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# Nuclear Fuel Cycle: Trends and Options for Innovative Nuclear Energy Systems

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Joint IAEA-ICTP Workshop on Physics and Technology of Innovative Nuclear Energy Systems

12-16 December 2022, ICTP, Trieste, Italy

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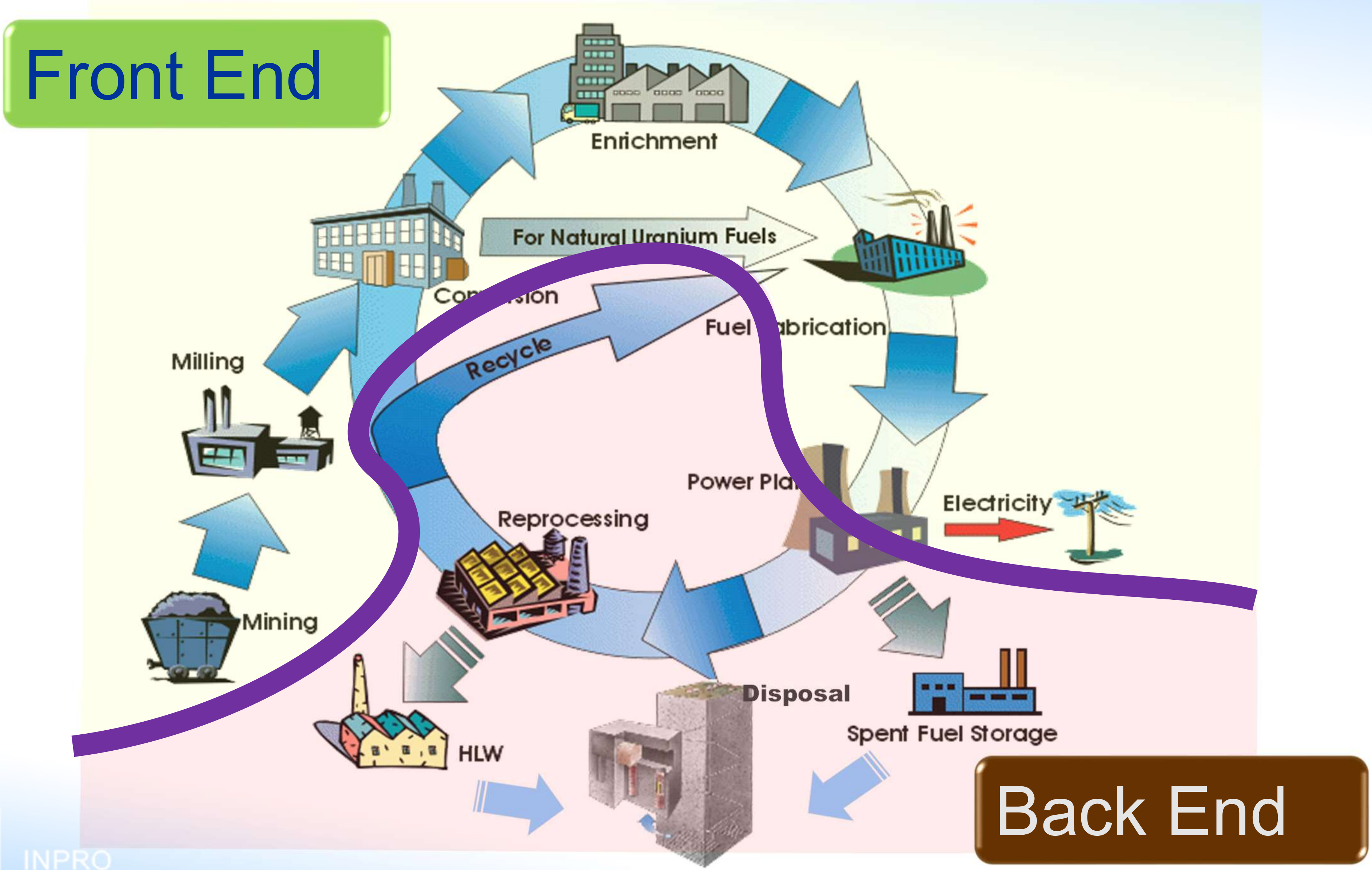
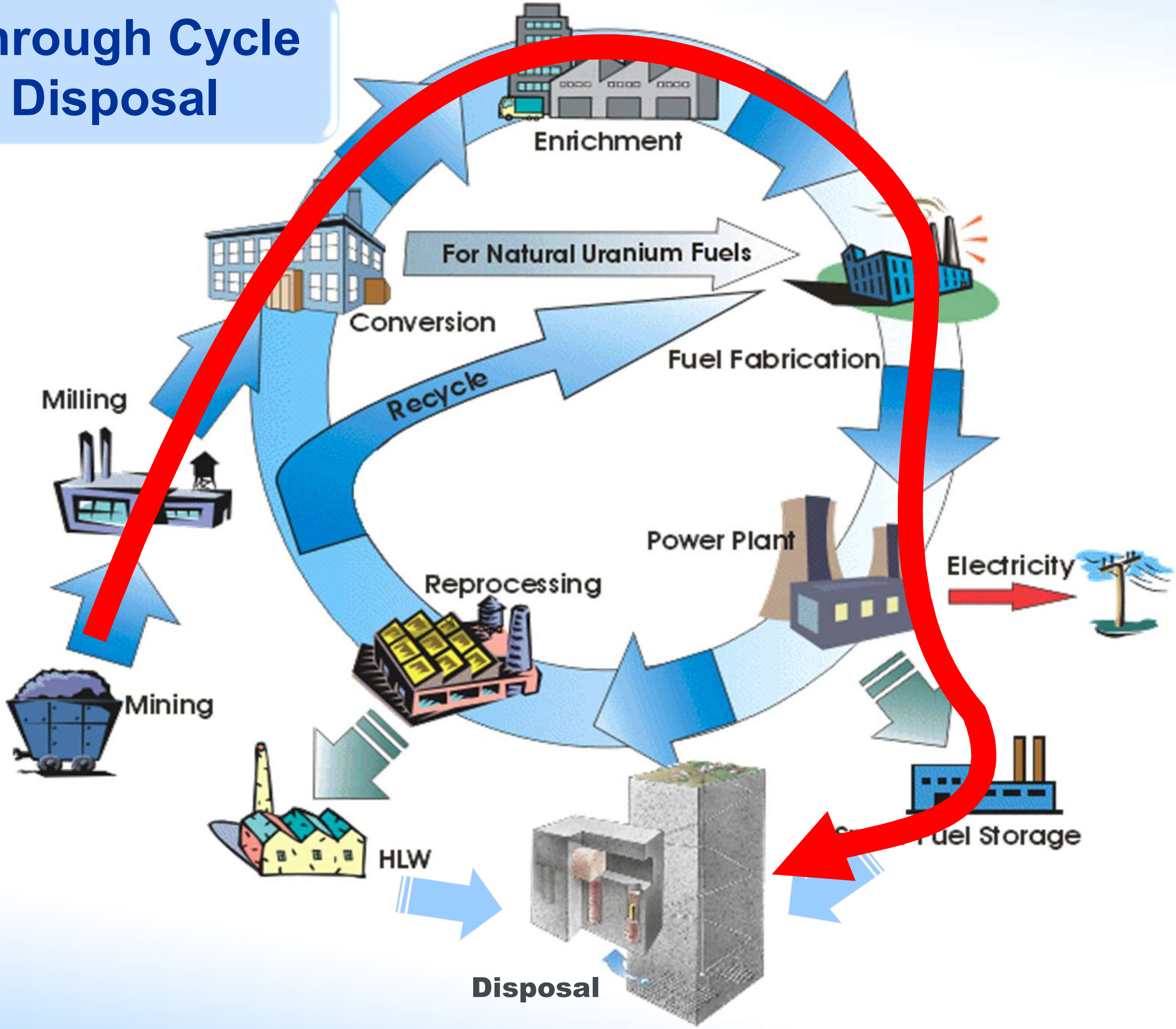
International Project on Innovative Nuclear Reactors and Fuel Cycles

# NUCLEAR FUEL CYCLE



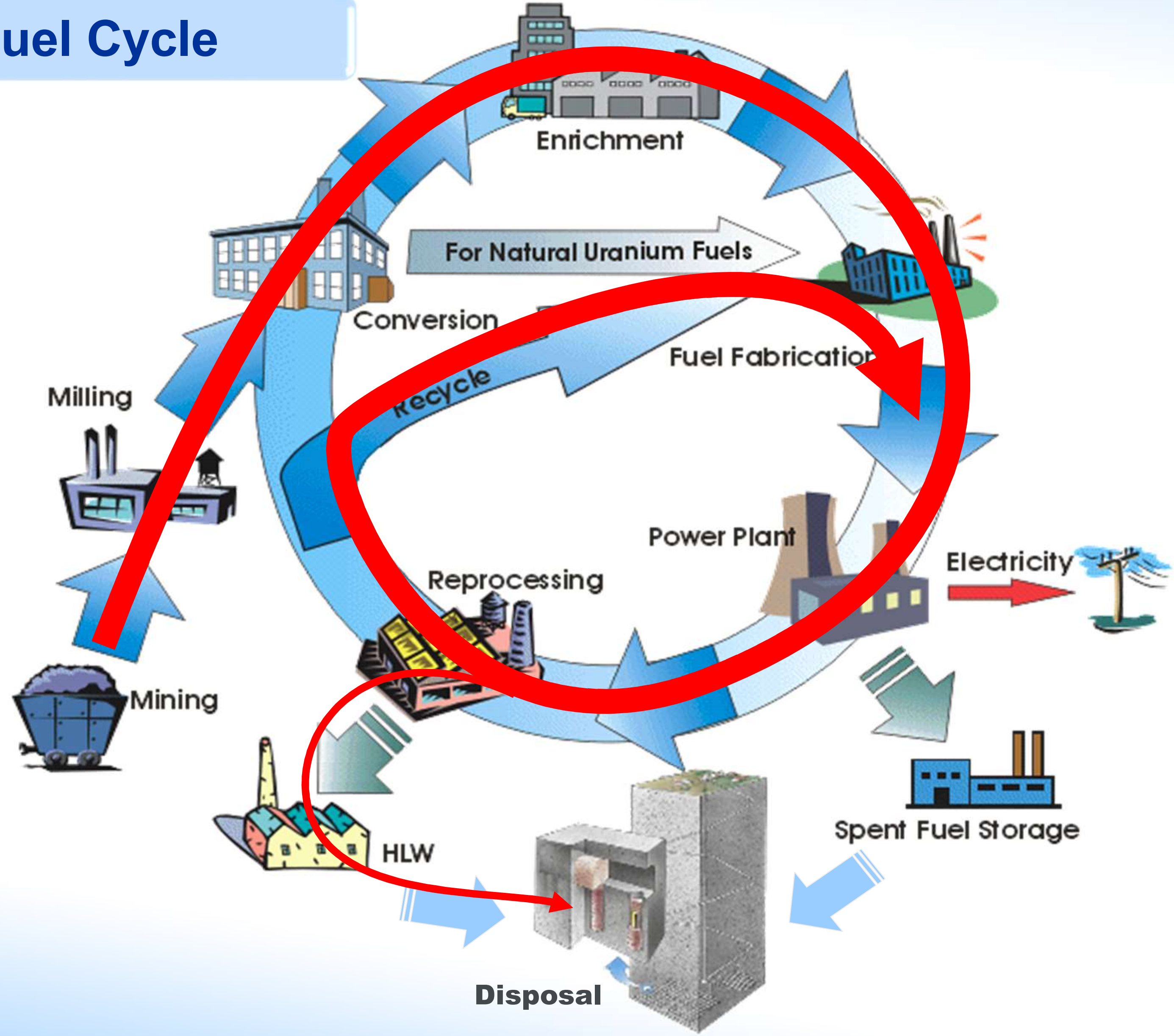
# TYPES OF NUCLEAR FUEL CYCLE

**Once Through Cycle**
**- Direct Disposal**



# TYPES OF NUCLEAR FUEL CYCLE

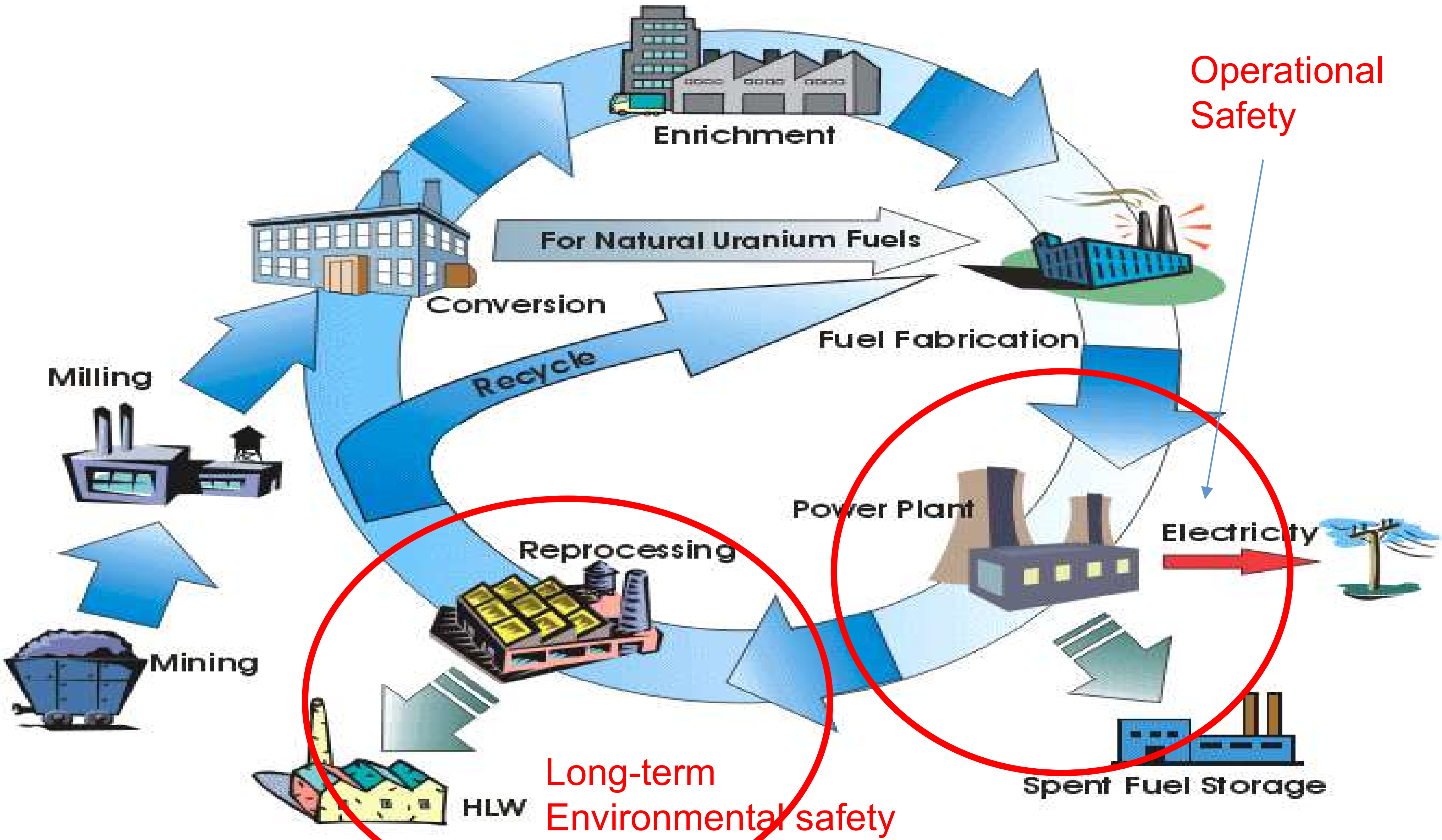
## Closed Fuel Cycle



# WHY THE CURRENT NUCLEAR FUEL CYCLE SHOULD BE IMPROVED?

- Nuclear Safety: a number of Nuclear Fuel and Fuel Cycle aspects effect on Nuclear safety
- Economics of Nuclear Power: Nuclear Fuel Cycle is important part of NP economics
- Non-proliferation: weapon grade nuclear materials - HEU and WG-Pu – can produced by NFC technologies
- Resources for Nuclear Power: the future of Nuclear Power depends on natural uranium and recycled actinides

# NUCLEAR FUEL CYCLE – SAFETY



# NUCLEAR FUEL FABRICATION – FUEL SAFETY

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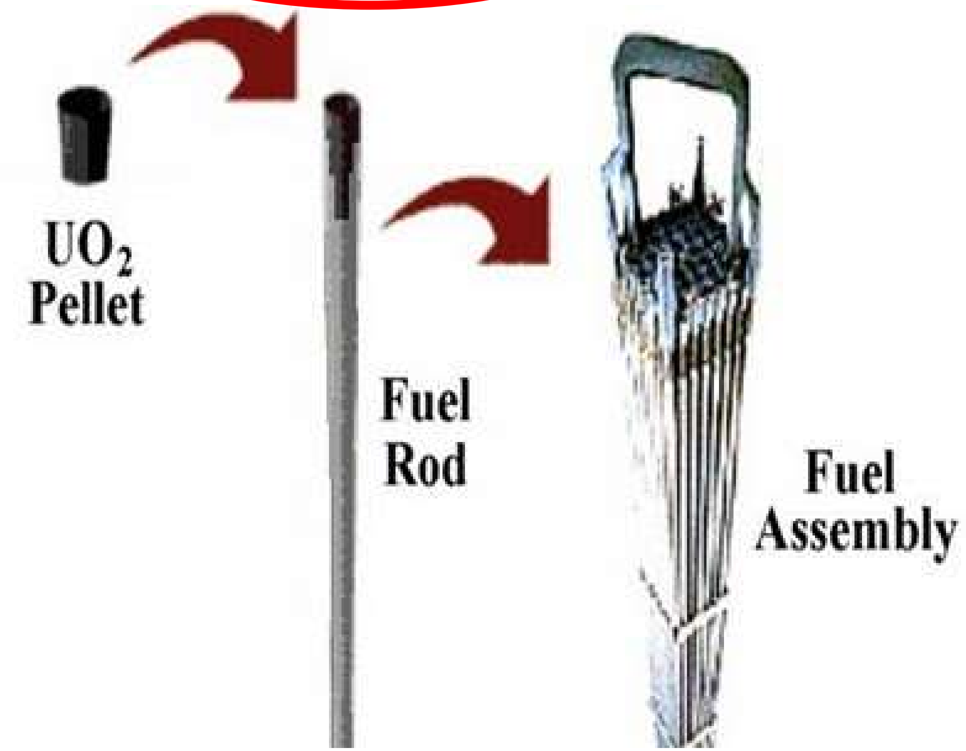
Quality control

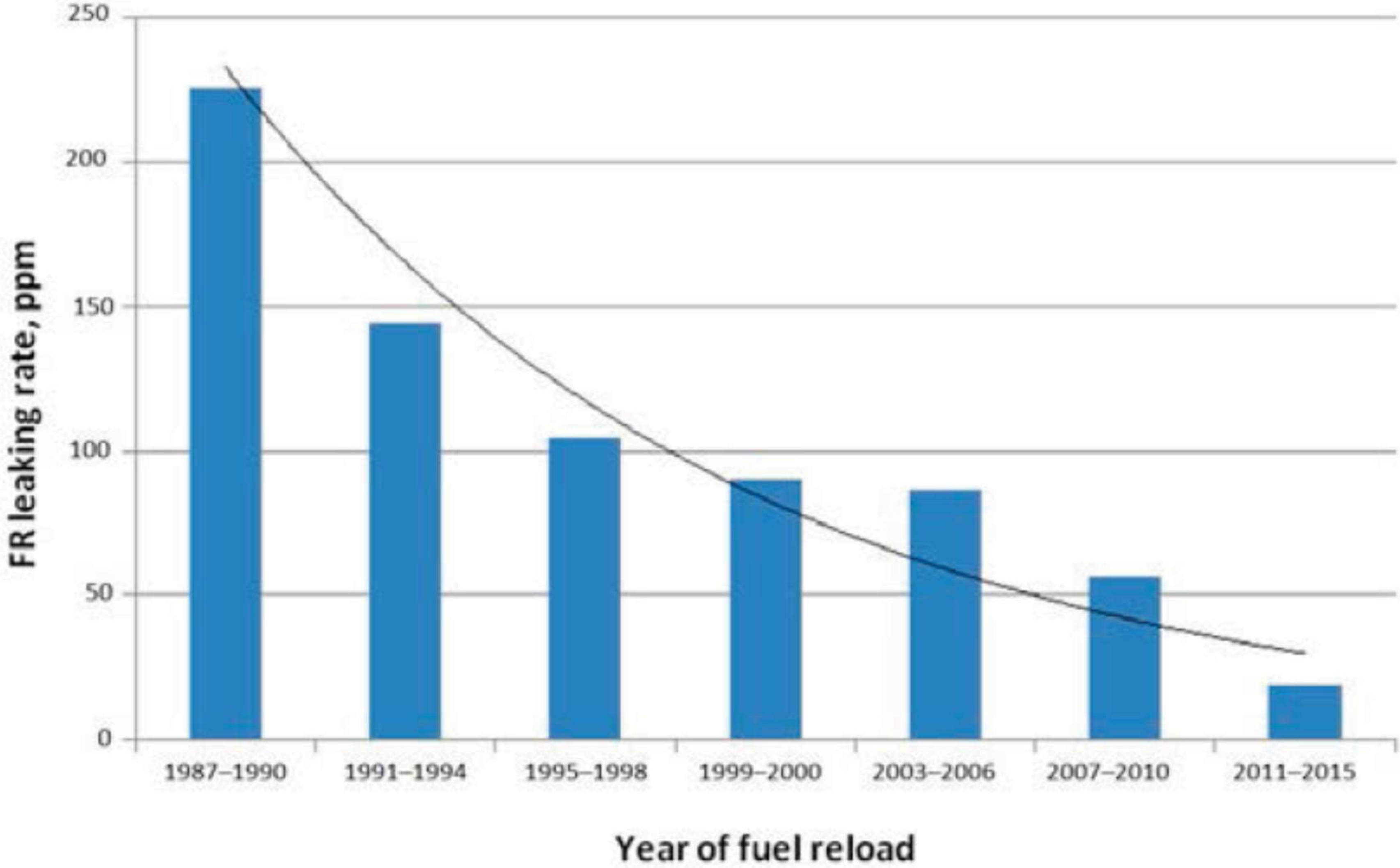



Fuel improvement

- (re) convert to $UO_2$
- Precompact, granulate
- Press
- Sinter
- Grind
- Inspect
- Load pellets into rods
- Load rods into fuel assemblies
- Inspection

Scrap Recovery

# WORLD AVERAGE PWR FUEL ROD FAILURE (IAEA DATA)



# NUCLEAR FUEL FABRICATION - IMPROVEMENT


Main lines for improvement:

Extension of irradiation period

High burn-up

Burning absorber (Gd, Er)

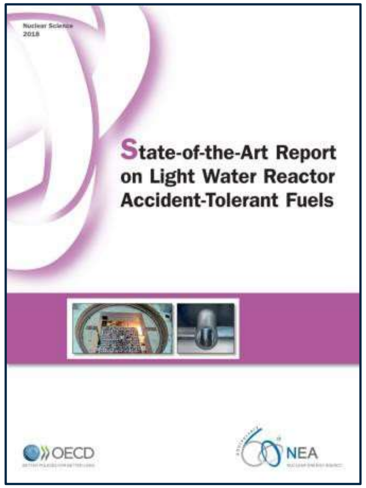
Increased enrichment

# ACCIDENT TOLERANT FUEL (ATF)

Accident at Fukushima-Daiichi in 2011

- Fukushima provided a focus for the industry to develop fuels with enhanced resilience to severe accident scenarios.
- Particular target to extend coping time during a Loss of Coolant Accident.
- Fuel and cladding concepts have been developed that range from *evolutionary* to *revolutionary* in their ambition.

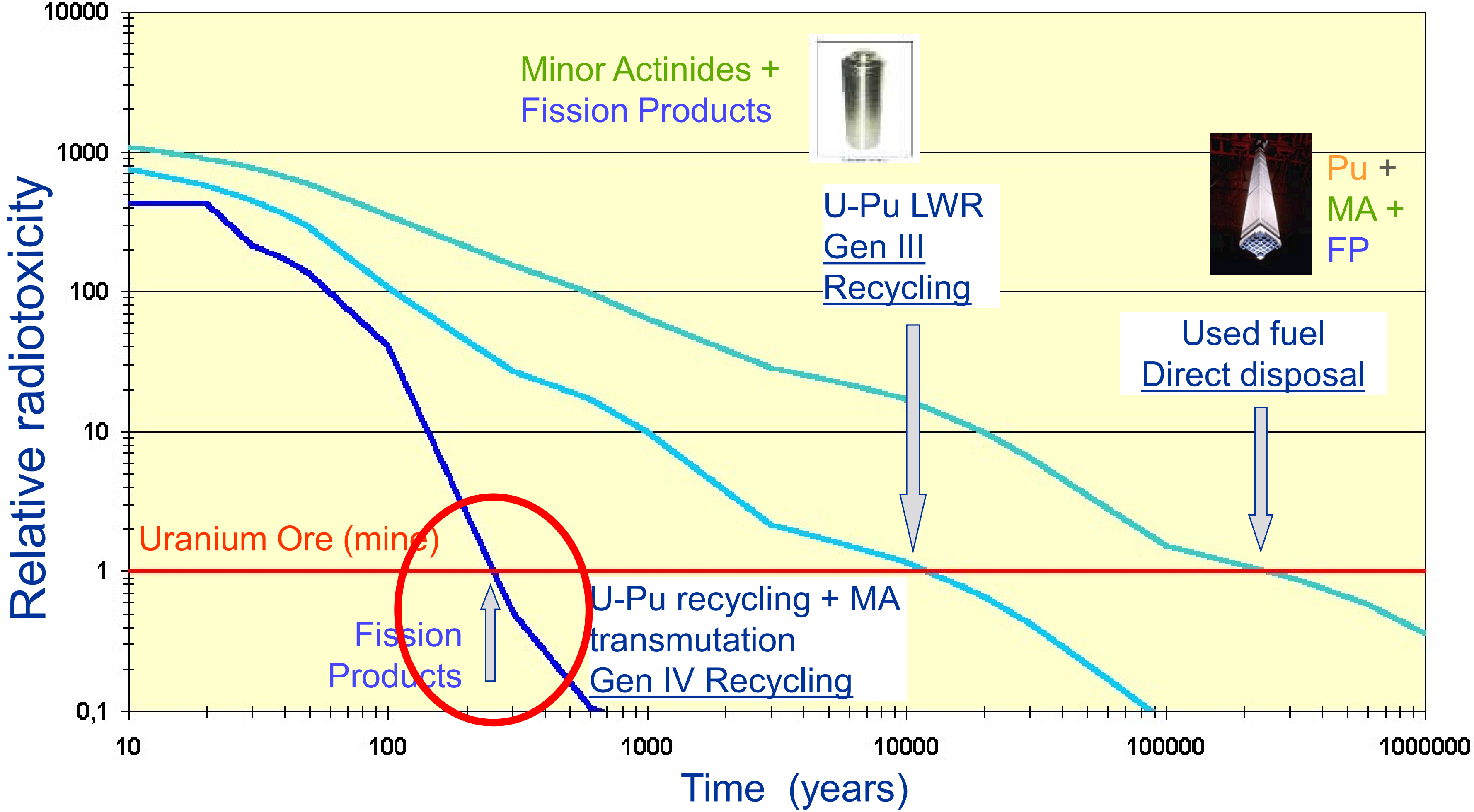
- Deployment potential in existing LWR fleets, new build LWRs and some SMR designs.
- *Revolutionary* concepts might also be applicable to Gen-IV reactors.
- Active irradiation programs are under way in USA and Russia.




OECD-NEA Report published in October 2018

372 pages of detailed analysis of concepts

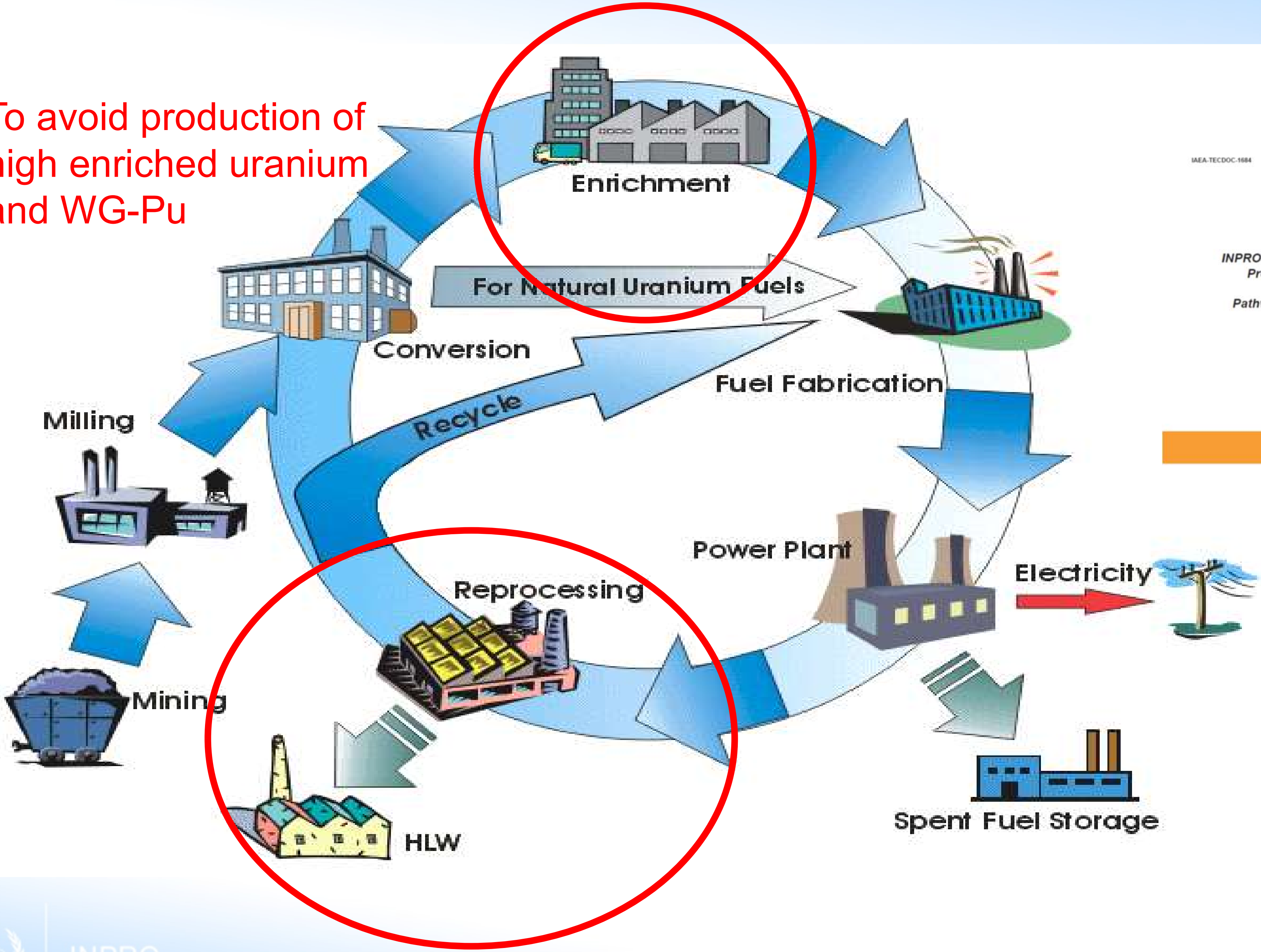
# LONG-TERM ENVIRONMENTAL SAFETY- REPOSITORY POTENTIAL RADIOTOXICITY

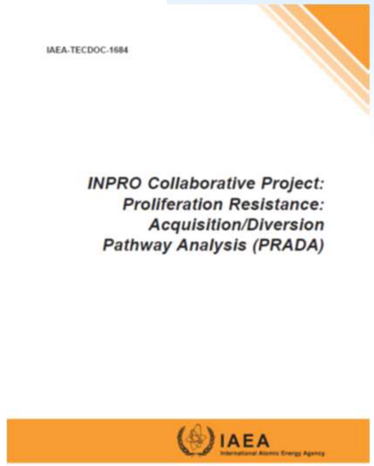



- Assuming an optimistic 100% efficiency in the partitioning and transmutation of all Minor Actinides with Gen IV recycling

# NUCLEAR FUEL CYCLE – NON-PROLIFERATION

To avoid production of high enriched uranium and WG-Pu

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*INPRO Collaborative Project: Proliferation Resistance: Acquisition/Diversion Pathway Analysis (PRADA)*

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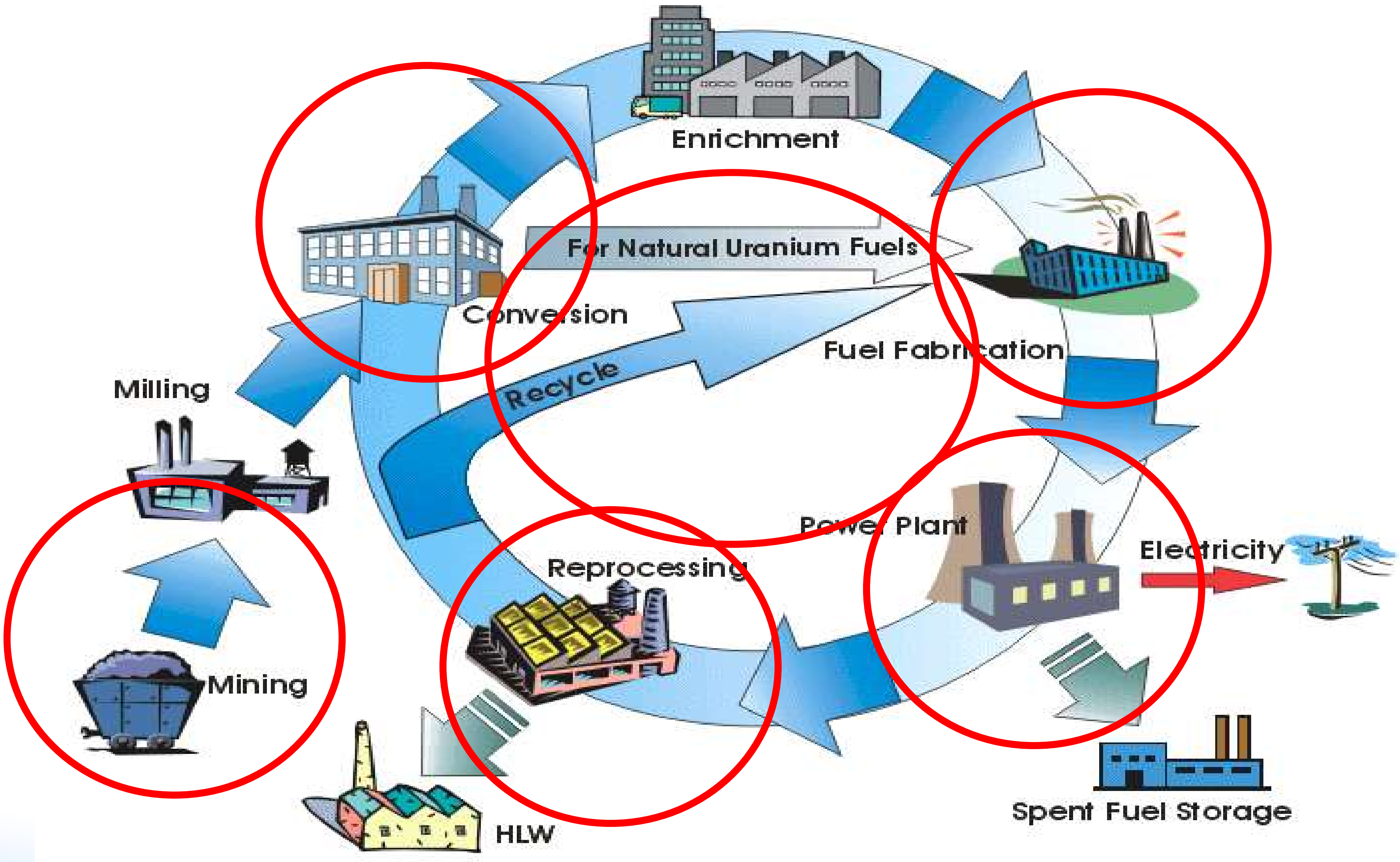
# NUCLEAR FUEL CYCLE – ECONOMICS



# NEW TECHNOLOGIES FOR ALL NUCLEAR FUEL CYCLE STAGES AS USUAL EFFECT ON ECONOMICS AND OTHER ASPECTS



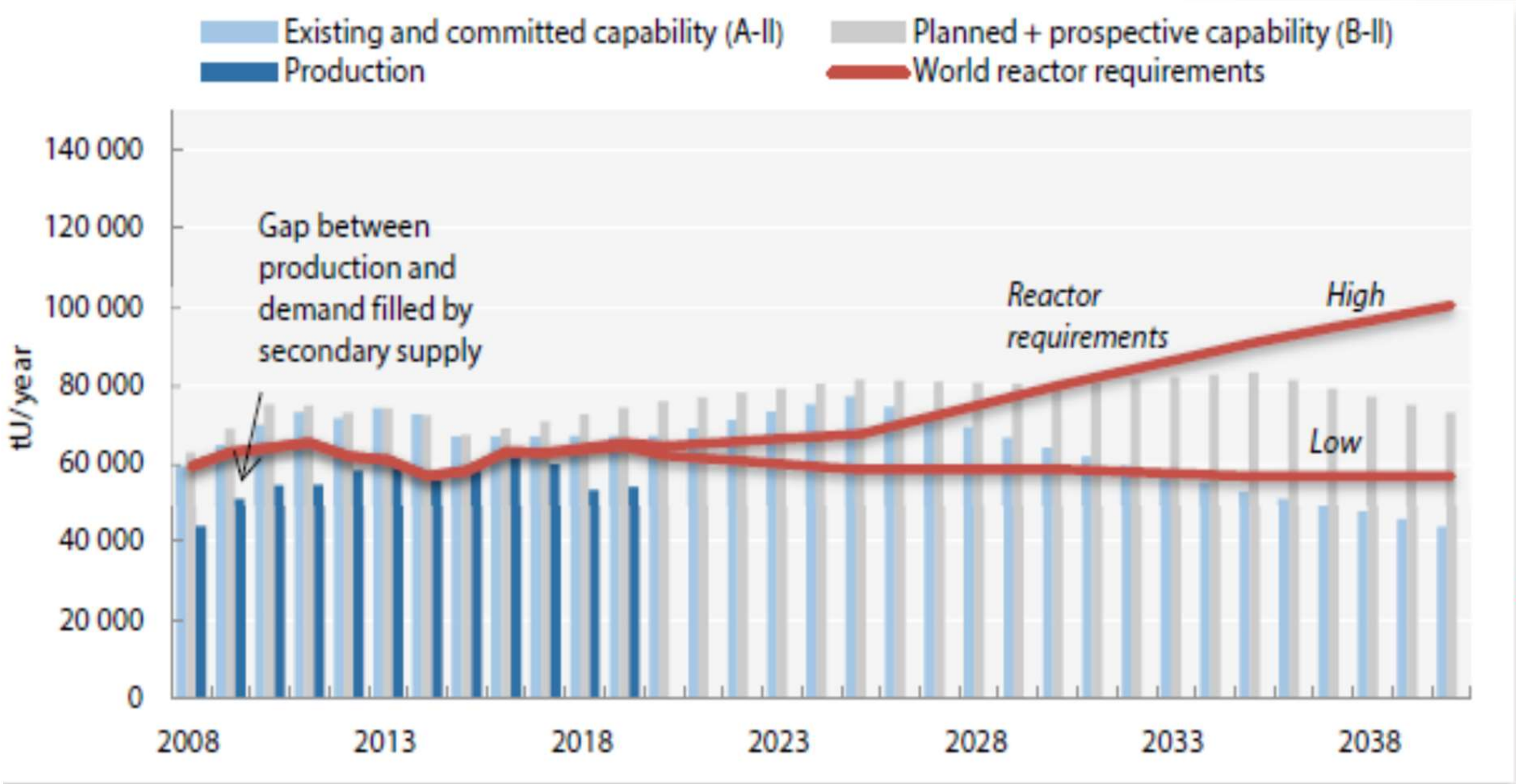
Examples:

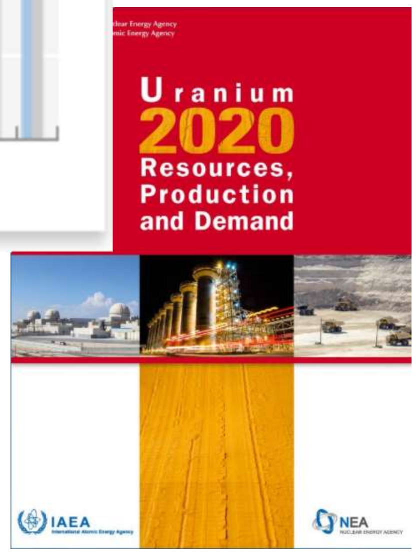
- **Uranium Exploration –** new remote technologies. Extension of available uranium resources
- **Uranium mining by ISL technology** – economically acceptable and drastically reduce environmental effects. No uranium mining tails etc.
- **Improvement of centrifuges and cascade management** – stable cost of LEU and possibility to use "depleted uranium" from early programs. Enrichment of $UF_6$ with 0.4% U-235 reduces demands of natural uranium and exclude all conversion stages.
- **Development and improvement of technologies for fuel manufacturing with reprocessed U and Pu** brings a complex effect: reduction of natural uranium demands, reduction of SNF storage expenses, reduction of HLW radiotoxicity, etc.
- **MOX (or mixed U-Pu nitride or metal) fuel technology** is a key technological way for closed fuel cycle of fast reactors.
- **GenIV Reactors demand advanced fuel technologies**

# URANIUM EXPLORATION

- A complex process to find a uranium deposit
  - a reliable geological model needed
- Three main methods used:
  - Geological methods (remote sensing, geologic mapping, drilling, trenching etc.)
  - Geochemical methods (sampling, analyses, advanced methods-dating, isotope studies)
  - Geophysical methods (radiometric, geomagnetic, geoelectric, gravimetric, seismic etc. methods and borehole logging)


# PROJECTED URANIUM PRODUCTION CAPABILITY TO 2040




Supported by identified recourses
at a cost of <USD 50/lb U3O8

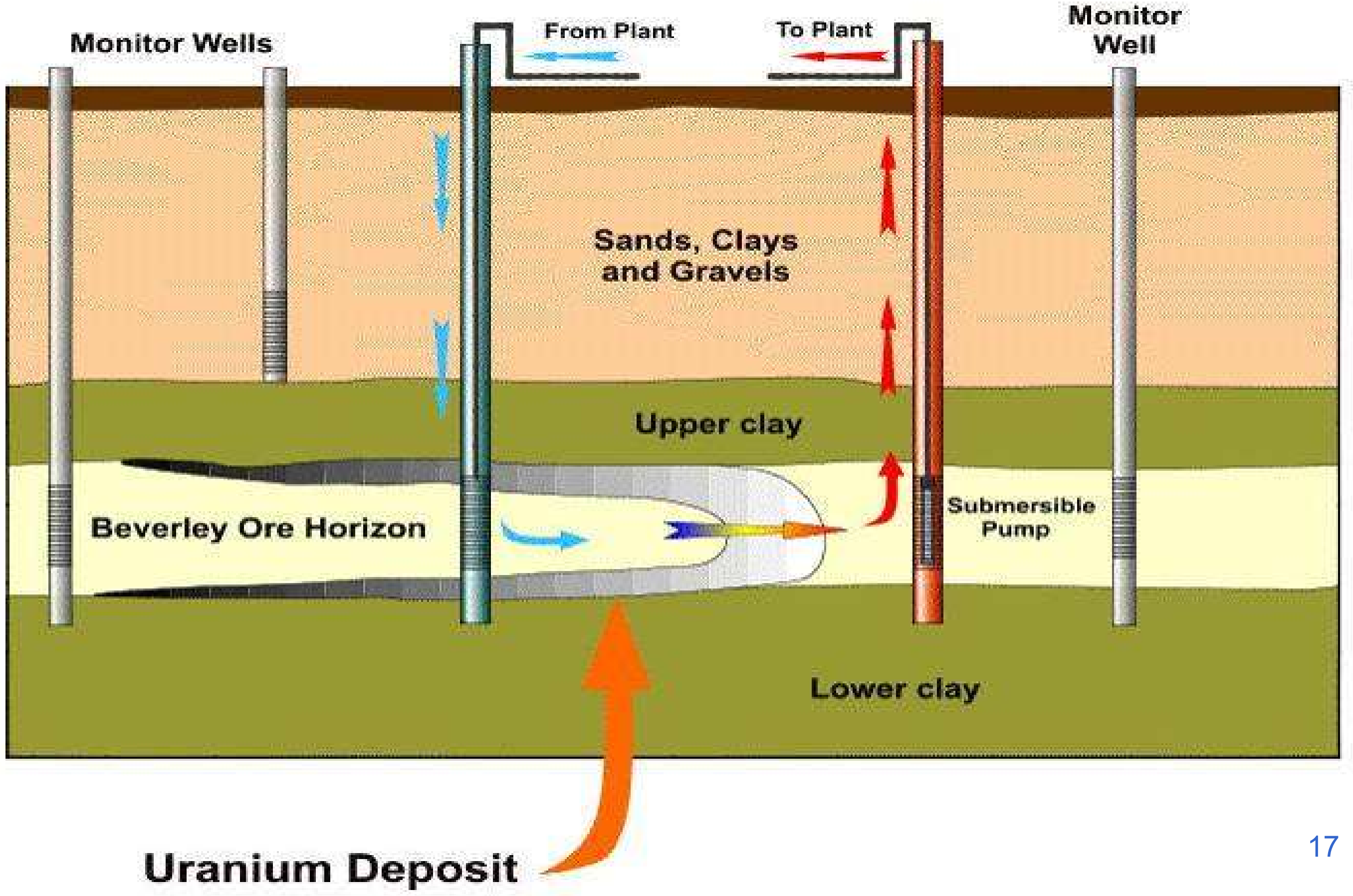
# URANIUM MINING METHODS: IN-SITU LEACH (ISL)

**Uranium is mined in one of following ways:**

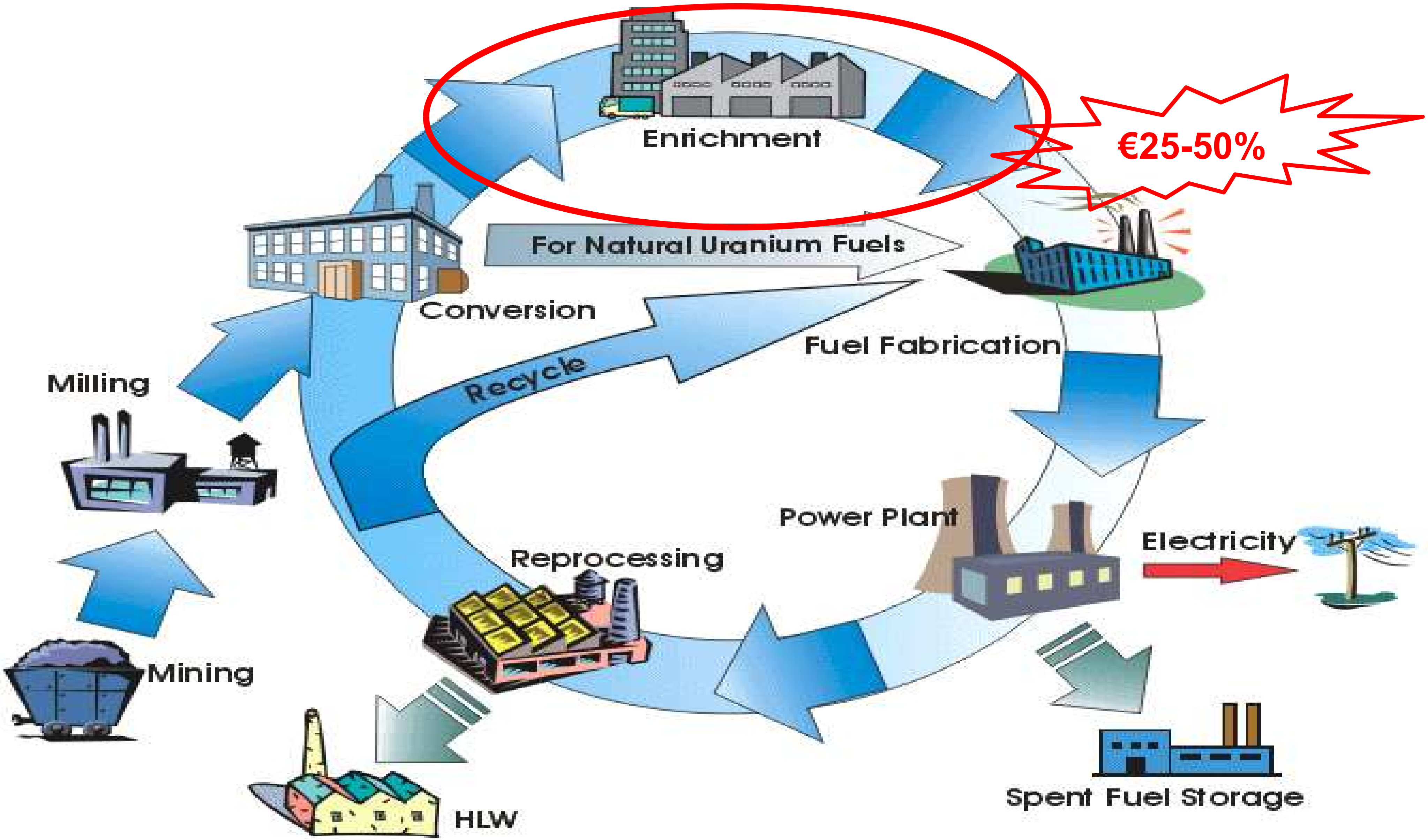
- Open pit, including surface excavations
- Underground with tunnels, galleries etc.
- In-situ leach mining – ISL [also ISR or solution mining]
- As a by-product from the mining of other minerals

- Currently (2019) ~57% of world mined uranium is mined by this way (in comparison with 2008 – only 28% of world mined uranium)

- Very small volume of waste generation
- Limited surface disturbance
- Can be acid or alkali each solution

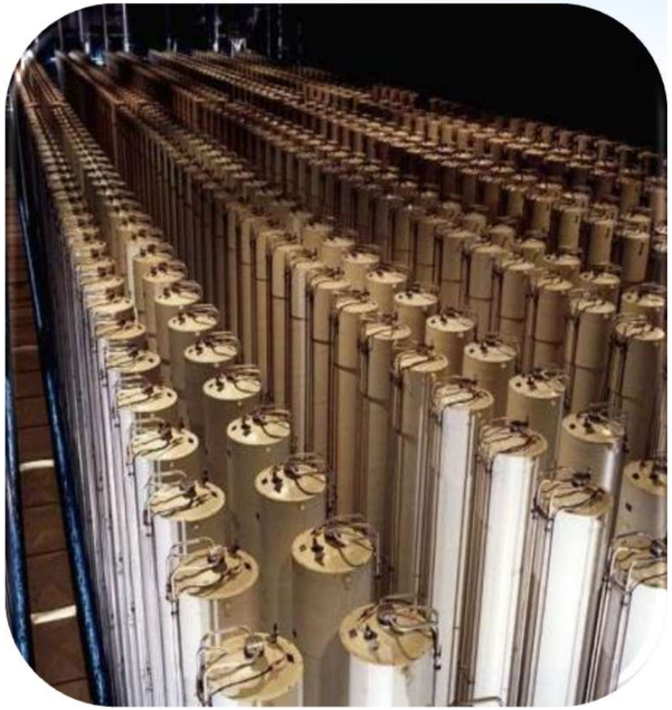


# NUCLEAR FUEL CYCLE



# URANIUM ENRICHMENT IMPROVEMENT

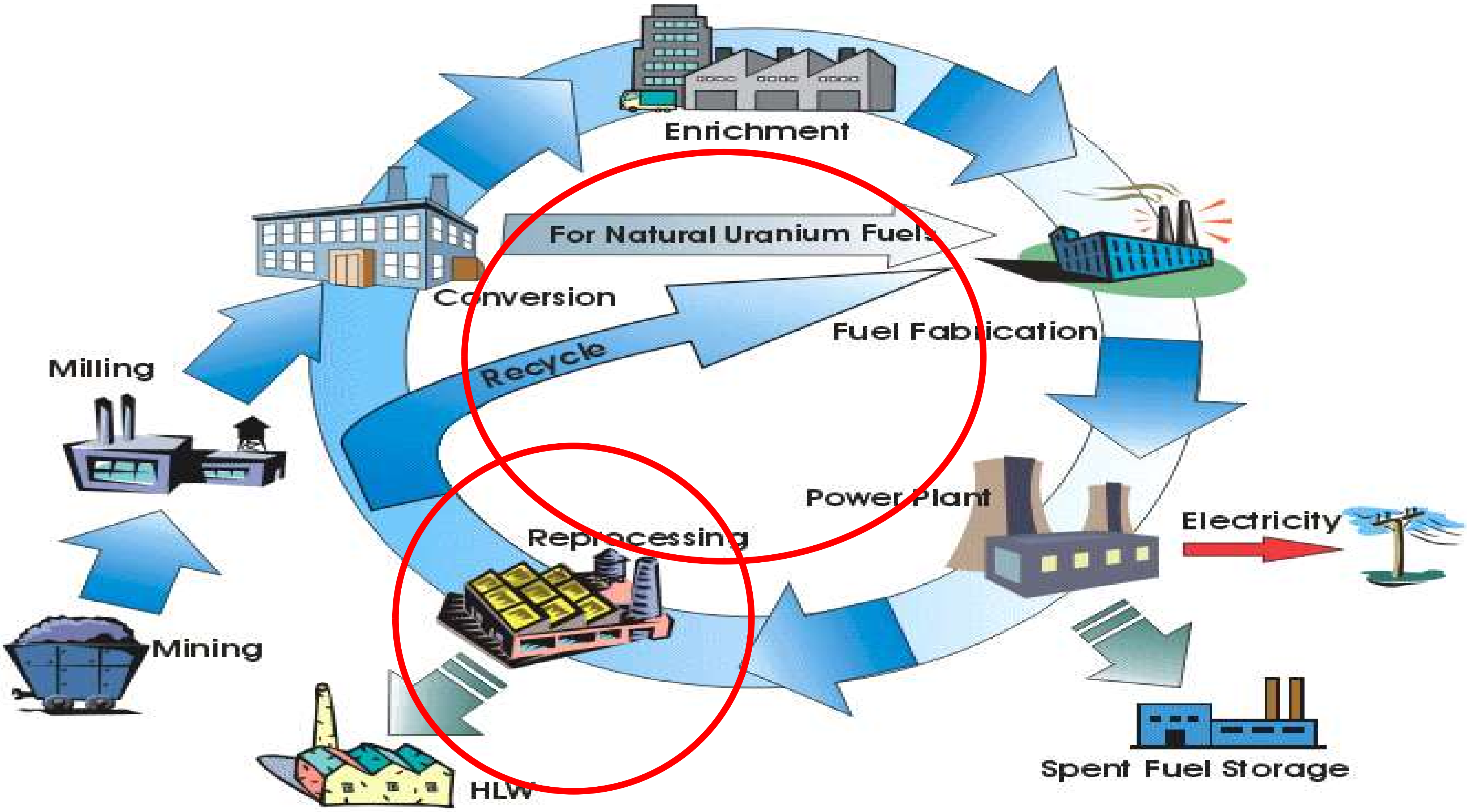
- Currently gas centrifuge process is basic commercial option
  - 2000 – 50% enriched by diffusion, 40% - by centrifuge, 10% - ex.weapon
  - 2015 – 100% enriched by centrifuge
- Energy consumption for the Separative Work Unit:
  2,400 kWh/SWU for Gaseous Diffusion,
  < 50 kWh/SWU for Centrifuge Process)



- There are acceptable to use “early depleted uranium” (U-235 content 0,3-0,4 %) as feed material for some Russian enrichment plants.
  - Possibility to re-enrich huge stores of depleted UF6
  - Reduction of natural uranium demand
  - Exclusion all conversion processes before enrichment UF6

- A laser enrichment technology is under development that selectively ionises $^{235}U$ atoms so that they can be separated electromagnetically

# NUCLEAR FUEL CYCLE – RECYCLING AS SPENT FUEL MANAGEMENT OPTION



# LAST DECADES TRENDS FOR SF REPROCESSING

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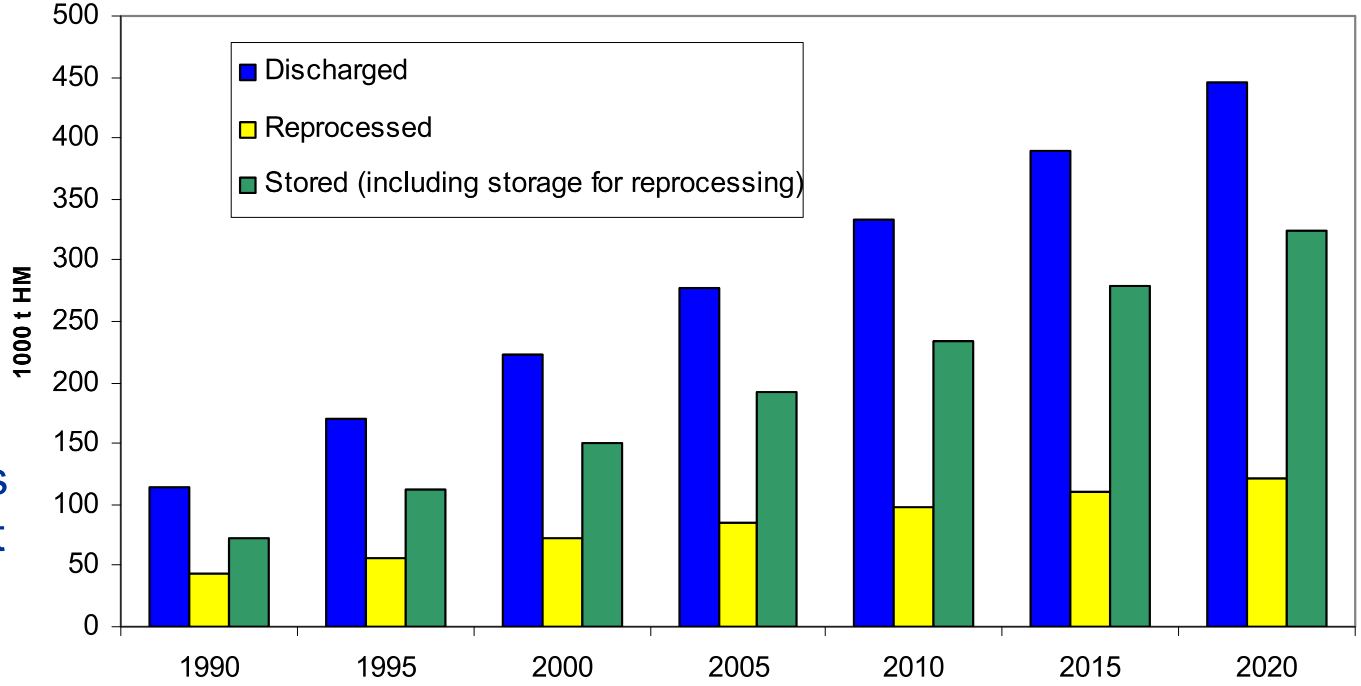
- Higher Burn-up of Spent Fuel
- Reduction in Dose to Plant Operator
- Reduction in Waste Volume
- Reduction in Discharge of Radioactivity to Environment
- Plant Expansion / Lifetime Extension / Decommissioning

- The total amount of spent fuel that has been discharged globally is approximately 400 000 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.

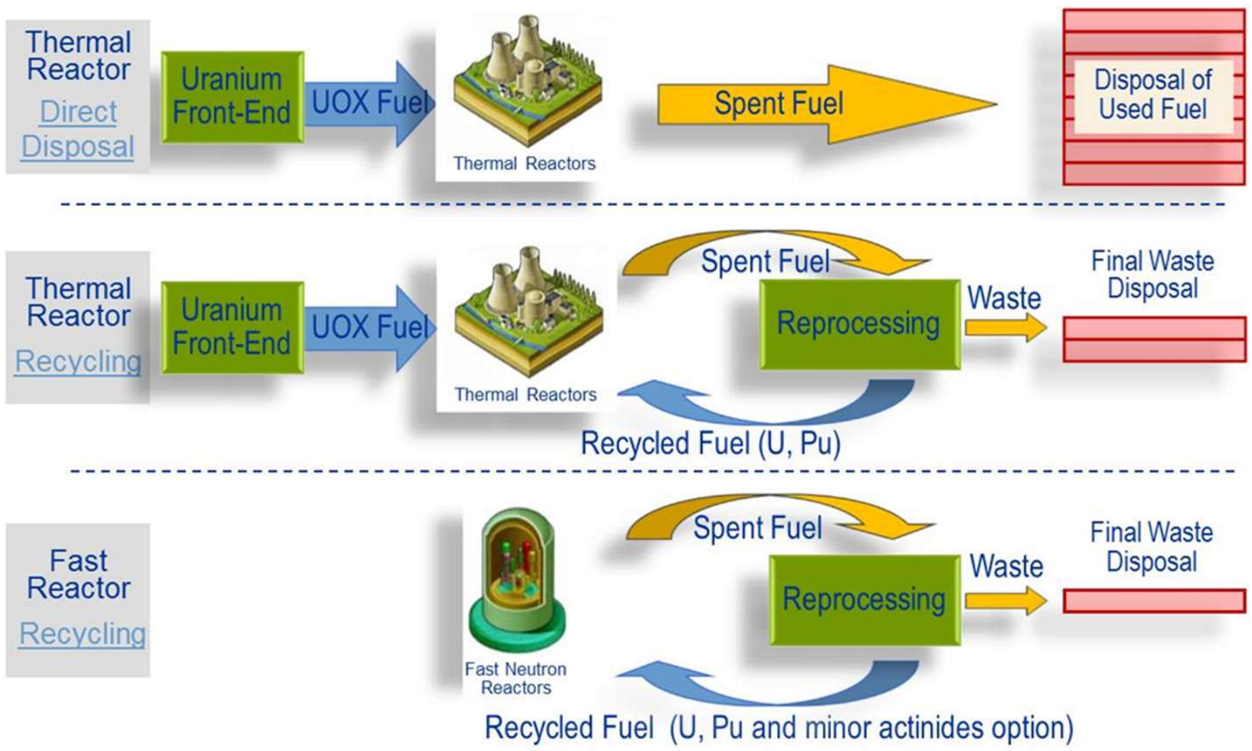



Currently only 5 States have commercial reprocessing plants (tHM/year): France (1700), India (260), Japan (exp.800), Russia (400) and UK (had 1500 till 2022).

IAEA INPRO International Project on Innovative Nuclear Reactors and Fuel Cycles

# NUCLEAR FUEL CYCLE OPTIONS AND TRENDS

- For Nuclear power **sustainability**, nuclear fuel cycle must remain economically viable and competitive through **Optimization of fissile materials**' use in reactor cores or valuable materials recycling
- This results in **different fuel cycle options**, some already implemented and others may be deployed in the future
- **Integrated approach** of the fuel cycle



# COUNTRY EXAMPLES OF SPENT FUEL REPROCESSING AND RECYCLING


Over 6 600 tHM of spent fuel reprocessed

Reprocessed uranium is reused to produce fuel for RBMK-1000 and VVERs

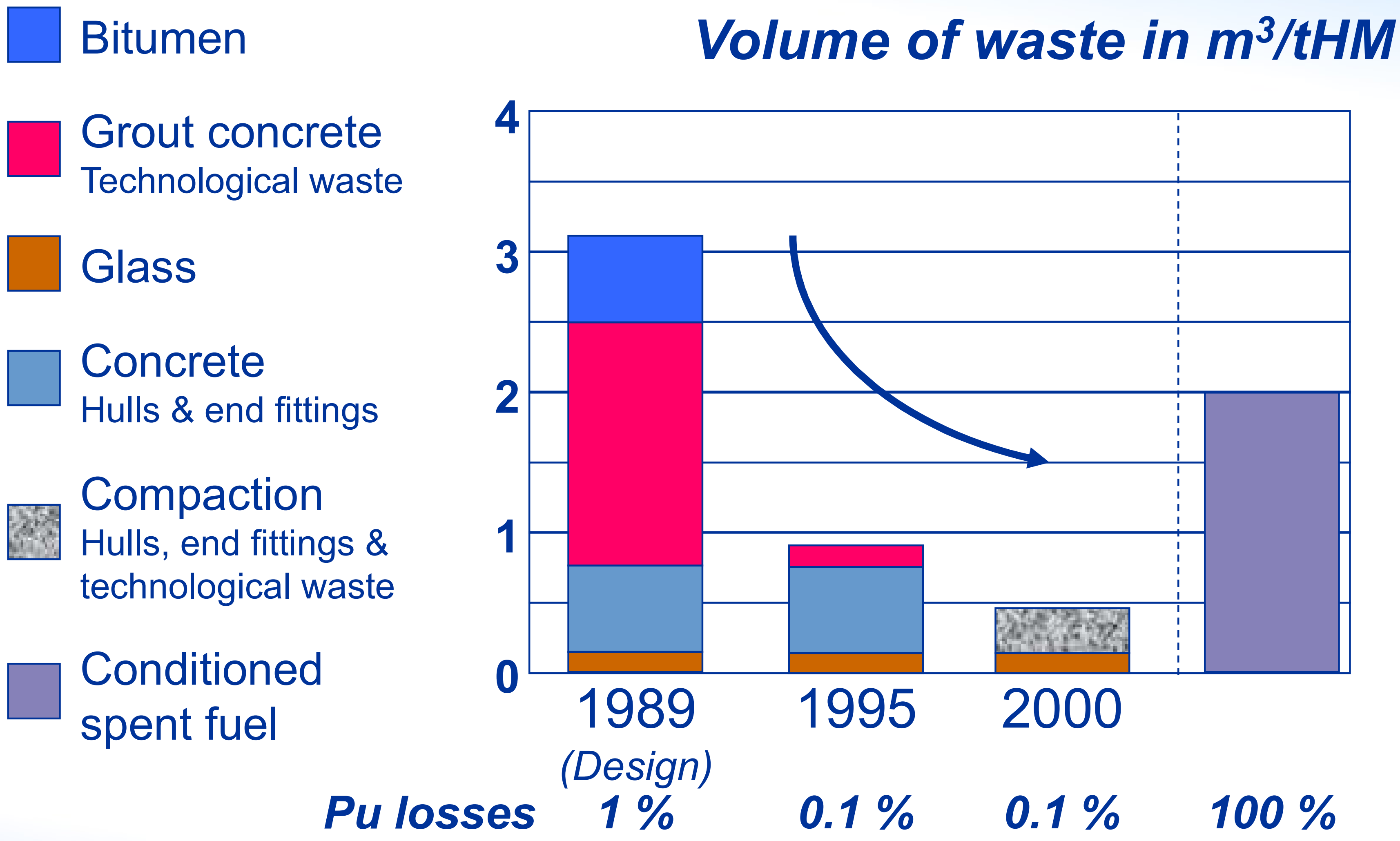
Plutonium is reused to produce MOX fuel for BN-800 fast reactor


Reprocessed over 50 000 tHM in over 60 years of operation


Trombay, Tarapur and Kalpakkam, 55 years of reprocessing experience


Tokai Reprocessing Plant, reprocessed 1 052 tHM of SNF

# "CLASSIC" EXAMPLE: SPECIFIC WASTE VOLUME FOR THE UP3 PLANT (FRANCE)



# RECYCLING STRENGTHENS NON-PROLIFERATION

- Recycling restricted to a few regional centres under international safeguards
  - Offering recycling services to a wide range of customers
  - Avoiding the accumulation of spent 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 unattractiveness 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 contributed to international non-proliferation initiatives
  - Weapon-grade plutonium disposition (Russian MOX Fuel Fabrication Facility is under operation, but the US stopped project in Savana River)
  - Securing « gap material »

# MOX FUEL MANUFACTURING AT INDUSTRIAL SCALE

- Cumulated experience of ~3000 tHM for LWRs

MELOX plant start in 1995

- Production of 30 million pellets a year
- Successful implementation of evolutions in production lines
  - Optimization of primary blend preparation → improvement of Pu agglomerates size distribution
  - Increase of scrap content in primary blend
  - Technological developments of control means, e.g. γ-scan → more efficient control of fuel rod final quality
- Improved management of plutonium confinement, radiation protection → continuous dose exposure reduction much below the regulatory dose limitations
- Development of remote handling devices and robotics → meet increased dose constraints in the future

framatome orano

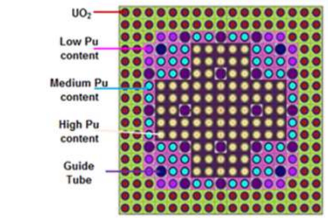
*From: IAEA International conference on SNF Management 2019*

Currently MOX fuel covers 5% of fresh fuel market

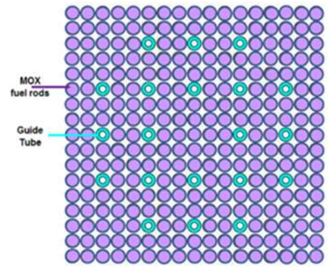
# DEMONSTRATED MULTIPLE RECYCLING IN LWRs CONTRIBUTE TO TRANSITION TO FRs

## In France

- CORAIL-A concept considers the use of $UO_2$ and MOX fuel rods in the same assembly

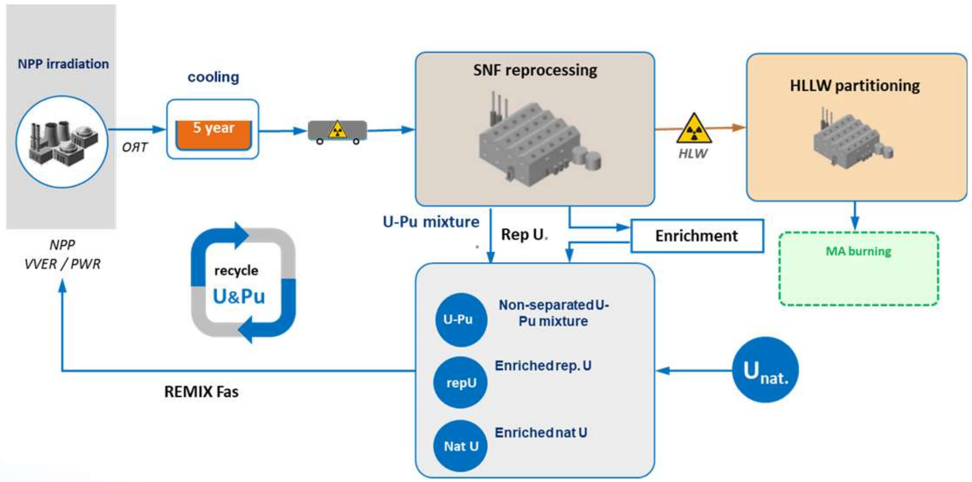



- MIX concept is only composed of MOX fuel rods with enriched uranium matrix (instead of depleted uranium as for current MOX fuel)




## In Russia

- REMIX fuel is made by non-separated mixture of U and Pu from LWR SNF reprocessing, with the addition of enriched uranium (natural or RepU )



# RUSSIAN EXPERIENCE IN FABRICATION OF FUEL ASSEMBLIES WITH RepU AND Pu


*From: IAEA International conference on SNF Management 2019*

# REPROCESSING AND RECYCLING: CURRENT INDUSTRIAL OPTIONS

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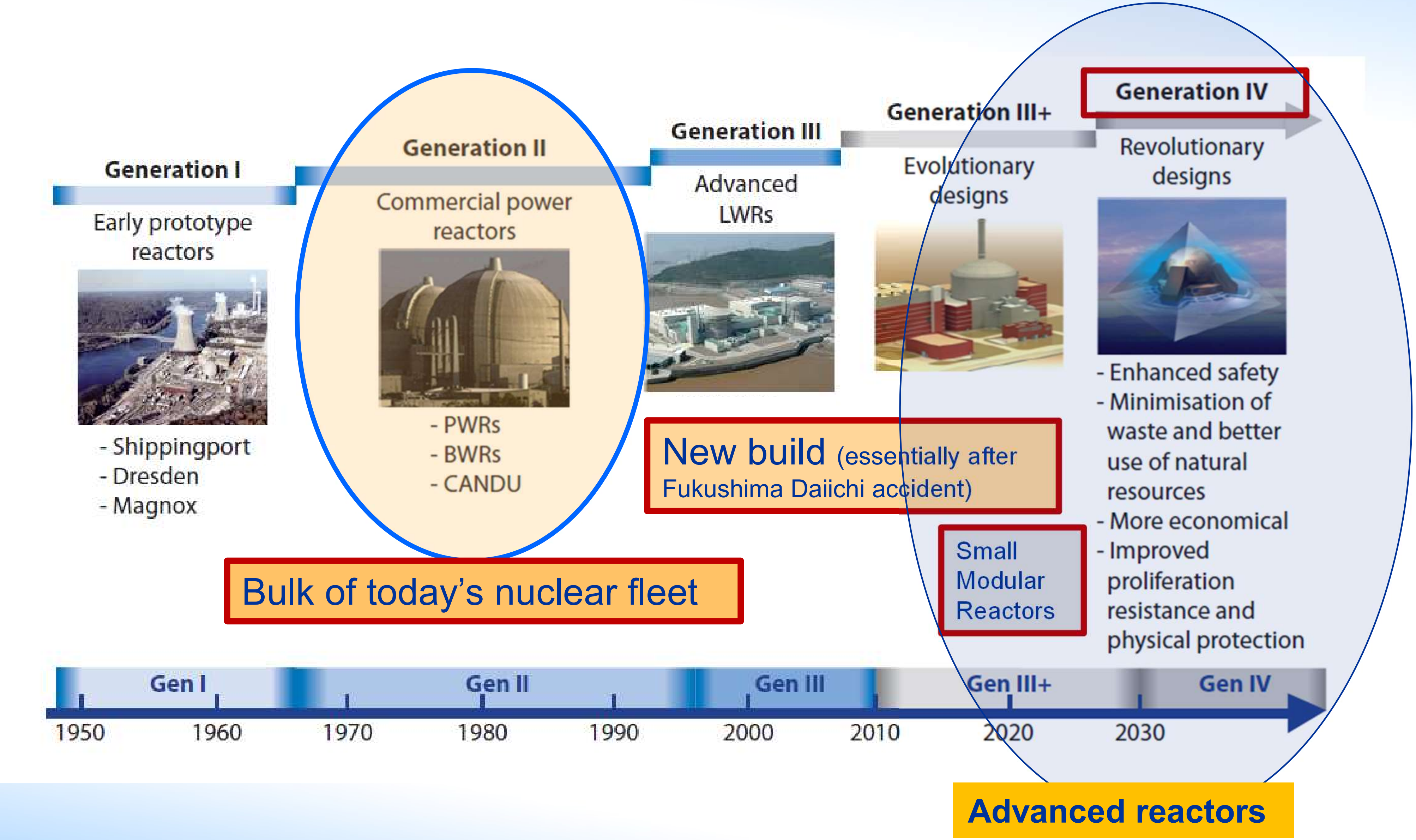
**Recycling Spent Fuel is a mature technology**

**Reference Options:**

- **Reuse as MOX in Light Water Reactors**
  - More than 40 years of experience worldwide (44 LWRs have used MOX fuel at industrial scale since 1986)
  - Use based on loading cores partially with MOX (25-50%) and the remainder with UOX fuel
  - Recent reactor designs can accommodate 100% MOX cores
  - Pu recycling in LWRs saves up to 25% of natural uranium resources
- **Reuse as MOX in FRs:** currently implemented in the Russian Federation in BN-800
- **Reuse as Enriched Reprocessed U (ERU) in Thermal Reactors** (TRs: PWRs, VVERs, RBMKs, AGRs, PHWRs)
  - More than 30 years of experience worldwide
  - TRs can accommodate 100% repU cores

# NUCLEAR REACTORS: GENERATIONS I TO IV



# COMPARISON OF GEN IV SYSTEMS

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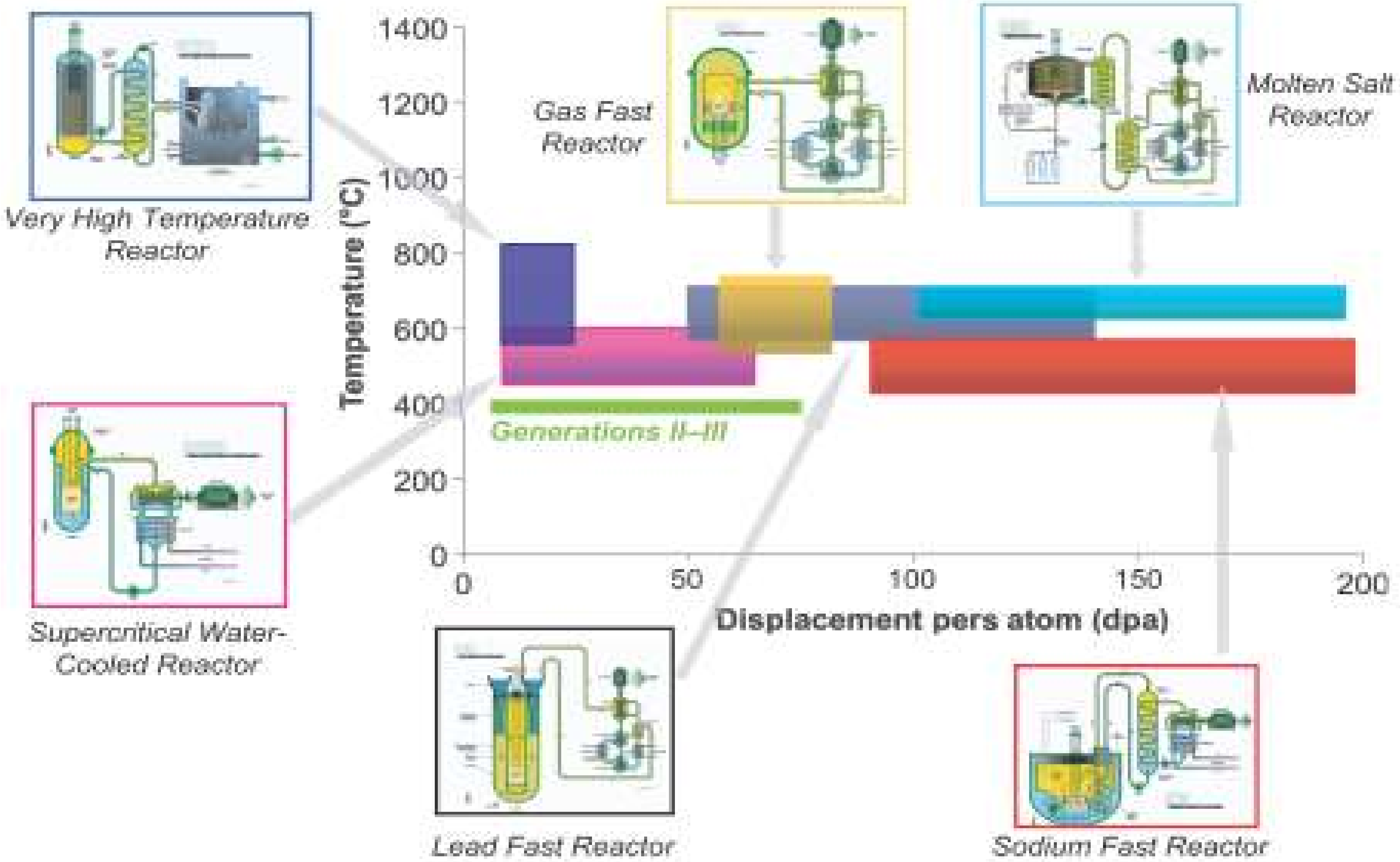
| System | Neutron Spectrum | Coolant | Outlet temp. (℃) | Fuel cycle | Power (MWe) |
|---|---|---|---|---|---|
| Sodium-cooled Fast Reactor (SFR) | Fast | Sodium | 500-550 | Closed | 50-1500 |
| Very-High-Temperature Reactor (VHTR) | Thermal | Helium | 750-1000 | Open | 250-300 |
| Lead-cooled Fast Reactor (LFR) | Fast | Lead | 480-570 | Closed | 20-1200 |
| Supercritical-Water-cooled Reactor (SCWR) | Thermal/ Fast | Water | 510-625 | Open/ Closed | 300-1500 |
| Gas-cooled Fast Reactor (GFR) | Fast | Helium | 850 | Closed | 1200 |
| Molten Salt Reactor (MSR) | Thermal/ Fast | Fluoride salts | 700-800 | Closed | 1000 |

# Long Term Trends:
# Advanced fuels for Generation IV Reactors



# POTENTIAL FUELS

**Ceramics :**

**Oxides** (single phase or solid solution)
($UO_2$ , $UPuO_2$)

**Nitrides**
(UN, UPuN)

**Carbides**
(UC, $UC_2$, UPuC)

Carbonitrides…

Oxicarbides…

**Fluorides (salt)**

**Metals, alloys and intermetallic compounds :**

UAl, PuAl, UZr, UPuZr, $U_3Si_2$, UMo

**Cercer or Cermet Composites:**

$PuO_2$-MgO, $UO_2$-Mo, $UO_2$-steel

Cercer = Ceramic - Ceramic
Cermet = Ceramic - Metal

# OPTIONS FOR FUEL RECYCLING IN GEN IV SYSTEMS

IAEA

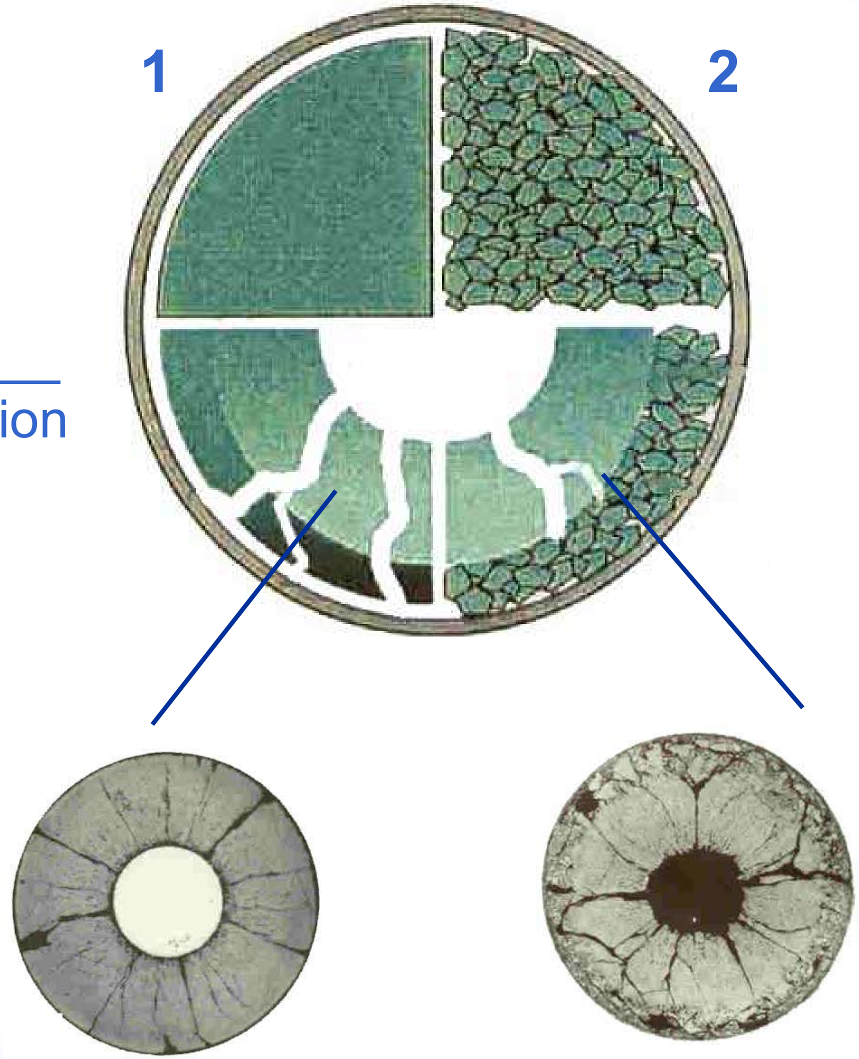
| System | Fuel cycle | Fuel type | Reprocessing method | Fuel refabrication |
|---|---|---|---|---|
| Sodium-cooled Fast Reactor (SFR) | Closed (U-Pu-MA) | Ceramic/ Metallic | Aqueous (for oxides mainly) pyroprocess | Pellets, vibro, injection melting |
| Very-High-Temperature Reactor (VHTR) | Open (U, U-Pu, Th-U) | Ceramic / TRISO | (complicated pyroprocess) | (TRISO) |
| Lead-cooled Fast Reactor (LFR) | Closed (U-Pu-MA) | Ceramic | Aqueous / pyroprocess | Pellets |
| Supercritical-Water-cooled Reactor (SCWR) | Open/ Closed | Ceramic (oxides) | Aqueous (pyroprocess) | Pellets (vibro) |
| Gas-cooled Fast Reactor (GFR) | Closed (U-Pu-MA) | Ceramic | Aqueous (for oxides mainly) pyroprocess | Pellets or others |
| Molten Salt Reactor (MSR) | Closed (U-Pu-MA, U-Th-MA) | Fluoride / chloride salts | Pyroprocess on-site | |

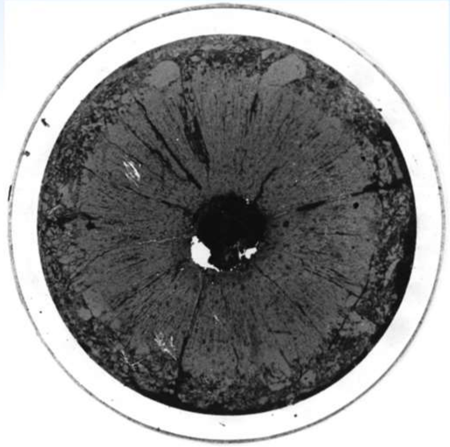
# VIBROPACKING FOR OXIDE FUEL

**Macrostructure of pelletizing (1) and vibropacking (2) MOX fuel for fast reactors**

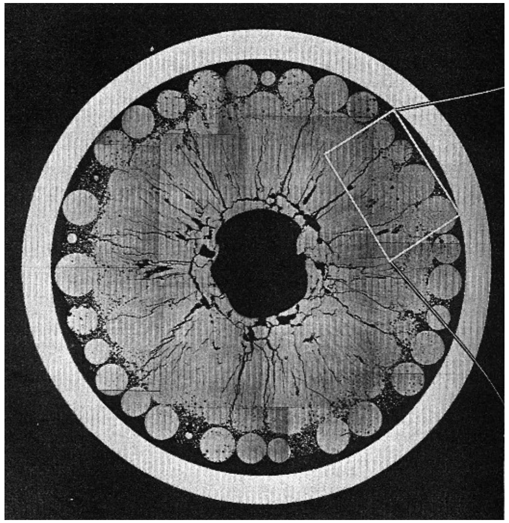
Before irradiation

After Irradiation



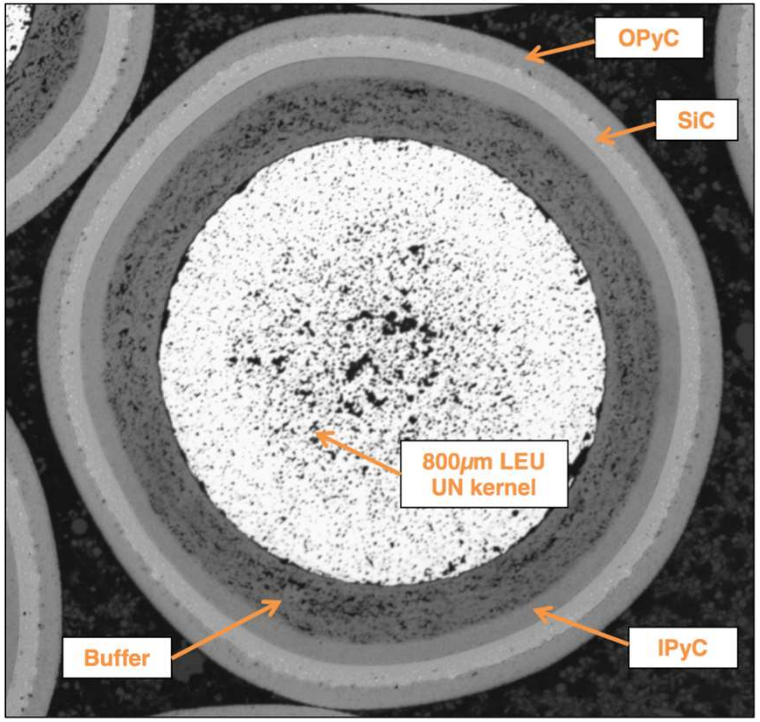
Cross-cutting of BN-600 pin



Cross-cutting of TREAT pin (ORNL)

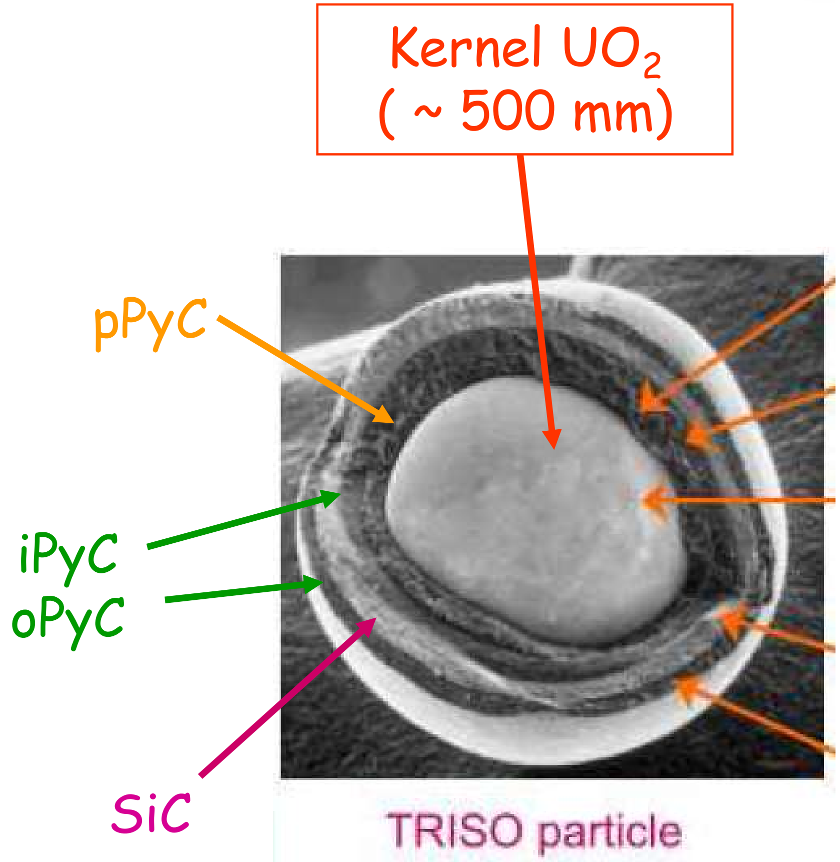
# $UO_2$ and UN TRISO Fuel Particle (for HTR and as ATF for other reactors)

**ATF - LEU UN TRISO particle**




Optical cross sectional image of typical 800μm LEU UN TRISO particle

**"Classical" UO2 TRISO particle**



# ADVANCED SPENT FUEL REPROCESSING

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**Advanced Aqueous Partitioning Methods**

**GANEX**
Uextraction 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

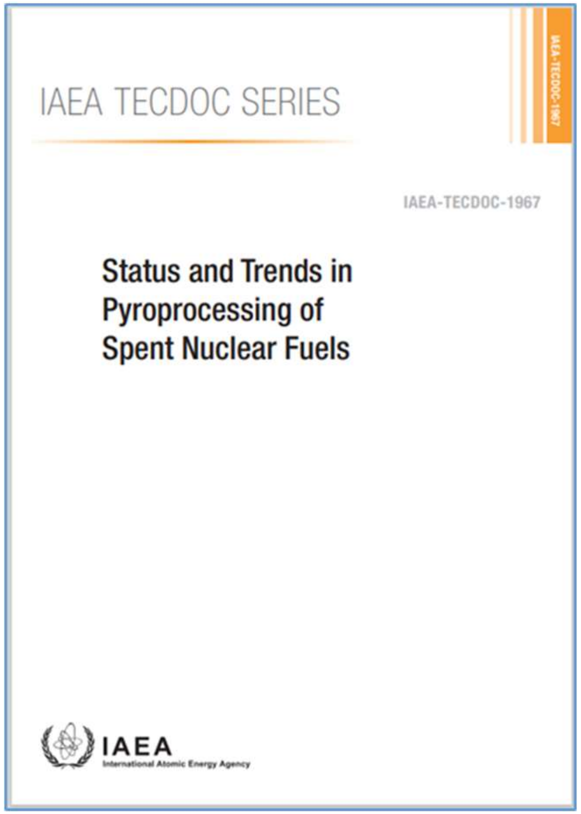
**DIAMEX, TODGA**
Separation of MA and Ln from HLLW

**TRUEX**
TRU elements extraction from HLLW

**SANEX, ARTIST, TALSPEAK**
Separation of Am, Cm from Ln

**SESAME**
Separation of Am from Cm

# ADVANCED PYRO-PROCESS OPTIONS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Status and Trends in Pyroprocessing of Spent Nuclear Fuels

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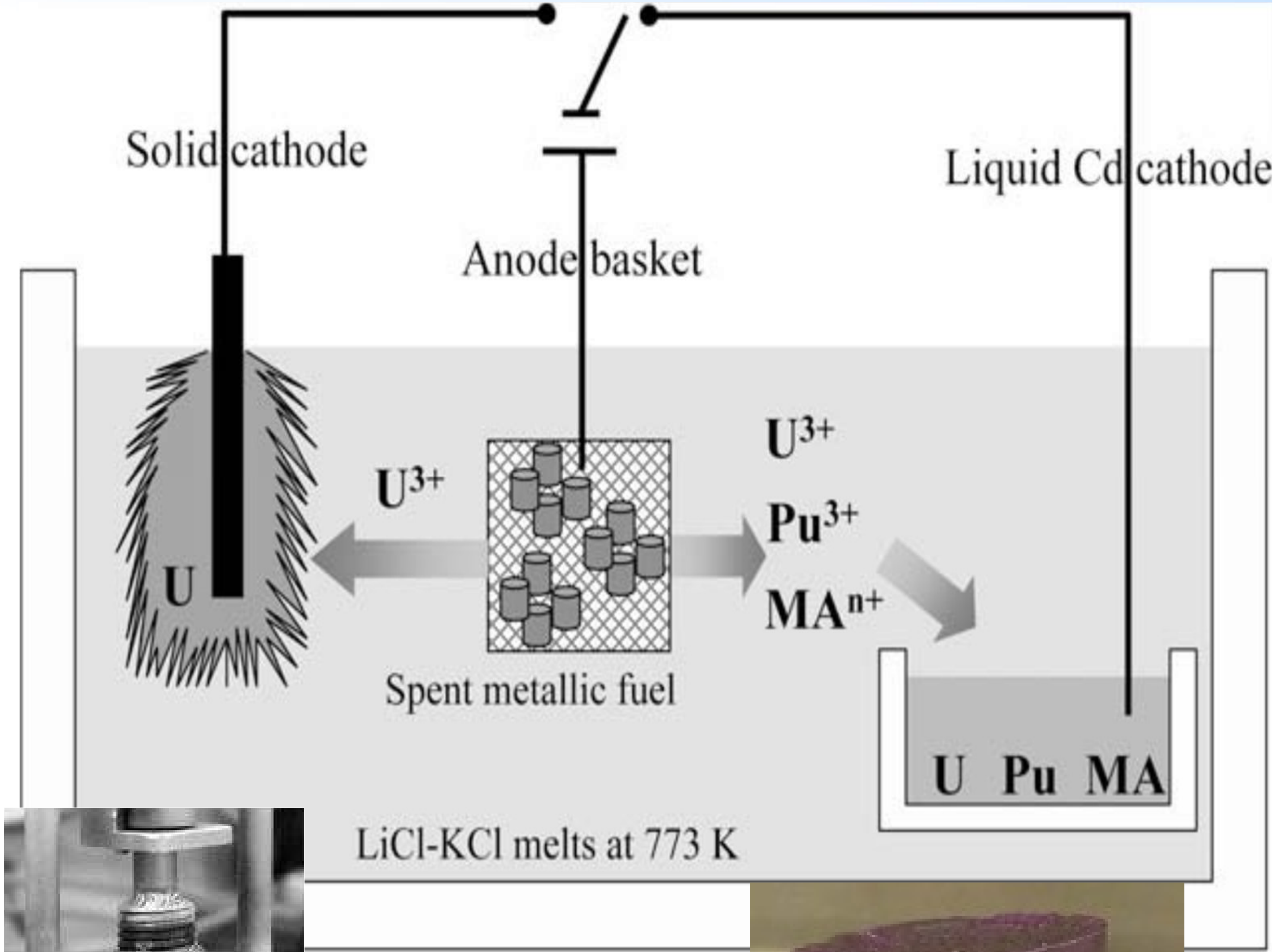
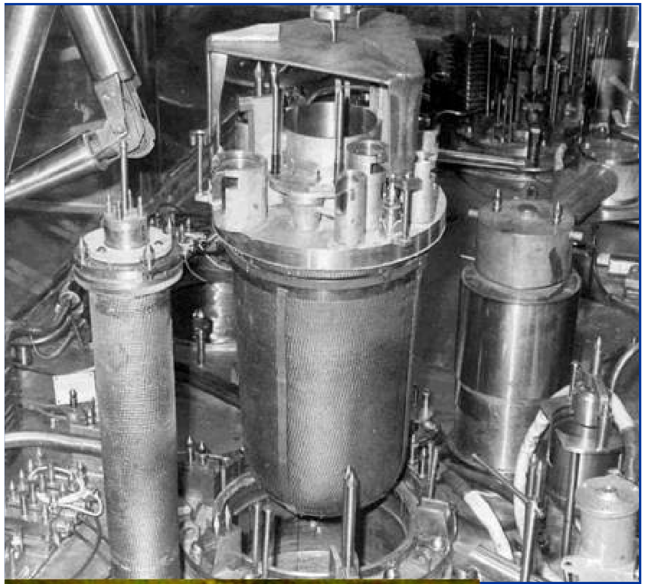


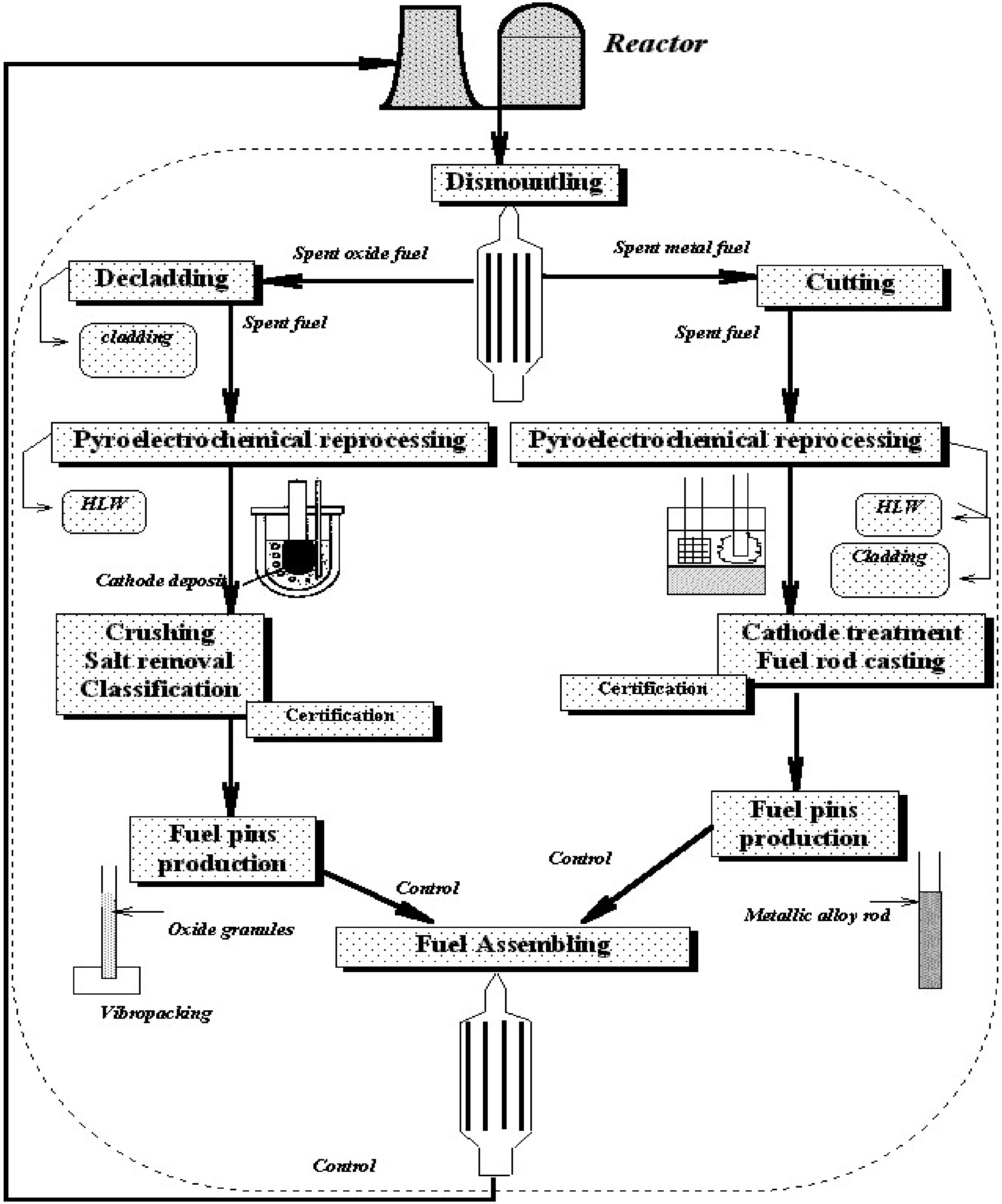

**The process for metallic U-Pu-Zr and nitride (U,Pu)N fuel**

U deposit

U, MA and Pu in a liquid Cd cathode

# RIAR developed Pyroprocess for MOX fuel 1970-2000



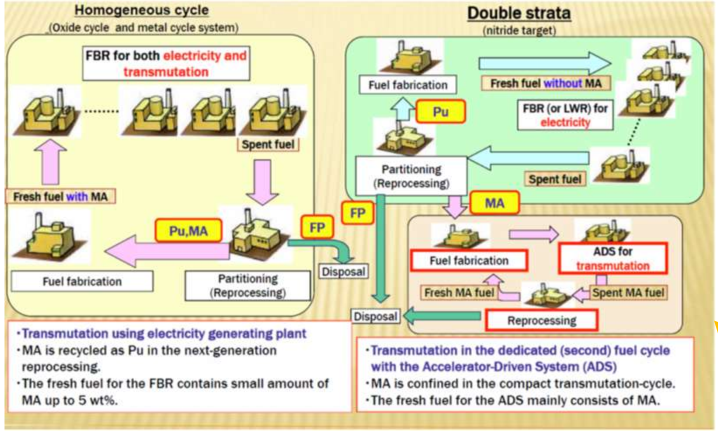


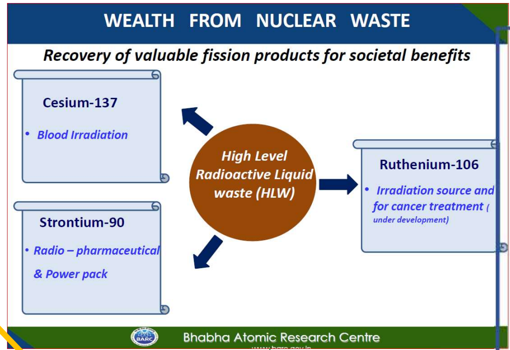

RIAR, Dimitrovgrad

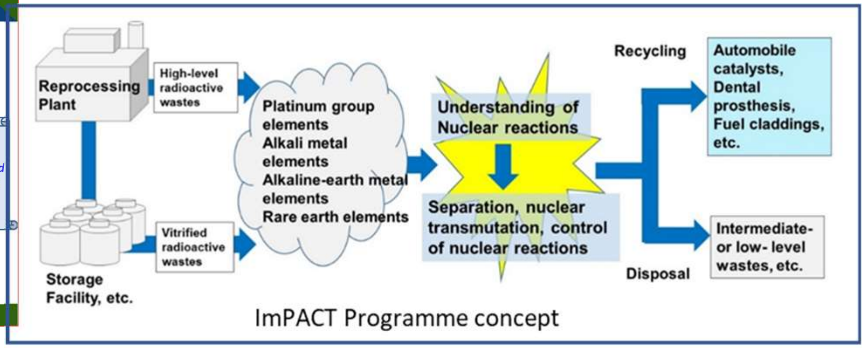
# IAEA'S ACTIVITIES ON ADVANCED FUEL CYCLES

"Existing and Advanced Nuclear Fuel Cycle Technical Options for Waste Burden Minimization"

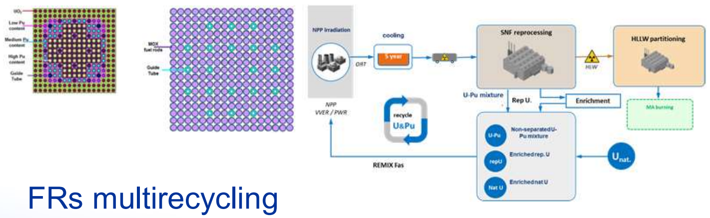
<u>Main Objective</u>: To describe relevant information of Nuclear Fuel Cycle Options in terms of nuclear materials and wastes involved and nuclear facilities and infrastructures needed



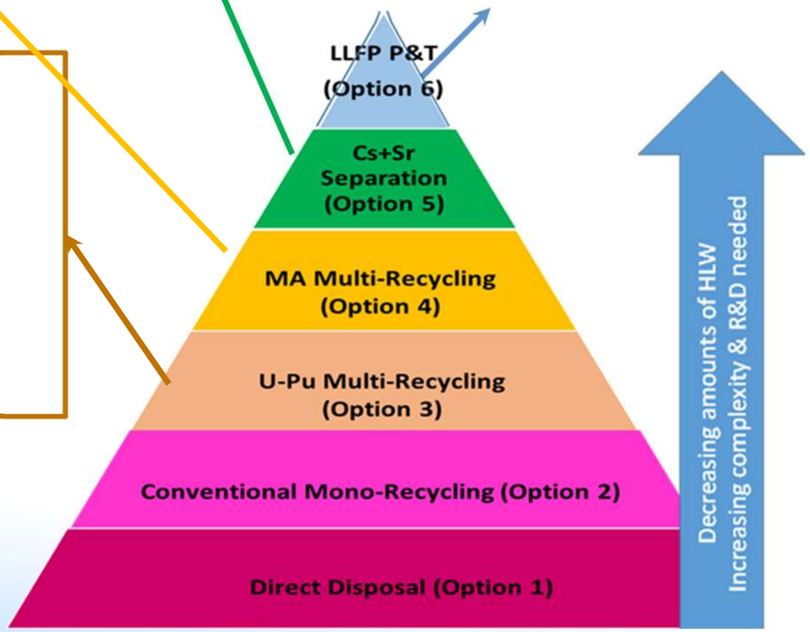



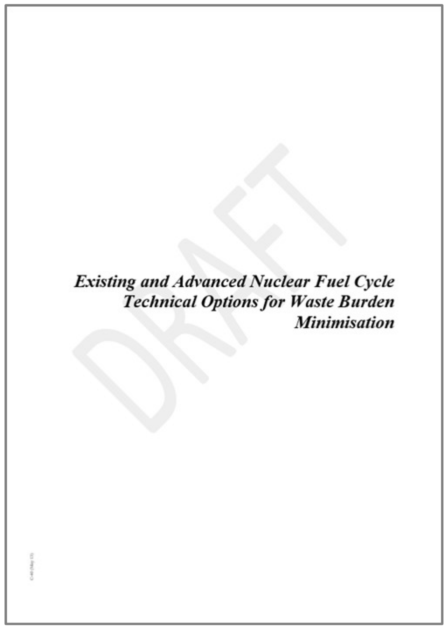




- LWRs multirecycling to enable transition to FRs
  - Corail and MIX processes (France)
  - REMIX process (Russian Fed.)



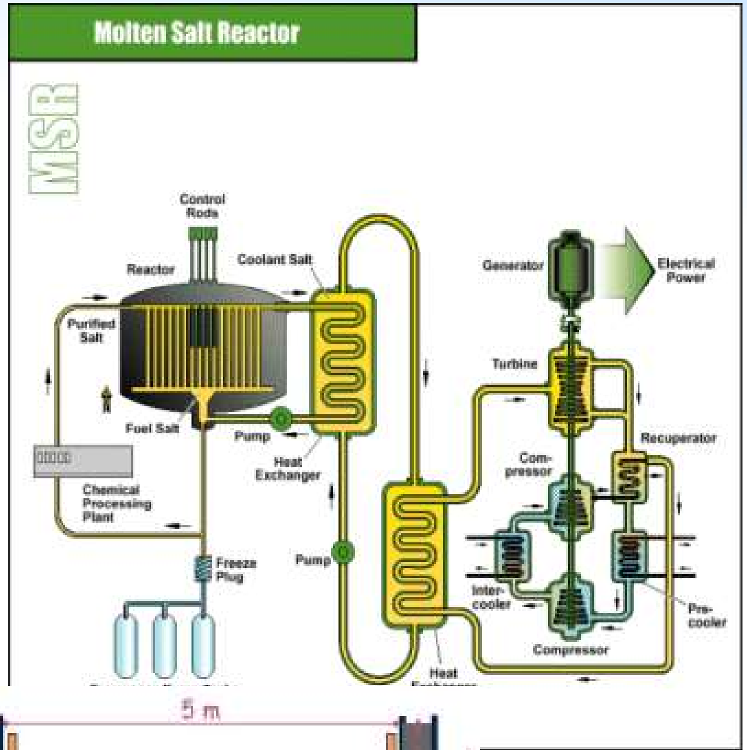
- FRs multirecycling

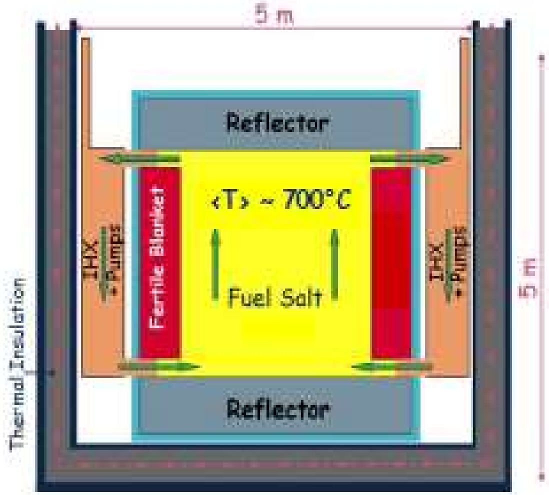


# Molten Salt reactor -
# Reactor and Fuel Cycle Facility as one unit

- **MSRs: systems with liquid fuel, molten fluoride (chloride) salts, circulating in primary circuit**
- **Actinide-free molten salt in secondary circuit**
- **Online fuel reprocessing instead of fuel fabrication**
- **Operation either as breeders (Th-U or U-Pu cycle), as nuclear waste incinerators (transmuters)**
- **Thermal (graphite moderator) or Fast neutron spectrum**
- **Typical fuel : Flourides of actinides dissolved in a carrier salt, such as $^{7}LiF-BeF_2$.**



# IAEA INPRO: “SYNERGIES” PROJECT

IAEA

## What Can We Do Before 2050?

Today | 2025 | 2040 | 2050

**‘Tech of the shelf’**

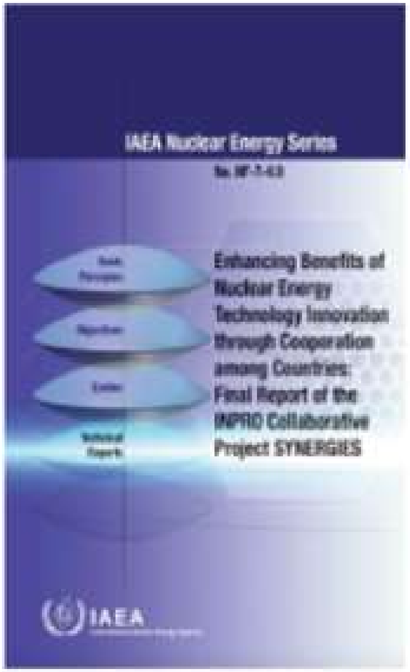
Synergistic Solutions:
- Shared NPP (investment)
- Shared capabilities & resources
- Front-End:
  - Multi-national facilities (URENCO, Angarsk)
  - Fuel Bank
  - MOX / 100% MOX / TOP-MOX/ERU & precycling schemes
- Back-End:
  - Recycling services
  - (Regional) interim storage solutions
- NPPs:
  - LWR / PHWR

**‘Result of today’s R&D’**

Additional Synergistic Solutions:
- Front-End:
  - Additional multi-national facilities
  - New fuels (« dense », metal, nitride, Th, TRISO) opening additional options
  - Fuel leasing
- Back-End:
  - Additional regional Recycling services (Japan, Russia, India, China)
  - DUPIC
  - Multi-Pu recycling in LWRs
  - Regional interim storage solutions
  - (Regional) geological disposal sites deployment
- NPPs:
  - ALWRs / AHWRs
  - (oxide-fuel) FRs
  - SMRs / HTRs

**‘Fruit of tomorrow’s R&D’**

Additional Synergistic Solutions:
- Front-End:
  - Th/233U-cycle deployment
- Back-End:
  - Additional regional Recycling services (South Korea, South America, USA)
  - Advanced repro technologies (P&T, Pyro, ...)
- NPPs:
  - Proven F(B)R & deployment
  - Maturing Symbiotic NPP-parks with integrated fuel cycle schemes



# FROM RECYCLING TO CIRCULAR ECONOMY

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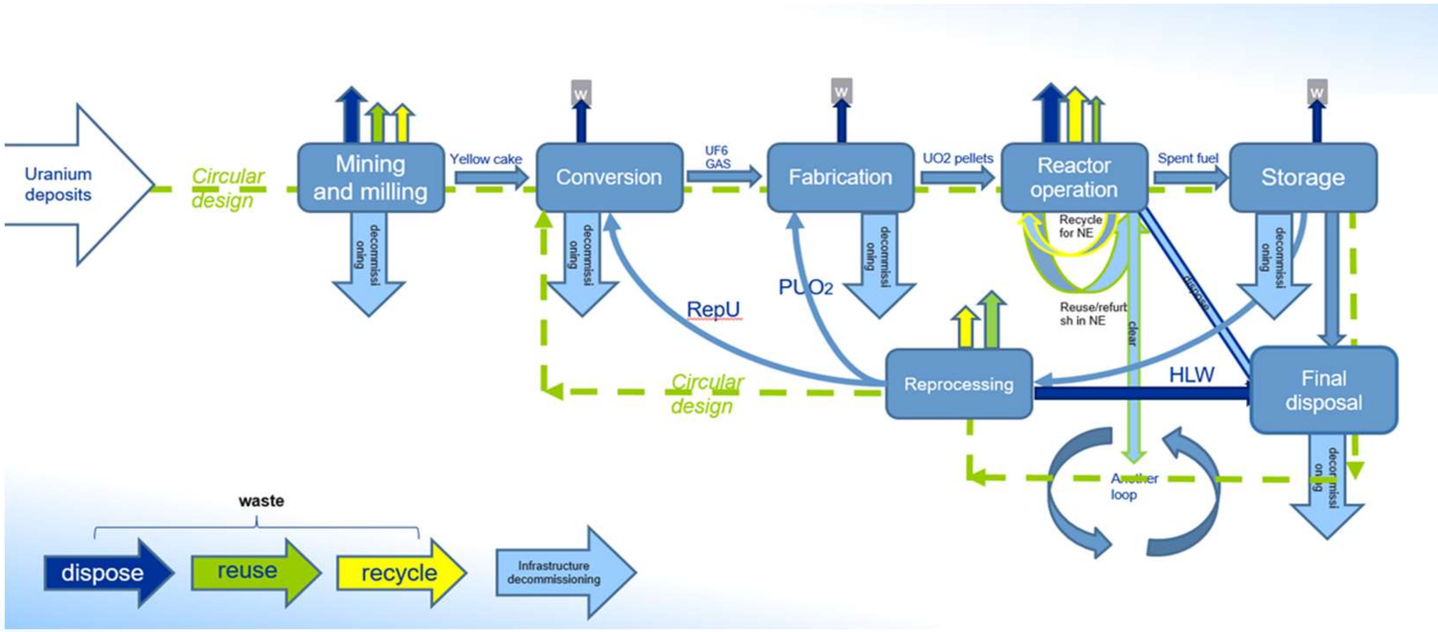
- There are opportunities to **enhance the "circularity"** of the nuclear fuel cycle, **identifying** already **existing good practices** and **socializing it.**

- Reprocessing technologies are an opportunity for **resource recovery** necessary for **long-term** sustainability of the Nuclear Fuel Cycle.

- And with a potential to contribute to reduce ultimate waste toxicity and volume



# NATIONAL POLICIES ON SPENT FUEL

| Country | NPP units | Policy | Remark |
|---|---|---|---|
| USA | 92 (2) (41 ps) | Review | AR/AFR interim storage (No reprocessing from 1977), Yucca Mt. licensing stopped |
| Finland | 5 | Disposal | ONKALO repository, operational license is expected (~2023)<br>AR wet storage |
| Canada | 19 (6 ps) | Disposal | AR dry storage<br>Repository site investigation |
| Sweden | 6 (7 ps) | Disposal | AFR wet storage (CLAP)<br>Östhammar repository site *(2009-2025)* |
| Germany | 3 (30 ps) | Disposal | 2005 reprocessing moratorium<br>AFR dry storage (Ahaus, Gorleben)<br>Gorleben repository site under investigation |
| Switzerland | 4 (2 ps) | Disposal | Zwilag AFR dry storage<br>3 repository candidate sites |

Red –under construction, ps – permanent shutdown

# NATIONAL POLICIES ON SPENT FUEL (2)

| Country | NPP units | Policy | Remark |
|---|---|---|---|
| France | 56 (1) (14 ps) | Reprocess | AFR wet storage<br>Bure repository site for HLW under development (pilot phase 2025) |
| Japan | 17 (2) (27 ps) | Reprocess (new debates) | Rokkasho reprocessing plant (long start-up)<br>Mutsu AFR dry storage |
| China | 55(18) | Reprocess | Pilot Reprocessing Plant is under operation<br>Second RP is under construction from 2021 (200t/a)<br>Commercial Reprocessing plant planned (800 t) |
| Russia | 37 (4) (10 ps) | Reprocess | AFR wet/dry storage, MAYAK Plant |
| UK | 9 (2) (36 ps) | Reprocess & Disposal | Magnox reprocessed – AFR wet storage<br>LWR spent fuel disposal |
| India | 22 (8) | Reprocess | Group of reprocessing facilities |

# NATIONAL POLICIES ON SPENT FUEL (3)

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- **New/old approaches:**
  - Storage SF, Send back to manufacturer, Reprocessing and recycling by manufacturer, Disposal of radioactive wastes
    - Bangladesh, Belarus, Iran, Turkey
    - Long term experience in the past:
      - France for Japan, Germany, Belgium, Switzerland etc.
      - Russia/USSR for Ukraine, Hungary, Bulgaria, Finland, Czech etc.

  - International repository is under consideration: National storage, Send to International Repository, Disposal SF
    - Under consideration: Slovenia / Croatia case for Krsko NPP
    - A number of States expressed the interest to International SNF repository

# INTERNATIONAL APPROACHES TO NUCLEAR FUEL CYCLE

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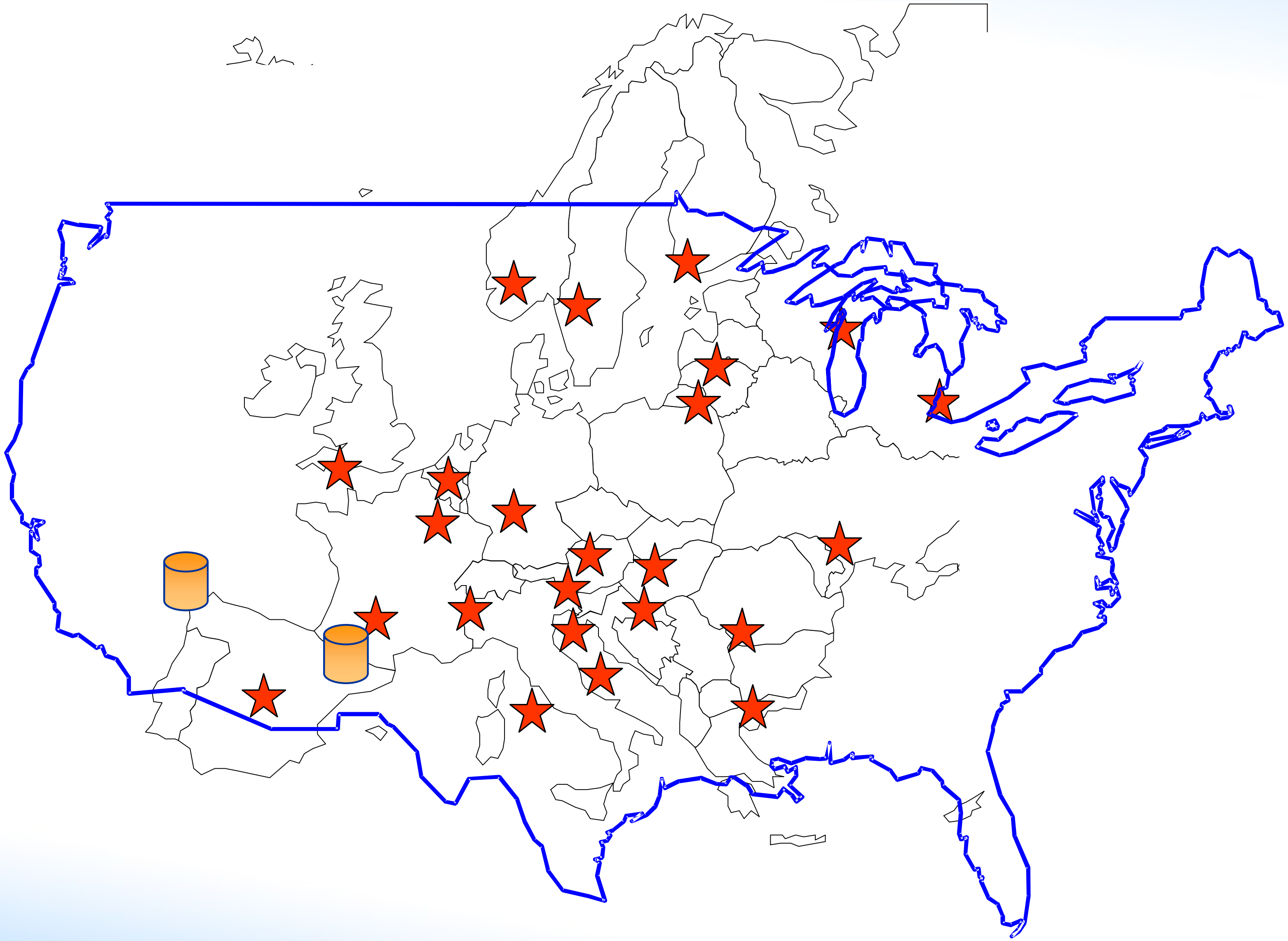
## Nuclear Fuel Cycle Front-end

International initiatives (Russia-IAEA, UK, Germany, USA) and IAEA LEU Fuel Bank established LEU assurance supply mechanism for Nuclear Power stable supply by fuel

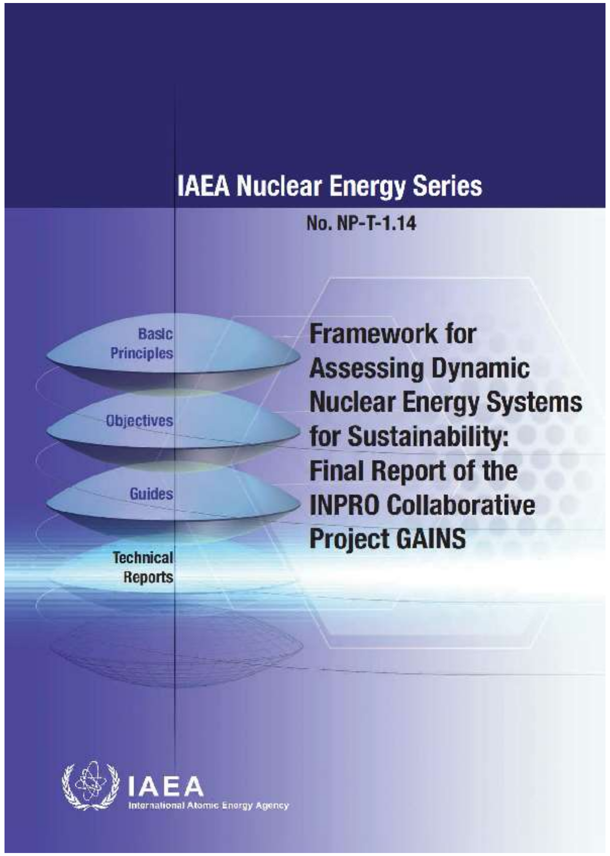
## Nuclear Fuel Cycle Back-end

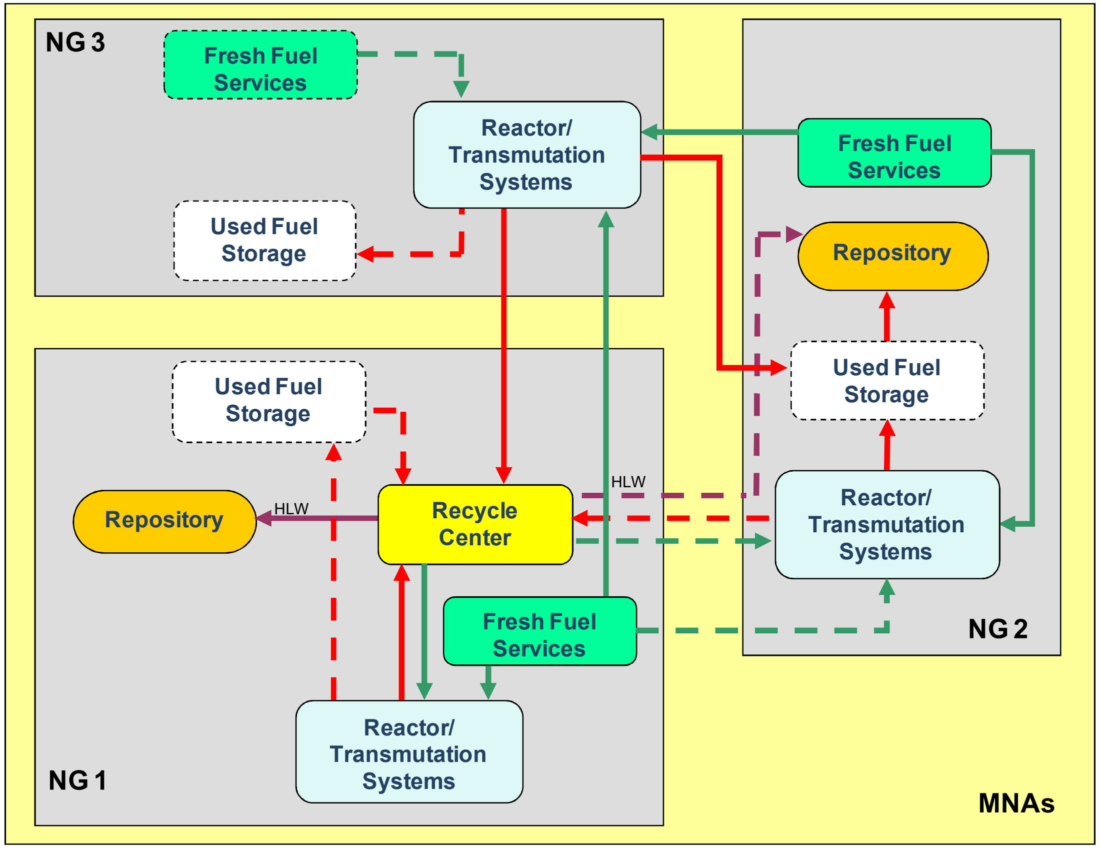
International Nuclear community had a number of attempt to discuss multilateral approaches to SNF Management.
Currently France and Russia suggest commercial service for SNF reprocessing and recycling.

# CAN/SHOULD EVERY COUNTRY HAVE ITS OWN GEOLOGICAL REPOSITORY?

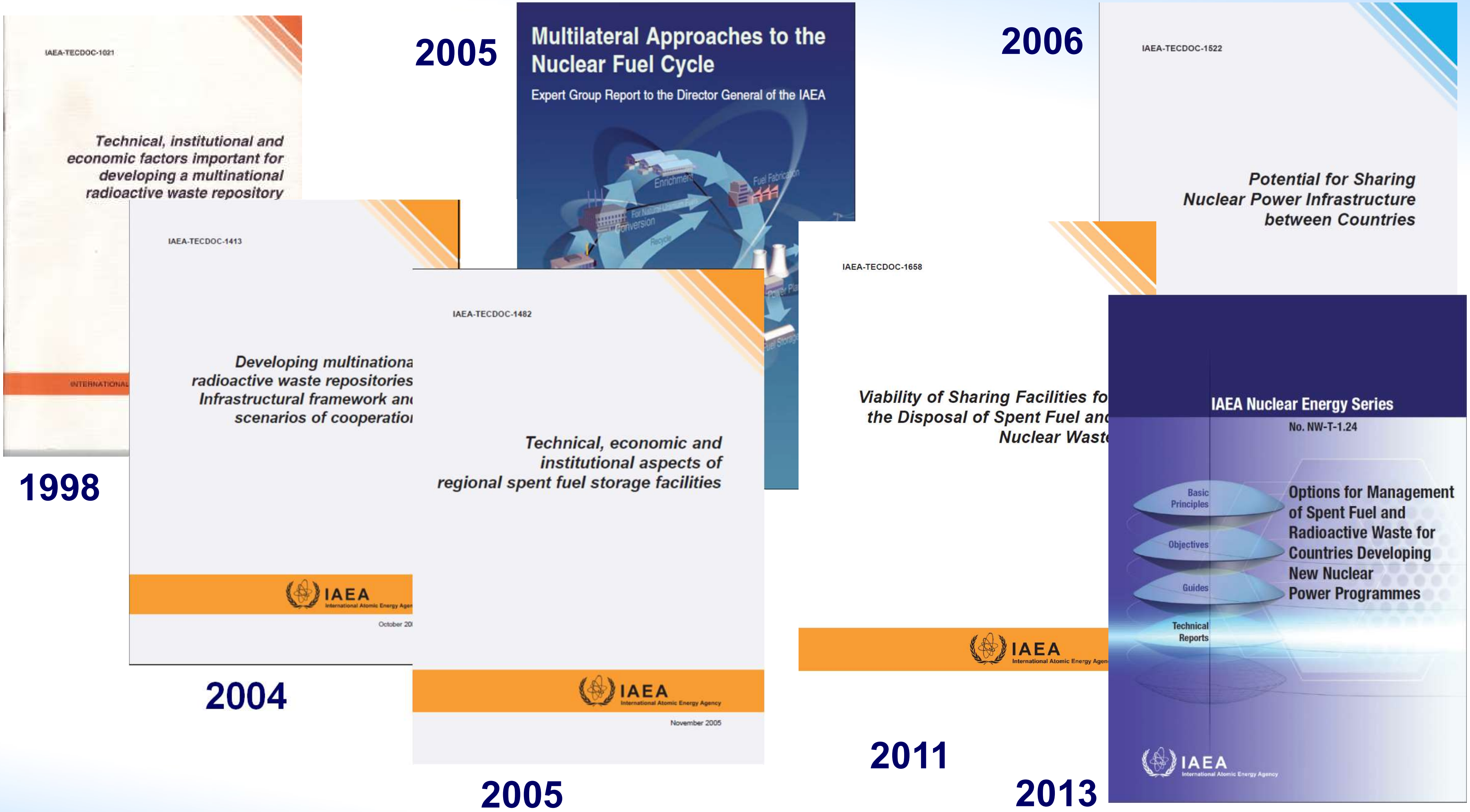


# INPRO COLLABORATION PROJECT GAINS 2008-2012



# IAEA DOCUMENTS ADDRESSING MULTILATERAL ISSUES




Current INPRO study: “Cooperative Approaches to the Back-end of the NFC: Drivers and Institutional, Economic and Legal Impediments”

# REMARKS ON SNF STRATEGY:

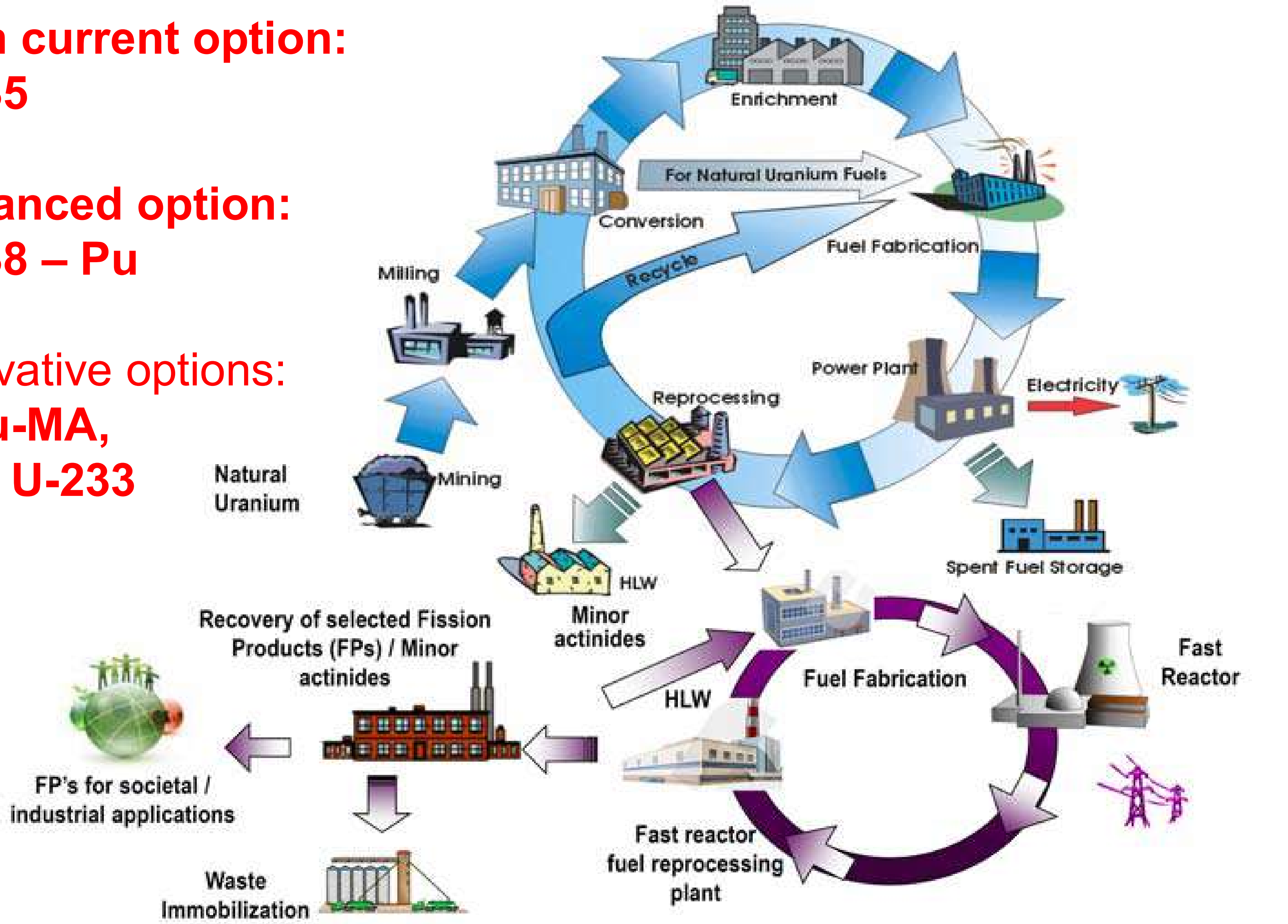
- Back-end of the Nuclear Fuel Cycle (FC) is one of key problems of Nuclear Power as a whole. Most nuclear power countries do not have final strategy for back-end of FC – final decisions related SNF. Long-term storage is intermediate decision. Final disposal keeps long-term dangerous related actinides and long-lived FPs (risk of future ecological problems). Reprocessing option is sensitive from non-proliferation point of view.
- Absence of standard / easy approach to back-end strongly influences decision of new countries to consider Nuclear as part of energy mix.
- Necessity to control all SNF (Spent Nuclear Fuel), contained Pu and its flow management, suggests limits on the number of SNF storage sites and/or reprocessing plants
- The Joint Convention, Safety Fundamentals, IAEA safety standards, NE Series documents and the EU waste management directive all emphasize “that the ultimate responsibility for ensuring the safety of spent fuel and radioactive waste management rests with the State”

# NUCLEAR FUEL CYCLE OPTIONS FOR FUTURE

**Main current option:**
**U-235**

**Advanced option:**
**U-238 – Pu**

Innovative options:
**U-Pu-MA,**
**Th – U-233**



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International Atomic Energy Agency

# *Thank you!*

a.bychkov@iaea.org


https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro

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