Outlook on France's R&D Strategy on Future Nuclear Systems

From Gen II to Gen IV reactors and fuel cycle

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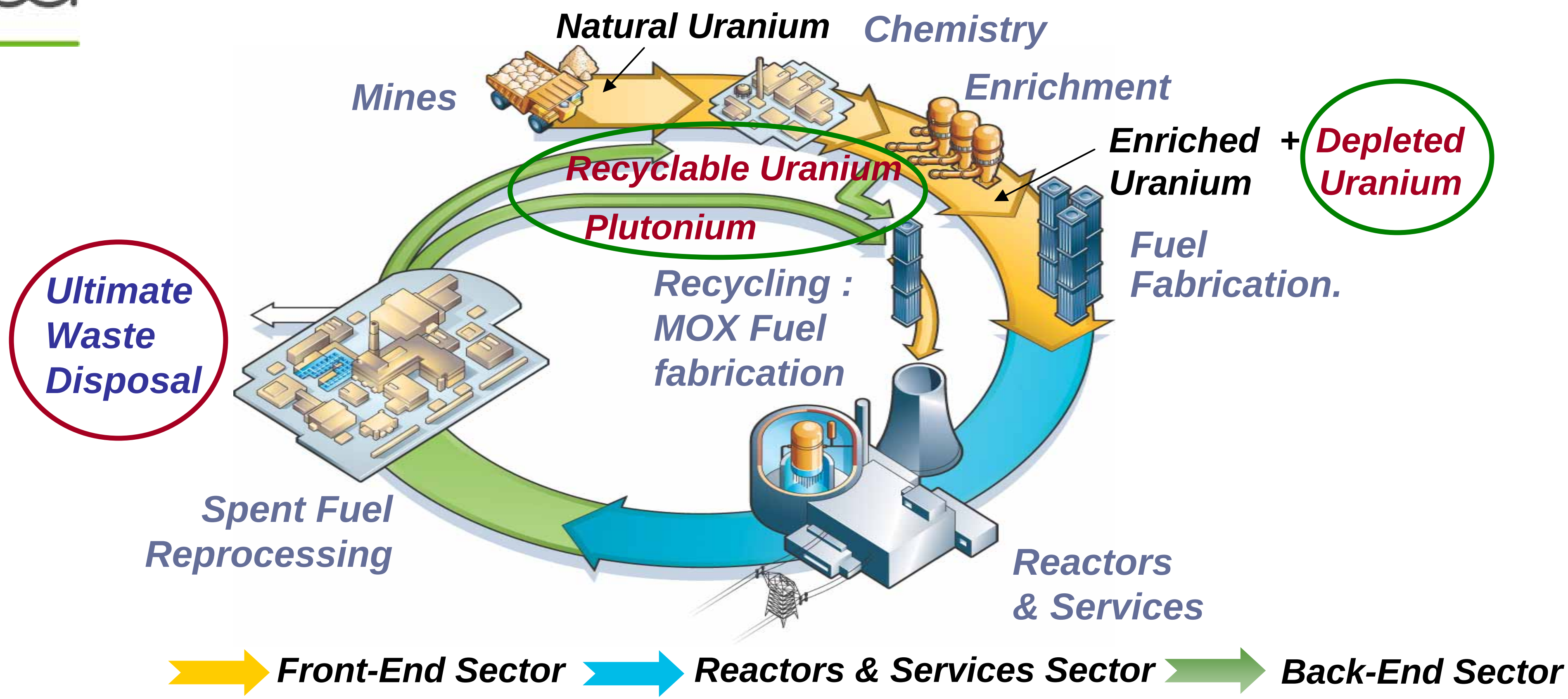
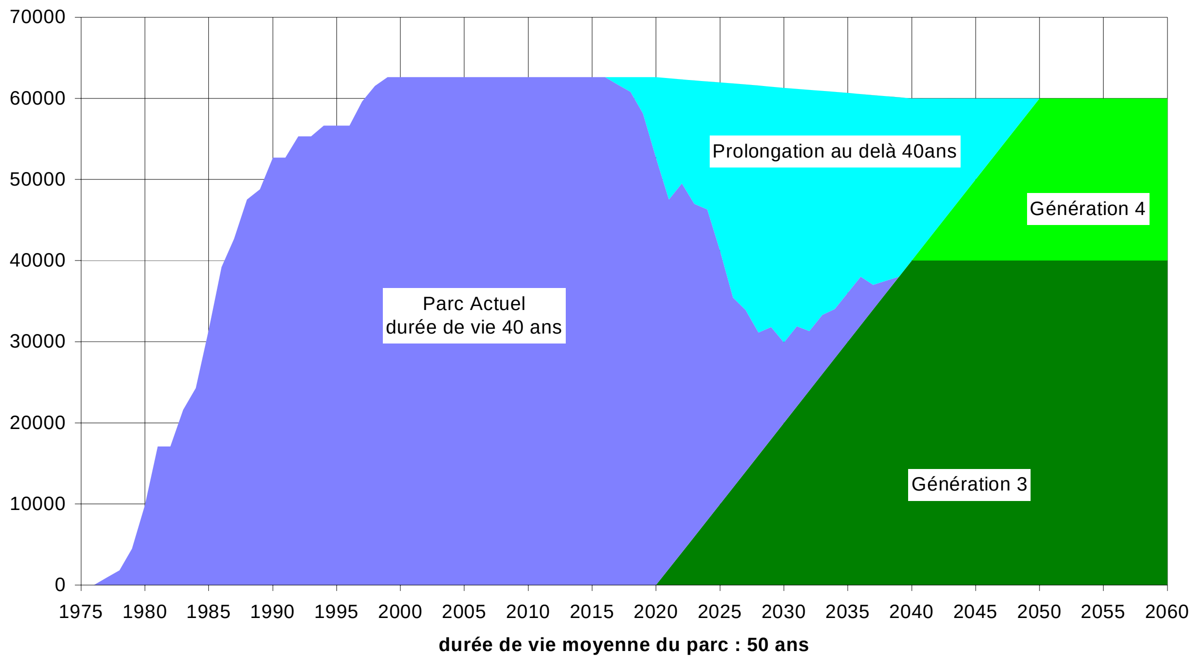
Closing the Fuel cycle… an industrial reality



- ✓ **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**

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

Prepare the *Generation III* reactor: EPR

EPR: a mature LWR based on operating PWRs' current experience and materializes significant advances in terms of safety and economic competitiveness

EPR (2010) under construction in Finland at Olkiluoto (TVO)

EPR (2012) Flamanville (EDF)

July 2005: French Energy orientation Act
→ a *Gen III* plant operational by 2012

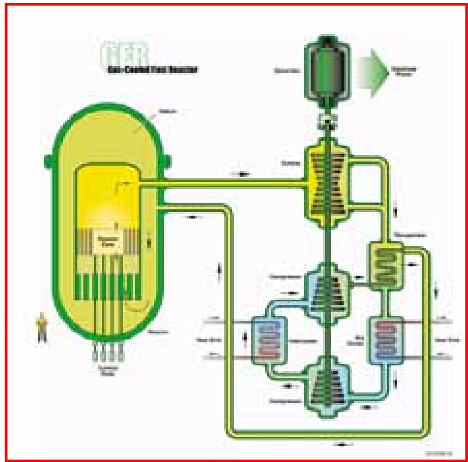
Oct 2005 – Feb 2006: public debate to build a FOAK EPR in Flamanville

R&D Strategy of France for Future Nuclear Energy Systems

Approved by the Ministries of Research and Industry on March 17, 2005

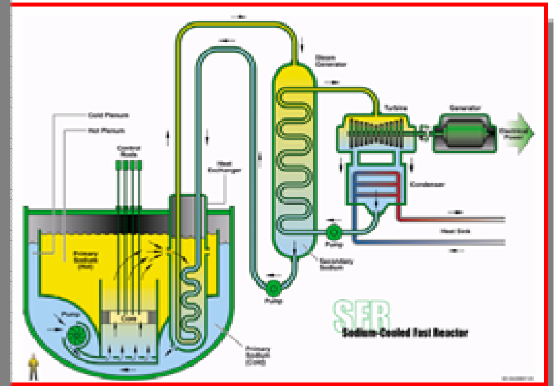
1 - Development of Fast Reactors with a closed fuel cycle:

- *Sodium Fast Reactor (SFR)*
- *Gas Fast Reactor (GFR)*
- *New processes for spent fuel treatment and recycling*



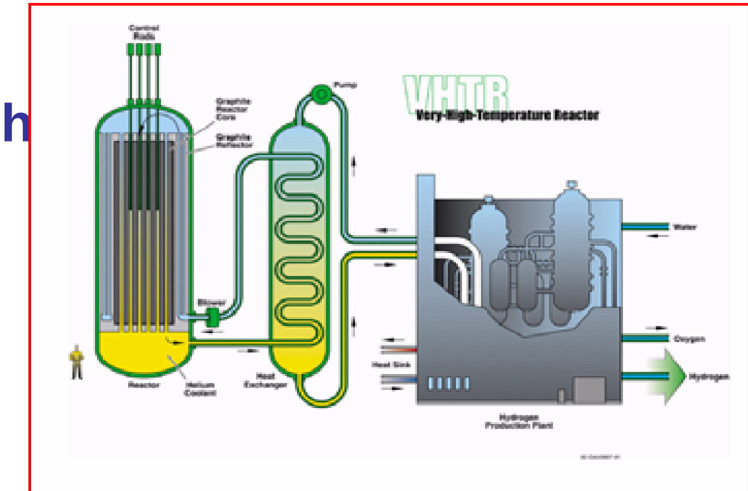
Gas Fast reactor

Sodium Fast Reactor



2 - Nuclear hydrogen production and very high temperature process heat supply to the industry

- *Very High Temperature Reactor (VHTR)*
- *Water splitting processes*



Very High Temperature Reactor

3 - Innovations for LWRs *(Fuel, Systems…)*

A prototype reactor 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 ».*

R&D Plan for a Prototype in 2020 of Fast Reactor & Fuel Cycle

Confirmation of technical options

Selection of design features

Preliminary & detailed design studies, SAR, & Construction

1st phase of studies

↗ Techno R&D

2006 | 2009 | 2012 | 2015 | 2020

La Hague plant

La Hague plants

- Head-end
- 1st extraction cycle
- 2nd U cycle | 2nd Pu cycle

MA →

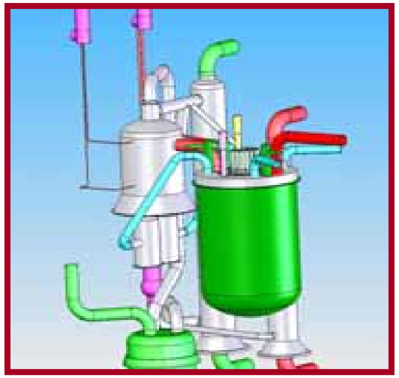
Experimental facility for MA

- MA separation
- MA fuel fabrication with remote handling
- 10's kg/yr

(U)PuO_2 →

MOX fabrication (prototype)

- Pu ~ 20 %
- 5-10 t/yr

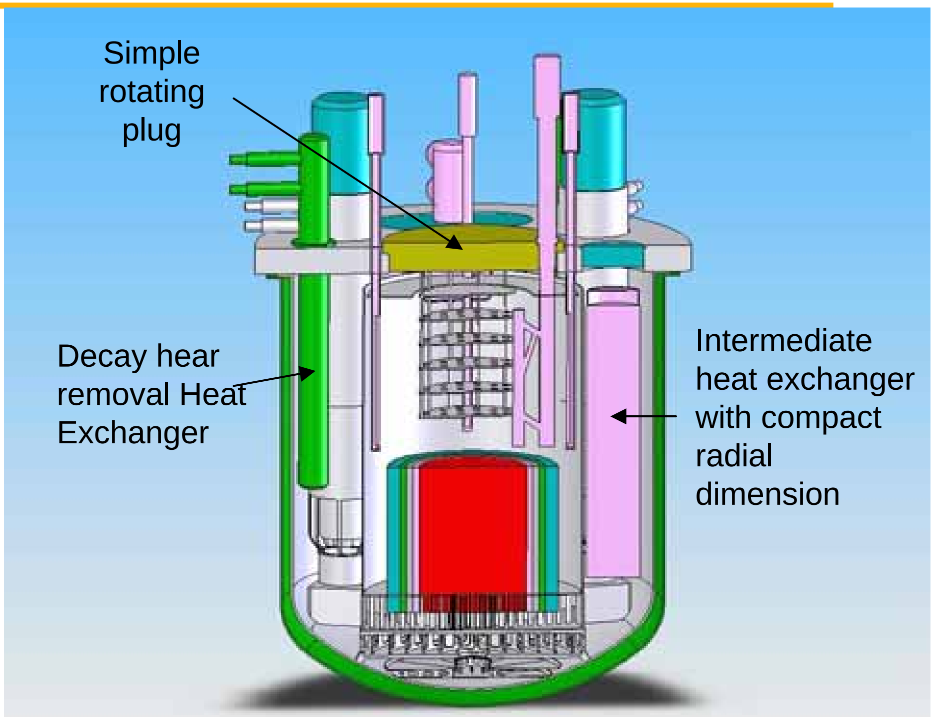


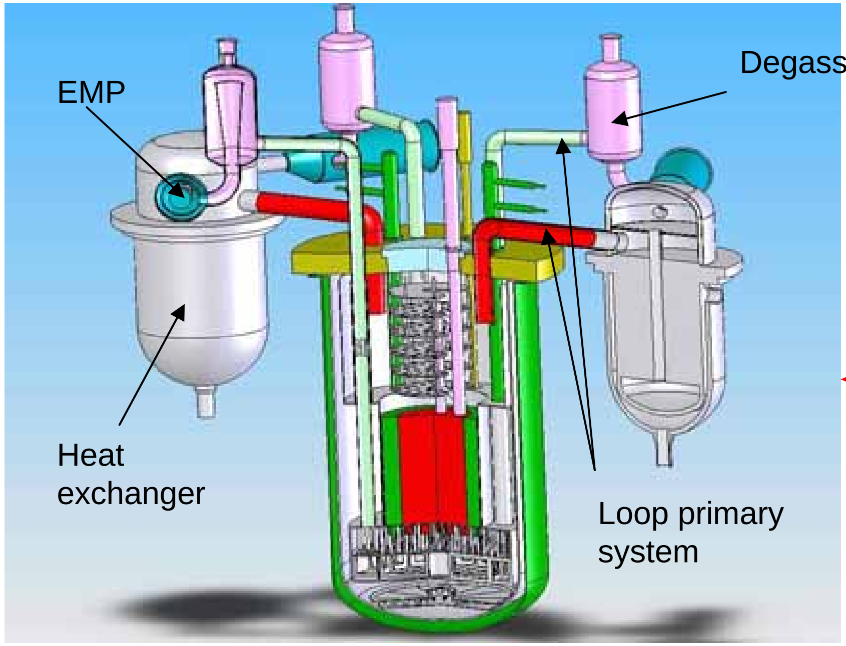
Reference technologies selected in 2012

Sodium Fast Reactor innovative designs *(SFR) (1/3)*

Large pool type

1500 MWe optimized size





Modular concept with gas conversion system

SFR Innovative core design *(SFR) (2/3)*

Core design features optimized for reduced void worth:

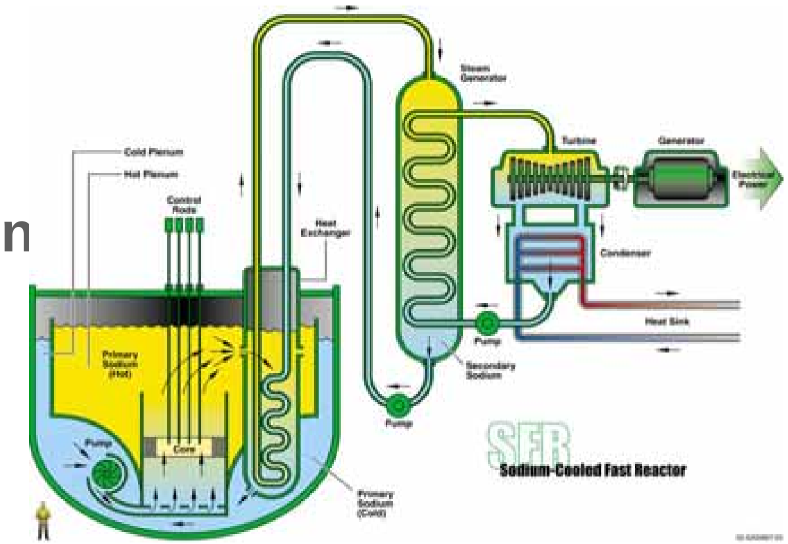
- ✓ Breeding Gain BG ≥ 0
- ✓ Minimizing Pu inventory
- ✓ Minimizing core size for keeping an attractive power density

	EFR oxide	Oxide	Carbide
Void worth ($)	8.7	4.5	4.2
Doppler worth ($)	1.3	1.4	1.6
Internal Breeding Gain	- 0.13	+ 0.04	+ 0.11
Pu inventory (tons)	8.8	10.5	8.5
Power density (MW/m^3)	303	230	290

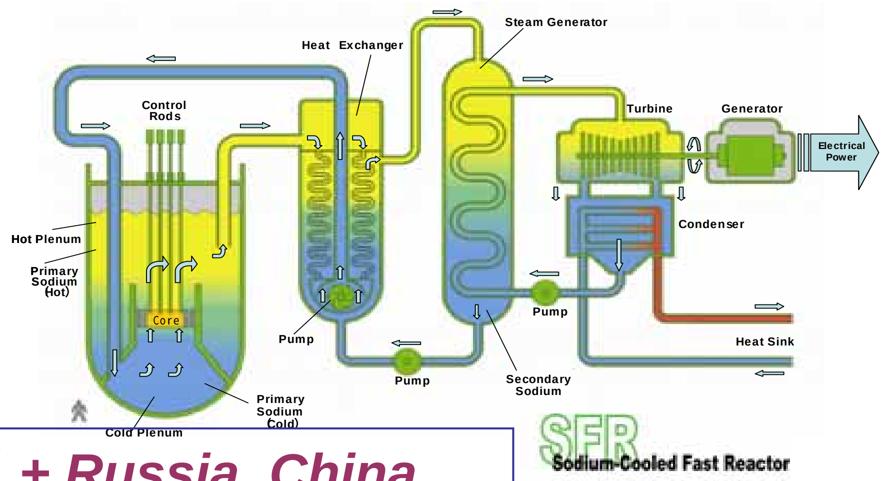
Attractive solutions exist.
To be checked more precisely against technology constraints

Sodium Fast Reactor *(SFR) (3/3)*

- **A new generation of sodium cooled Fast Reactors**
- **Reduced investment cost**
  Simplified design, system innovation
  (Pool/Loop design, ISIR – SC CO_2 PCS)
- **Towards a passive safety approach**
- **Integral recycling of actinides**
  Remote fabrication of TRU fuel



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



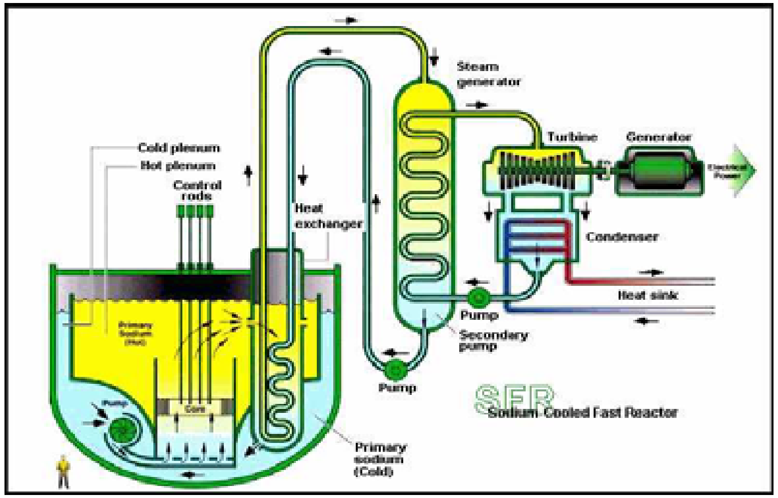
+ Russia, China …

GFR: an alternative Fast Reactor to SFR *(GFR) (1/3)*

SFR

A significant past experience and innovation objectives

- → **Reduction of investment cost**
- → **Safety level comparable to 3rd generation LWRs**
- → **Potential for integral recycling of actinides**

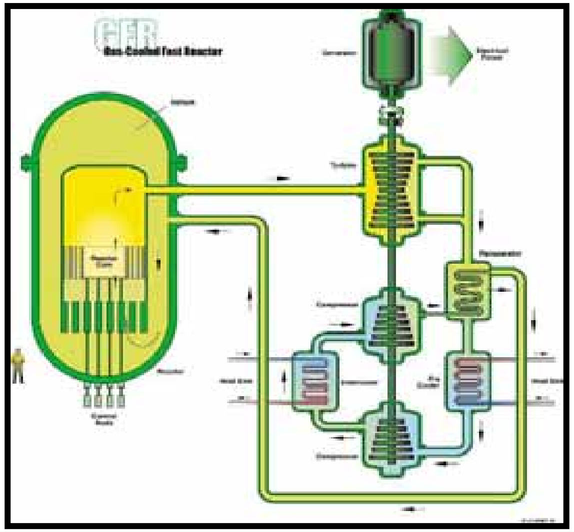


Milestone 2020: prototype (250-600 MWe)

GFR

An alternative FNR track based on:

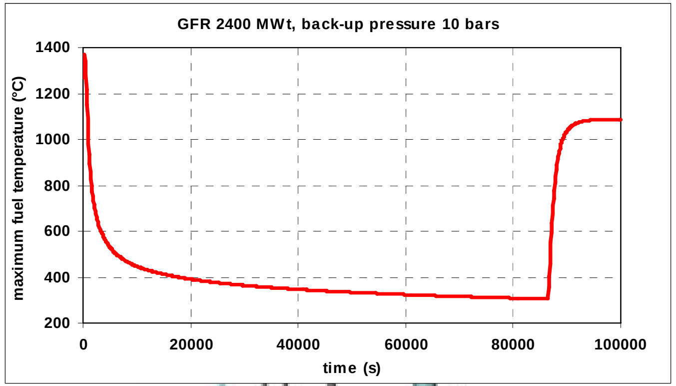
- → **Benefits from helium as a coolant**
- → **Robust fuel *(including severe accident conditions)***
- → **Potential for high temperature applications**

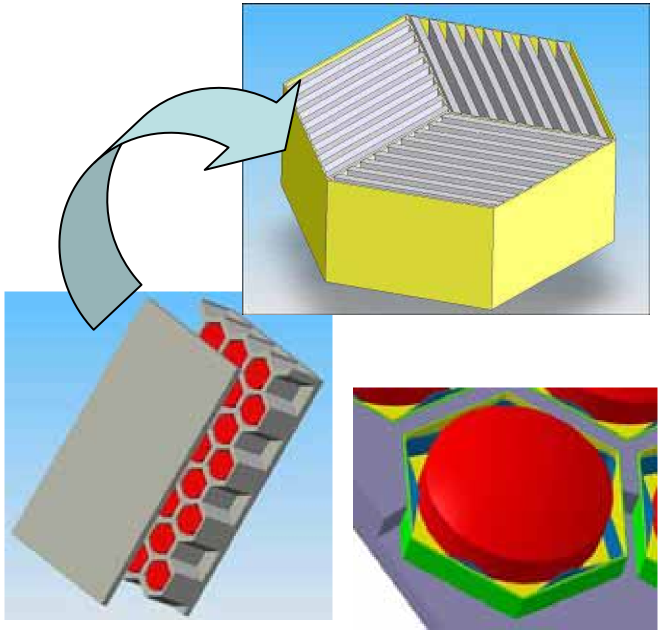


Milestone 2020: experimental reactor *(ETDR, 50 MWt)*

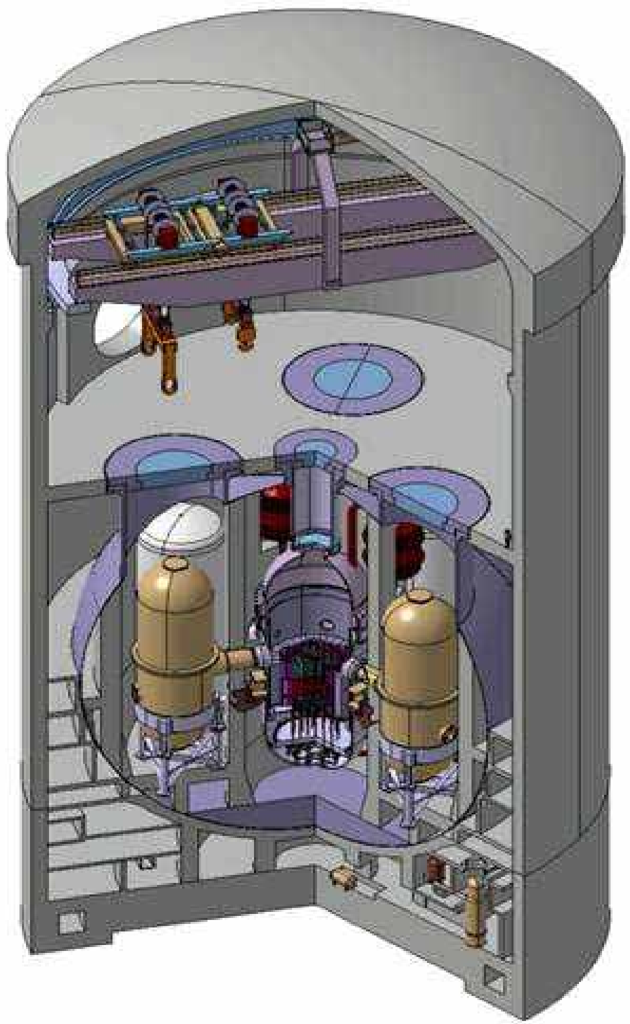
ETDR and GFR pre-conceptual designs *(GFR) (2/3)*

Robust decay heat removal strategy (passive after 24hrs)

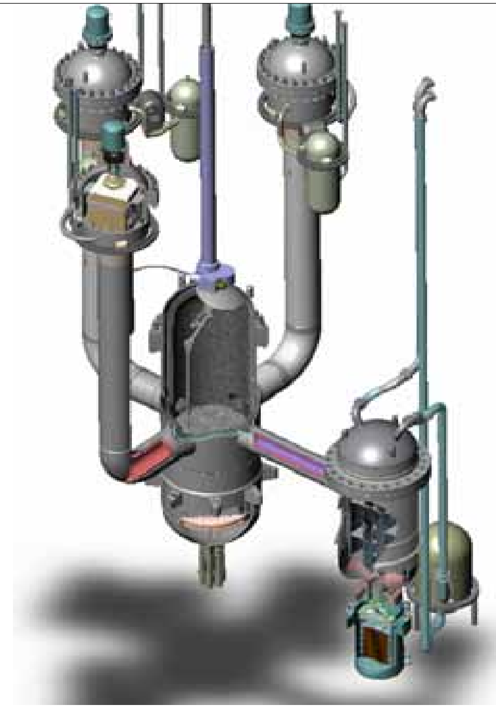




Innovative fuel



GFR 2400 MWt reference concept

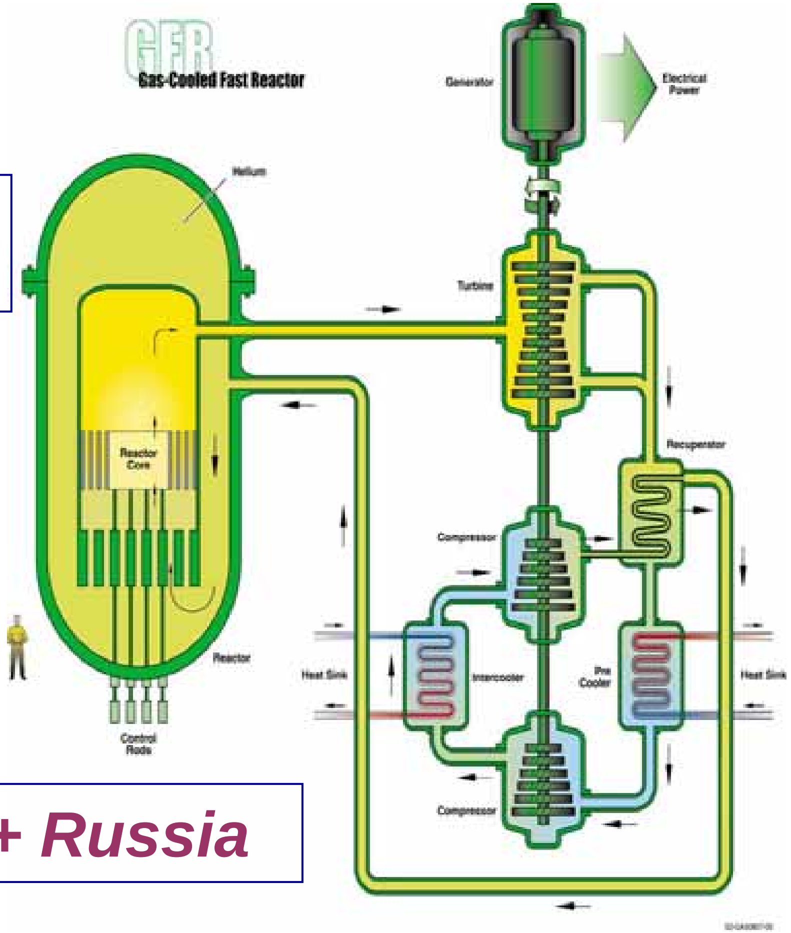


ETDR (50 MWt)

Gas Fast Reactor – Generation IV Forum *(GFR) (3/3)*

- **A new concept of Gas cooled Fast Reactor**
  → Natural uranium resource saving, minimum production of waste
- **Robust fuel** *(ceramics)*
- **1200 MWe – t He ~ 850 °C – Co-generation** *(electricity + H2)*
- **Active + passive safety approach**
- **Integral recycling of actinides**
  Remote fabrication of TRU fuel

→ 2012 : Feasibility → ~2020 : ETDR *(EU ?)*
2020 : Performance → 2025+ : Demo GFR



+ Russia

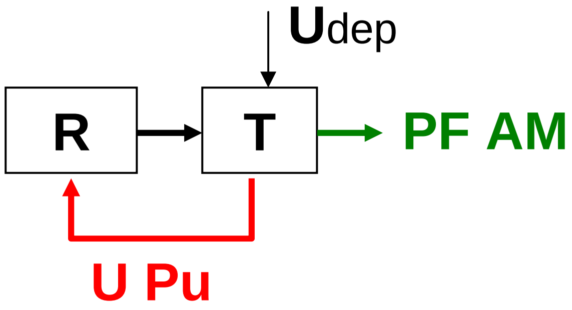
Options for a closed fuel cycle

→ Resource saving

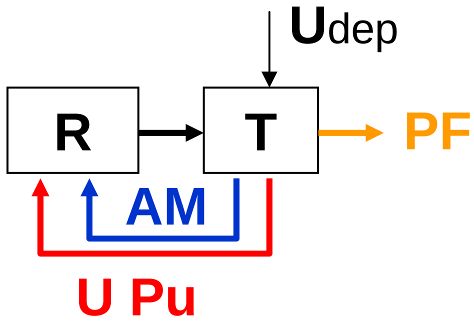
→ Waste minimization

→ Non-proliferation

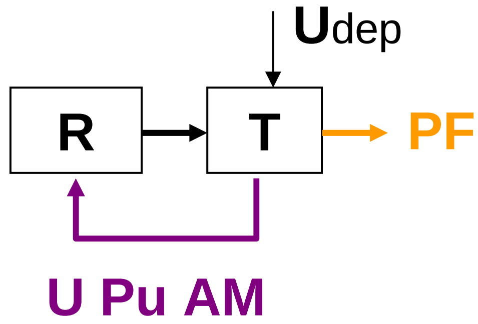
- Develop international non-proliferation standards to allow for diverse fuel cycle processes
- Keep all options open as they could be deployed in sequence



Recycling U Pu only



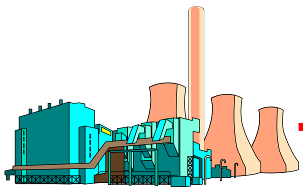
Heterogeneous recycling

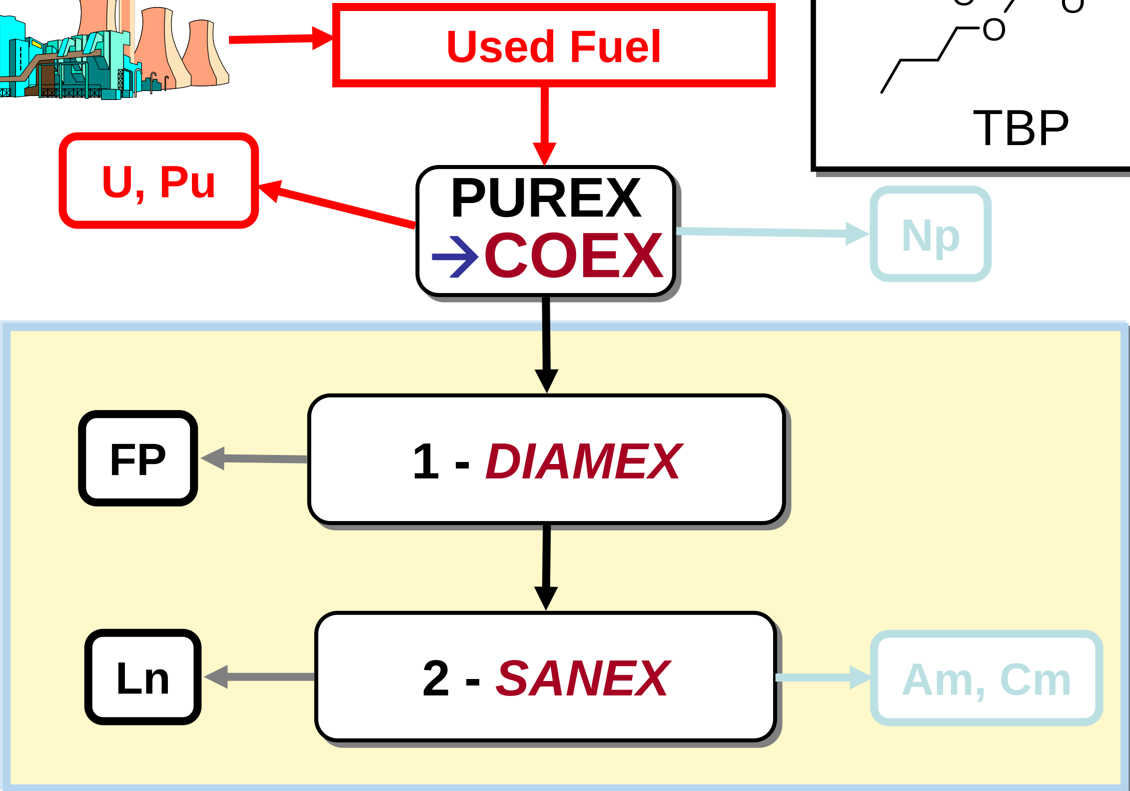


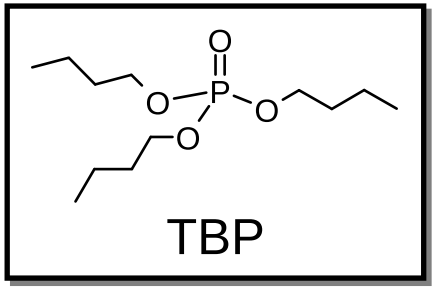
Homogeneous recycling (GenIV)

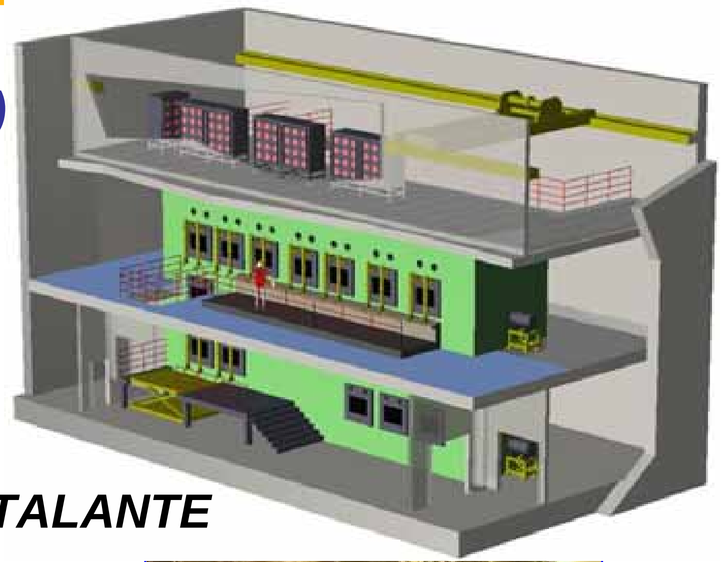
Minor actinide partitioning

Demonstration test on 15 kg of spent fuel implementing industrial technologies (2005)

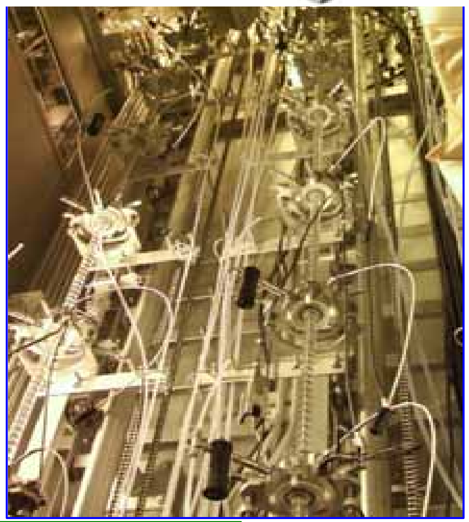








ATALANTE



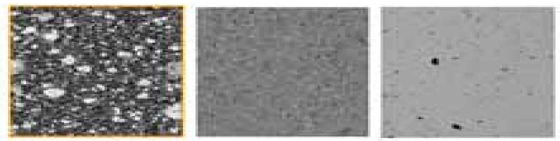
→ Towards GANEX, a Grouped Actinide Extraction Process

Prototype 2020: fuel cycle related needs

Two pre-industrial Pilot Plants:

- ✓ Fabrication of $(U,Pu)O_2$ fuel ***(COEX)*** *(a few tons/year)*
- ✓ Advanced separation and fabrication of Micropilot plant *(~10s kg/year)*
  GANEX → $(MA,U,Pu)O_2$ *as driver fuel*
  Diamex-Sanex → $(MA, U)O_2$ *as blanket fuel*

MOX X-ray micrography
MIMAS COCA COEX



Micro Pilot Plant
Diamex-Sanex, ***GANEX***

- **MA Separation**
- **…**
- **Fabrication**
  - **Tele-operated**
  - **Fuel pins**
- **a few 10 kg/y**

MA Fuels
- ***GACID in MONJU***
- ***Proto 2020***
- ***…***

A.M.

LA HAGUE Plant

CD	
Extractions	
MAU	**MAPu**

$(U)PuO_2$

MOX *(COEX)*
FN Proto 2020

- **Pu 20 %**
- **a few tons/year**

Commercial interest
- ***US***
- ***…***

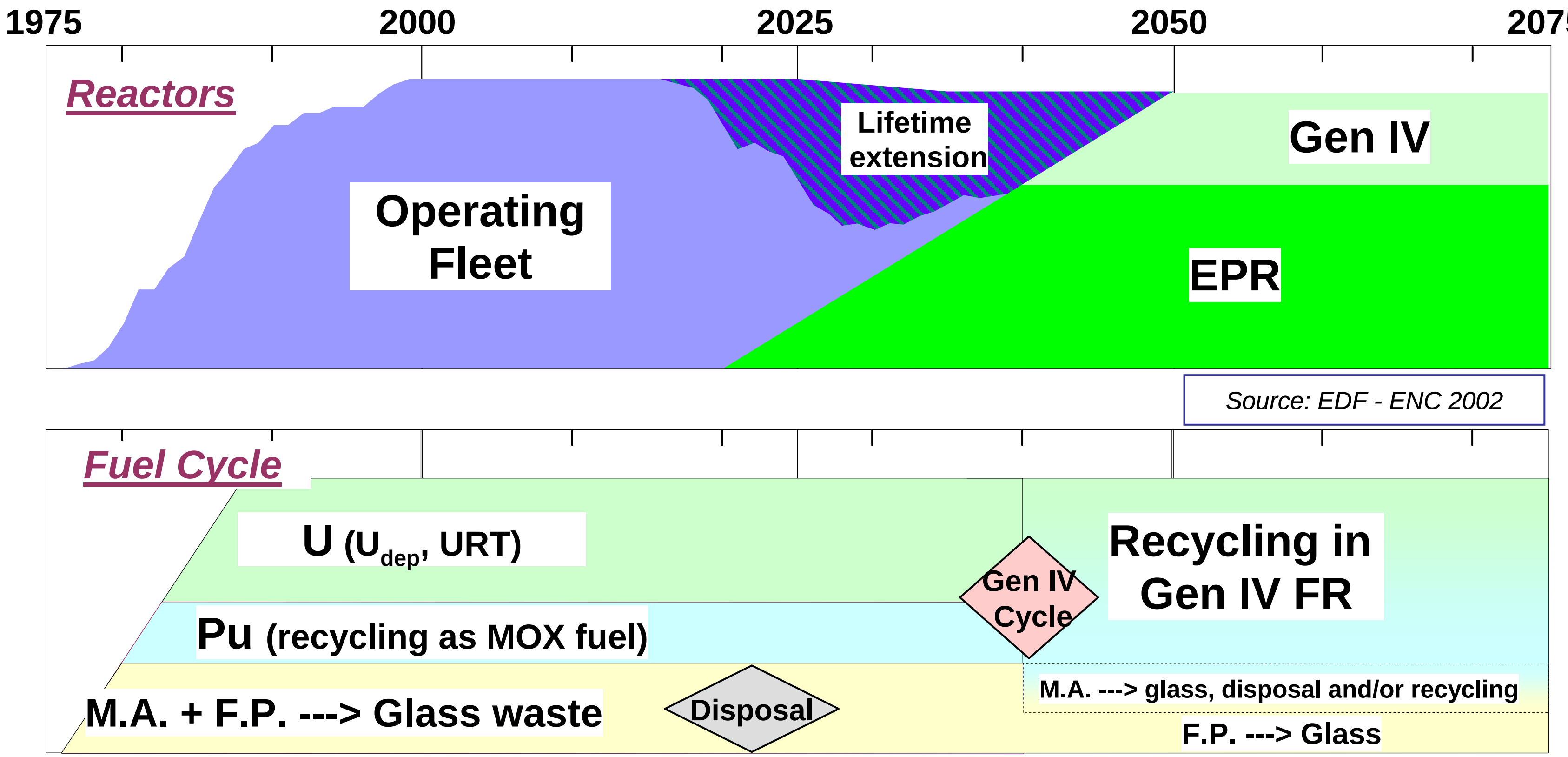
+ Participation in GACID: the Global Actinide Cycle International Demonstration (2015-2025)

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) –

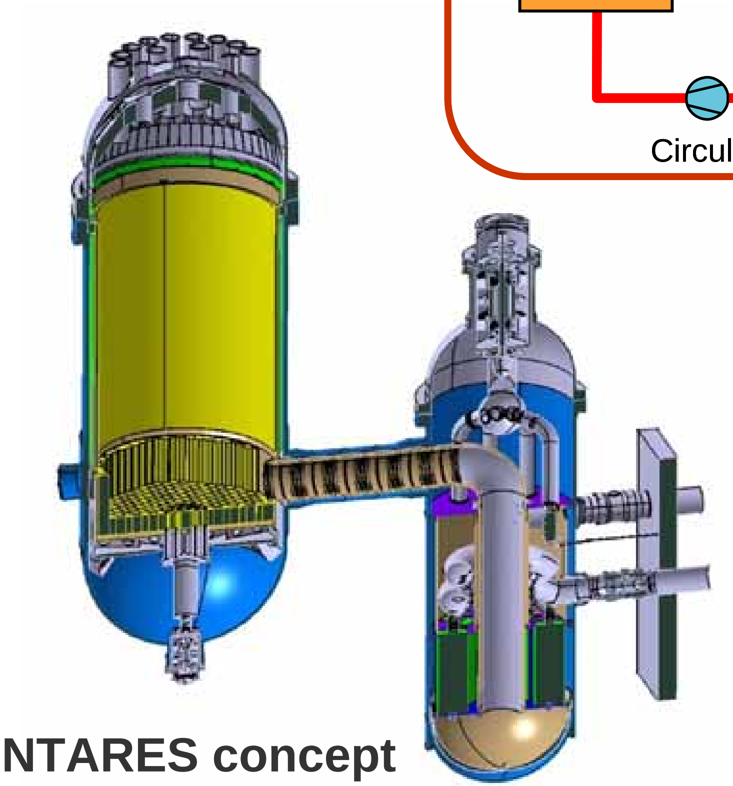
- **Future goal : Integral recycling of U-Pu-MA**
- **Interim goal : Recycling of U-Pu and separate management of MA** *(to waste or interim storage)*



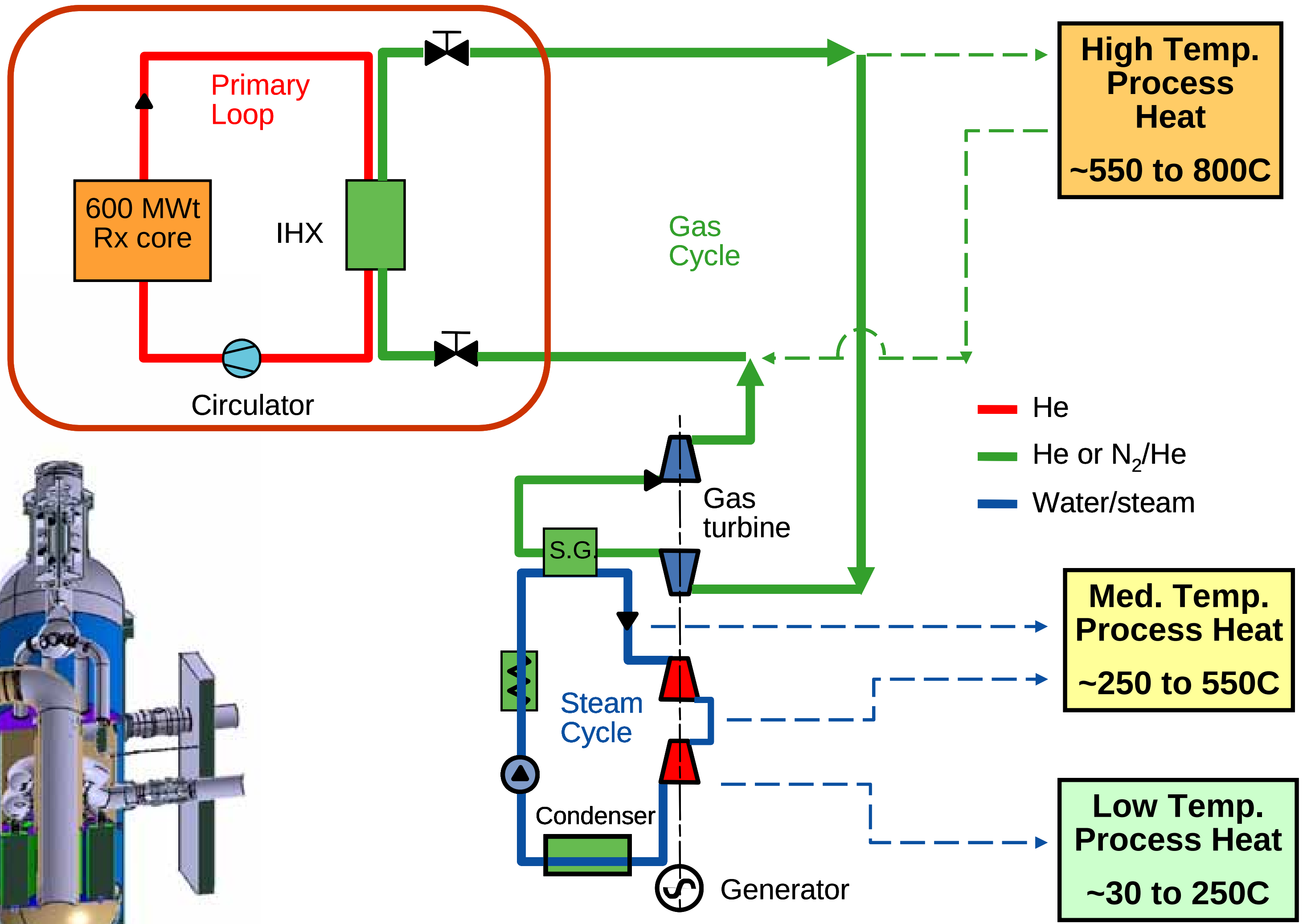
ANTARES: a multipurpose nuclear heat source for hydrogen and process heat production *(V/HTR) (1/6)*

A-HTR

ANTARES PROJECT



ANTARES concept (600 MWt, 850°C)

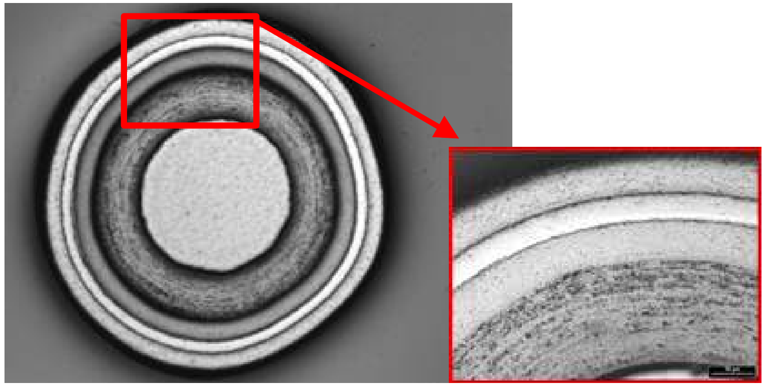


R&D on V/HTR fuel manufacturing *(V/HTR) (2/6)*

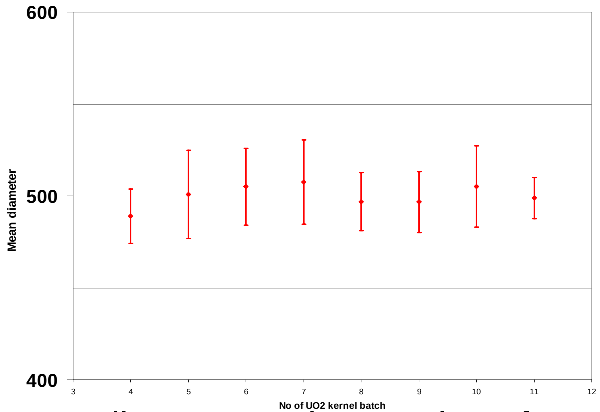
GAIA fabrication line (CEA Cadarache)
(under operation since mid 2005)

Sol-Gel apparatus

Kernel manufacturing



TRISO UO_2 particles
(natural uranium)
manufactured in GAIA



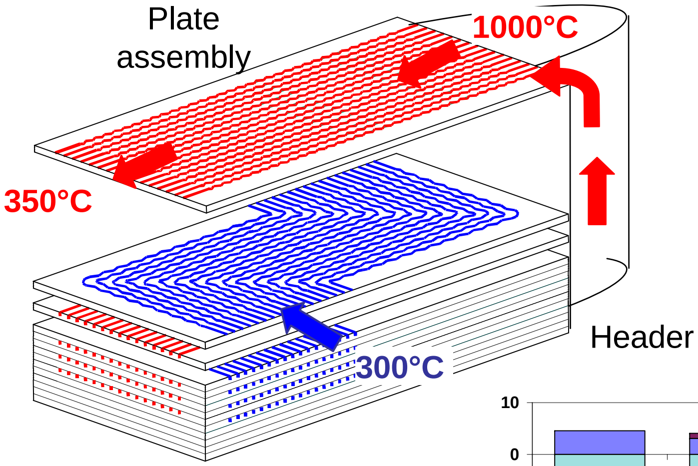
Mean diameter and scattering of UO_2 kernels

CVD line

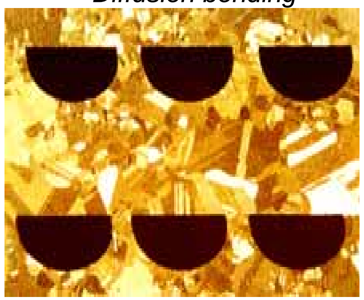
TRISO particle coating

R&D on high temperature gas-gas IHX & materials *(V/HTR) (3/6)*

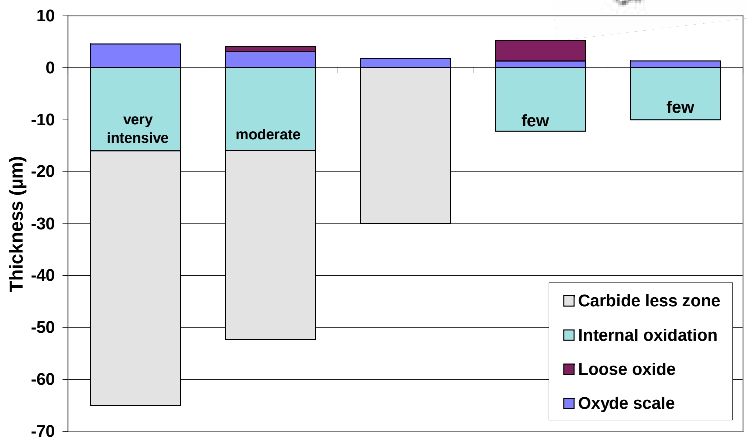
Different plate concepts appear as good candidate technologies



Diffusion bonding

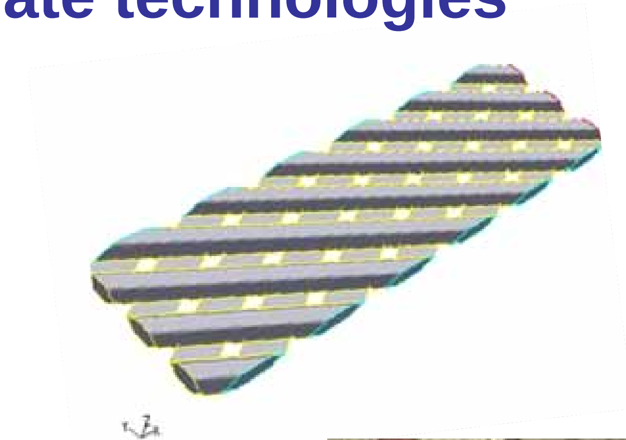


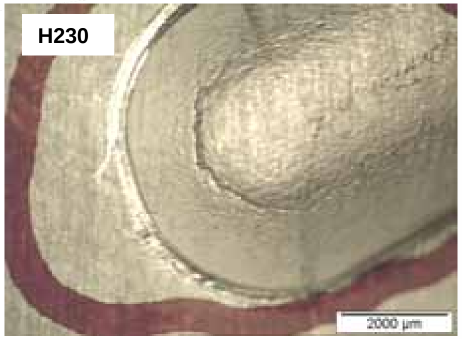
Printed Circuit Heat Exchanger (PCHE) (temperature < 550°C)



Alloys composition effect on corrosion behavior

CORALLINE tests in impure helium with low PO_2 (950°C, 800 hr)





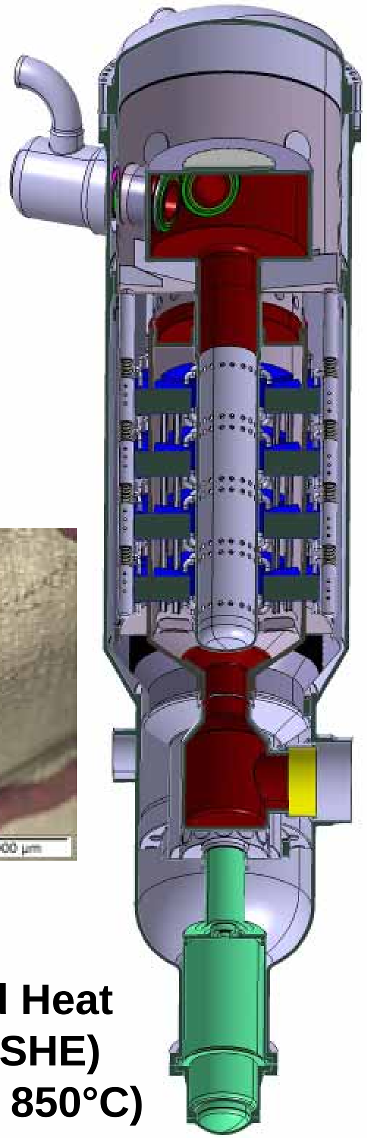


Plate Stamped Heat Exchanger (PSHE) (temperature → 850°C)

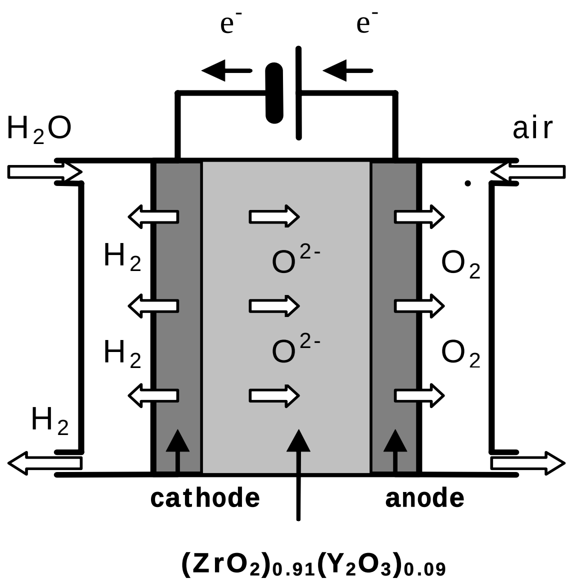
Nuclear production of Hydrogen *(V/HTR) (5/6)*

R&D on two main processes

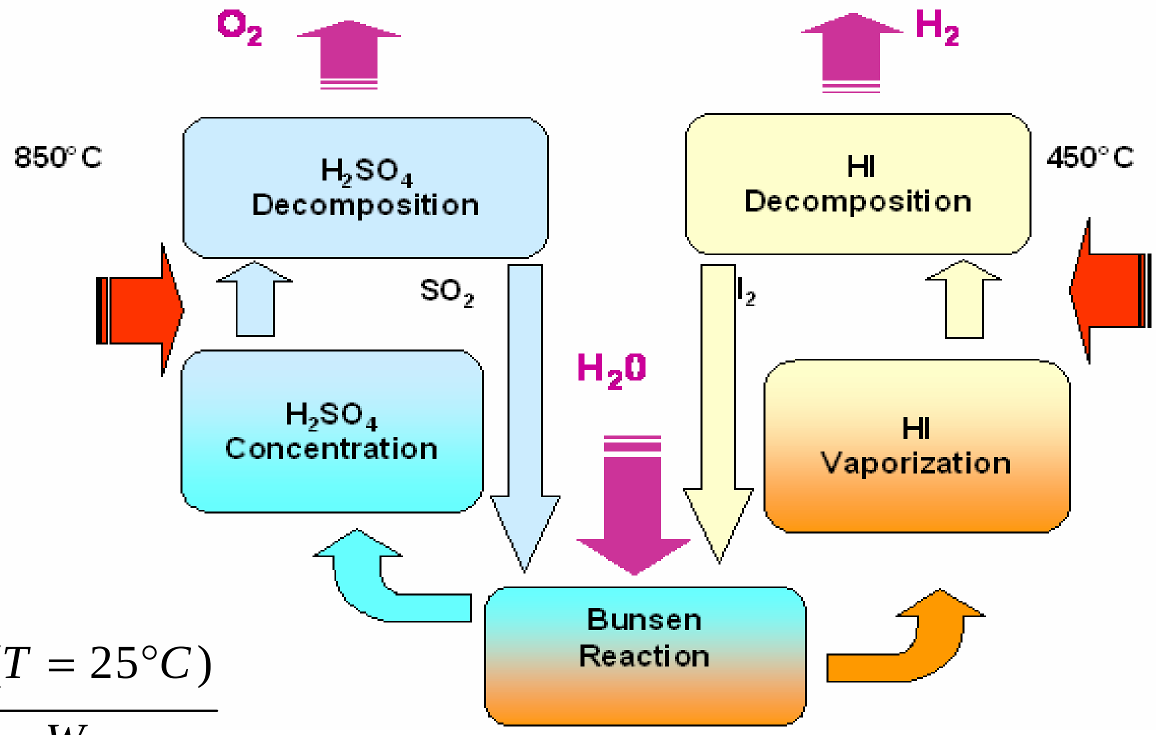
An important mile-stone in 2008 about feasibility and performances

Many collaborations : Europe, Gen IV, USA, Japan

HIGH TEMPERATURE ELECTROLYSIS



IODINE/SULFUR CYCLE (I/S)



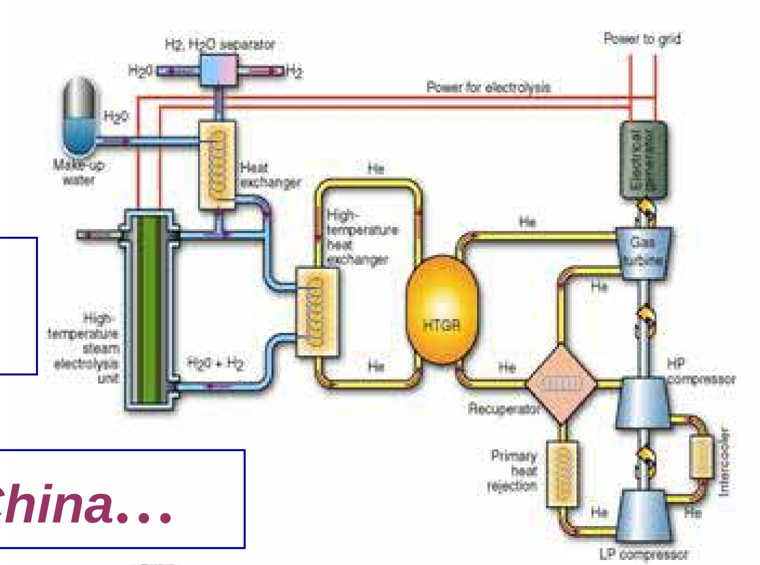
MATERIALS PROBLEMS…

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

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

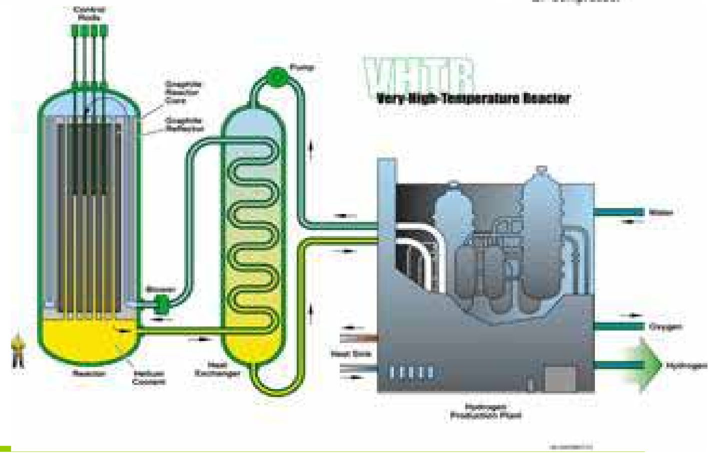
Very High Temperature Reactor – Gen IV Forum *(V/HTR) (6/6)*

- 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 approach**
- **I-S Cycle or HT Electrolysis for H2**



→ 2009 : Feasibility – 2015 : Performance
~ 2020 : PBMR, NGNP & other NT Projects

+ Russia, China…

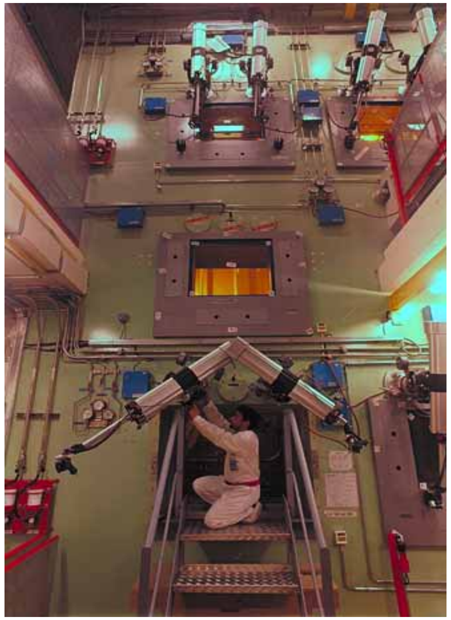


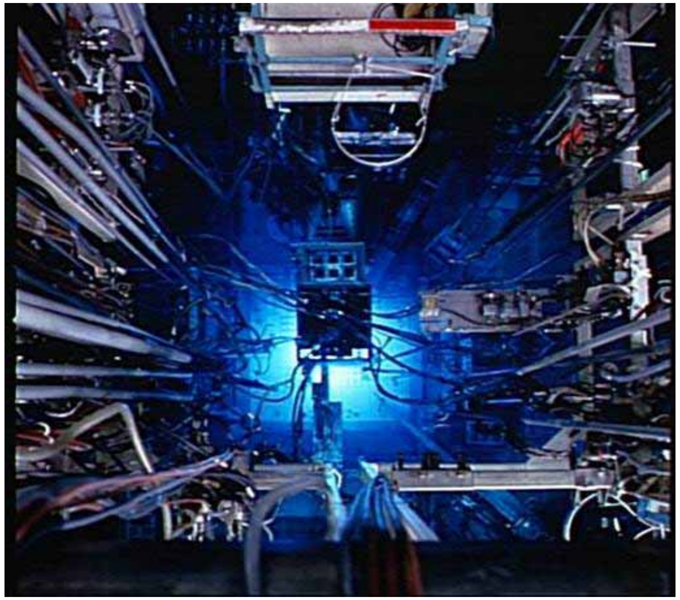
Development of Nuclear experimental facilities

➢ Research Reactors

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

- Jules Horowitz Reactor ➔ 2014

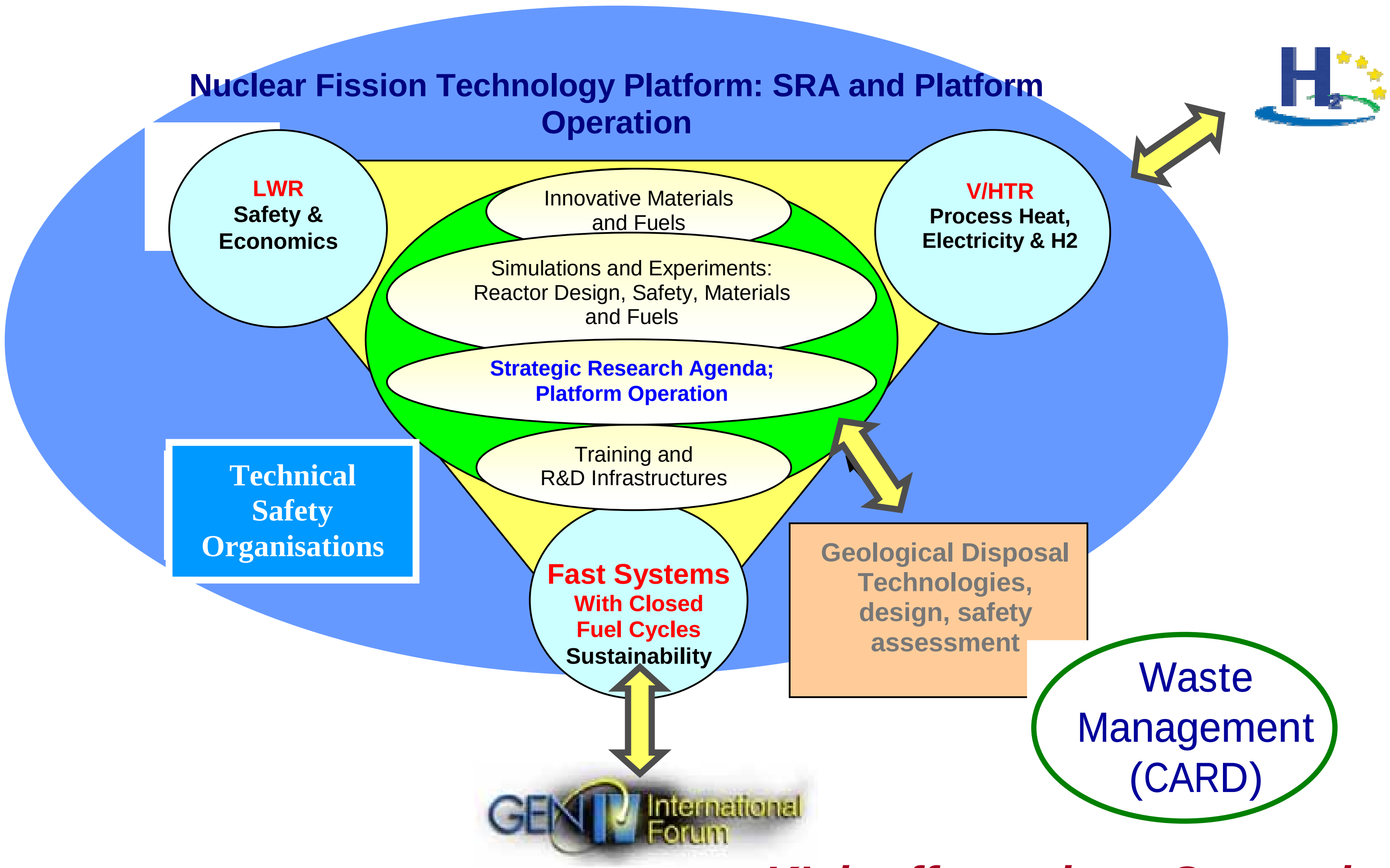




➢ Hot laboratories

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

SNF-TP objectives & organization



Kick-off meeting : September 20, 2007

Summary

- 2006: steps towards an EPR + a waste management strategy in France
- CEA R&D to optimize Gen II & III reactors + fuel cycle facilities, and to prepare Gen IV Nuclear Energy Systems:
  - ✓ *A dual approach on Fast Neutron Systems:*
    - *- SFR: focus on remaining difficulties*
    - *- GFR: revisit of GCFR with robust fuel and renewed safety approach*
      - *→ Decision in 2012 on prototypes to be put in service in 2020*
      - *→ Proliferation resistant fuel cycle processes*
  - ✓ ***Development of V/HTRs by the industry** (Customers & Vendors)*
  - ✓ ***Innovative concepts & technologies for LWRs** (Fuels, Core, Systems)*
- Extension of reactor & fuel cycle simulation codes performances + Correlated European strategy to renew large experimental facilities
- International cooperation to increase R&D work, prospects of Demo builds and active support the nuclear industry
- European dimension to be developed to create opportunities for Labs & Industry, and to best serve Europe's strategic interests