The Abdus Salam International Centre for Theoretical Physics

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Joint ICTP-IAEA School of Nuclear Energy Management

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Nuclear Fuel Cycle Policies,Fuel Cycle Technologies

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Nuclear Fuel Cycle Policies, Fuel Cycle Technologies

Kevin Alldred

November 2012
Trieste

IAEA
International Atomic Energy Agency

Presentation Outline

- An introduction to the nuclear fuel cycle
- Nuclear fuel cycle policies
- Major process steps and options
- Materials involved

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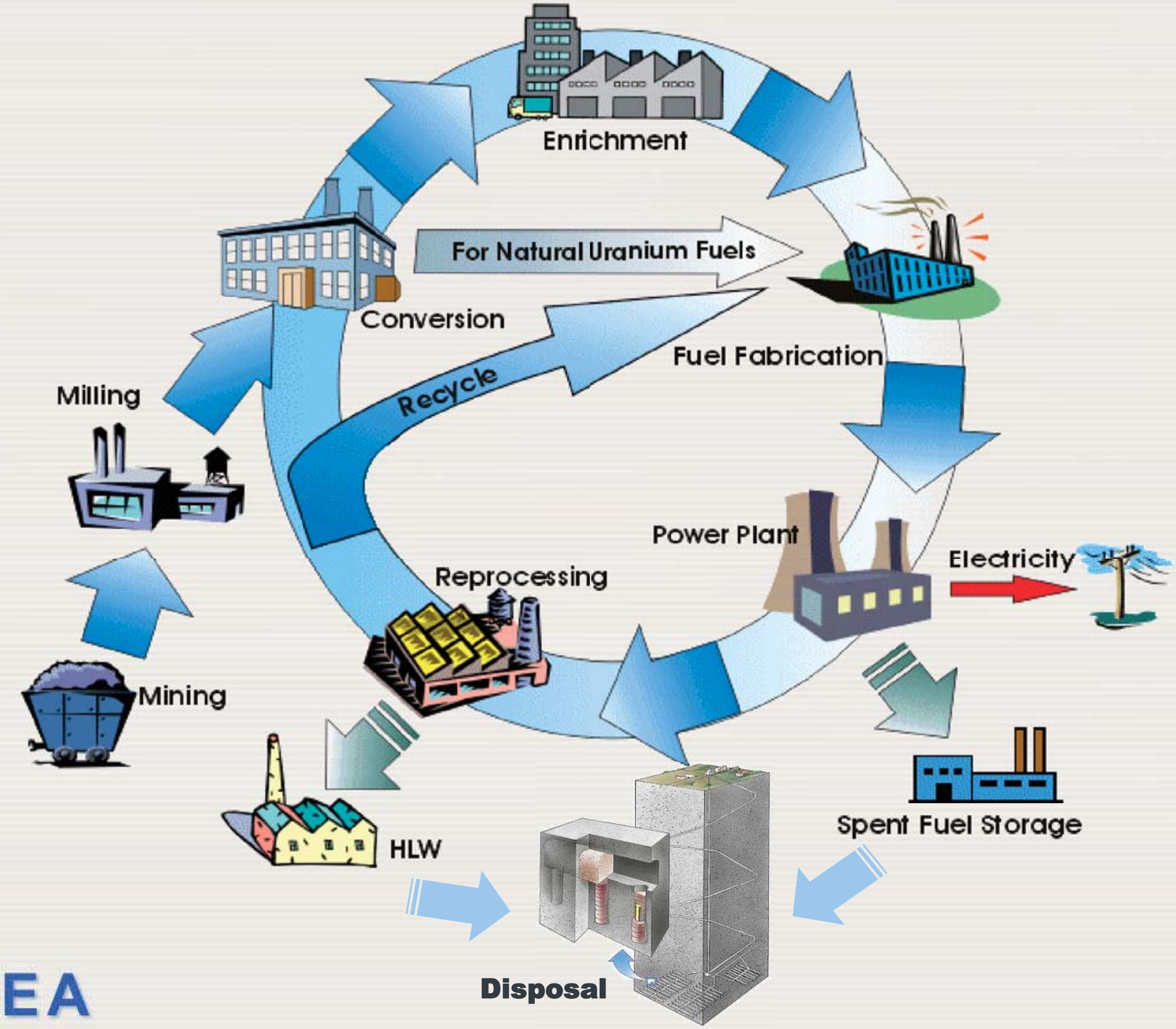
Nuclear Fuel Cycle



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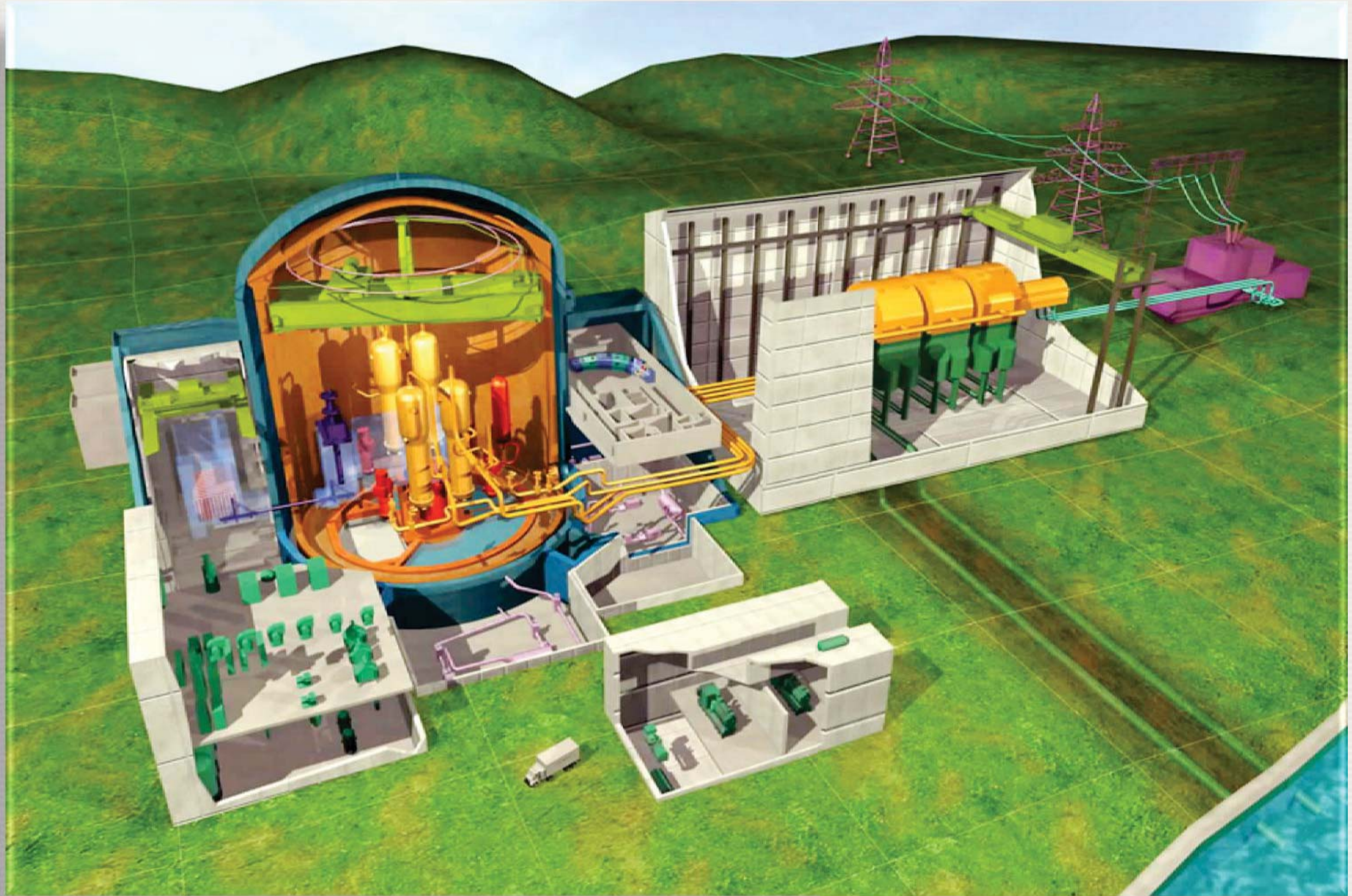
The Reactor: Core of the Nuclear Fuel Cycle



Picture courtesy of Areva

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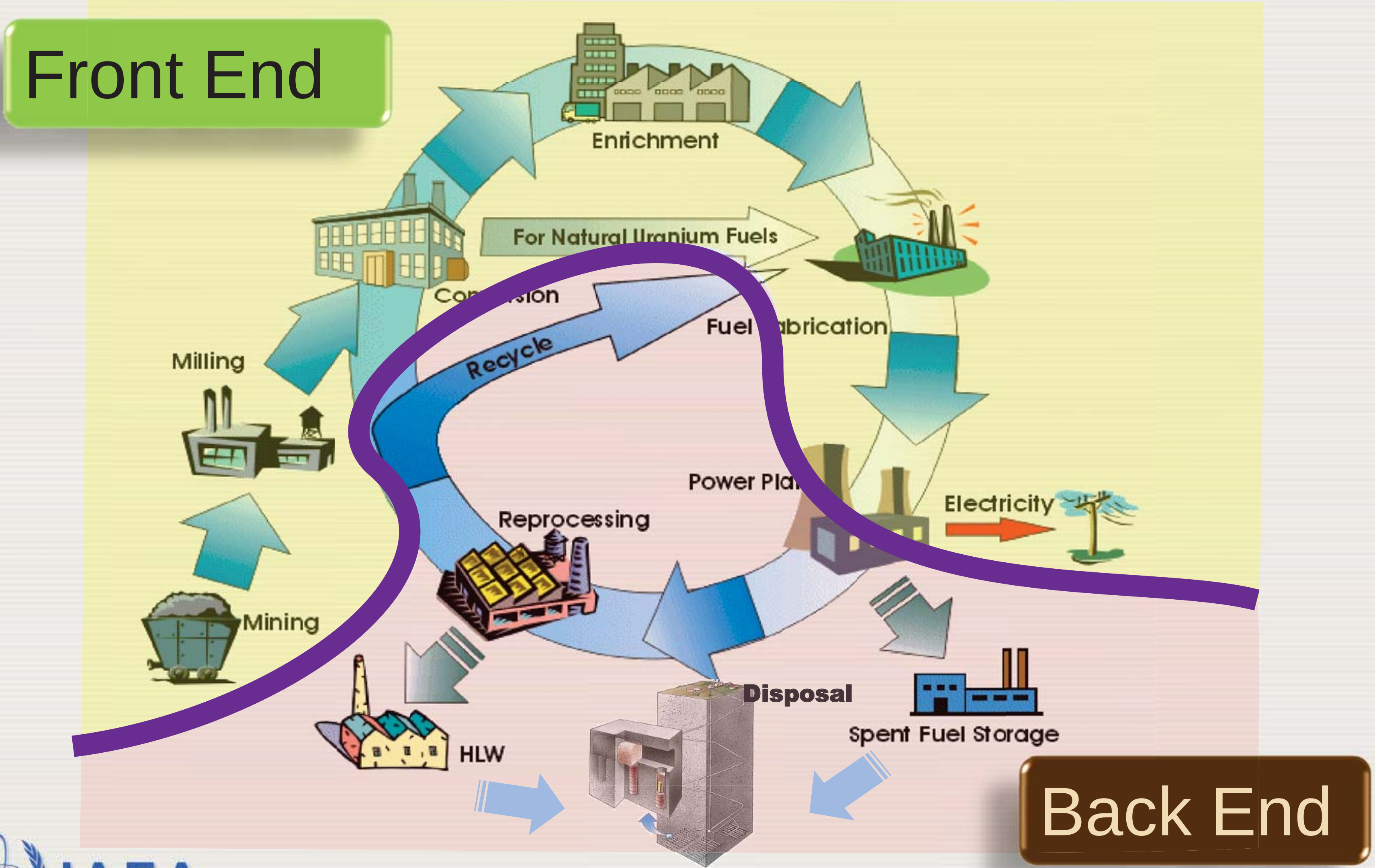
Nuclear Fuel Cycle: Terminology



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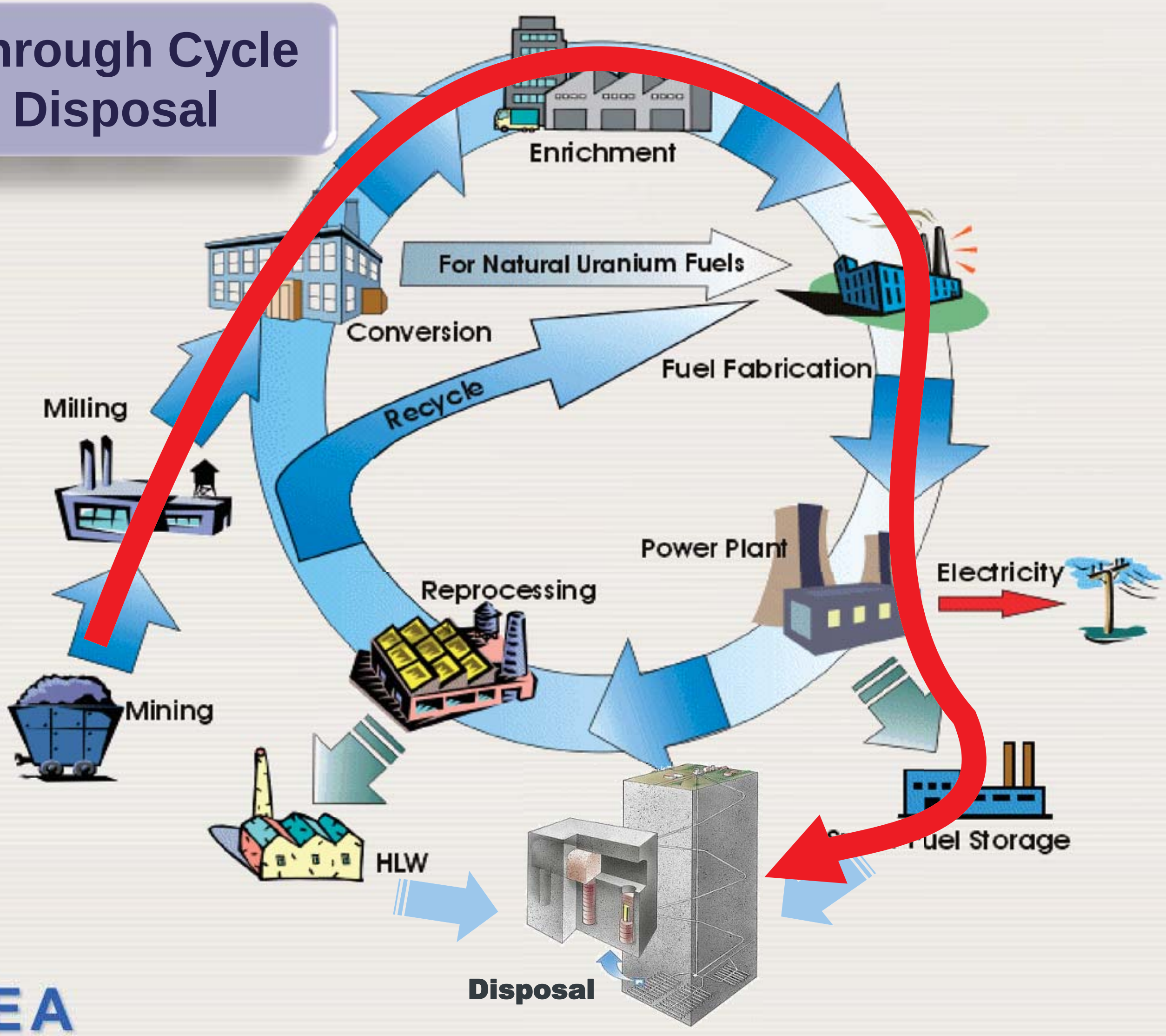
Types of Nuclear Fuel Cycle

Once Through Cycle
- Direct Disposal



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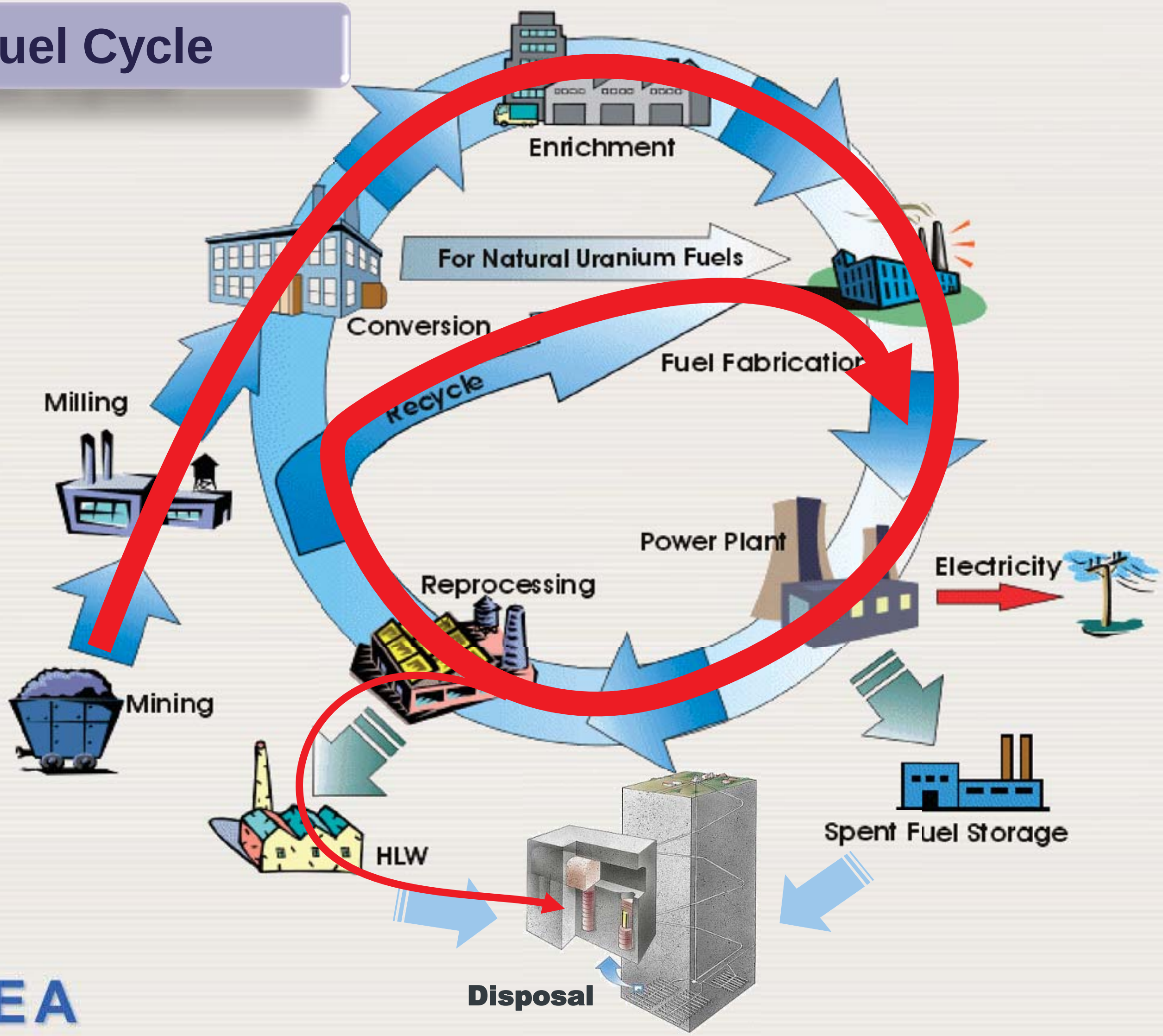
Types of Nuclear Fuel Cycle

Closed Fuel Cycle



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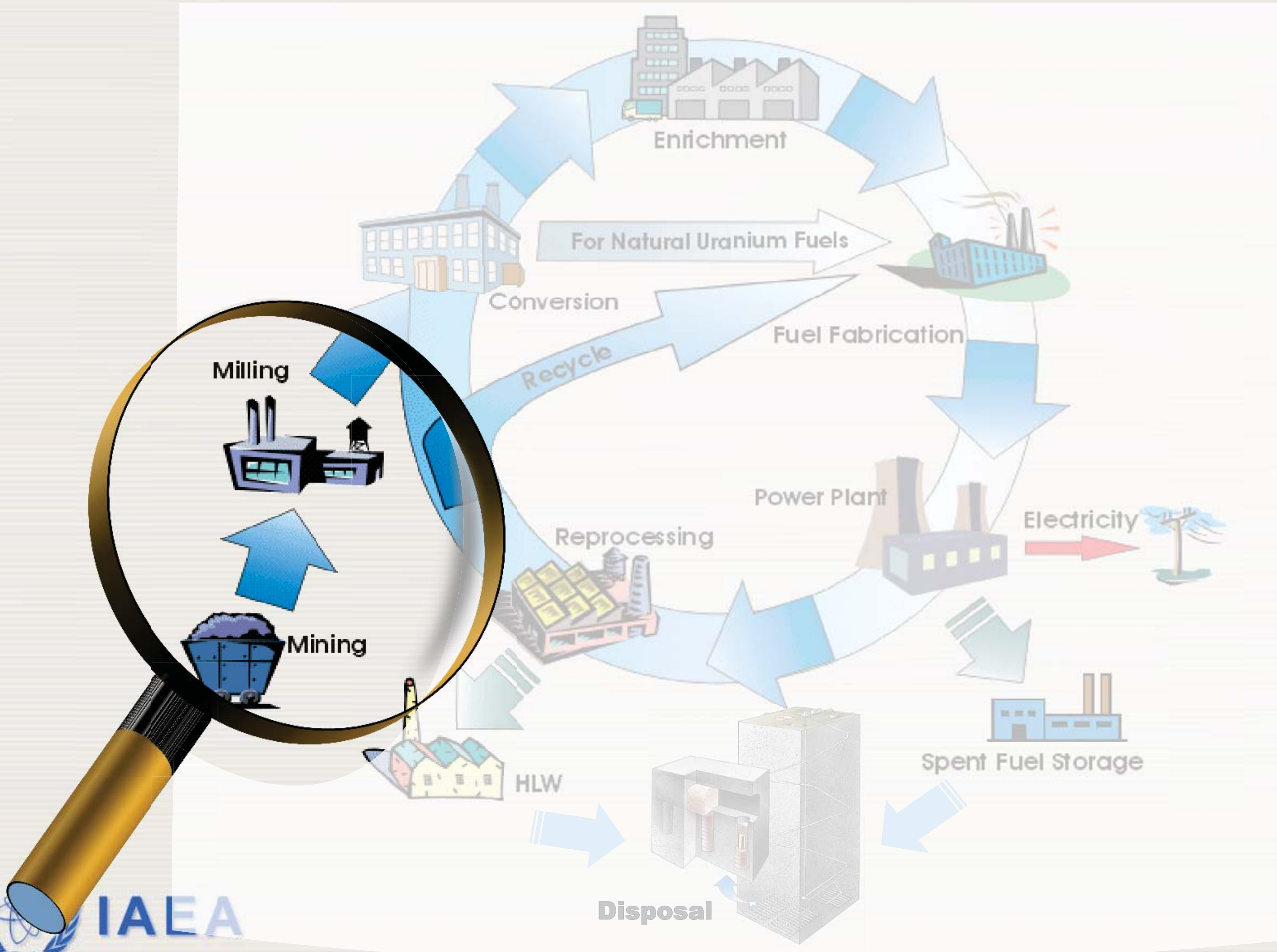
Mining and Milling



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Uranium Mining

Mine types

- Open pit
- Underground
- In-situ leach – ISL

By-product recovery

Ranger Uranium Mine, Australia

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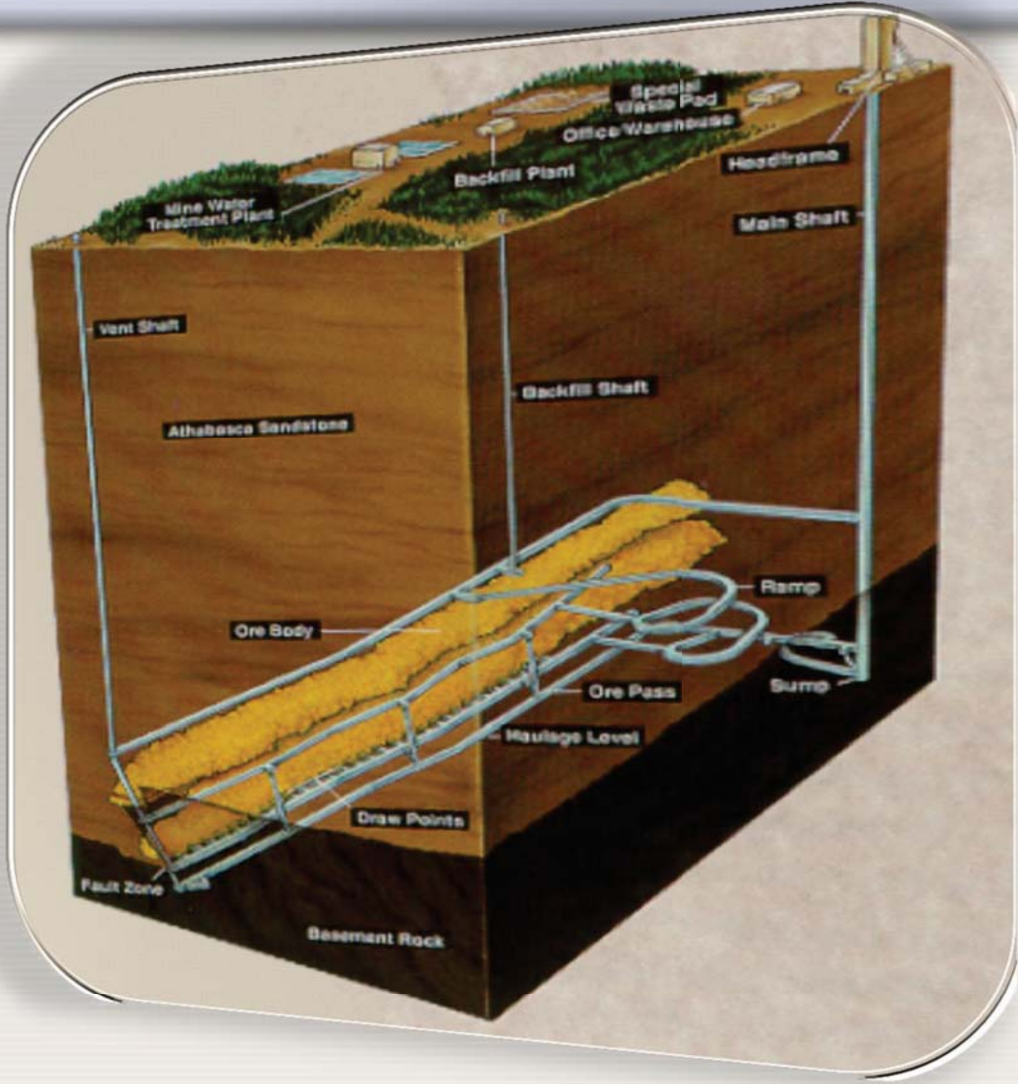
Uranium Mining

Mine types

- Open pit
- **Underground**
- In-situ leach – ISL

By-product recovery



Underground Uranium Mine Schematic

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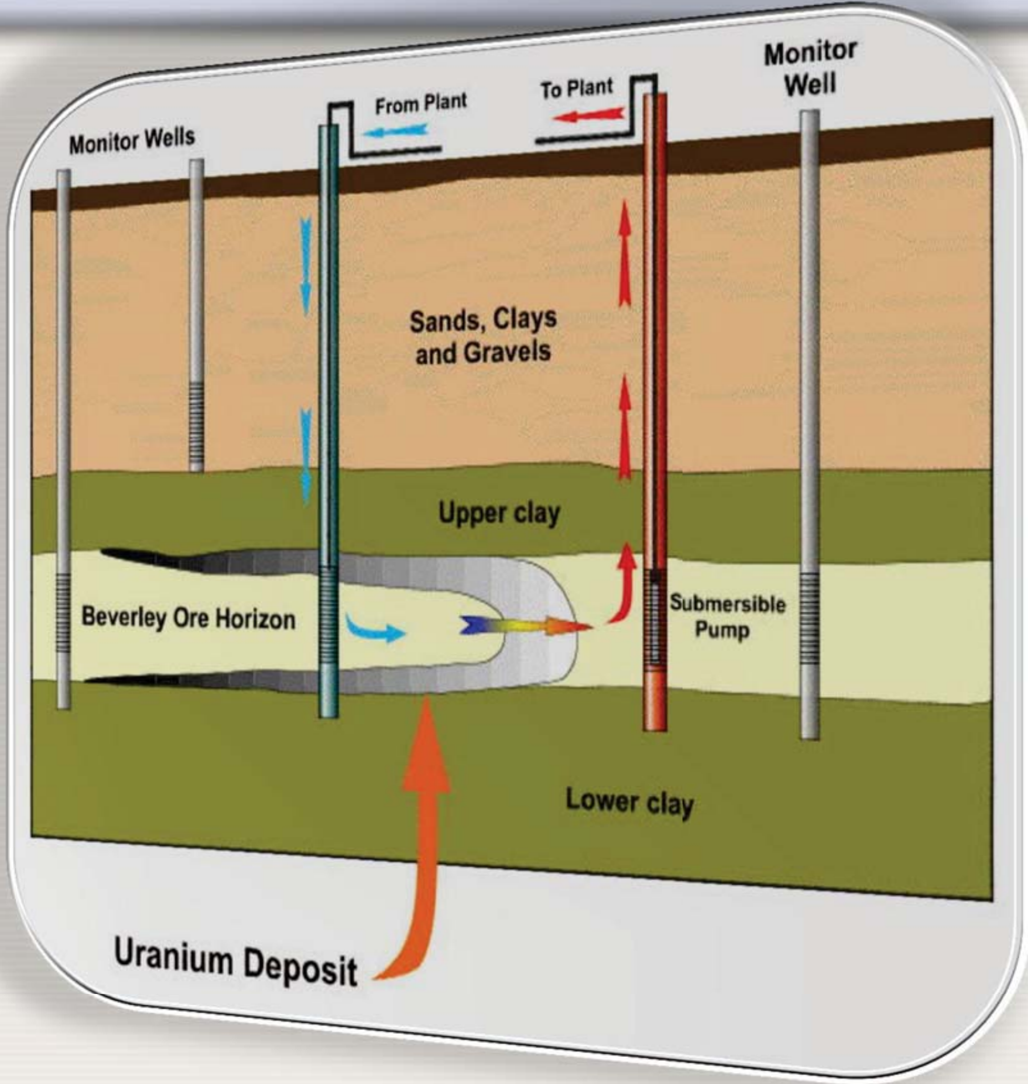
Uranium Mining

Mine types

- Open pit
- Underground
- In-situ leach – ISL

By-product recovery



ISL Uranium Mine Schematic

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Uranium Mining

Mine types

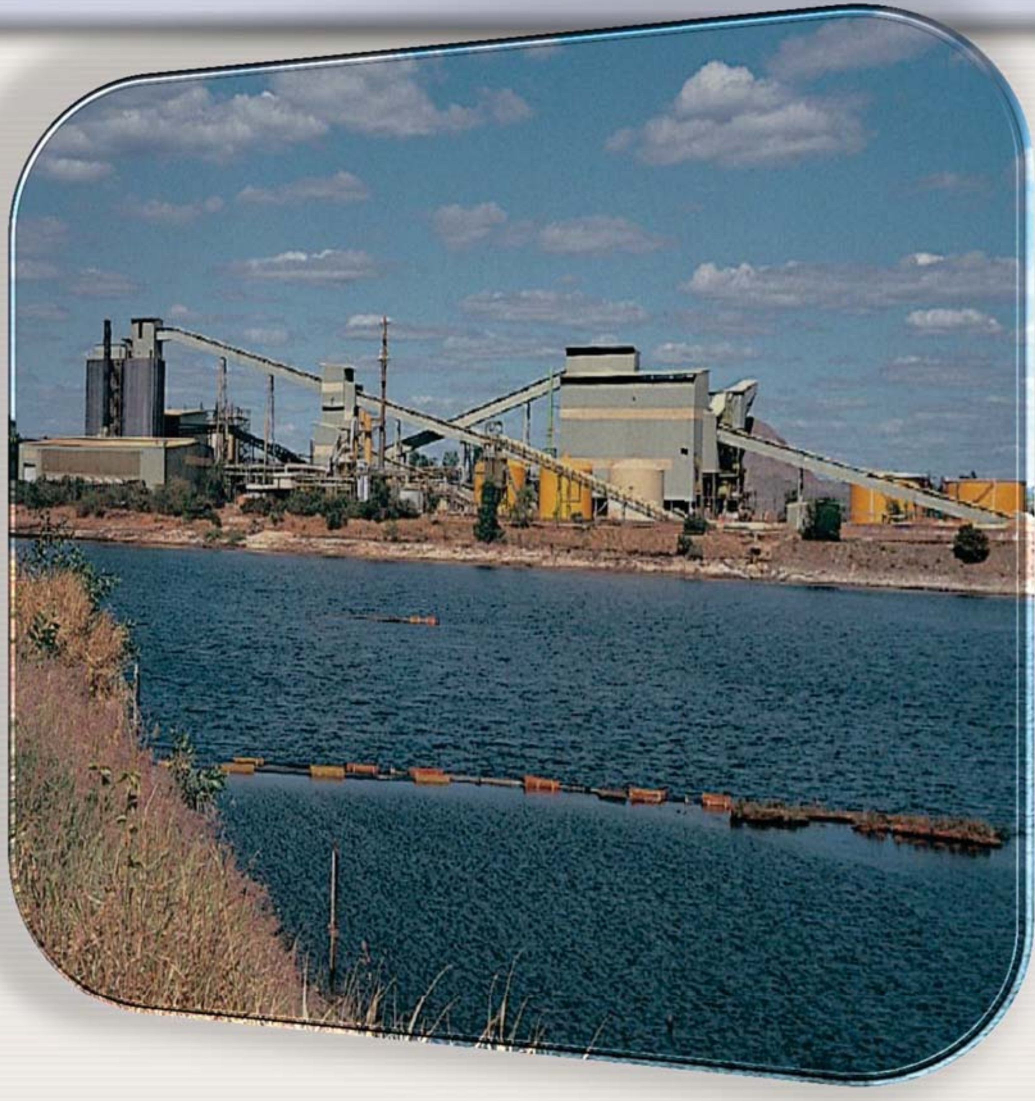
- Open pit
- Underground
- In-situ leach – ISL

By-product recovery

By product recovery, USA

Uranium Recovery Process

- Crushing
- Grinding
- Leaching
- Liquid-solid separation
- Purification and concentration
- Precipitation and drying
- Packing & dispatch



Uranium mill, Ranger mine, Australia

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Uranium Milling

- Uranium concentrates or Yellowcake
  - Uranium oxides - UO_4, U_3O_8, ADU, MgDU
  - Orange to yellow naturally;
  - Green to black when calcined
  - Packed in drums & shipped to conversion plant

Uranium Conversion

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Uranium Conversion

- Yellowcake from the mine is **converted** to UF_6
- UF_6 is the only gaseous form of uranium
- All current industrial uranium enrichment processes work with gas

A “48Y” Cylinder containing natural UF_6

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Enrichment

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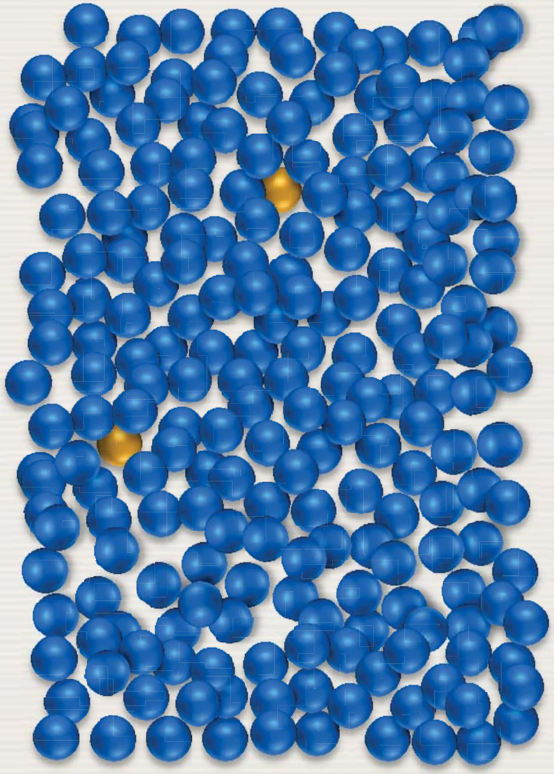
Why to we enrich uranium?

- Uranium from the mine contains 0.71% ^{235}U
  - 1 atom of ^{235}U for every 140 atoms of ^{238}U
- Most reactors need 4% – 5% ^{235}U
  - We need to "enrich" the uranium by increasing the concentration of ^{235}U



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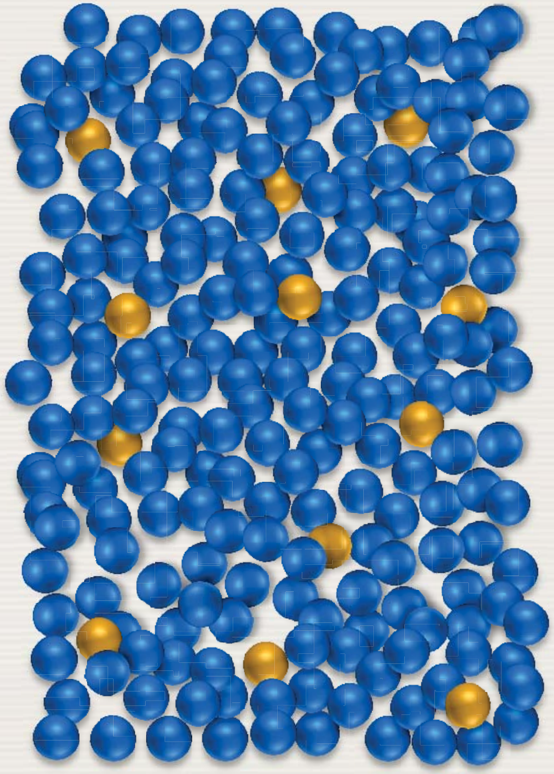

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Enrichment

- Several enrichment processes demonstrated
- Only two, gaseous diffusion and gas centrifuge, are currently operating on a commercial scale
- Both exploit the mass difference between ^{235}U atoms and ^{238}U atoms
- A laser enrichment facility is proposed in the USA that selectively ionises ^{235}U so that it can be separated electromagnetically
- Large commercial enrichment facilities operate in France, Germany, Netherlands, UK, USA, and Russia, with smaller facilities elsewhere

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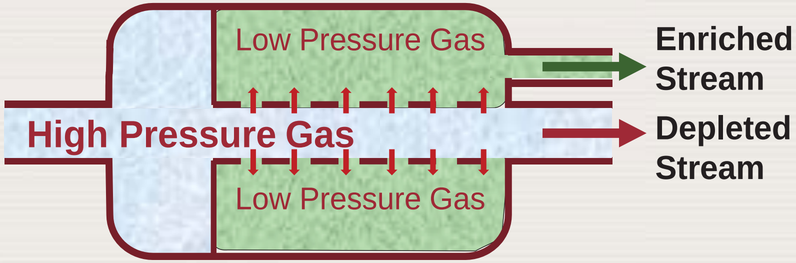
Enrichment: Gaseous Diffusion

- UF_6 forced through porous membranes
- Lighter, faster moving ^{235}U molecules more likely to pass through the membrane
- UF_6 diffused through the membrane is slightly enriched
- Process is repeated some 1400 times to obtain 4% ^{235}U
- 2,400 kWh/SWU



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Georges Besse 1, France

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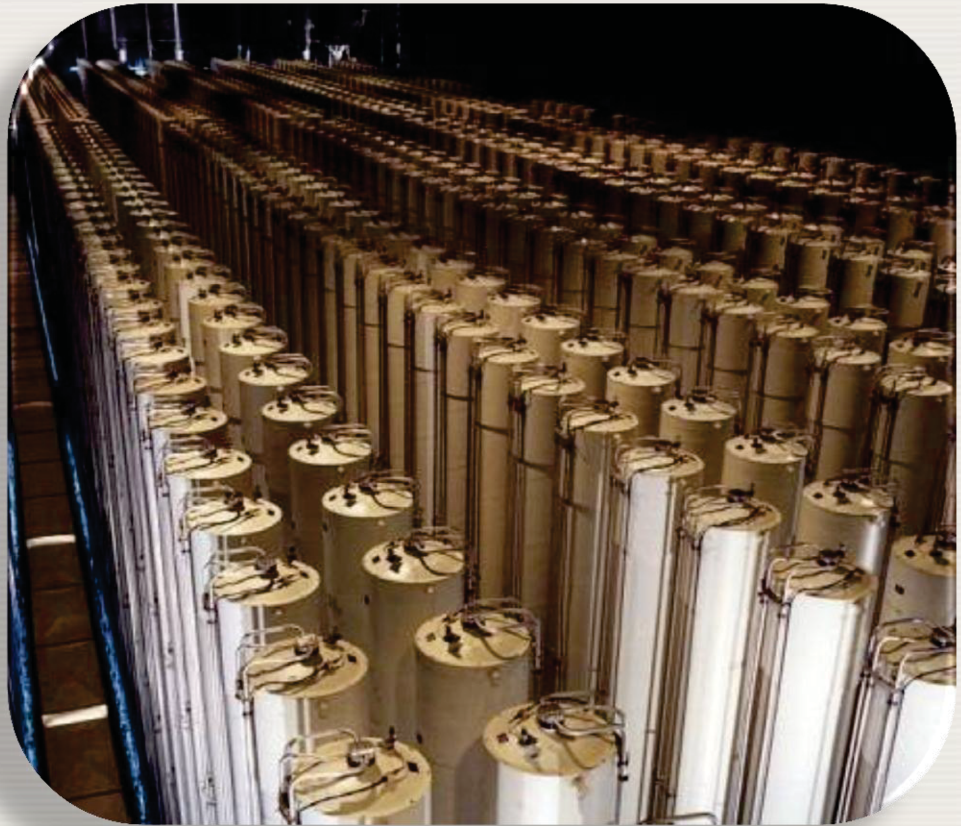
Enrichment: Centrifuge Process

- Vacuum tubes, each containing a rotor
- Spun at very high speeds:
  - 50,000 to 70,000 rpm
  - Outer wall moves at >400 m/s
  - 10^6 G
- ^{238}U concentration greater near outer cylinder wall,
- ^{235}U concentration greater near the centre.
- < 50 kWh/SWU



Uranium enrichment centrifuges

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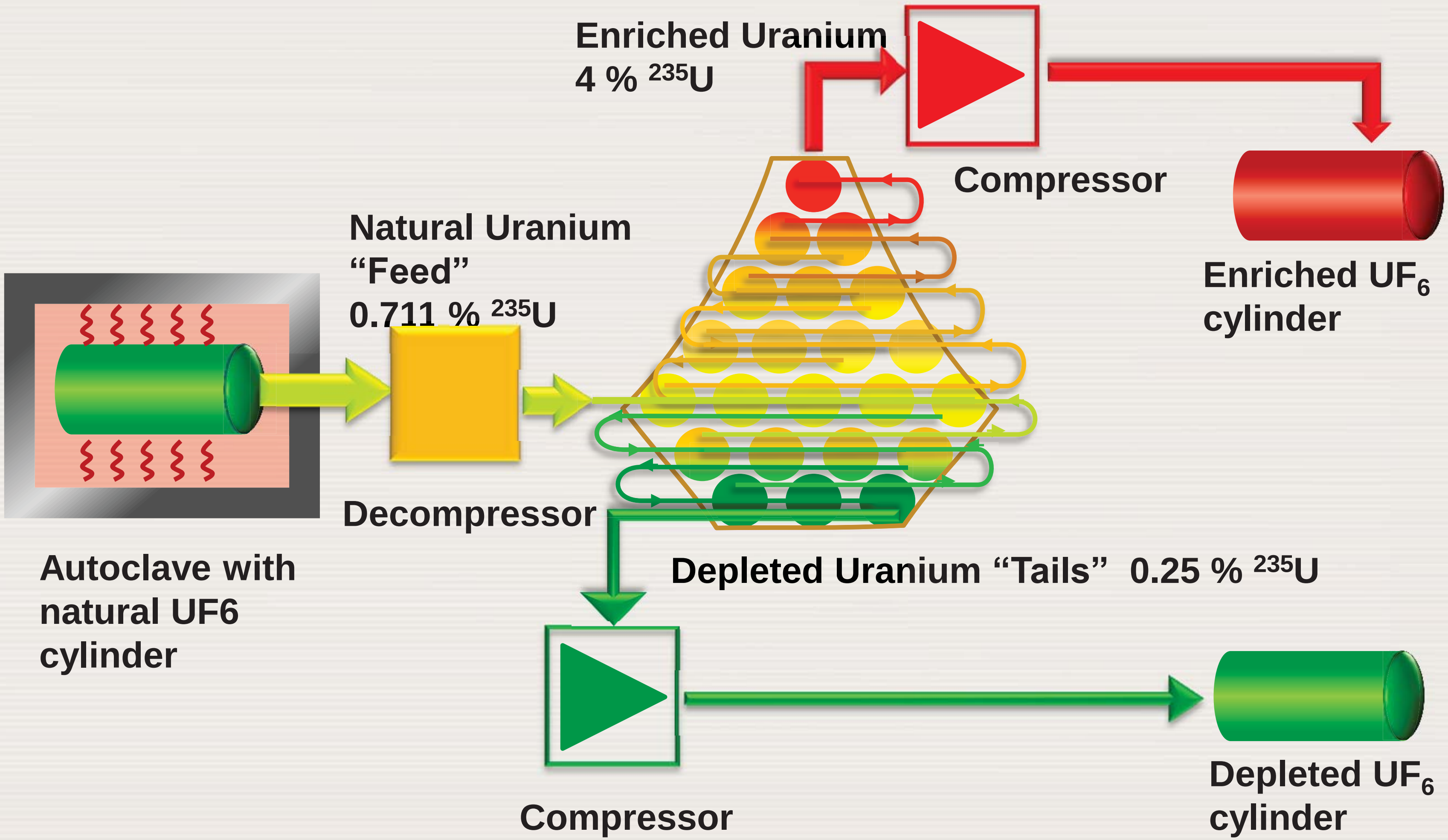
Enrichment: Cascade Schematic



The Separative Work Unit

- Separative Work Units are used to quantify uranium enrichment

$$\delta U = P\, V(n_p) + T\, V(n_T) - F\, V(n_F) \text{ where } V(n) = (1-2n)\ln\left(\frac{1-n}{n}\right)$$

- Referred to as kilogram SWU (or simply SWU)
- 1 kg of 4% ^{235}U requires around 6 SWU using a tails fraction of 0.25% ^{235}U and natural uranium feed.
- Separative Capacity is the rate of separative work (i.e. SWU/year)
- Separative capacity is a good measure of the effort (e.g. energy consumption) required by the enrichment facility

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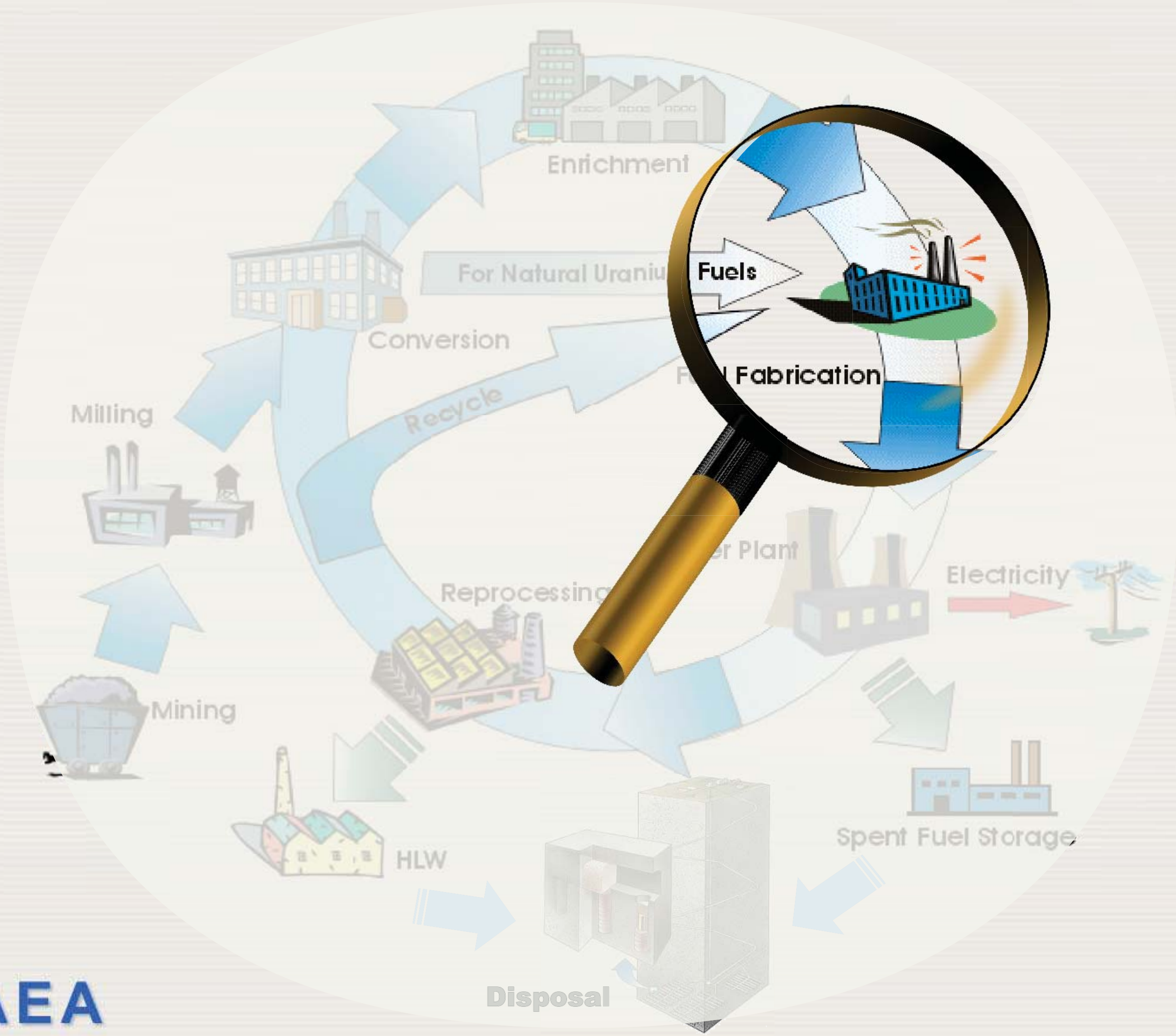
Fabrication



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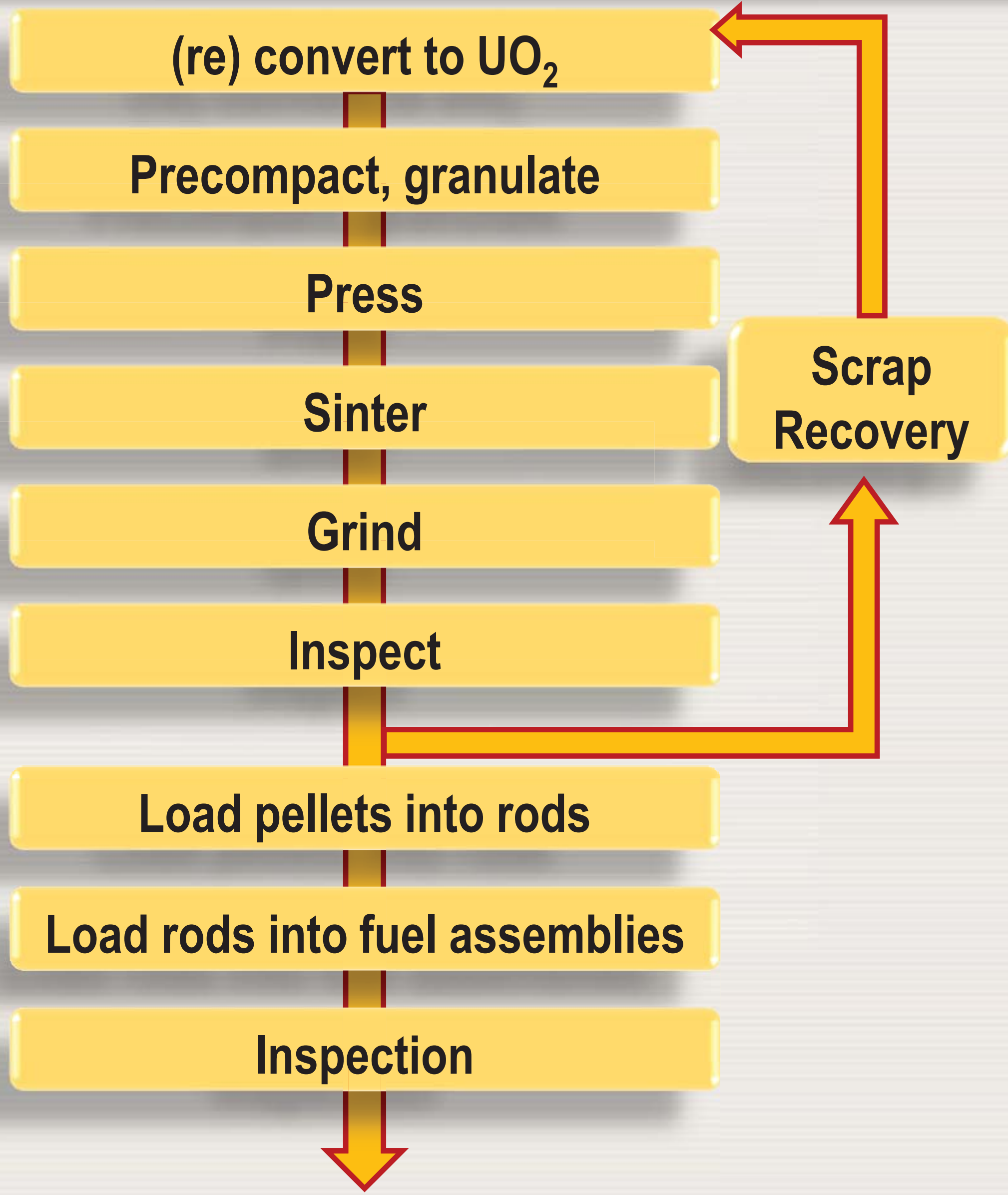
Fuel Fabrication



Fuel Fabrication

Uranium Oxide Fuels

UO_2 Pellets

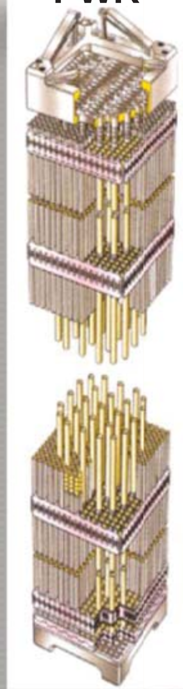
Enriched UO_2

Natural UO_2

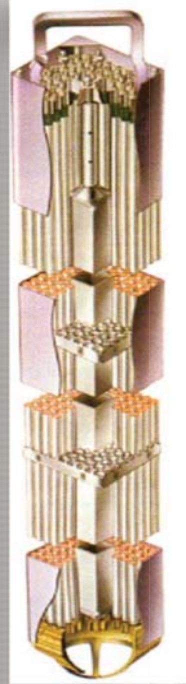
e.g.

36 Rods
Zircaloy
Natural or SEU

PWR



BWR



VVER

AGR

FNR

e.g.

PWR	BWR	VVER	AGR	FNR
17 x 17	9 x 9	312 rods	36 pins	
Zircaloy	Zircaloy	Zr-Nb	SS	SS
<5% ^{235}U	<5% ^{235}U	<5% ^{235}U	<5% ^{235}U	$(U,Pu)O_2$

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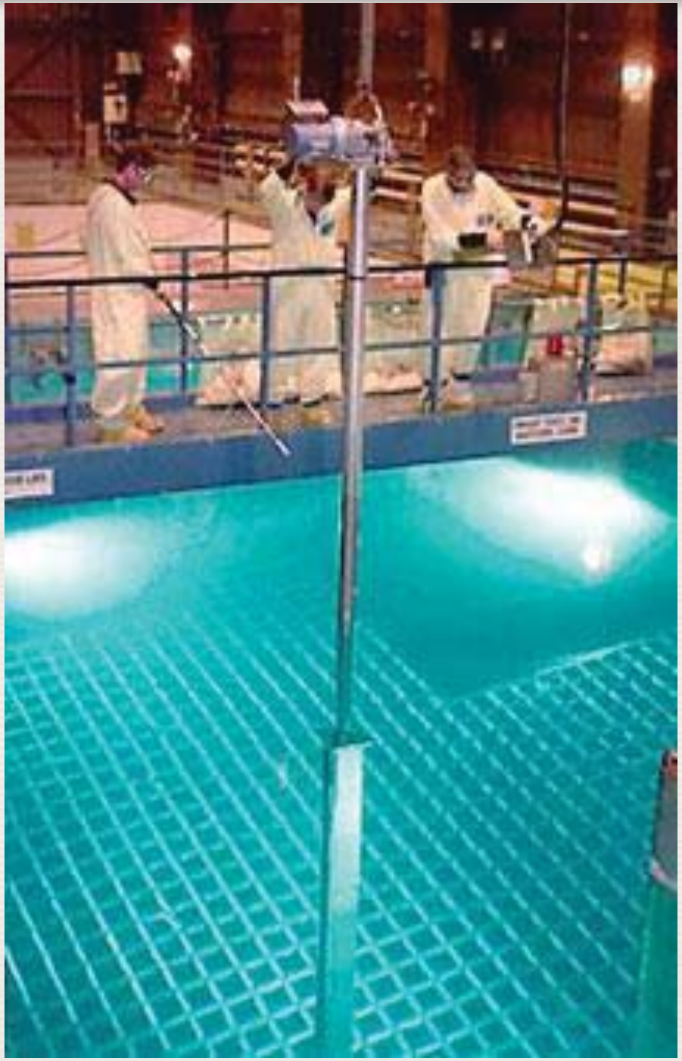
Spent Fuel Storage

Spent Fuel



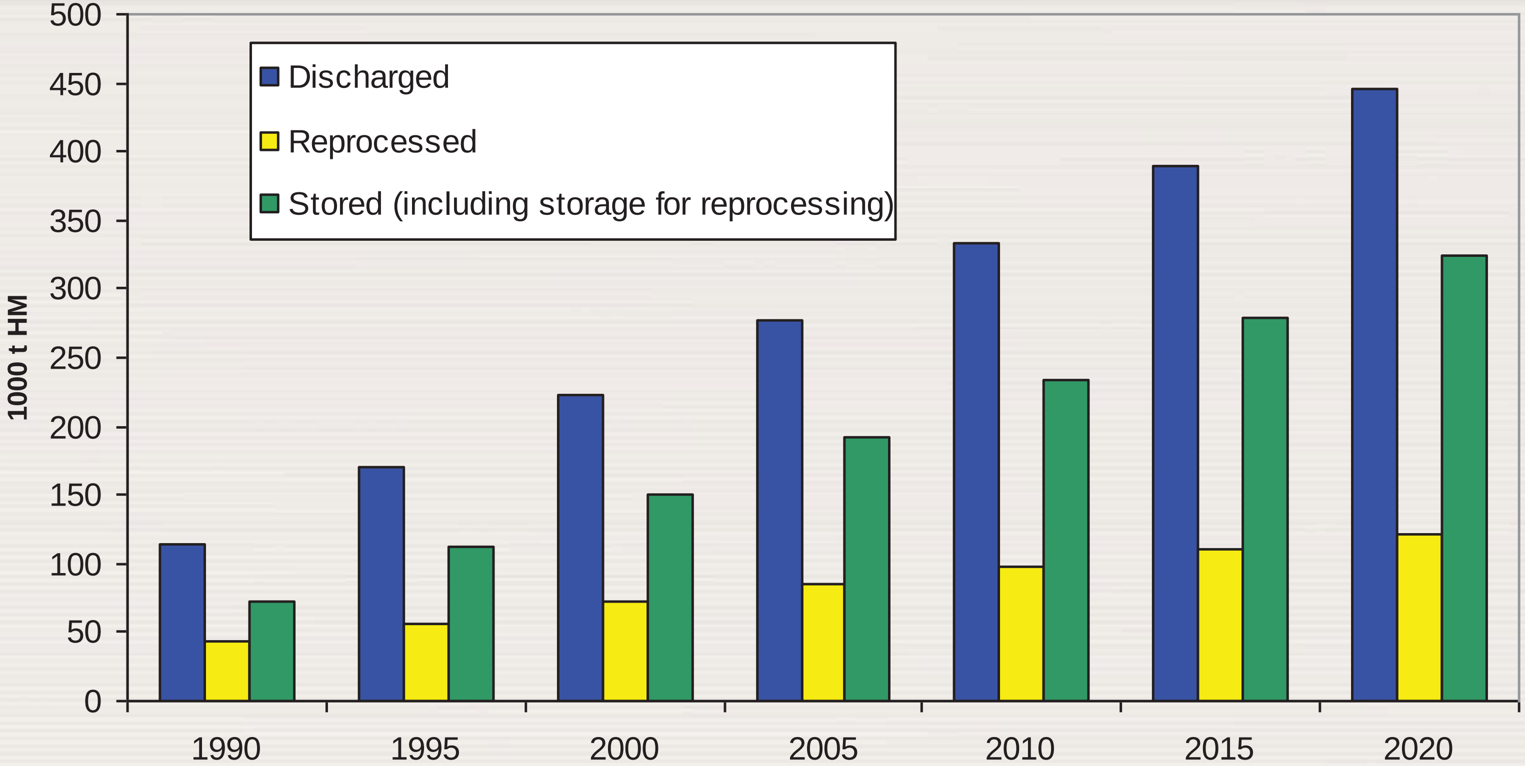
Spent Fuel Storage

- Wet and dry storage provide flexibility for spent fuel management

Wet Storage (CLAB-Sweden)

Dry Storage (Surry – USA)

Status of Spent Nuclear Fuel



- The total amount of spent fuel that has been discharged globally is approximately 360 800 tonnes of heavy metal (MTHM).
- The annual discharges of spent fuel from the world's power reactors total about 10 300 MTHM per year.

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Nuclear Fuel Cycle

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Spent Fuel Reprocessing

- Spent fuel is:
  - Chopped
  - Dissolved
  - Processed by solvent extraction
- Recovers:
  - Uranium
  - Plutonium
- Wastes (FP, TRU)
  - Separated and vitrified

THORP, UK

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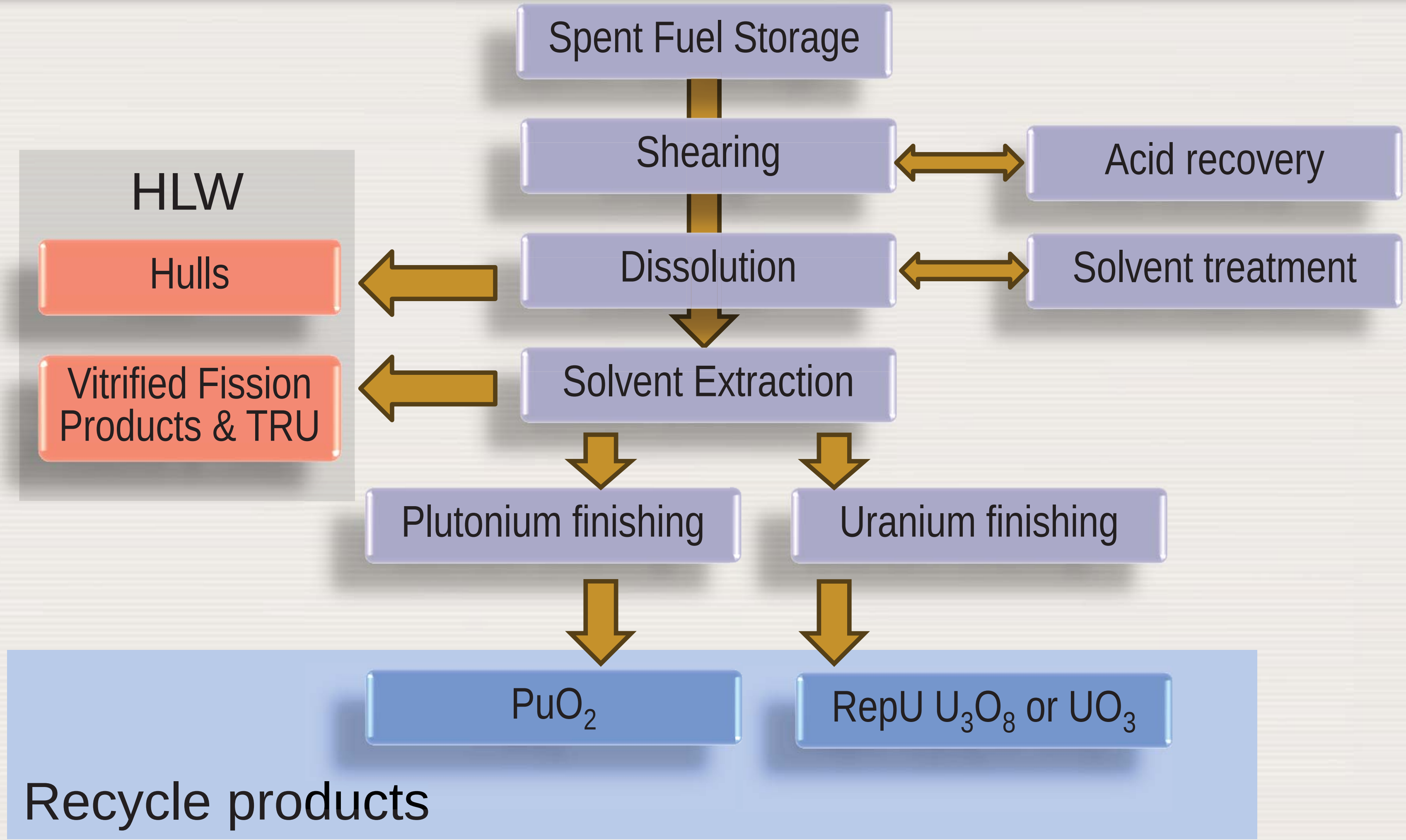
PUREX Process



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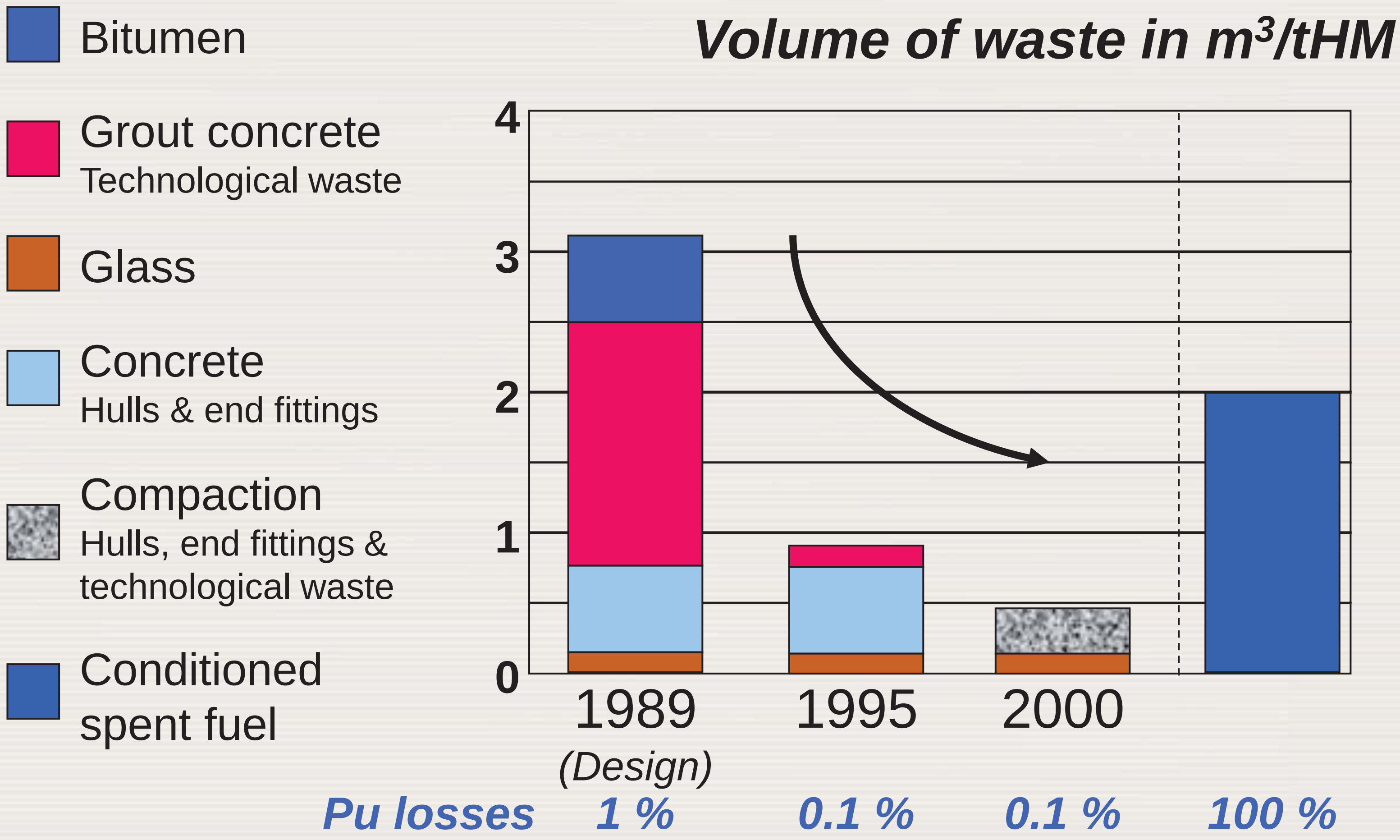
Specific waste volume for the UP3 plant



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

DIAMEX, TODGA
Separation of Minor Actinides and Lanthanides from HLLW

TRUEX
Transuranic element extraction from HLLW

SANEX, ARTIST, TALSPEAK
Separation of Am, Cm from Lathanides

SESAME
Separation of Am from Cm

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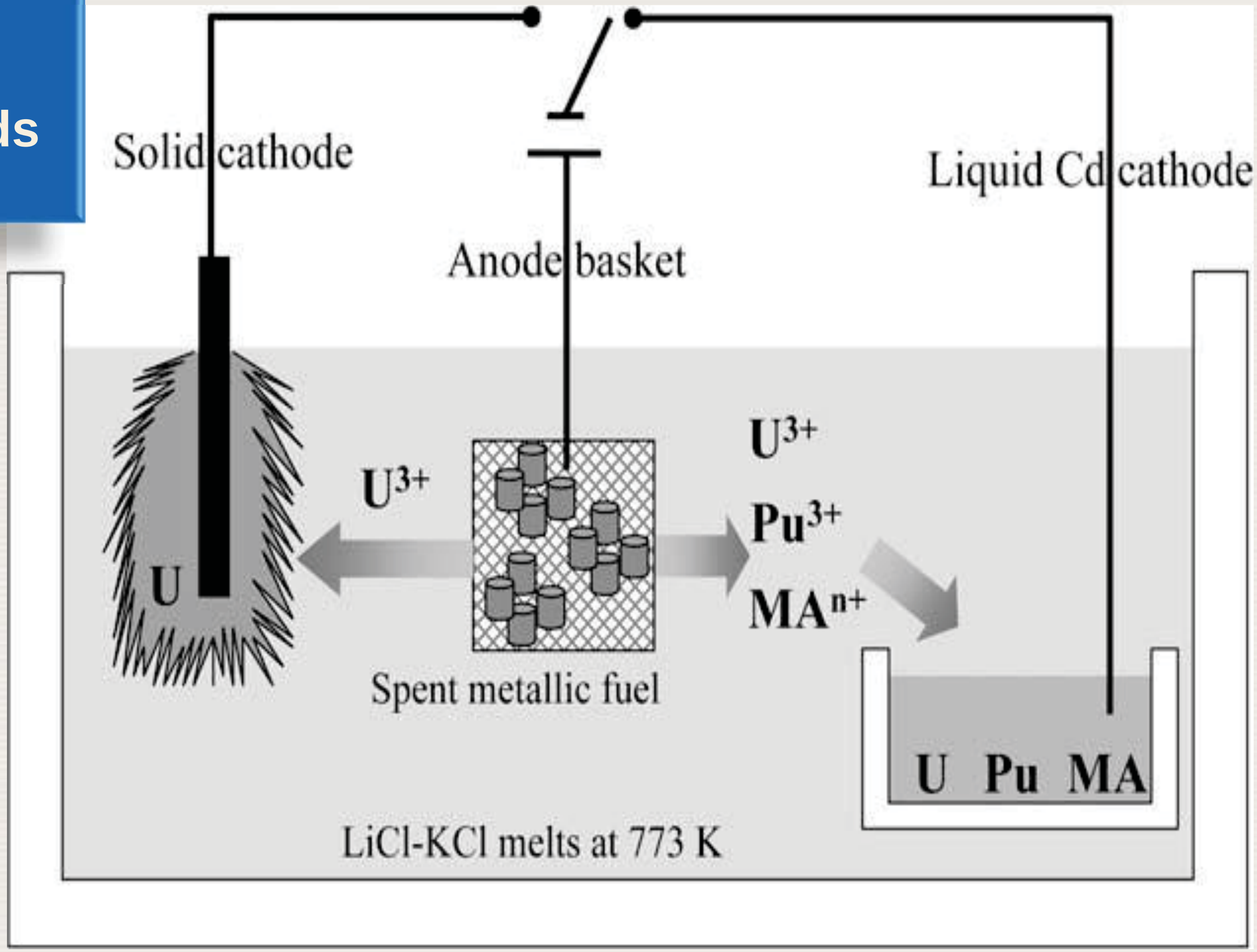
Spent Fuel Recycle

Advanced Pyro-Metallurgical Partitioning Methods



Nuclear Fuel Recycle

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MOX Fuel

- 5 major plutonium isotopes:
  - ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu

Fissile, can replace ^{235}U in nuclear fuel

- PuO_2 + depleted UO_2 are mixed, pelletized and loaded into fuel rods.
- MOX fuel assembly externally identical to UO_2 equivalent
- Plutonium is radiologically hazardous:
  - Inhalation hazard
  - Must be handled in shielded glove boxes

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Plutonium Isotope Composition

Reactor type	Mean fuel burn-up (GWd/t)	Percentage of Pu isotopes at discharge					Fissile content %
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	
PWR	33	1.3	56.6	23.2	13.9	4.7	70.5
	43	2.0	52.5	24.1	14.7	6.2	67.2
	53	2.7	50.4	24.1	15.2	7.1	65.6
BWR	27.5	2.6	59.8	23.7	10.6	3.3	70.4
	30.4	N/A	56.8	23.8	14.3	5.1	71.1
CANDU	7.5	N/A	66.6	26.6	5.3	1.5	71.9
AGR	18	0.6	53.7	30.8	9.9	5.0	63.6
Magnox	3	0.1	80	16.9	2.7	0.3	82.7
	5	N/A	68.5	25.0	5.3	1.2	73.8

Courtesy Plutonium Options, NDA 2008

Reprocessed Uranium

- Reprocessed Uranium (RepU, or RU) can be re-enriched and used for new fuel manufacture
- RepU is segregated during processing because of minor isotopes
- Additional shielding and ventillation required for fuel fabrication

Isotope	Concentration	Comment
^{232}U	~ 1 ppb	>2 MeV γ ray.
^{234}U	160 ppm	α radiation hazard
^{235}U	0.6 – 1.2 %	
^{236}U	~ 0.3 %	neutron absorber that reduces fuel effectiveness
^{238}U	98 - 99%	

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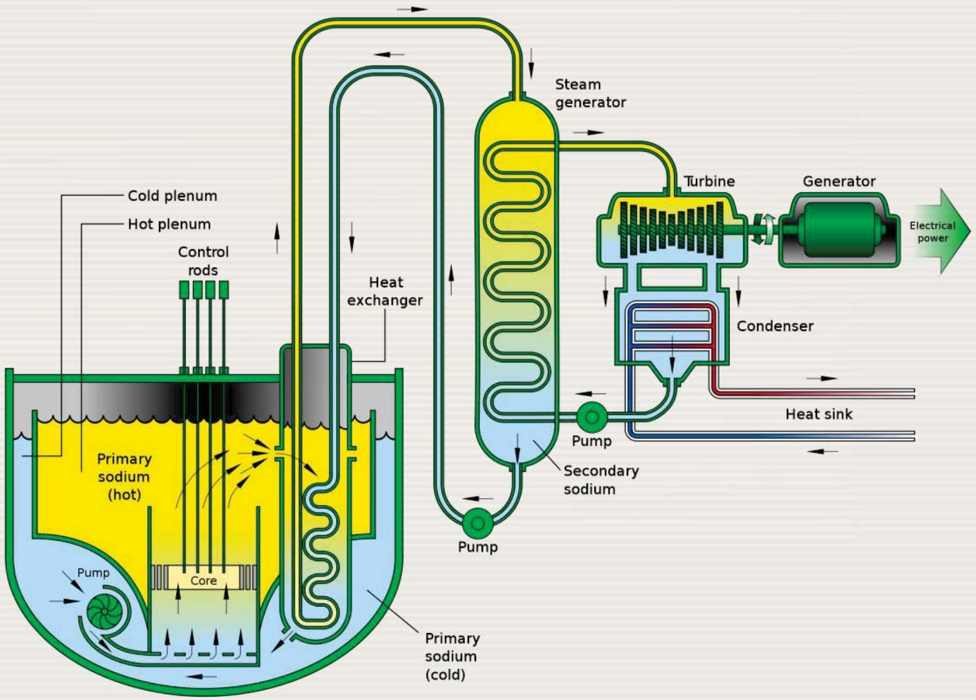
Fast Neutron Reactors

- Fast neutron reactors - compact core with no moderator
- More neutrons from fast fission, so FNR can be configured to:
  - Produce more fissile material (Pu) than they consume (breeding)
  - Or transmute long lived actinides:



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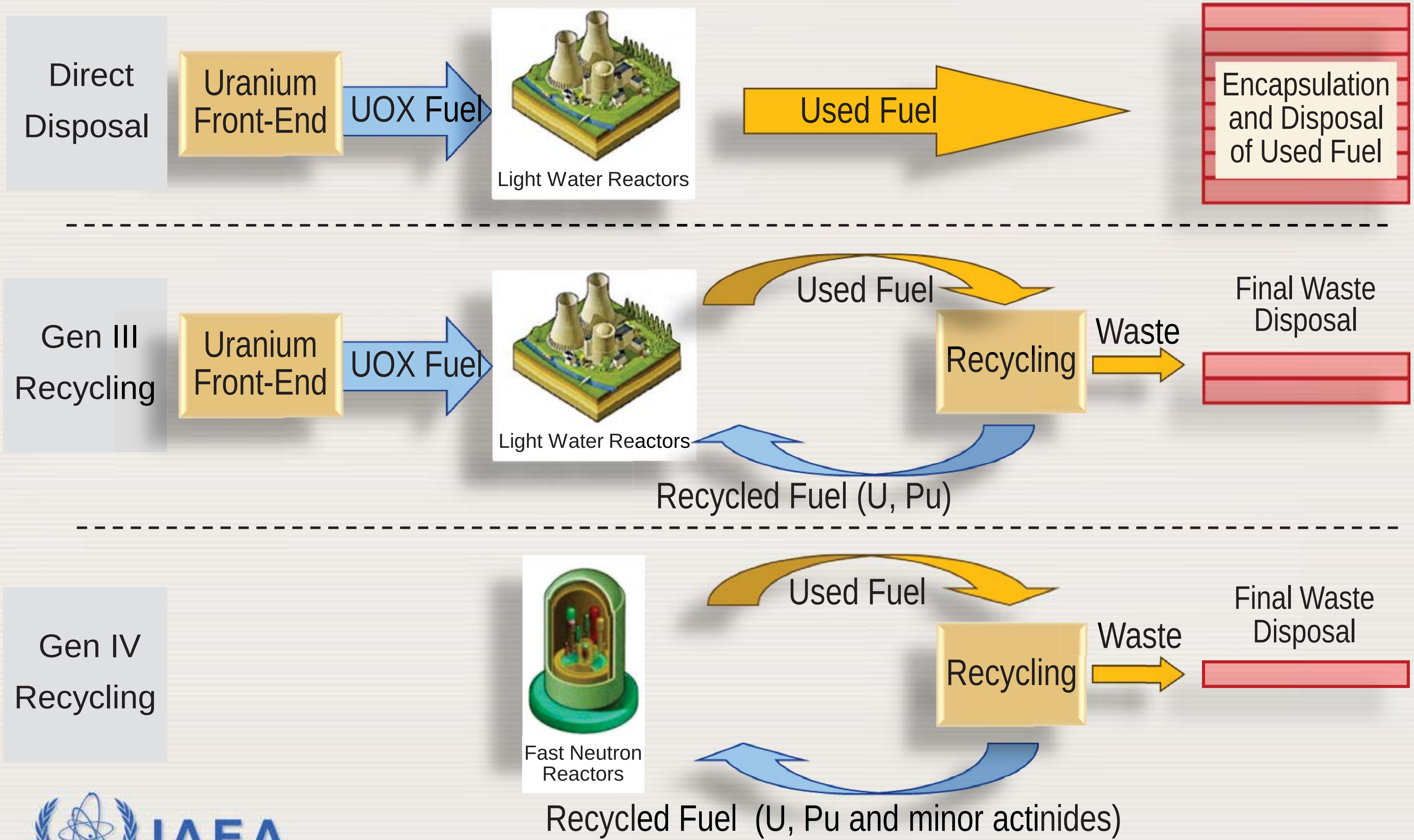
Uranium Fuel Cycle Options / Policies



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Comparison of Recycling Options

- Gen III LWR recycling (thermal reactors):
  - 25% uranium savings through LWR MOX and RepU fuel
  - Radiotoxicity reduction by 10 compared to direct disposal
  - Proven technologies and commercial models
- Gen IV recycling (fast neutron reactors)
  - Significant extension of the uranium resource
    - From several hundred to several thousands of years of availability of the total uranium resource
  - Accesses depleted uranium as a directly available resource
  - Much reduced radiotoxicity of the final waste

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National Policy on Spent Fuel

Country	NPP	Policy	Remark
USA	104	Disposal	AR/AFR interim storage Work on Yucca Mt. repository stopped
Finland	4	Disposal	Olkiuoto repository AR wet storage
Canada	18	Disposal	AR dry storage Repository site investigation
Sweden	10	Disposal	CLAB AFR wet storage Osthammar repository site
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
Russia	31	Reprocess	AFR wet/dry storage
UK	19	Reprocess & Disposal	Magnox and AGR reprocess – AFR wet storage LWR spent fuel disposal
India	18	Reprocess	

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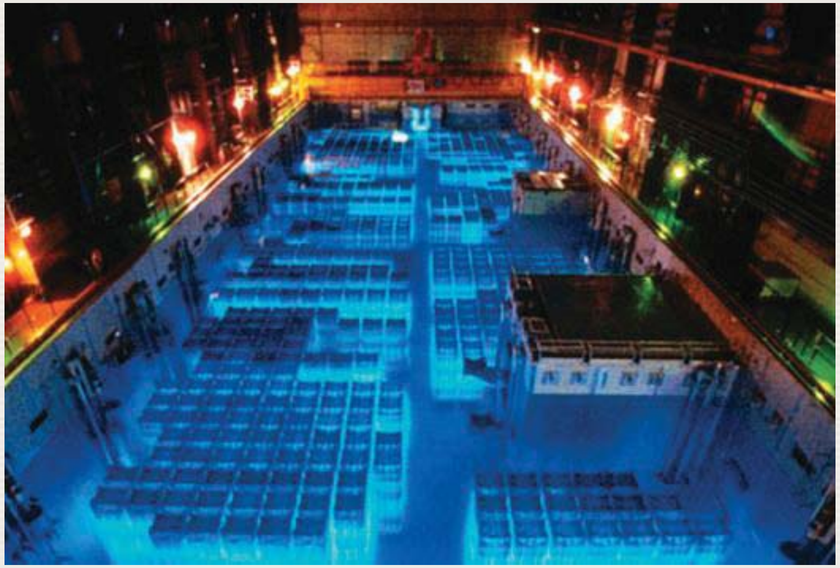
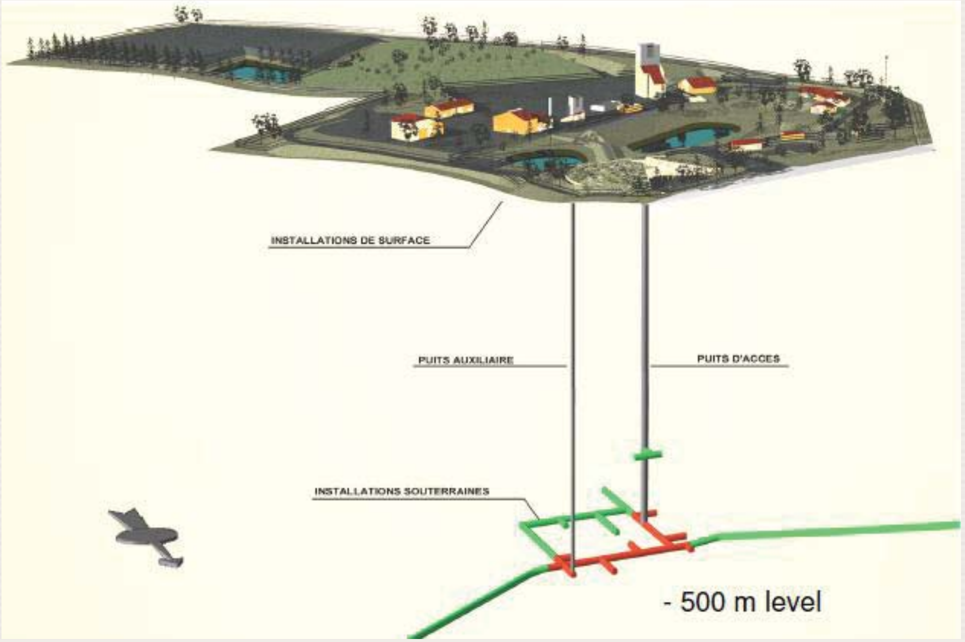
France

- Most used fuel is reprocessed
  - 58 NPP in operation - 1250 tons of used fuel every year.
  - La Hague: operated since 1966; capacity 1700 tHM/yr
  - HLW repository 2025 → Bure underground laboratory





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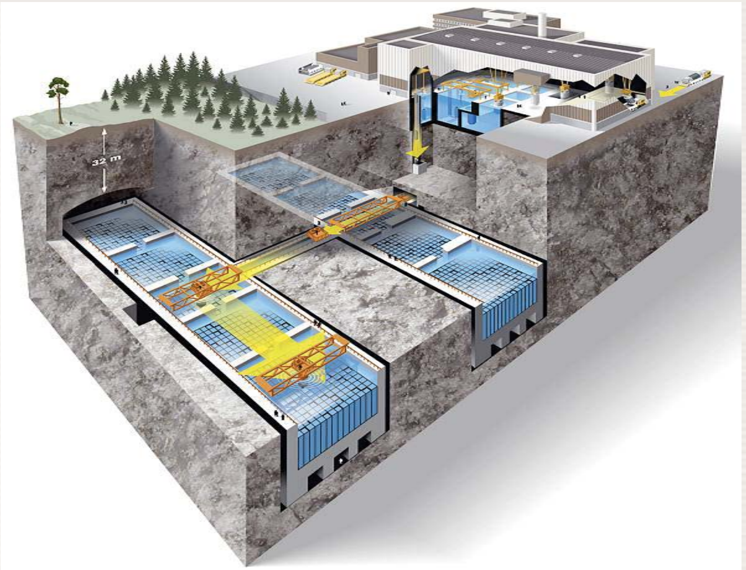
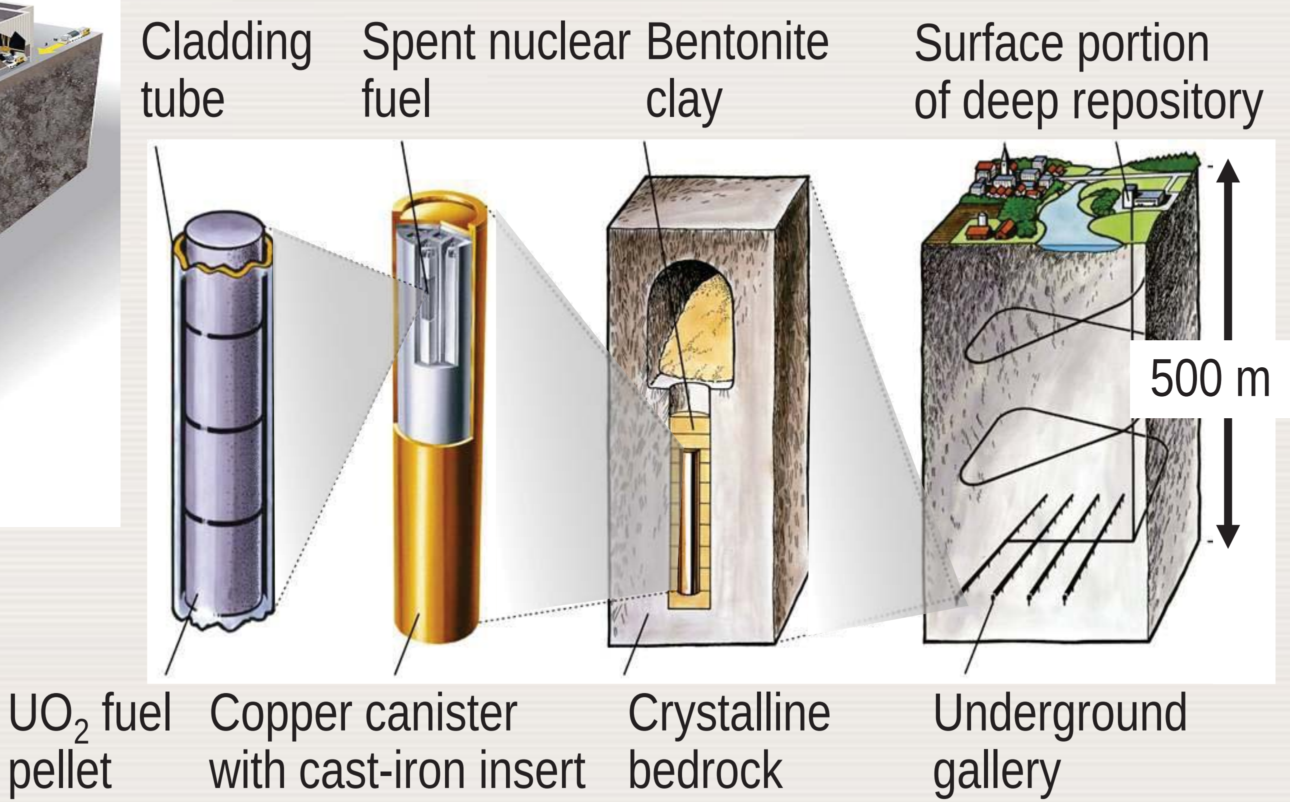
Sweden

- 10 NPP in operation
- CLAB Centralized wet storage (Oskarshamn) 8000 tHM
- Repository construction: 2015-2025 (Forsmark)



CLAB



USA

- 104 operating NPPs
- Wet storage: ~ 50 000 MTHM, mainly at reactor sites
- Dry storage: ~ 18 000 MTHM
- Final repository not yet defined: Yucca Mt. project stopped
- Confidence in 60 years of interim storage, considering extended storage ~120 years

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Switzerland

- 5 NPPs in operation
- ZWILAG: Interim storage for vitrified HLW and spent fuel
- 200 cask capacity
- 1 139 MTHM of used fuel sent to France and the UK for reprocessing
- 10 years reprocessing moratorium from July 2006 during which period, spent fuel must be managed as radioactive waste.

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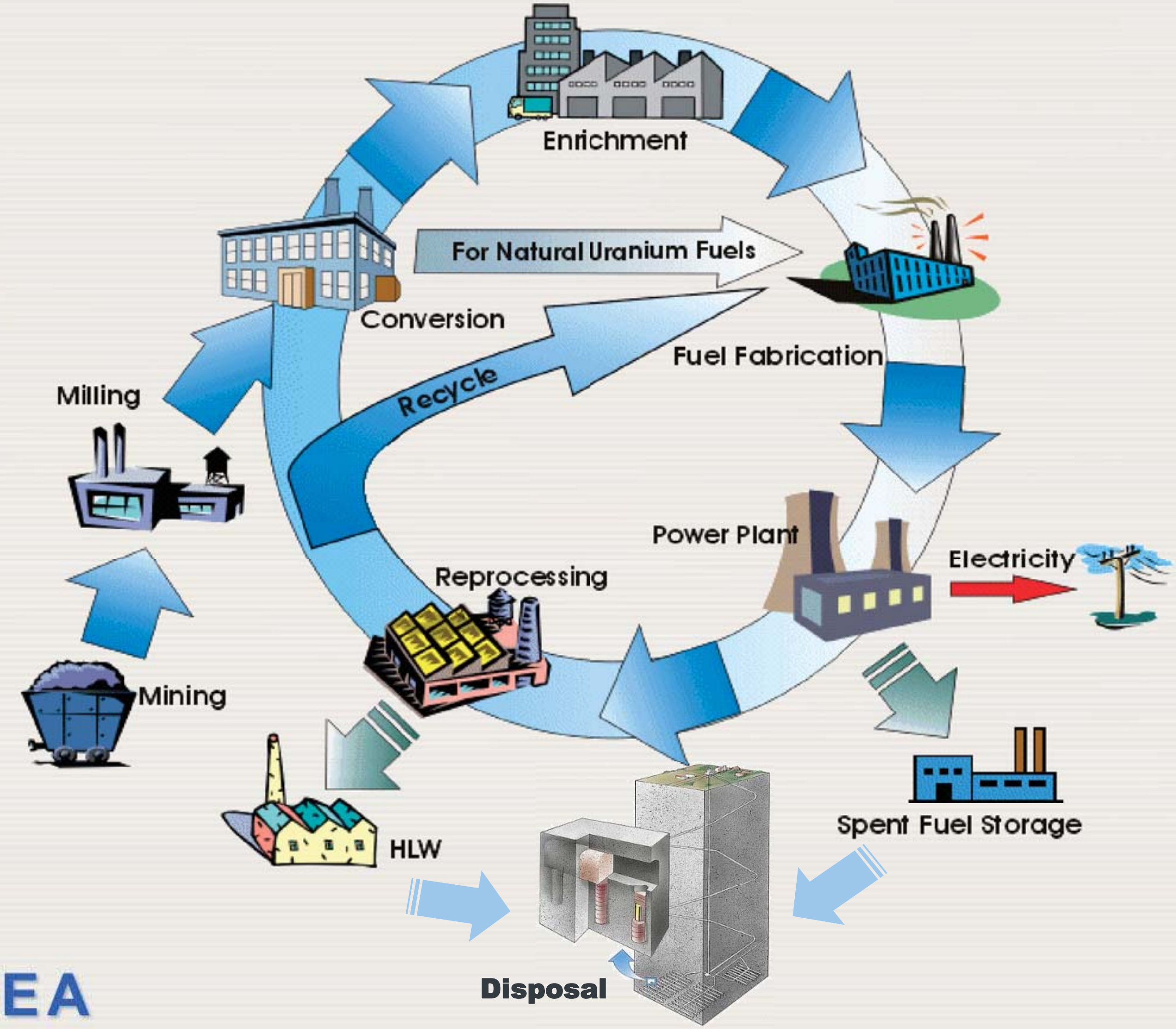
Nuclear Fuel Cycle



Thank you for your attention

…atoms for peace.

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