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International Atomic Energy Agency

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Joint ICTP/IAEA School on Physics and Technology of Fast Reactors Systems

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Reprocessing and recycling of fast reactor fuel

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IAEA/ICTP School on
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The nuclear fuel cycle

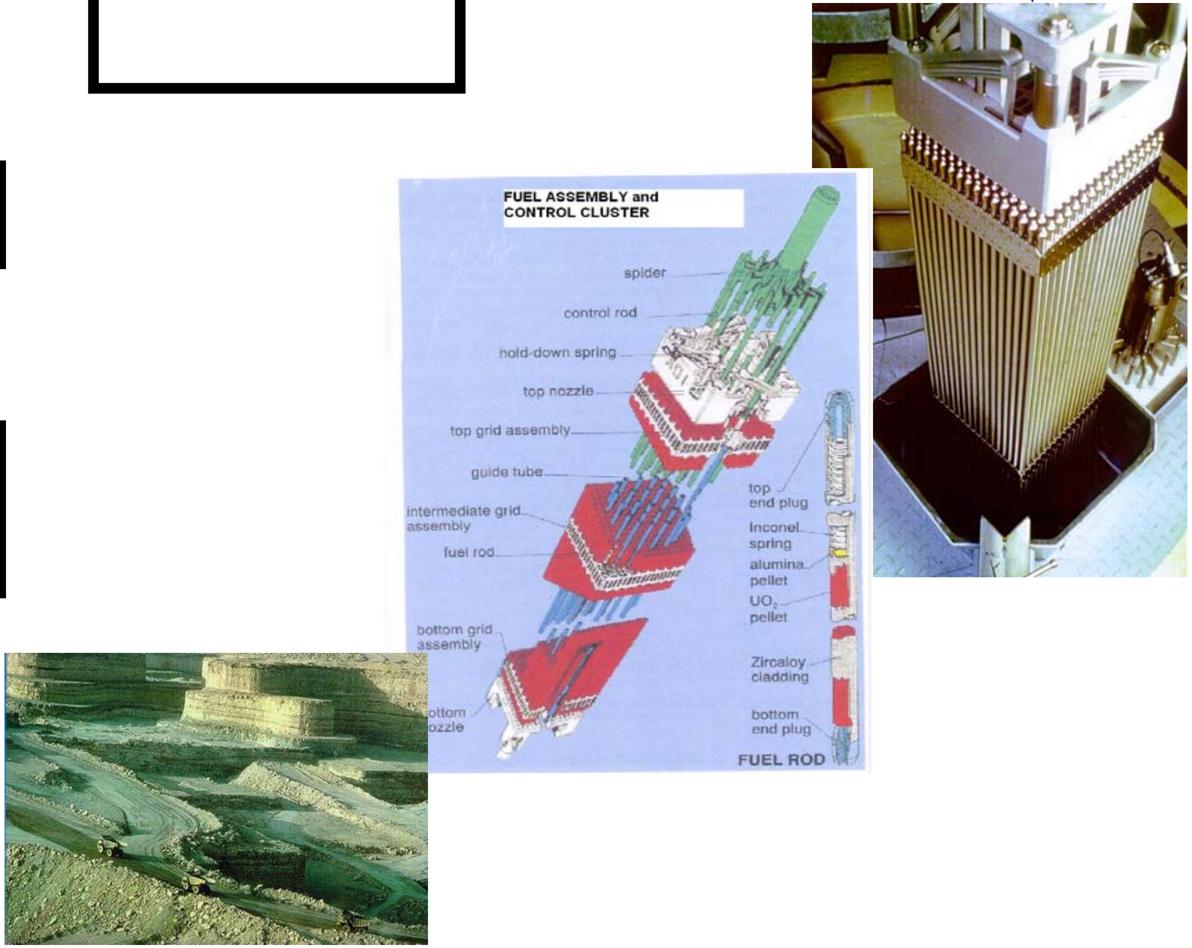
REACTOR

Spent Fuel

Fuel Fabrication

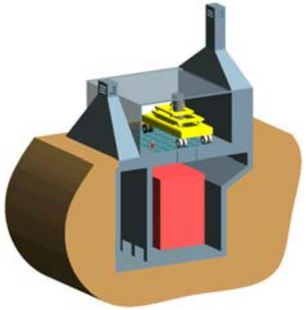
Uranium Enrichment

Mining and Milling

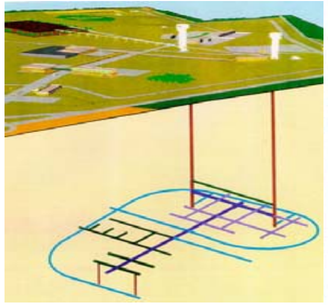


Spent fuel management : what options ?

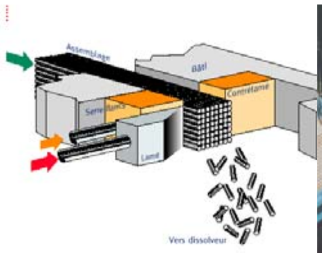
- ***Interim storage***



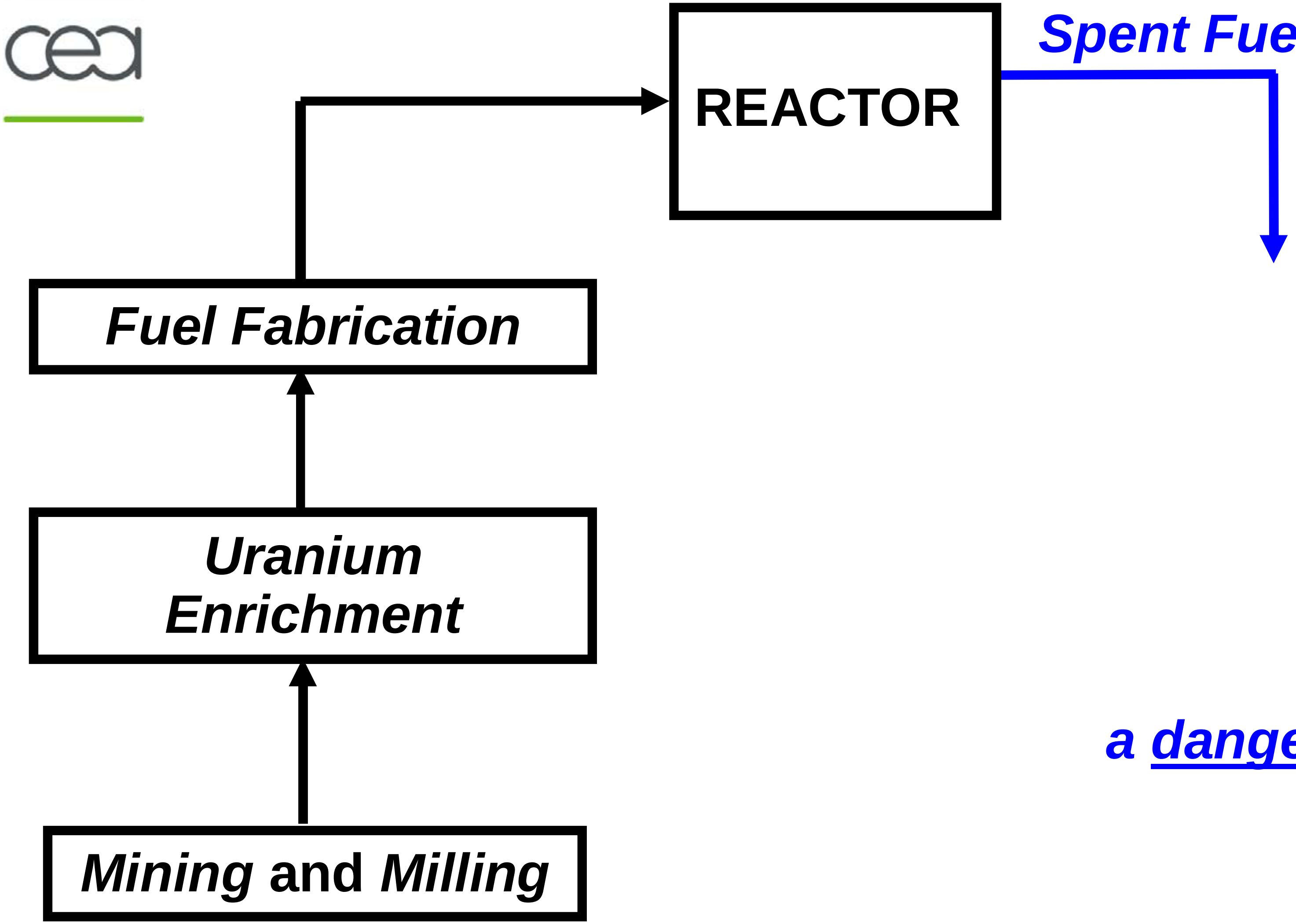
- ***Direct disposal***



- ***Process and recycle***



The nuclear fuel cycle



REACTOR

Spent Fuel

Fuel Fabrication

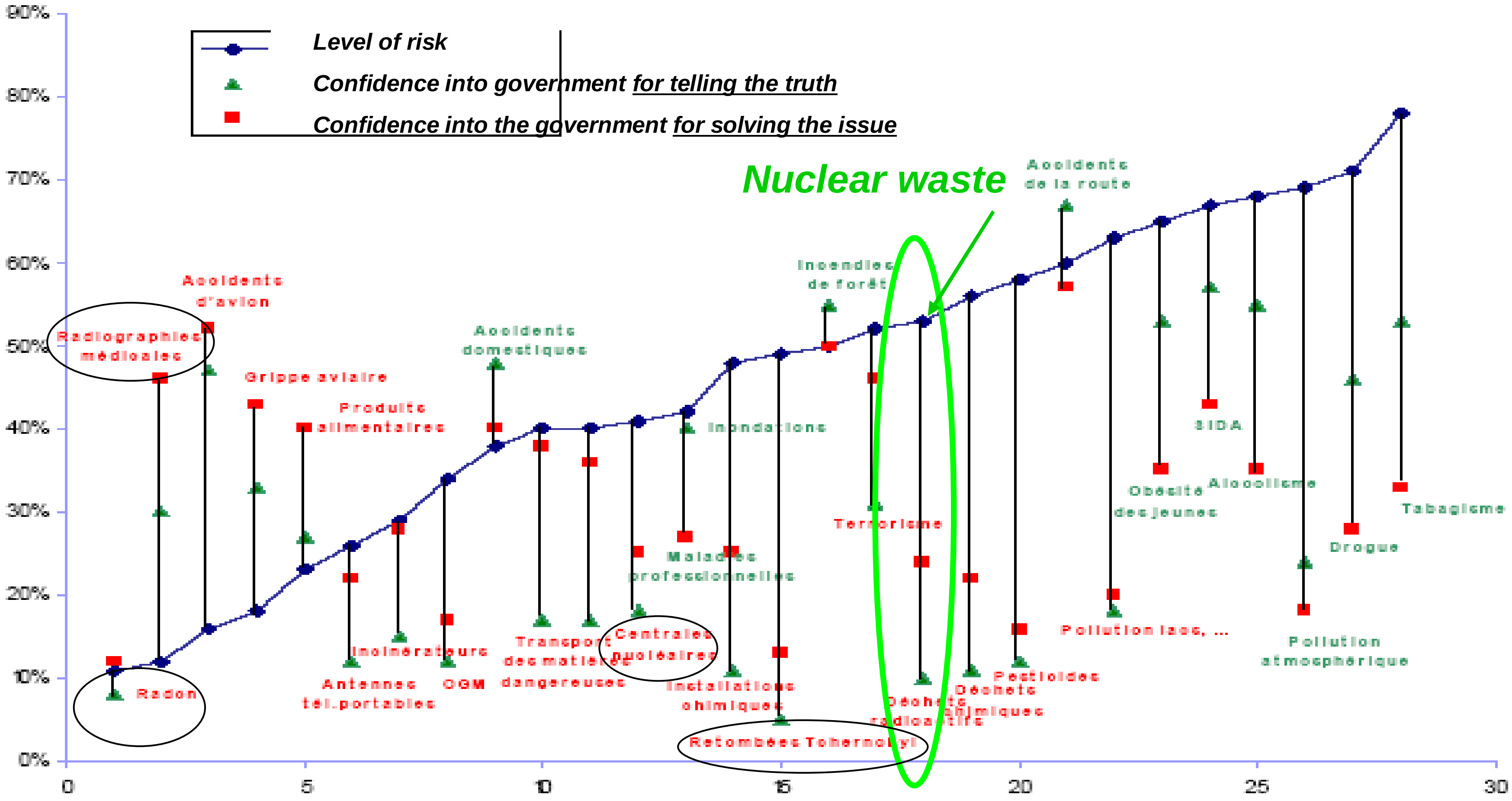
Uranium Enrichment

Mining and Milling

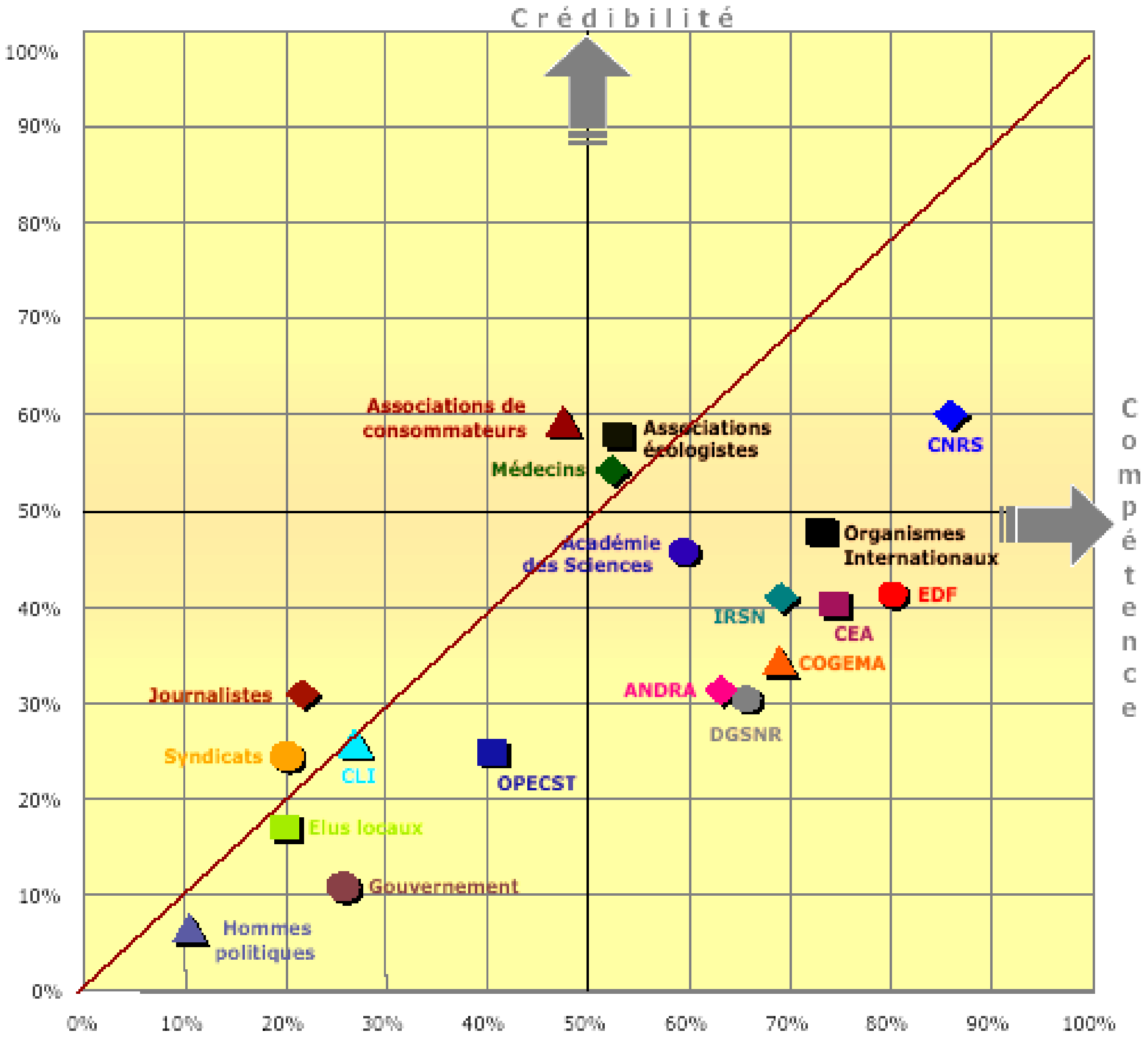
a dangerous waste,
& an asset

About risks…

Source: "IRSN barometer" ***2006***



Nuclear acceptance : credibility and competence



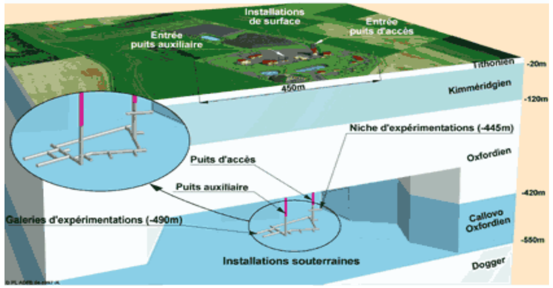
The French Act of December 1991, for 15 years

Waste management in France: which goals?

Goal 1 research : to reduce the overall radwaste quantity by solutions that would allow partitioning and transmutation of long lived radionuclides present in HL LL nuclear waste

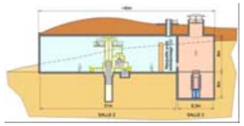
Goal 2 research : to study the feasibility of reversible or irreversible repository in deep geological formations

Positive results of Underground Laboratory:
Dossier Argile 2005 : clay in Meuse/Haute Marne site



Goal 3 research : to study conditioning processes and feasibility of long term storage, above-grade or below-grade

Sub surface long term storage demonstration gallery constructed at CEA-Marcoule ; long term storage demonstration containers (scale 1)



Galerie

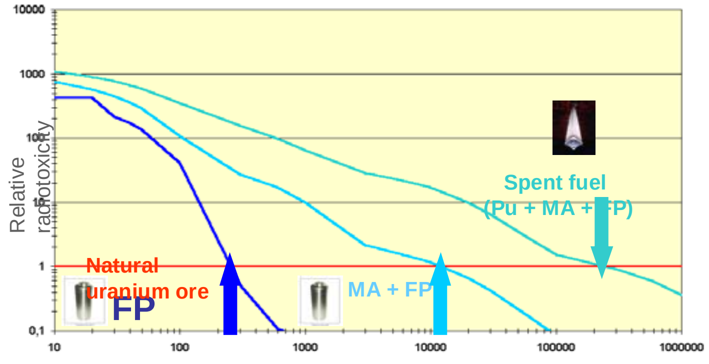
⇨**Deadline set in law : 2006**

The main results of P and T research programs

- New possibilities, continuous progress :
  - Extraction molecules have been developed at lab scale, and pre industrial demonstrations have proved successful : industrial partitioning is feasible
  - Transmutation of Fission Products (I, Cs, Tc) is either not feasible or unrealistic
  - MAs transmutation is unrealistic in PWR
  - Transmutation experiments, at pin scale, have been carried out for americium and neptunium in a power reactor, such as Phénix, which demonstrates the feasibility of their transmutation in SFR
  - Feasibility of transmutation in ADS is not obtained today, and research must going on
  - Realistic scenario : Transmutation can be carried out only with the new generation of fast neutron reactors, as a contribution to sustainable nuclear energy by homogeneous or heterogeneous mode

Recycling strategy

- Aim of recycling : to minimize the **quantity and radiotoxicity** of long lived nuclear waste
- Potential gain : to reduce at hundreds years the life time of future waste (compared to the level of initial U_{nat}) and to ease the conditions of a deep geological repository



- Main radiotoxicity contributors : 1) Pu 2) MA 3) LLFPs
- Fundamental hypothesis : closed cycle, GEN IV fast neutron reactor implemented at mid or long term (whatever the cooling : Na, gaz,…)
- Reference strategy :
  - PWRs: Pu management by multi recycling
  - GEN IV SFR or GFR: full actinides recycling, beginning 2040
  - Option of the « double strata » PWRs – Accelerator Driven Systems

- Demonstrations of scientific and technical feasibilities,

before pre industrial development of recycling

Recycling strategy : systems evolution…

(Fuel cycle)

- ***The new requirements*** **:**

  - **Save resource**
  - **Minimize environment impact** ***(waste nocivity)***
  - **Increase resistance vs proliferation risks**

  - **New purposes, other than electricity**
    (heat, H2, dessalinization)…
  - ***And obviously :*** **safety, costs…**

(Reactors)

Save resource : Uranium ore

Ore: 0.5 -10 kg U/ ton

^{235}U : 0.7 %

^{238}U : 99.3 %

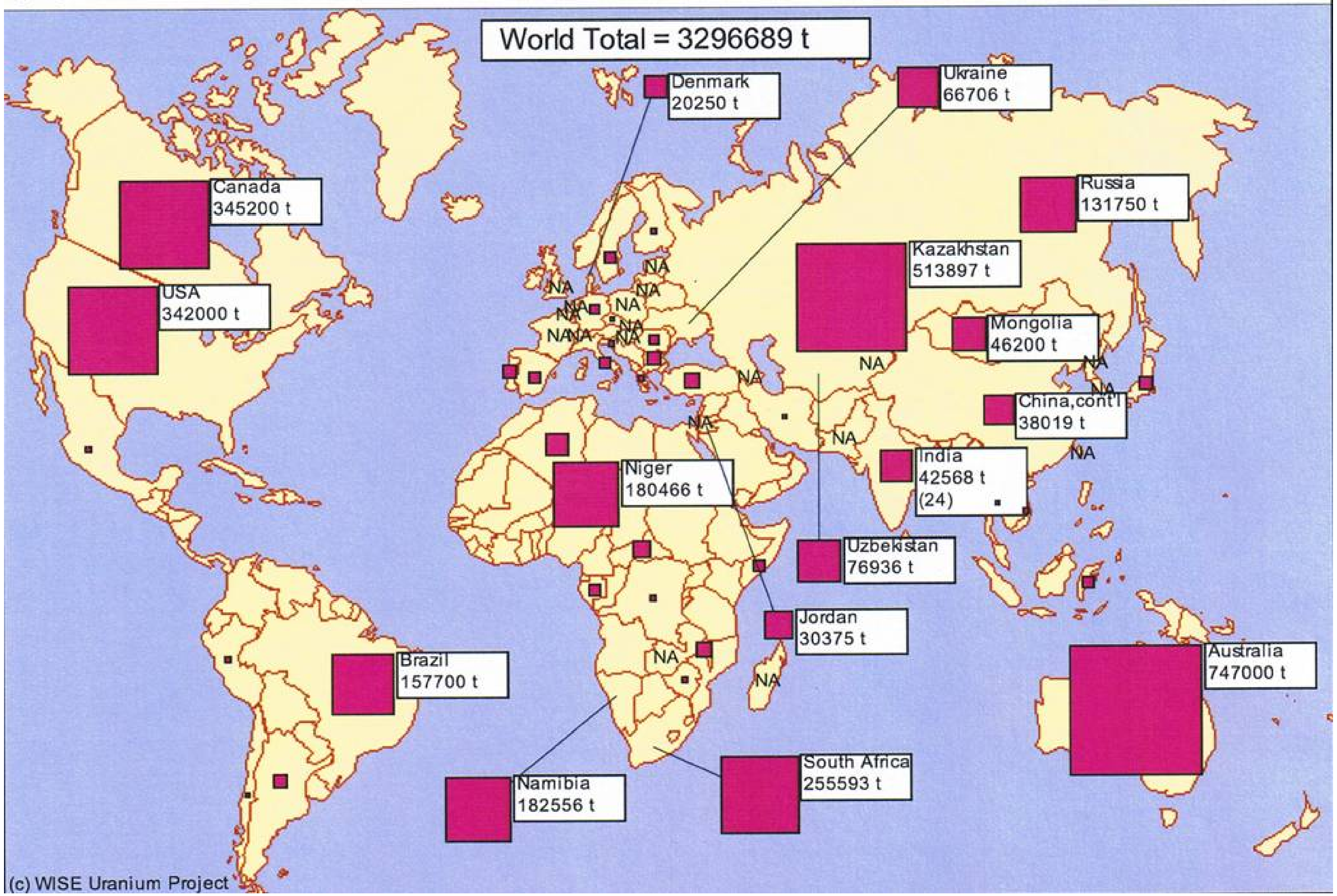
Average earth crout :few grams U/ ton

Seawater: few mg U / ton water

Save resource : Uranium resources

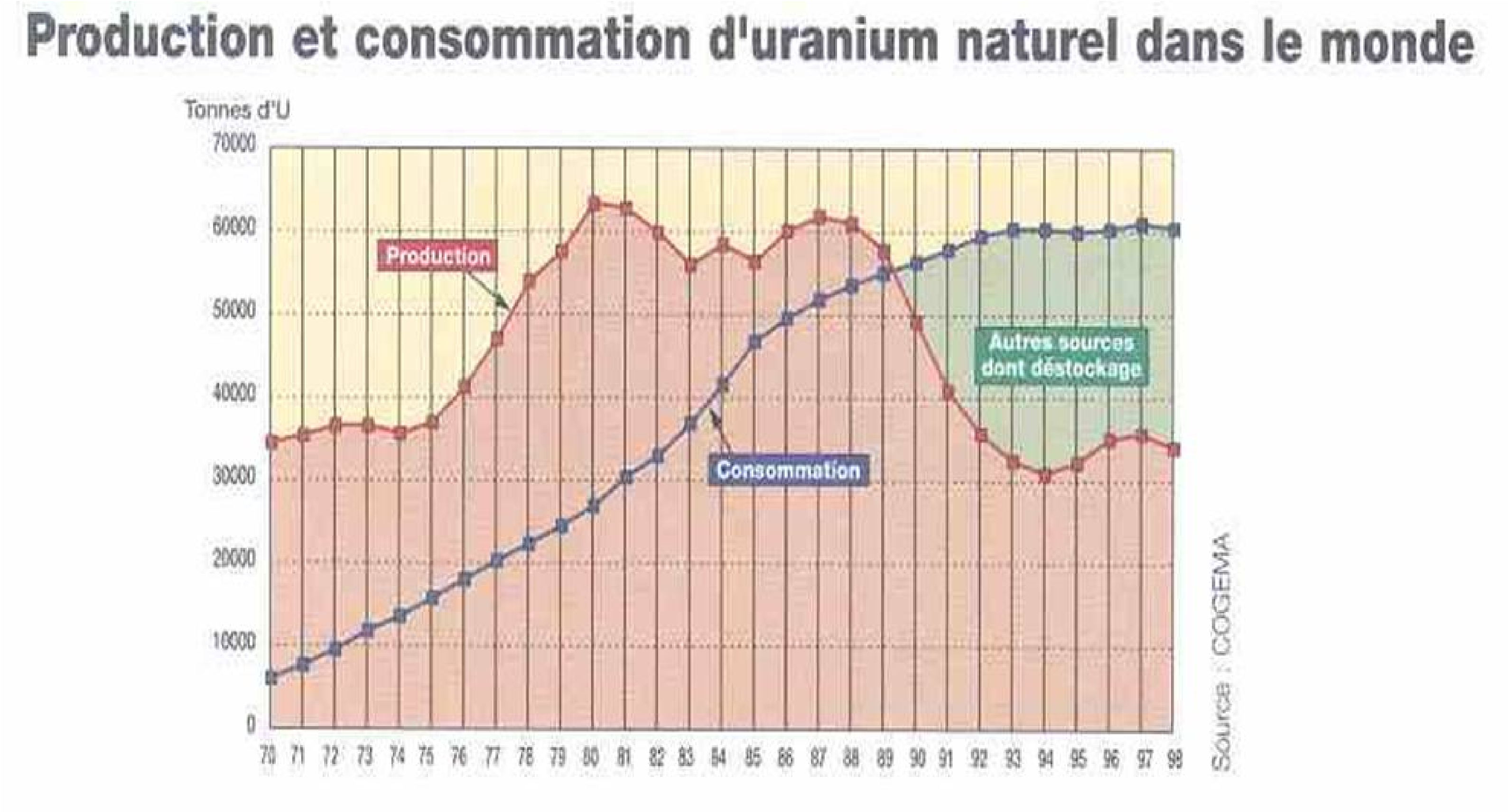
Uranium Resources (RAR - $130/kg U)

[t U] Reasonably Assured Resources, recoverable res. as of 1/1/2005, Cost range < US$130/kg U (OECD 2006)



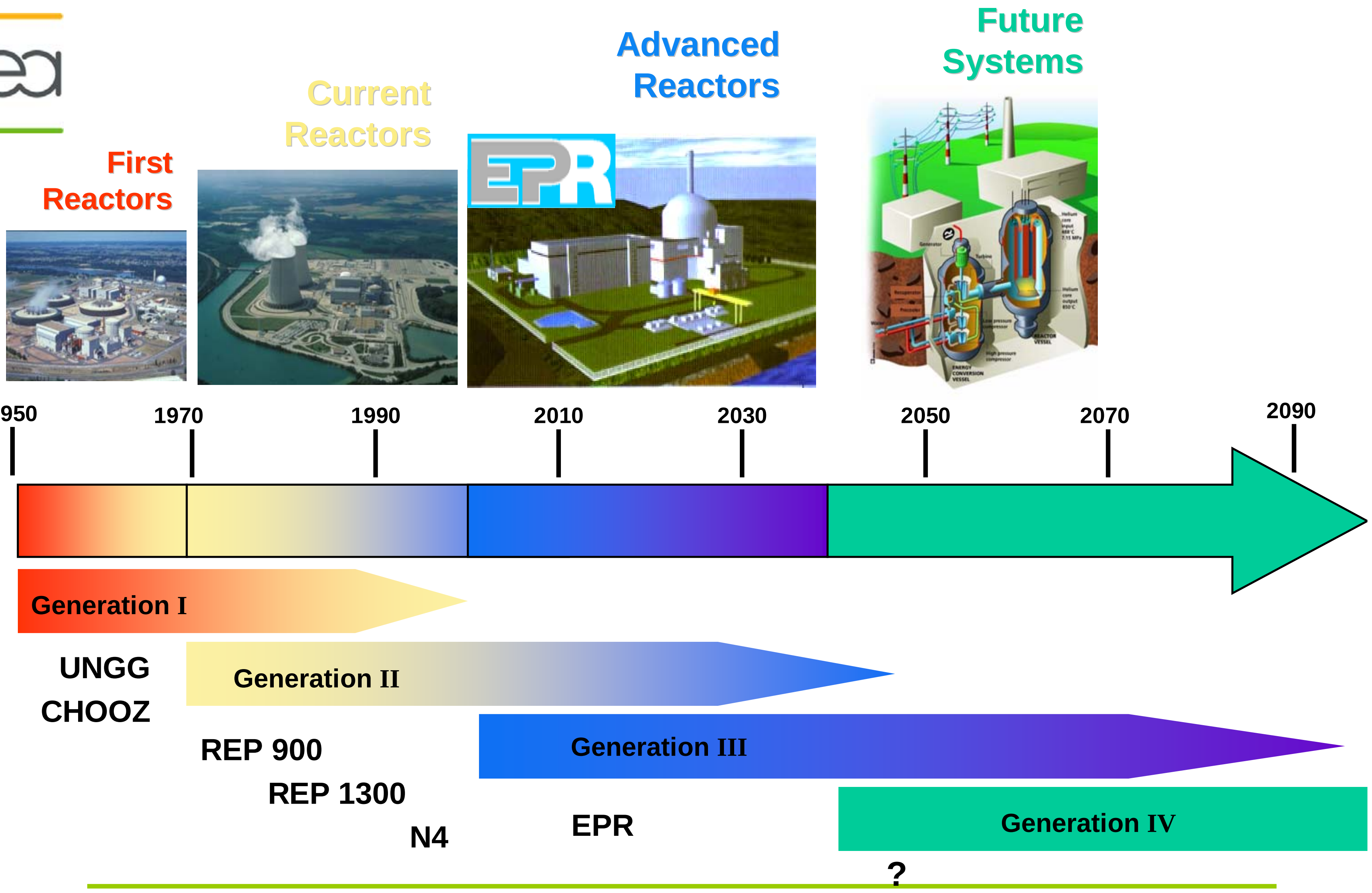
(c) WISE Uranium Project

Uranium world production and consumption



2005 records : 41 600 tons produced
67 500 tons needed

The Evolution of Nuclear Power to fast systems



First Reactors

Current Reactors

Advanced Reactors

Future Systems

1950 1970 1990 2010 2030 2050 2070 2090

Generation I

UNGG
CHOOZ

Generation II

REP 900
REP 1300
N4

Generation III

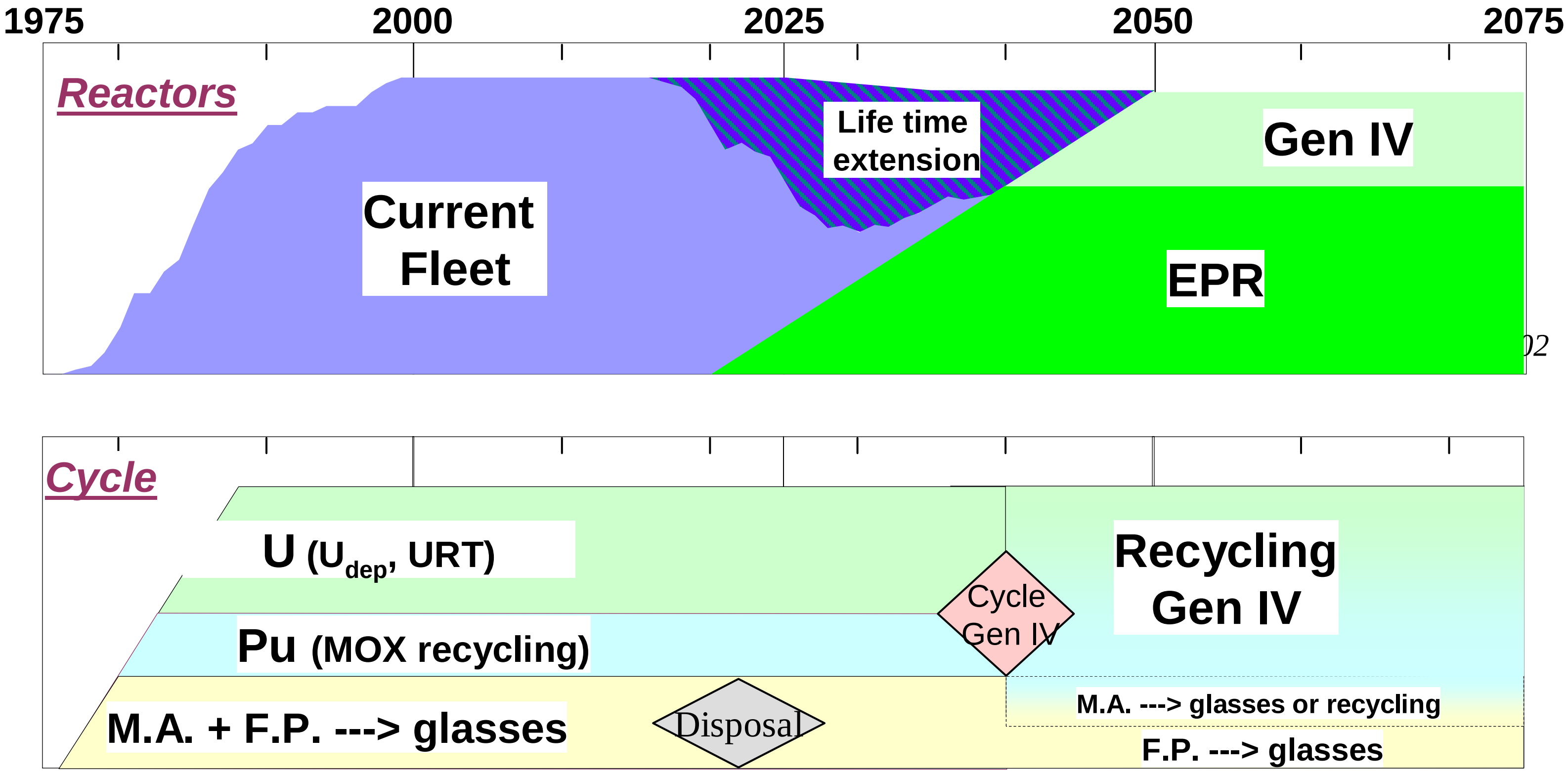
EPR

Generation IV

?

Transition scenarios between generations in France

- **Major role of LWRs in the 21st century**
  - Current PWRs (Gen II): life time extension (> 40 years)
  - Gen III/III+ PWRs : current PWRs replacement around 2015 (EPR) – Operation during 21st century
- **A transition scenario between LWRs and Fast Neutrons Systems**



Nuclear acceptance and a responsible management of spent fuel and waste

A responsible management of nuclear spent fuel :

- Recycles 96% of spent fuel materials
- Saves 30% of natural resources
- Costs less than 6% of the kWh total cost
- Reduces by 5% the amount of wastes
- Reduces by 10% the waste radio toxicity
- Adapted technologies allow a safe conditioning of wastes to guarantee their long term confinement and stability, during dozens of thousands of years

Recycling, such as implemented today in France, GB or Japan, gives time and opens a large range of options for the satisfactory management of nuclear wastes.

→ more sustainable policy

better public acceptance

The spent nuclear fuel

235U=0.9%

🟨 **Uranium (95%)**

🟨 **Fission Products (4%)**

🟨 **Plutonium (1%)**

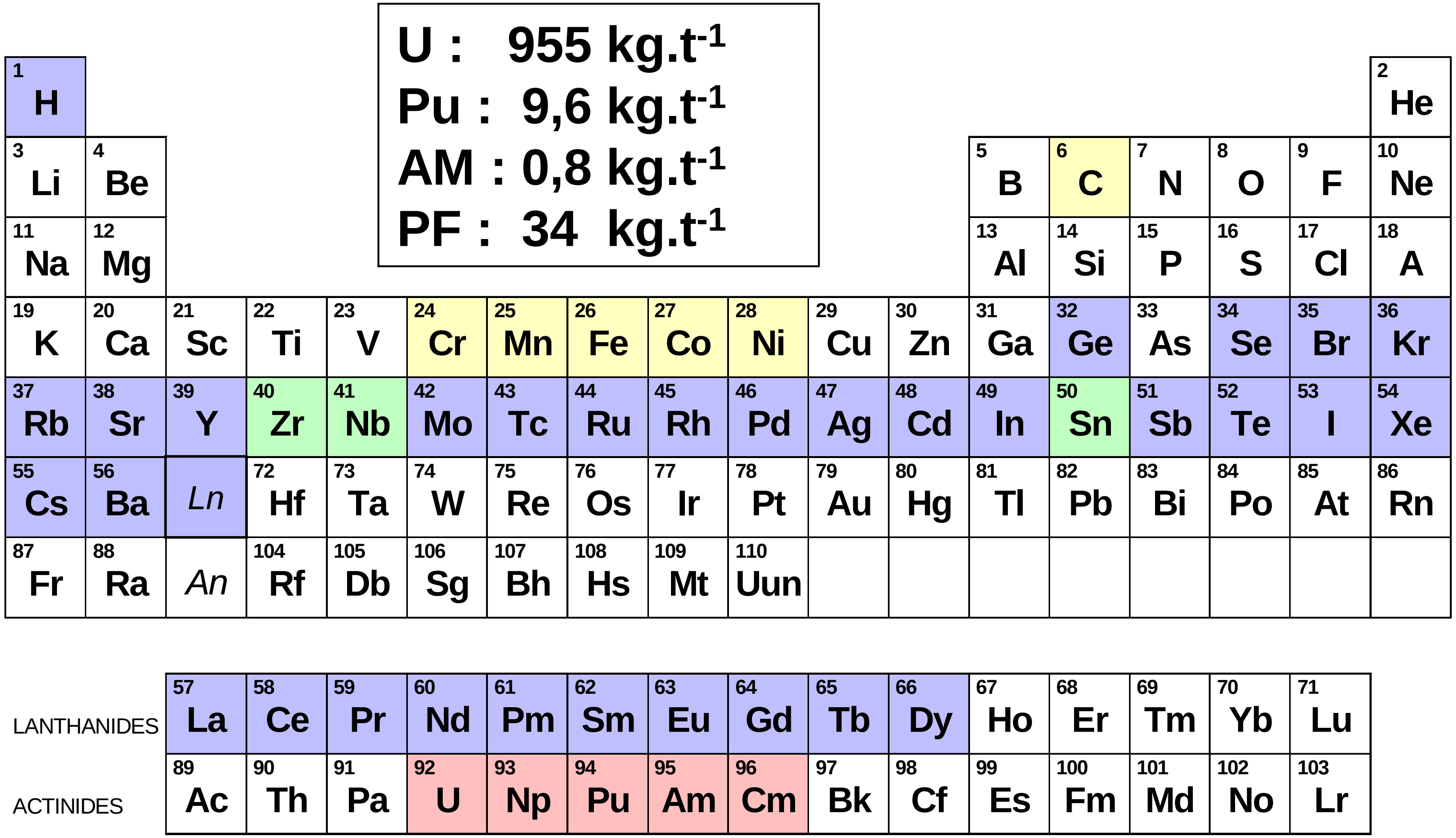
🟨 **Minor Actinides (0.1%)**

Average Content

Fissile isotopes = 75%

UOX Nuclear spent fuel

(UOX : 3,5 % ^{235}U ; 33 GWj.t^{-1})



U : 955 kg.t^{-1}
Pu : 9,6 kg.t^{-1}
AM : 0,8 kg.t^{-1}
PF : 34 kg.t^{-1}

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 A
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*Ln*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	*An*	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun								

LANTHANIDES	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
ACTINIDES	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

🟥 NOYAUX LOURDS
🟦 PRODUITS DE FISSION
🟨 PRODUITS D'ACTIVATION
🟩 PRODUITS DE FISSION ET D'ACTIVATION

UOX and MOX spent fuels : typical content

	UOX (45 GW/t)	MOX (45 GWj/t)
URANIUM	~ 940 kg	~ 890 kg
PLUTONIUM	~ 11 kg	~ 56 kg
FISSION PRODUCTS	~ 48 kg	~ 48 kg
MINOR ACTINIDES	~ 1 kg	~ 6 kg

(for 1 tonne initial HM)

Spent fuel : radioactive content

AVERAGE BU ~ 33 000 MWd/t

6 months after unloading : assembly : 150 000 TBq (18 kW)

3 years after : 30 000 TBq (3 kW)

FISSION PRODUCTS

β^- mainly

very diverse radioactive periods

CAPTURE PRODUCTS

Actinides (Pu 1 %, Minor Actinides ~ 0.4 %)

α and long radioactive periods

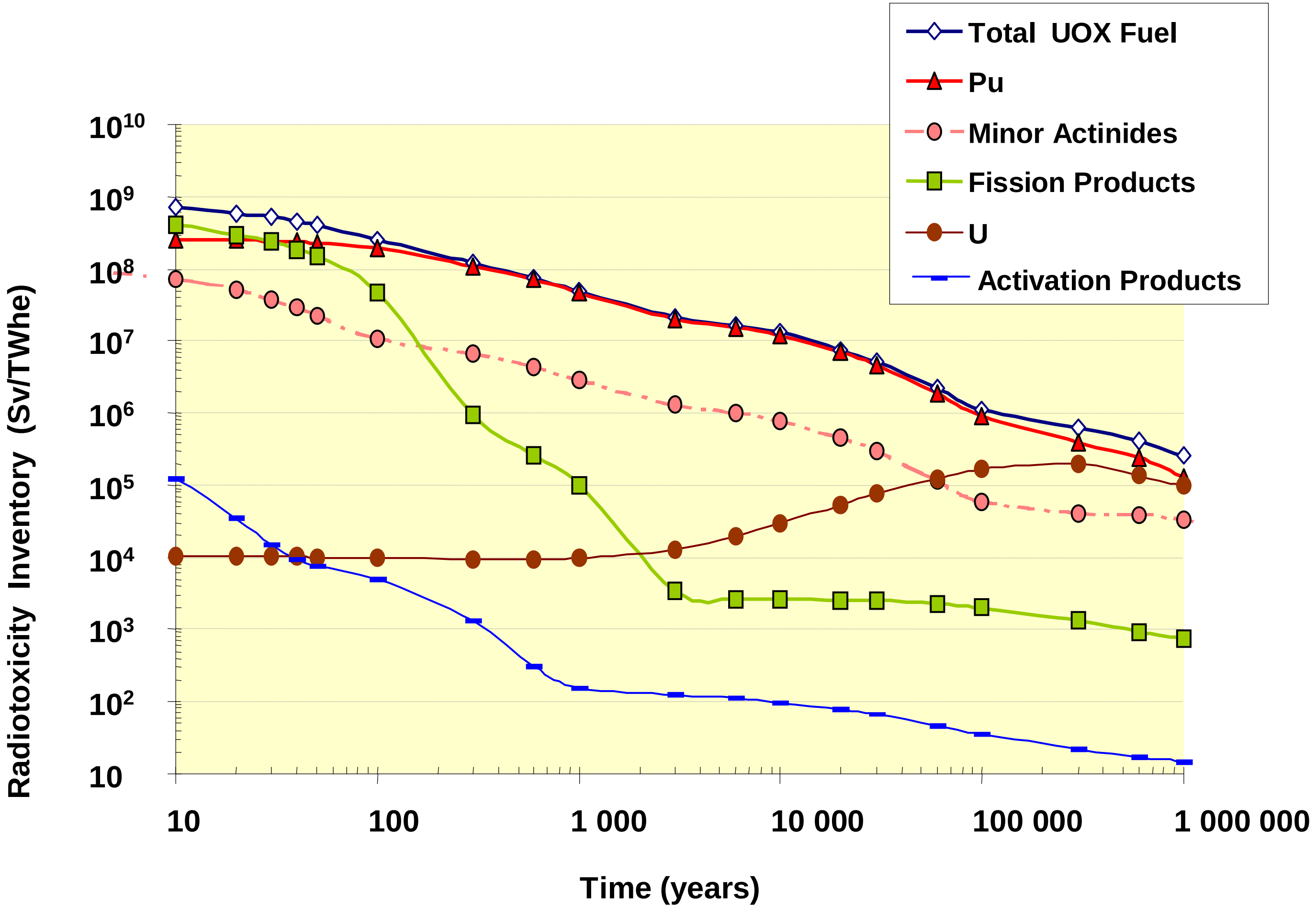
ACTIVATION PRODUCTS

structure metallic materials (Zr isotops)

or fuel initial contaminants

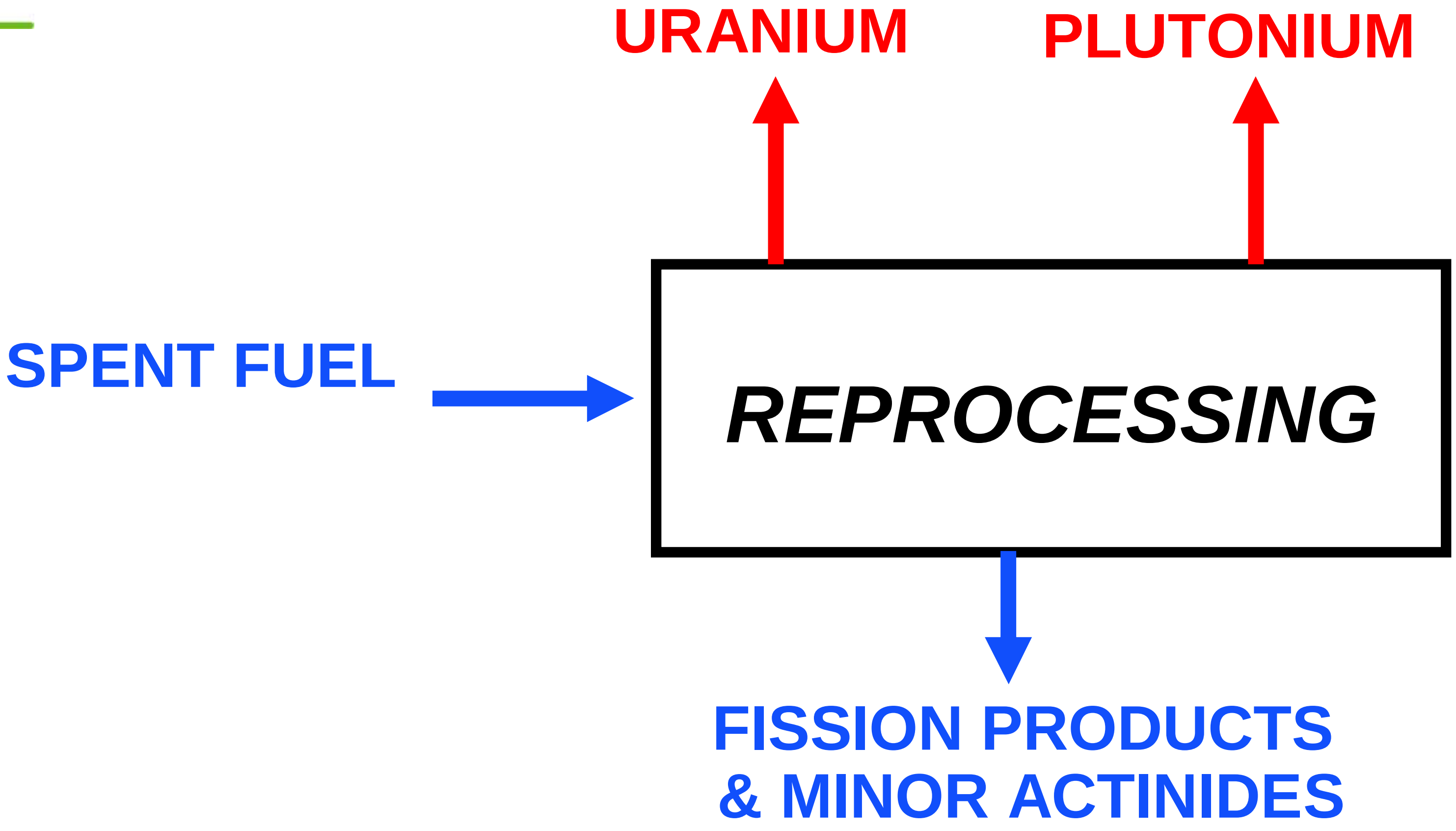
(^{14}C from ^{13}N or ^{17}O traces in initial oxide)
(36Cl from 35Cl traces in initial oxide)

Radiotoxicity of LWR-UOX Spent Fuel

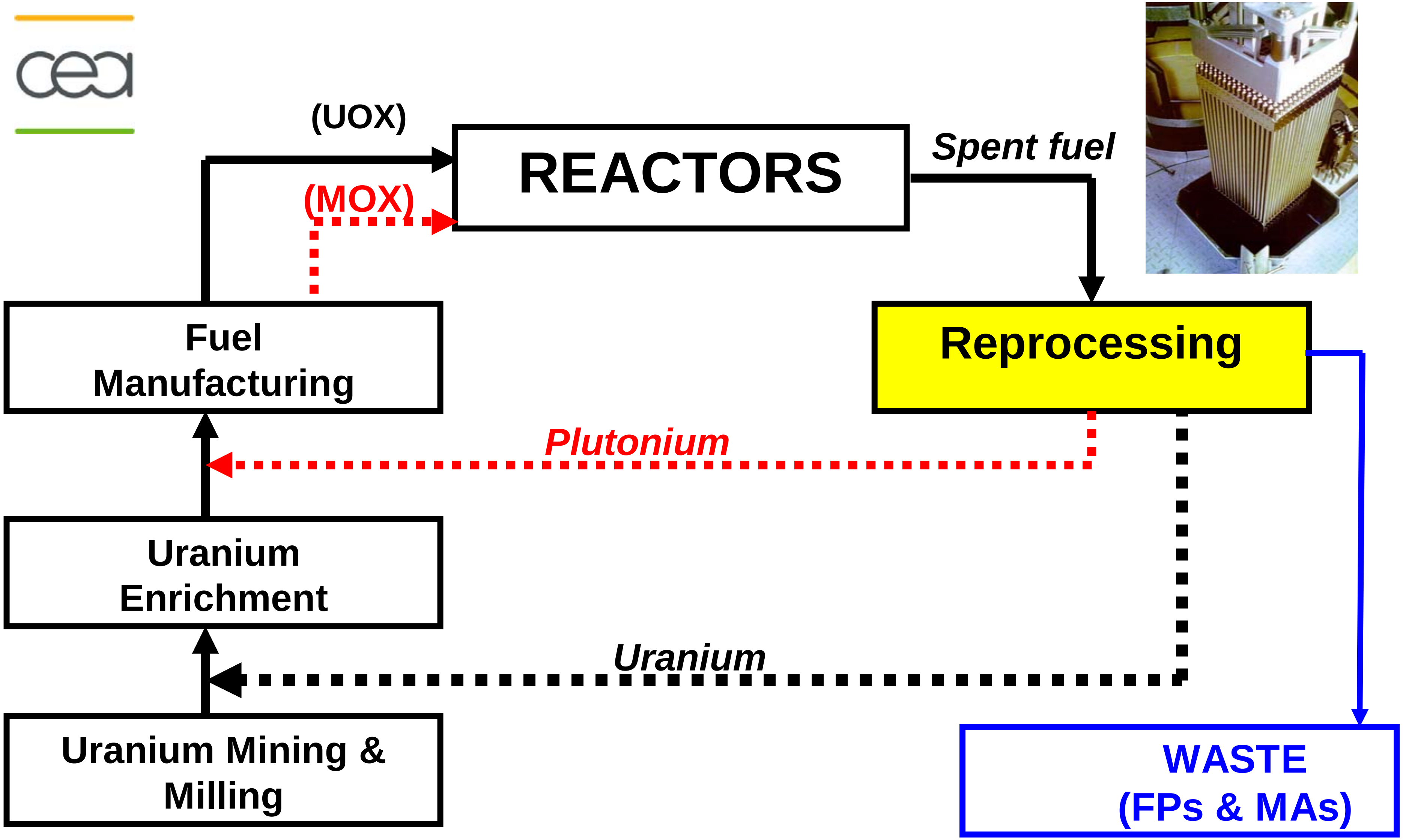


Ingestion Doses Coefficients from ICRP72

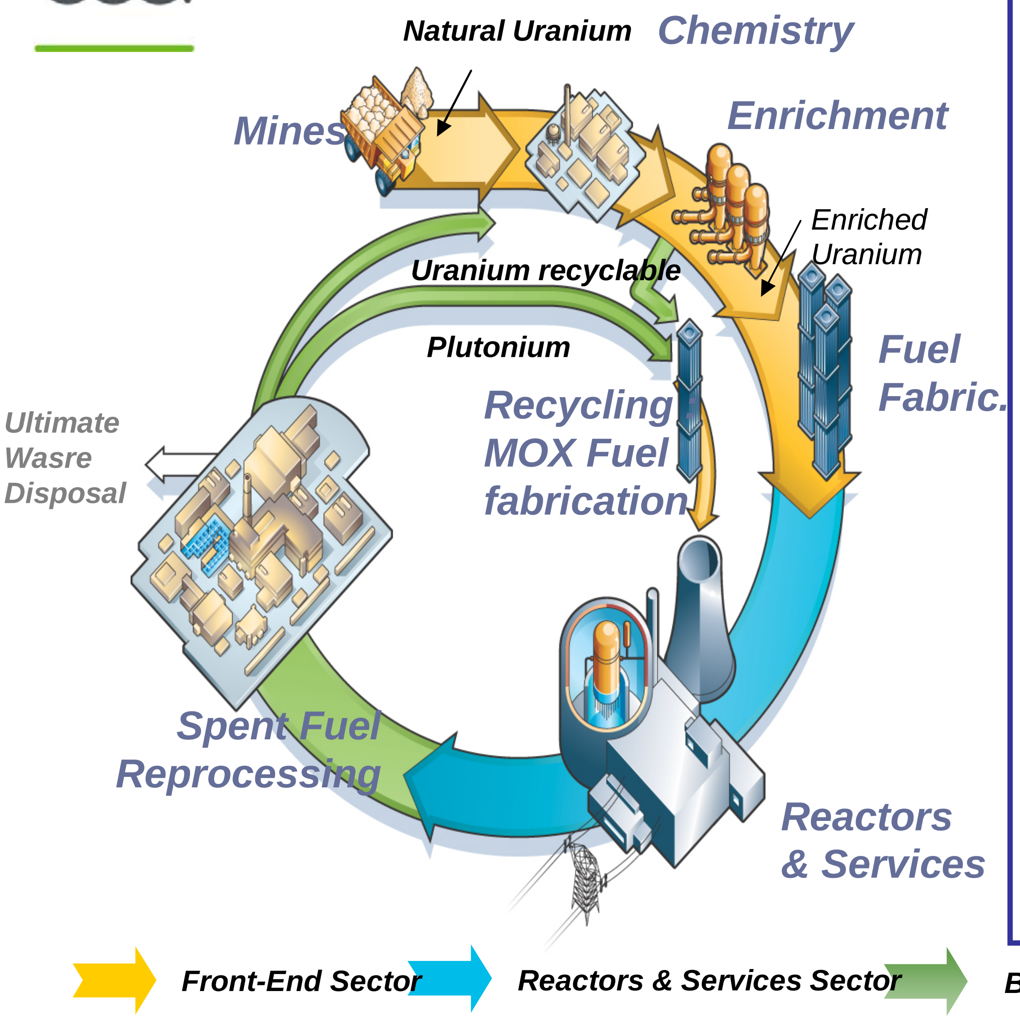
Reprocessing : the principle



Recycling Uranium and Plutonium



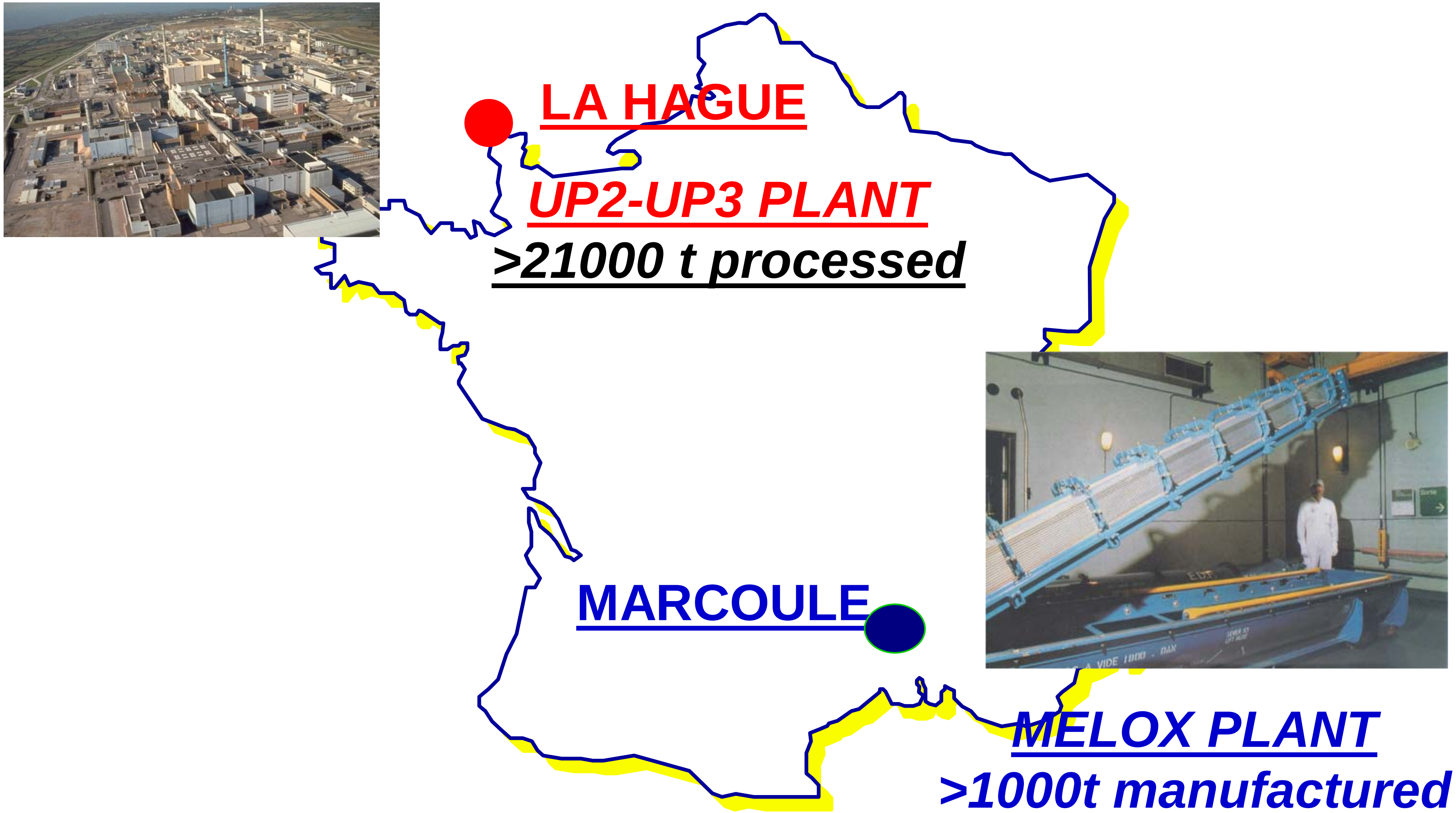
Closing the Fuel cycle … an industrial reality



The exemple of the french situation :

- **58 PWRs → 400 TWh annually**
- **~ 78 % of french electric production**
- **Fuel processing : more than 25 years of experience**
- **1100 t_{HM} /yr of spent fuel discharged from the French PWRs**
- **850 t_{HM} /yr of domestic spent fuel reprocessed + foreign**
- **Until now: ~ 20 000 t_{HM} spent fuel reprocessed and more than 1500 t_{HM} MOX fuel recycled**

Fuel Reprocessing and recycling



LA HAGUE

UP2-UP3 PLANT

>21000 t processed

MARCOULE

MELOX PLANT

>1000t manufactured

La Hague Repocessing plants

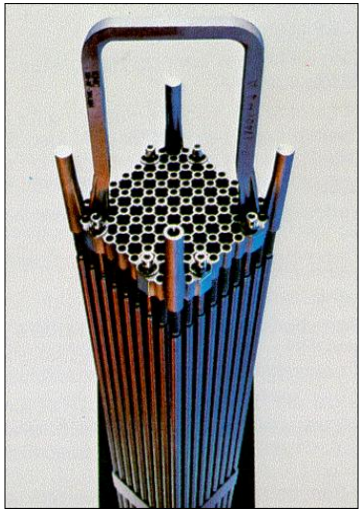
History

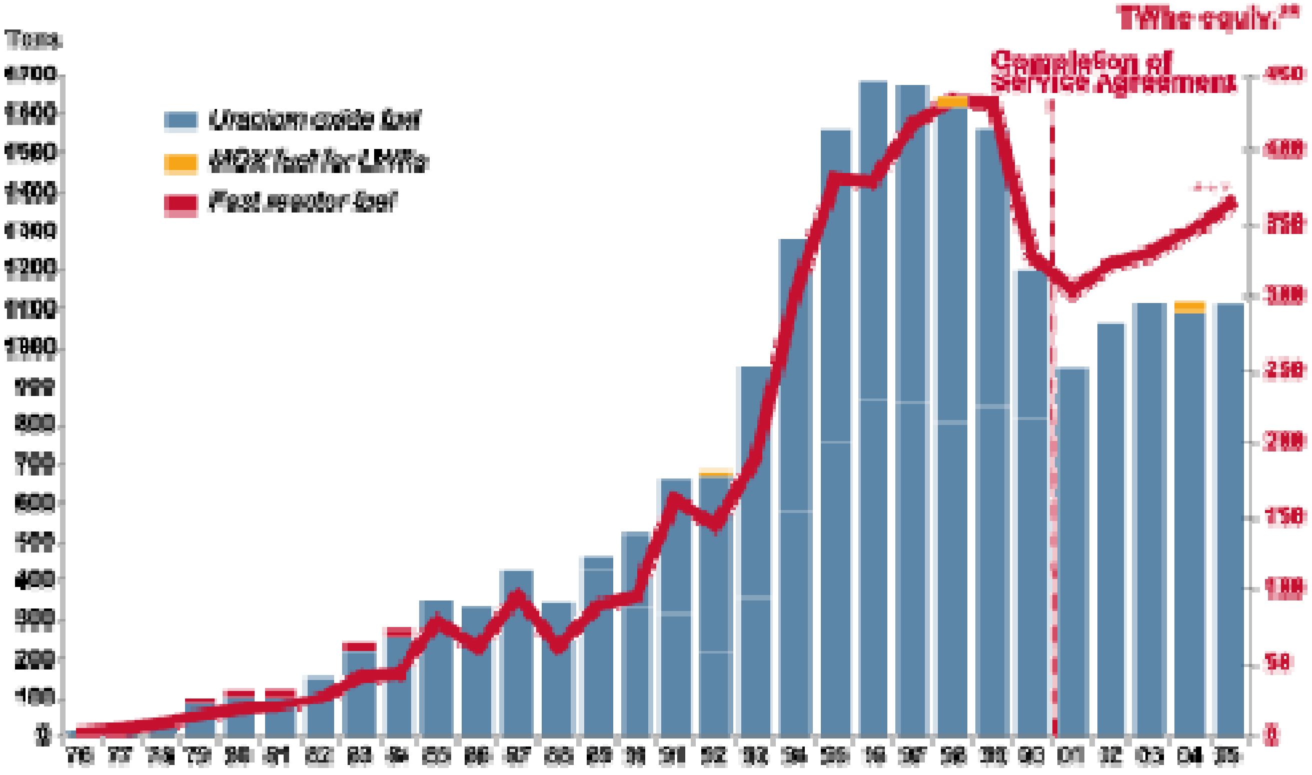
- **1966 – 1976 : UP2, 400t/y, UNGG Fuel**

- **1976 – 1994 : UP2/HAO, 400 t/y LWR Fuel**
- **1990 - …, : UP3, 800 t/y, LWR Fuel**

- **1994 - …, : UP2/800, 800 t/y, LWR Fuel**

La Hague plants production (treated fuels)





(*) Excluding gas graphite fuel
(**) Annual consumption in France is close to 500TWhe
(***) Electricity generated with the treated spent fuel

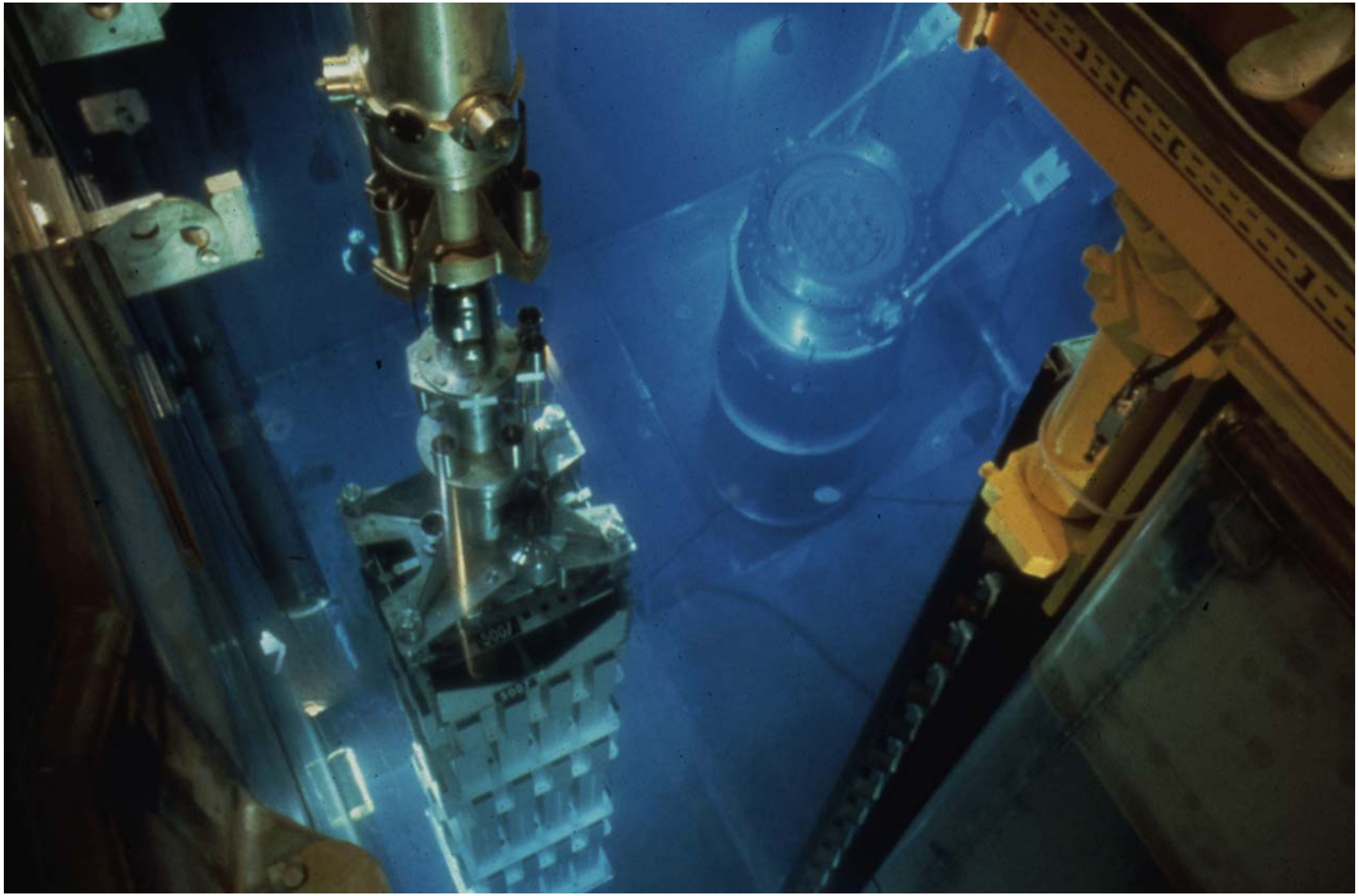
UP2/HAO Feedback

Many difficulties at the beginning of the operation

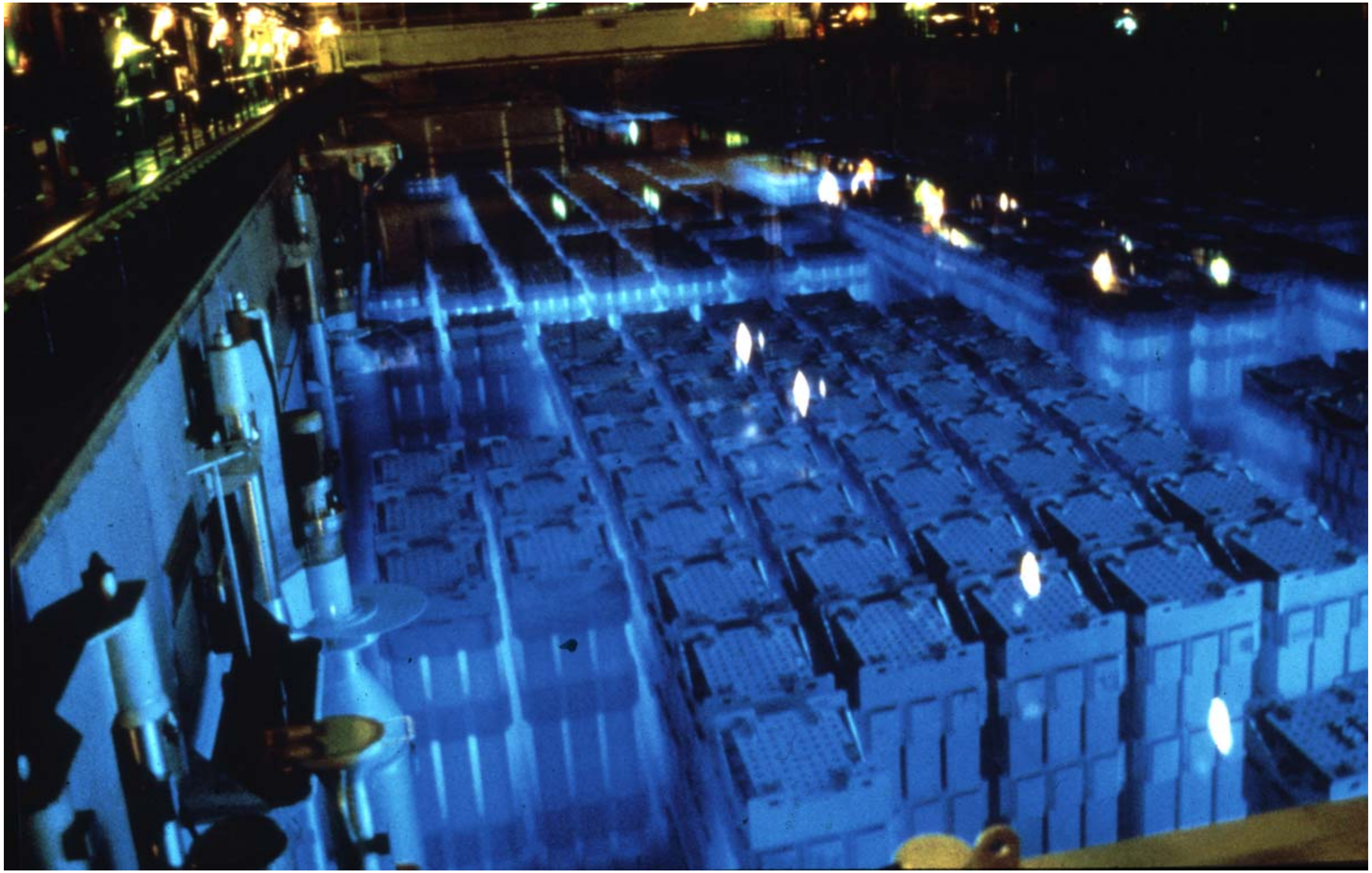
- **Bad estimation of hard-linked to the reprocessing of LWR fuel**
  - ***Technological gap from the UNGG to the LWR spent fuel***

- **French decision to launch a major R & D plan for the UP3 process**
  - ***From the head end process to the waste conditionning***
  - ***Clean Plant***
  - ***Continuous dissolution***
  - ***The increasing of the Burn Up of the LWR fuel***
  - ***The LWR MOX Spent Fuel Treatment***

Closing the Fuel cycle … an industrial reality



Closing the Fuel cycle … an industrial reality

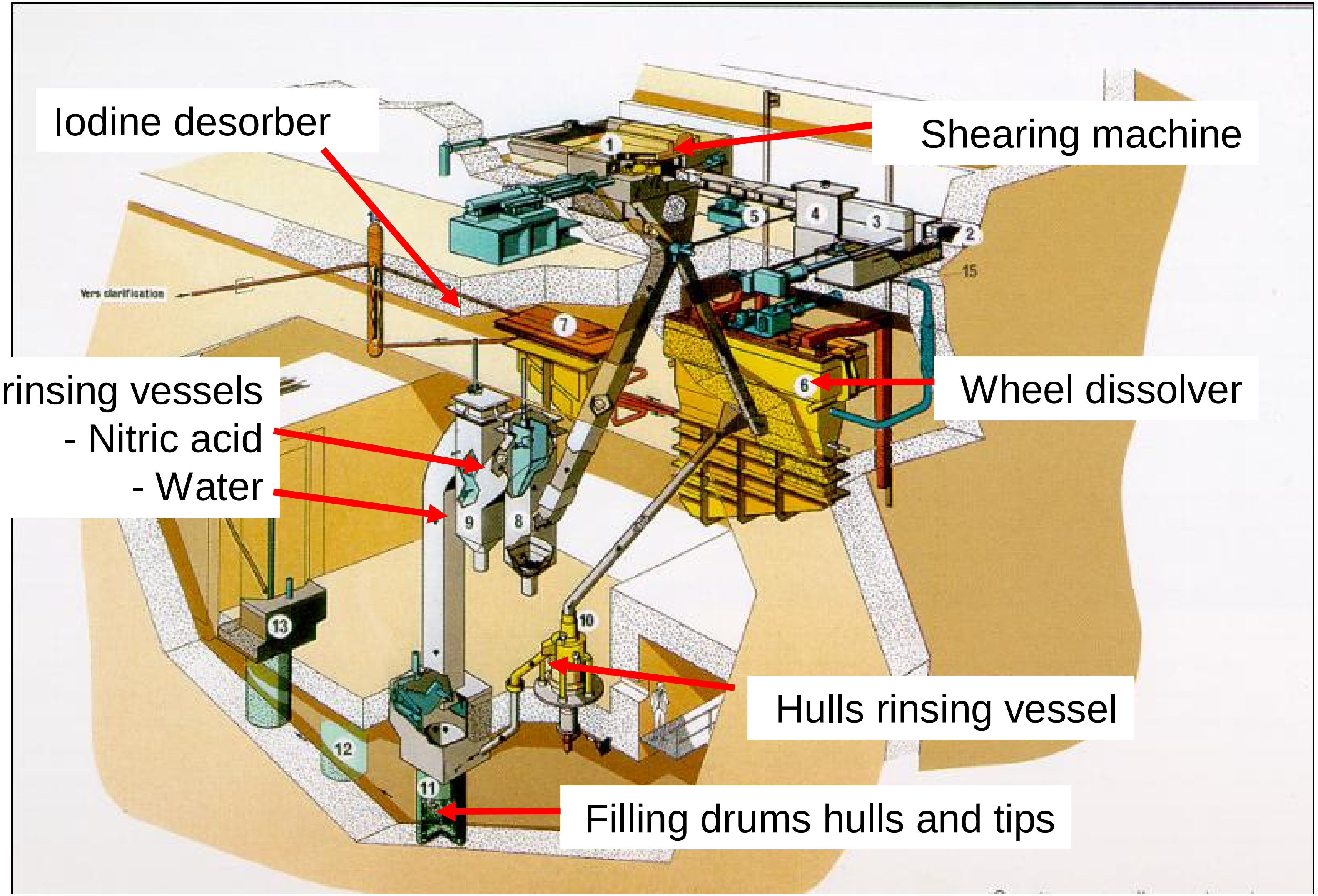


Exemple of La Hague cooling pool

- **Dimensions :**
  - L : 50 m
  - l : 16 m
  - P : 9 m
  (about 7200 m^3 water)

- **Storage capacity :**
  - 730 baskets, each bearing :
    . 9 PWR assemblies
    . or 16 BWR assemblies
  (~ 4000 t, ~ 200 reactor.years)

UP3 Dissolution Line Mock-Up



Iodine desorber

Shearing machine

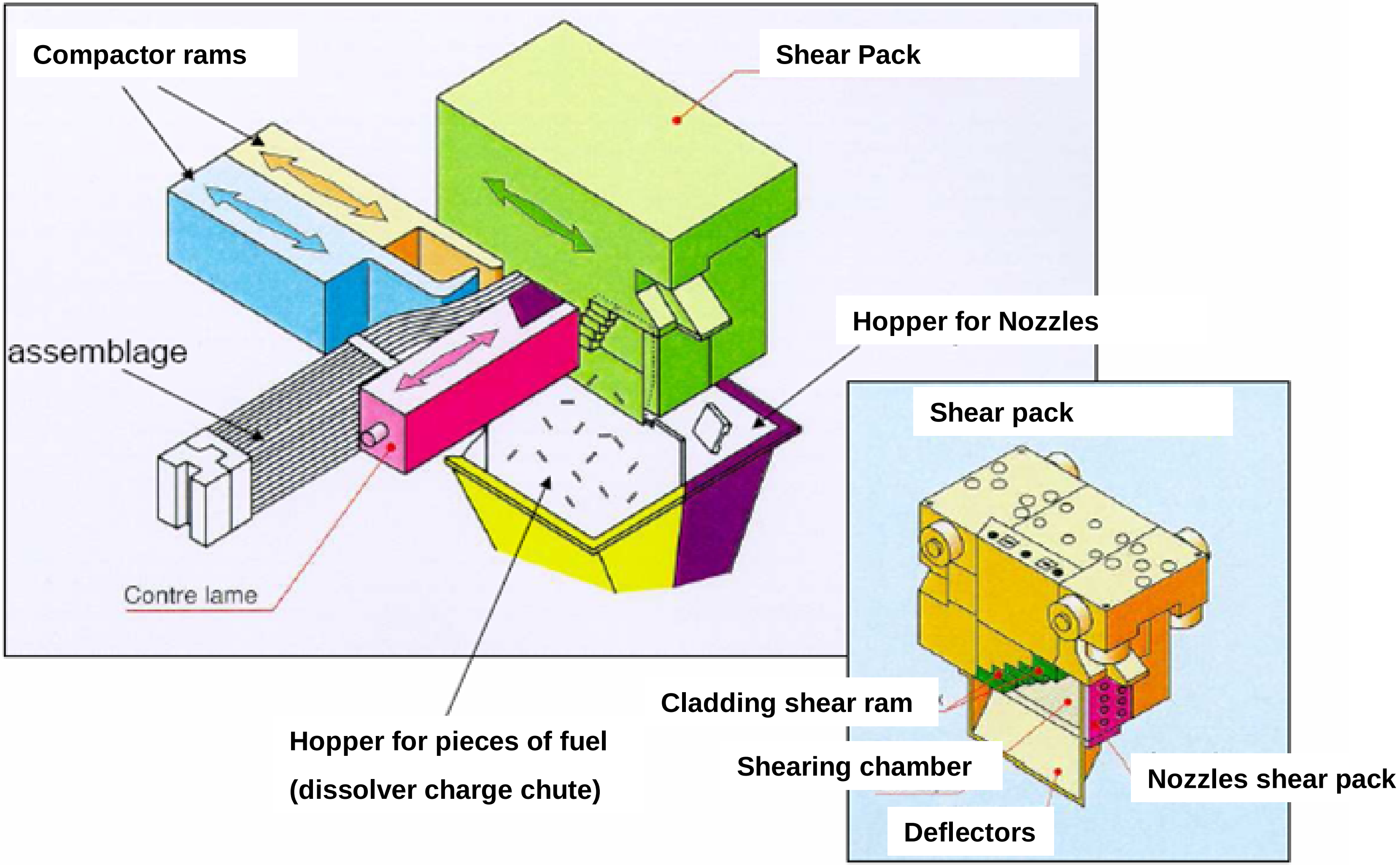
Nozzles rinsing vessels
- Nitric acid
- Water

Wheel dissolver

Hulls rinsing vessel

Filling drums hulls and tips

Operating mock-up of UP3 shearing tools



Compactor rams

Shear Pack

Hopper for Nozzles

Shear pack

Cladding shear ram

Shearing chamber

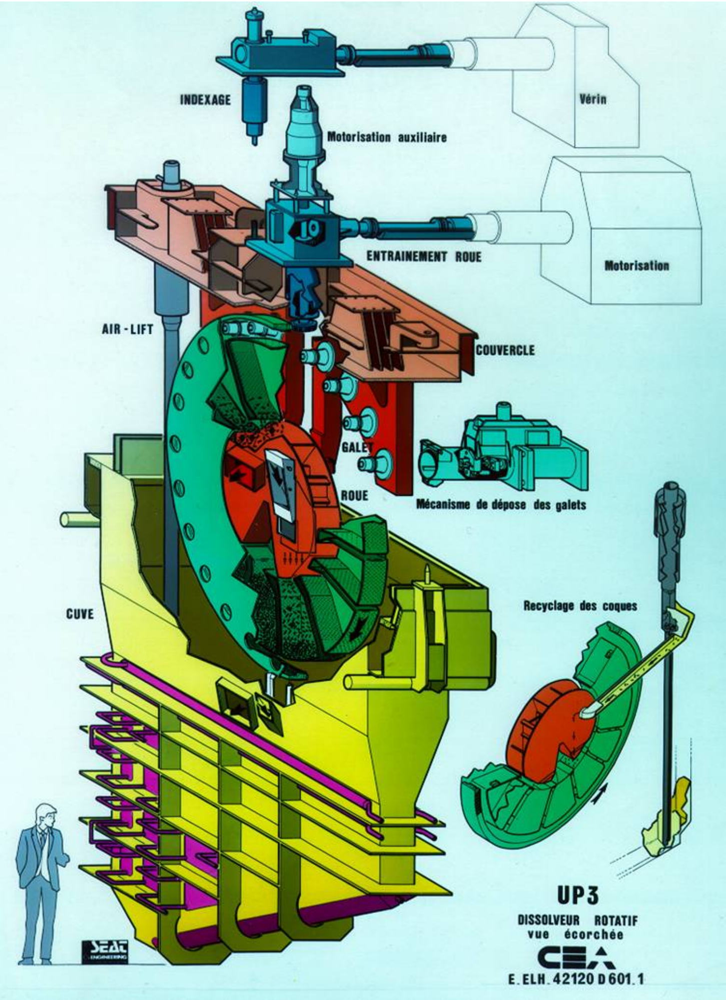
Nozzles shear pack

Deflectors

Hopper for pieces of fuel
(dissolver charge chute)

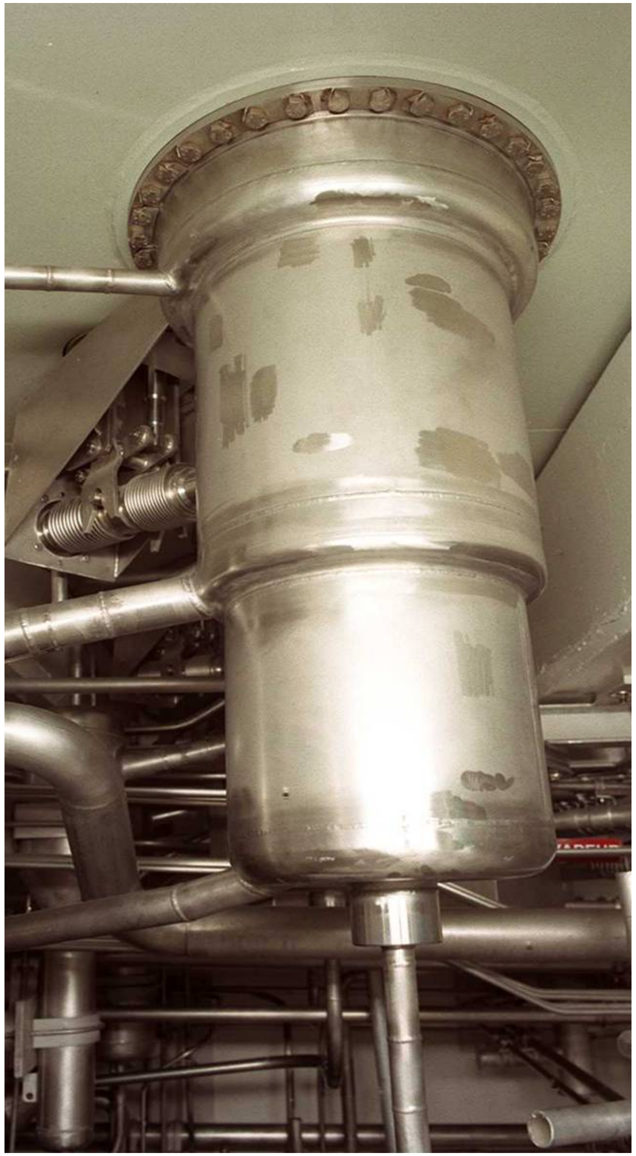
Continuous Wheel Dissolver

UP3 Dissolver vessels

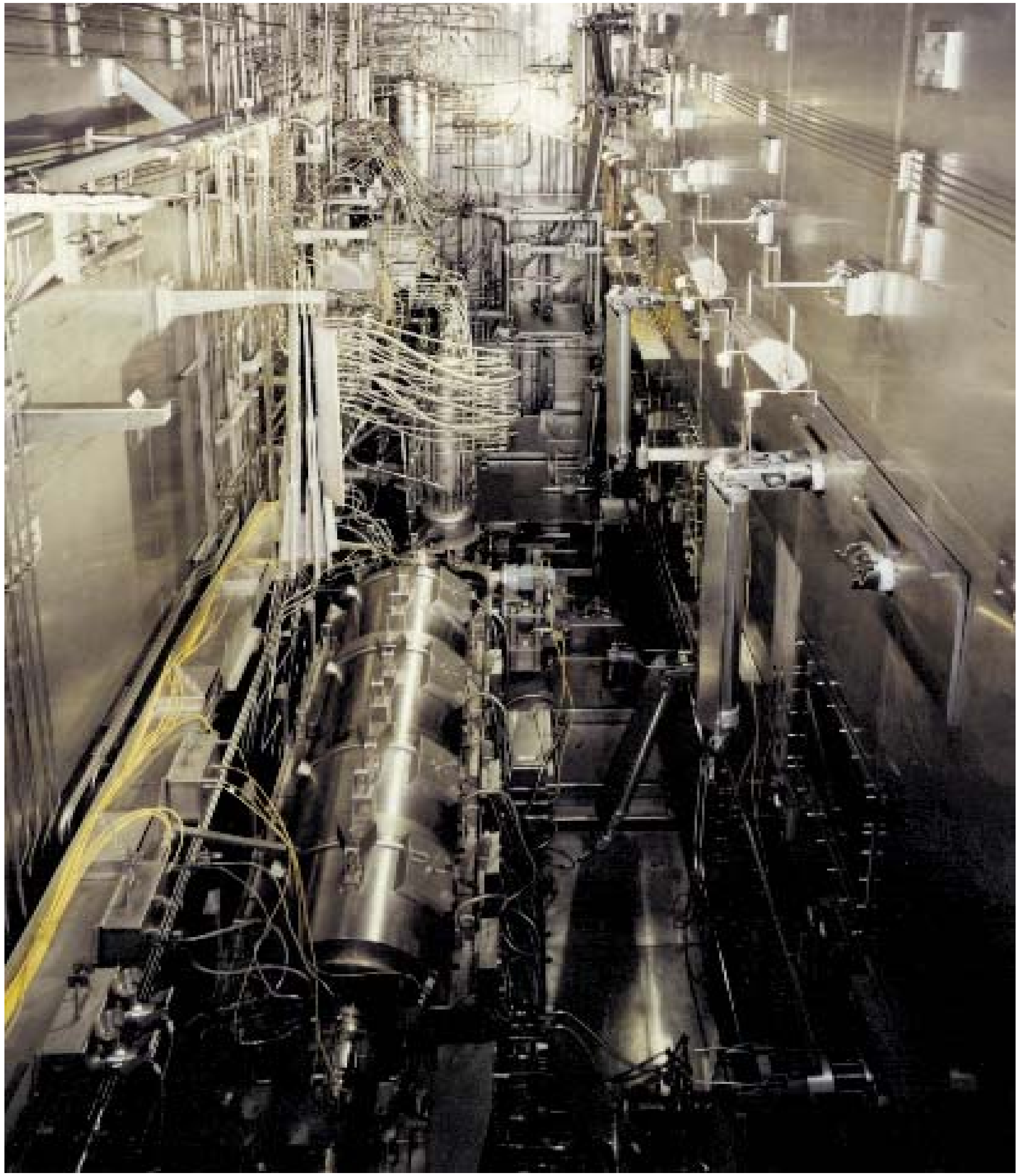


UP3 and UP2-800/R4 : Pulsed columns

UP2-800/R4 : Centrifugal contactors



La Hague Vitrification line



Feedback of UP3 and UP2-800 operation

At the Beginning : UOX from 10 to 30 GWd/tHM

Today : UOX 45 GWd/tHM

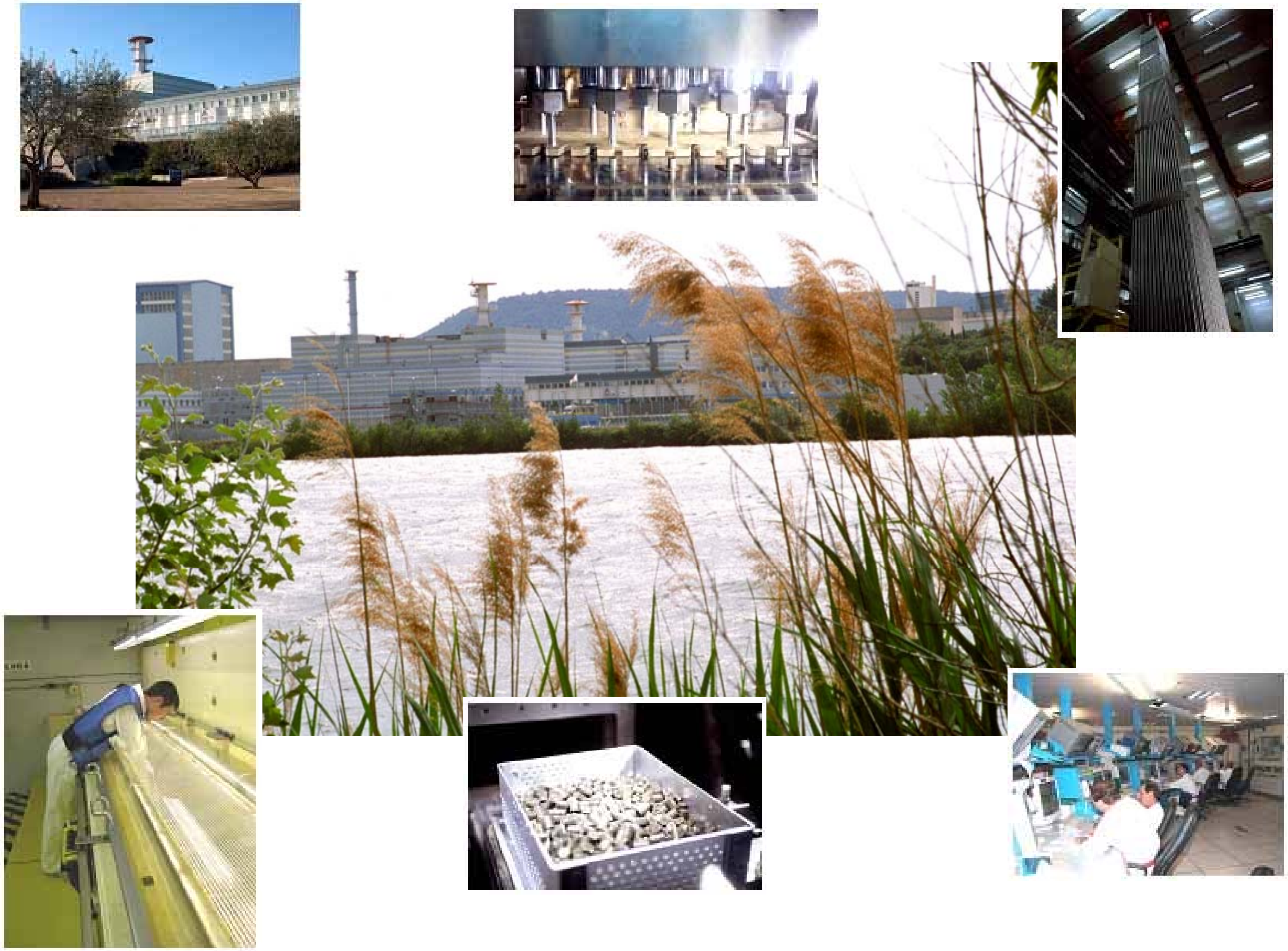
Tomorrow : 60 GWd/tHM

***And also :* 72,6 t of LWR MOX irradiated from 30 to 53 MWd/HM in industrial conditions (Demonstration Campaigns)**

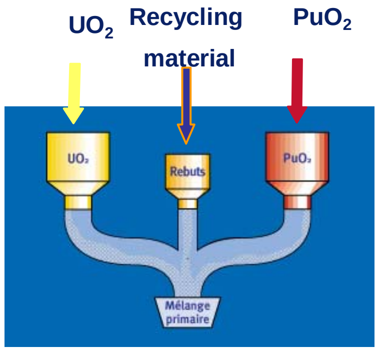
Feedback after 20 years of UP3 and UP2-800 operation (more than 22 000 tons of LWR fuels reprocessed)

- **Robust PUREX Process, large capacity, safety, …**
- **Flexible Plants**

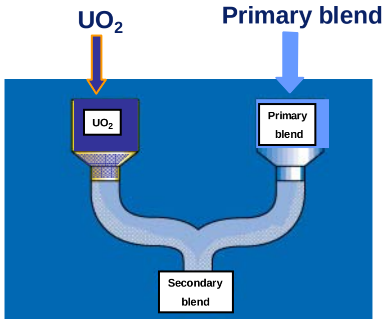
Pu Recycling with MOX fuels : the MELOX plant



Key advantages of the advanced MELOX high-throughput process



1 *Preparation of primary blend*

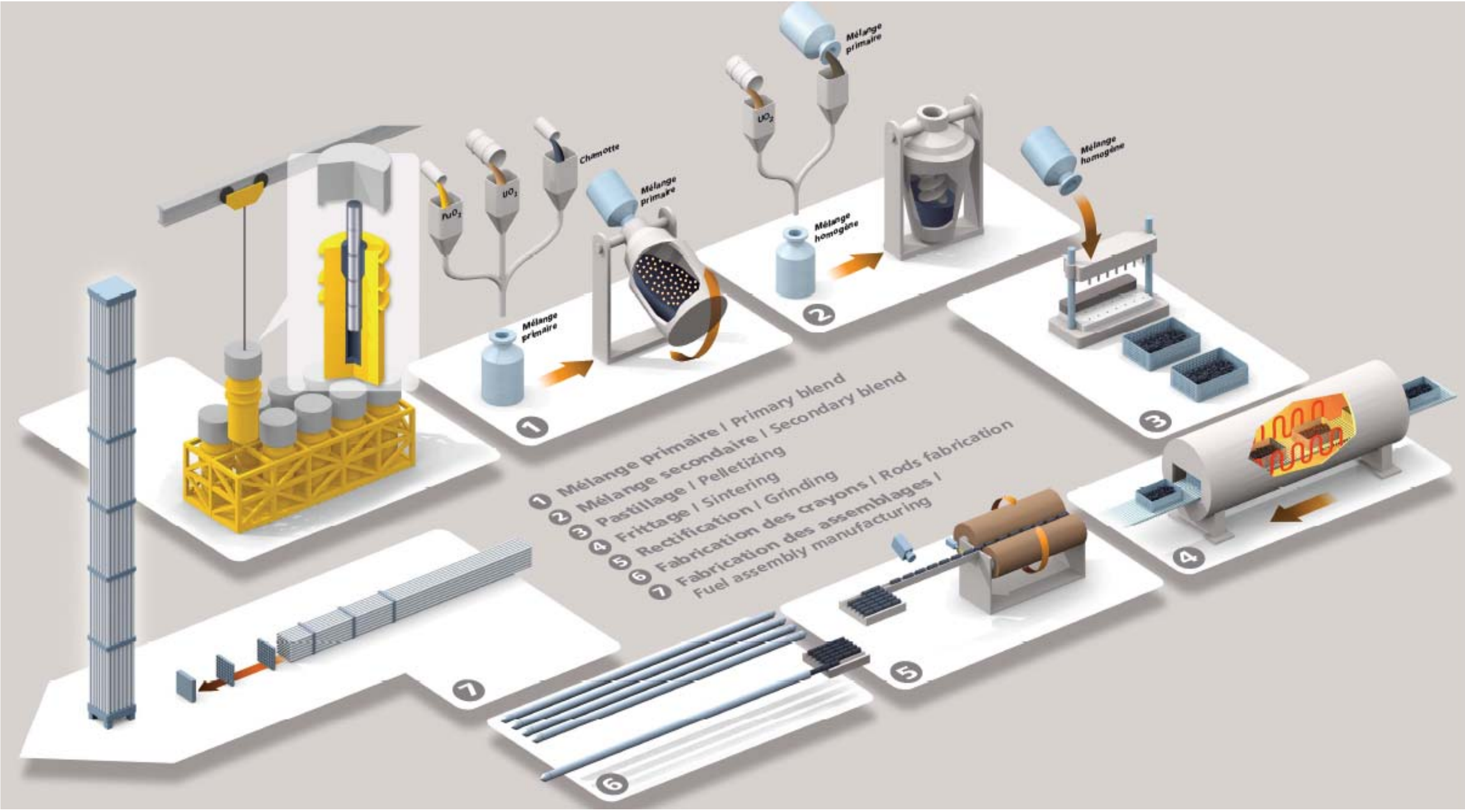


2 *Preparation of secondary blend*

- **Powder blending is the key to the MELOX process.**
- **The MELOX process allows an on-line recycling of almost all scrap.**
- **More than 35 years of PWR and BWR operating experience have demonstrated the high quality of MOX fuel fabricated by the AREVA group.**
- **MOX fuel behavior in the reactor is similar to UO_2 fuel in normal and off-normal conditions.**

The performance and reliability of the MELOX process are recognized worldwide

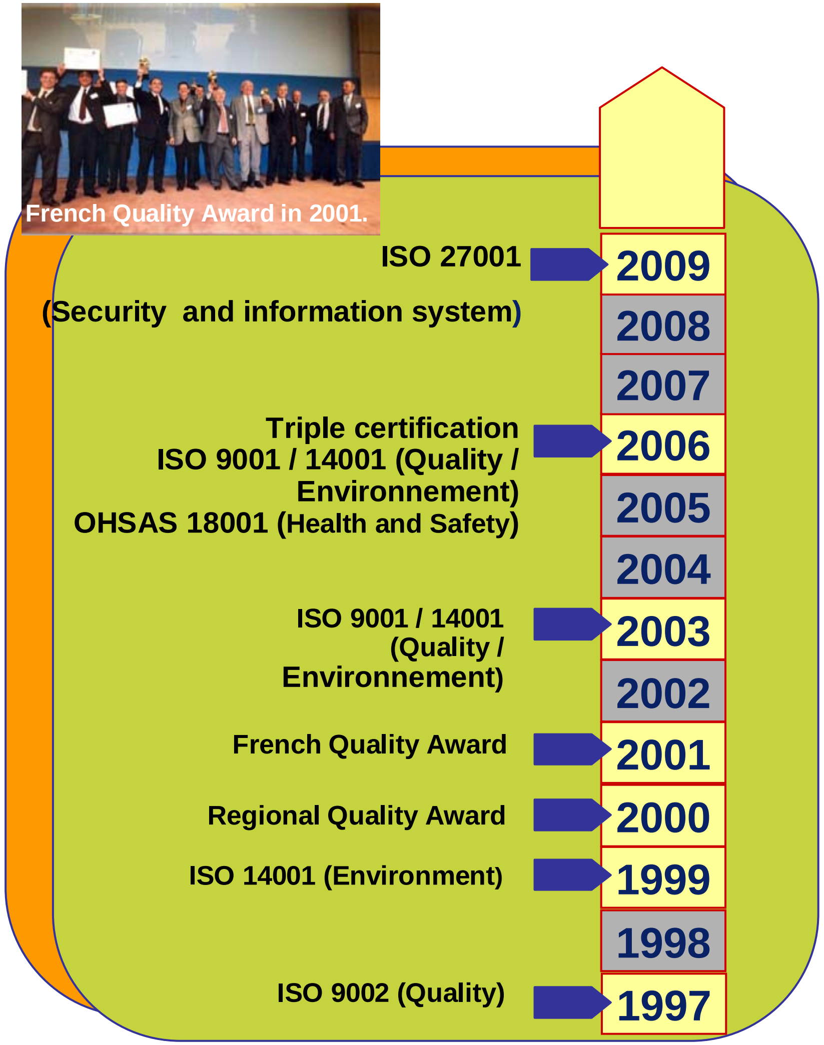
MELOX Fuel fabrication process



One MOX fuel assembly contains enough energy to supply a city of 100,000 with electricity for an entire year

Total Quality Management at MELOX

- **Continuous improvement to achieve customer satisfaction**
- **Constant attention to successful environmental integration**



French Quality Award in 2001.

ISO 27001 (Security and information system) → 2009

2008

2007

Triple certification
ISO 9001 / 14001 (Quality / Environnement)
OHSAS 18001 (Health and Safety) → 2006

2005

2004

ISO 9001 / 14001 (Quality / Environnement) → 2003

2002

French Quality Award → 2001

Regional Quality Award → 2000

ISO 14001 (Environment) → 1999

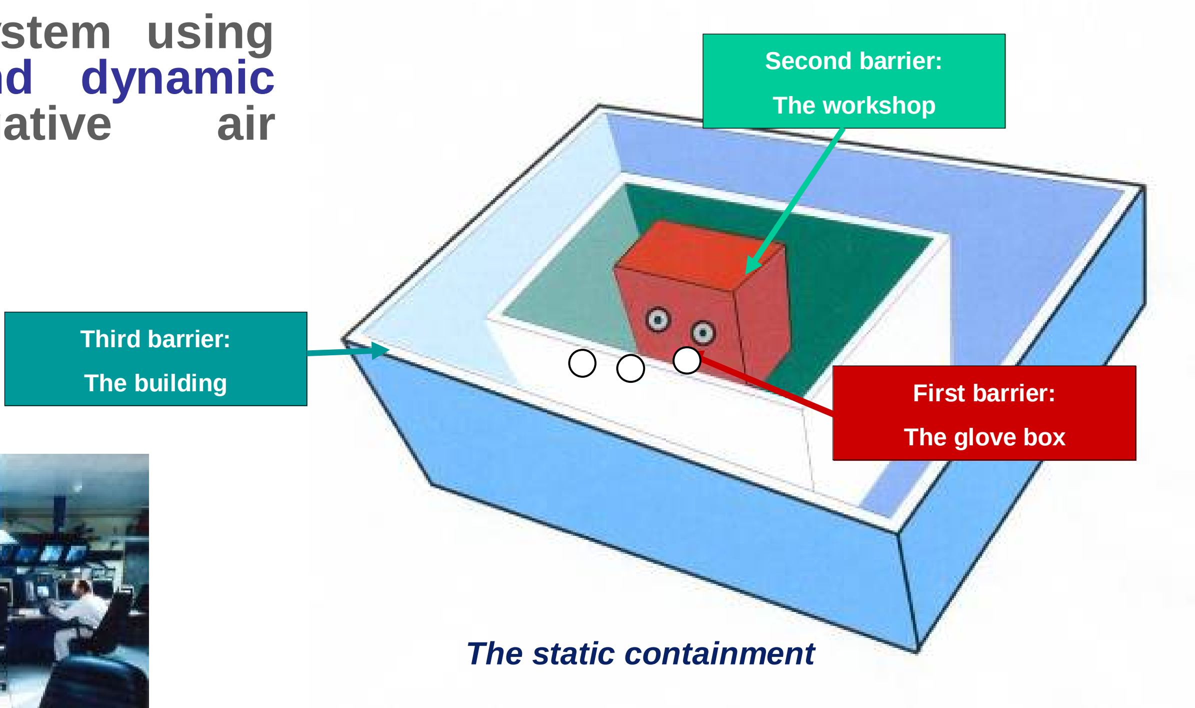
1998

ISO 9002 (Quality) → 1997

MELOX Plant safety

Prevention and control of nuclear materials dispersion and external exposure are based on:

- A confinement system using **three barriers and dynamic containment** (negative air pressure)



Second barrier:
The workshop

Third barrier:
The building

First barrier:
The glove box

The static containment

- **High level of plant automation**

MELOX Plant design

- **Major risk prevention has been integrated into facility design**
  - **Fire**
  - **Criticality**
  - **Seismic measurements**
  - **Thermal risks**

Seismic support

Thermocouple

Fire door

Neutron radiation detector

CO_2 fire extinguisher

MELOX: a continuous and effective system of safeguards

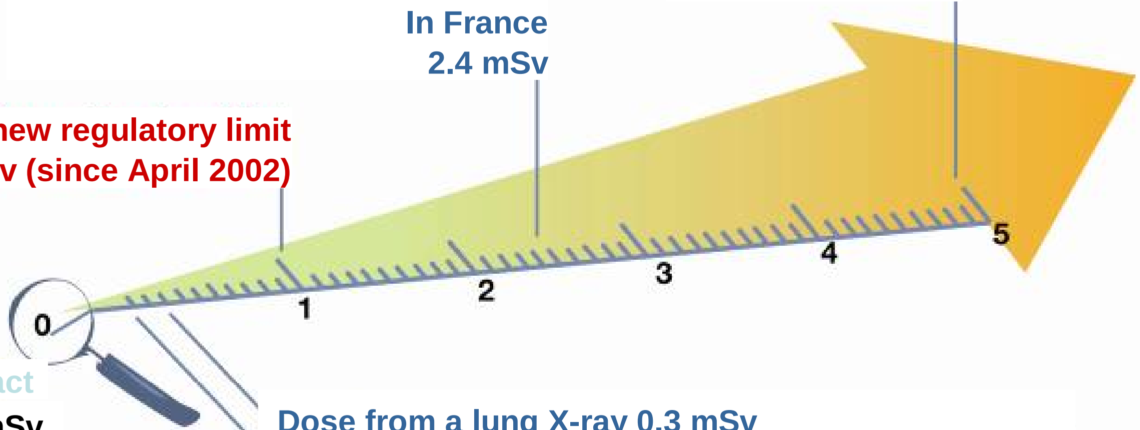
- **National and international organizations (Euratom, IAEA) monitor nuclear materials at AREVA MOX fabrication plants.**
- **Euratom worked with the French regulatory authorities and the plant operator during the MELOX design phase to develop the system of safeguards with the objective of "Continuous Inventory Verification"**

- **This system is specific to the plant characteristics:**
  - **Control of inputs/outputs**
  - **Independent, automatic measurements**
  - **Control of the annual inventory of nuclear materials**
  - **Sample analysis**

- **This system complies with IAEA requirements**

Radiological impact of the MELOX plant

- In year 2008, the **impact** of liquids and gaseous radioactive effluents of **MELOX plant** is about **0.000014 mSv**



Old regulatory limit 5 mSv

Background radiation In France 2.4 mSv

Dose to the public new regulatory limit 1 mSv (since April 2002)

MELOX impact 0.000014 mSv

Dose from a lung X-ray 0.3 mSv

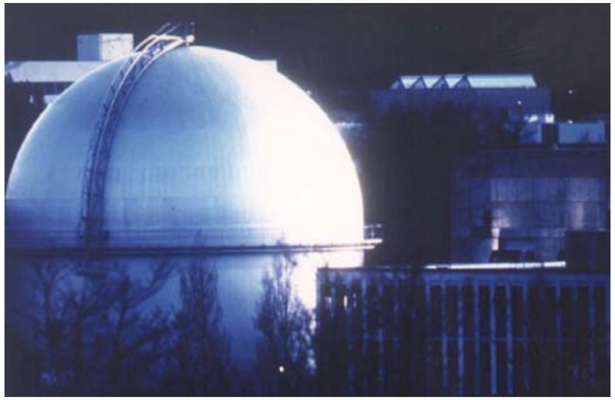
Dose from a Paris / New York flight 0.02 mSv

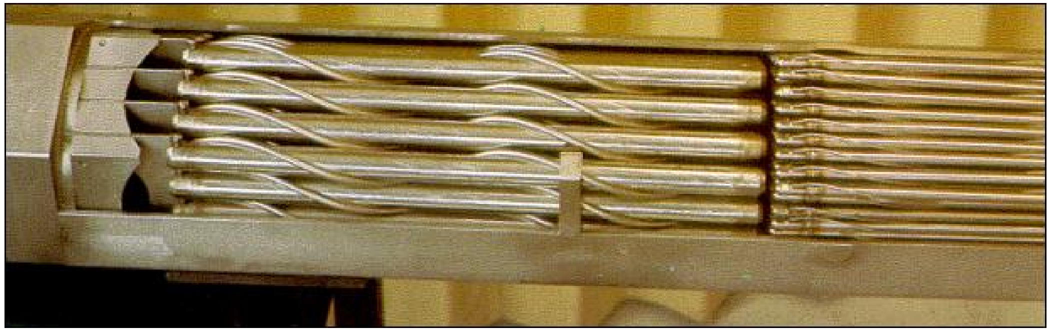
Maximum effluents impact allowed by the decree:

0.0017 mSv per year

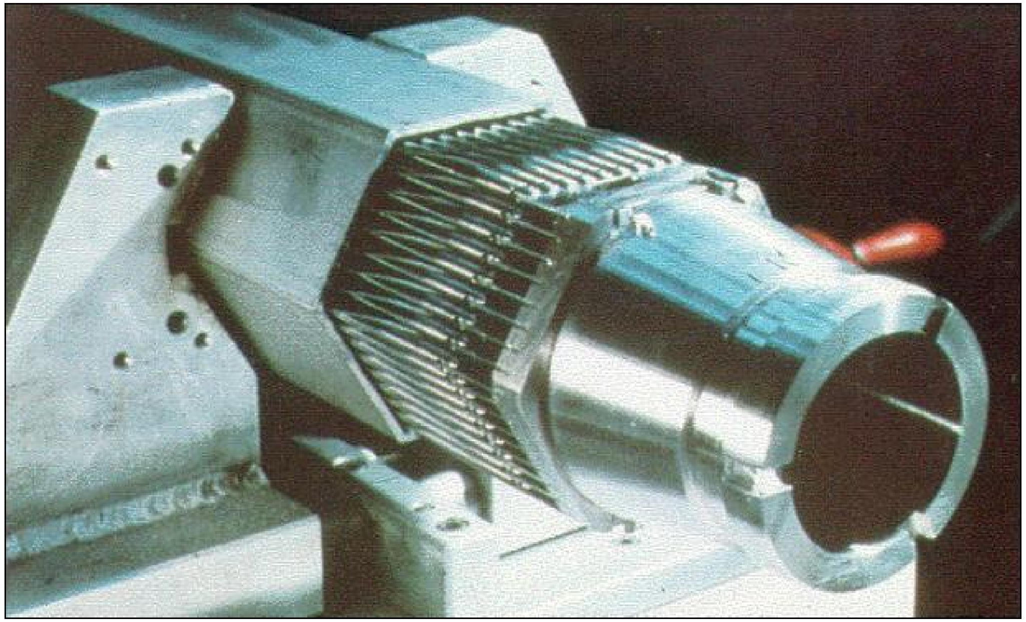
Reprocessing of SFR MOX FUEL : French experience

RAPSODIE Reactor
40 MWTh
1967-1983

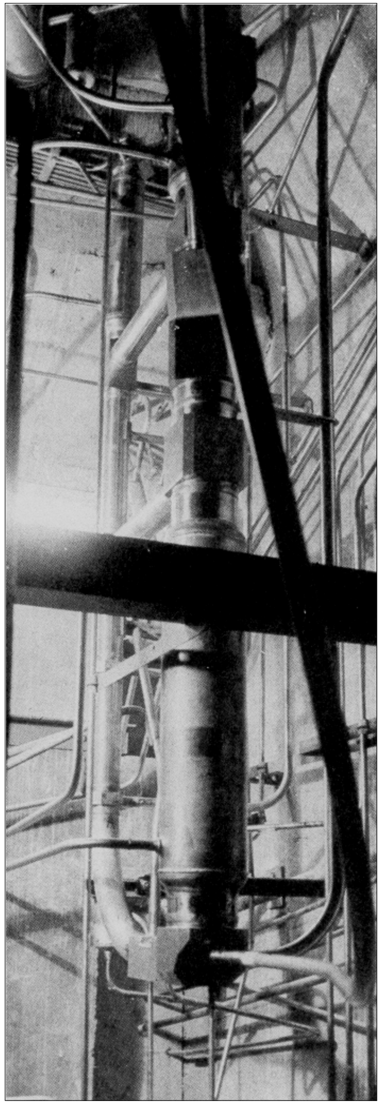




PHENIX Reactor
600 MWth / 250 MWe
1973-2009



Reprocessing of SFR MOX FUEL : French experience



AT1 La Hague Facility (1969 – 1978)

First French facility for the reprocessing of SFR MOX FUEL (from Rapsodie and Phénix reactors) :

- **Capacity : 1 kg/d**
- **Burn Up : 40 to 120 GWd/t mixed oxide**
- **Cooling time : from 6 months to 2 years**
- **~1 t of MOX SFR spent fuel treated**

Reprocessing of SFR MOX FUEL : French experience

UP2-400 La Hague Facility (1978 – 1984)

Reprocessing of ~11 t of PHENIX Fuel
- Burn Up : 20 to 90 GWd/t mixed oxide
- Cooling time : from 16 months to 4 years

Batch dissolution and extraction of U and Pu by dilution in UNGG fuel dissolution

Reprocessing of SFR MOX fuel : French experience

Marcoule Pilot Facility

- TOP Facility (1973 – 1983)

RAPSODIE, KNK and PHENIX Spent fuel

- ~ 8 t of MOX SFR Spent fuel
- Burn Up : 35 to 105 GWd/t mixed oxide
- Cooling time : from 10 to 50 months

- TOR Facility (1988 – 1997)

KNK and PHENIX Spent fuel

- ~ 7 t of MOX SFR Spent fuel
- Burn Up : 60 to 103 GWd/t mixed oxide
- Cooling time : from 3 to 10 years

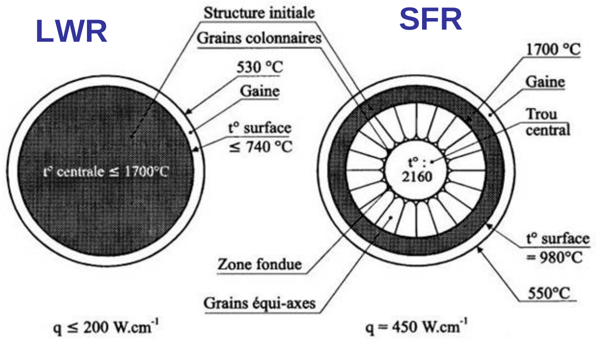
What characterize the SFR MOX Fuel at the reprocessing

Fuel	Characteristics	LWR		MOX RNR
		UOX	MOX	
Composition before. irr.		UO2 enrichi	(U,Pu)O2	(U,Pu)O2
		^{235}U: 3 - 4,5%	Pu: 3 - 8,5%	Pu: 13 - 20%
Metallic Materials	Assembly	270 pins		200-300 pins
	Cladding	Zircaloy	Zircaloy	Stainless steel
	Others materials	Nozzles, grids, …		SNP, nozzles, wrapper, spacewire, …
	Ø pins (mm)	11 à 12	11 à 12	6 à 8
Irradiation	BU (MWd/t)	33000/60000	33000/45000	80000/120000
	Average temperature (°C)	850-1300°C)	850-1300°C	1700
Thermal power (KW)	Cooling 1 year	10	25	40
Composition after irr.	Plutonium	1	1 - 5	8 - 15
	Minors Act.	0,03 - 0,1	0,55	0,5
	FP	3,5	5	8 - 12
	Nobles metals	0,4	0,9	2 - 3

Solubility
Criticality

Corrosion Fe, Cr, ...

Technology



Pu-PF compounds

Glasses Incorporation

The french Act of June 2006, up to 2015 and 2020

⇨ **Key-points for waste management, and future R and D** :

- A national plan on radioactive materials and radioactive waste management (up-grading by Parliament every three years)
- A program on R & D with a time schedule to implement this plan
- A secured financing of radioactive waste management and R & D (dedicated fund)
- A step by step program of HLLL waste management, including the 3 complementary solutions :

  - Geological disposal for the final HL waste (dossier and Parliament decision in 2015, operation in 2025) ; existing wastes will be disposed
  - Intermediate storage for industrial flexibility

  - MA Recycling :

    - R & D in the framework of Gen IV Systems; international framework
    - interest (as consequences on the geological repository) to be proved with a cost/benefit detailed analysis by 2012
    - 2012 decision : demo by 2020 ; industrialization by 2040…