GEN IV International Forum℠

CLOSING NUCLEAR FUEL CYCLE

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NEA Nuclear Energy Agency

DE LA RECHERCHE À L'INDUSTRIE cea

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens

NATIONAL NUCLEAR LABORATORY

Argonne NATIONAL LABORATORY

INL Idaho National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

NPS PRAESTANTIA PER SCIENTIAM 1909

YOUNGSAN UNIVERSITY

MEET THE PRESENTER

Prof. Yang graduated from the Seoul National University with a B.S. in metallurgical engineering in 1973 and from the Northwestern University with a Ph.D. in materials science and engineering in 1984.

He has been working at KAERI(Korea Atomic Energy Research Institute) for 30 years on the Research and development of PWR/CANDU fuel fabrication, quality control of fuel, DUPIC(direct use of spent PWR fuels in CANDU) cycle and the pyroprocessing. He gained his experience in nonproliferation while participating to the GIF Proliferation Risk and Physical Protection (PR/PP) activities as well as the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) activities.

He served as the President of KAERI during 2007 to 2010 and he is a member of the National Academy of Engineering of Korea. He is a professor at the Institute of Energy and Environment at Youngsan University of Republic of Korea since 2015.

He received a decoration “Woong-Bee Order” from the Korean government in 2011, and a WNA (World Nuclear Association, London) Award in 2009 for his contribution to the peaceful use of nuclear energy.

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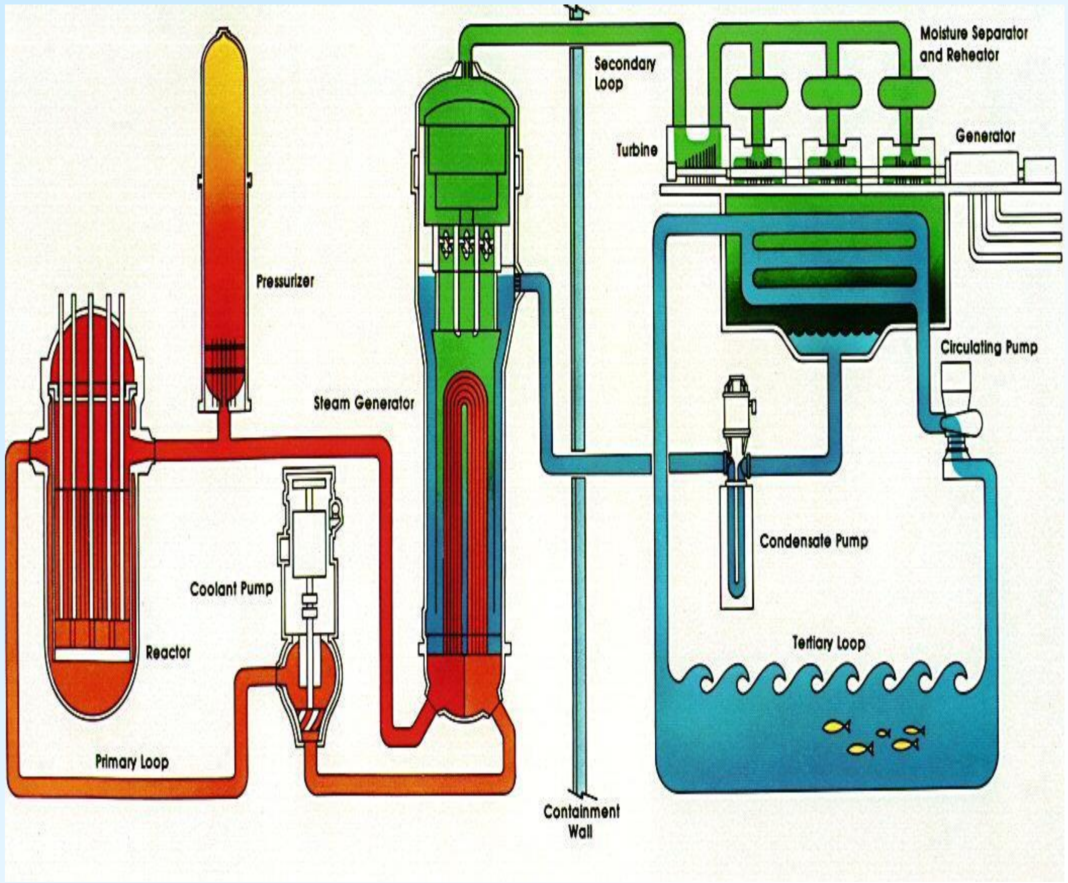
OUTLINE

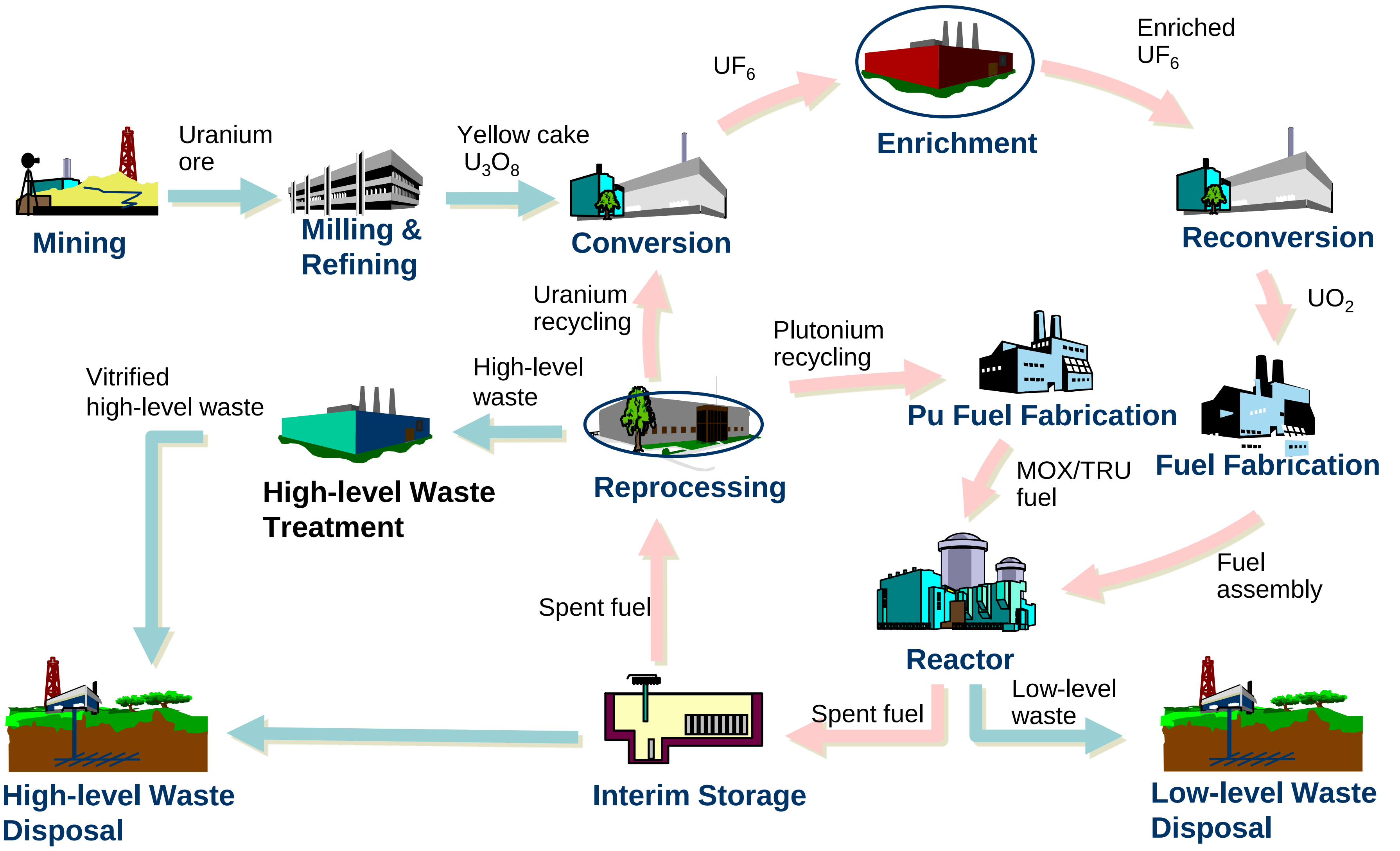
- Concept of Nuclear Fuel Cycle
- Spent Nuclear Fuel Management
- Nuclear Fuel Cycle Technology
- Summary

NUCLEAR REACTOR

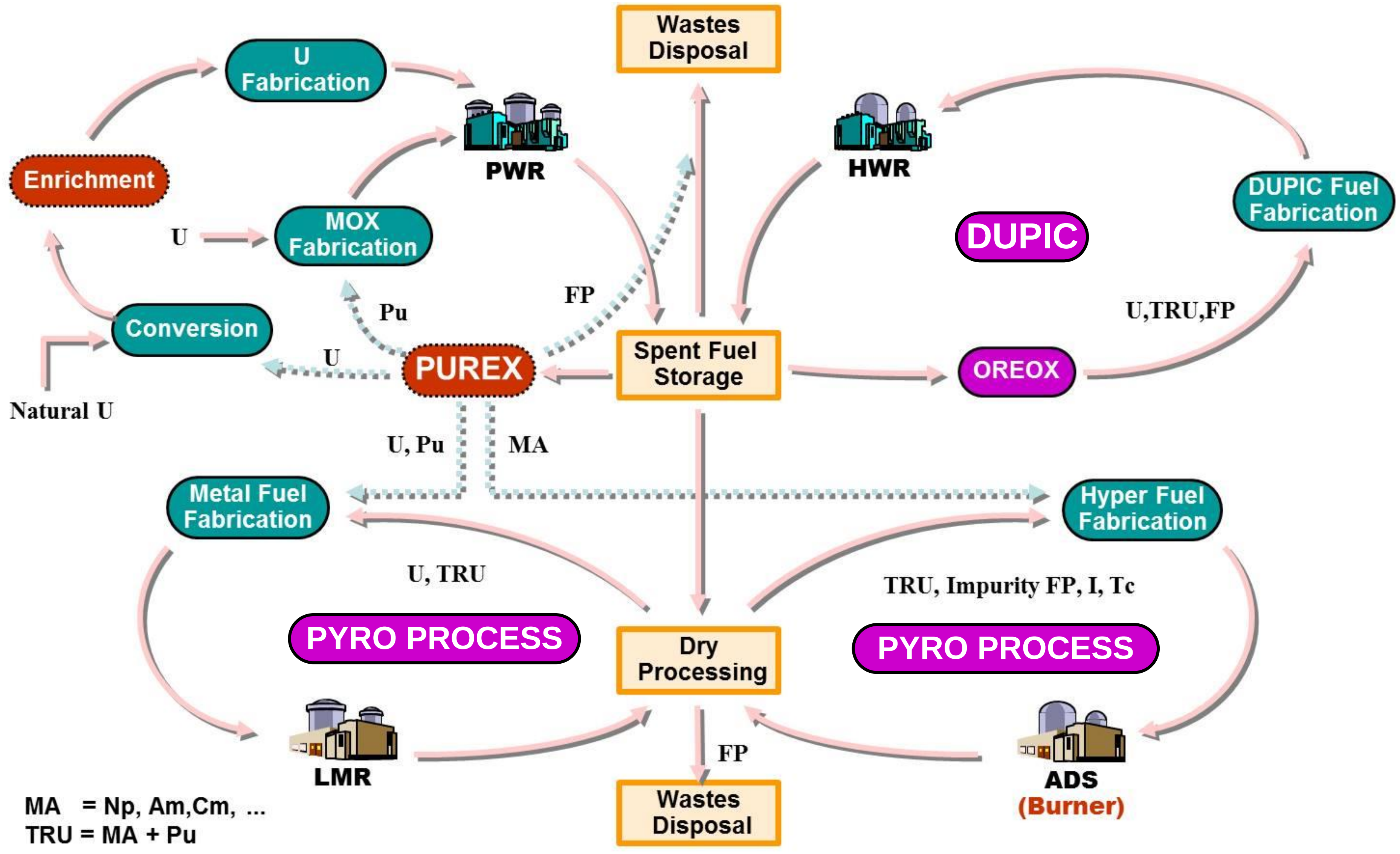


- Neutron Energy
  - Thermal (< 0.1 eV)
  - Fast (0.1 ~ 2 MeV)
- Moderator
  - Light Water (H2O)
  - Heavy Water (D2O)
  - Graphite (C)
- Coolant
  - Light Water (H2O)
  - Heavy Water (D2O)
  - Liquid Metal (Na. Pb)
  - Gas (He)
- Reactor/Fuel
  - LWR(PWR, BWR)/Fuel : Enriched UO2
  - PHWR(CANDU)/Fuel : Natural UO2
  - LMR(SFR)/ Fuel: (U/Pu)O2, U-TRU

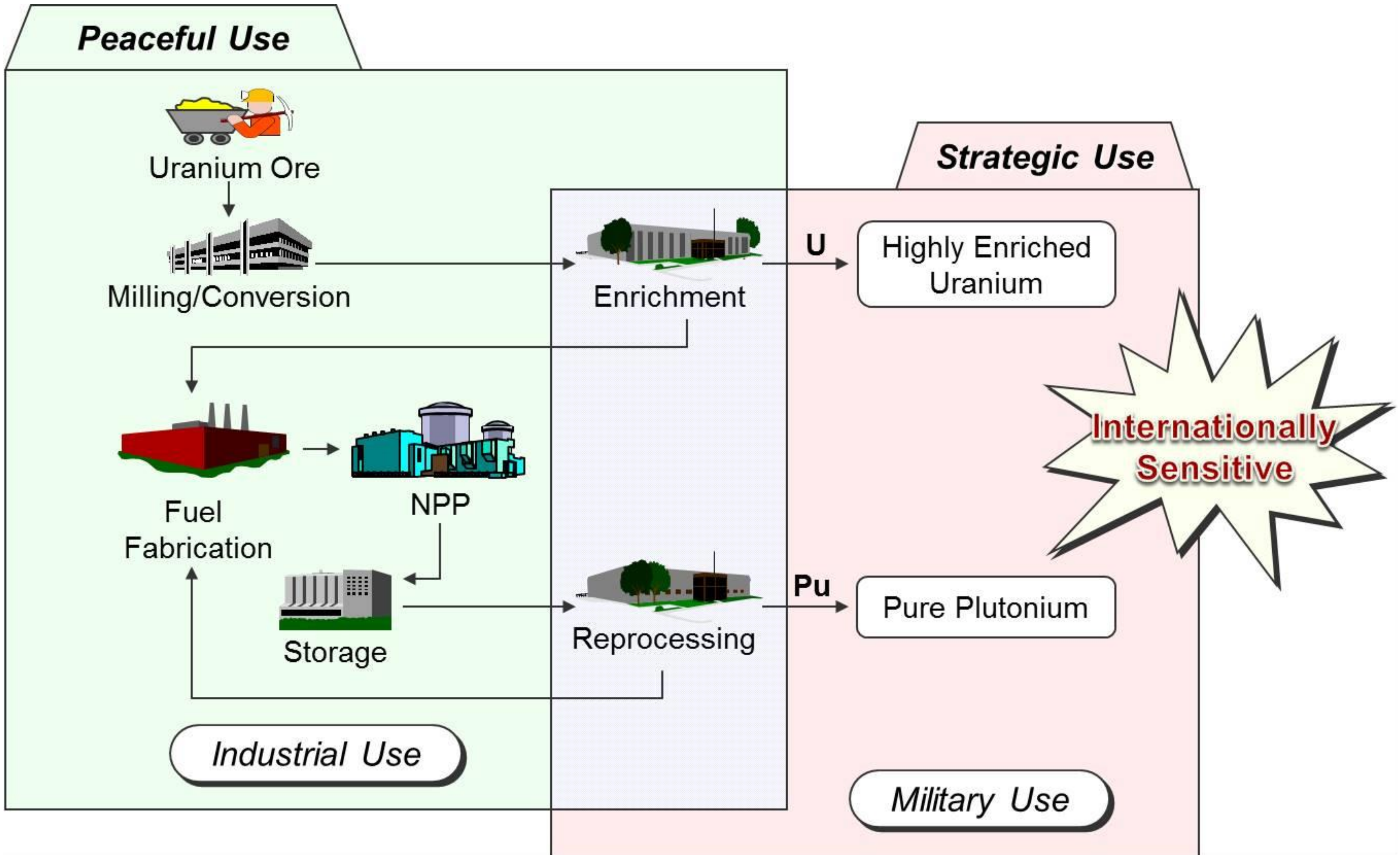
NUCLEAR FUEL CYCLE



FUEL CYCLE ALTERNATIVES



CHARACTERISTIC OF NUCLEAR FUEL CYCLE



COMPOSITION OF SPENT NUCLEAR FUEL

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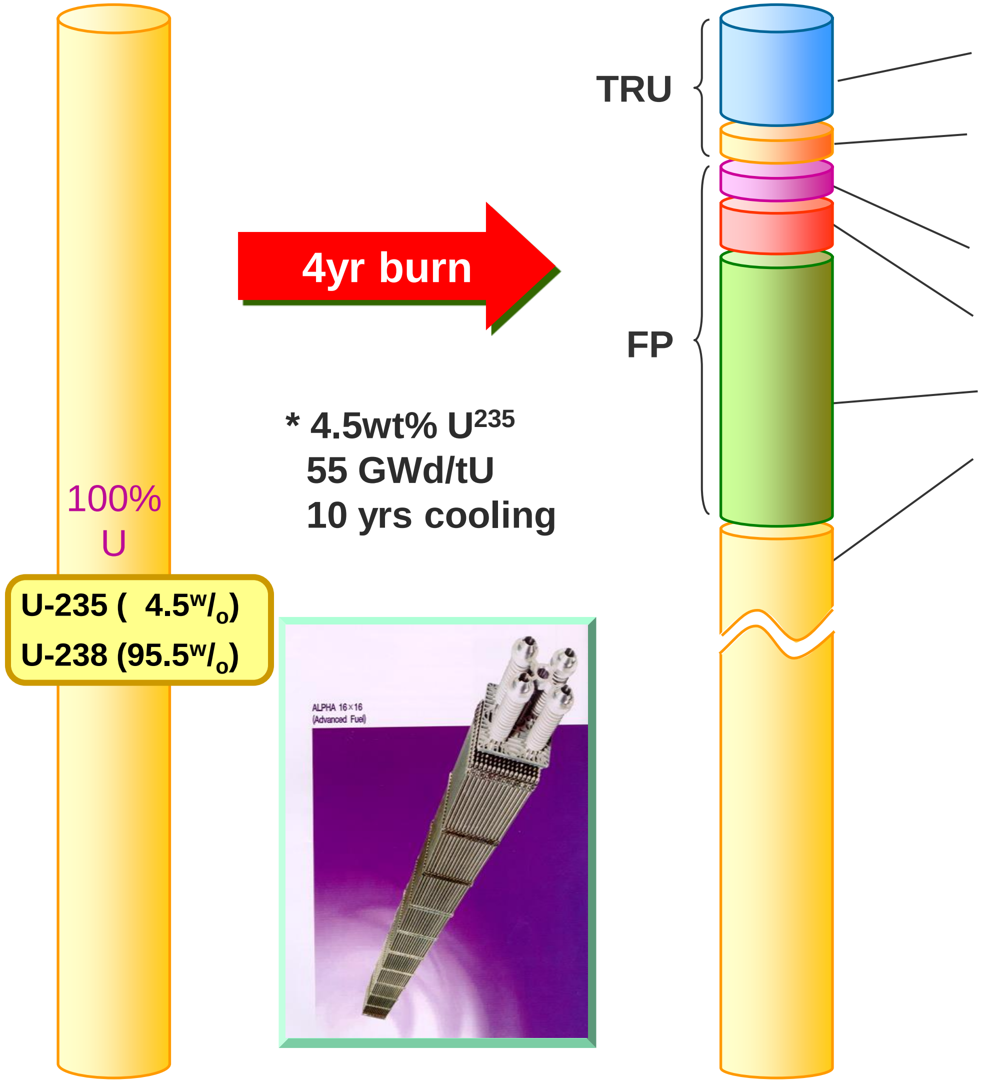


1.1% : Plutonium → **Recycle**

0.2% : Neptinum, Americium, Curium

} TRU Recycle

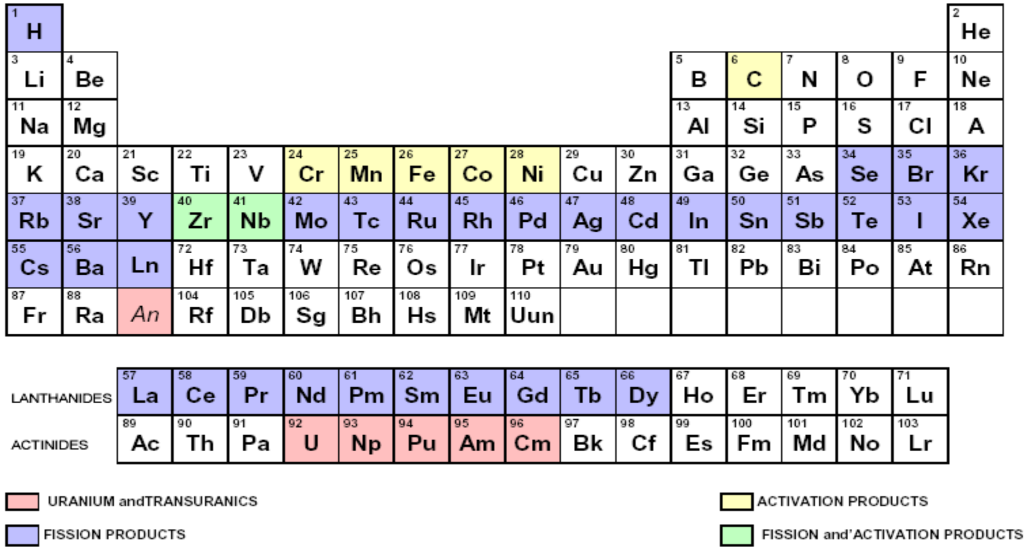
0.2% : Long Half-life (I, Tc)

0.5% : High Decay Heat(Cs, Sr)

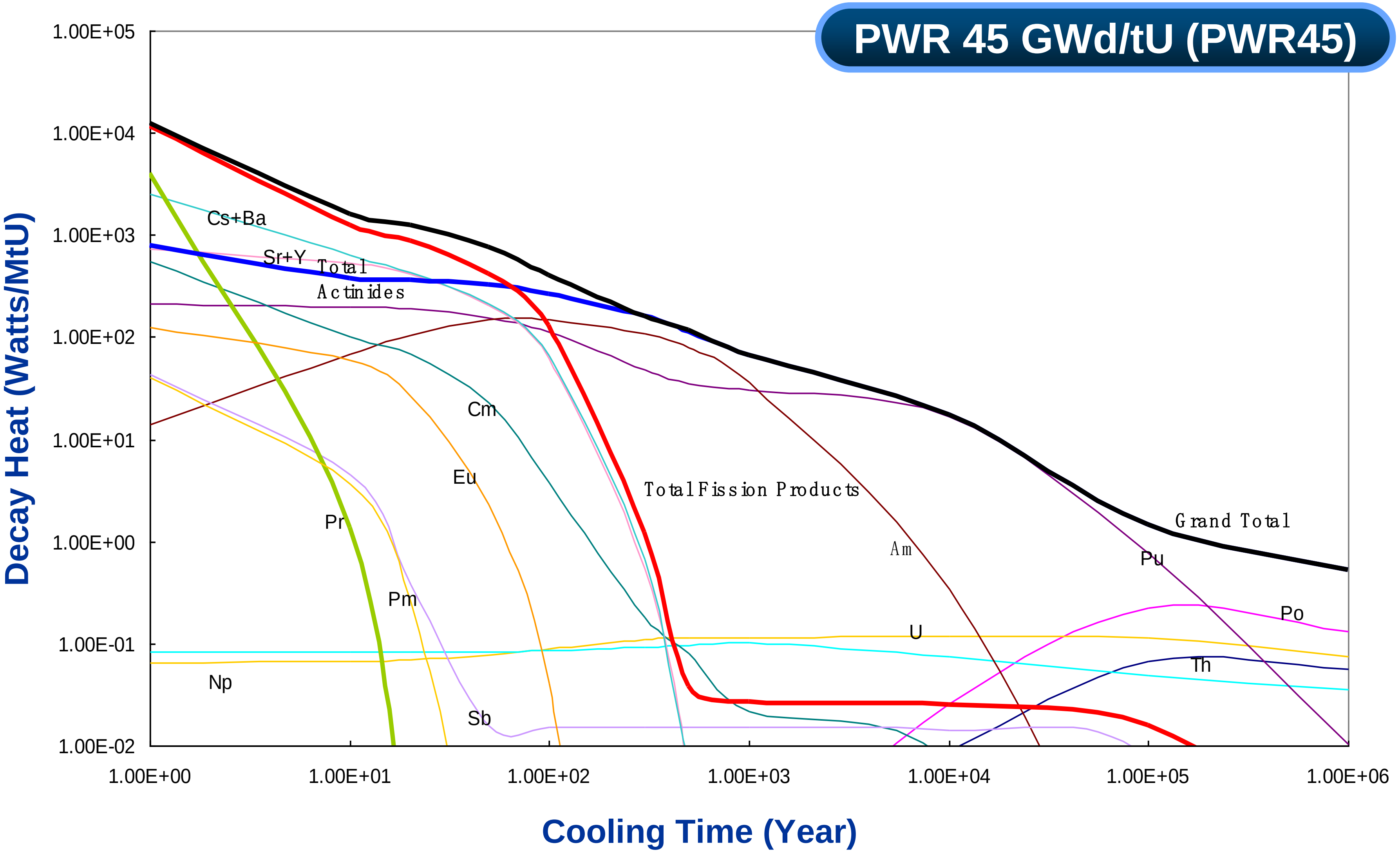
4 % : Short Half-life (less than 300 yr)

} Treatment & Disposal

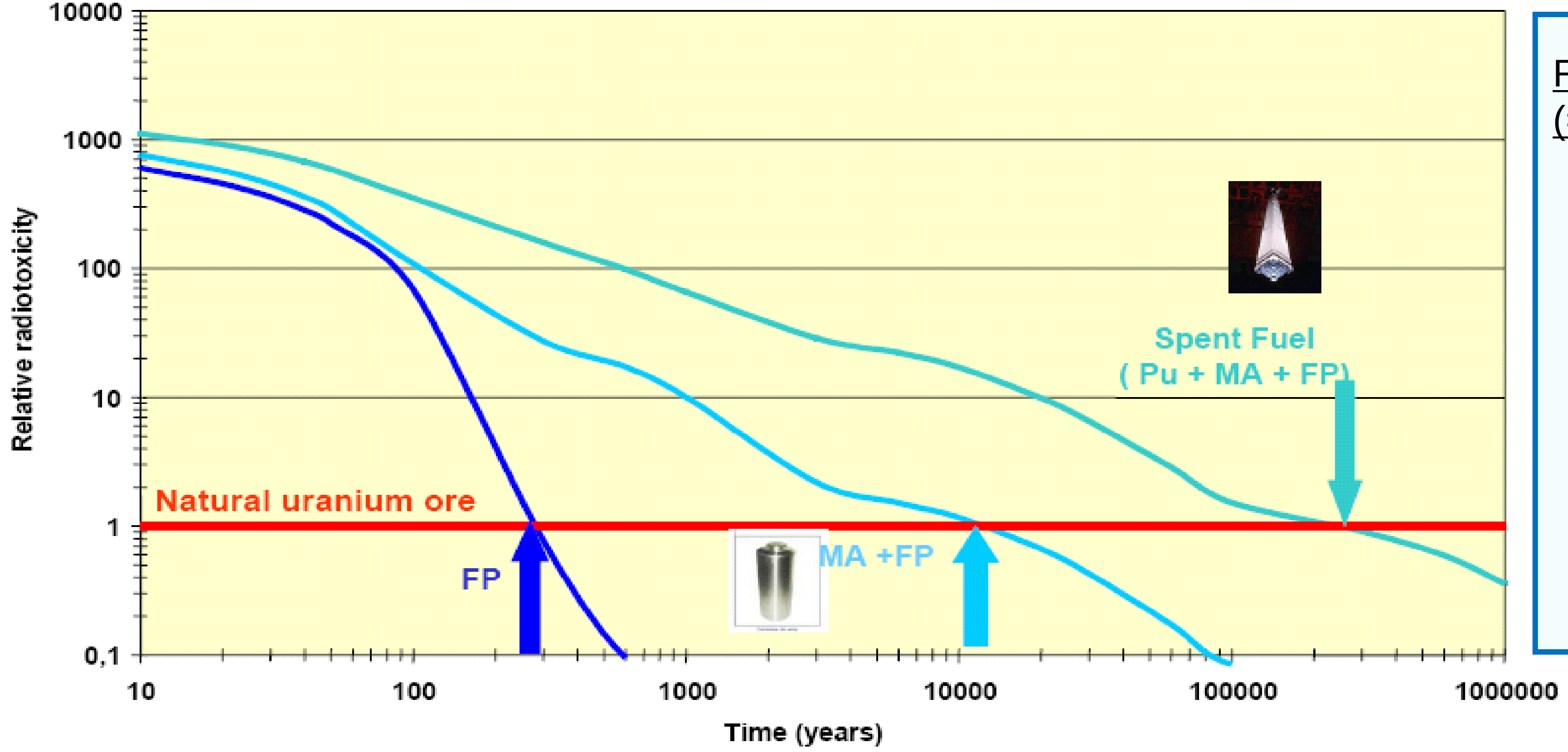
94 % : Uranium → Recycle



DECAY HEAT OF SNF



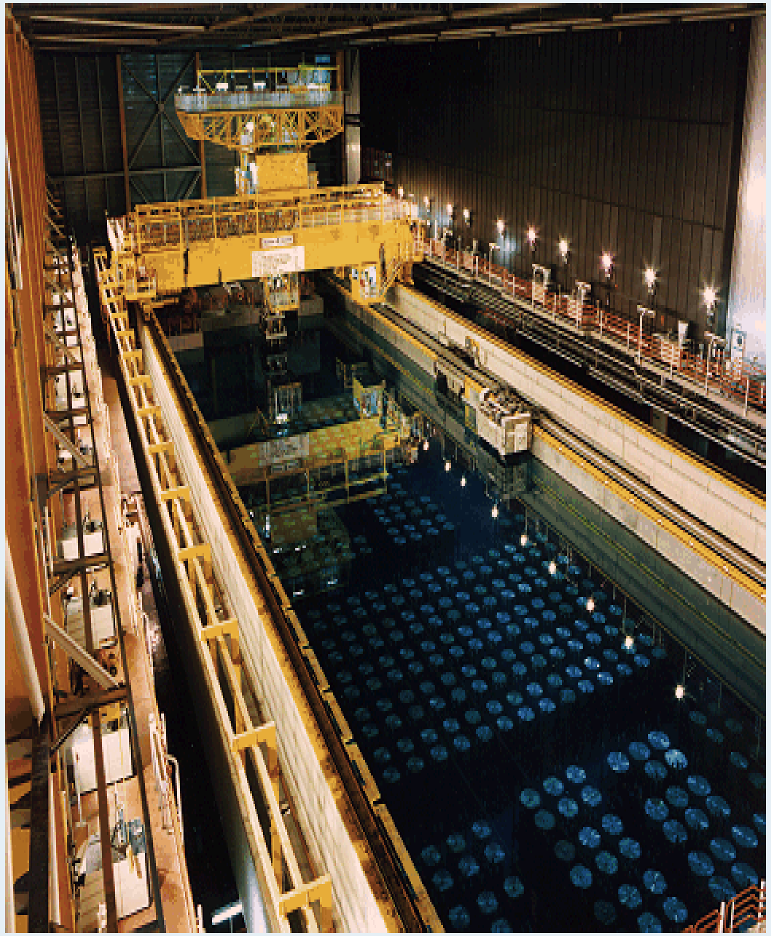
RADIOTOXICITY WITH SNF TREATMENT METHODS



Radiotoxicity with SNF management
(= Disposal site management period)

- Direct disposal :
  Over 300,000 yrs
- Pu separation from SNF:
  Below 15,000 yrs
- TRU(Pu + MA) separation:
  About 300 yrs

SNF STORAGE



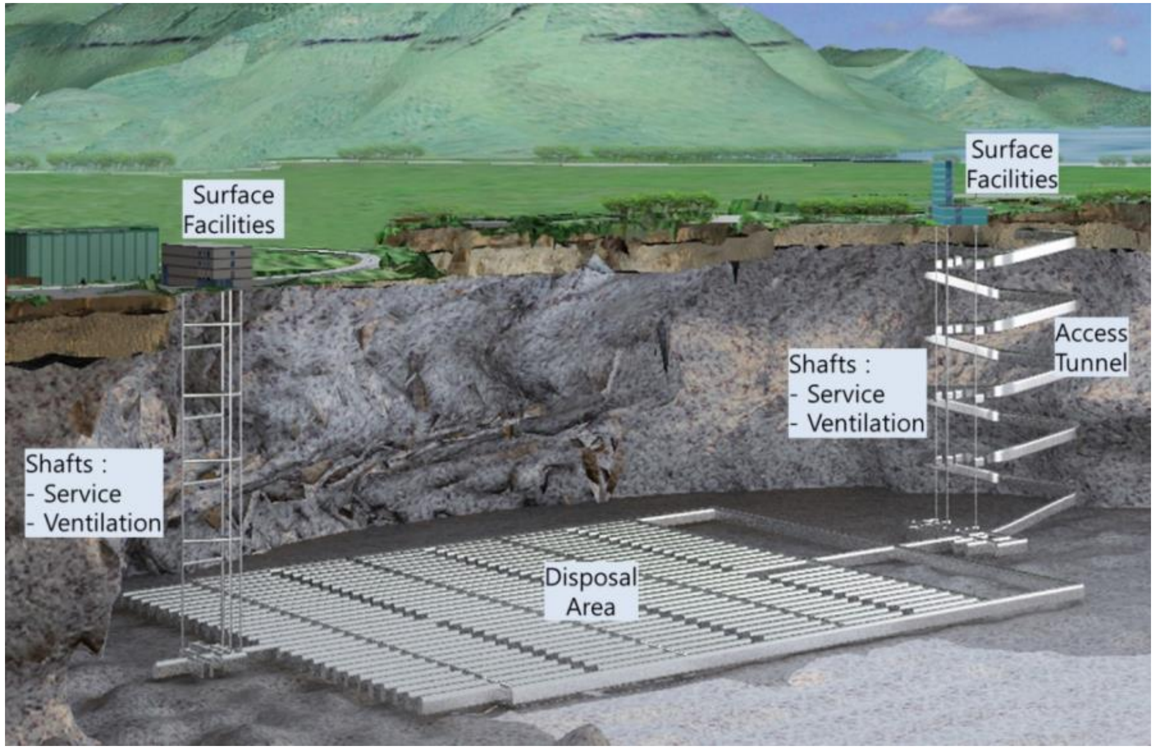
Wet

Dry

HLW DISPOSAL

- **Surface Facilities**
  - Encapsulation Plant
  - Bentonite Plant
  - Crushed Rock Plant
  - Utilities

- **Underground Facilities**
  - Shafts : Operation, Ventilation
  - Access Tunnel
  - Disposal Area

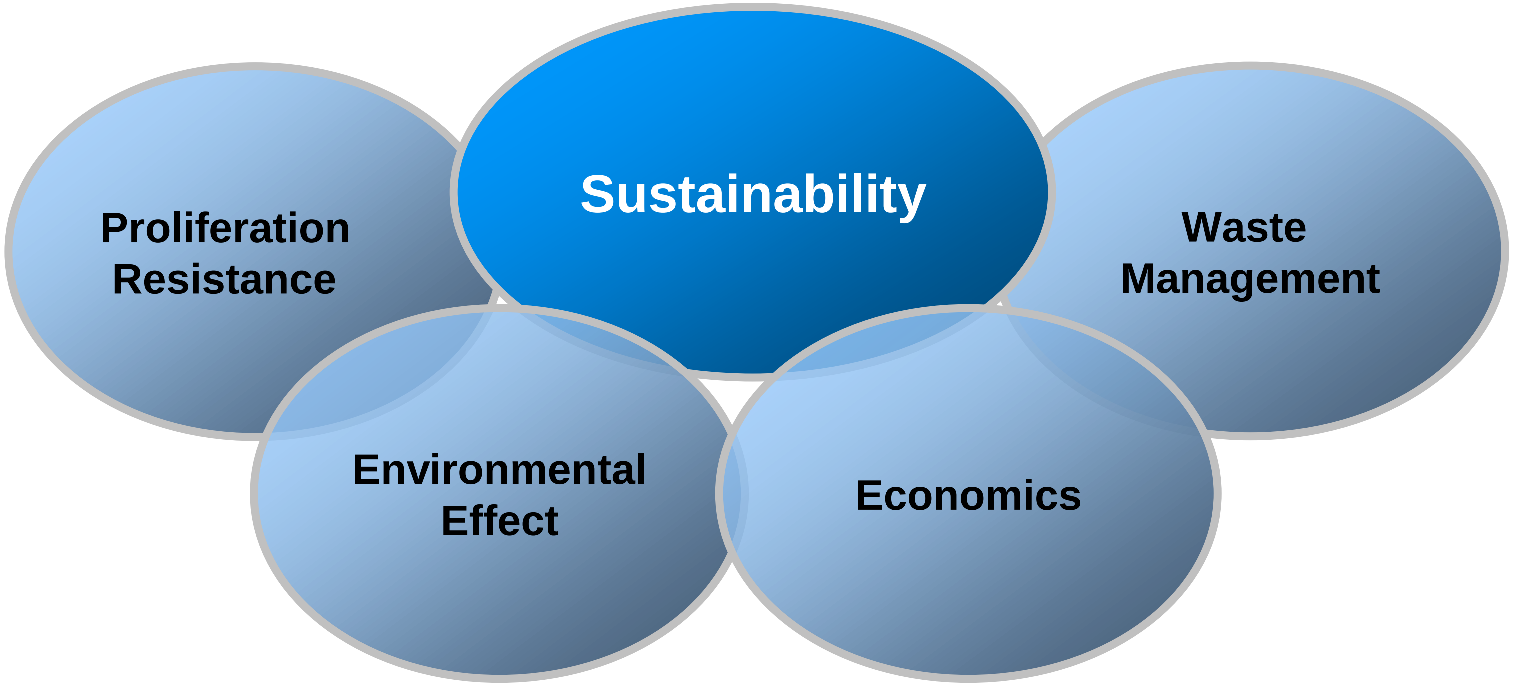


CONSIDERATIONS FOR DISPOSAL SITE

- How will prolonged exposure to heat and radiation affect the surrounding rock?
  - Radiation shielding of canister
  - Maximum allowable thermal loading per disposal package
  - Long-term integrity of engineering & natural barriers under high radiation and heat environments
- How soon will the repository be filled with groundwater?
  - Prevention of groundwater intrusion/retardation → buffer and backfill material with low permeability.
- How fast will the disposal canister corrode ?
  - High corrosion resistance of canister material → Cu, titanium, stainless-steel, etc.
- How fast will the various radionuclides dissolve ?
  - Waste matrix → insoluble solid form
- How will the dissolved substances travel through rock?
  - Buffer/backfill material with high sorption ability
  - Groundwater movement in the rock → natural process (dilution effect, additional sorption effects)

INNOVATIVE NUCLEAR ENERGY SYSTEM

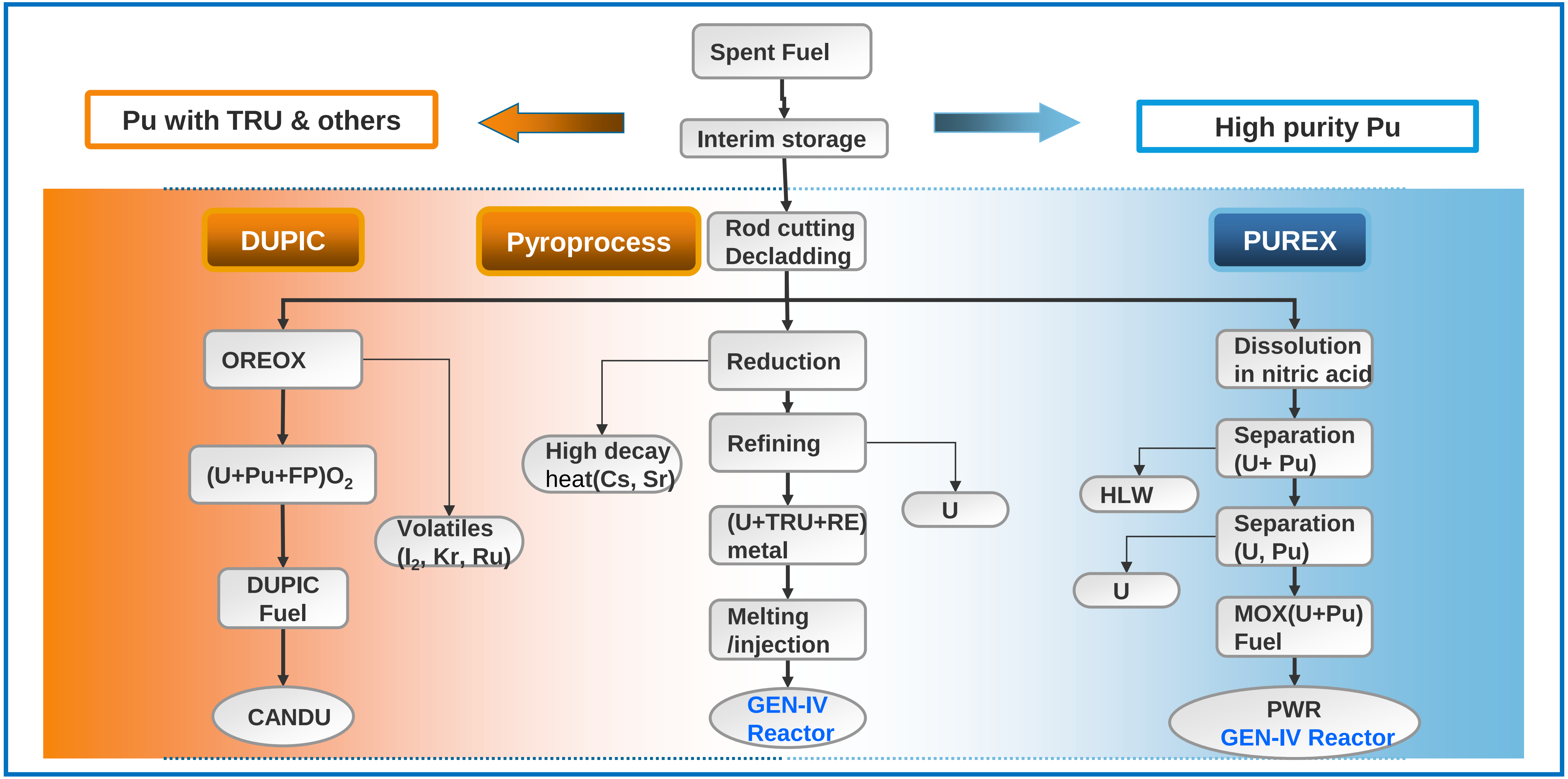
- GIF (Generation IV International Forum)
- INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles)



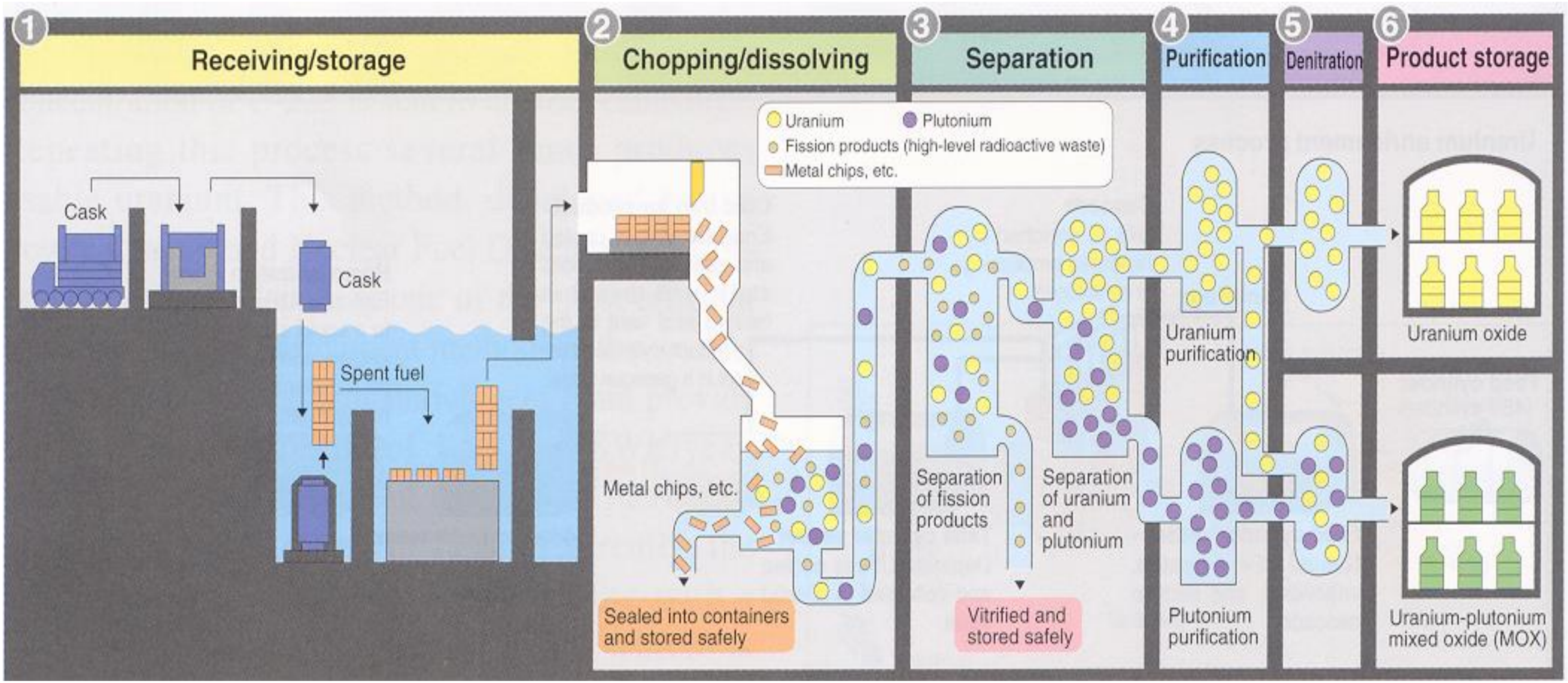
REQUIREMENT OF ADVANCED NUCLEAR FUEL CYCLE

- **Environmental Aspects**
  - Reduction of environmental burden : Reduction of radiotoxicity
  - Time of decay to the toxicity level of the initial uranium ore < 300 yrs
- **Waste Aspects**
  - Minimization of repository footprint
  - Reduction of the heat load of HLW to be disposed off < 1/100
  - Reduction of needed repository footprint < 1/100
- **Proliferation Resistance Aspects**
  - Enhancement of proliferation resistance
  - “Dirty fuel-clean waste” with homogeneous recycling of all TRUs
- **Economics Aspects**
  - Economic compatibility with the current options

PROCESS FLOW OF WET/DRY FUEL CYCLE



WET REPROCESSING (EX: PUREX)



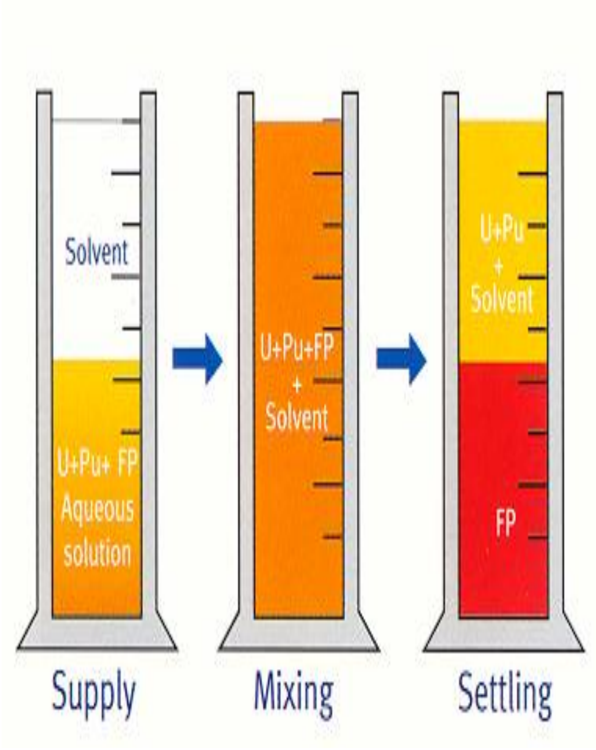
PUREX(EX)-UNIT PROCESS AND EQUIPMENT

Process	Equipment	Function
Disassembly Chopping	Mechanical Laser	Cutting fuel rods (4~5 cm)
Dissolve	Dissolver	Dissolution in hot and high HNO_3 (~130℃)
Offgas Treatment	Scrubber Adsorption column HEPA filter	Absorption of NOx gas Removal of iodine Removal of particles
Solvent Extraction	Mixer-Settler Pulsed Column	Separation of U-Pu/FP Partition of U/Pu (with oxidation control of Pu)
U Purification	Mixer-Settler Pulsed Column	Purification by solvent extraction
Pu Purification	Ion Exchanger column Mixer-Settler	Purification by ion exchange/solvent extraction
U/ Pu concentration	Evaporator	Evaporation/concentration/denitration
Rad Waste Treatment	Evaporator Compacter Cementation Vitrification	Evaporation/concentration Volume reduction of solid waste Solidification/stabilization Solidification of aqueous HLW

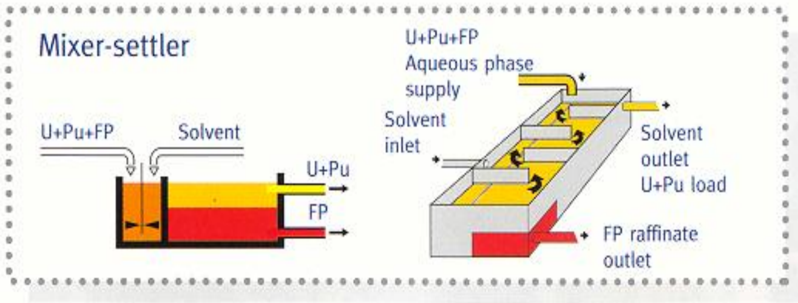
SOLVENT EXTRACTION :

U-PU COEXTRACTION, U/PU PARTITION, U & PU PURIFICATION

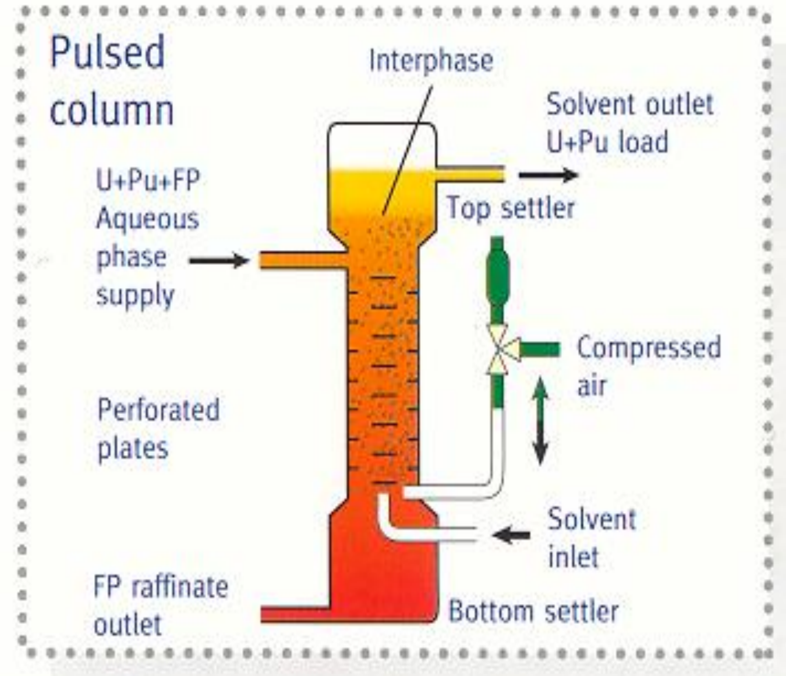
- Solvent extraction principle



- Solvent extraction equipment



Mixer-Settler



Pulsed Column

ADVANCED WET PROCESS

Commercial PUREX

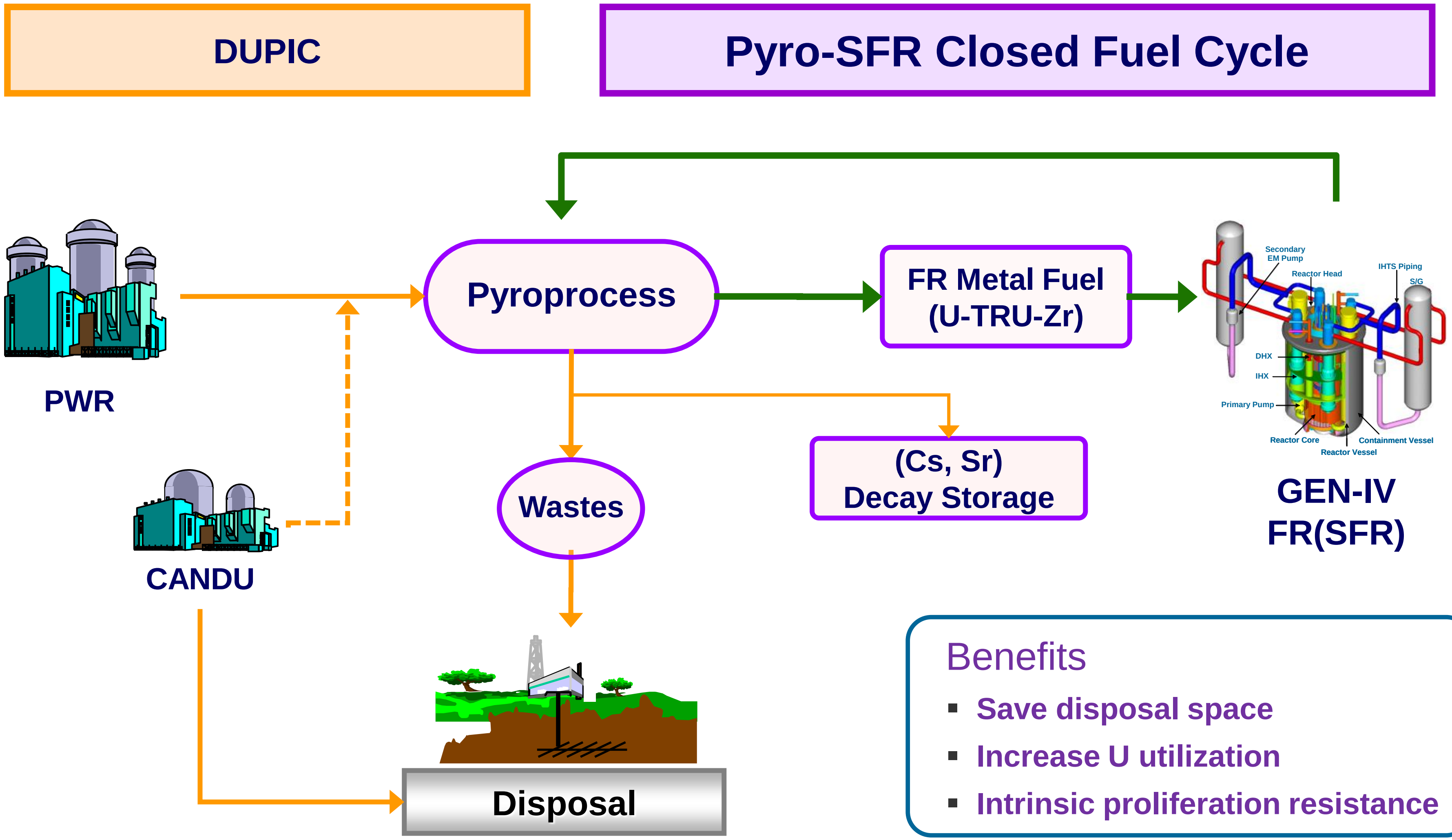
- PUREX → pure Pu extraction→ MOX fuel fabrication → LWR (Pu-thermal)
- 5 nuclear weapon states & Japan, India (PUREX)
- Economics of utilization of MOX fuel in LWR

Advanced Wet Processes

- Improved economics & proliferation resistance & HLW volume reduction
  - Transmutation of long lived nuclides → Environmentally friendly
  - Improved U utilization (closed fuel cycle)
  - Partition of long-lived and highly heat-generating nuclides

    → Improved disposal efficiency (reduced HLW volume. short management term)
  - Reuse of valuable elements (PGM, Pu, etc)
- Advanced wet process: CoDCon and ALSEP (U/Pu and TRU: USA), NEXT (U-Pu-Np: Japan), COEX (U-Pu: France)
  - Improve the recovery of TRU, Cs/Sr, long-lived fission products
  - Reducing secondary process waste amounts
  - Co-separation of U, Pu, MA, and Ans+3/Lns+3 partition
  - Use of eco-friendly salt-free solvents

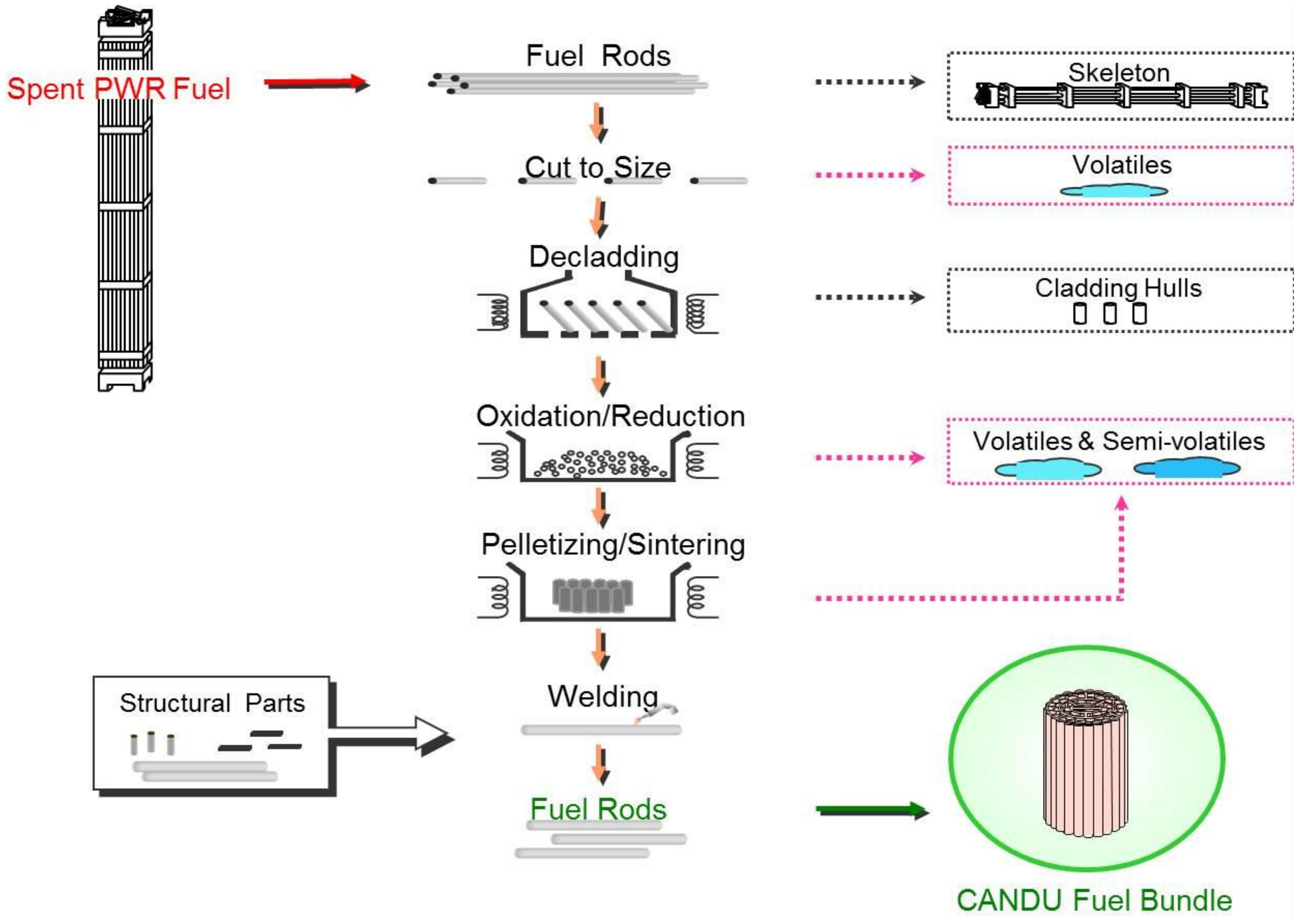
NUCLEAR FUEL CYCLE STRATEGY
(EXAMPLE)



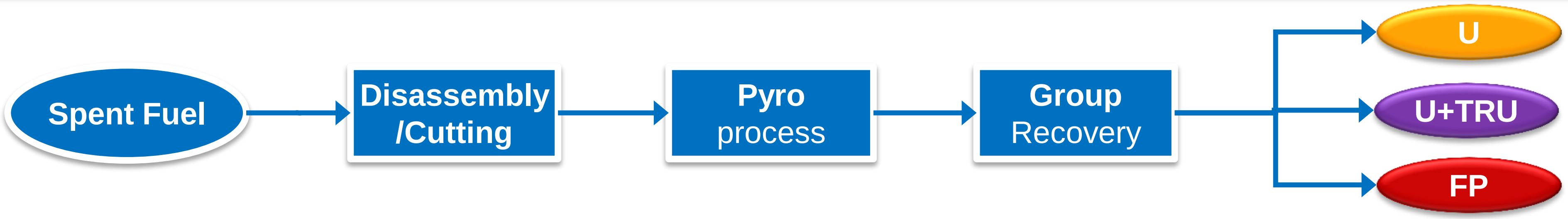
Benefits

- **Save disposal space**
- **Increase U utilization**
- **Intrinsic proliferation resistance**

DUPIC (DIRECT USE OF SPENT PWR FUEL IN CANDU REACTORS)



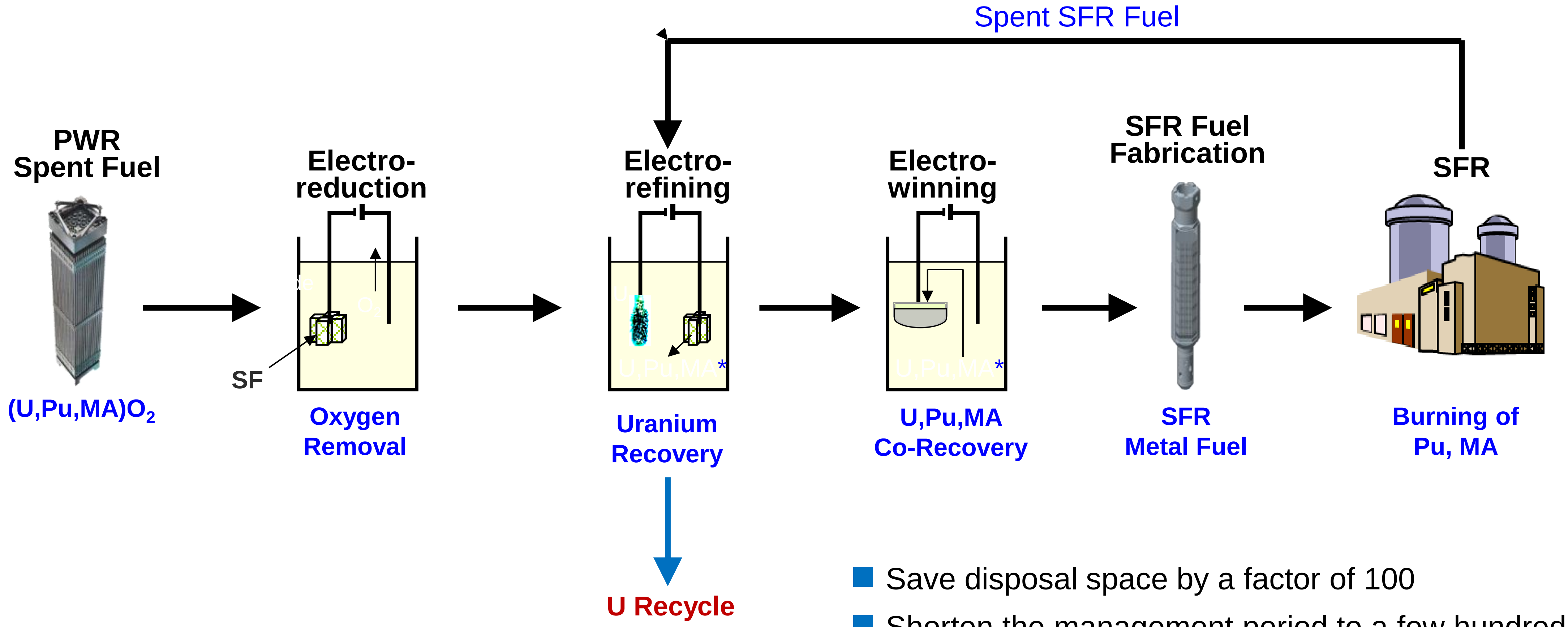
DRY PROCESS TECHNOLOGY



Process	Fuel	Operation	Chemical agents
Pyro-metallurgical	Metal fuel (EBR-II)	Batch	UCl_3 $ZnCl_2$, $MgCl_3$ $LiCl\text{-}NaCl\text{-}MgCl_2$
Pyro-chemical	Oxide fuel	Batch	$LiCl\text{-}KCl\text{-}MgCl_2$ Cu-<g-Ca alloy
Fluoride volatility	Metal & Oxide fuel	Batch	UF_6 PuF_6 F_2, ClF_3

- High PR due to no Pu separation, Fuel type with Mixture of U+TRU (Pu+MA) linking to Gen-IV SFR
- Korea, USA, China, India, Russia, etc.

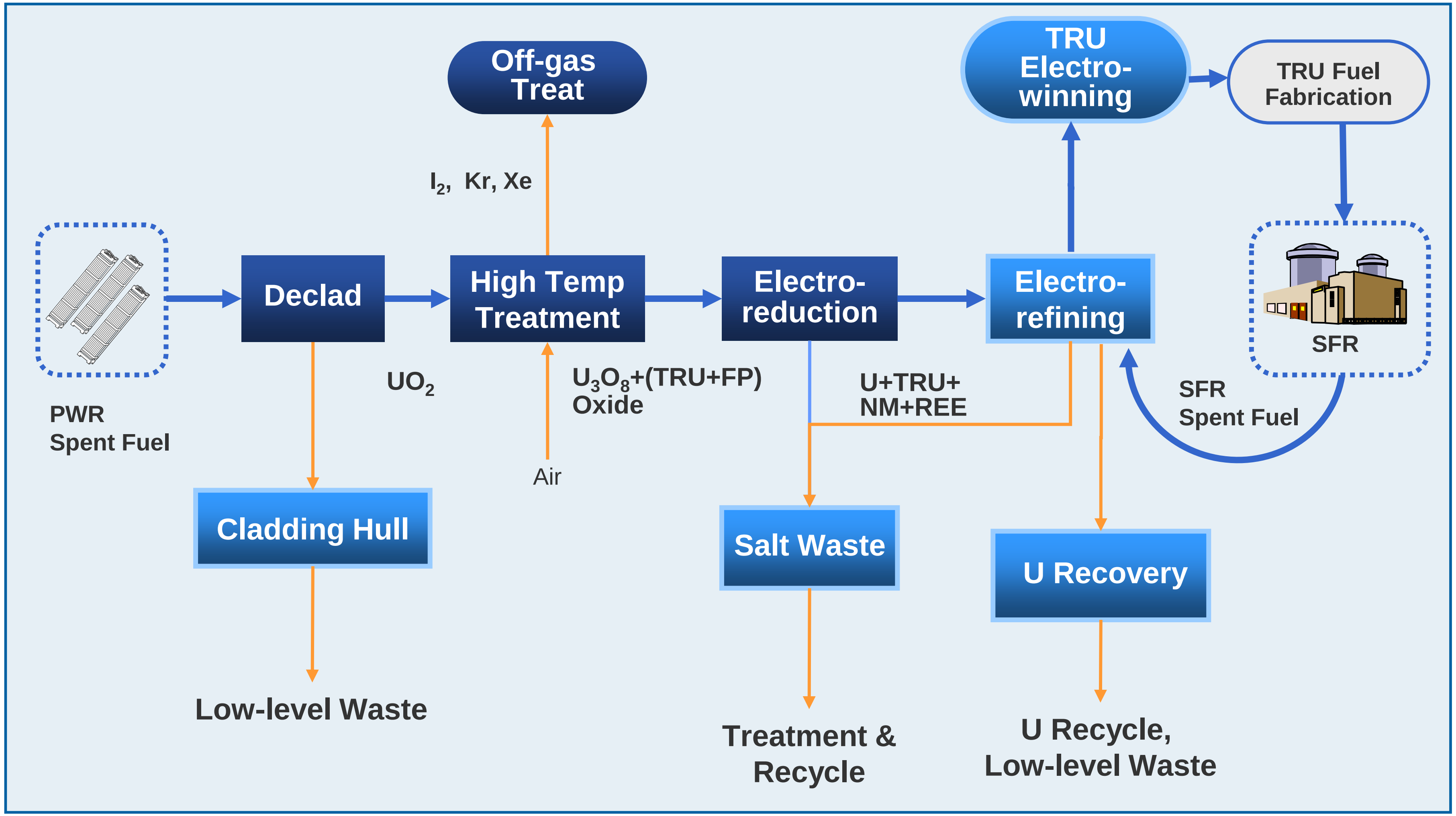
PYRO-SFR CLOSED FUEL CYCLE



- Save disposal space by a factor of 100
- Shorten the management period to a few hundred years
- Increase U utilization by a factor of 100
- Ensure intrinsic proliferation resistance

❖ MA: Np, Am, Cm

PYROPROCESSING - PROCESS FLOW

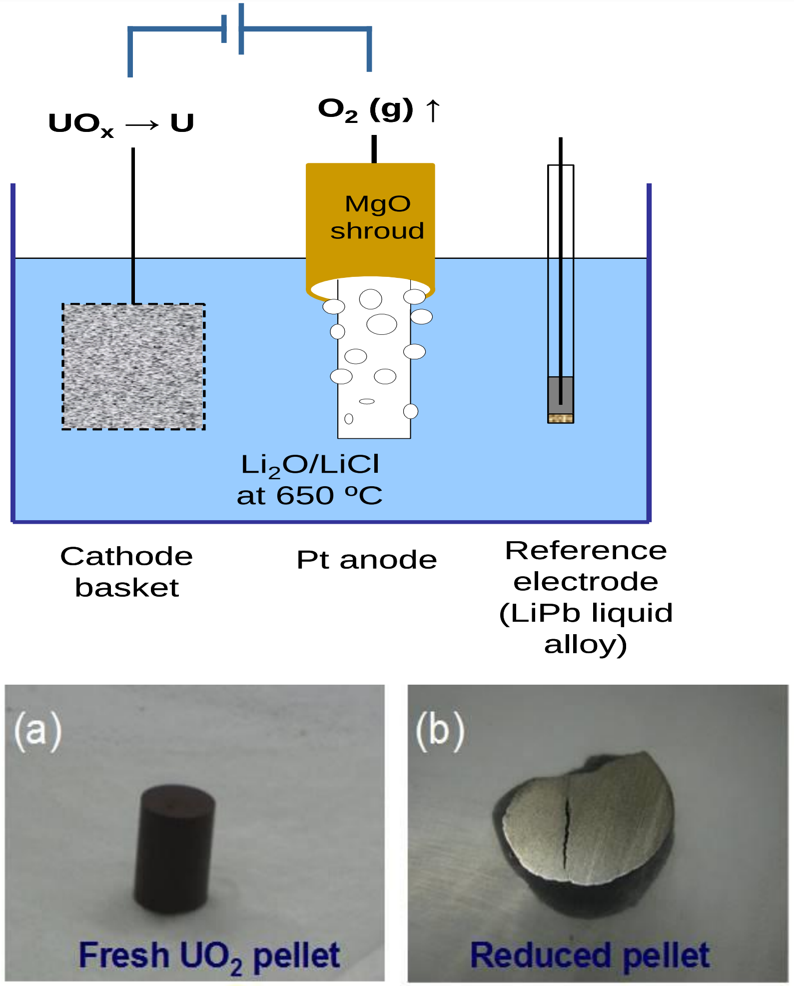


TRU: TRansUranium (Pu,Np,Am,Cm)

REE: Rare Earth Element (Eu, Gd, Nd, Ce)
NM: Noble Metal (Pd,Ru,Rh)

PYROPROCESSING - ELECTROLYTIC REDUCTION

Electrolytic reduction in molten salt: Metal product (U+TRU+Some FPs) for elctrorefining



- Cathode : Reduction

  $UO_2 + 4e^- \rightarrow U + 2O^{2-}$

  $Li^+ + e^- \rightarrow Li$

  $U_xO_y + 2yLi \rightarrow xU + yLi_2O$

  $2Li_2O \rightarrow 2Li^+ + O^{2-}$

- Anode : Oxidation

  $O^{2-} \rightarrow ½O_2 + 2e^-$

Metal product	Reduction to metal	U, TRU(Pu, Am, Cm, Np) NM(Zr, Pd, Rh, Ru etc.)
	No reduction	RE(Y, Pr, Nd, La etc.)
Salt	Remaining salt phase	AM & AEM(Cs, Sr, Ba)

COMPARISON OF WET & DRY PROCESS

Process	PUREX	Pyroprocess
No. of components[1)] [Compactness]	About 180	< 20
Cooling time	> 5 years	< 1 year
Criticality hazard	High	Low
Pure Pu separation	Yes	No [U+TRUs]
Operation mode	Continuous type	Batch type
Waste generation[2)] (HLW)	230 te (UREX+)	490 te
Demonstration	Commercial	Laboratory

- **Process Development**
  - High throughput reactor system
  - Corrosion-resistant materials including electrodes
- **Process Waste Minimization**
  - Recycling of used salts
  - Waste form integrity
- **Safeguardability Improvement**
  - Near real time accounting
  - Safeguards by design
- **Economical Feasibility**
  - Process modeling & simulation
  - Integrated engineering-scale demonstration

1) H. Tanaka, et al., "Design Study on Advanced Reprocessing System for FR Fuel Cycle," Global-2001, September 2001, Paris.
2) USDOE, AFCI Comparison Report, May 2005 [Basis: 2,000 MT of Spent Fuel].

NUCLEAR NONPROLIFERATION REGIME

- System to prevent the diversion of peaceful use technology from military use and to prevent the nuclear weapon test to improve nuclear weapon
  - Vertical Proliferation
    - Increase in the nuclear arms of the five nuclear weapon states
    - Preventive measures : Test-ban, Fissile material cutoff
  - Horizontal Proliferation
    - Increase the number of countries with nuclear weapons
    - Preventive measures : Safeguards, Exports control, Physical protection
- Safeguards : Activities that impede the diversion of undeclared production
  - Material control and accounting, Containment and Surveillance (C/S)
  - IAEA inspection, Record/Reporting/Verification
- Safeguardability
  - **Degree of ease** with which IAEA technical objectives can be, Including features to help the implementation of safeguards (e.g., Material control, Facility design) met in cost effectiveness and to establish facilities whose process, design, and layout support the effective and efficient implementation of IAEA safeguards

PROLIFERATION POTENTIAL & SAFEGUARDS CHALLENGES

- Pyroprocessing has lower proliferation potential
  - Limited capability in separating Pu, additional chemical separation activity is required for further separation of Pu
  - Less flexibility in changing product purity and throughput
  - High dose of U/TRU product requires additional radiation shielding
- Safeguards challenges
  - Less safeguards experience (no commercial scale facility)
  - Larger measurement uncertainties of feed, product, waste and process material
  - Sampling procedures, DA(destructive analysis), NDA and process parameters are not yet established
  - Signature and indicators of the IAEA physical model need to be updated

- To develop the nuclear material accounting and surveillance technology
- To design a safeguards system based on the concept of Safeguards-by-Design
- To Investigate the safeguardability of a pyroprocessing facility

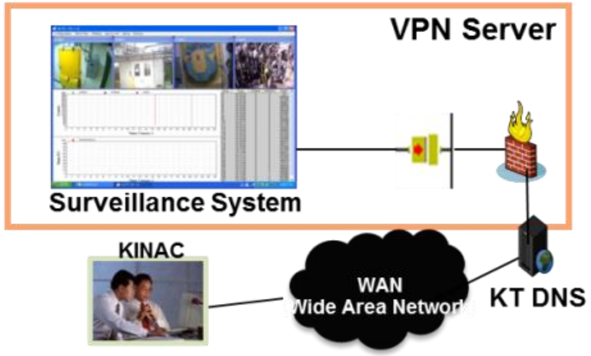
SAFEGUARDS R&D

- Safeguards Neutron Counter and C/S system
  - Development of built-in safeguards system in international cooperation with IAEA
  - Passive neutron coincidence counter with a full remote maintenance capabilities
  - C/S monitoring data transmitted to Regulator and IAEA through Virtual Private Network
  - Upgrade with enhanced remote control capability

EXAMPLE

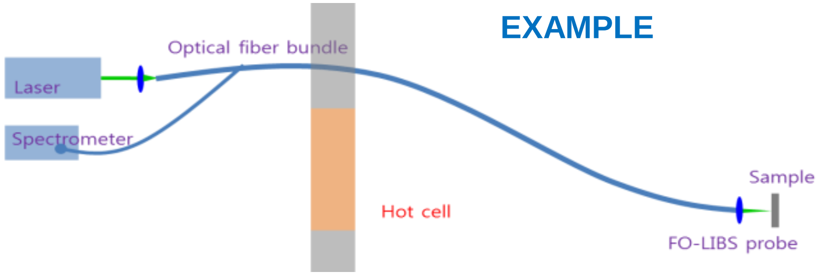
ASNC installed in the ACPF hot cell

EXAMPLE



- LIBS(Laser Induced Breakdown Spectroscopy) Monitoring system
  - To determine the elemental composition of the samples of interest through real-time analysis, in-situ measurement and multi-elemental analysis
  - Applicability test to address safeguards and process monitoring

EXAMPLE



ECONOMICS EVALUATION OF NFC

The dynamic behavior of nuclear energy system economics (from 2013 to 2100) by comparing the total system costs for the once-through fuel cycle with those for the closed fuel cycle associated with pyroprocessing and SFR

- For the total system costs, the closed nuclear energy system is more expensive than that the once-through system.
- For the fuel cycle costs only, the once-through fuel cycle is expected to increase the cost of nuclear generated electricity compared to the fuel cycle cost of the closed fuel cycle

- However, the levelized cost distributions of the two nuclear energy systems largely overlap because of large cost uncertainties involved with all system steps
- Cost saving for the closed system is to be proved and requires further development and demonstration of the technology on the engineering-commercial scale basis

POLICY FOR SNF MANAGEMENT(EXAMPLE)

	Korea	USA	Japan	France	Russia	China	India
Fuel Cycle Policy	Wait & See	Direct disposal/ Wait & see (P&T)	Recycle (P&T)	Recycle (P&T)	Recycle (P&T)	Recycle (P&T)	Recycle (P&T)
Target Yr for INS	2020's	2040s	2040s	2020 ~ 2040	2020s	2020s	2020s
Recycle Method	Pyro	Wet (Advanced Aqueous) Pyro	Wet (NEXT) Pyro	Wet (COEX /GANEX)	Wet (Advanced Aqueous) Pyro	Wet (PUREX) Pyro	Wet (PUREX) Pyro
Reactor (Fuel)	SFR (Metal)	SFR (Metal, Oxide)	SFR (Oxide)	SFR (Oxide) GFR (Carbide, Nitride)	SFR (Oxide, Nitride)	SFR (Mixed oxide)	SFR (Mixed carbide, Oxide, Metal)

SUMMARY

- Benefits of closing nuclear fuel cycle
  - Sustainability
  - Management of high level waste
  - Environmental friendly
  - Management of repository for permanent disposal
  - Enhanced proliferation resistance
- Advanced wet & dry fuel cycle processes along with safeguards technology under development
- National policy of spent fuel management to be decided

UPCOMING WEBINARS

22 November 2016	Introduction to Nuclear Reactor Design	Dr. Claude Renault, CEA, France
15 December 2016	Sodium Cooled Fast Reactors	Dr. Robert Hill, ANL, USA
25 January 2017	Very High Temperature Reactors	Mr. Carl Sink, DOE, USA