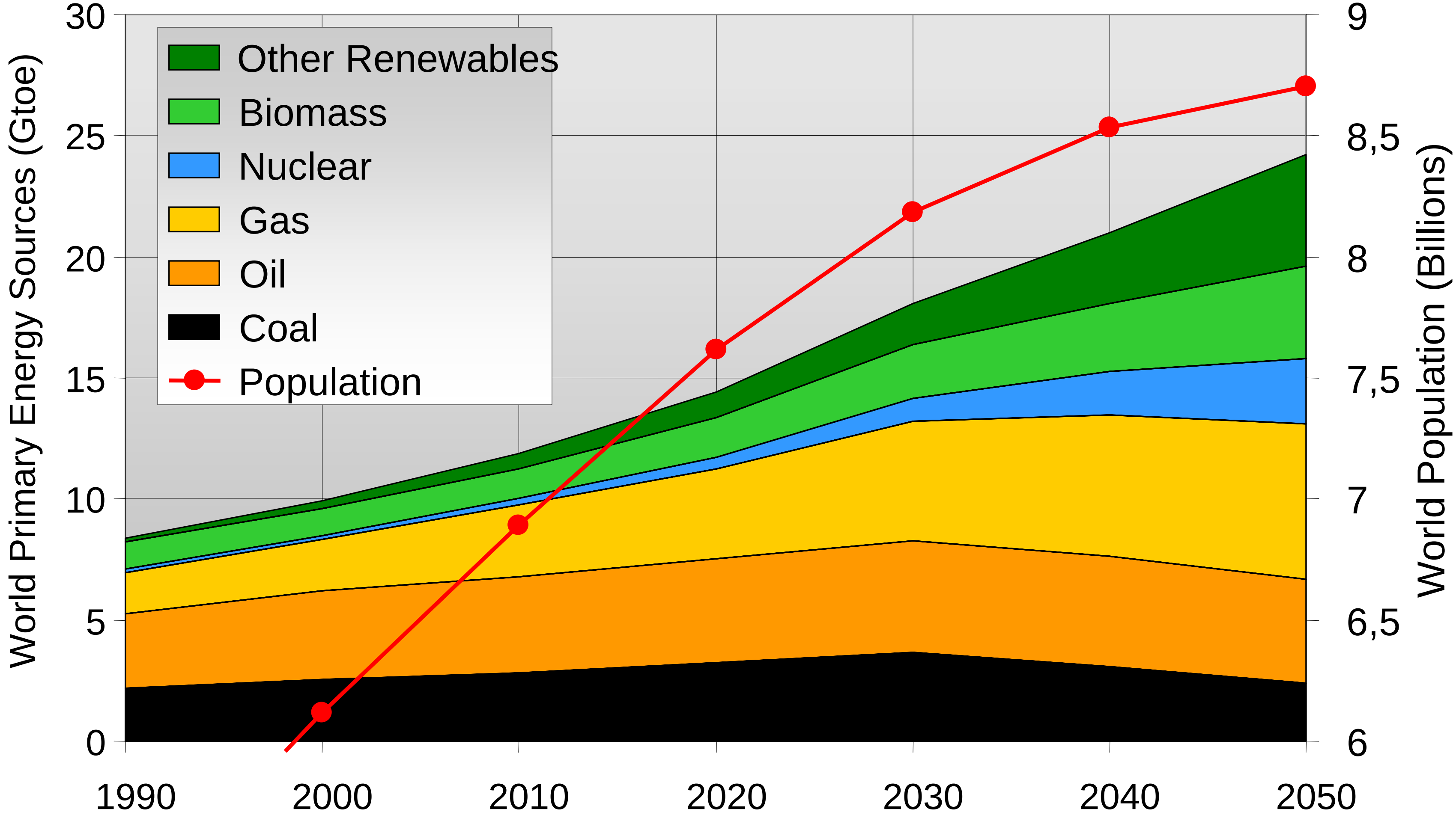
Efforts for Next Generations Reactor Systems Development in the World

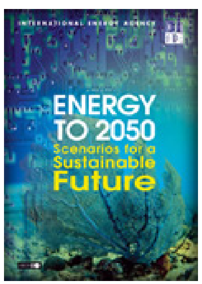
1 – Renewed interest in sustainable nuclear energy systems
2 – Generation IV International Forum and IAEA INPRO Initiatives
3 – R&D on Fast neutron Reactors & closed fuel cycles
4 – R&D on High Temperature Reactors & non-electricity applications
5 – Scientific challenges and perspectives for industrial deployment

Frank Carré
franck.carre@cea.fr

CEA – Nuclear Energy Division

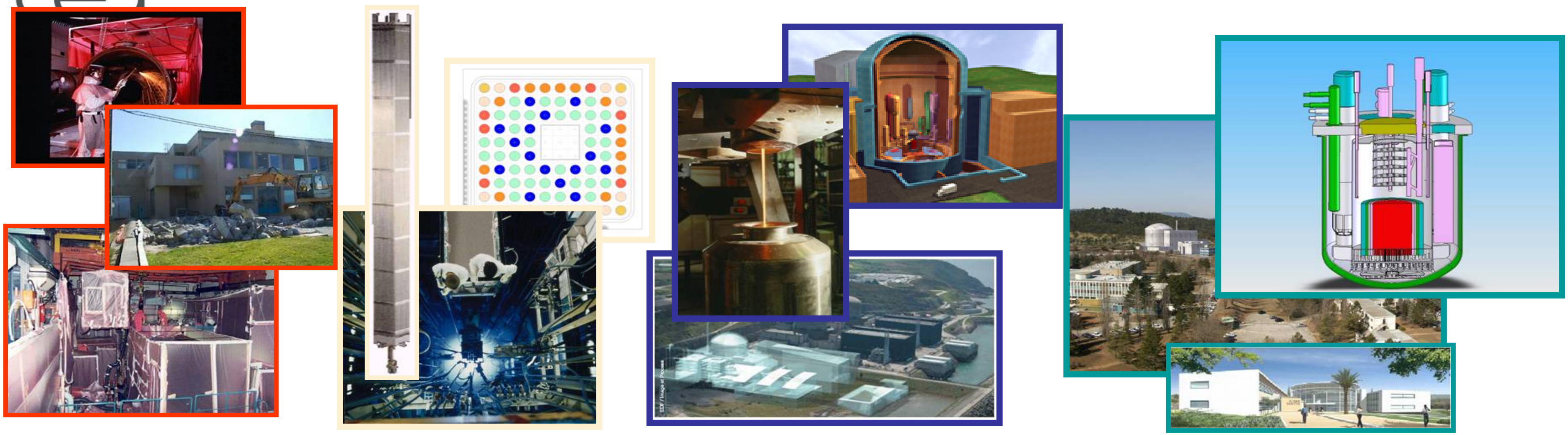
Sustainable energy development scenario (IAE - 2003)

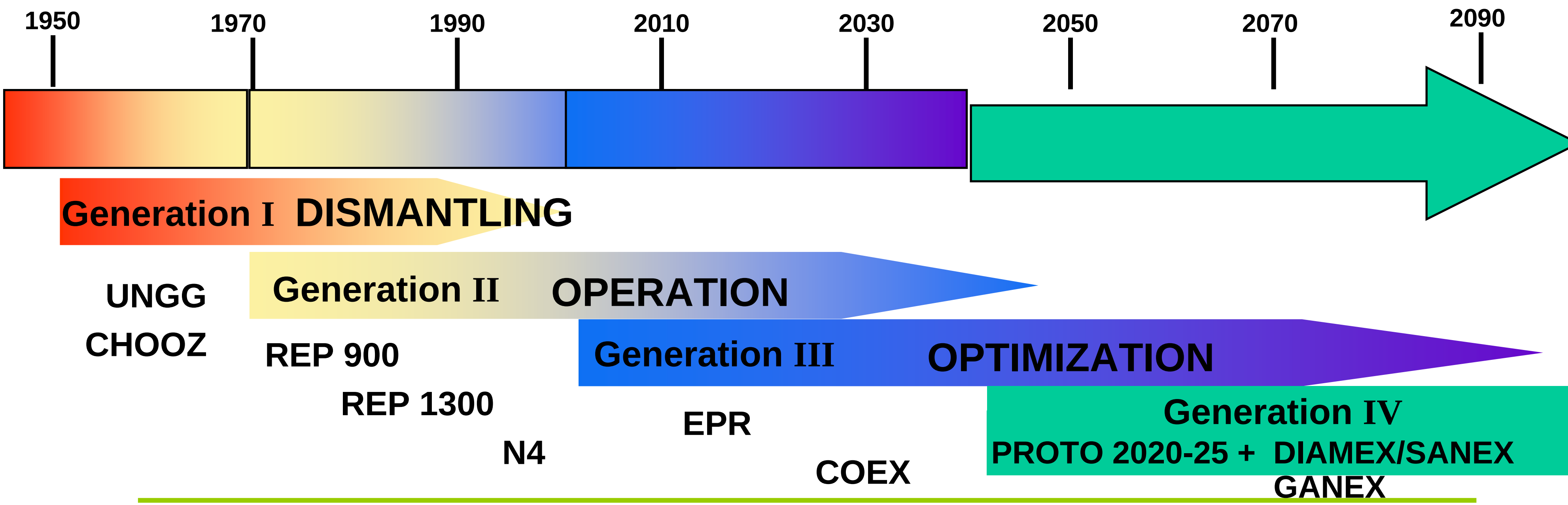




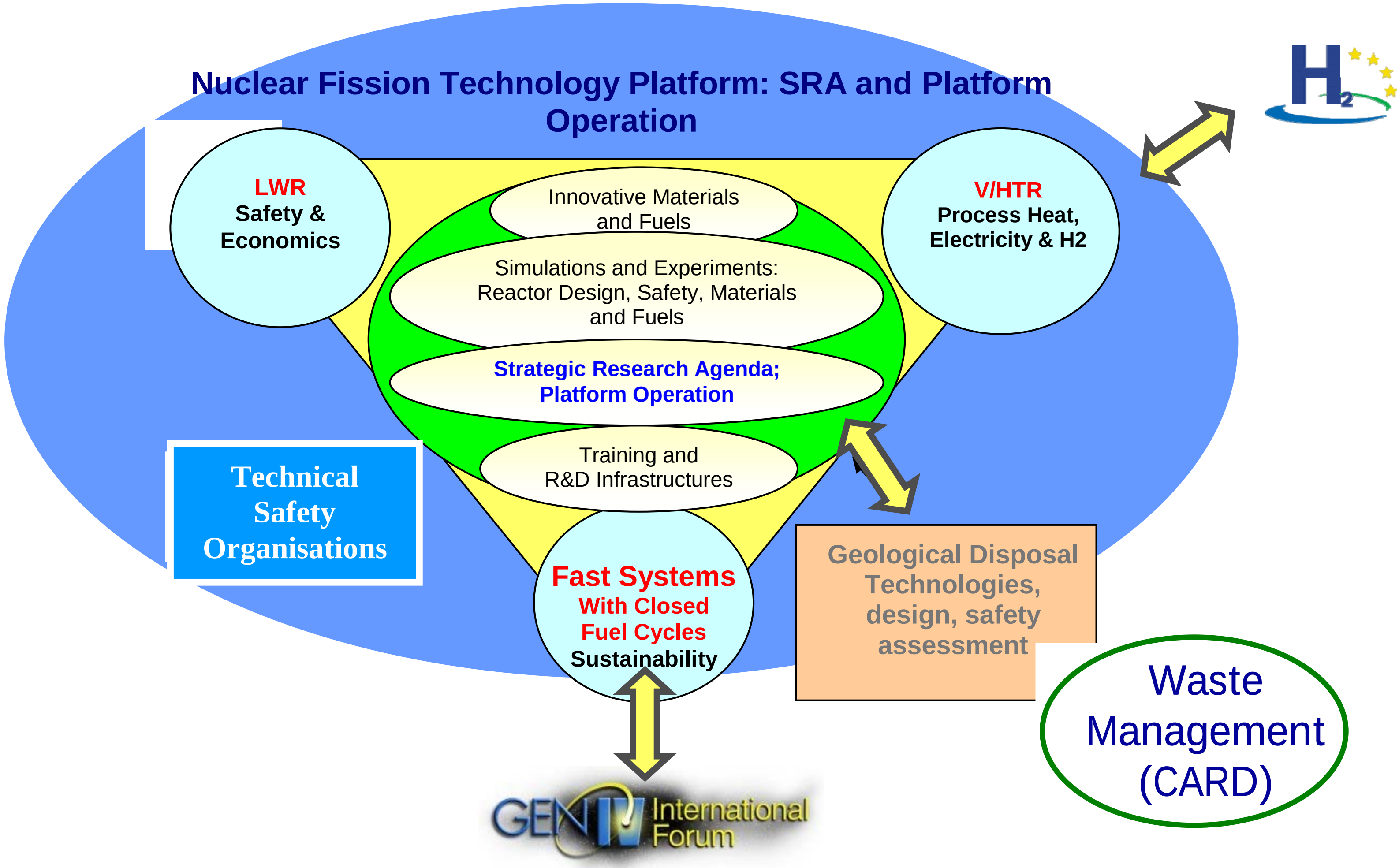
Source IEA : Energy to 2050 -
Scenarios for a Sustainable Future

Generations of Nuclear Power Systems





SNF-TP objectives & organization



Kick-off meeting : September 20, 2007

Sustainability

- **Resource utilization** ***(t Unat/GWy)***
- **Ultimate waste form**
  - ✓ ***Direct disposal of Spent Nuclear Fuel***
  - ✓ ***Vitrified waste package***
    - ***- Fission products + Minor actinides***
    - ***- Fission products only ?***
- **Economic competitiveness**
  - ✓ ***Generating cost (€/MWh)***
    - ***- Investment, Operating costs, Fuel cycle costs***
- **Safety + Security**
  - ✓ ***Safety***
  - ✓ ***Physical protection***
  - ✓ ***Proliferation resistance***
- **Integration in the socio-economic context**
  - ✓ ***Acceptation***
  - ✓ ***Social and economic impact***
  - ✓ ***...***

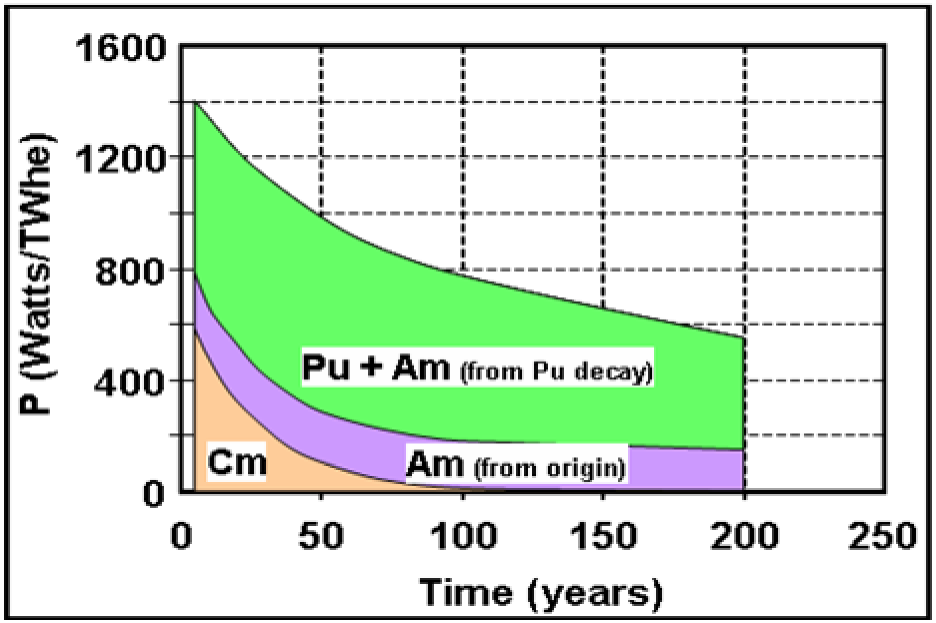
Radiotoxicity and decay heat of TRU in spent fuel

- 1st contributor : Pu
- 2nd contributor : Minor Actinides (MA): *Am, Cm ?, Np ??*

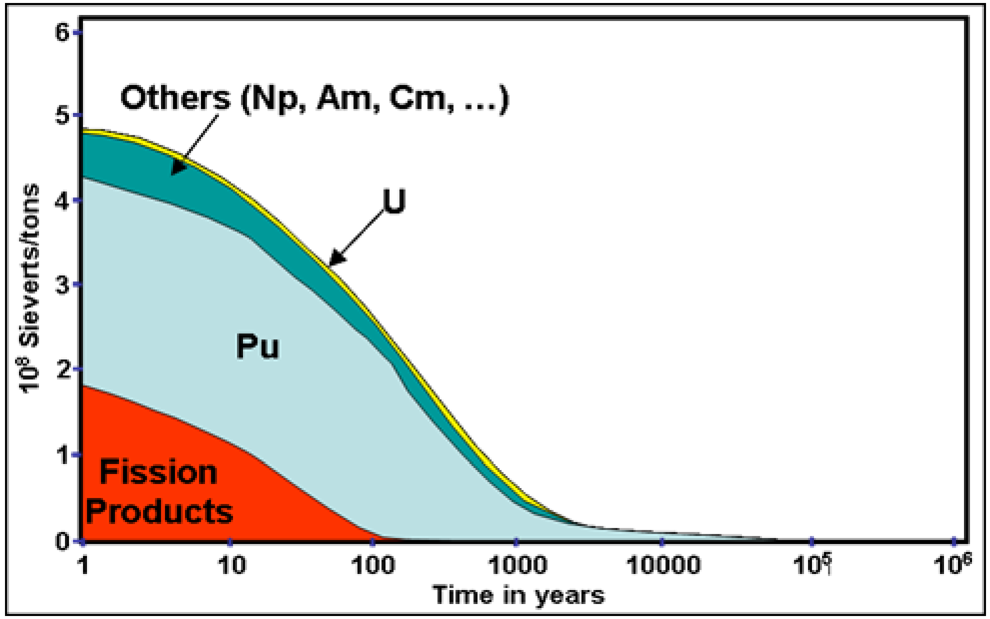
→ **Guidelines to optimize the management of nuclear spent fuel and waste: design of repository and environmental impact**

- *LL Fission Products: P/T feasible but not very efficient for ^{99}Tc and non practically feasible for ^{135}Cs & ^{129}I*

Heat load of the TRU



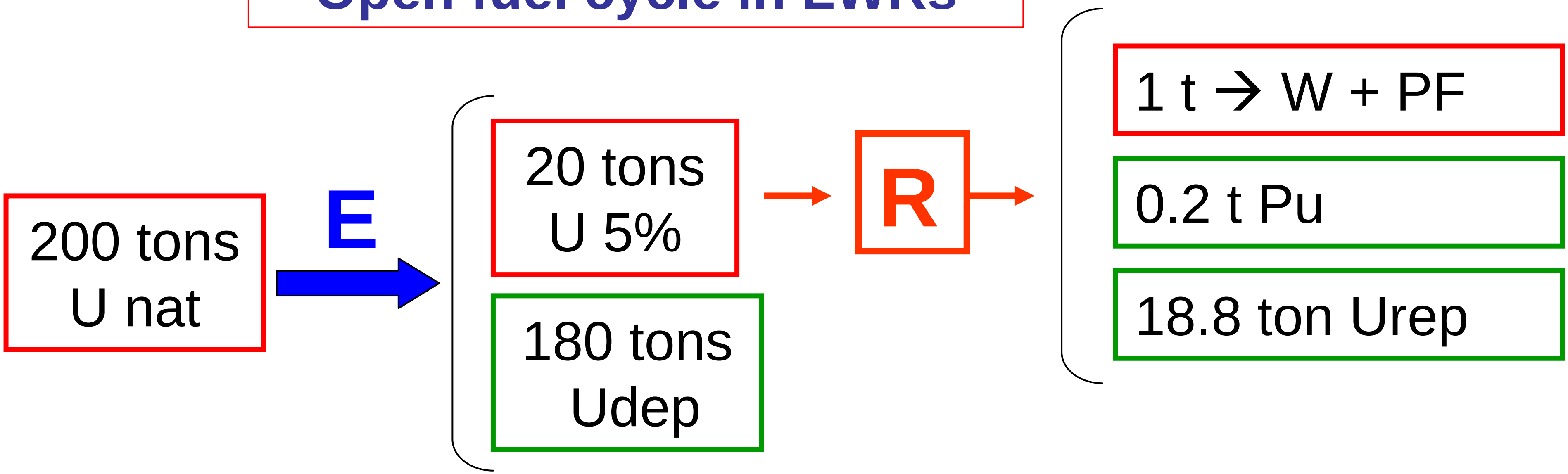
Potential radiotoxicity



(^{241}Pu ---> ^{241}Am ---> ^{237}Np)

Utilization of uranium ore for 1 GWe x year

Open fuel cycle in LWRs



Fast neutron reactors burn plutonium while converting U 238 (U dep & U rep) into plutonium that is burnt in situ ***(~1 t U/GWey)***
(Regeneration → Breeding of fissile fuel)

→ Existing Plutonium & Depleted Uranium in nuclear countries is worth ~5000 years of current nuclear production.

The Red Book 2005: Resources, Production and Supply

21st Edition by OECD/NEA (June 1, 2006)

MtU	<130$/kg	Phosphates
RAR	3.3	
EAR-I	1.4	
Total	4.7	
EAR-II	14.8	22
SR		
Total	19.5	22

Uranium demand for the expected growth of nuclear power:

370 GWe LWR → 1000-1300 GWe LWR by 2050 with 60y lifetime

→ Need for 1,2 + 11/14.5 Mt Unat

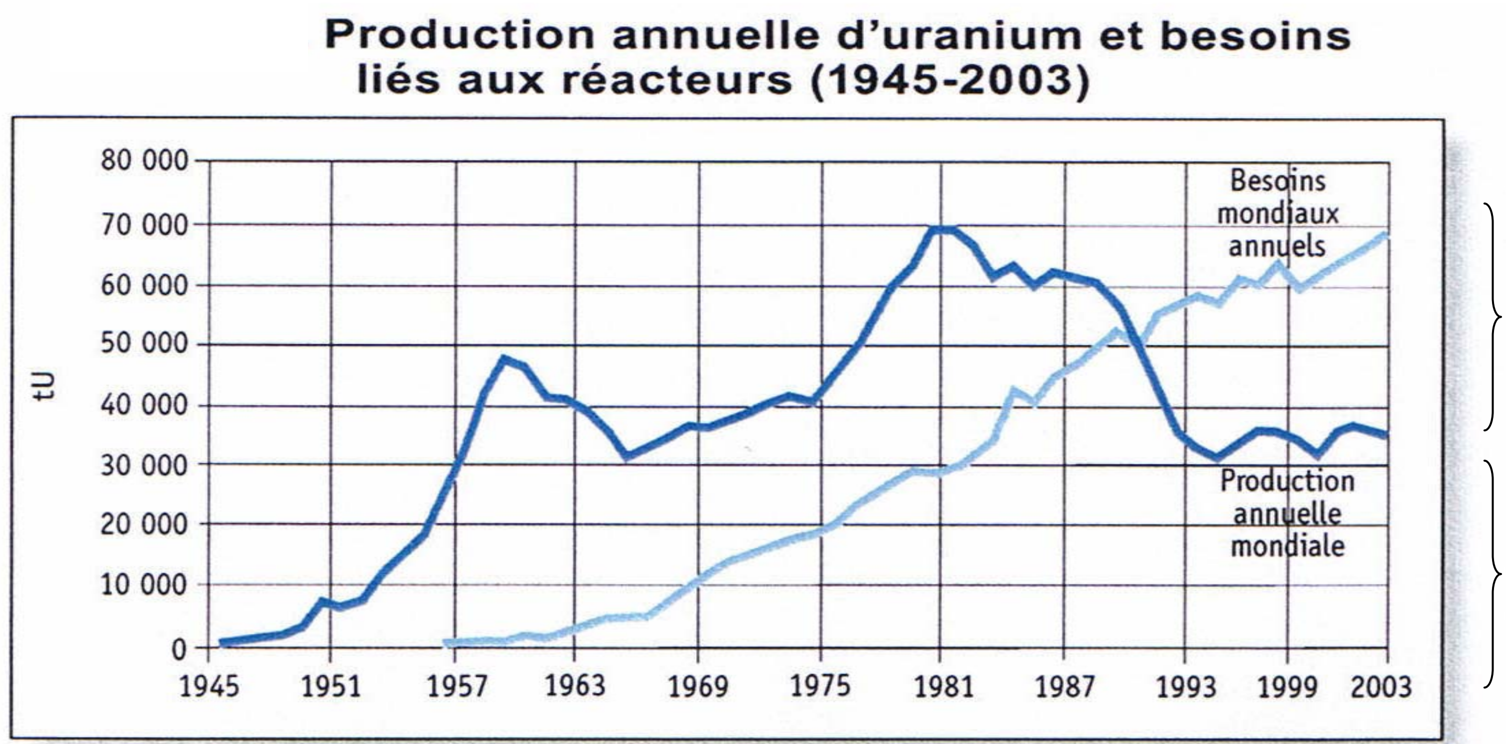
→ Incentive to switch around 2050 to Fast neutron Systems that make a much more efficient use of Uranium than LWRs

Uranium Demand & Supply

Demand > Supply

→ *Additional resources* *(WPu, U_{rep}, MOX)* ***used so far***

Annual demand and supply of Uranium (1945 → 2003)

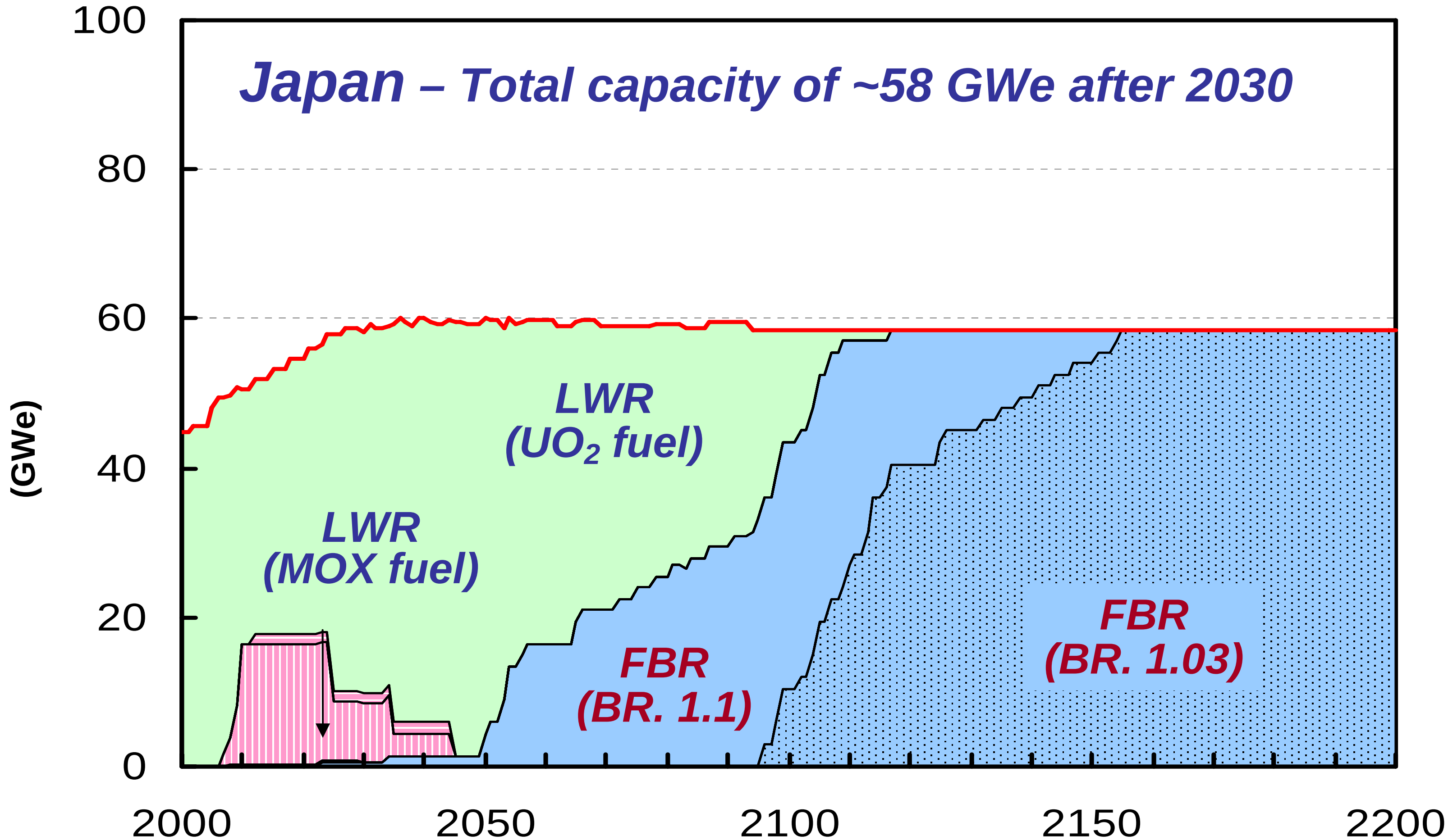


If nuclear energy grows significantly, uranium resources could be engaged by 2050

NEA Source 2006

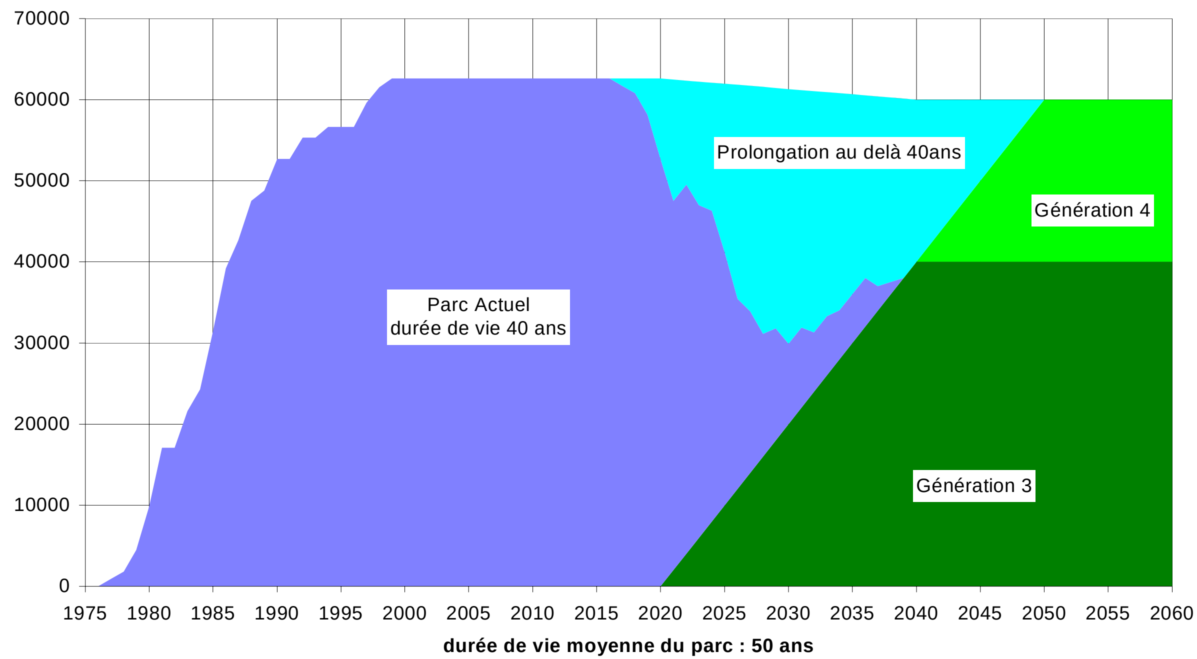
Scenario for the renewal of power reactors in Japan

- **Major role of LWRs over the 21st century**
  - ✓ **Lifetime extension + Deployment of Gen III LWRs up to ~58 GWe**
- **Transition to FBRs > 2050**



Scenario for the renewal of power reactors in France *(EDF)*

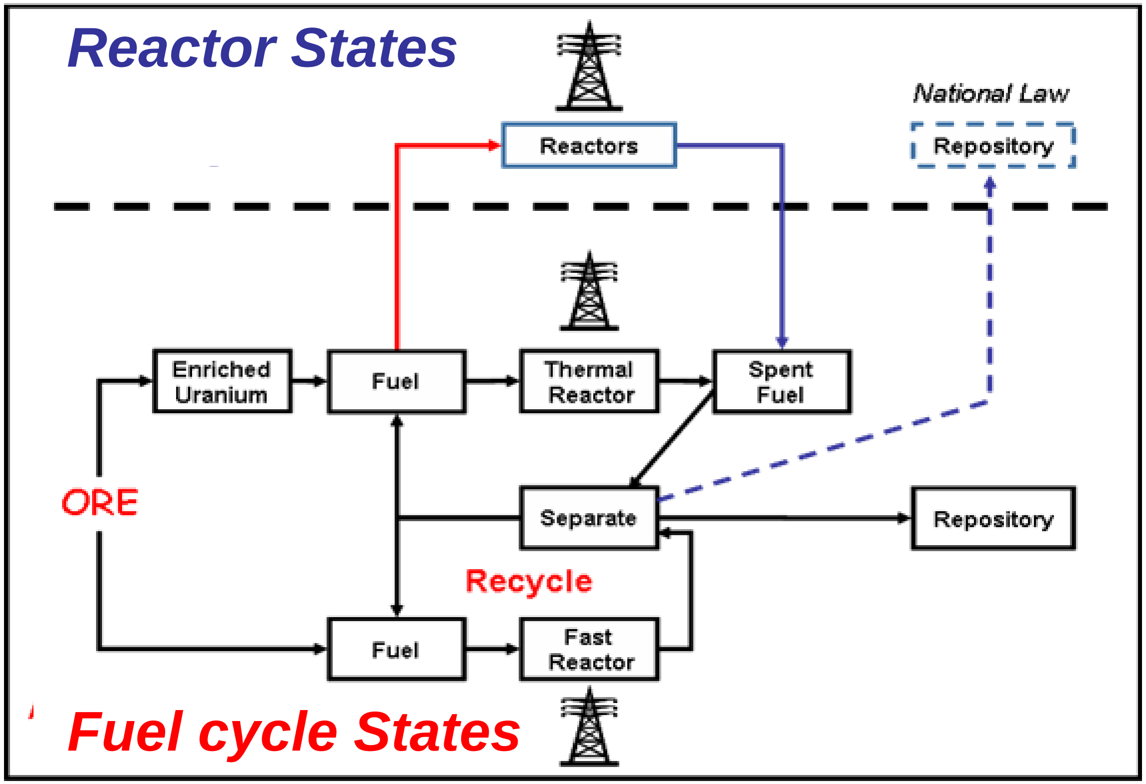
- **Major role of LWRs over the 21st century**
  - Operating PWRs *(Gen II):* lifetime extension (> 40 years)
  - Gen III/III+ PWRs: relacement of current PWRs around 2015 – Operation over most of the 21st century
- **~2040 – Transition from PWRs to Gen IV Fast neutron systems**



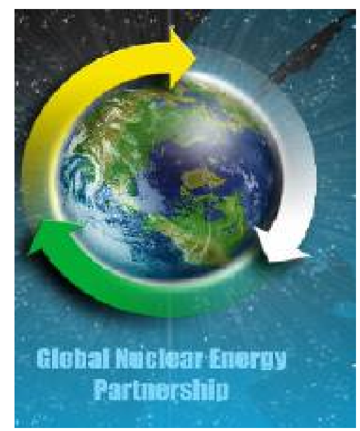
Source: EDF and Nuclear Energy in the Long Term Dec 2004

The GNEP Initiative

Nuclear fuel supply & take back



- **Recognizes the benefit of treatment/recycling strategies:**
  - Regional centers
  - Large scale facilities
- **Sets new requirements for future reprocessing needs:**
  - Address non-proliferation
  - No pure plutonium



Experience in Sodium cooled Fast Reactors

18 experimental or prototype Sodium Fast Reactors so far
385 Reactor x Years of cumulated operation in 2007

United States

- *EBR-1* — *1951*
- *EBR-II (20 MWe)* — *1963 → 1994*
- *FFTF (400 MWth)* — *1980 → 2000*
- *Clinch River Project cancelled in 1983*

Europe

- *Rapsodie (20 MWth) 1967 → 1983*
- *DDFR (60 MWth)*
- *KNK-II (17 MWe)* — *1978 → 1991*
- *Phénix (250 MWe)* — *1973 → 2009*
- *PFR (250 MWe)* — *1975 → 1994*
- *SNR300 (300 MWe) never put into service*
- *Superphenix (1200 MWe) 1986 → 1998*
- *EFR Project cancelled in 1998*

Japan

- *Joyo (140 MWth)*
- *Monju (280 MWe)* — *1994 →*

Russia & Kazakhstan

- *BOR-60 (60 MWth)*
- *BN-350 (90 MWe)* — *1973 → 1999*
- *BN-600 (600 MWe)* — *1980 →*
- *BN-800 (800 MWe)* — *2012*

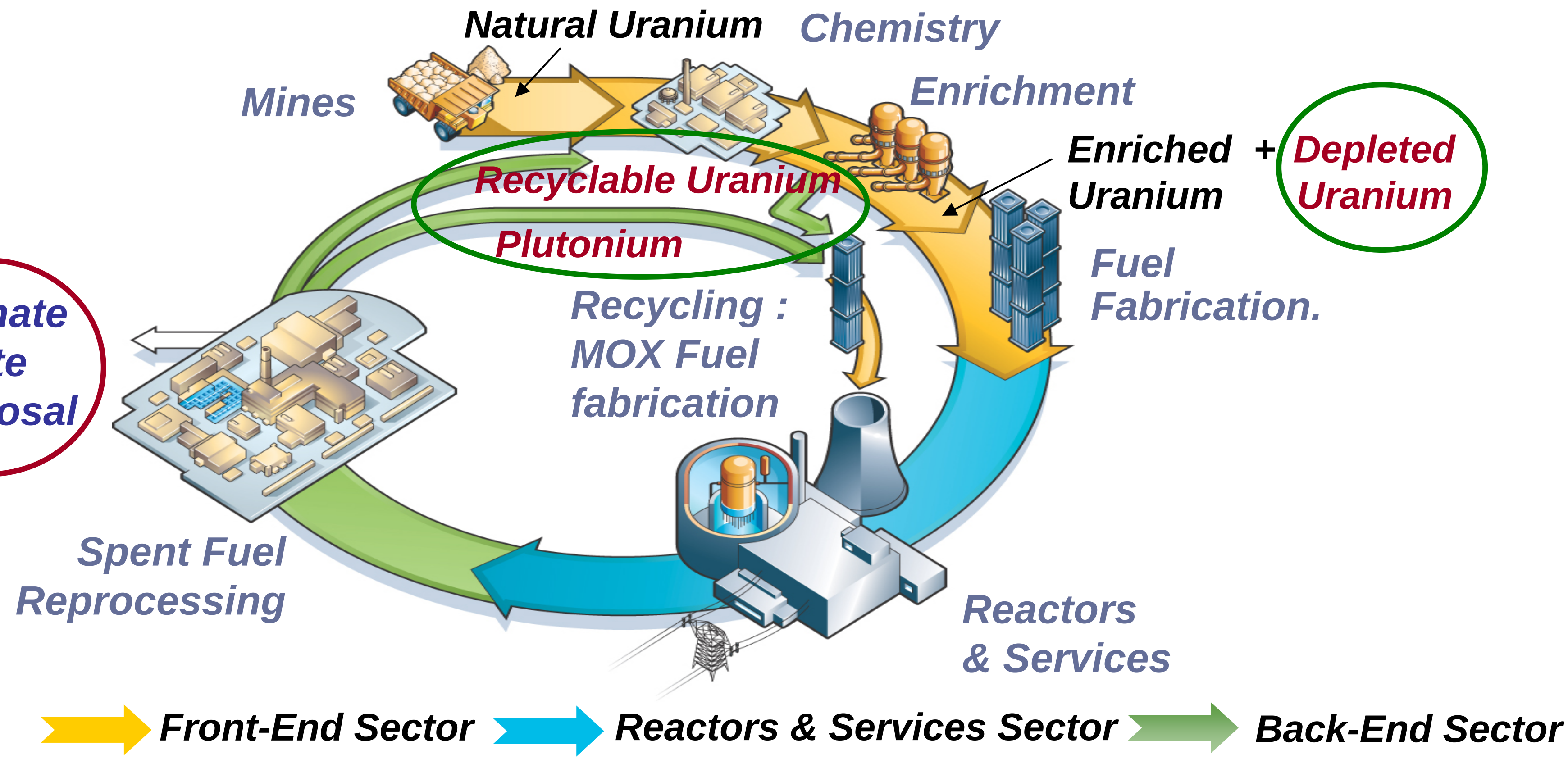
India

- *FBTR (40 MWth)* — *1985 →*
- *PFBR (500 MWe)* — *2010*

China

- *CEFR (25 MWe)* — *2010*

Closed Fuel Cycle: an industrial reality in France & Japan



- ✓ More than 25 years of industrial experience in France
- ✓ 58 PWRs → 415 TWh in 2004
- ✓ 1100 Mt_{HM} /yr of spent fuel discharged from the French PWRs
- ✓ Up to 1 600 Mt_{HM} /yr of spent fuel reprocessed *(domestic + foreign)*
- ✓ So far: ~ 20 000 Mt_{HM} spent fuel treated and > 1200 Mt_{HM} MOX fuel recycled

New goals for sustainable nuclear energy systems

Continuous progress:

- ✓ Economically competitive
- ✓ Safe and reliable

Break-throughs:

- ✓Natural resources conservation
- ✓Waste minimisation
- ✓Proliferation resistance
- ✓Physical protection
- ✓Non-electricity applications

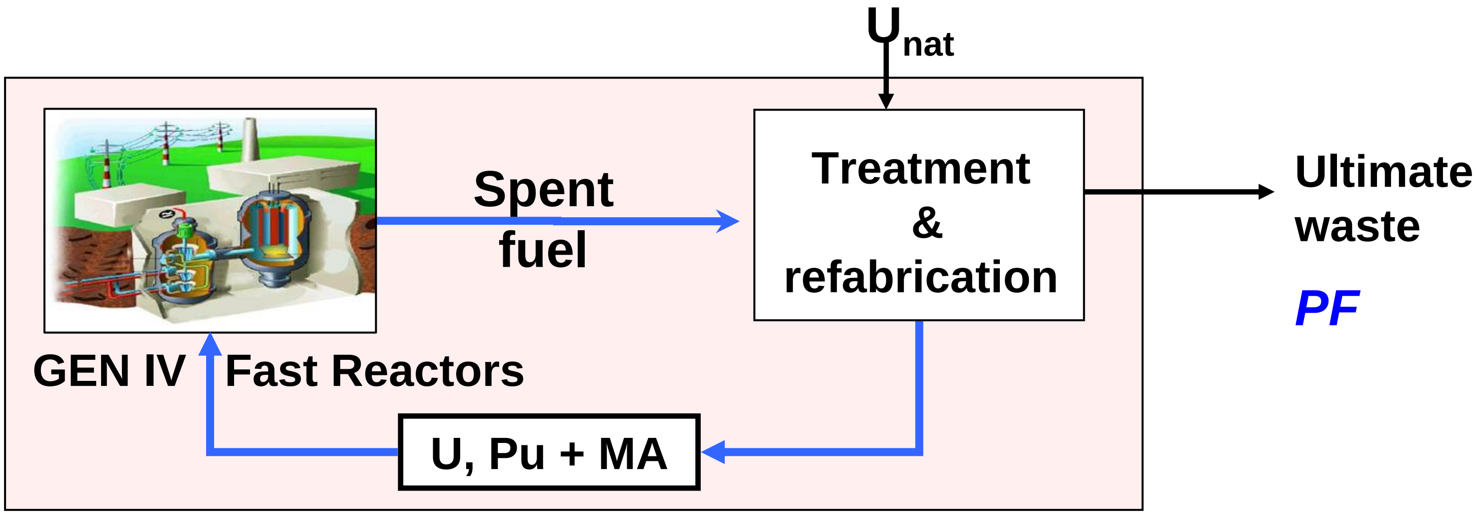
Systems marketable from 2040 onwards

A closed fuel cycle

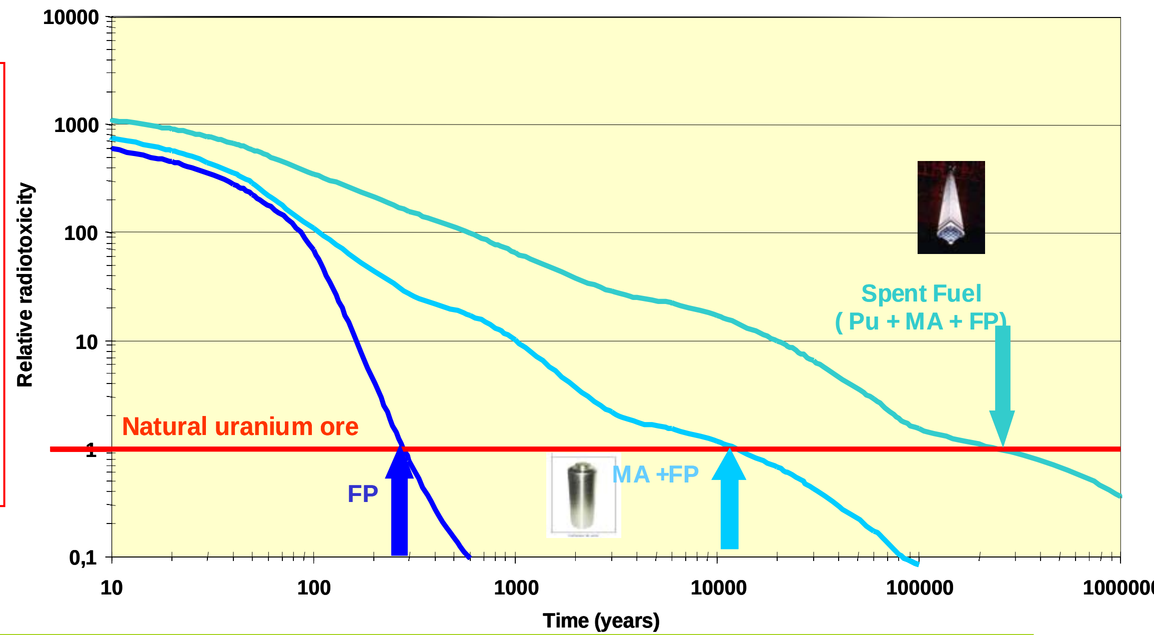
True potential for new applications: ***Hydrogen, Syn-fuel, Desalinated water, Process heat***

Internationally shared R&D

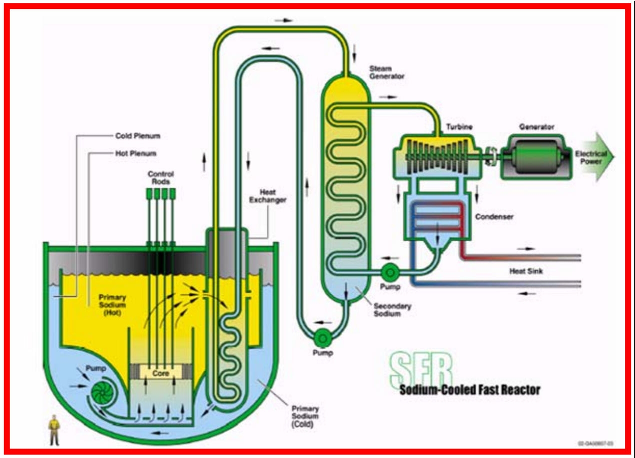
Gen IV Vision of closed fuel cycle: integral & homogeneous recycling of actinides



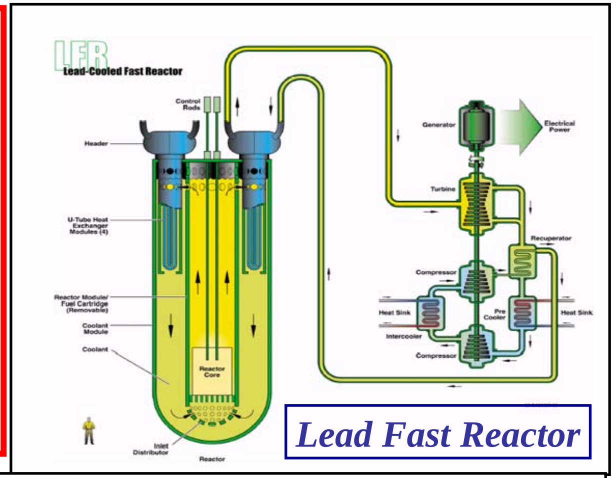
- **Minimization of HLLL ultimate waste:**
  - *- Very small amount*
  - *- Radiotoxicity ~ that of initial Uranium after a few centuries*
- **Optimum use of U_{nat}**



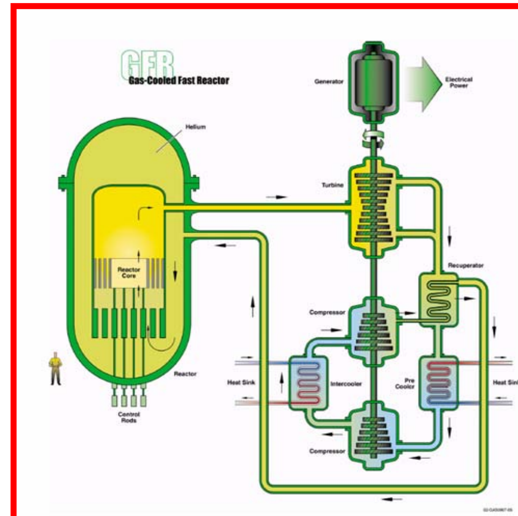
Generation IV Forum: selection of six nuclear systems



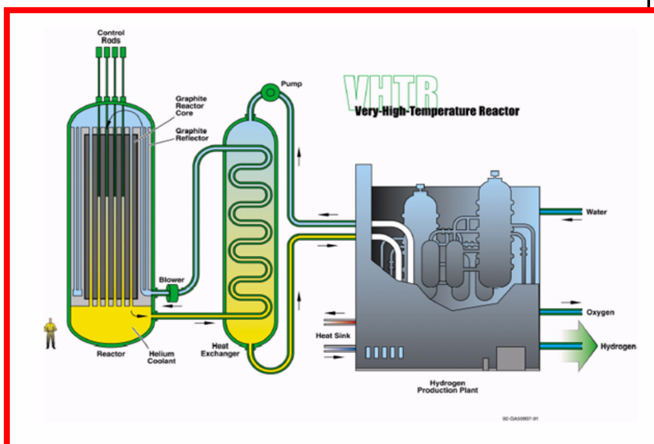
Sodium Fast Reactor



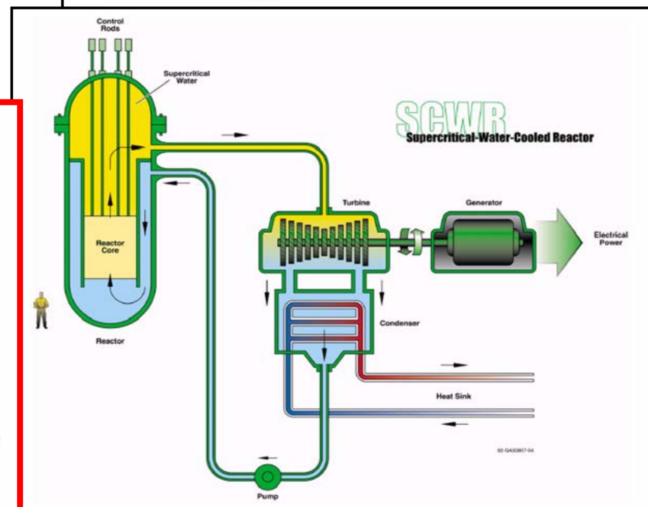
Lead Fast Reactor



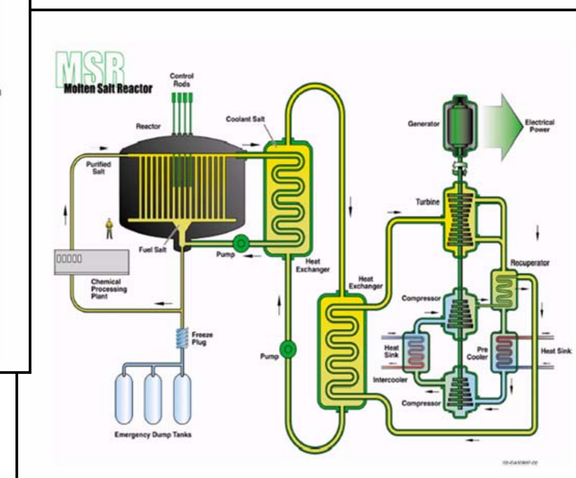
Gas Fast Reactor



Very High Temperature Reactor



Supercritical Water-cooled Reactor

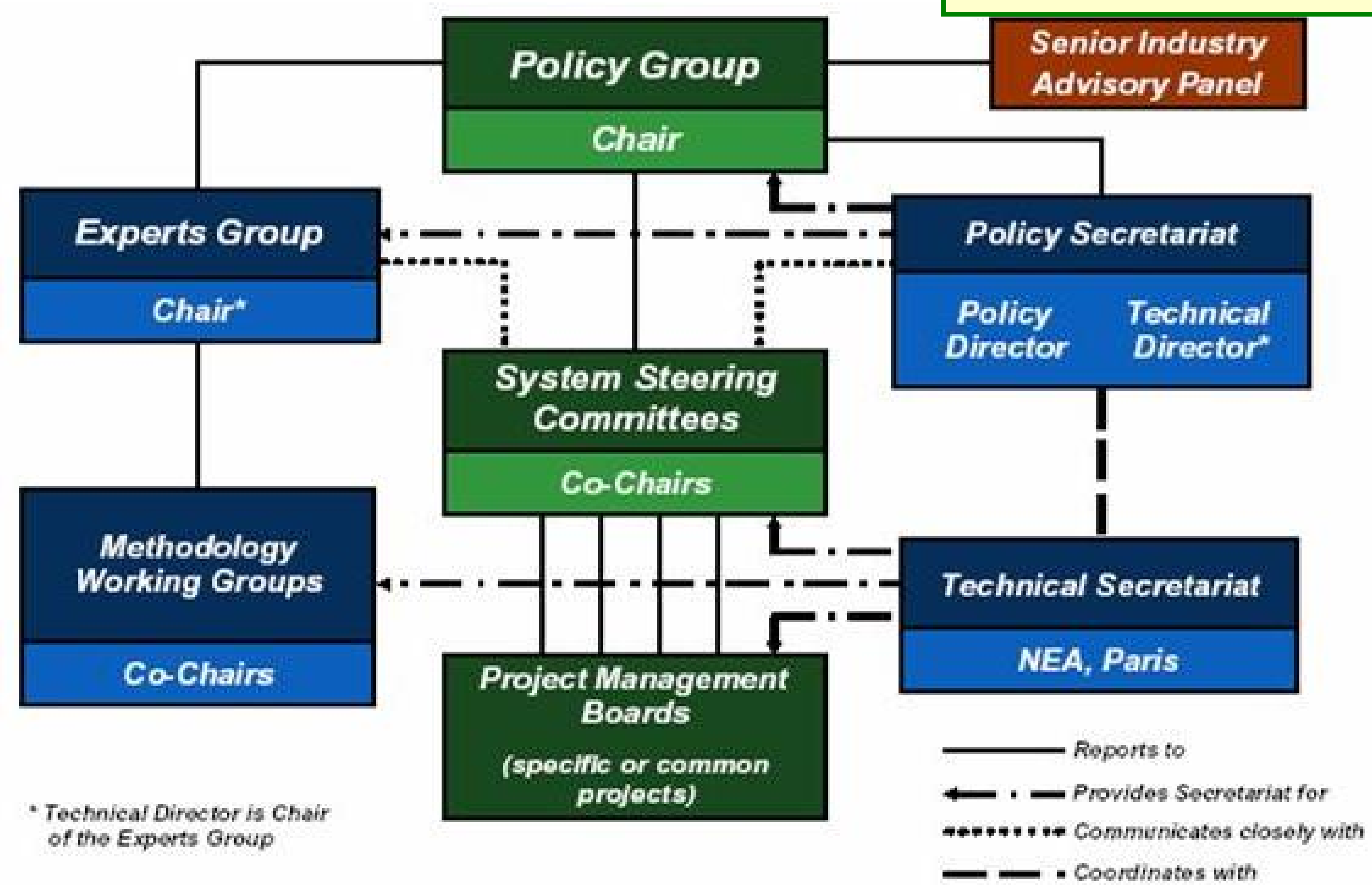


Molten Salt Reactor

(12-20y) R&D (~1 B€) before a 1st prototype or techno demo

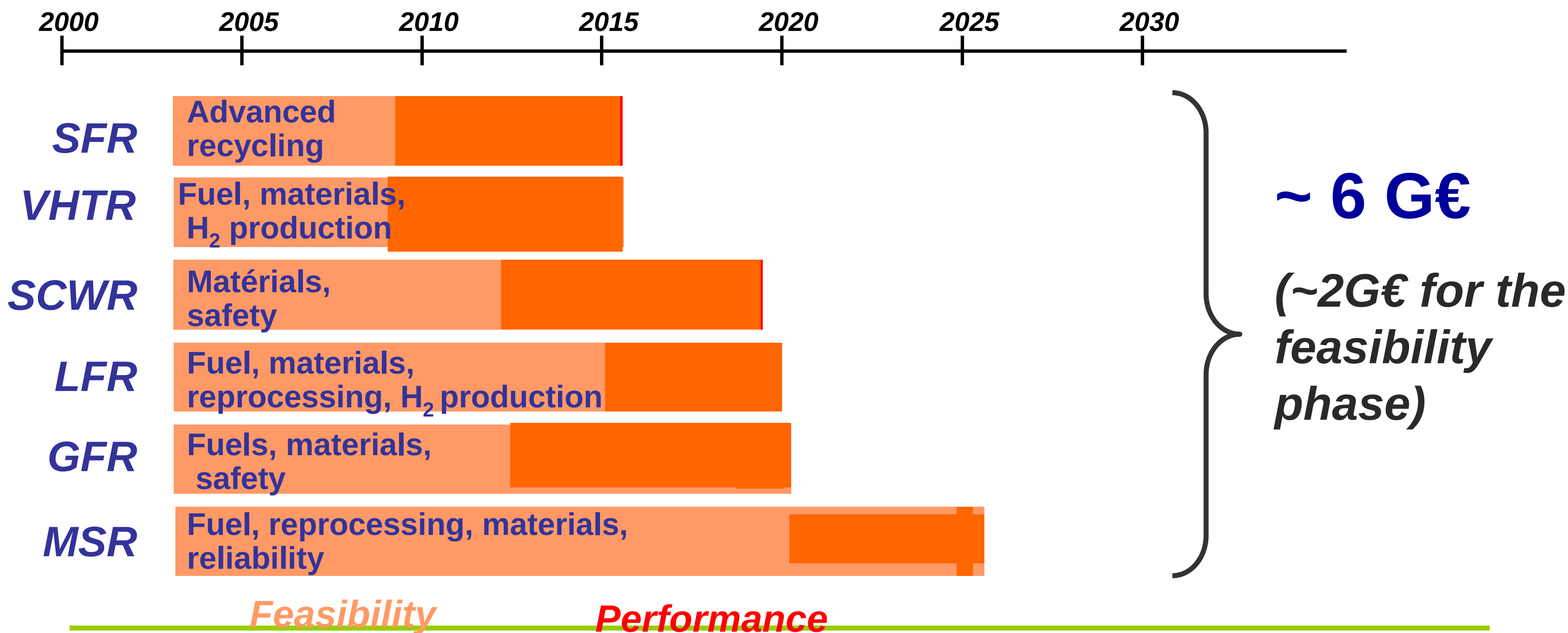
Governance of the Generation IV Forum

Utilities & Vendors



Generation IV System selection

GEN IV Systems	Acronym	Spectrum	Fuel Cycle
Sodium Cooled Fast RS	SFR	Fast	Closed
Lead Alloy-Cooled RS	LFR	Fast	Closed
Gas-Cooled Fast RS	GFR	Fast	Closed
Very High Temperature RS	VHTR	Thermal	Open
Supercritical Water Cooled RS	SCWR	Th.&Fast.	Open/Closed
Molten Salt RS	MSR	Thermal	Closed



Status of the Generation IV International Forum

- **Framework Agreement:**
  - Signed on Feb. 28, 2005 in Washington D.C.

- **System Arrangements:**
  - Feb. 15, 2006: ***SFR Arrangement*** signed
  - Nov. 30, 2006: ***VHTR, GFR & SCWR Arrangements*** signed

- **Project Arrangements:**
  - March 2007: Signature of the ***SFR – Advanced fuel*** Project
  - ***SFR – GACID & VHTR – Materials, Fuel and fuel cycle, Hydrogen production*** to be signed by Dec.2007

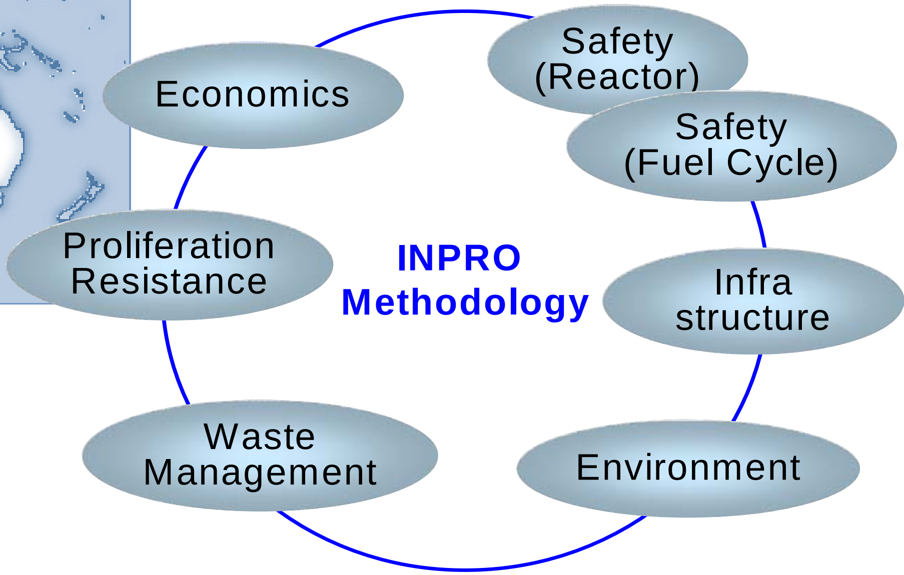
- **Russia & China join the Forum:** Charter signed Nov. 30, 2006

- **J. Bouchard as Forum's Chairman for 3 years** (Nov. 2006-09)

INPRO: an initiative to specify and assess nuclear systems for IAEA member countries

[INPRO](#): *A unique forum for the development of nuclear energy in IAEA affiliated countries & strengthening cooperation between Technology "Holders" & "Users"*

27 MEMBER STATES (status July 2007)

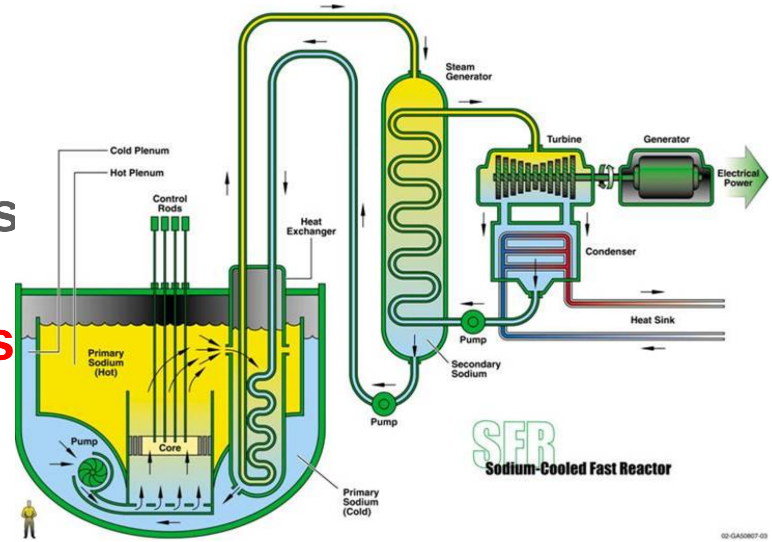


INPRO Methodology

A concrete achievement of INPRO phase 1, to be further assessed and improved during phase 2

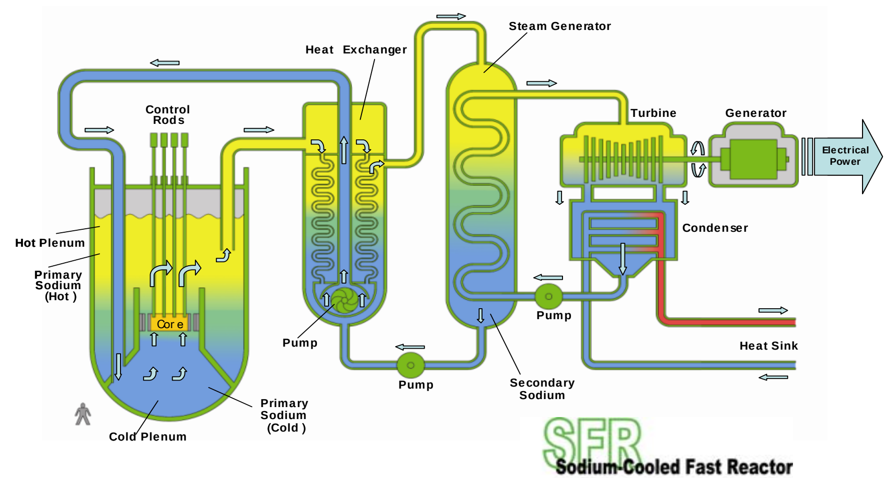
Sodium Fast Reactor *(SFR)*

- **A new generation of sodium cooled Fast Reactors**
- **Reduced investment cost**
  Simplified design, system innovations
  (Pool/Loop design, ISIR – SC CO_2 PCS)
- **Towards more passive safety features + Better managt of severe accidents**
- **Integral recycling of actinides?**
  → Remote fabrication of TRU fuel



→ 2009: Feasibility – 2015: Performance → 2020+ : Demo SFR *(FR, US, JP…)*

2007
+



A prototype reactor in France in 2020

➢ **President Chirac statement *(Jan 06)*:**

« A number of countries are working on future generation reactors, to become operational in 2030-2040, which will produce less waste and will make a better use of fissile materials. I have decided to launch, starting today, the design work by CEA of a prototype of the 4th generation reactor, which will be commissioned in 2020.

We will naturally welcome industrial or international partners who would like to get involved. »

➢ **Bill on a long-lasting sustainable management of radioactive materials and waste *(June 28, 2006)*:**

Section 3.1: *« Research on Partitioning and Transmutation is conducted in relation with that on* ***new generations of nuclear reactors*** *mentioned in the Energy Policy Bill of July 13, 2005, as well as on* ***accelerator driven systems*** *dedicated to the transmutation of waste, so as* ***to have in 2012 an assessment of the industrial prospects of these reactor types*** *and to put a prototype into operation by the end of 2020 ».*

French R&D Strategy on Fast Reactors revisited in 2006

2nd Atomic Energy Committee meeting on December 20, 2006

→ Two types of Fast Reactors studied in parallel

1 – Sodium Fast Reactor, reference type for a Prototype in 2020

- → *Initiative of CEA and coordination with industrial partners*
- → *Search for significant innovations*

2 – Gas Fast Reactor, alternative Fast Reactor type

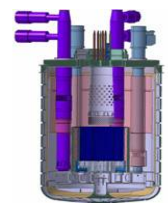
- → *Active collaboration in Europe towards a technology demo reactor?*

Confirmation of design features

Selection of technologies

Innovation Scoping studies (reviews of *innovative features*)

Integration, Confir-mation of selected technologies (design reviews)



2007 — **2009** — **2012** — **2015** — **2020**

Point design studies to assess candidate innovations

Reference Concept of selected reactor + alternative

Launch of preliminary and detailed detailed design studies, PSAR, Qualification R&D, Construction

Design features of the **Prototype**

Decision to build

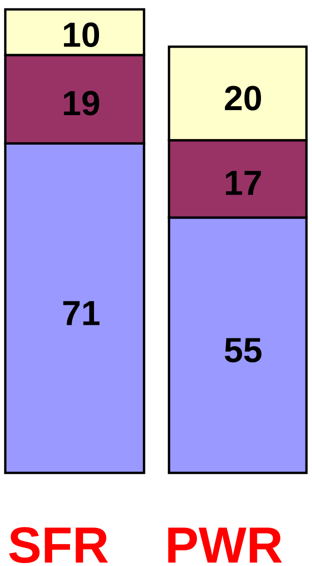
Requirements for Gen IV Sodium Fast Reactors (1/2)

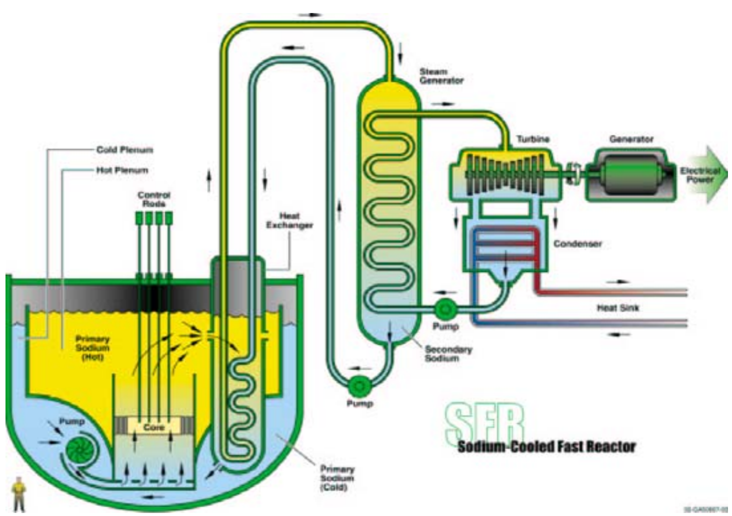
➢ Economic competitiveness with Gen III LWRs

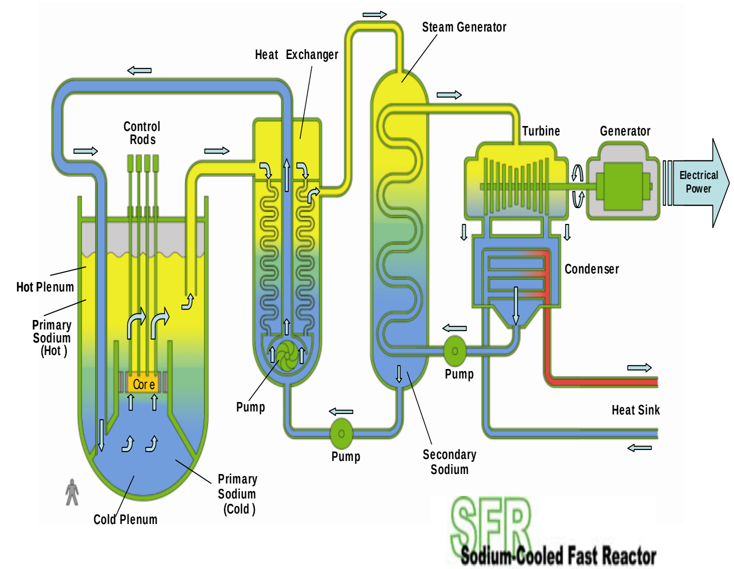
– **Reduction of the *investment cost* through system simplification and increase of compactness**
  - *Pool concept*
  - *Loop system (with simplified or suppressed intermediate system)*

– **Optimization of *operation* with a design that alleviates as far as possible constraints associated with a metallic coolant**

– **Optimization of *in service inspection, maintenance and repair***





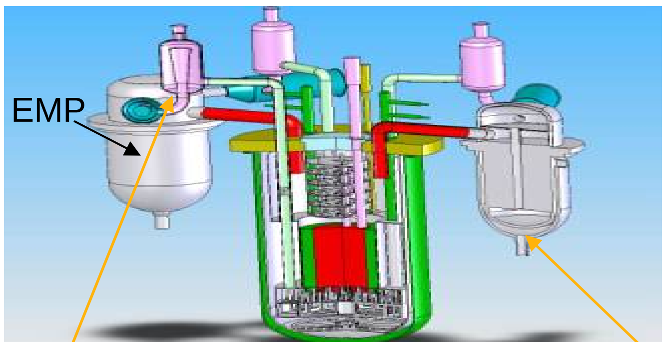


Requirements for Gen IV Sodium Fast Reactors (2/2)

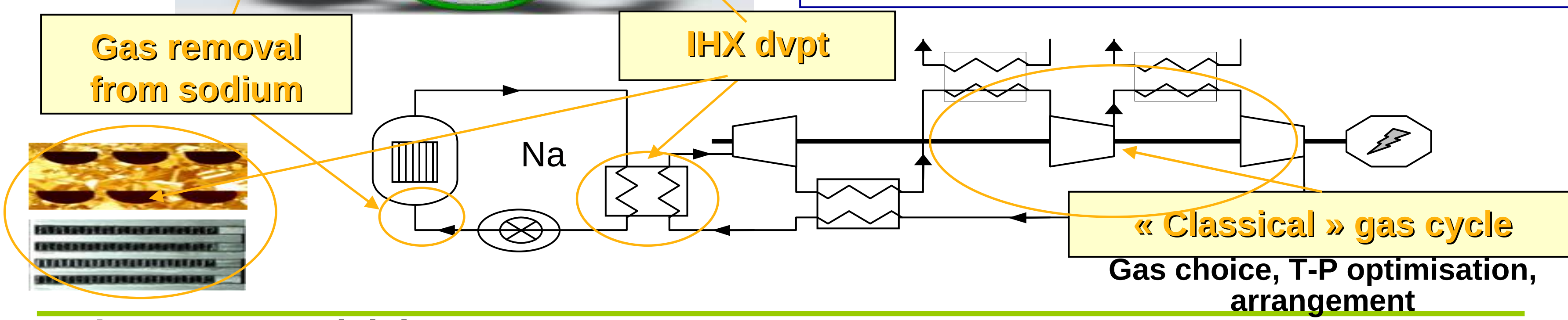
Enhanced safety

- Decrease or suppression of ***risks of sodium/water interaction*** through optimizing the Power Conversion System
  - *Optimized Steam Generator*
  - *Gas Turbine (nitrogen/helium or supercritical CO_2)*
- ***Practical exclusion of large energy release in case of severe accidents***

  → *Reduced sodium void reactivity effect + Enhanced Doppler effect with a dense and high thermal conductivity fuel + Increased reliance on passive safety features*



- **Loop design** without intermediate system; **conversion with Gas Turbine**
- **Specific design features to prevent gas from flowing through the core**
- **Design of sodium/helium IHX**
- **Impact on safety features**

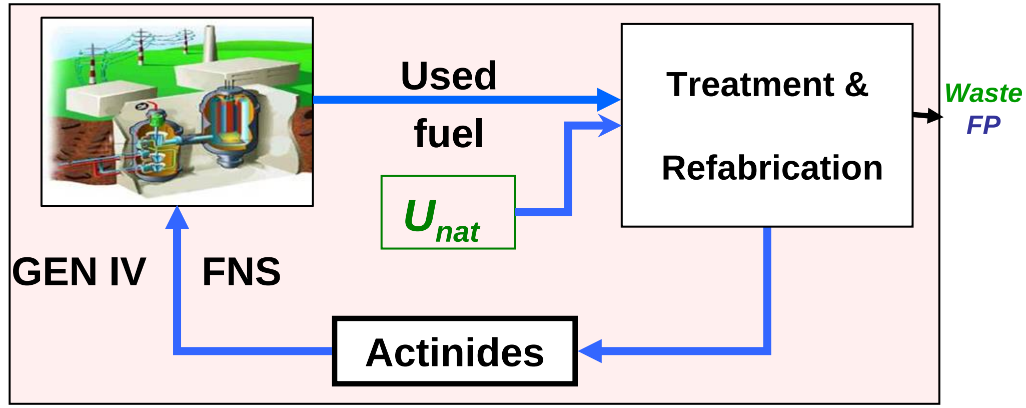


Flexible fuel cycle (U, Pu, MA) + Burning or Breeding

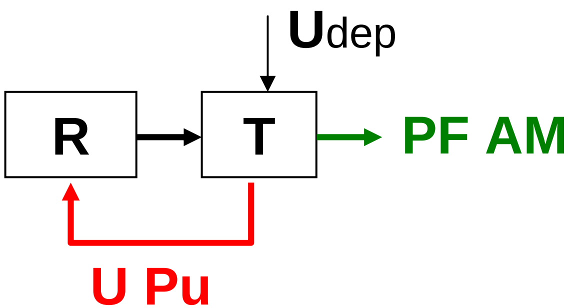
→ Resource saving

→ Waste minimization

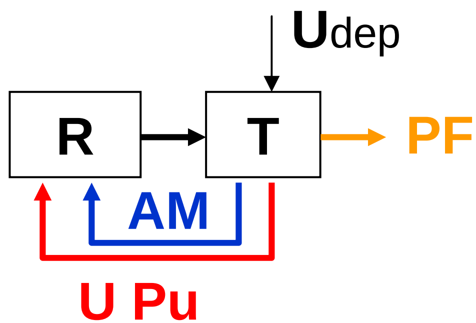
→ Non-proliferation



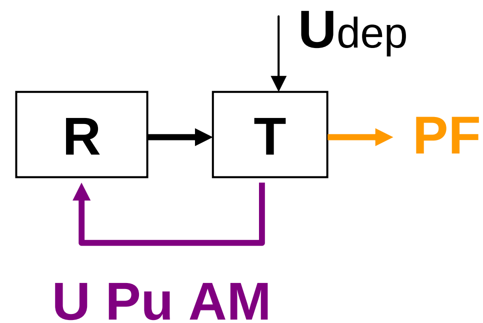
- Develop international non-proliferation standards to allow for diverse fuel cycle processes
- Keep all options open as they could be deployed in sequence



Recycling U Pu only



Heterogeneous recycling



Homogeneous recycling (GenIV)

TRU fuel tests in Phenix & Superphenix

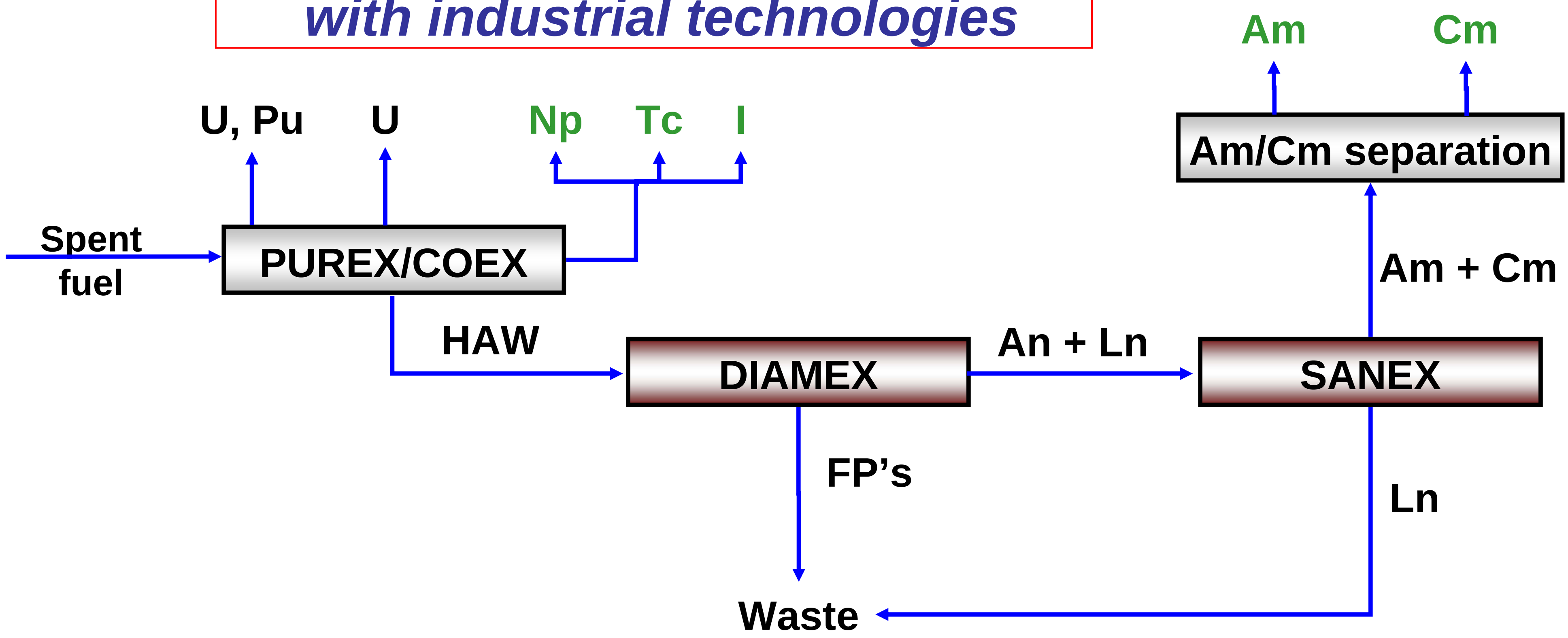
	SUPERPHENIX		PHENIX	
	Homogeneous	Heterogeneous	Homogeneous	Heterogeneous
Np	NACRE UO_2,PuO_2 + 2% Np Fabricated Not irradiated		SUPERFACT pins UO_2 + 2% NpO2	SUPERFACT pins UO_2 + 40% NpO_2 METAPHIX Metal Np, Am, Cm
Am Cm	Few pins with 1% Am		SUPERFACT pins UO_2 + 2% AmO2	SUPERFACT pins UO_2 + 20% AmO_2 ECRIX AmO_2 + MgO CAMIX/COCHIX Oxide FUTURIX FTA

Completed | On-going (2003-2009)

+ **PROFIL** *(nuclear data)*
+ **ANTICORPS** *(transmutation of Tc)*

Advanced separation processes of actinides

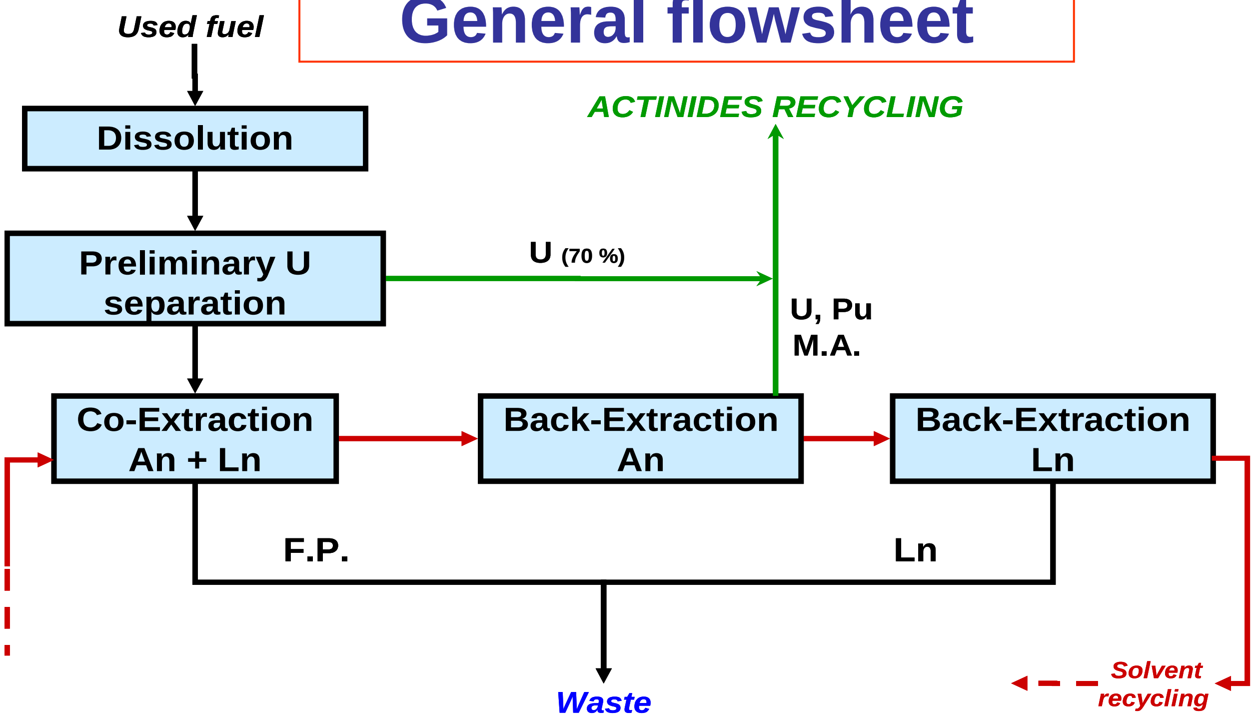
Demonstration test in 2005
on 15 kg of spent fuel
with industrial technologies



Processes such as UREX+/Talspeak or NEXT/Todga are other viable options

R&D on spent fuel separation processes

GANEX
General flowsheet



Co-conversion of actinides through the solgel process

Beads of U(VI)-Pu(IV) hydroxide gel

Oxalic co-precipitation of actinides

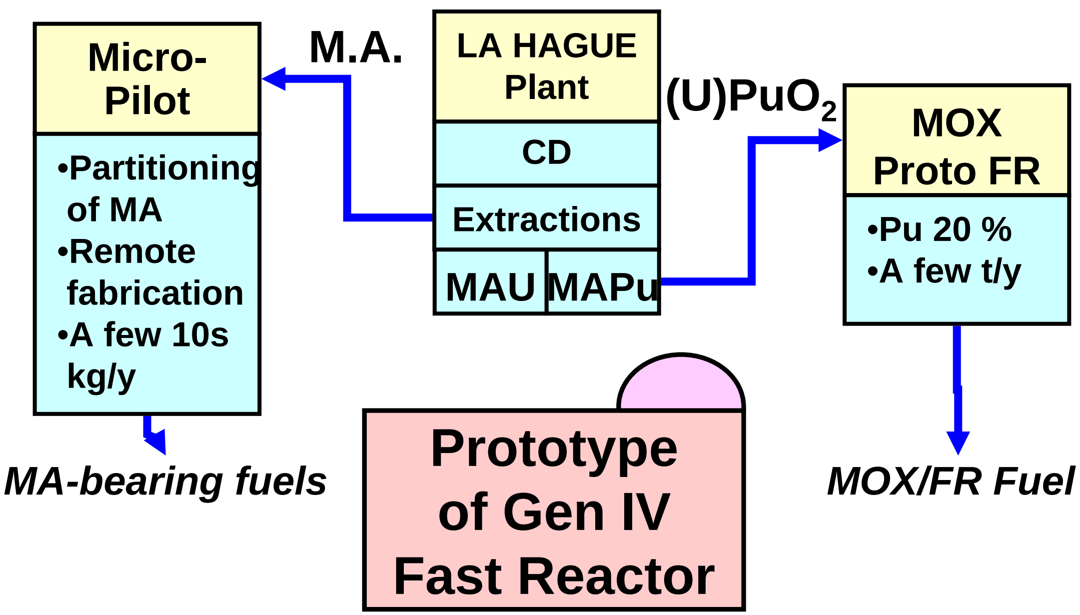
(U,Np,Pu,Am) 78/1/20/1

- **Demonstration of GANEX in 2012**
- **Experience from the R&D performed on HL radioactive waste management**

Demonstration of Advanced reactor and recycling technologies (U, Pu, MA)

- **French Prototype 2020**
  - 250-600 MWe
  - **Break-even breeding**
  - **Multiple recycling of U-Pu & Demo of MA management**

- **Advanced fuels and recycling**
- **Innovations for a generation of competitive Fast Reactors**
- **Innovative technologies in support** *(materials, PCS…)*



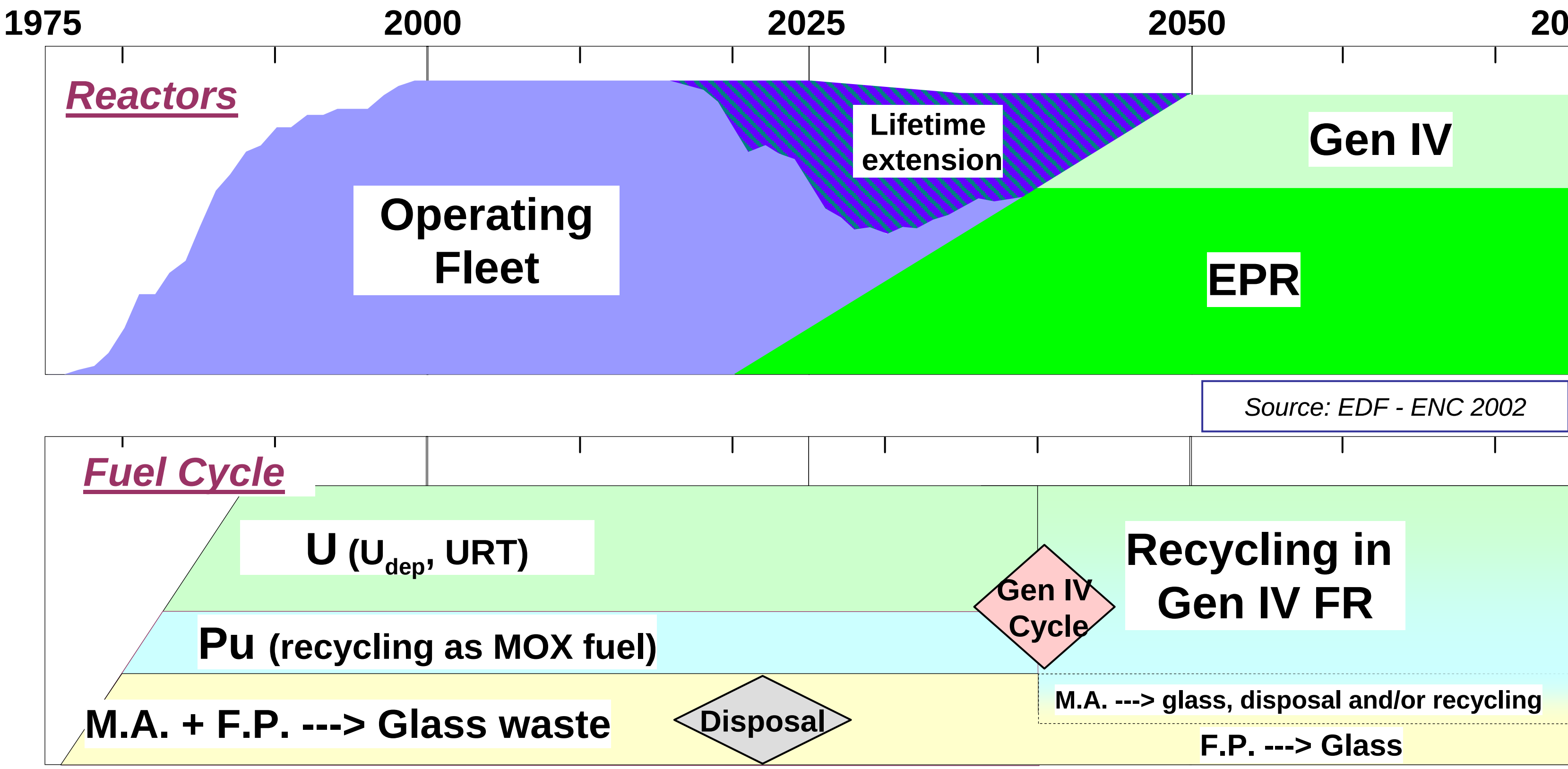
- **Pilot scale facilities on the site of La Hague to manufacture driver & MA fuels (~2017):**
  - **Manufacturing of (U,Pu)O_2 fuels** ***(a few tonnes/year)***
    - ***(COEX)***
  - **Manufacturing of experimental MA-bearing fuels** ***(~10s kg/year)***
    - ***- GANEX → (MA,U,Pu)O_2***
  - ***- Diamex-Sanex → (MA,U)O_2***
- **Sustained R&D for decision on reactor and fuel options in 2012**

French scenario with FR and New Fuel Cycle Plant in 2040

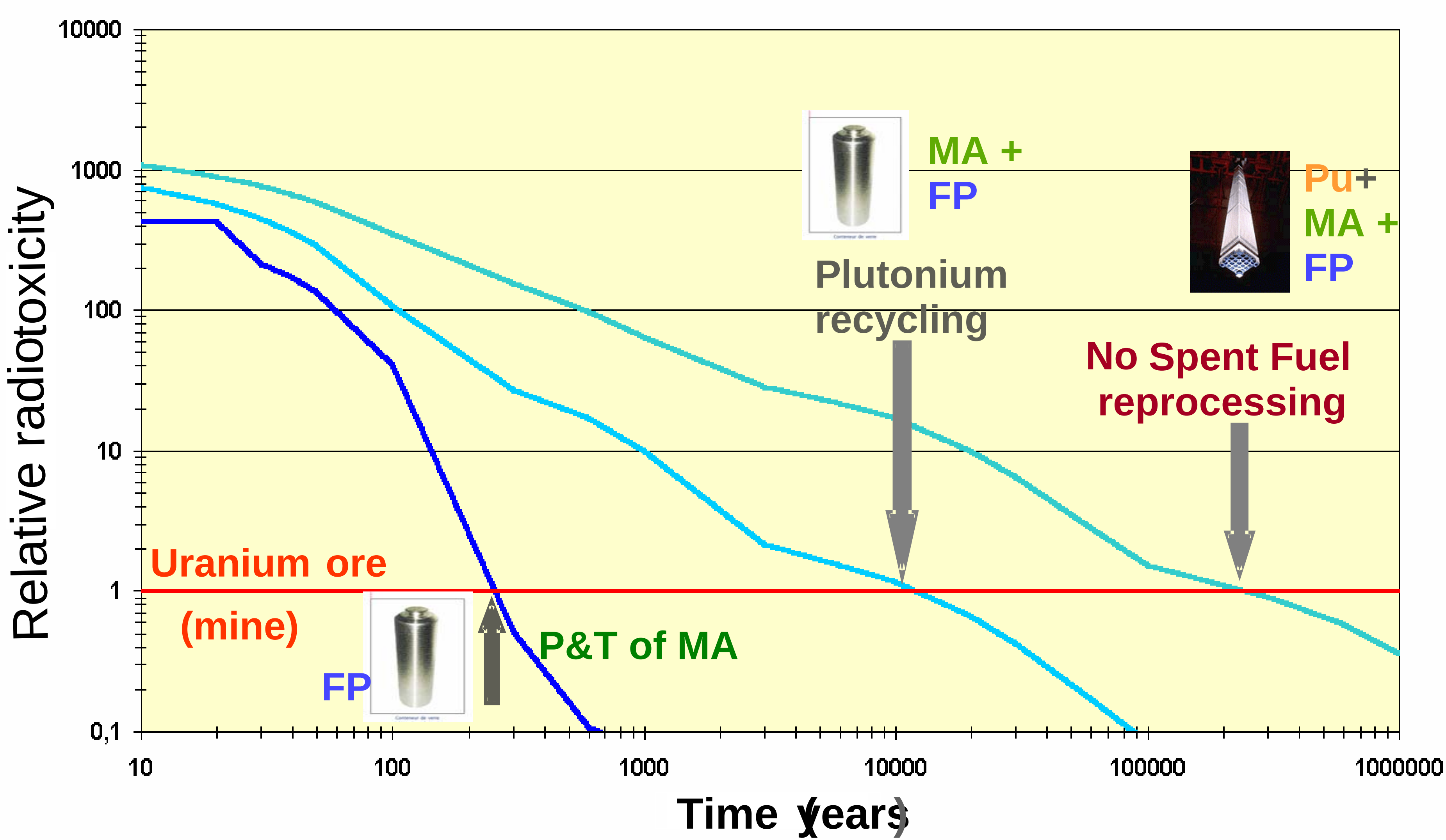
~2040: - Deployment of Fast neutron systems *(SFR or GFR)*

- New spent fuel treatment plant at La Hague (Ganex) –

- ✓ ***Future goal : Integral recycling of U-Pu-MA***
- ✓ ***Interim goal : Recycling of U-Pu and separate management of MA*** *(to waste or interim storage)*

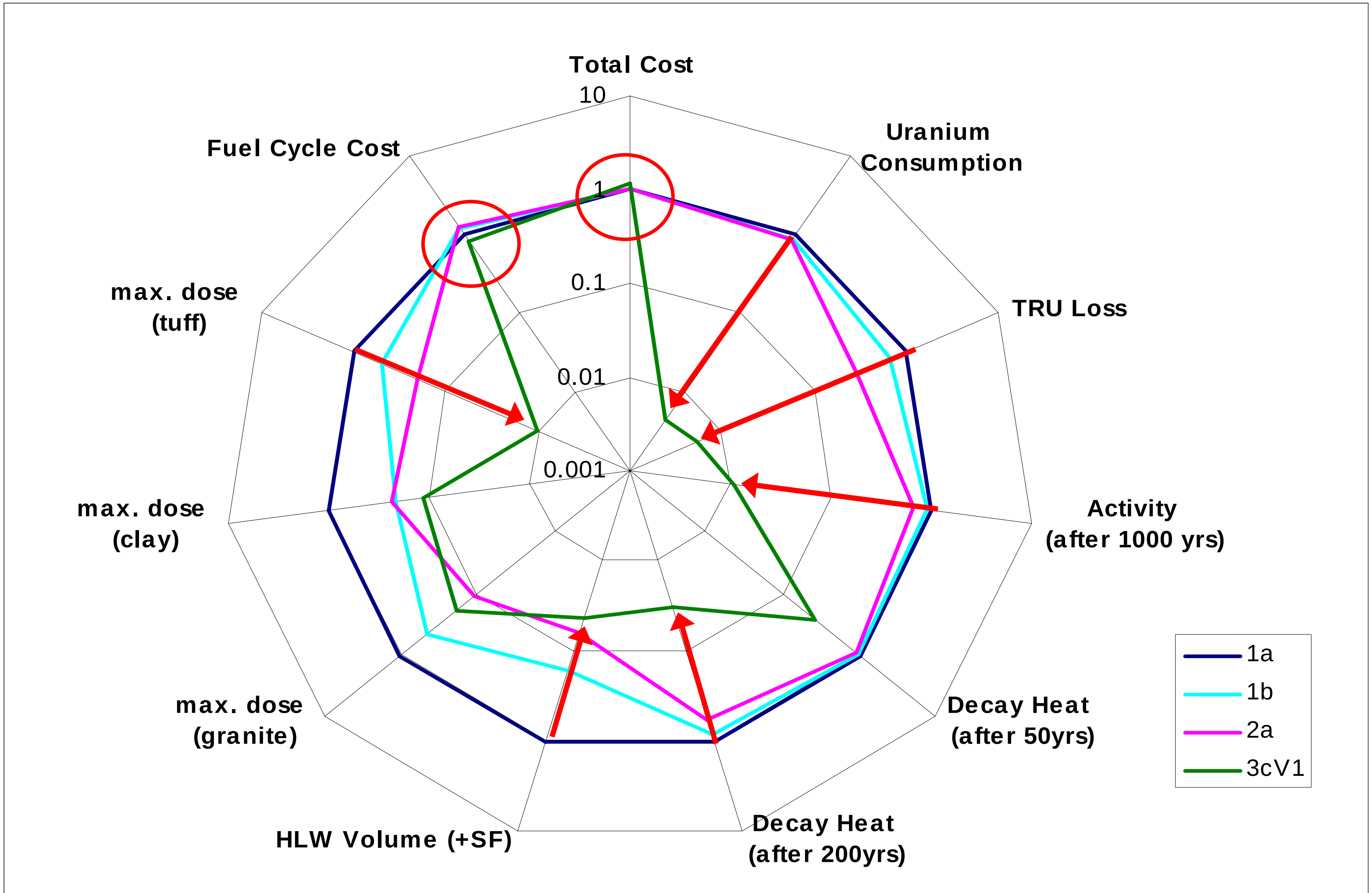


Minimizing waste with advanced Actinide recycling



Summary of main results of NEA P&T study (ENC 2005)

Gen IV and P&T impacts



1a: ***Once-through cycle as reference.***

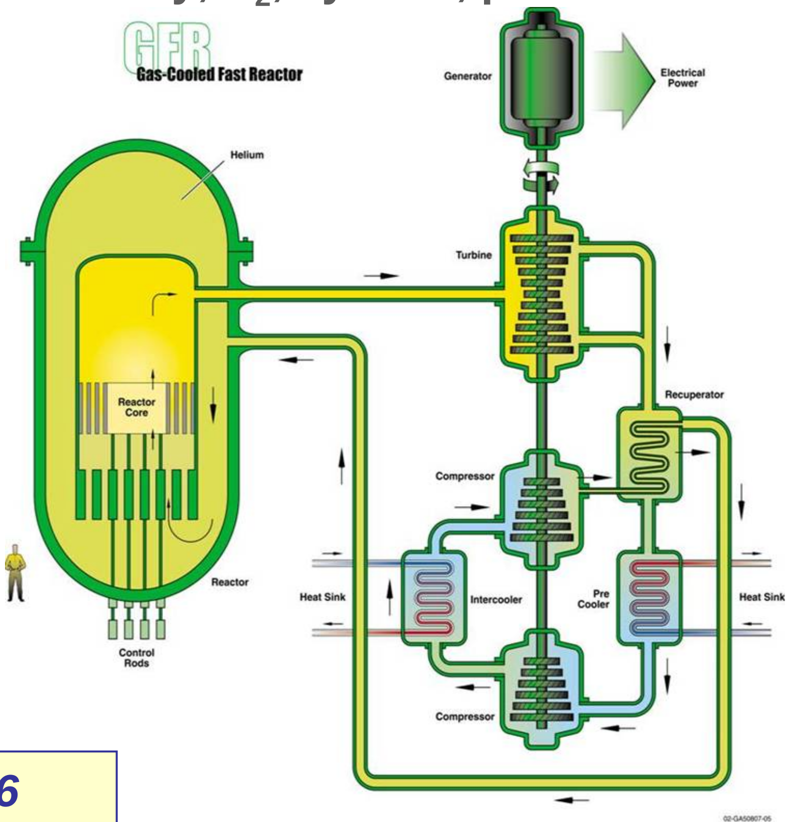
1b: ***full LWR park, Pu re-used once***

2a: ***full LWR park, multiple re-use of Pu***

3cV1: ***full fast reactor park and fully closed fuel cycle (Gen IV).***

Gas Fast Reactor *(GFR)*

- A novel type of Gas-cooled Fast Reactor:
  → *an alternative to the Sodium Fast Reactor, and*
  → *a sustainable version of the VHTR*
- Robust heat resisting fuel *(<1600°C)*
- 1200 MWe – T_{He} ~ 850 °C - Cogeneration of electricity, H_2, synfuel, process heat
- Safe management of cooling accidents
- Potential for integral recycling of Actinides



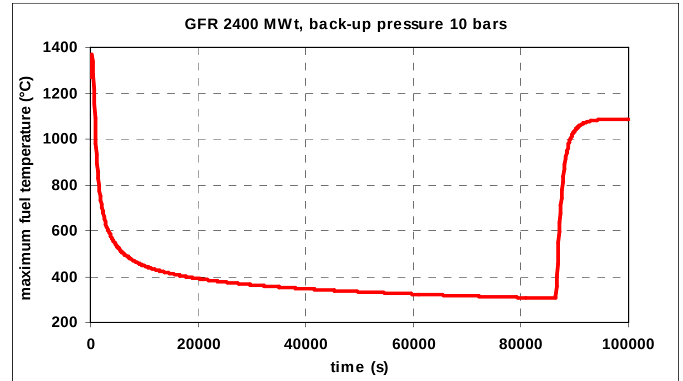
→ 2012 : Feasibility → ~2020 : ETDR *(EU ?)*
2020: Performance → 2030+: GFR Prototype

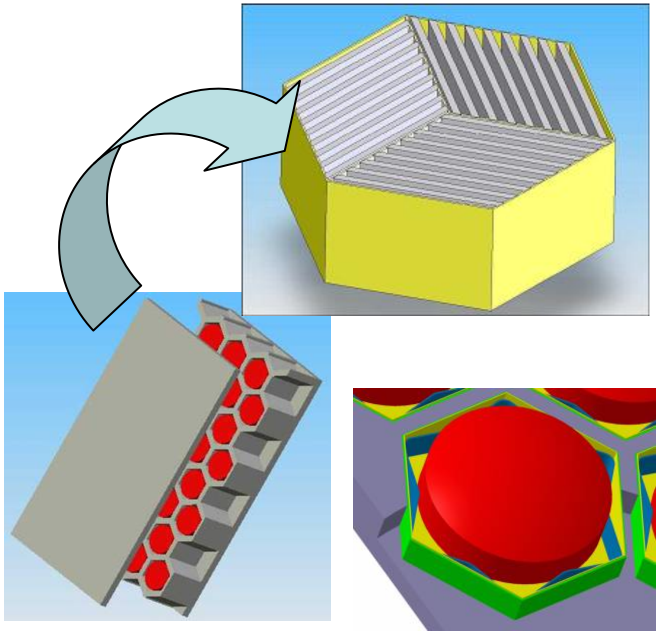
GCFR
5-6 EU
PCRD

✓*System Arrangement GFR signed Nov. 30 Nov.,2006*
✓*Project Arrangements "Fuel " &*
"Design-Safety-Integration" in 2007

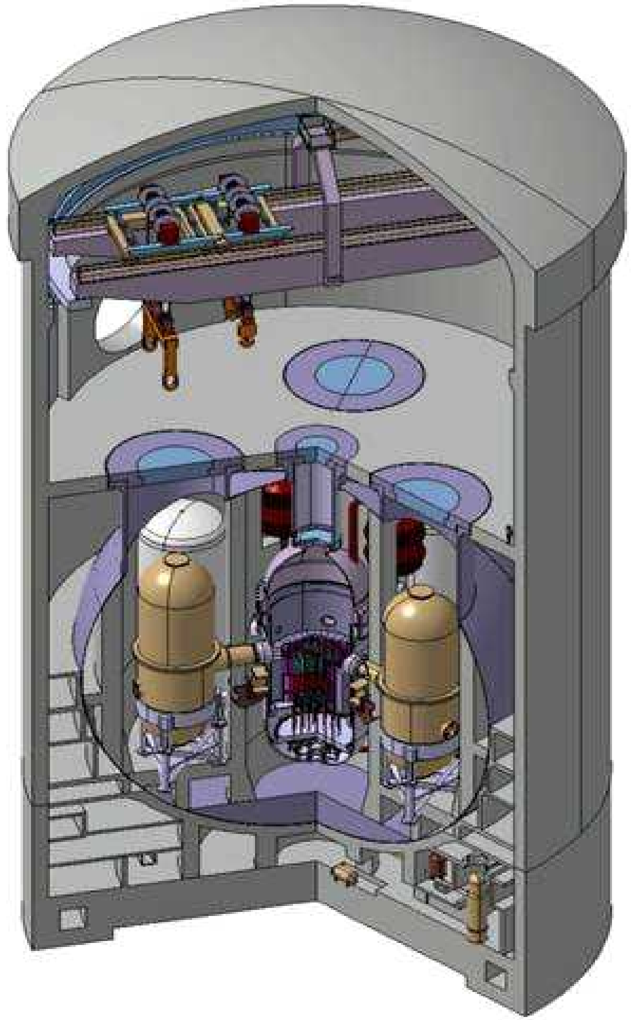
ETDR and GFR pre-conceptual designs *(GFR)*

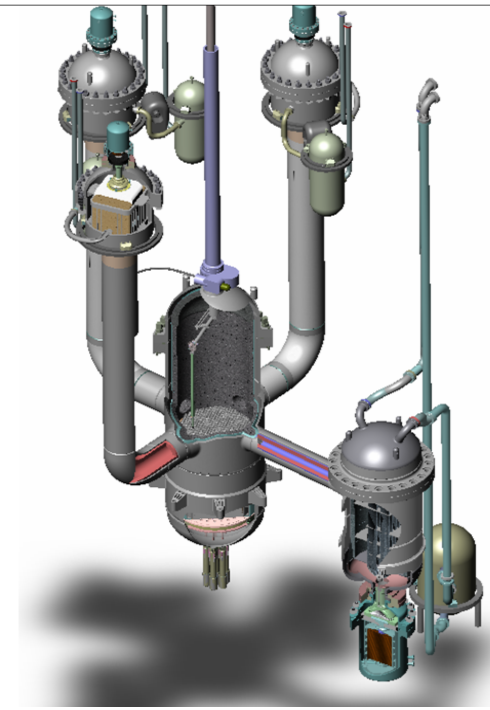
Robust decay heat removal strategy (passive after 24hrs)





Innovative fuel



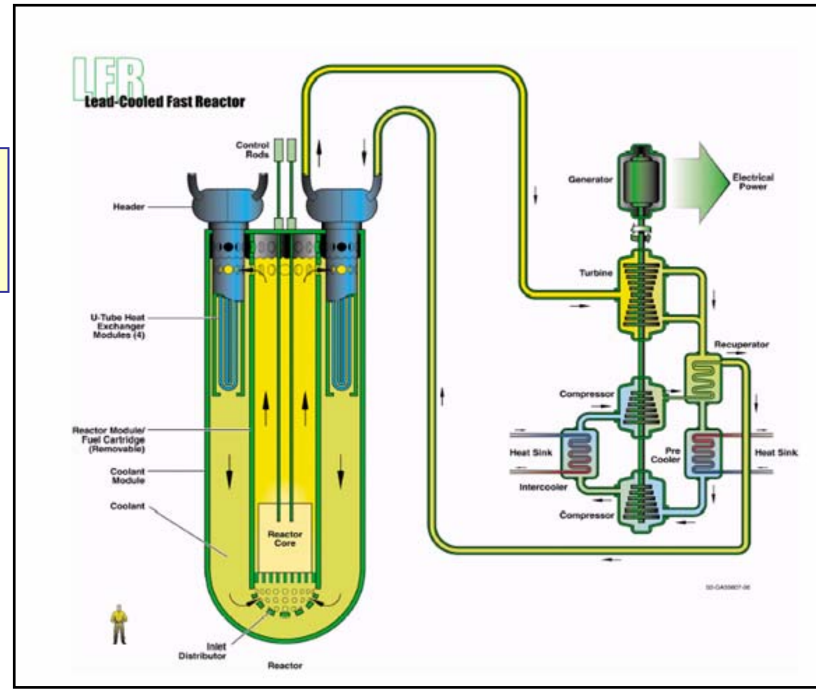


GFR 2400 MWt reference concept

ETDR (50 MWt)

Lead Fast Reactor *(LFR)*

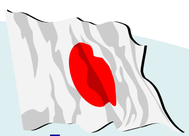
- **An alternative Liquid Metal cooled Fast Reactor:**
  → thermal management of lead
  → in service inspection and repair
- **Weight of primary system** *(seismic behaviour…)*
- **Prevention of corrosion of 1ʳʸ system structures**
- **600 MWe – T_{He} ~ 480 °C**
- **Potential for integral recycling of Actinides**



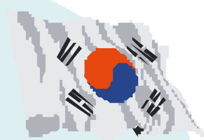
→ 2015: Feasibility → 2020+: Techno Demo *(EU ?)*
→ 2020: Performance → 2030+: LFR Prototype

ELSY
EUROTRANS
in EU FP6

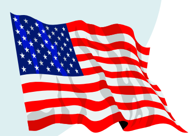
Euratom countries



Japan



South Korea



U.S.A.

LFR Steering Committee

✓System Arrangement LFR to be signed end-2007 or 2008

Supercritical Water Cooled Reactor *(SCWR)*

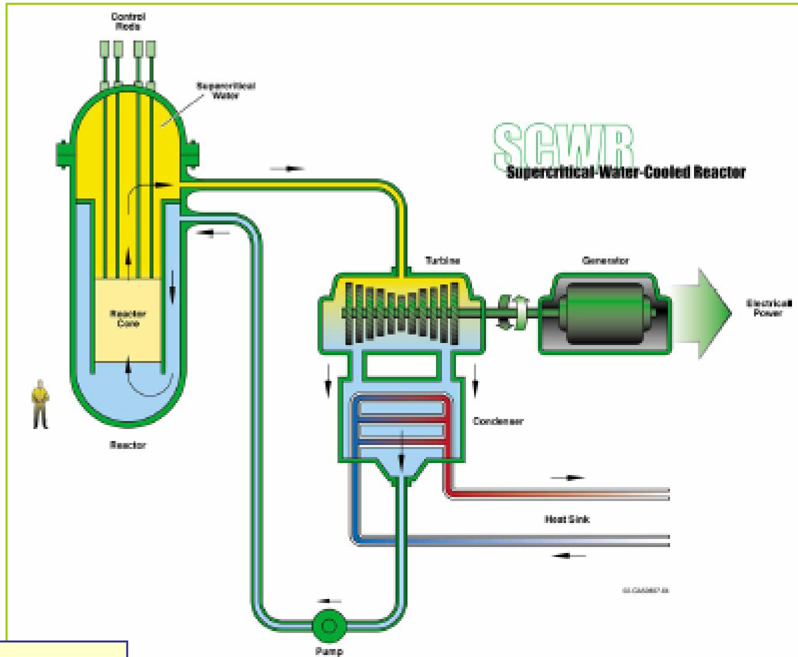
- ***Open cycle & thermal / closed cycle & fast spectrum***
- ***High pressure, High temperature (>22.1 Mpa, 374 °C)***

→ ***Highly ranked in economics (thermal efficiency, plant simplification)***

→ ***Electricity production (and others)***

→ 2012: Feasibility → 2020: Performance

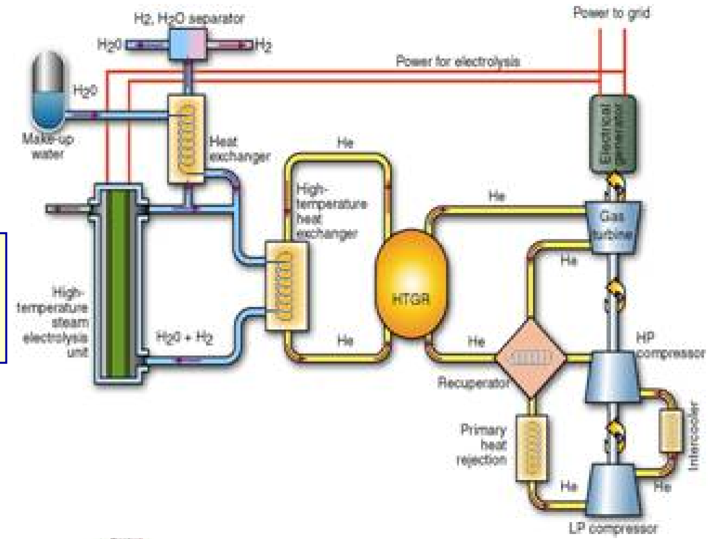
HPLWR in EU FP6



✓***System Arrangement SCWR signed Nov. 30,2006***

Very High Temperature Reactor *(V/HTR)*

- **A nuclear system dedicated to the production of high temperature process heat for the industry and hydrogen**
- **600 MWth - T_{He} >1000 °C**
  Thermal neutrons
  Block or pebble core concept
- **Passive safety features**
- **I-S Cycle or HT Electrolysis for H_2**



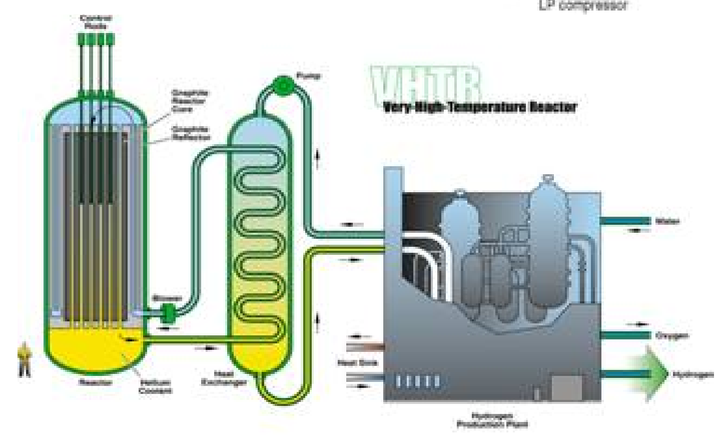
→ 2009: Feasibility – 2015: Performance
~ 2020: PBMR, NGNP & Other Near Term Projects

2007

South Africa

+

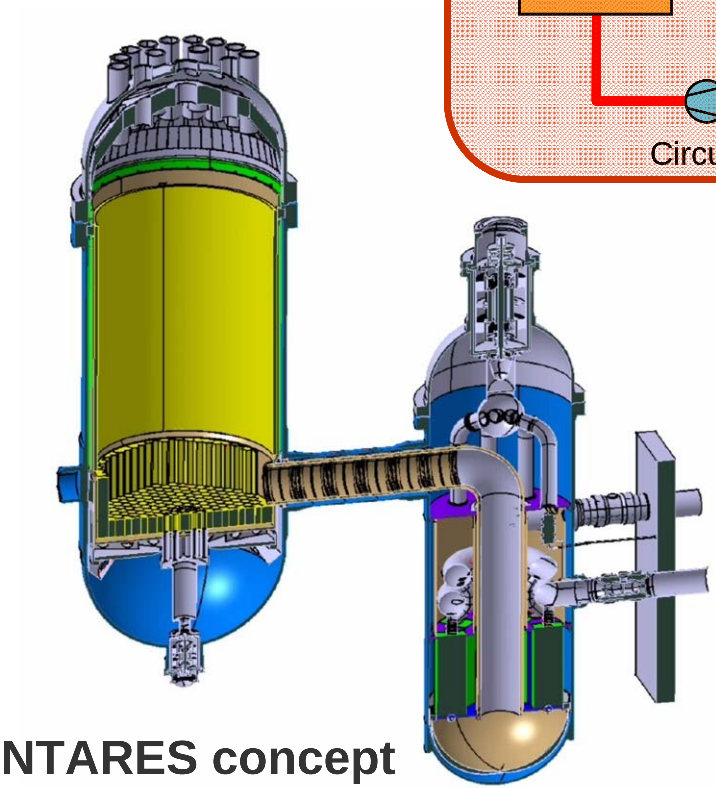
China



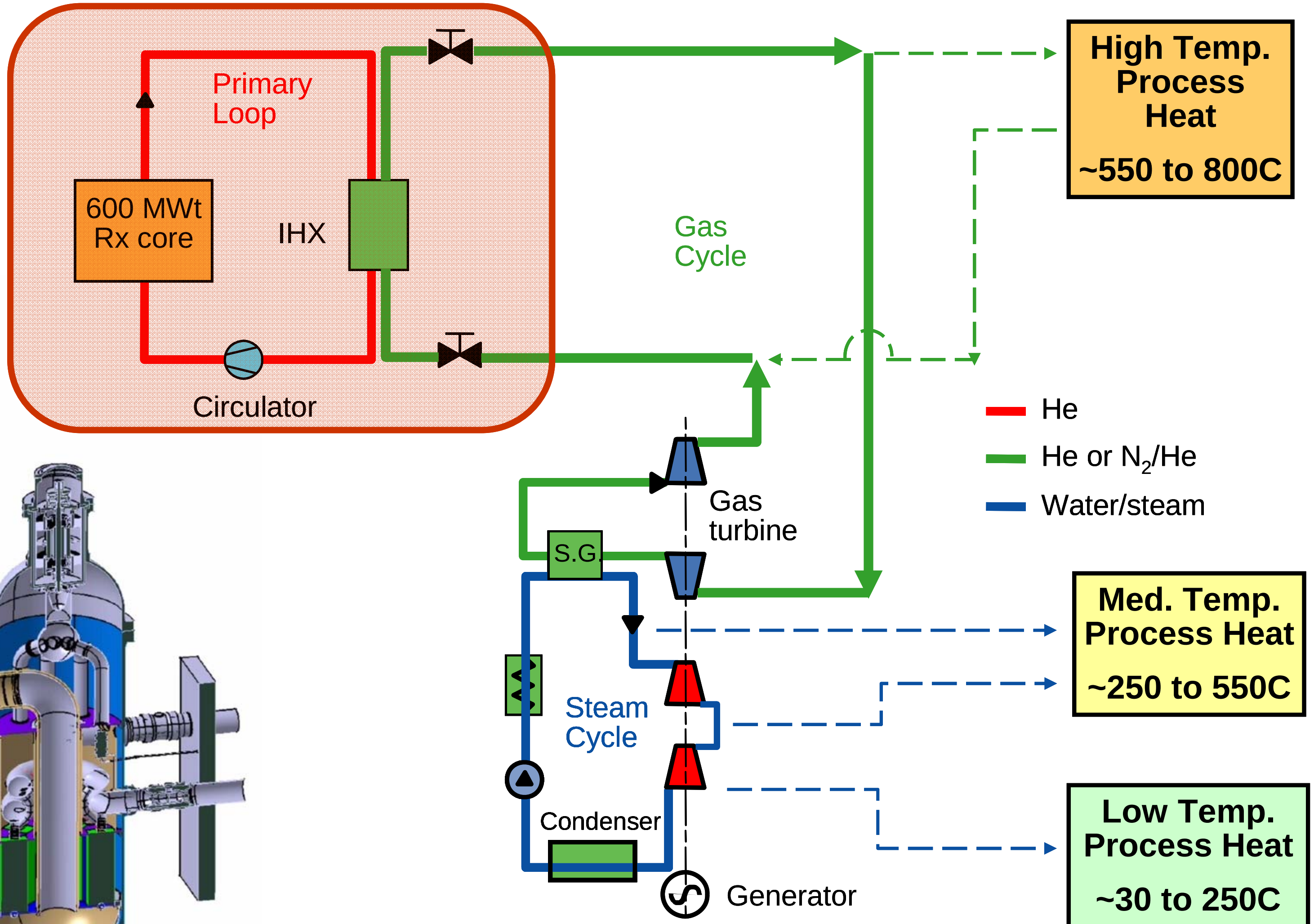
ANTARES: a multipurpose nuclear heat source for hydrogen and process heat production

A-HTR

ANTARES PROJECT

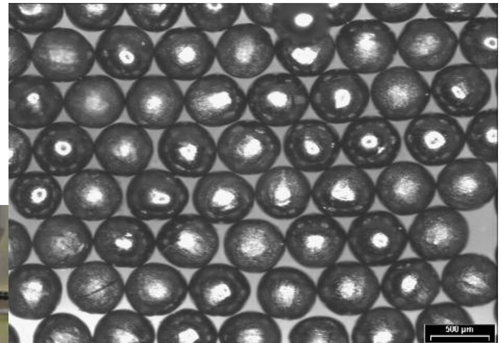


ANTARES concept (600 MWt, 850°C)

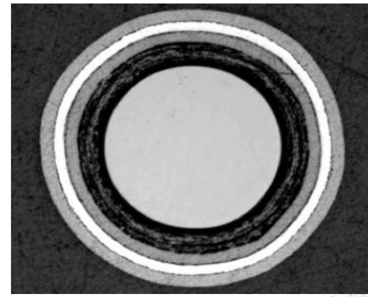


R&D on VHTR fuel manufacturing

GAIA fabrication line (CEA Cadarache)
(under operation since mid 2005)



UO_2 kernels



ZrO_2 TRISO
SiC particle

Sol-Gel apparatus

Kernel manufacturing

Drying calcination furnace

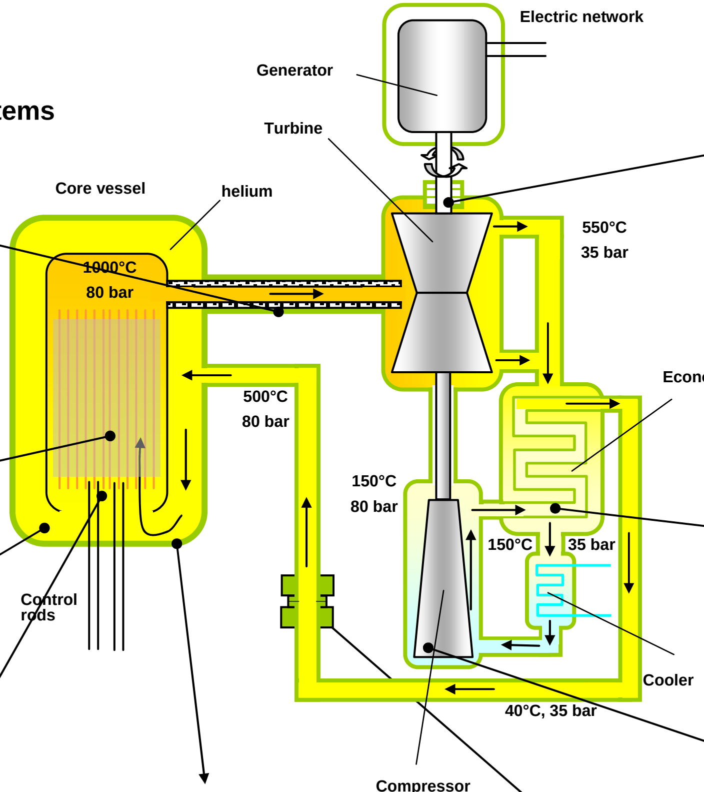
CVD line

TRISO particle coating

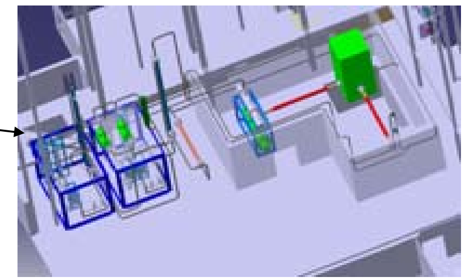
R&D on helium technology and components

Thermal insulation systems for hot gas pipe

Dynamic He tightness systems

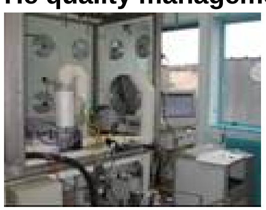


He components (heat exchangers, cooler, circulator, valves)



Graphite oxidation in HTR reactor core

He quality management



Wear and friction (operability of CRDM)

Mechanical behavior of welded junctions

Static He tightness

He compressor/circulator

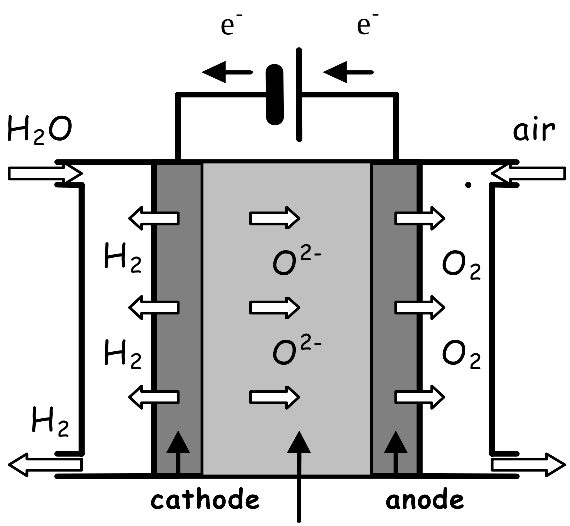
Nuclear production of Hydrogen

R&D on two main processes

An important mile-stone in 2008 about feasibility and performances

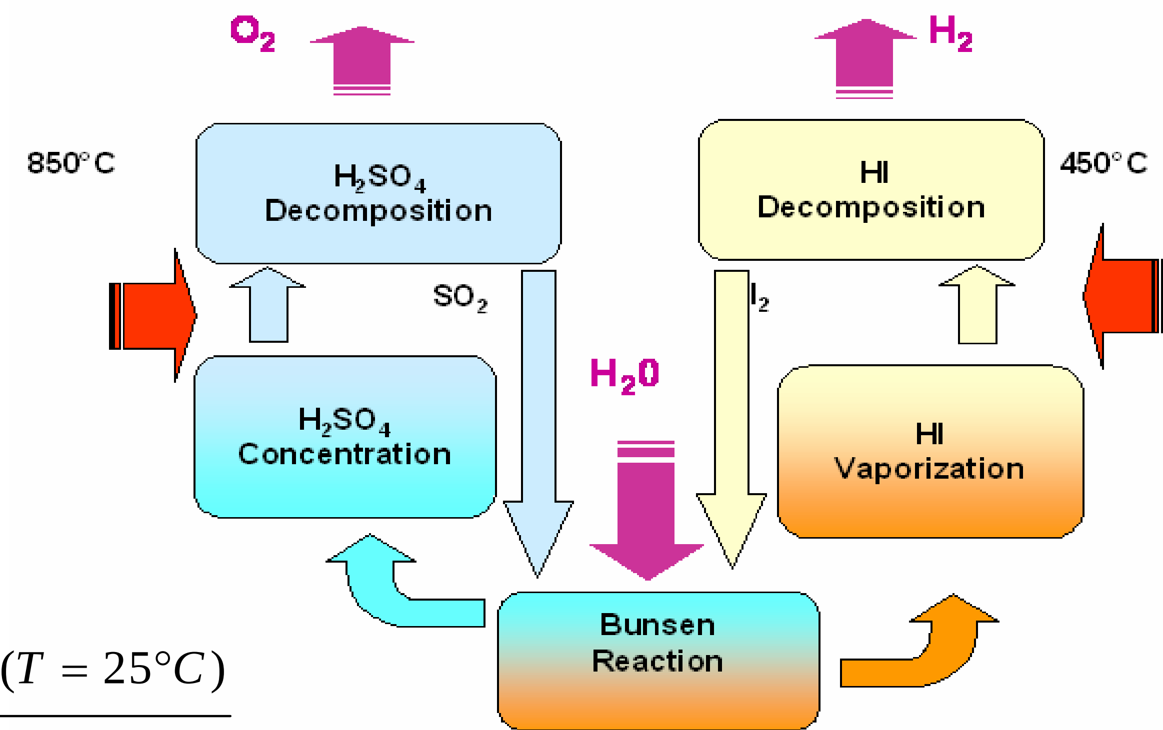
Many collaborations : Europe, Gen IV, USA, Japan

HIGH TEMPERATURE ELECTROLYSIS



$(ZrO_2)_{0.91}(Y_2O_3)_{0.09}$

IODINE/SULFUR CYCLE (I/S)



MATERIALS PROBLEMS…

$$\eta = \frac{\Delta H^0_{H_2O}(T = 25°C)}{Q + \frac{W}{\eta_{el}}}$$

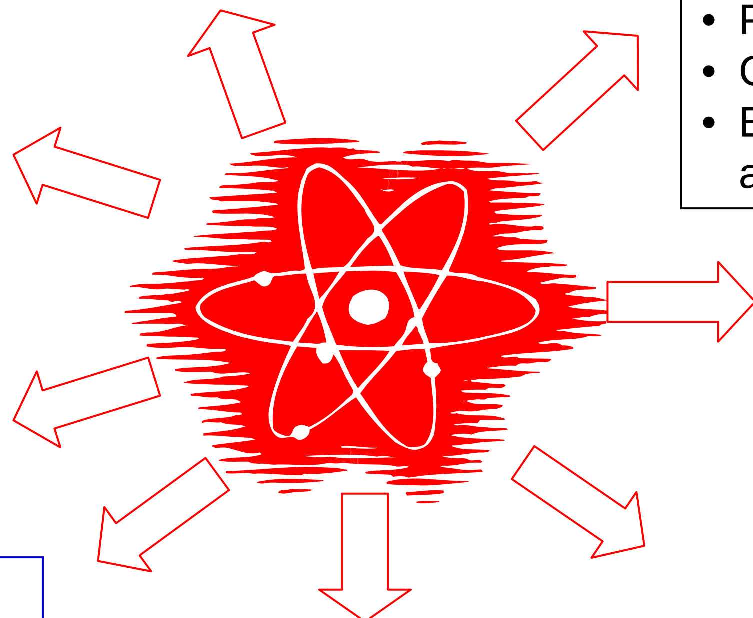
SEARCH FOR AN IMPROVED EFFICIENCY 35% → >50% ?

Potential applications of process heat for the industry

Paper mill
- Production of paste
- Drying

Oil companies
- Reffinery
- De-sulfurization of heavy oils
- Production of gas
- Coal gazification
- Extraction from oil shales and tar-sands

Cement industries
- Production of cements
- Production of lime



Metallurgy
- Steel making

Electricity
- Electric production

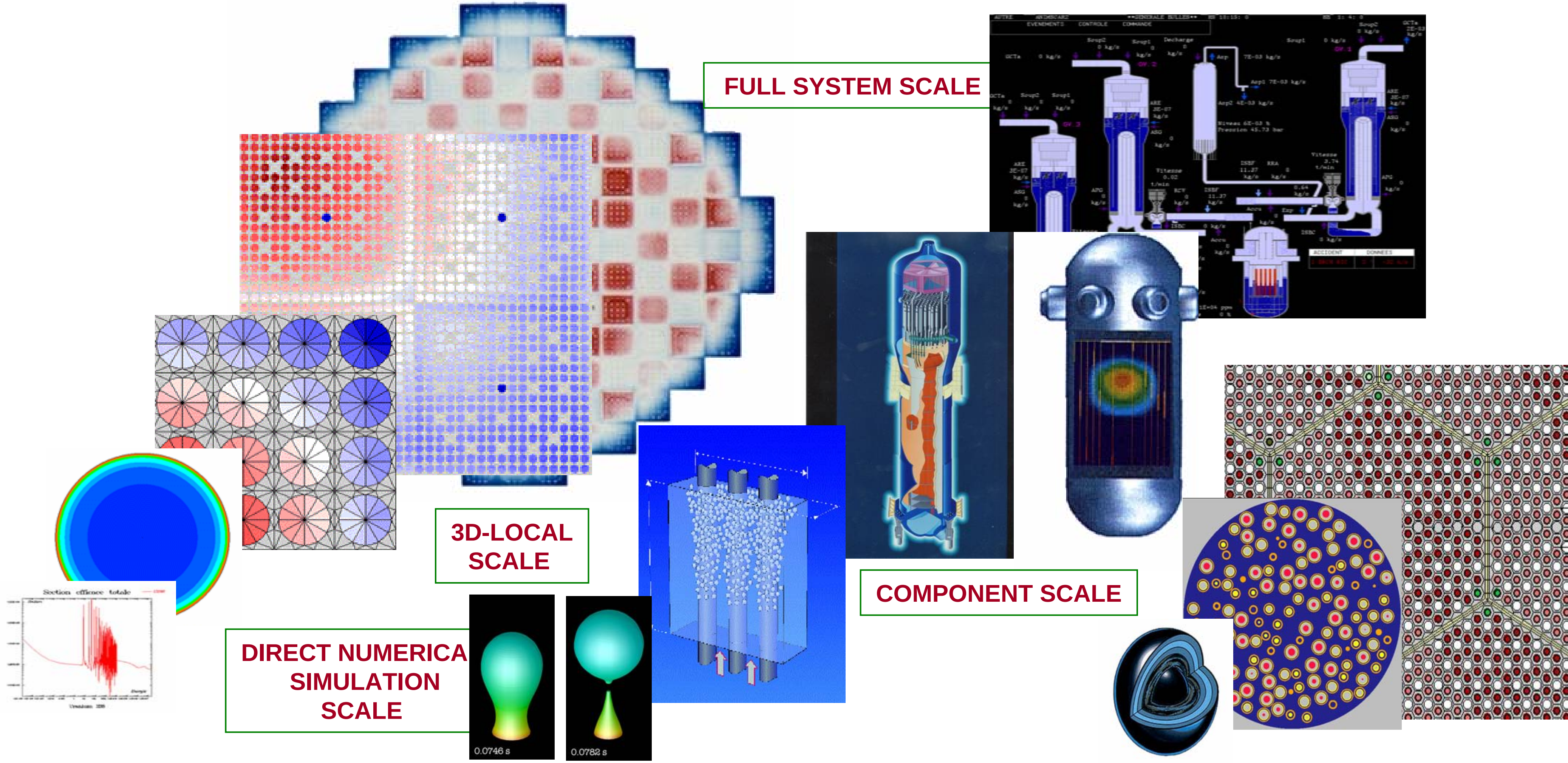
Chemical industries
- Hydrogen production
- Ethylen production
- Styren production
- …

Other industries
- Production of other metals *(aluminum, …)*
- Glass making

Others
- Sea water desalination
- District heating

Computational tools for current and future nuclear systems

Simulation: - *Multi-physics, multi-scale modelling*
- *Co-developed numerical platforms*

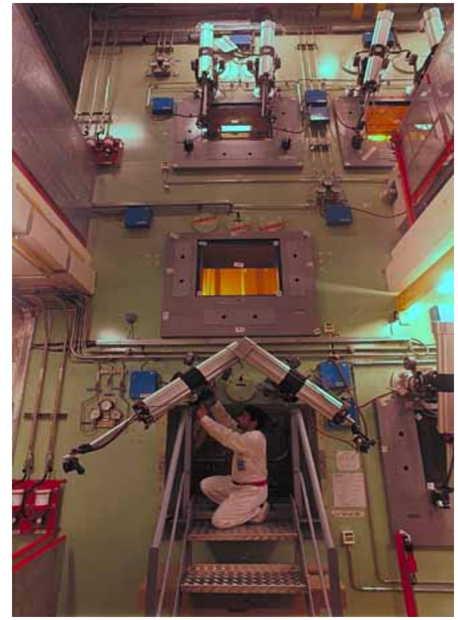


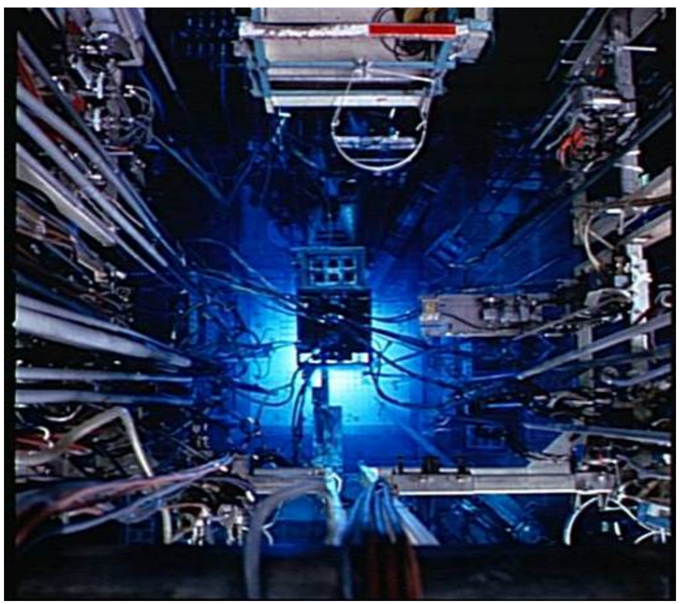
Development of Nuclear experimental facilities

➢ Research Reactors

- ✓ OSIRIS, ORPHEE, HFR, LVR-15…
- ✓ PHEBUS, CABRI
- ✓ EOLE, MINERVE, MASURCA

- Jules Horowitz Reactor ➔ 2014





➢ Hot laboratories

- ✓ LECI
- ✓ *PE-LECI*
- ✓ LECA-STAR
- ✓ ATALANTE…

Strategic Techno for Sustainable Nuclear Systems *(1/2)*

➢ Advanced spent fuel recycling processes

✓***Stakes:*** International non-proliferation standards

✓***Status:*** Experience of existing spent fuel treatment plant, R&D on advanced treatment processes, Pilot-scale demonstration facilities of these processes (~2017) to provide driver and experimental TRU fuels for the Fast Reactor Prototypes (> 2020)

➢ Advanced fuels *(incl. MA bearing fuels for Fast Reactors)*

✓***Stakes:*** International non-proliferation standards

✓***Status:*** first tests of MA bearing fuels in Phenix, dynamic R&D, International demo of integral recycling in MONJU (GACID), Advanced recycling Demonstrations planned in Fast Reactor Prototypes (>2020)

➢ Advanced materials for the core and reactor systems

✓ ***Stakes:*** techno breakthroughs for fast neutron & high temperature reactors

✓***Status:*** Active R&D on advanced steels *(austenitic, ferritic/martensitic, ODS)* + SiC_f-SiC & other composite ceramics: a synergistic R&D field with Fusion techno. *(key feasibility issues for the Gas Fast Reactor)*

Strategic Technologies for Future Nuclear Systems (2/2)

➢ Innovations for sodium & other Fast Reactors

✓***Stakes:*** innovations to advance sodium Fast Reactor systems and technologies beyond EFR, MONJU and the Indian PFBR (500 MWe)
→ Progress on *1 – Investment, 2 – Safety, 3 – Operation*

✓***Status:*** experience derived from Phenix, Superphenix, BN600, FFTF… Current effort to select innovative design features by ~2012, to be demonstrated in Fast Reactor Prototypes or Technology Demonstrators (> 2020)

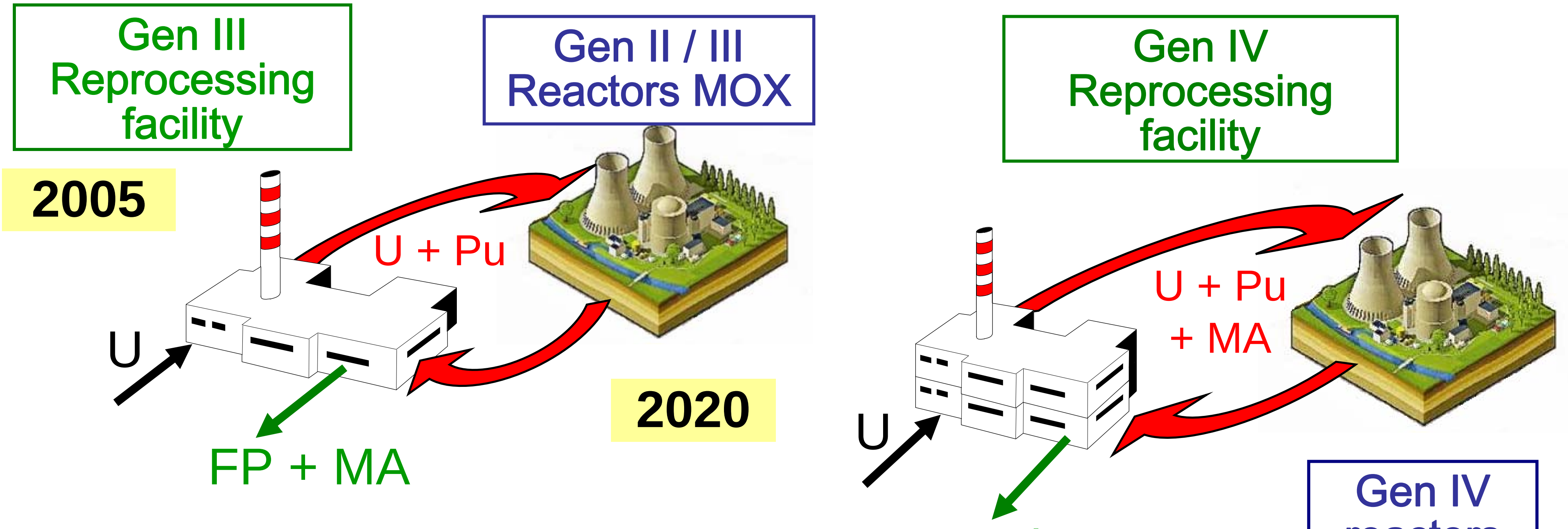
➢ Other innovations for nuclear systems *(gas turbine power conversion, co-generation of heat, hydrogen, synthetic hydrocarbon fuels…)*

✓***Stakes:*** widening the range of nuclear applications; developing potential key technologies for future nuclear energy systems for the national and the international markets

✓***Status:*** medium term projects of V/HTRs *(PBMR, NGNP, GT-HTR300, PMR…),* dynamic R&D on V/HTR fuel, system technology, HT heat exchangers & power conversion, hydrogen technologies, production of synthetic fuel from coal or biomass…

Phased Development of Gen III & IV Reactor & Fuel cycle

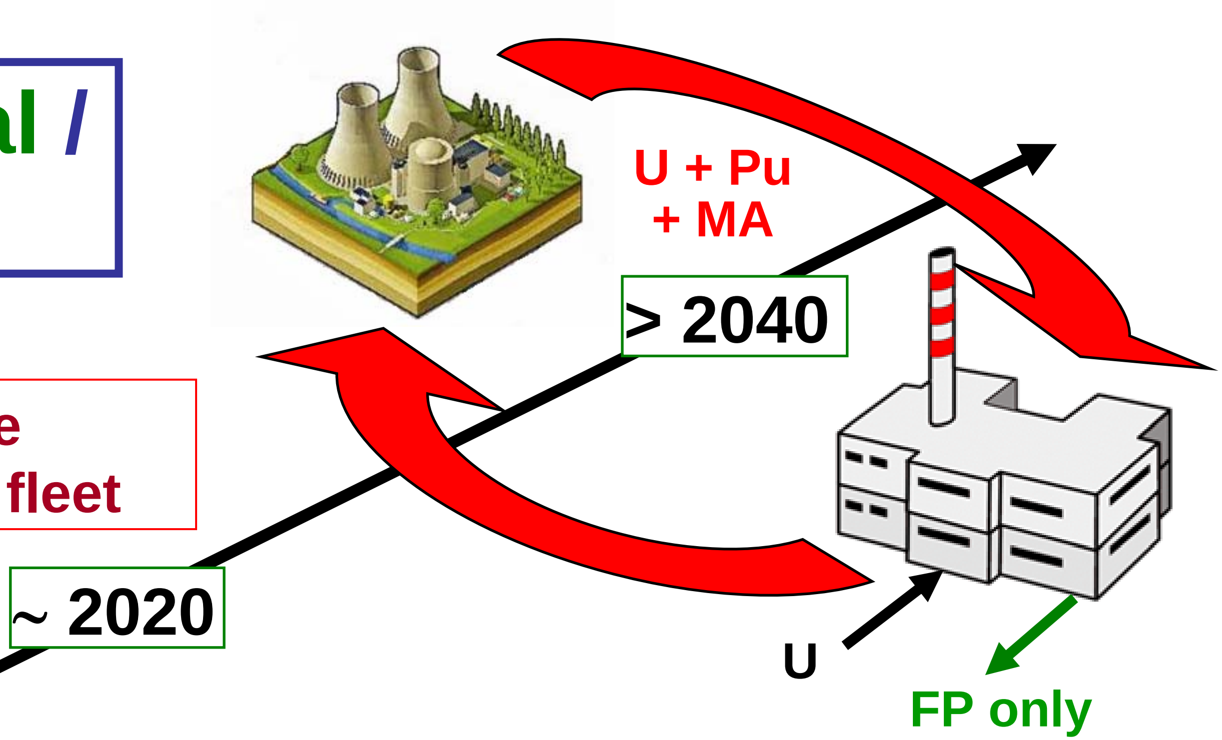
- Natural resources conservation
- Waste minimisation
- Proliferation resistance

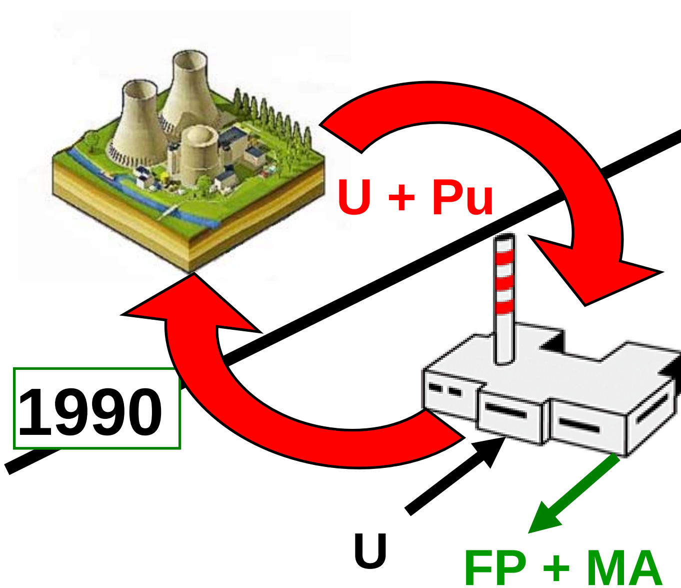


Fuel cycle technology aligned with nuclear reactor technology

International / National

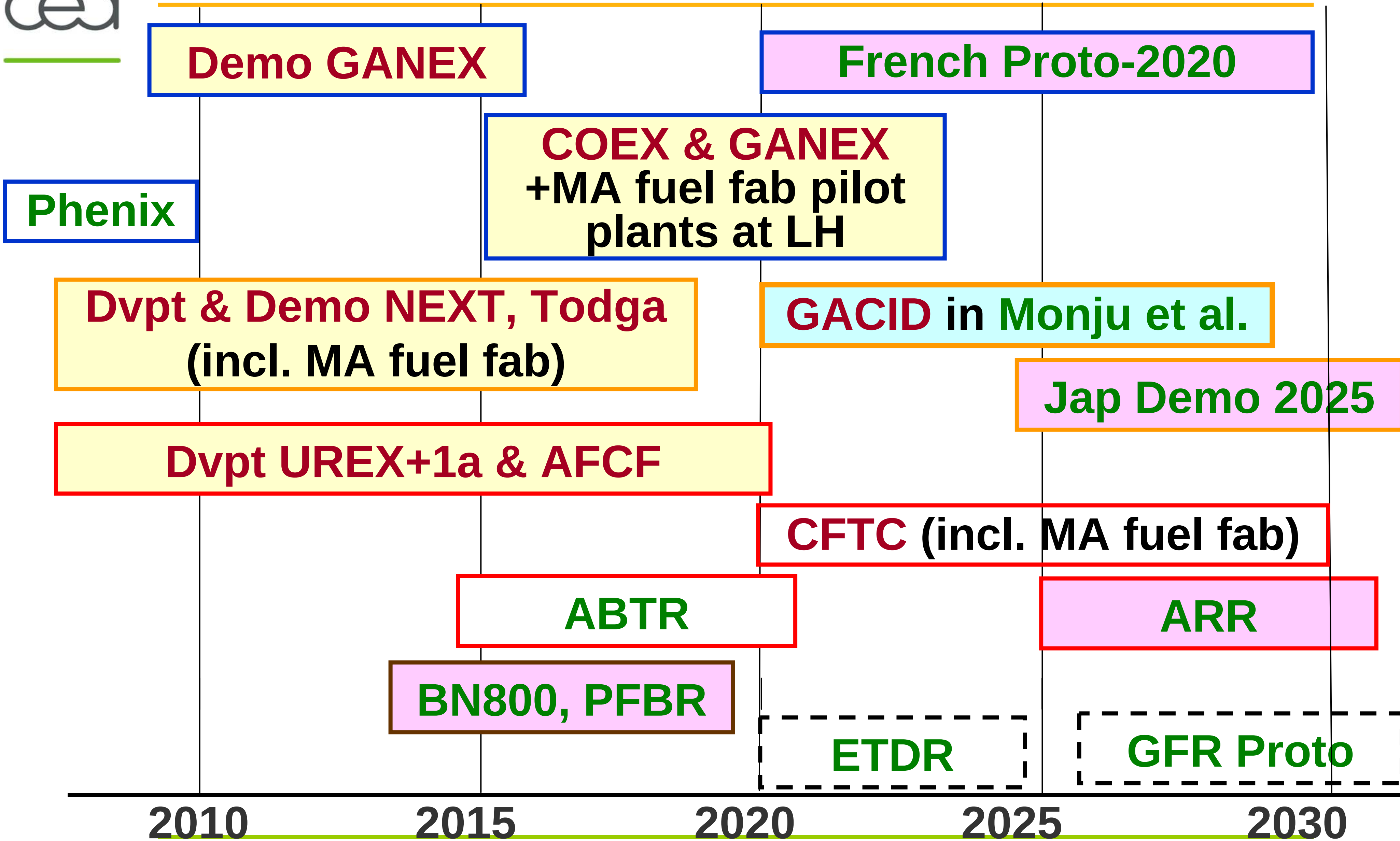
- Past experience / Time line
- Legacy of current nuclear fleet





- Safety standards / Codification
- Non-proliferation standards
  + Physical protection, Safeguards…
- Resource utilization
- Waste form
- Technology

International Roadmap for Sustainable Nuclear Systems



Summary and perspectives

- International cooperation on future nuclear systems *(Gen IV, INPRO…)*:
  - ✓ Fast Reactors & closed fuel cycles ***for sustainability***, and
  - ✓ High Temperature Reactors for **co-generation** *(H_2, Synfuels, Process heat)*
  - → ***Updated goals: Competitiveness, Safety, Non-proliferation, Physical protection***
  - → ***A dual approach on Fast Neutron Systems: SFR + GFR, LFR…***
  - → ***Development of V/HTRs by the industry*** *(Customers & Vendors)*
  - → ***Innovative concepts & technologies for LWRs*** *(Fuels, Core, Systems)*

- Scientific challenges in ***MA-fuels, Recycling, Structural materials, System innovations*** *(RCS, PCS…):*
  - ✓ Key role of Simulation and Large experimental facicilties *(MTR, Hot Labs)*
  - ✓ Significance of international cooperation *(R&D + Demos GACID…)*
  - → ***Demonstrations in Joyo/Monju, US-ARR, Prototypes FR-2020, JP-2025…***

- Towards a parallel & phased development of reactor & recycling technologies
  - ✓ Federation of national initiatives into an international technology roadmap
  - → ***Enhancing R&D and technology demonstrations*** *(Gen IV, EU FP7…)*
  - → ***Progressing towards harmonized international standards*** *(safety, PR & PP)*