Nuclear Fuel Cycle Development: Balancing Innovation and Resource Management

Alexander Bychkov - international expert
Ex-DDG-NE IAEA (2011-2015)

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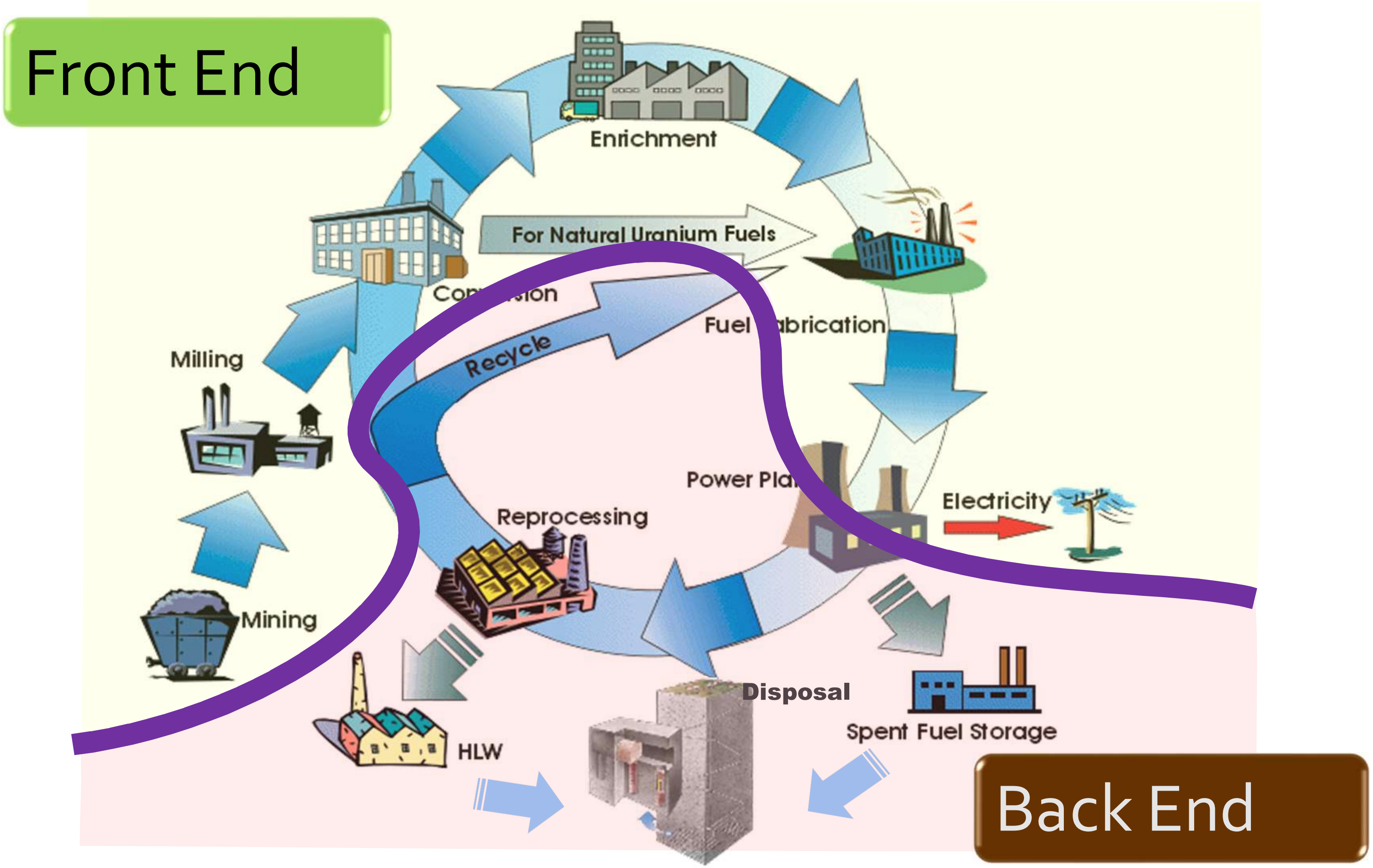
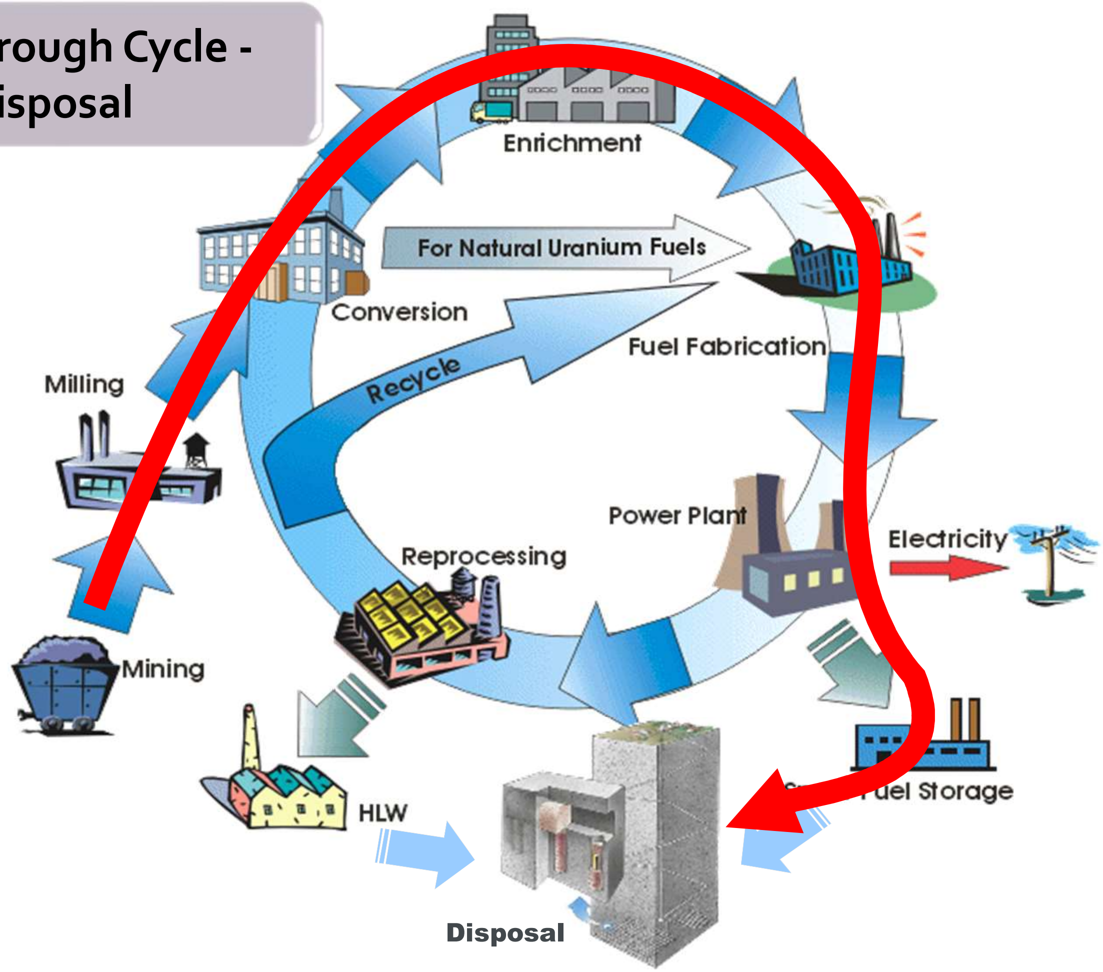
Nuclear Fuel Cycle



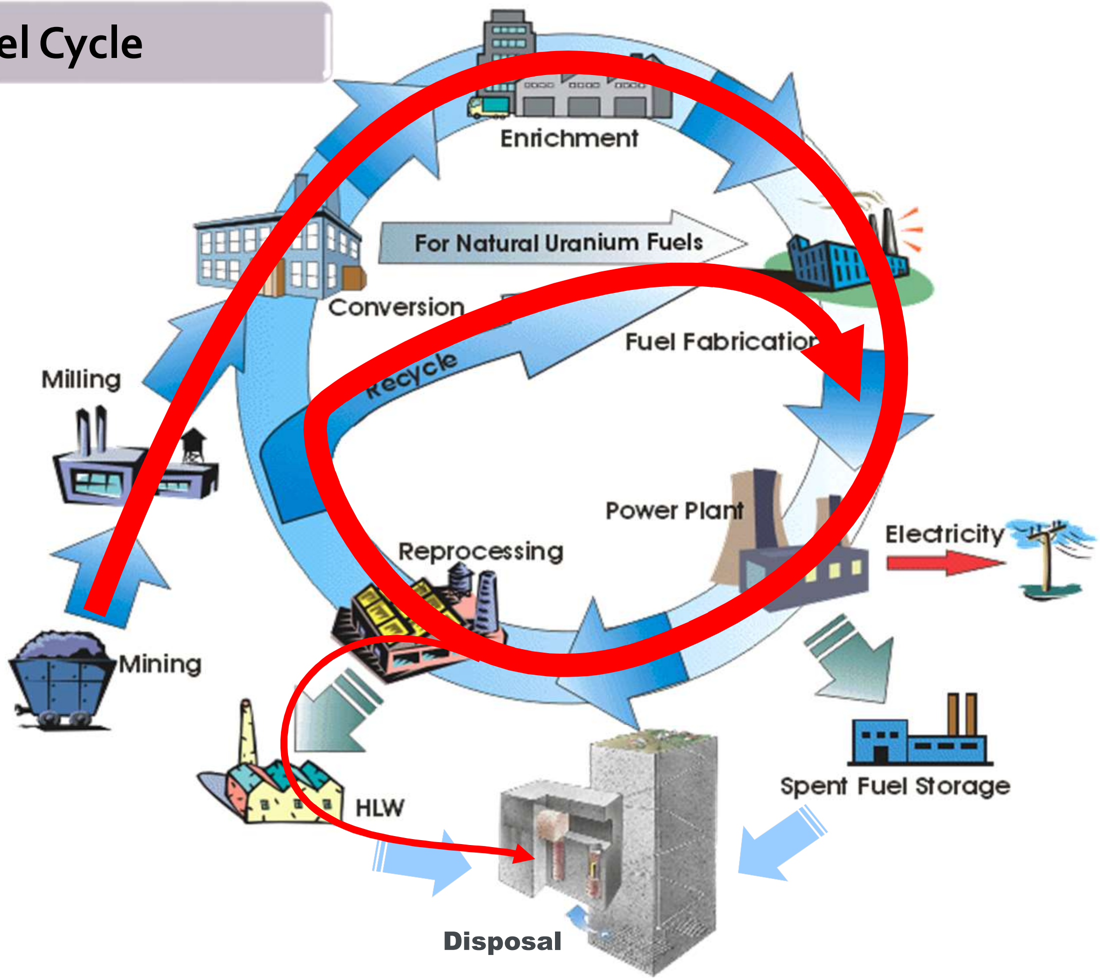
Types of Nuclear Fuel Cycle

Once Through Cycle - Direct Disposal



Types of Nuclear Fuel Cycle

Closed Fuel Cycle



Nuclear Fuel Cycle more attractive for innovations than Reactor Systems

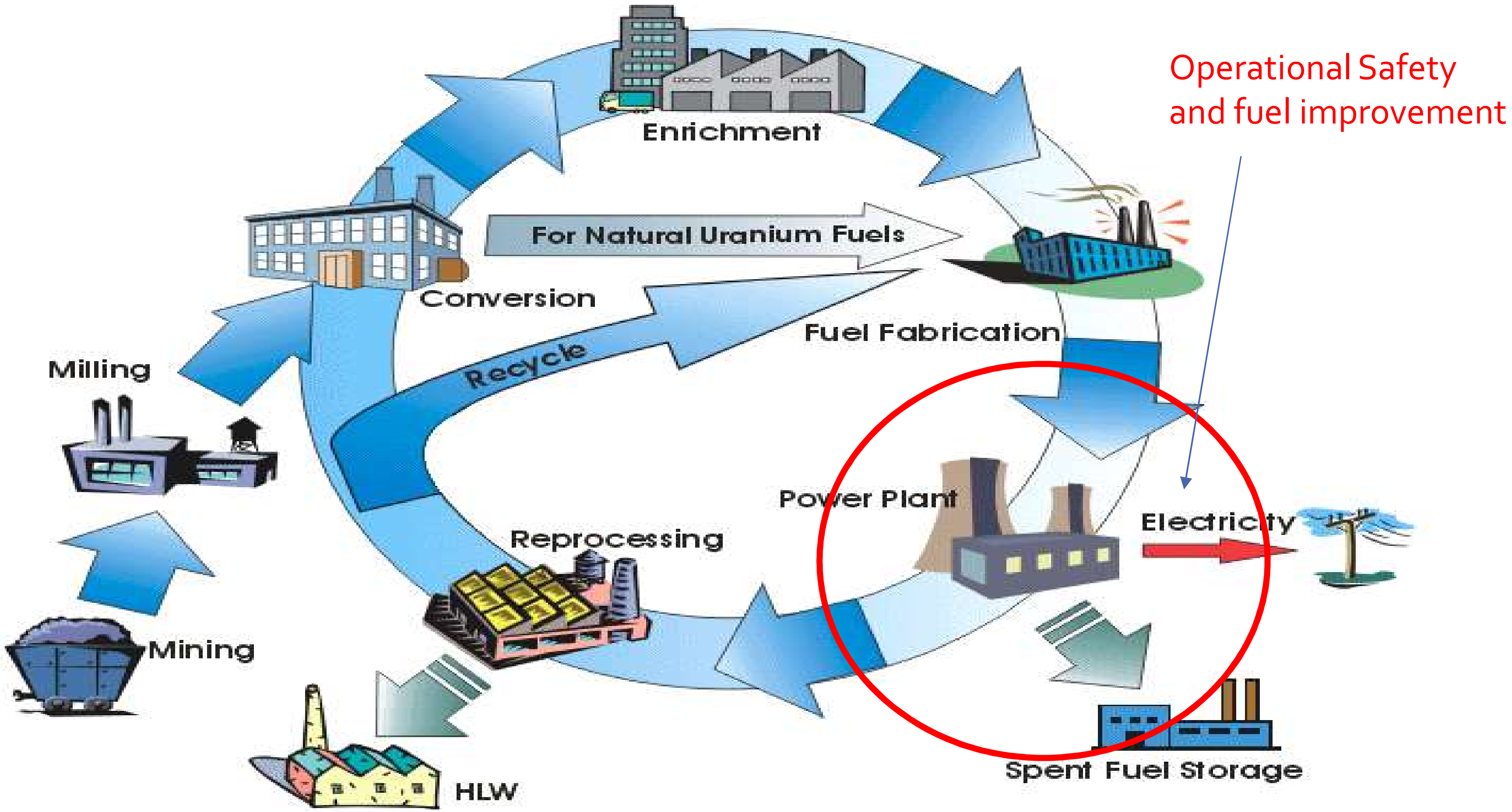
Innovations in Nuclear Fuel Cycle Front-end:

- **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.

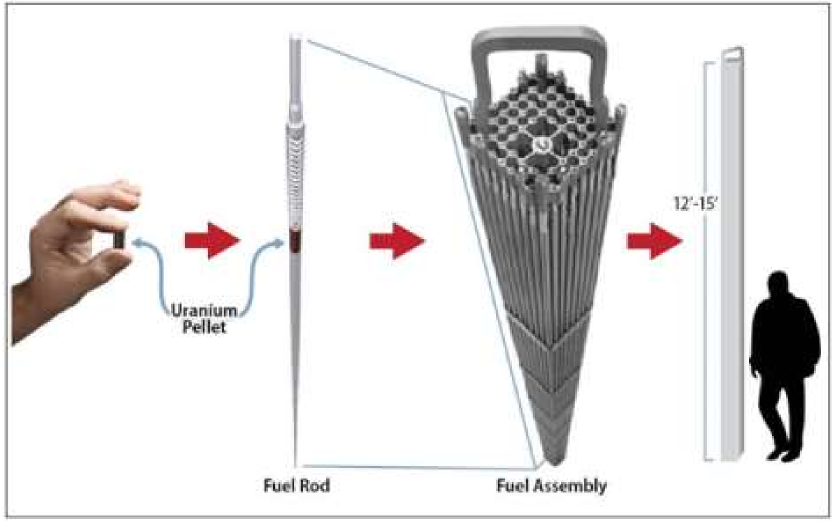
Some steps to Innovations in Nuclear Fuel Cycle Back-end:

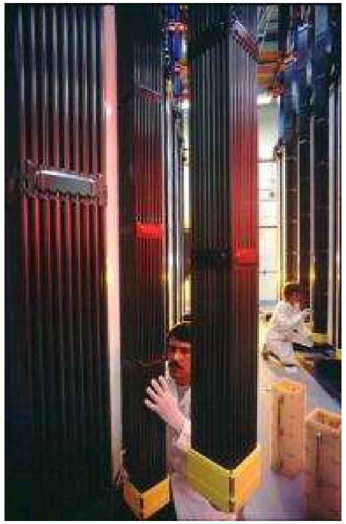
- **Development and improvement of technologies for fuel manufacturing with reprocessed U and Pu** brings a complex effect: reduction of natural uranium demands, reduction of SNF storage expenses, reduction of HLW radiotoxicity, etc.
- **MOX (or mixed U-Pu nitride or metal) fuel technology** is a key technological way for closed fuel cycle of fast reactors.

Nuclear Fuel Cycle – Fuel Fabrication



Nuclear Fuel Fabrication





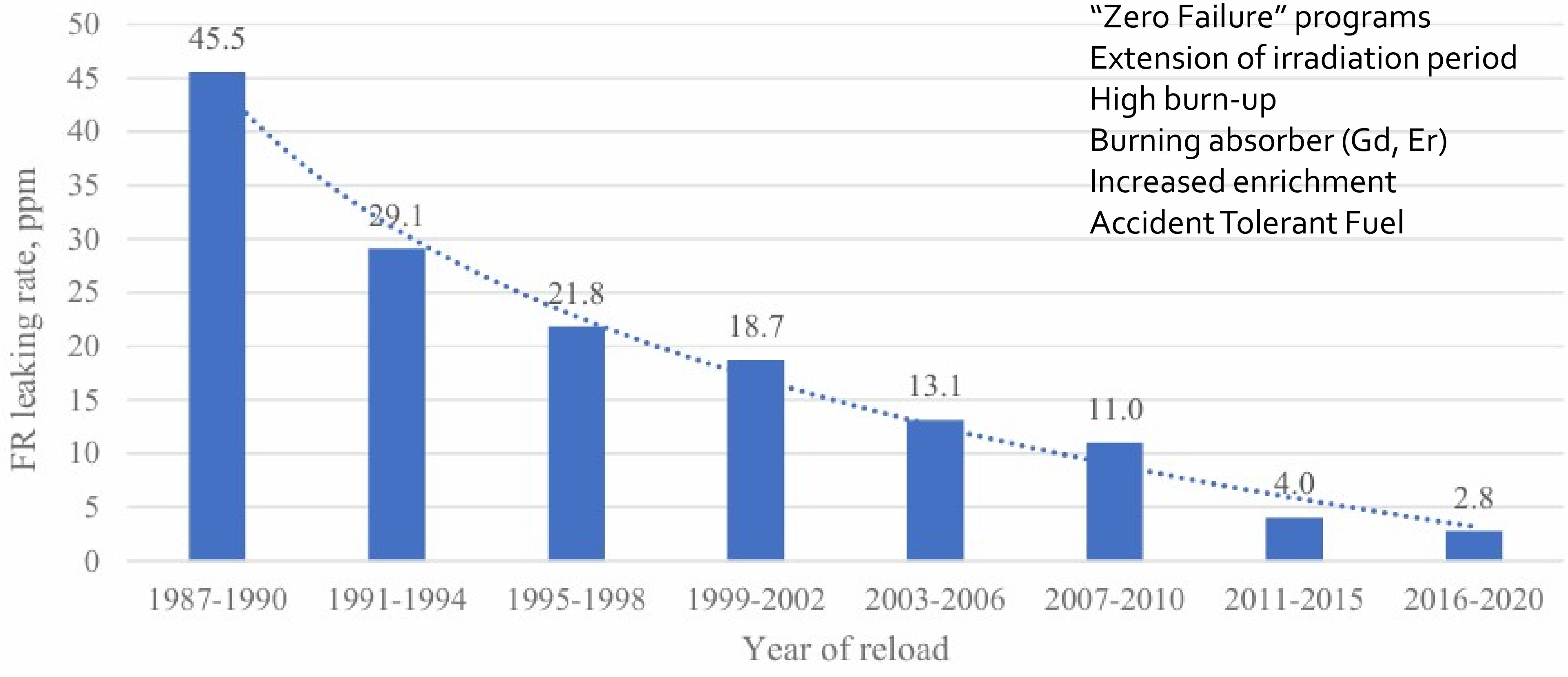
Fuel must be placed in a robust physical form capable of enduring high operating temperatures and an intense neutron radiation environment

Fuel assembly needs to keep its integrity: key element of safety

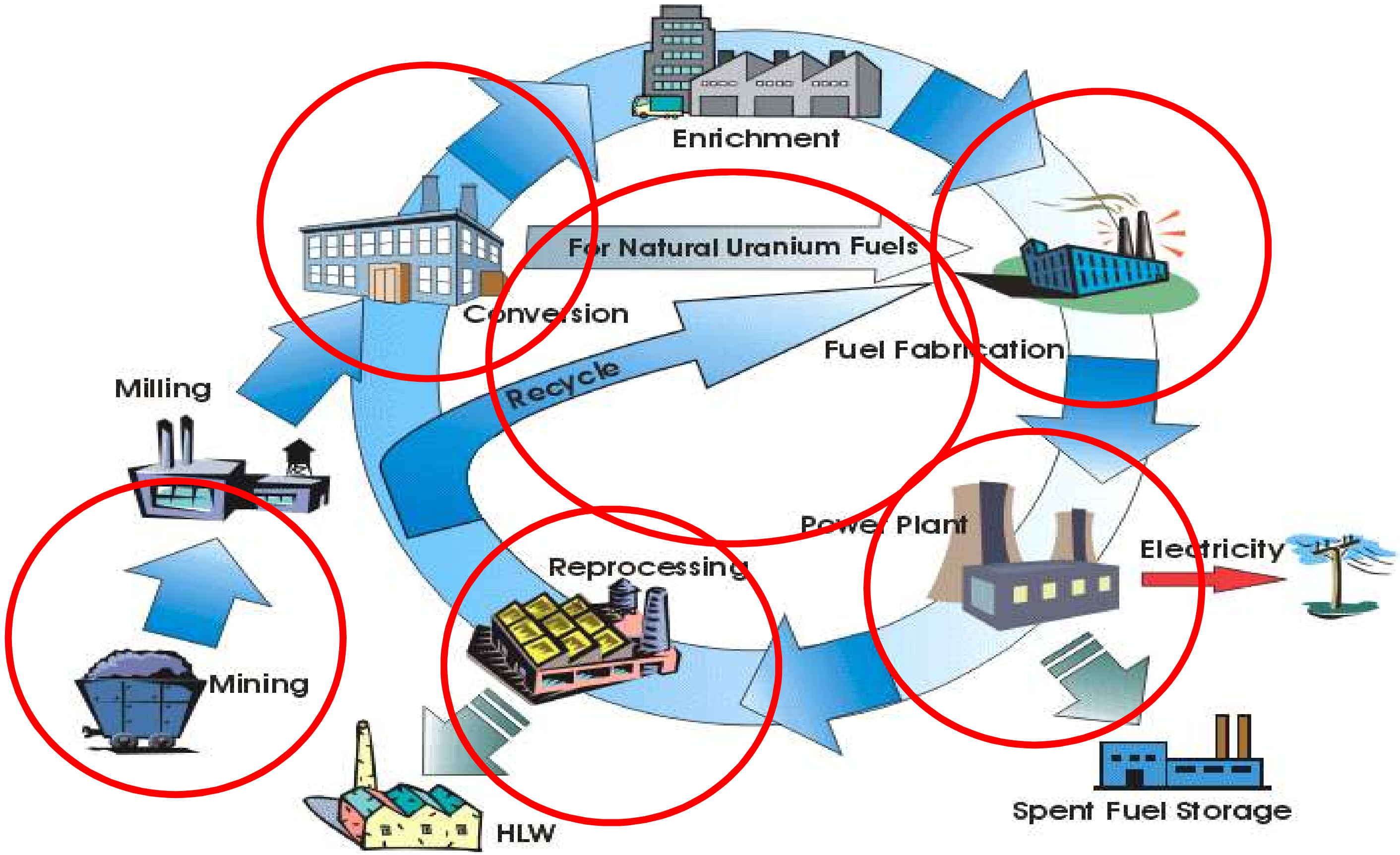
Quality control + fuel improvement

World average PWR fuel rod failure (IAEA data)

Main lines for fuel improvement:
"Zero Failure" programs
Extension of irradiation period
High burn-up
Burning absorber (Gd, Er)
Increased enrichment
Accident Tolerant Fuel



Nuclear Fuel Cycle – technologies evolution or innovations?

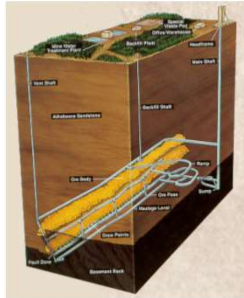


Uranium Exploration

- 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)

Growth of affordable resources

Uranium Mining Methods: In-situ Leach

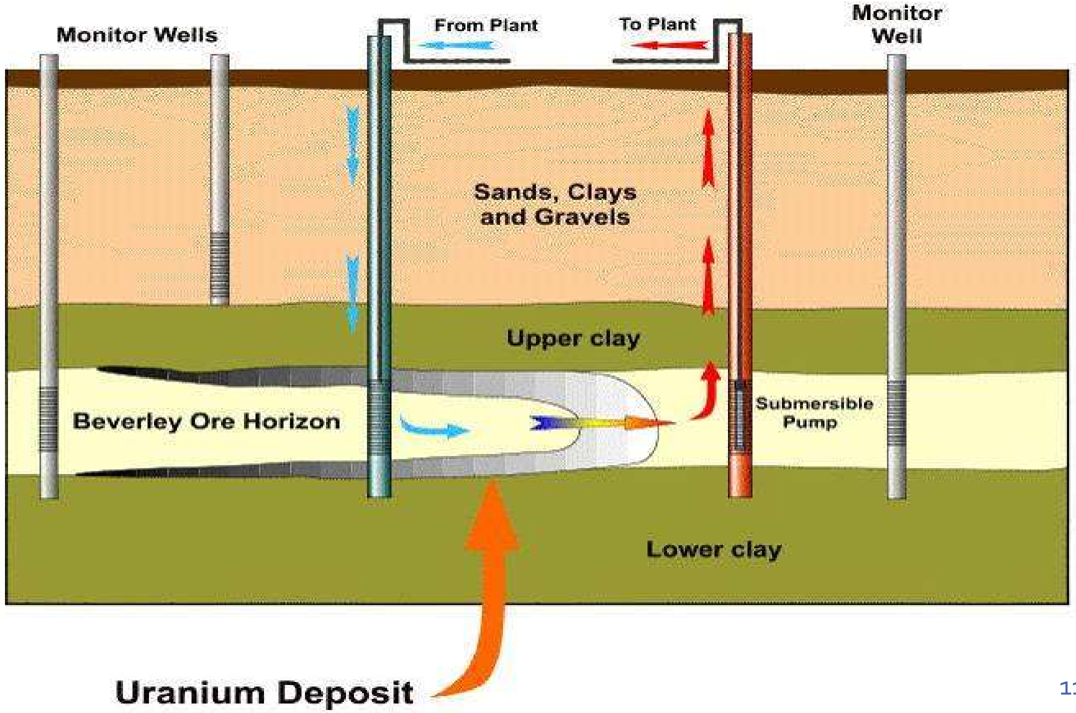


Uranium is mined in one of following ways:

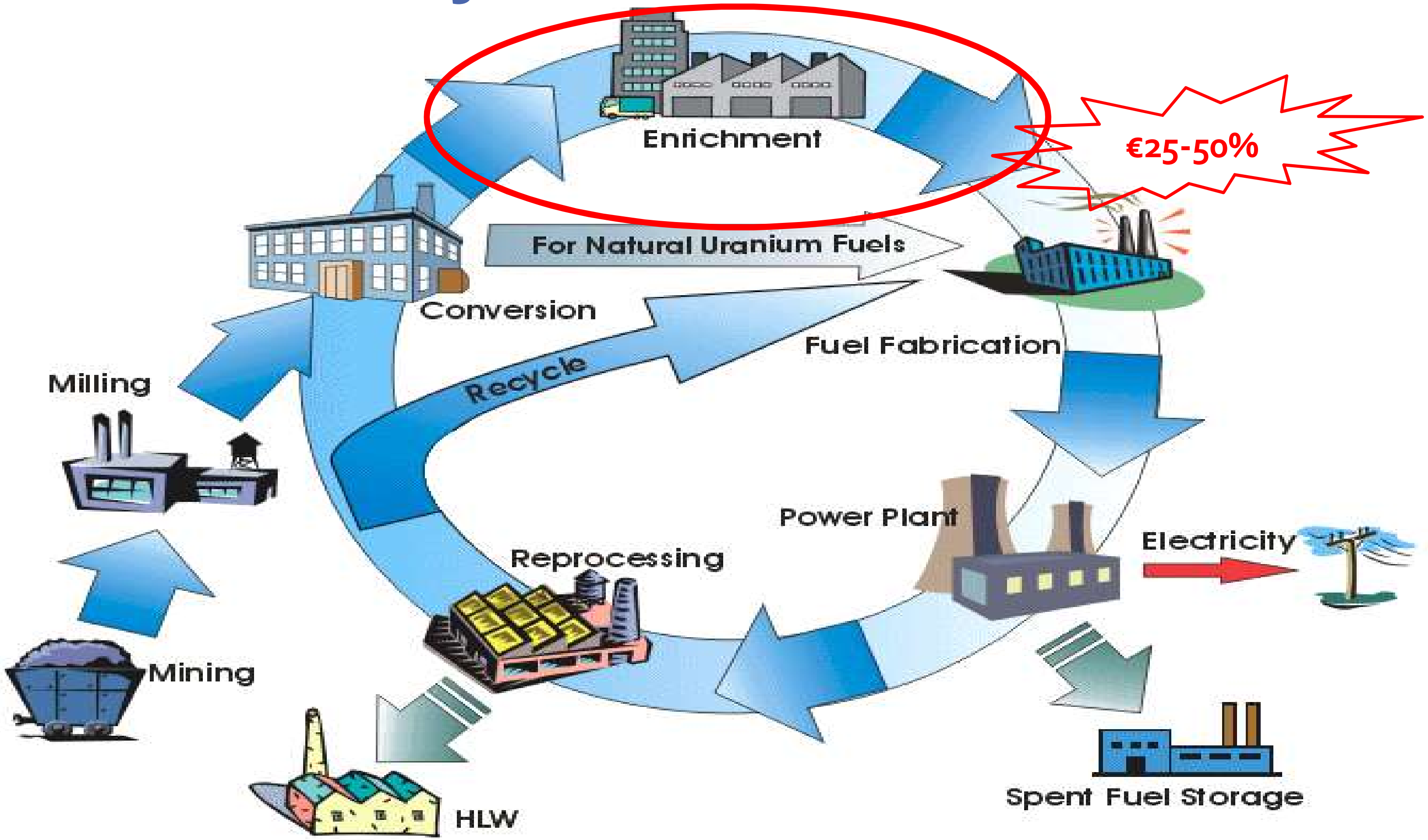
- Open pit, including surface excavations
- Underground with tunnels, galleries etc.
- In-situ leach mining – ISL [also ISR or solution mining]
- As a by-product from the mining of other minerals

- Currently (2022) ~ **60%** of world mined uranium is mined by ISL (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



Uranium Enrichment Improvement

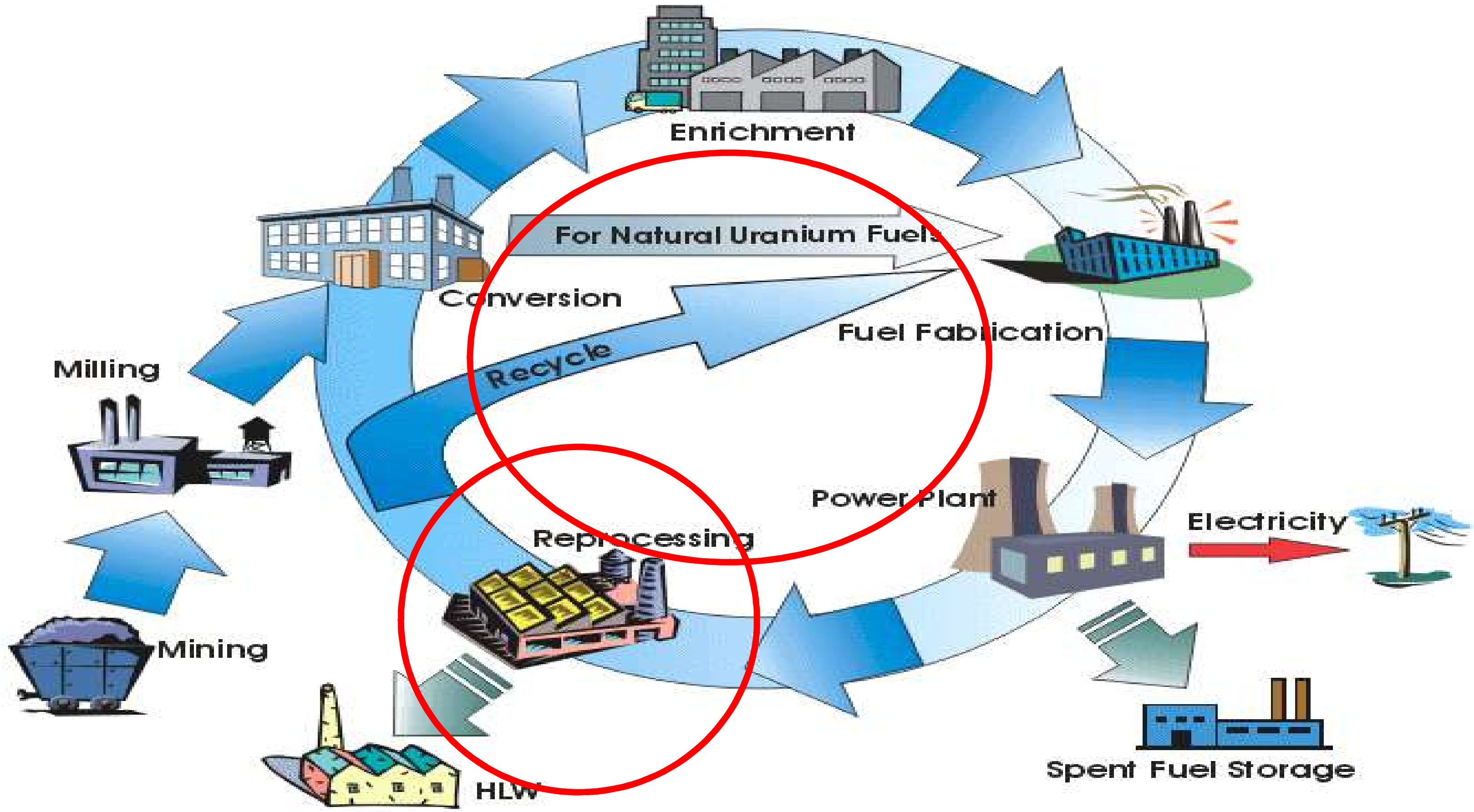
- Currently gas centrifuge process is basic commercial option
  - 2000 – 50% enriched by diffusion, 40% - by centrifuge, 10% - ex.weapon
  - 2015 – 100% enriched by centrifuge
- Energy consumption for the Separative Work Unit:

  2,400 kWh/SWU for Gaseous Diffusion,

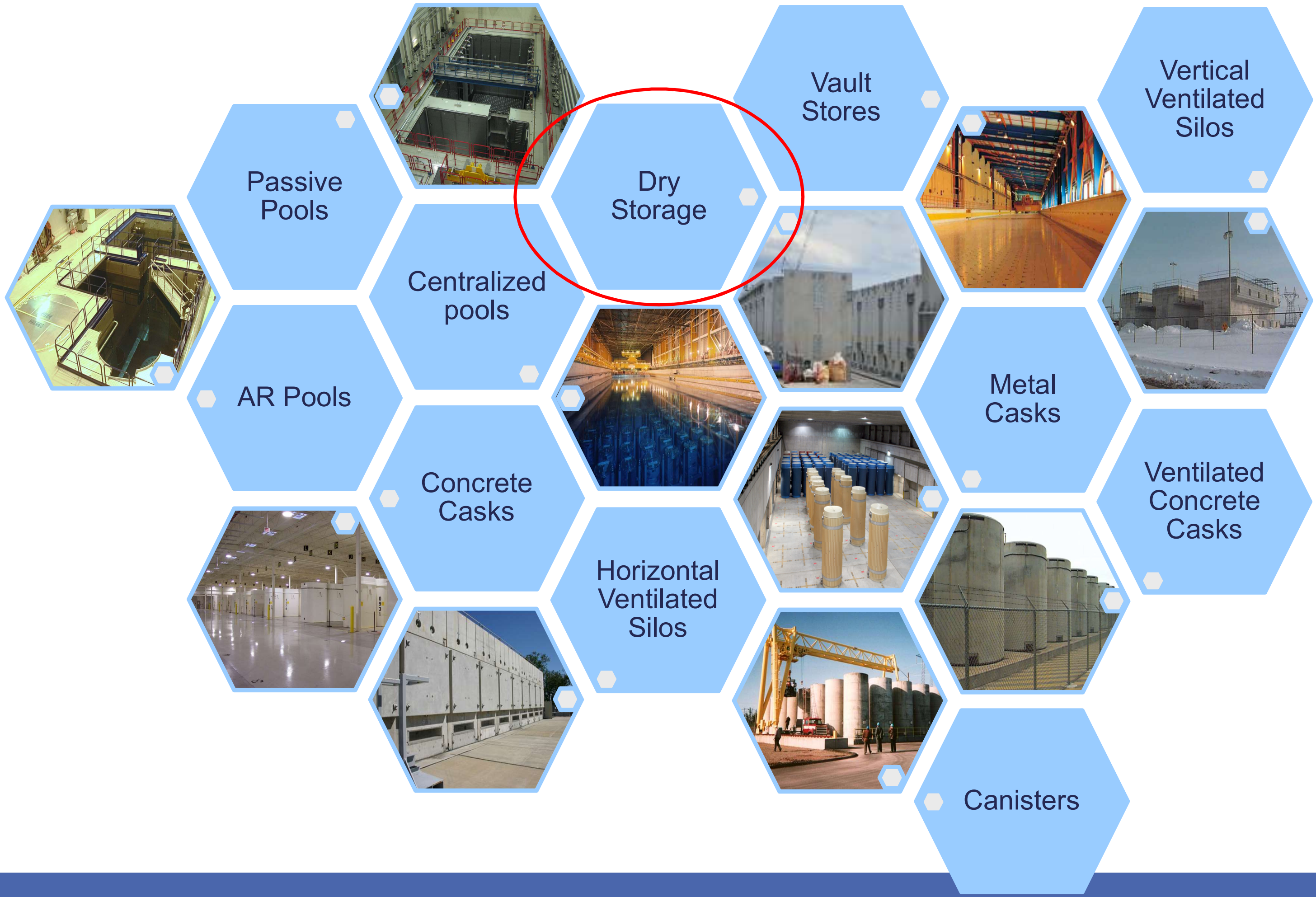
  < 50 kWh/SWU for Centrifuge Process)

- 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

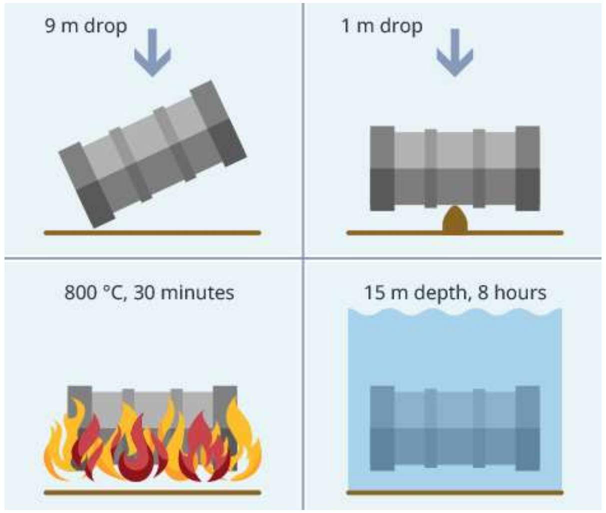
Nuclear Fuel Cycle – Spent Fuel Management options



Spent Fuel Storage Technologies



Spent Fuel Storage Technologies – Dry Storage



https://www.iaea.org/publications/12288/regulations-for-the-safe-transport-of-radioactive-material

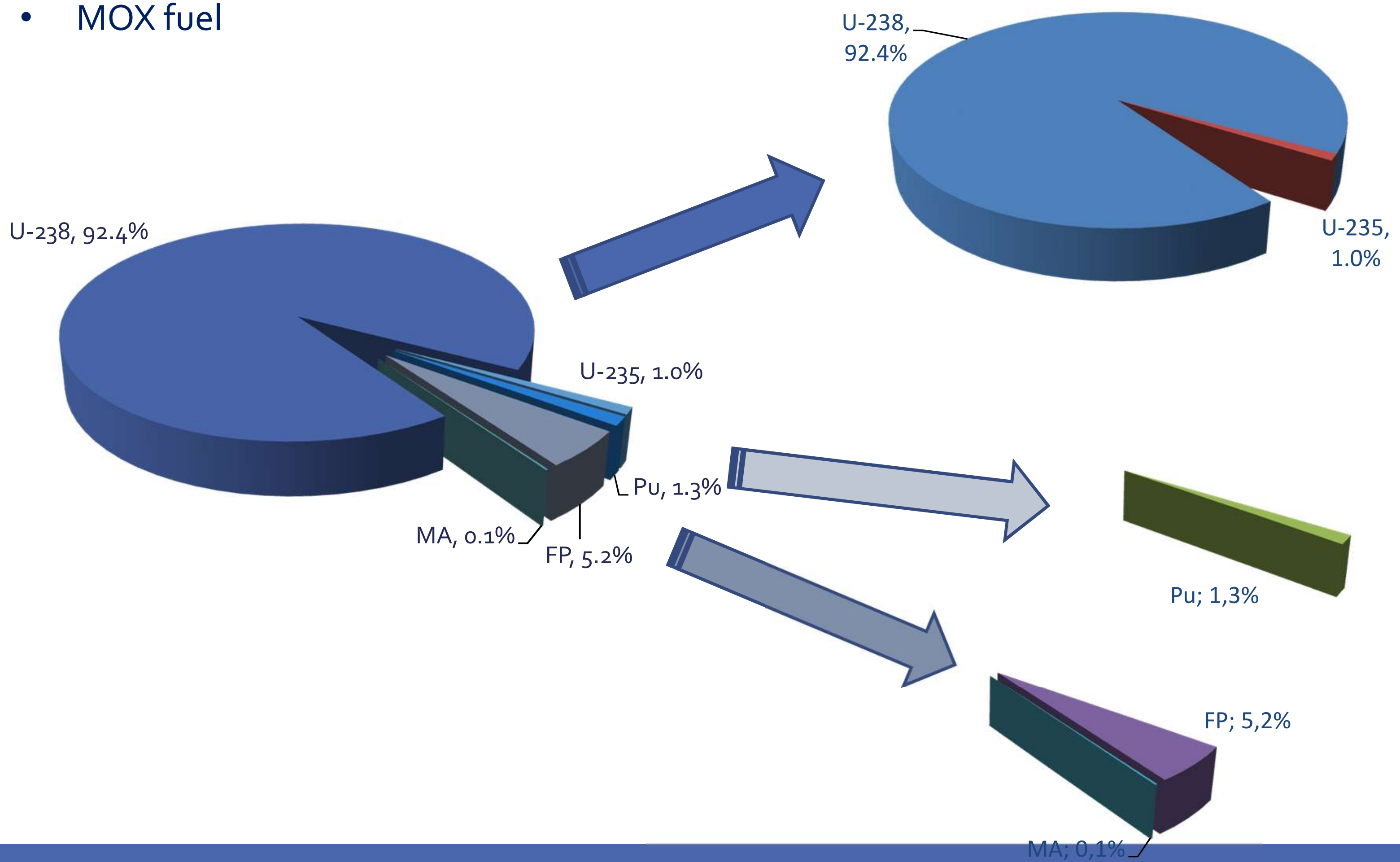
- Dry storage experience exists for fuel from different reactor types:
  - CANDU, PHWR, PWR, BWR, WWER, Magnox and AGR

- Dry storage systems have evolved:
  - Initial systems only designed for storage (past)
  - Now Dual-Purpose Systems, designed for storage and transport (present)
  - In future Multipurpose Systems, designed for storage, transport and disposal (future)

Spent Fuel Reprocessing

Reprocessing and Recycling today is largely based on:

- Recovering U (RepU) and Pu
- MOX fuel

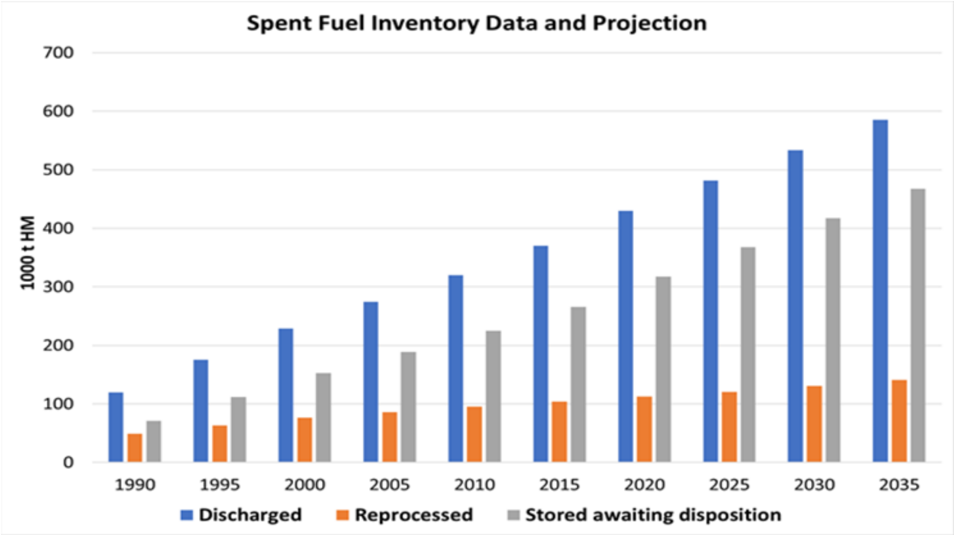


Last Decades Trends on SF Reprocessing

- **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**

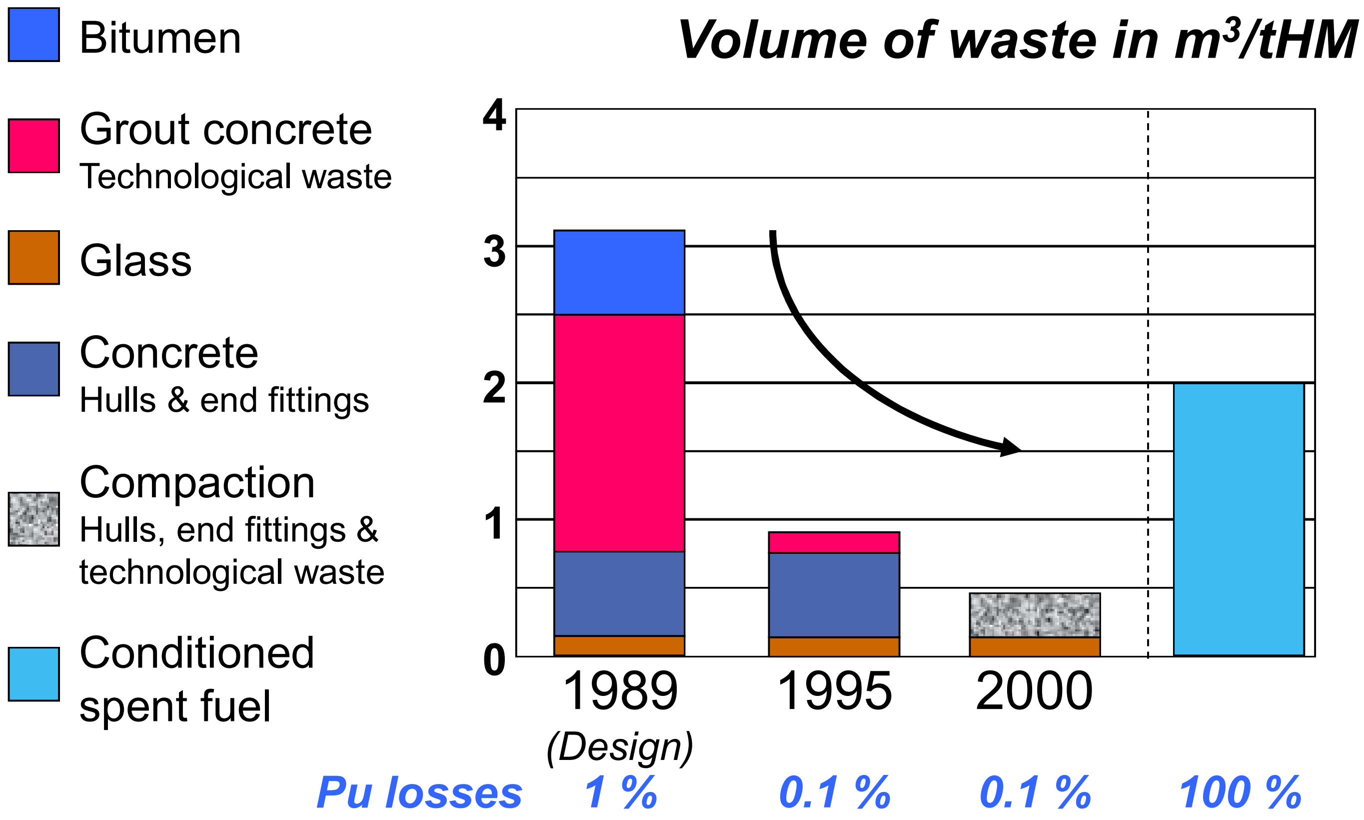
- Global Inventory in storage by the end 2025 ~ **322 000 tHM**

- The annual discharges of spent fuel from the world's power reactors total about 10 500 tHM per year.



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

"Classic" Example of innovative solution: Specific waste volume for the UP3 plant (France)



Reprocessing and Recycling – current status (briefly)

Recycling Spent Fuel is a **mature technology**

Reference Options exist worldwide:

- Reuse of reprocessed Pu 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 by 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 of reprocessed Pu as **MOX in Fast Reactors:** 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% Rep U cores
- **Reprocessing capacities** exist in France, Russia, India, Japan and China

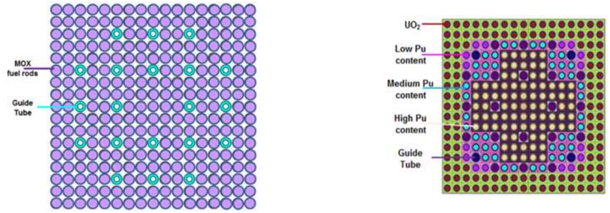
MOX fuel manufacturing: industrial scale and advances

❑ Cumulated experience of ~3000 tHM for LWRs
MELOX plant start in 1995

framatome orano

From: IAEA International conference on SNF Management 2019

Currently MOX fuel covers 5% of fresh fuel market

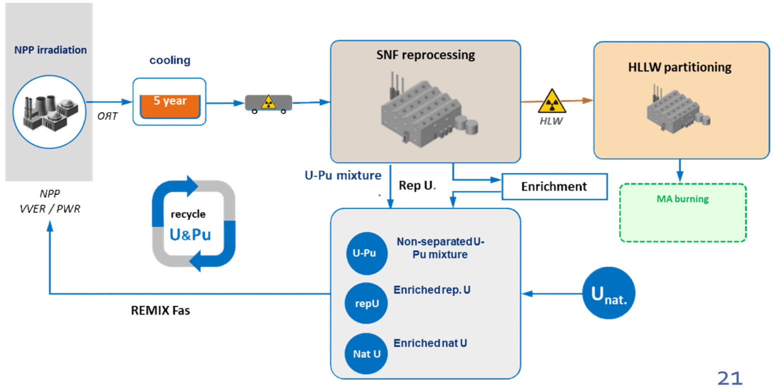


In France

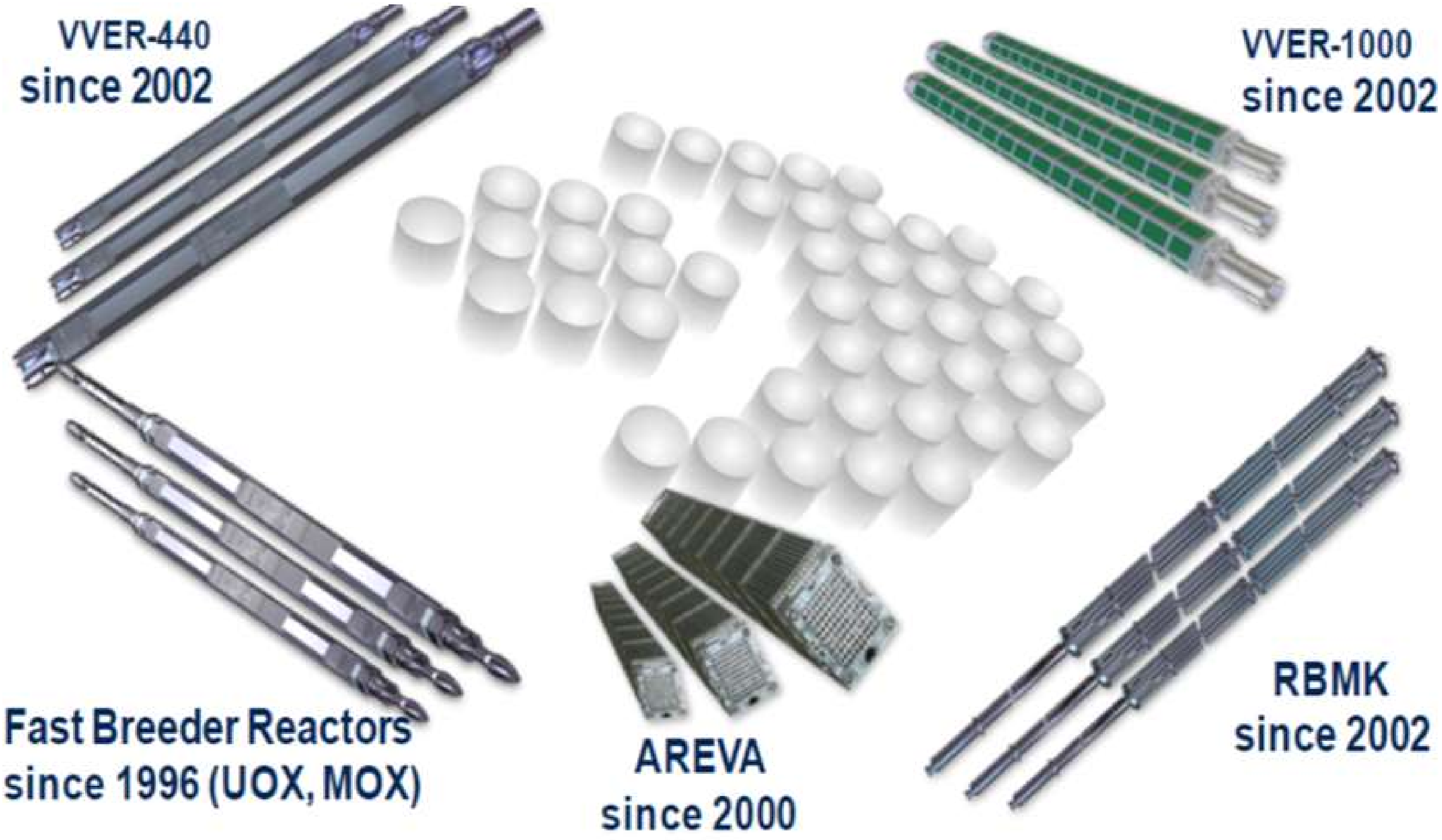
- CORAIL-A concept considers the use of UO_2 and MOX fuel rods in the same assembly
- MIX concept is only composed of MOX fuel rods with enriched uranium matrix (instead of depleted uranium as for current MOX fuel)

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



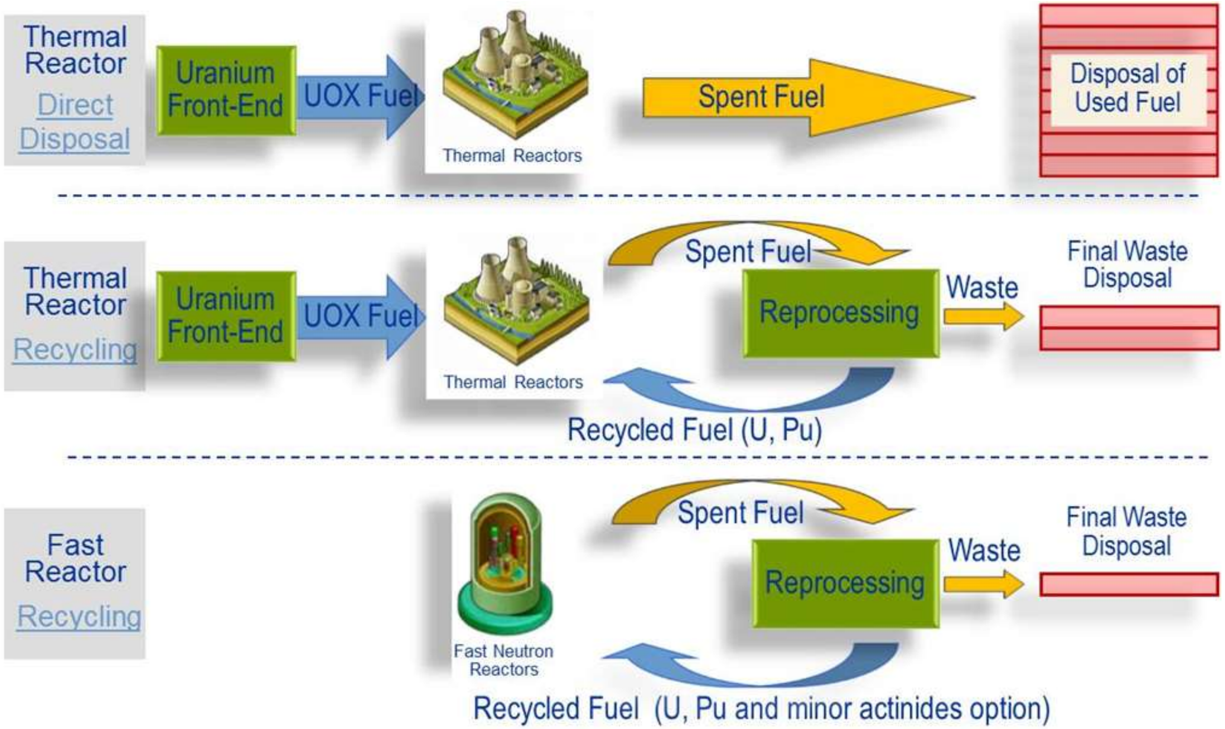
From: IAEA International conference on SNF Management 2019

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

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 for advanced reactors

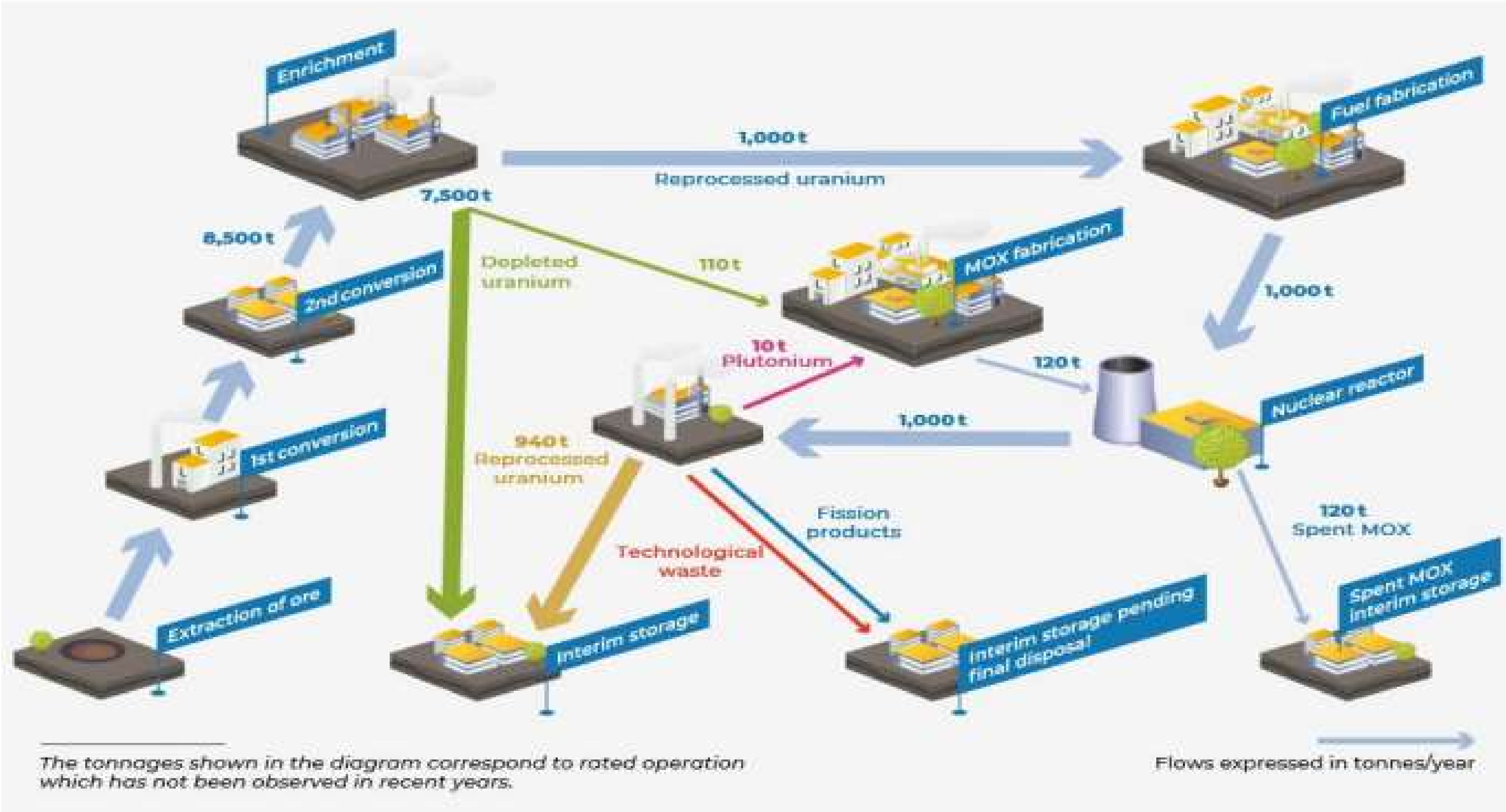


National Policies on Spent Fuel Management

- **Three current options for SNF Management:**
  - Reprocessing/recycling (France, Russia, Japan, China, India…)
  - SNF final disposal (Canada, Sweden, Finland, Germany…)
  - Postponed decision – SNF long-term storage (USA…)

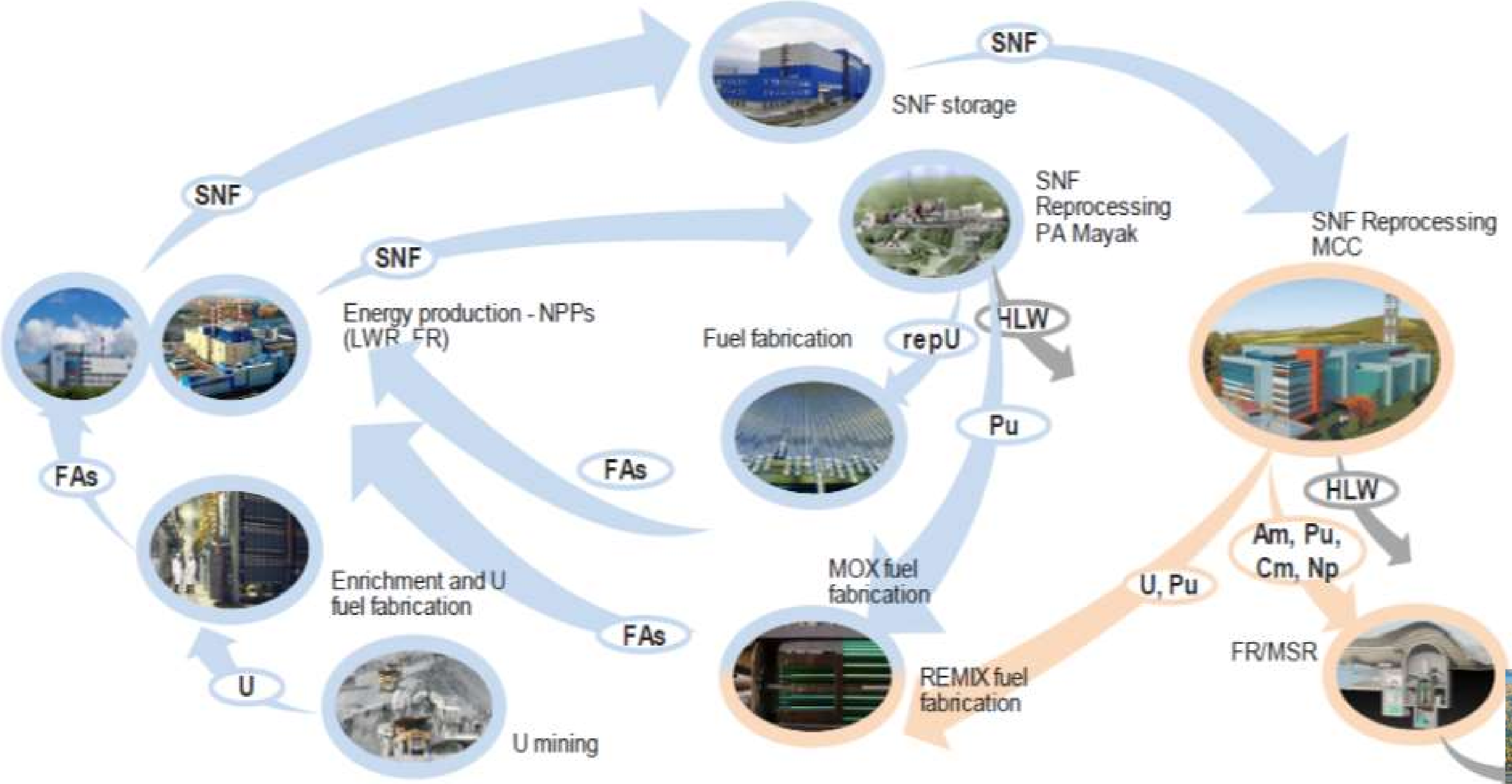
- **New/old approaches:**
  - Storage SF, Send back to manufacturer, Reprocessing and recycling by manufacturer, Disposal of radioactive wastes
    - Bangladesh, Belarus, Iran, Turkey
    - Long term experience in the past:
      - France for Japan, Germany, Belgium, Switzerland etc.
      - Russia/USSR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

The French Fuel Cycle



From: IAEA International conference on SNF Management 2024

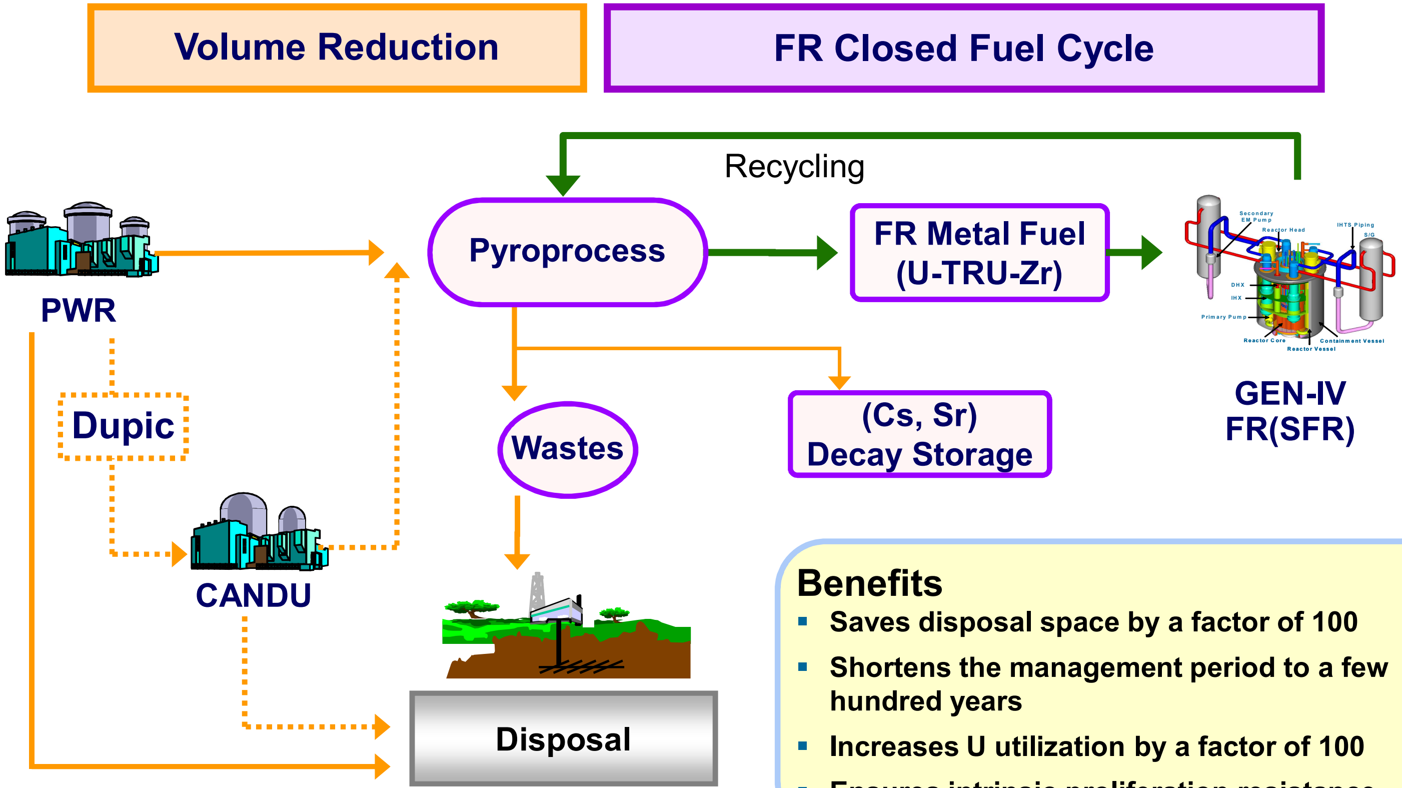
Infrastructure of Advanced Nuclear Fuel Cycles in Russia



From: IAEA International conference on SNF Management 2019

Republic of Korea:
Example of Advanced complex NFC

Promising Fuel Cycle Concept (KAERI)

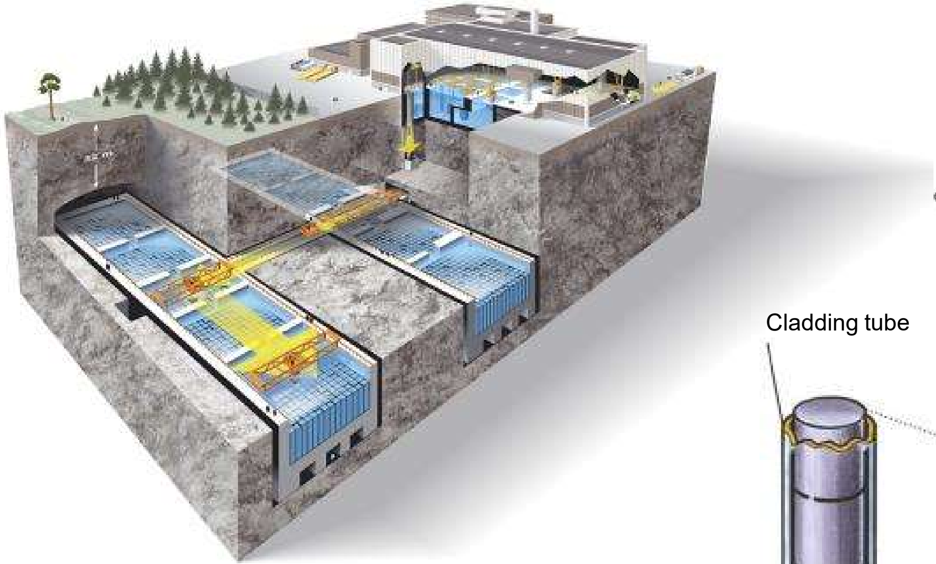


Benefits

- 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

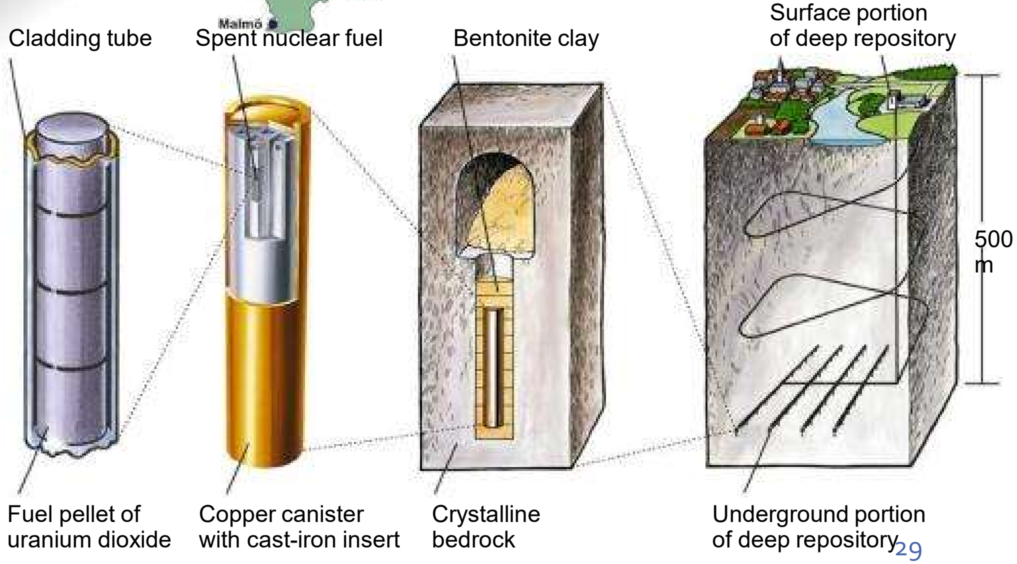
Sweden – SNF management: central storage and disposal

6 reactors are under operation,
7 – permanent shutdown

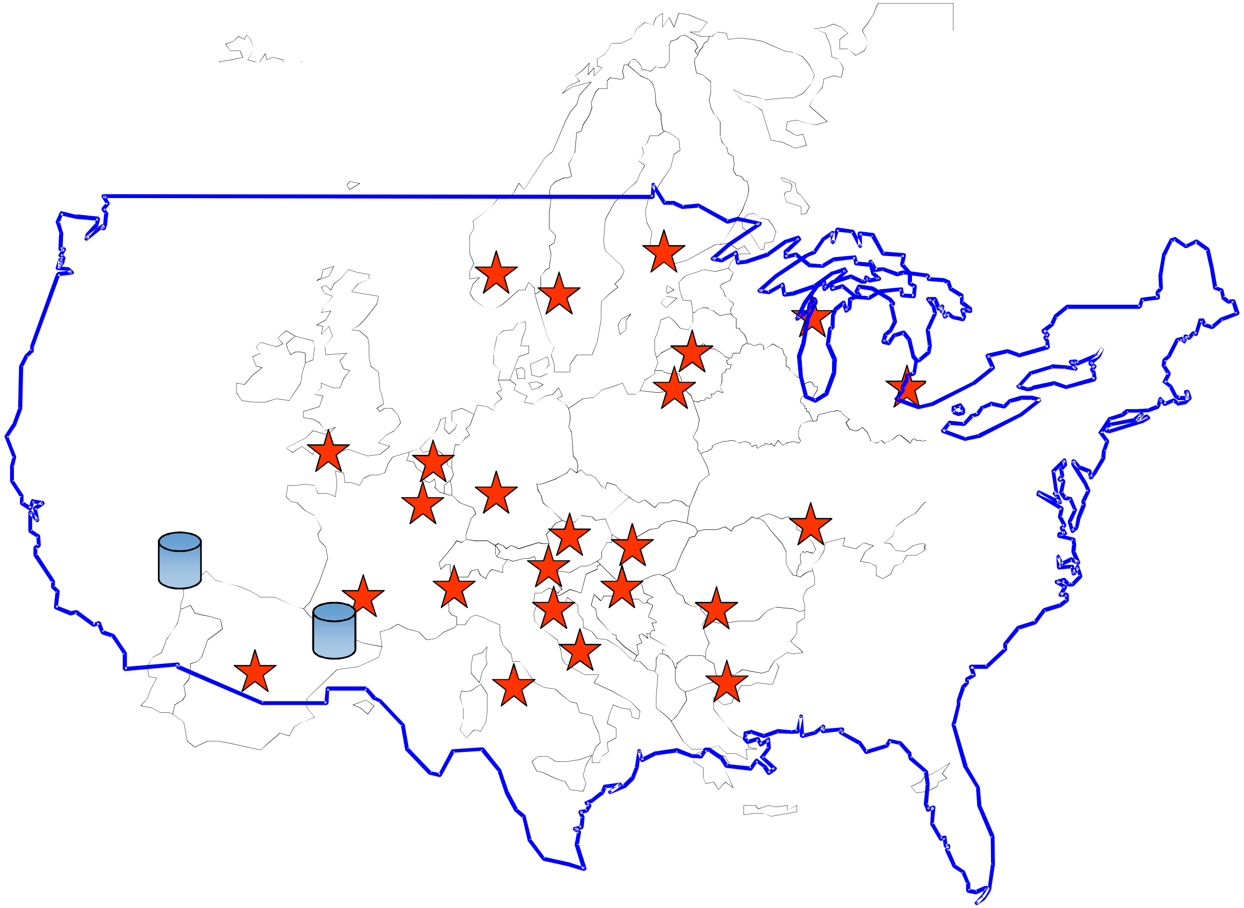


Centralized Wet Storage
(Oskarshamn)
8000 tHM

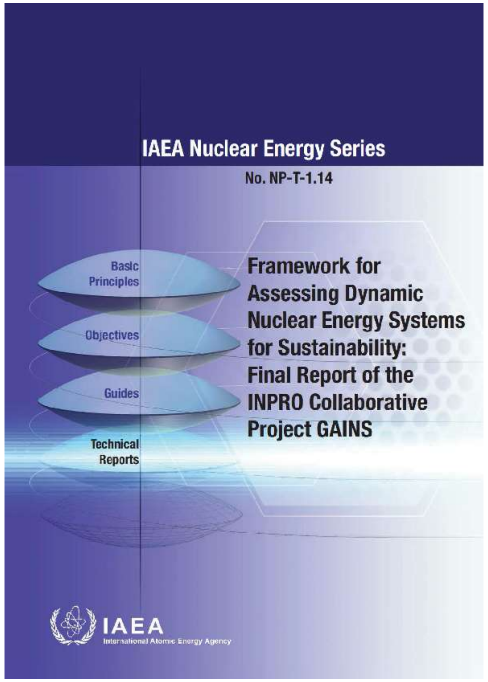
Repository Construction: Forsmark

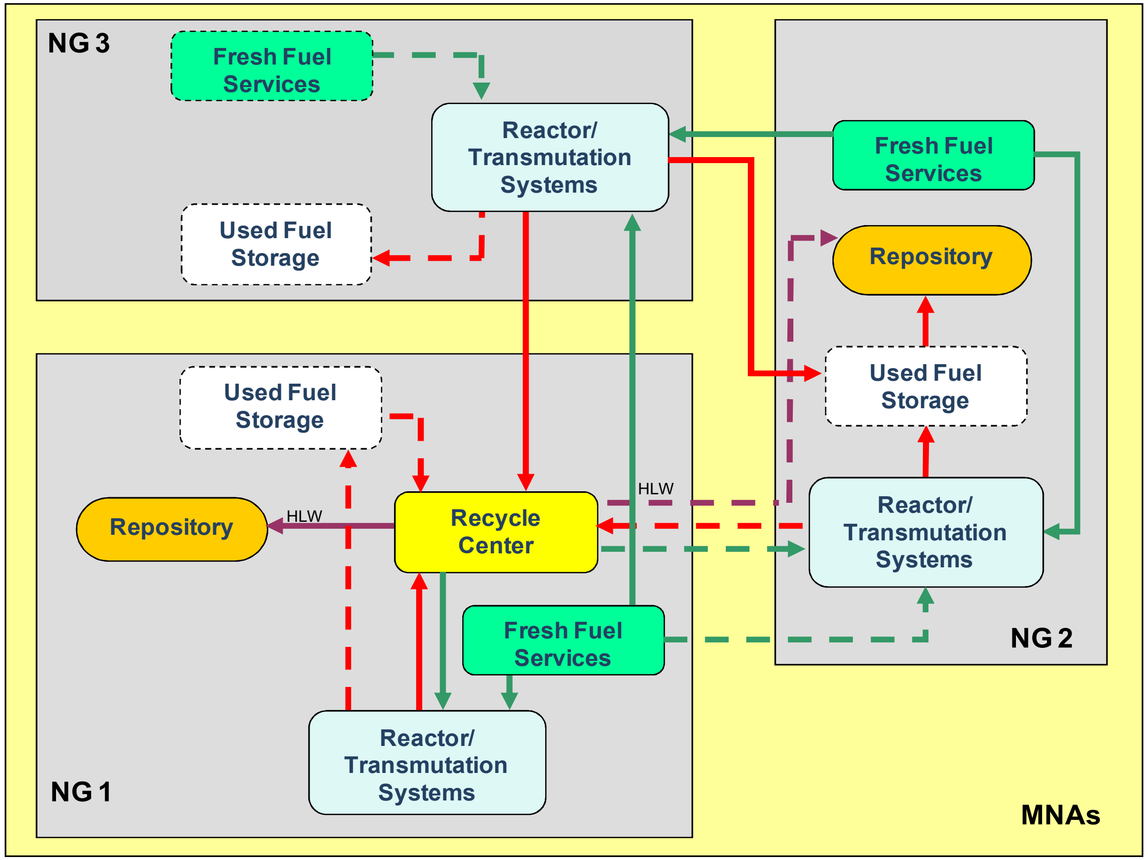


Can/should every country have its own geological repository?

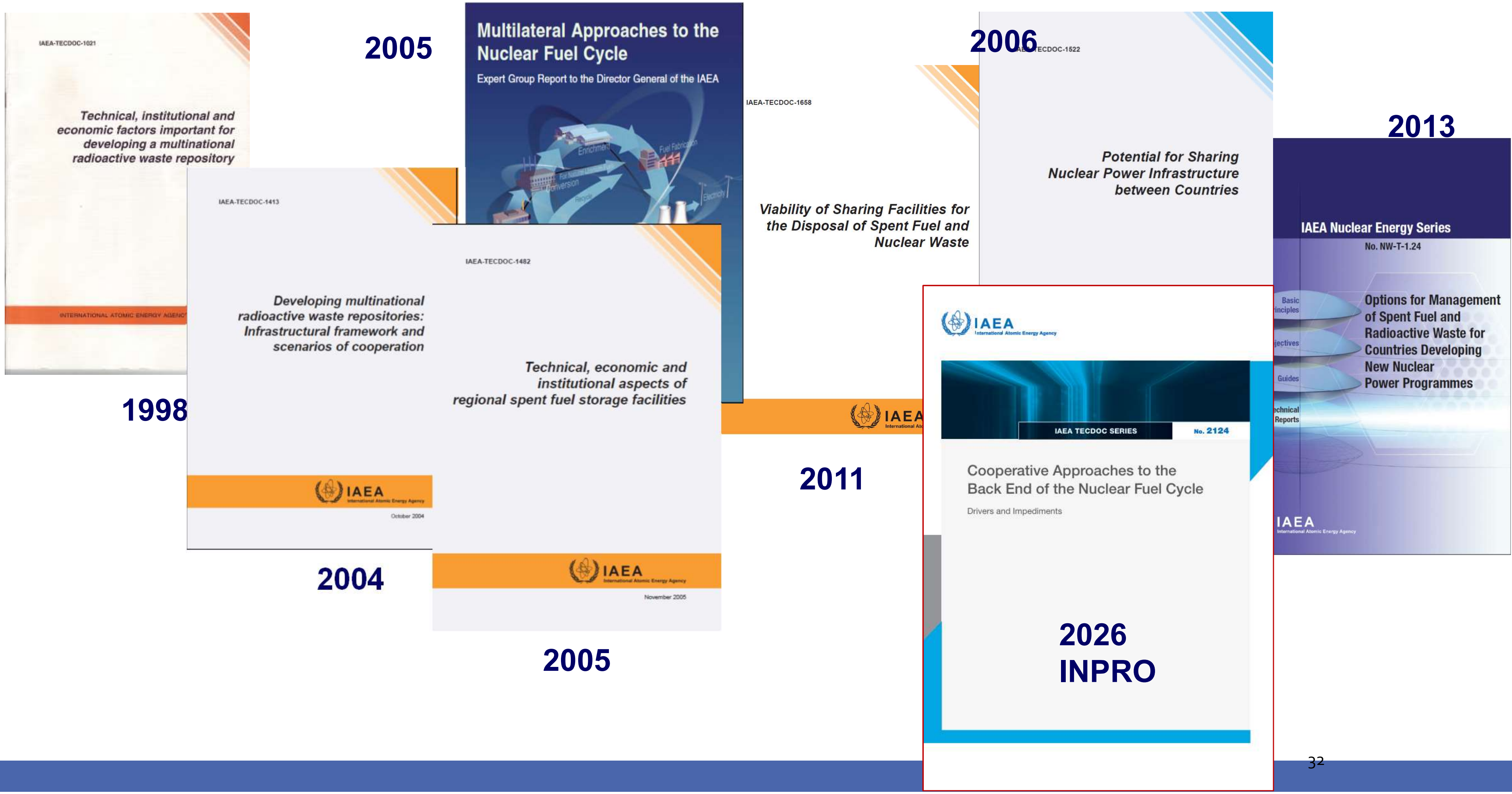


International architecture of Nuclear Power and Nuclear Fuel Cycle (INPRO Collaboration Project GAINS)





IAEA documents addressing multilateral issues



International approaches to Nuclear Fuel Cycle

Nuclear Fuel Cycle Front-end

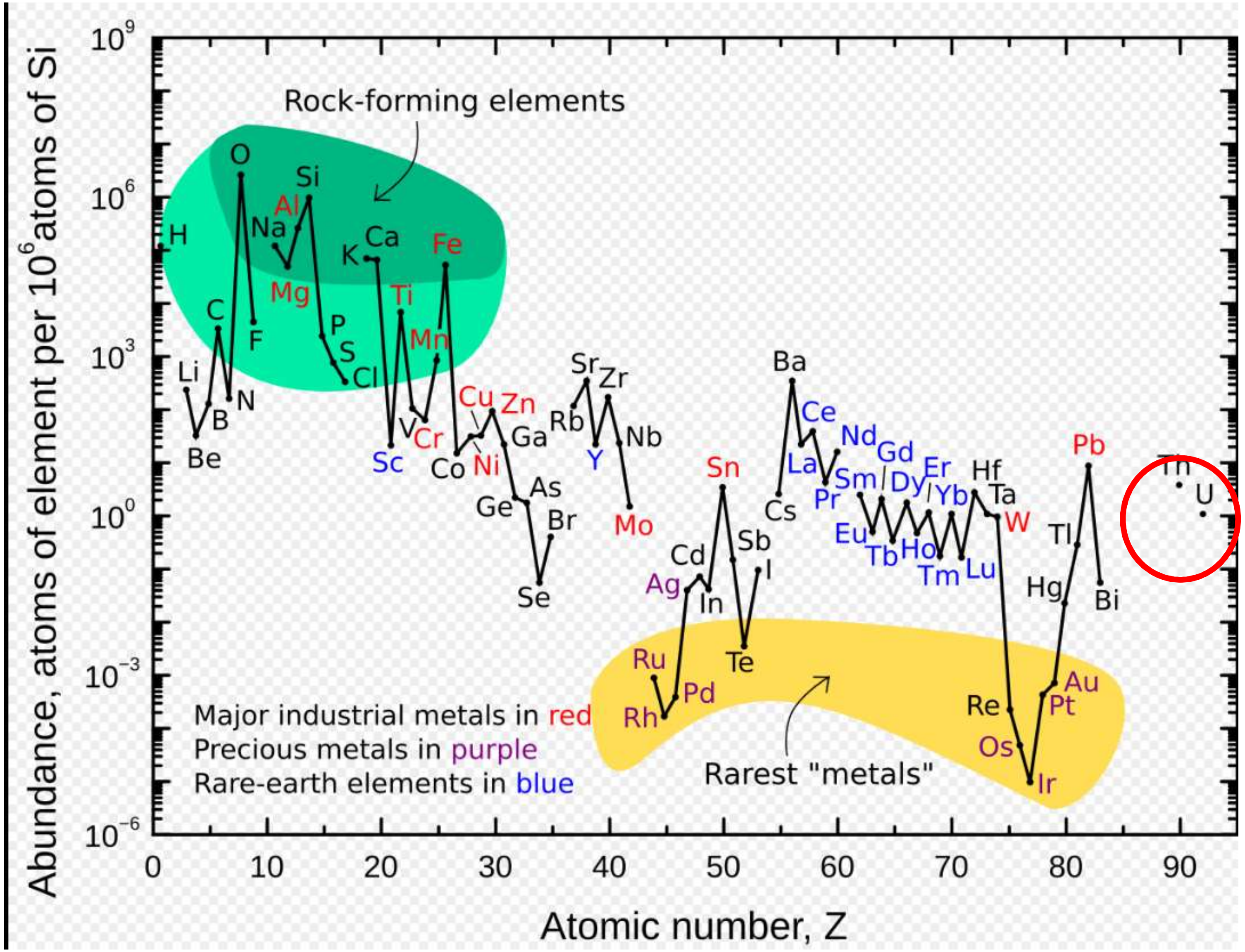
International initiatives (Russia-IAEA, UK, Germany, USA) and IAEA LEU Fuel Bank established LEU assurance supply mechanism for Nuclear Power stable supply by fuel

Nuclear Fuel Cycle Back-end

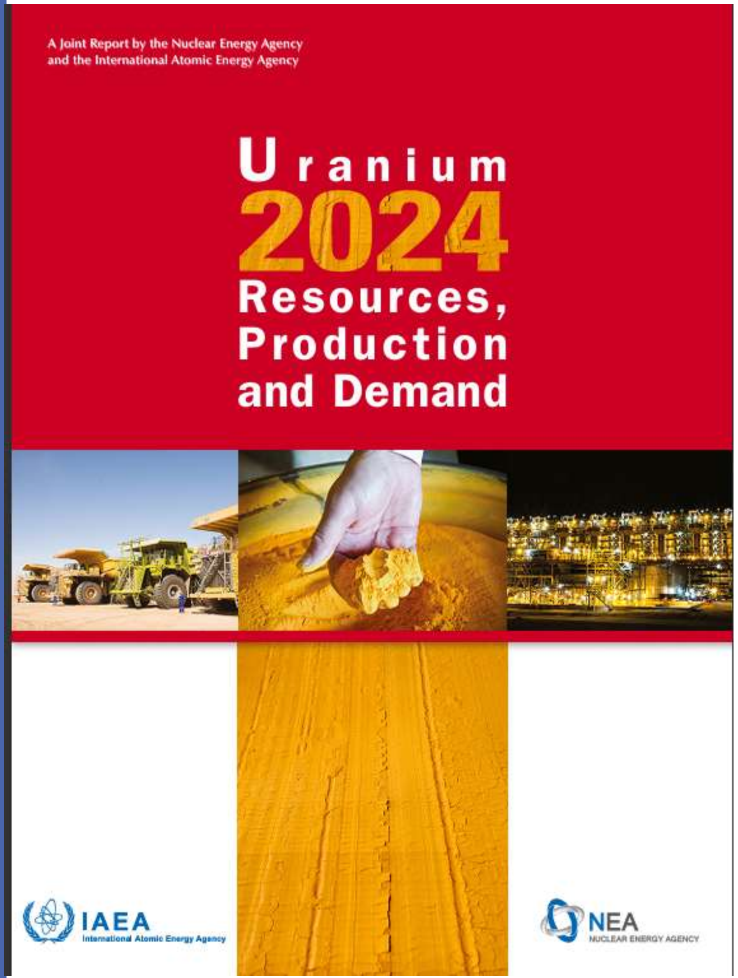
International Nuclear community had a number of attempt to discuss multilateral approaches to SNF Management.
Currently France and Russia suggest commercial service for SNF reprocessing and recycling.

Resources for Nuclear Power

Abundance (atom fraction) of the chemical elements in Earth's upper continental crust



Analysis of the availability of uranium and thorium resources

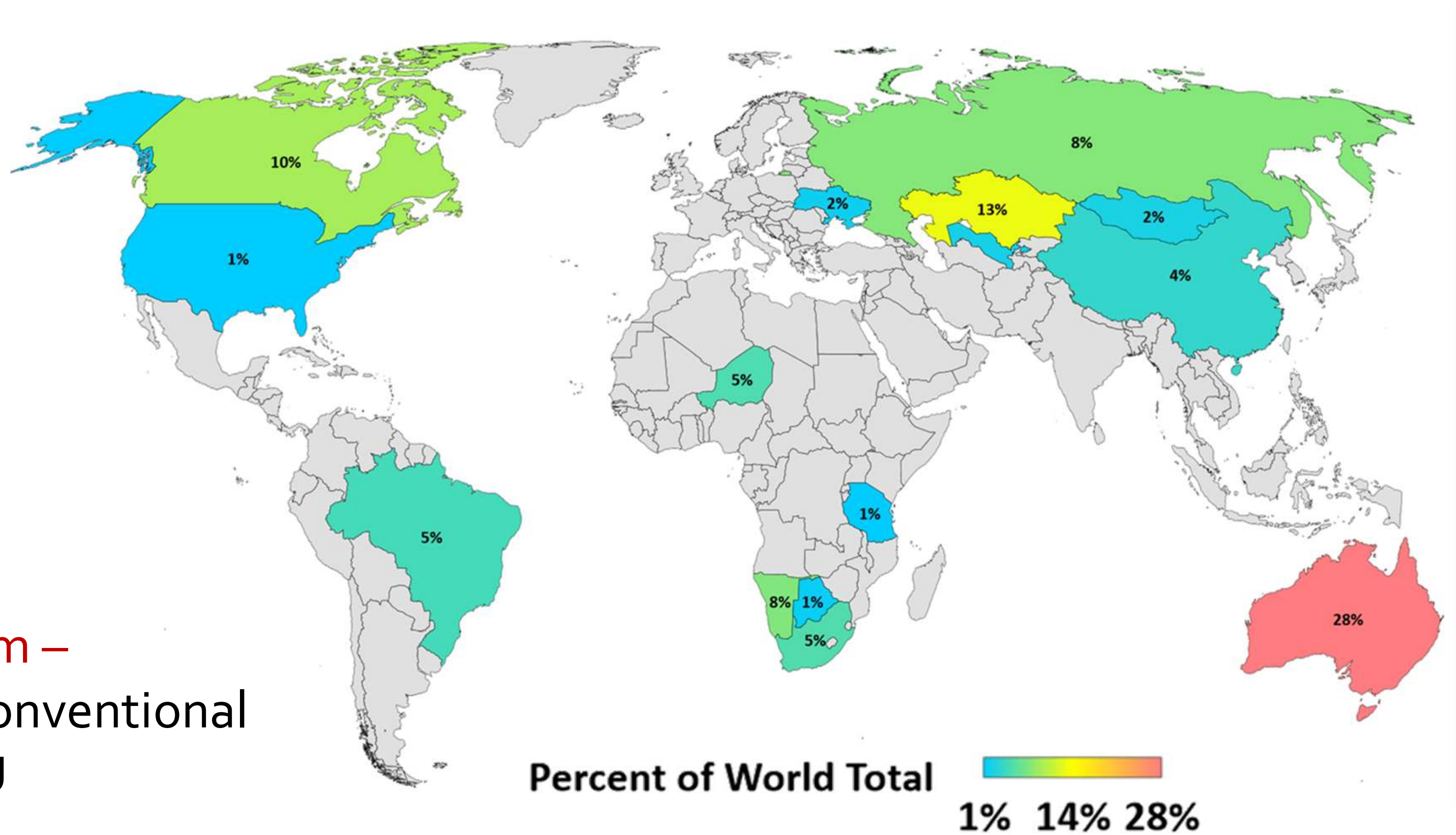


NEA/OECD and IAEA are publishing biannually **Red Book:**

- **Uranium: Resources, Production and Demand**
- Statistics and analysis are based on:
  - forecasts for explored uranium resources (Reasonably assured resources - RAR),
  - data on uranium mining and production, including information from countries
  - Prognosis on the growth of nuclear power, and the corresponding demand for uranium.
- Periodically analyzed:
  - Thorium resources
  - utilization of recycled materials: reprocessed uranium and separated plutonium

Global distribution of identified recoverable conventional uranium resources (<USD 130/kgU as of 1 January 2023)

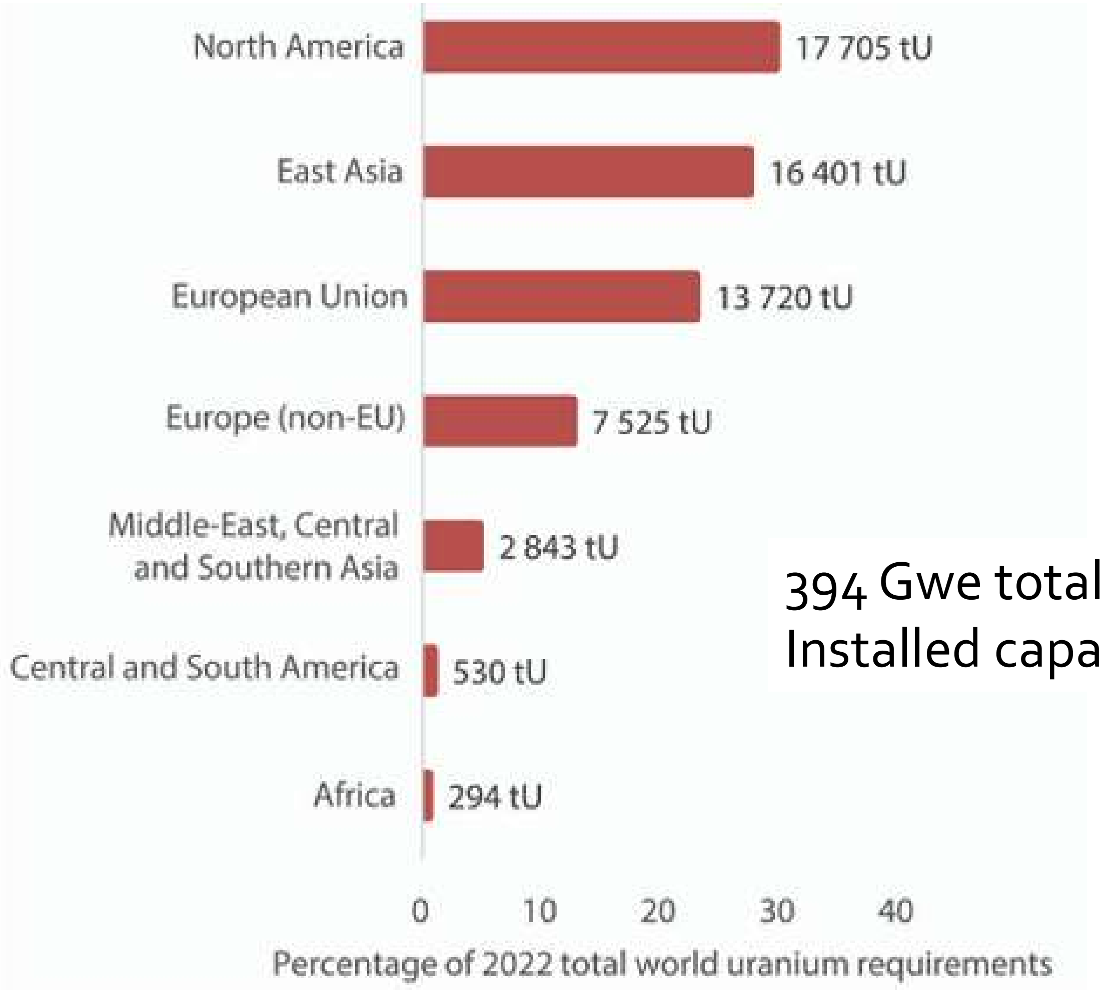
Australia	28%
Kazakhstan	13%
Canada	10%
Russia	8%
Namibia	8%
South Africa	5%
Niger	5%
Brazil	5%
China	4%
Mongolia	2%
Uzbekistan	2%
Ukraine	2%
Botswana	1%
United States	1%
Tanzania	1%



5 925 700 tons of uranium – identified recoverable conventional resources <USD 130/kgU

7 934 500 uranium tons – resources with <USD 260/kgU

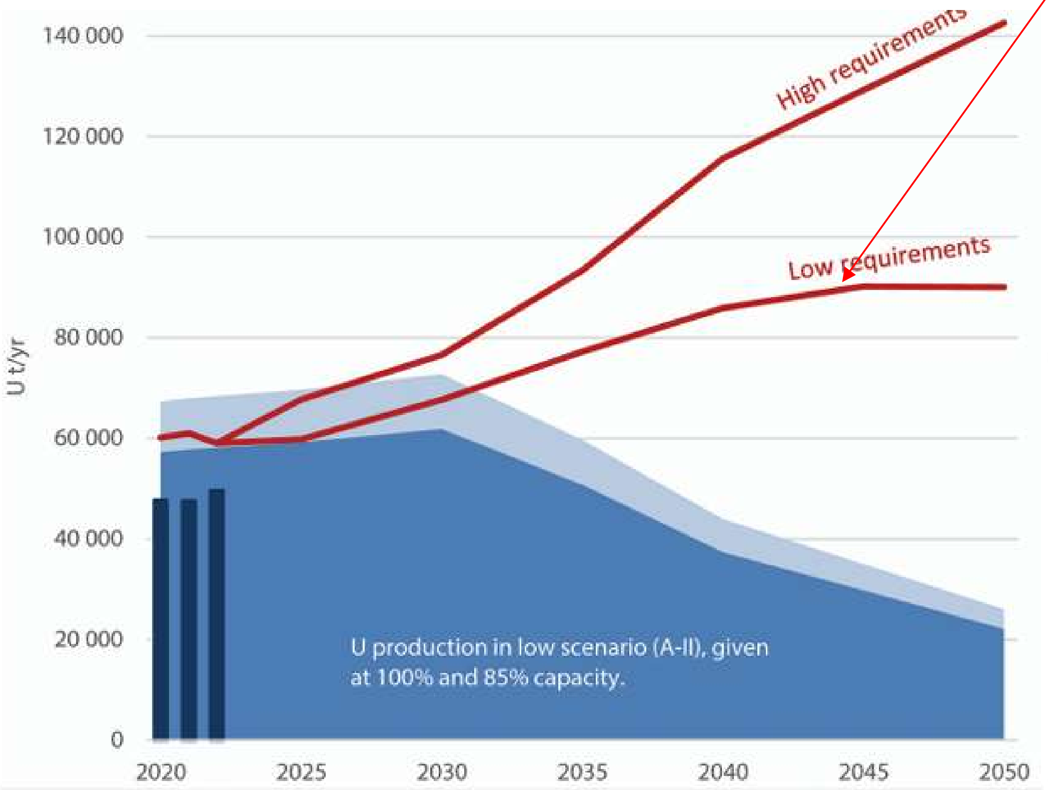
World uranium requirements: 59 018 t U
(as of 1 January 2023)

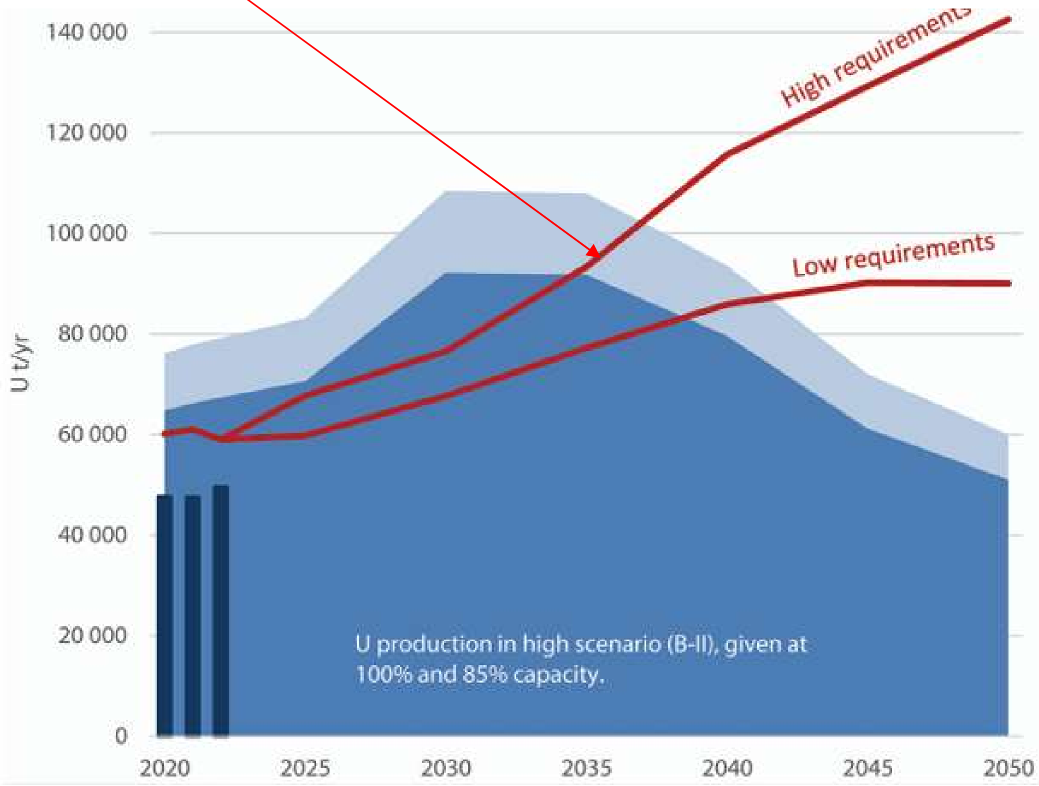


394 Gwe total NPP Installed capacity

Projected world uranium production capability to 2050 compared with reactor requirements (supported by identified resources at a cost of USD 130/kgU)

Uranium demands for “low” and “High” scenarios of NP growth





Secondary resources of fissile materials

Depleted uranium

- Depleted uranium "tails" contain from 0.25% to 0.35% U-235 compared to 0.711% in natural uranium.
- The world's depleted uranium reserves was about 2.2 million tons (for 2023) . About 50,000 tons of depleted uranium are added annually.
- Depleted uranium reserves represent a significant source of uranium that can replace primary production.
- The re-enrichment of depleted uranium has been limited because it is economically justified only in enrichment plants with reserve capacities and low operating costs.
- Depleted uranium is an essential resource for the development of GenIV Fast Neutron reactor technologies.

Separated Plutonium

About 70 tons of reactor-grade plutonium are discharged from the reactors annually. Part of the spent fuel is processed with the plutonium separation.

The annual production of MOX fuel for PWR is equivalent to 1,000 tons of uranium.

By the end of 2019, the world has accumulated separated plutonium:

- UK - 139 tons of civilian Pu
- France - 75 tons of civilian Pu
- Russia – 63 tons of civilian Pu (+34 tons of Pu from military programs)
- Japan – about 9 tons of civilian Pu
- USA – about 45 tons of Pu have been withdrawn from military programs
- China (as of 2016) – about 41 tons of civilian Pu

Reprocessed uranium

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% Rep U cores

Example (Red book):

- France produced more than 31 000 tons of RepU to 2021, and used 5 300 tons
- UK produced 15 000 tons of RepU to 2018, and used 1 700 tons

Thorium Resources

Country	Tones
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	**6,355,000**

Evaluated world resources of thorium with <USD 80/kg Th

on «Uranium 2016: Resources, Production and Demand» ('Red Book')

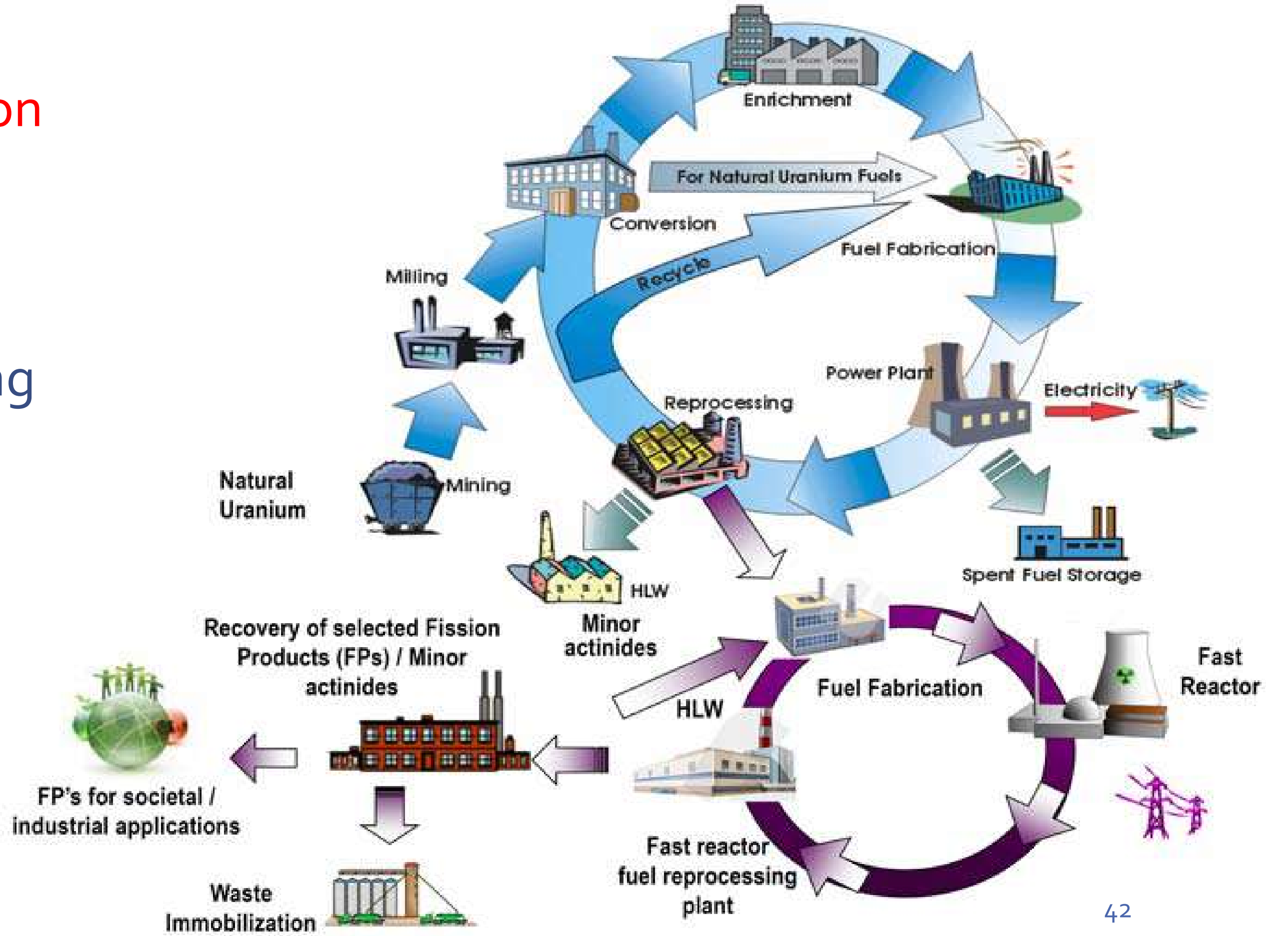
Thorium is intended for using in reactor as fertile nuclear material in the fuels based on Th-U233 и Th-Pu

What kind of fissile and fertile materials are necessary for the sustainable development of nuclear energy?

Modern nuclear fuel cycle based on
U-235

Advanced option of modern nuclear fuel cycle: additional using of **U-238 – Pu**

Innovative options of nuclear fuel cycle:
Using of **U-Pu-MA,**
Transition to **Th – U-233**



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”

Thank you!

The lecture prepared on the basis of the author’s lectures for IAEA NEM Schools from 2011 till 2025 and INPRO Schools 2021-2025 with using of materials from IAEA International Conferences on the Management of Spent Fuel from Power Reactors 2019 and 2024, and “Uranium Red Books” (OECD/NEA – IAEA)