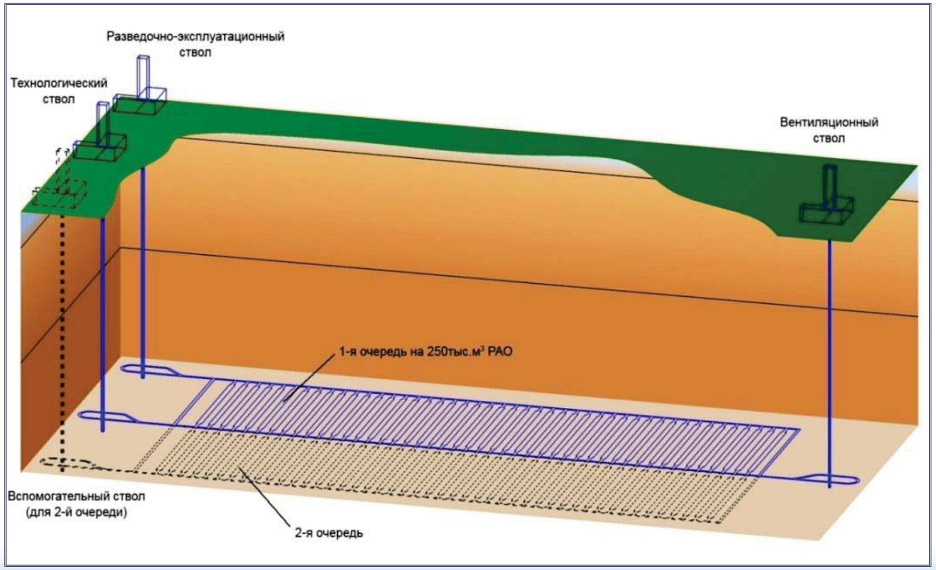
Transition from LWR to FBR

Reprocessing reduces LWR-SF and supplies Pu (MOX) for FBR deployment.



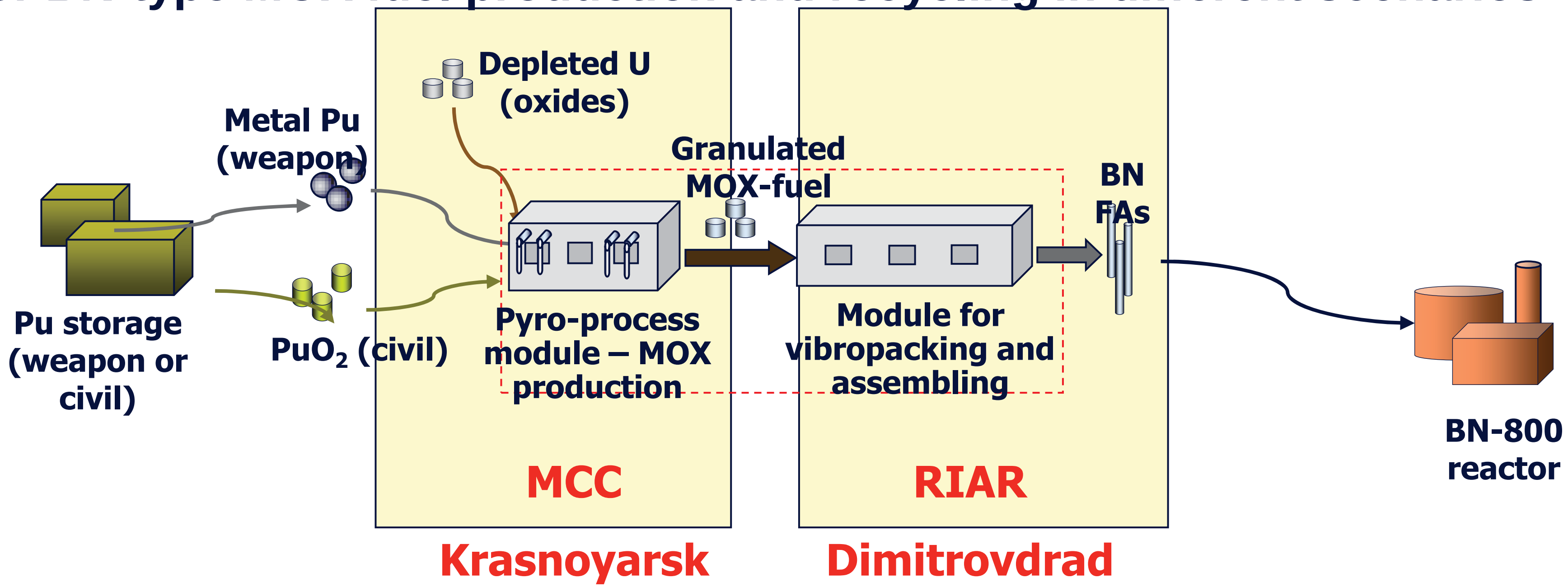
Russia

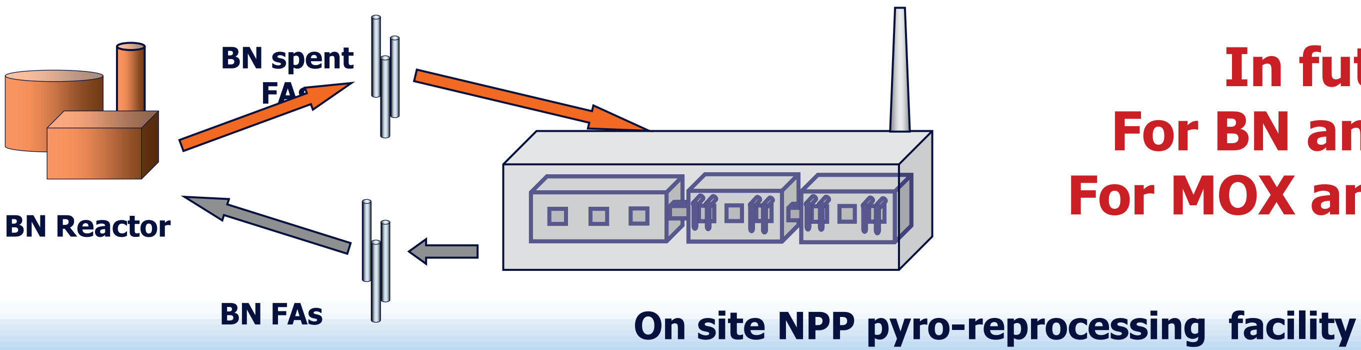
- Annual Spent Fuel Discharge from Russian Power Reactors is ~650 t from 31 units
  - Total amount of accumulated fuel is 19 000 t
- Center for SF Management at Mining Chemical Combine (MCC) site
  - RT-2 Reprocessing plant
  - Dry storage 8100 t (2010), Wet storage 8600 t, HLW disposal



Implementation Pyroprocess for BN-800 Fuel Cycle

Combination of pyroprocess and vibropacking technology is the basis for BN-type MOX fuel production and recycling in different scenarios.



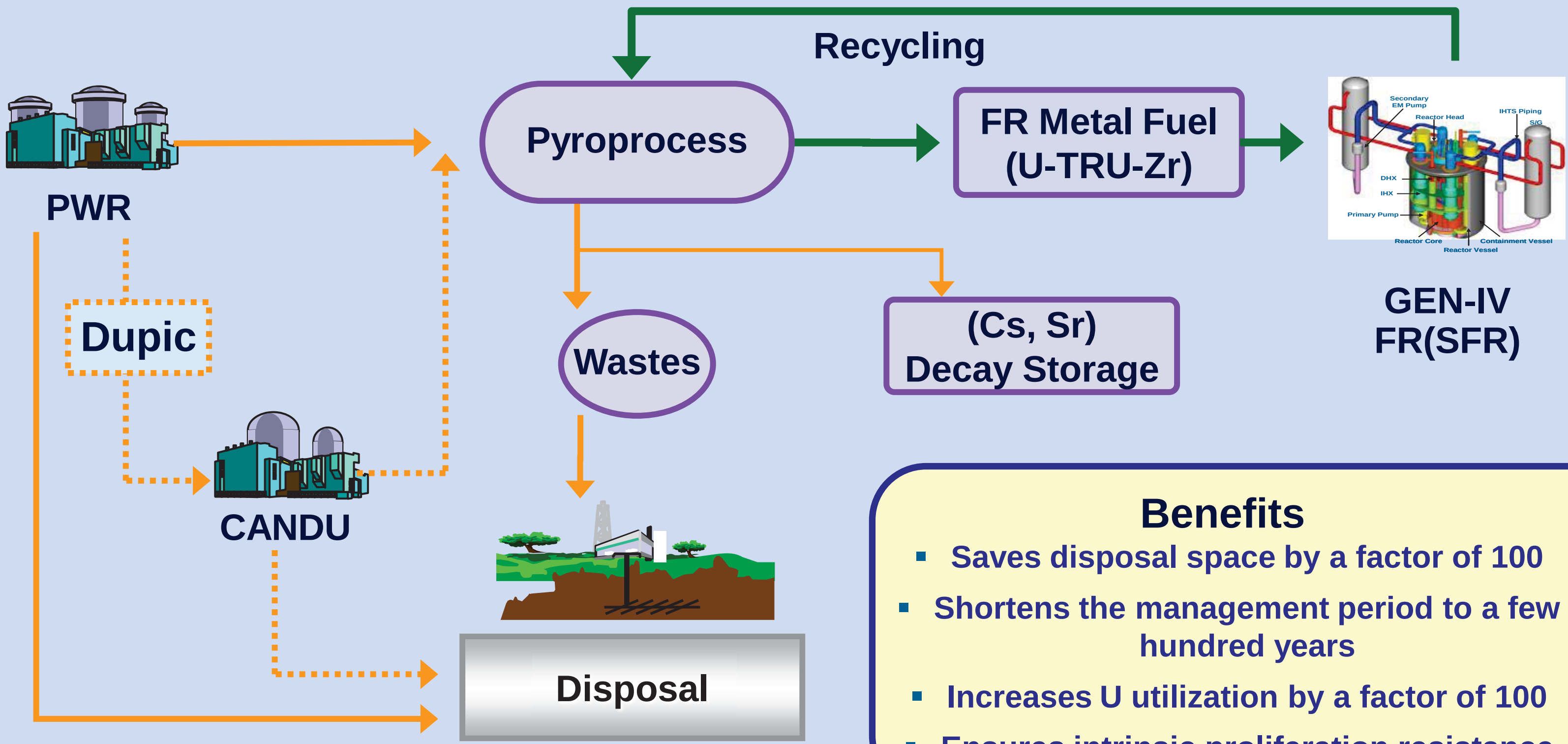


In future:
For BN and BREST
For MOX and (U,Pu)N

Republic of Korea

Promising Fuel Cycle Concept (KAERI)

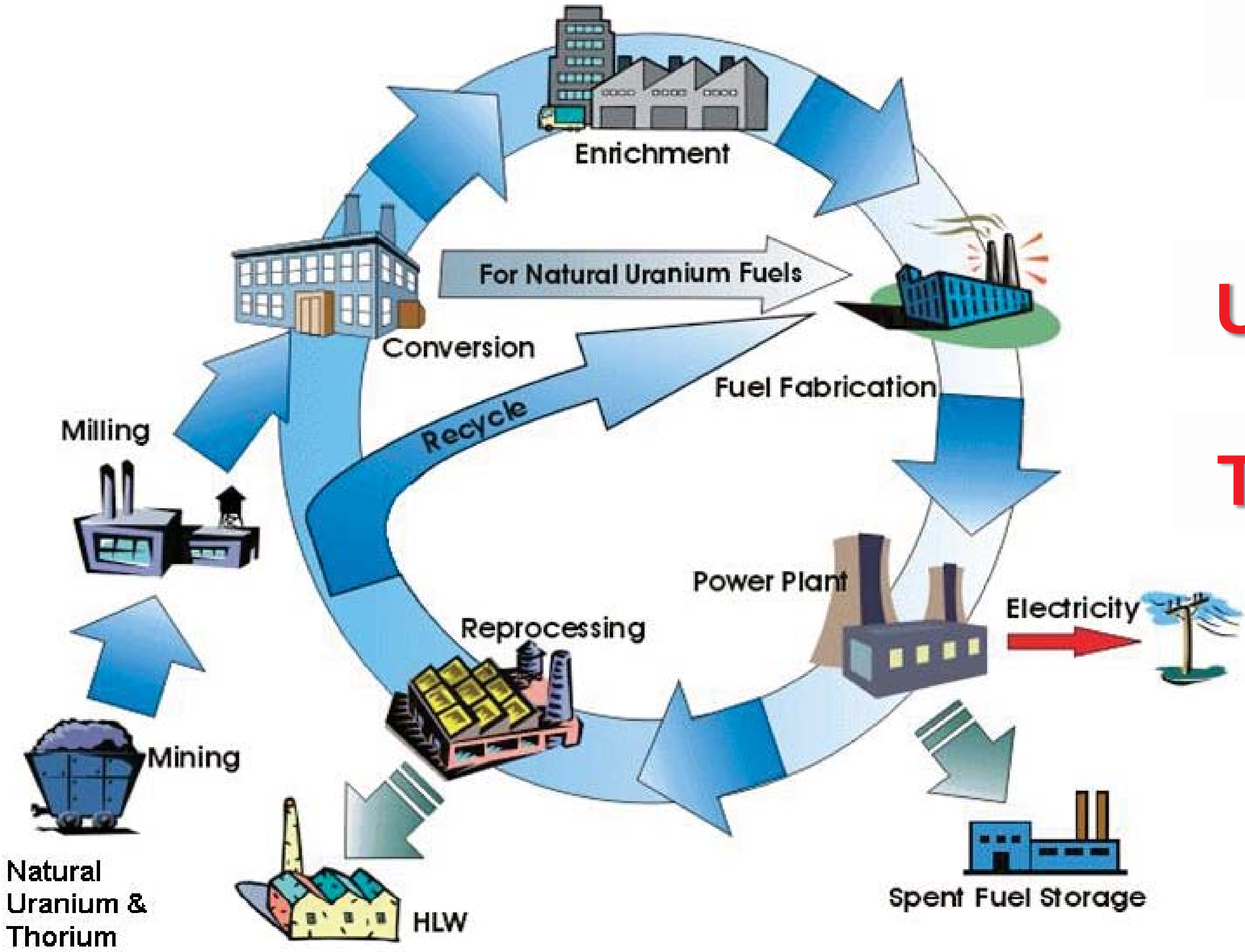
Volume Reduction | **FR Closed Fuel Cycle**



Benefits

- Saves disposal space by a factor of 100
- Shortens the management period to a few hundred years
- Increases U utilization by a factor of 100
- Ensures intrinsic proliferation resistance

Nuclear Fuel Cycle



Options:
U-235

U-238 – Pu

Th – U-233