The Nuclear Fuel Cycle: key to Generation IV Nuclear Energy Systems’ Sustainability and transition from LWRs

1 – Significance of closed fuel cycle for future Nuclear Energy Systems
2 – Plans in France for fuel cycle transition from PWRs to Fast Reactors
3 – International technology roadmap for Actinide recycling optimization and phased industrial deployment aligned with that of Gen III & IV reactors

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Generations of Nuclear Power Systems

Generation I  DISMANTLING
UNGG
CHOOZ

Generation II  OPERATION
REP 900
REP 1300
N4

Generation III  OPTIMIZATION
EPR

Generation IV  DESIGN & R&D
PROTOTYPES 2020-25
DIAMEX/SANEX, GANEX

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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 $U_{\text{nat}}$
GNEP: 3 Supporting Facilities for its Initial Operation

**Nuclear fuel recycling center (CFTC)**

- LWR Spent Nuclear Fuel
- Process Storage
- Spent Nuclear Fuel Separations
- Separated Transuranics and Uranium
- Excess Uranium
- Robust Waste Forms

**Advanced recycling reactor (ABR)**

- Uranium and/or Plutonium
- Driver Fuel
- Sodium Fast Reactor
- Transuranic Destruction
- Transmutation Fuels
- Partially Transmuted Fuel
- Transmutation Fuel Fabrication
- Transmutation Fuel Separation
- Fabrication Process Losses
- Robust Waste Forms

**Advanced Fuel Cycle Facility (AFCF)**

- DOE Lab led, NRC, Universities, Industry, International Partners

**Industry led**

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Uranium & Plutonium recycling... an industrial reality today

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

Chemistry

Natural Uranium

Enrichment

Enriched + Depleted Uranium

Recycling:

MOX Fuel fabrication

Reactors & Services

Fuel Fabrication

Recyclable Uranium

Ultimate Waste Disposal

Spent Fuel Reprocessing

Front-End Sector

Reactors & Services Sector

Back-End Sector

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Major role of LWRs over the 21st century

- Operating PWRs (*Gen II*): lifetime extension (> 40 years)
- *Gen III/III+ PWRs*: replacement 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
R&D Strategy of France for Future Nuclear Systems

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

2 - Nuclear hydrogen production and high temperature process heat supply to the industry:
   - Very High Temperature Reactor (VHTR)
   - Process heat, water splitting processes for hydrogen, synthesis of hydrocarbon fuels...

3 - Innovations for LWRs (Fuel, Systems...)

Approved by the Ministers of Research and Industry on March 17, 2005
January 6, 2006:
- Decision to launch design studies of a GenIV prototype reactor to be put in service by 2020
- Creation of an Authority of Nuclear Safety and Transparency

June 28, 2006:
- Promulgation of a bill on a sustainable management of radioactive materials and waste
- Explicit link between Partitioning & Transmutation and advanced recycling modes in Gen IV Fast Reactors
- Have in 2012 an assessment of industrial prospects of candidate fast reactor types and 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 New Generation Fast Reactors 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, Confirmation of selected technologies
(design reviews)

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

2007                 2009                              2012     2015                        2020

Point design studies to assess candidate innovations

Reference Concept of selected reactor + alternative

Two types of New Generation Fast Reactors in parallel

Design features of the Prototype to build

Decision to build

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Options to close the fuel cycle of Fast Reactors

- 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)

U_{dep}
2020 Prototype and fuel cycle pilot plants at La Hague

A demonstration of Partitioning & Transmutation and key technologies for sustainable nuclear energy

- **Prototype 2020**
  - 250-600 MWe
  - Breeding ratio ~ 1
  - Multiple Pu recycling & Recycling Demos (AM)

- Advanced fuels and fuel cycle processes
- Innovations for a new generation of competitive FRs
- Enabling technology innovations (materials, power conversion)

- Two pilot plants on the site of La Hague (~2017):
  - Fuel fabrication (U,Pu)O₂ (a few tonnes/y)
    - (COEX)
  - AM bearing micro-pilot plant (~10s kg/y)
    - GANEX ↩ (MA,U,Pu)O₂
    - Diamex-Sanex ↩ (MA,U)O₂
  - Sustained R&D for decision making in 2012

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2040: - Deployment of Fast neutron systems (SFR or GFR)  
- New spent fuel treatment plant – 2 options:  
  ✓ U-Pu recycling and MA to waste or interim storage  
  ✓ U-Pu-MA integral recycling (Ganex) 

Source: EDF, ENC 2002
NEA assessment of closed Fuel Cycles (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 closed fuel cycle (Gen IV).
Sodium Fast Reactor (SFR)

- A new generation of sodium cooled Fast Reactors
- Reduced investment cost
- Simplified design, system innovation (Pool/Loop design, ISIR – SC CO₂ PCS)
- Towards a passive safety approach
- Integral recycling of actinides
- Remote fabrication of TRU fuel


SFR Steering Committee

2007 +

France

Japan

U.S.A.

Russia

China

Euratom countries

South Korea

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Global Actinide Cycle International Demonstration (GACID)

Milestones:
2008-12 - Demonstration of the GANEX process in Atalante

2015-20 - International Laboratory at La Hague to demonstrate at pilot scale the Grouped Actinide Extraction (GANEX) and the fabrication of Minor Actinide bearing fuels

2020-25 - Irradiation experiments in Monju
   > 2025 French Sodium Fast Reactor Prototype, ABR in the US…

Collaborations:
Japan (JAEA), USA (DOE)… within the framework of Gen IV & GNEP
Phased Development of Gen III & IV Reactor & Fuel Cycle Technologies

- Natural resources conservation
- Waste minimization
- Proliferation resistance

Fuel cycle technology aligned with nuclear reactor technology

Gen III Reprocessing facility
2005

Gen II / III reactors MOX
2020

Gen IV Reprocessing facility
2040+

U + Pu + MA

FP only

U

FP + MA
Phased development of recycling technologies

Gen II
UOx – LWR fuel
1000 t/year
PUREX process

Gen III
~ 2020
MOX & UOx LWR fuels, Higher throughput
Integrated fuel processing & recycling
Advanced separation technologies
COEX, + Np…

Gen IV
LWR & FR fuels
> 2000 t/year
New technologies
DIAMEX-SANEX, GANEX,
UREX+1A, NEXT…
> 2040

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<td>Resource utilization</td>
<td>U-Pu</td>
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Phased development of Sodium Fast Reactors

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<tr>
<td>Non-prolif, PP</td>
<td>Standard</td>
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Existing plants
- BOR60, FBTR
- <1990 Phenix, Monju
- BN600, FFTF?

Proto & Demo Plants
- ARR
- 2020 French Prototype 2020
- 2025 Japanese Demo

Under construction
- CEFR
- BN800, PFBR

Gen IV Systems
- Gen IV SFR
- > 2040

1990

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Phased development of Fast Nuclear Energy Systems

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

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

International / National
Nuclear Fuel Cycle: key to Gen IV systems sustainability

Summary and perspectives

- Advanced recycling processes and Fast Reactors are key to a sustainable development of nuclear power: *Resource saving, Waste minimization, Non-proliferation*

- Industrial experience of recycling as well as national plans for more advanced fuel cycle demonstrations are seeds for the international development of optimized recycling modes in fast neutron systems
  - Key role of Joyo/Monju, US-ARR, French prototype 2020… for demonstrations of global actinide management

- Crucial need to federate current national initiatives as well as longer term R&D and demonstration program into a consistent international technology roadmap
  - Enhancing R&D and technology demonstrations, + Progressing towards harmonized international standards (safety, non-proliferation, physical protection…)

- Towards a phased development of recycling technologies aligned with that of successive reactor generations (II, III, IV)