WNU Summer Institute

Towards a sustainable renaissance

Philippe Pradel
Head of the Nuclear Energy Division

French Atomic Energy Commission (CEA)

...with specialities *« à la française »*

Sodium fast reactor

-**1980** French Atomic Energy Commission (CEA) as a research scientist on the SUPERPHENIX liquid metal fast breeder reactor and part of the team that started up that reactor.

Philippe PRADEL

Closed fuel cycle, treatment and recycling

-**1987** COGEMA as manager of start-up testing for chemical extraction and vitrification facilities of the UP3 Treatment Plant at La Hague.

- then Technical Director, Treatment Division Director, Treatment Business Unit Director and

-**2003**, Senior Executive Vice President of COGEMA, in charge of Treatment, Recycling and Logistics.

the French Atomic Energy Commission

- **Since 2005**, Director of the Nuclear Energy Division at the French Atomic Energy Commission (CEA), in charge of the whole nuclear energy sector (4500 pers.)

A career also devoted to international partnership

GNEP interministerial meeting may 2007

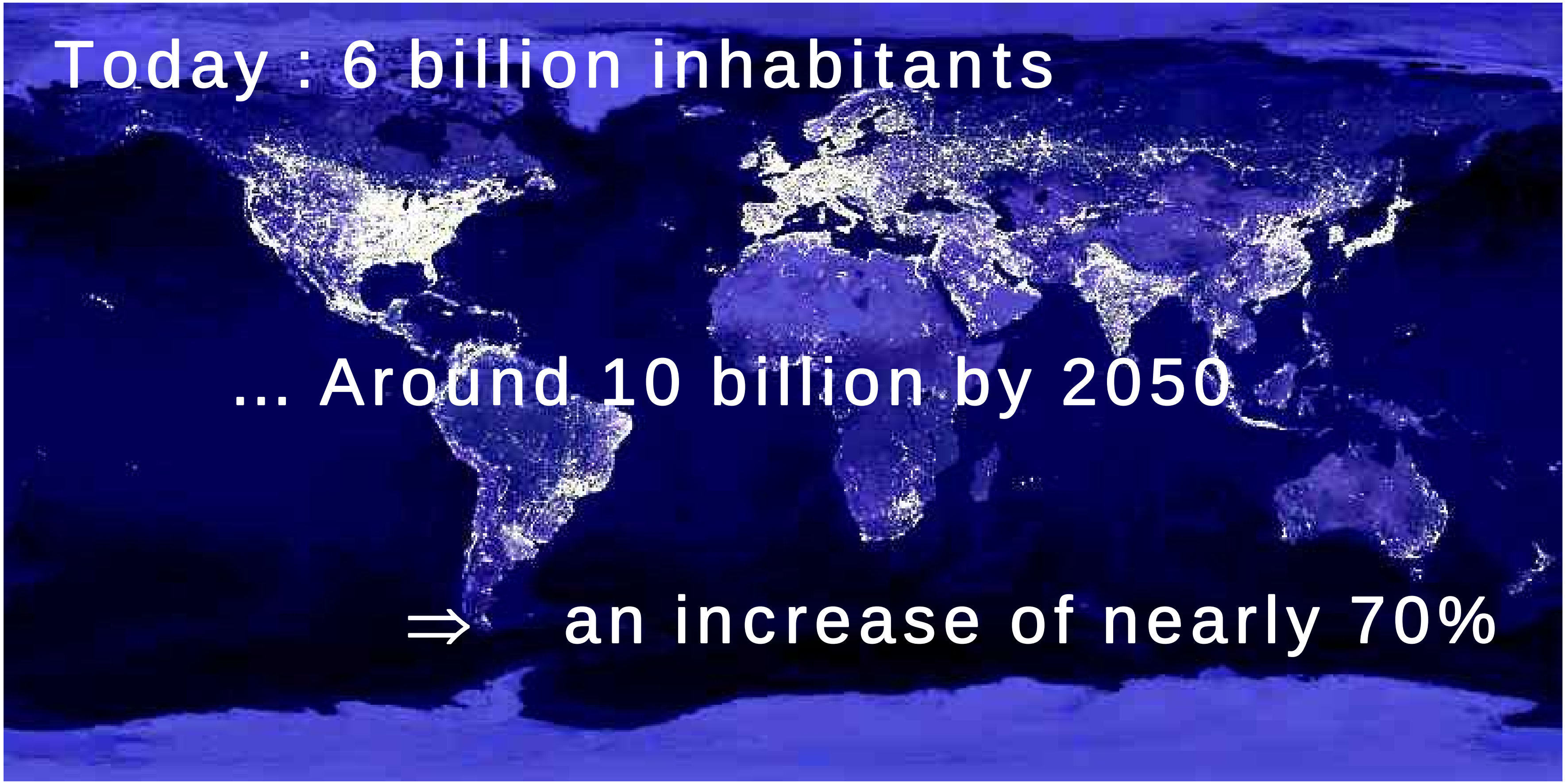
With MM.Spasskiy and Bodman

France-Japan meeting june 2007

France-Belgium meeting october 2006

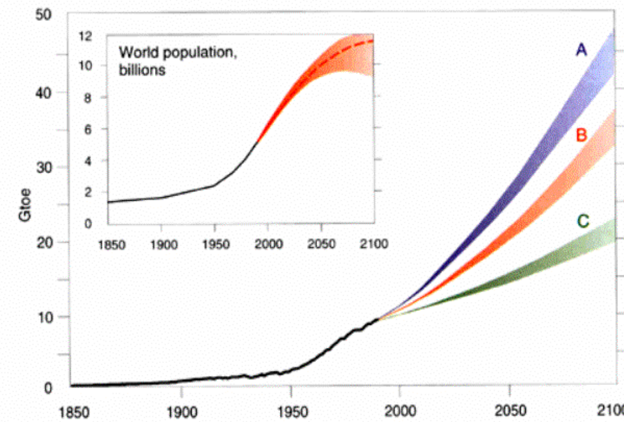
Towards a worldwide nuclear renaissance

Evolution of Population on Earth ...



- **Increasing energy demands**

- **Proven correlation between CO_2 emissions and climate change**

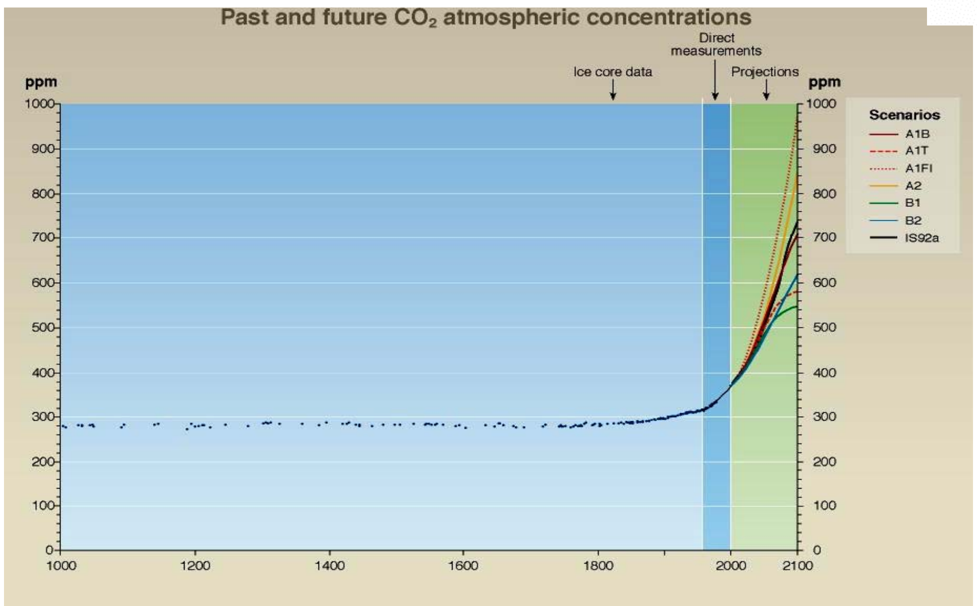


A : High growth (Income, energy, technology)

B : Modest growth

C : Ecologically driven growth

Hypothesis B ⇒ 19.7 Gtoe in 2050



Reduce CO_2 emissions

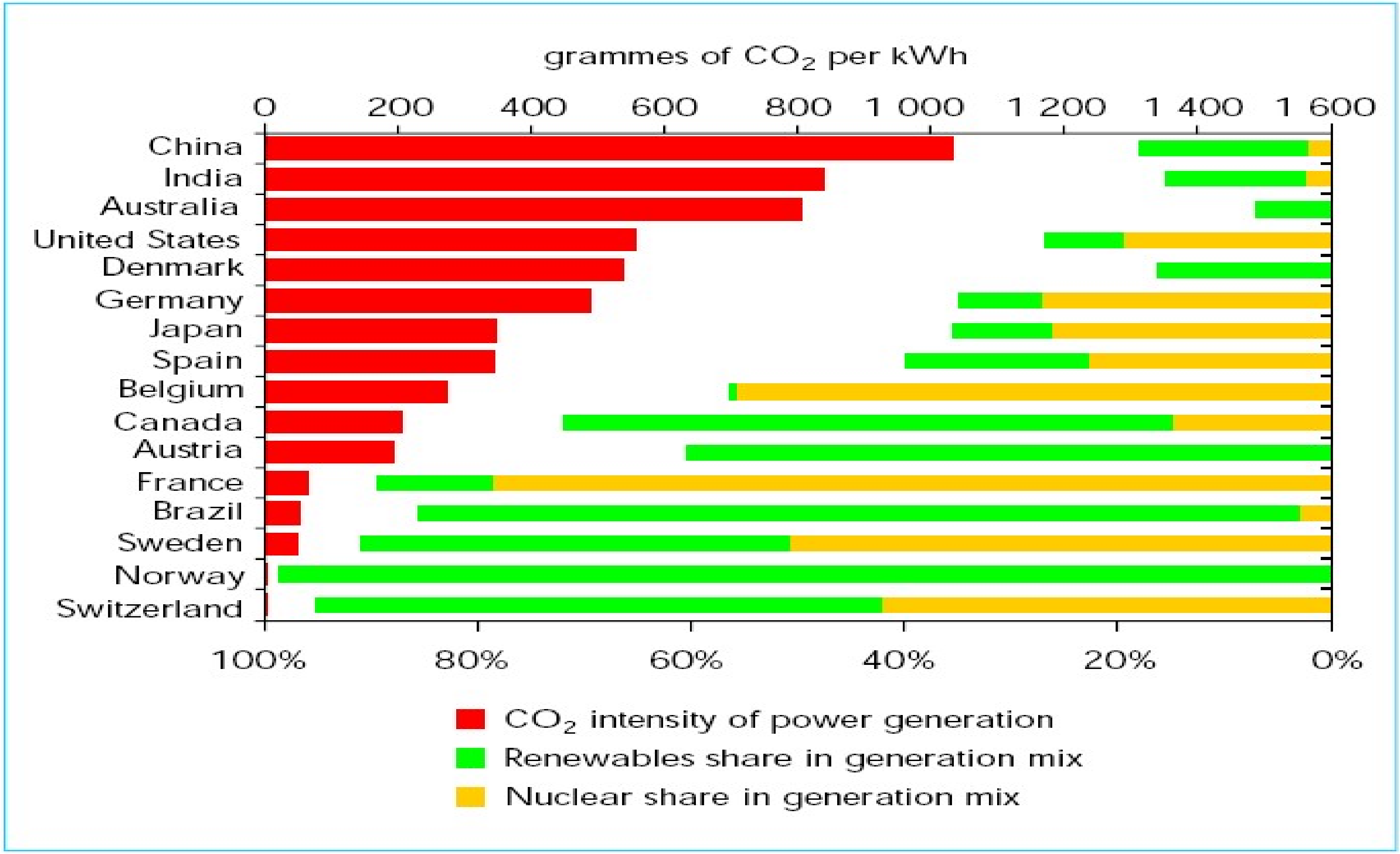
While Producing

more energy

An increasing world energy demand ...

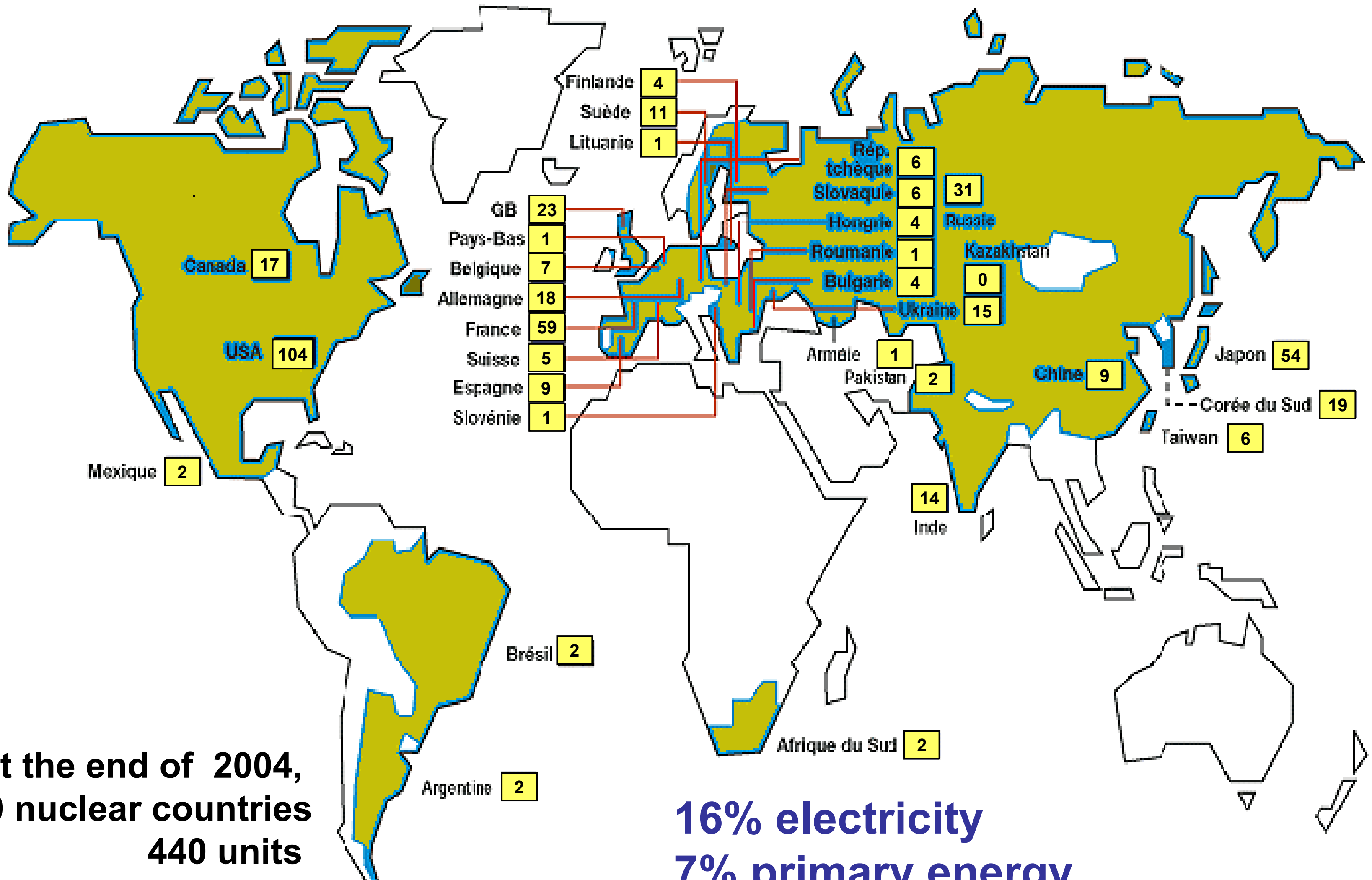
... and various answers

Figure 13.1: **Power Sector CO_2 Emissions per kWh and Shares of Nuclear Power and Renewables in Selected Countries, 2004**



Source AIE 2006

Nuclear power plants in the world

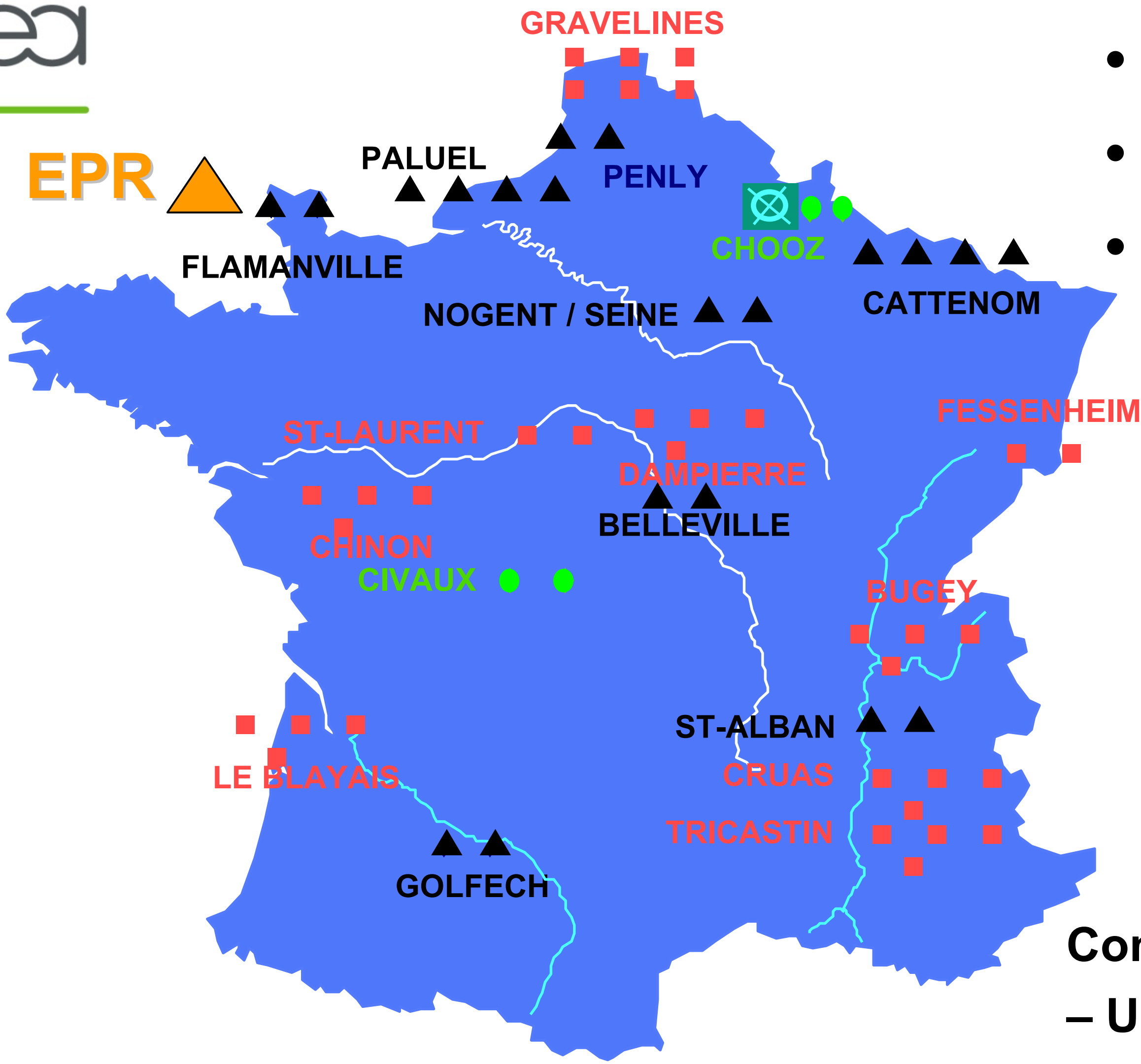


At the end of 2004,
More than 30 nuclear countries
440 units
366 Gwe connected

16% electricity
7% primary energy

Without greenhouse gas emission

The French Nuclear Program at a glance



- 34 900 MWe units ■
- 20 1300 MWe units ▲
- 4 1500 MWe units ●

58 PWR units

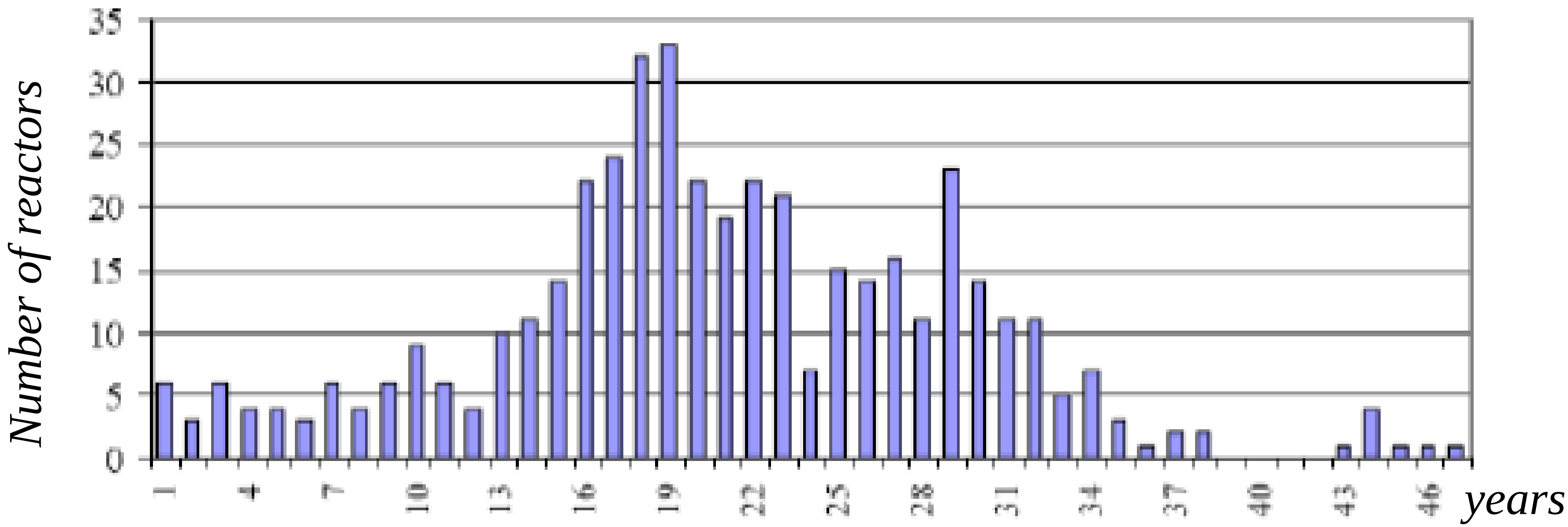
63184 MWe installed

Connection to the grid :

- **Unit 1 (Fessenheim 1) : April 1977**
- **Unit 58 (Civaux 2) : Décember 1999**

The world current nuclear fleet

For the 441operating reactors in 2003

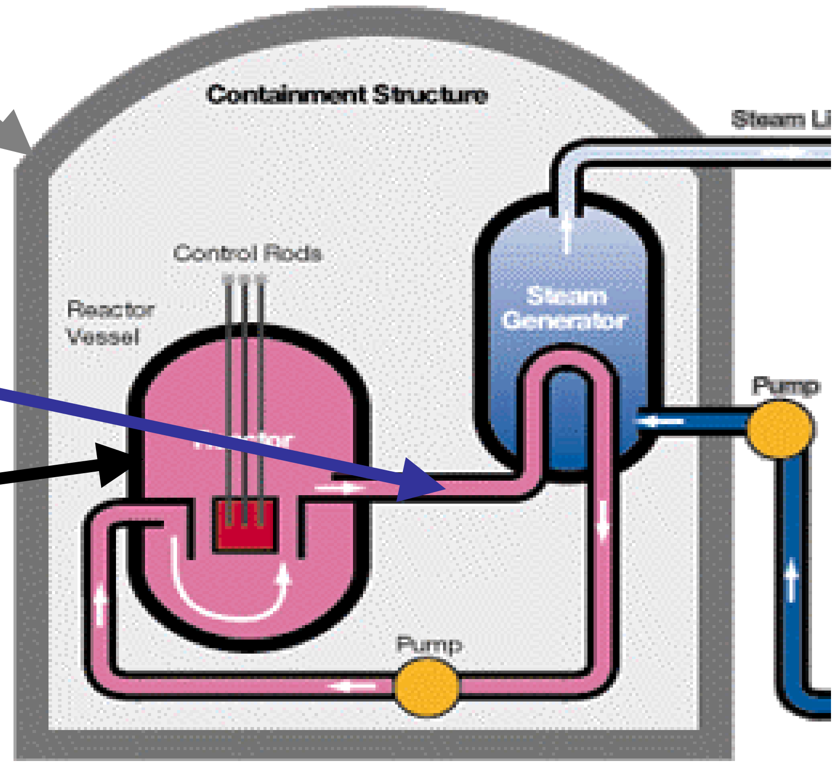


Ageing and Lifespan extension : a major stake

➔ Tools and studies for a better understanding

Main concerned components

- **Containement structure**
- **Steam generator**
- **Pressurizer**
- **Circuits**
  (primary loop)
- **Internals**
- **Vessel**



- **Six scientific fields**
  - Concretes (containement and structures)
  - Circuits (integrity)
  - Seismics
  - Corrosion
  - Vessel – neutron flux
  - Internals (evolution)

Vessel : which studies for a longer life ?

- **Demonstration : no risk of fracture during all the operating time**
    - Margins (Mesures and physics)
    - Methodology

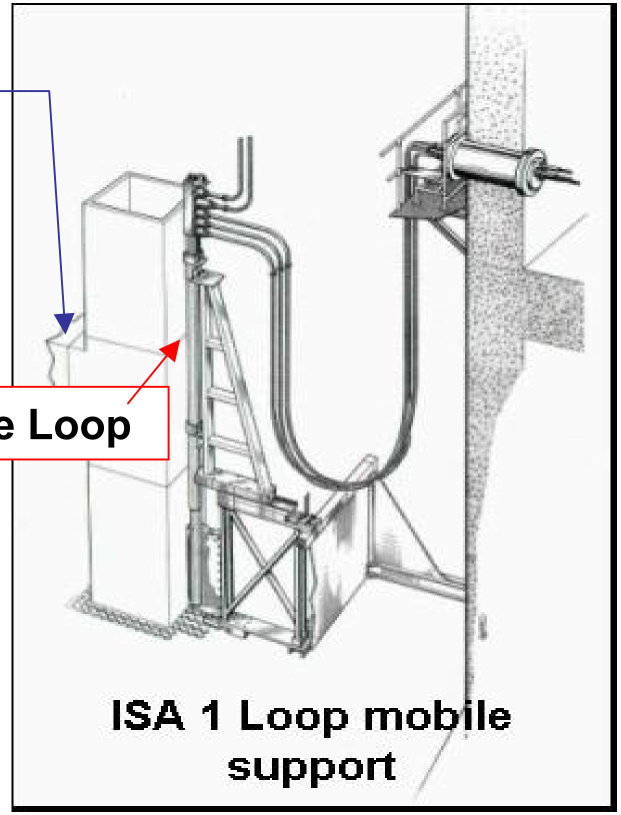
  – Mechanical tests, modelisation
  – Criteria for crack propagation
  – Neutronics and Flux (code TRIPOLI, FLUOLE test) ; effect on the ductile-to-brittle transition

R&D in the field of pellet clad interaction

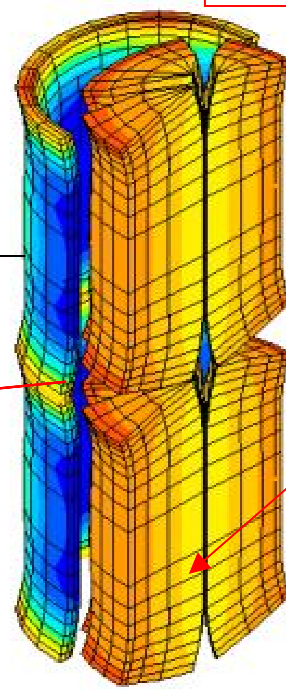
- Power ramp in-pile tests for the determination of a technological limit of new fuel elements
- 3D modelling to take into account the various effects of clad and fuel evolutions

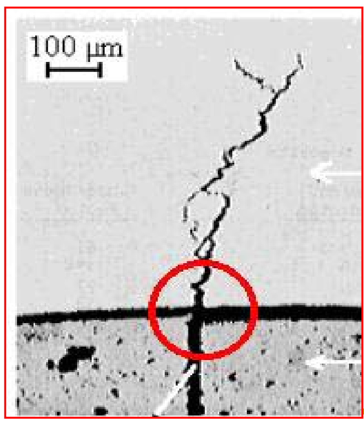
Osiris Core

Isabelle Loop



Clad
Viscoplastic behaviour
Iodine SCC damaging



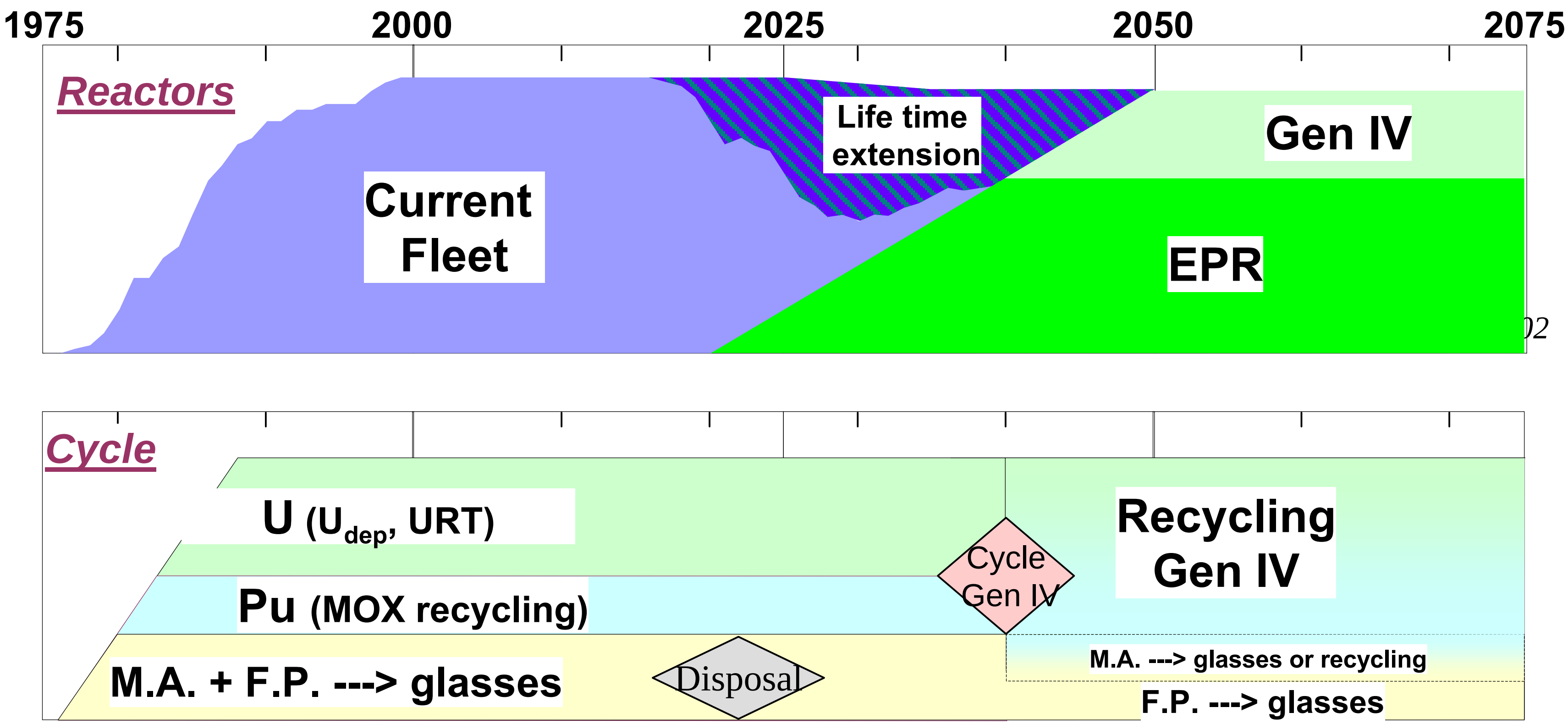


Stress concentration zone with I-SCC

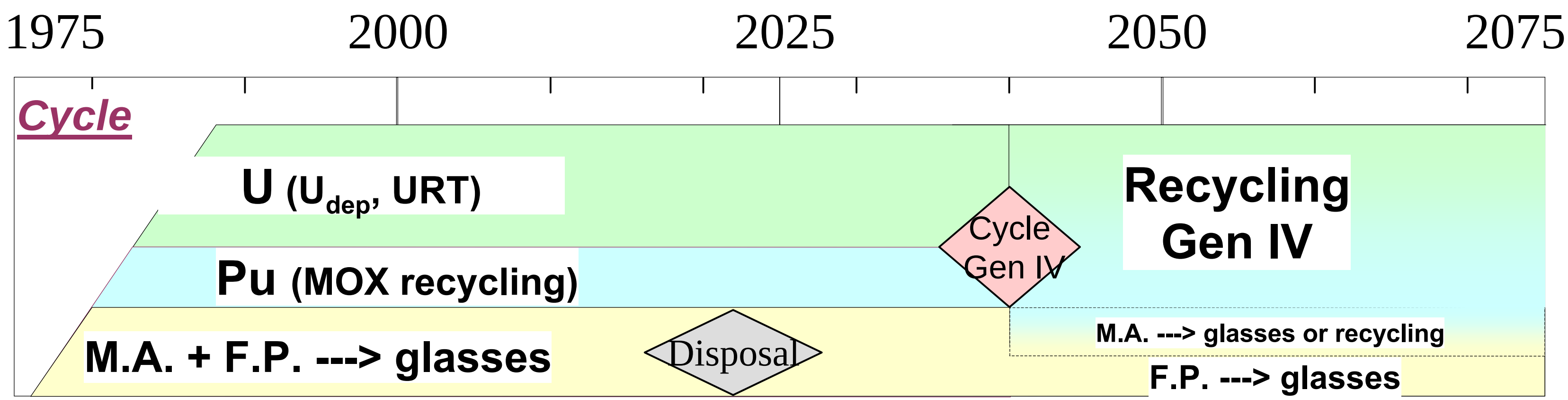
Pellet
Viscoplastic behaviour
Porosity, gazeous swelling, fractures

Transition scenarios between generations

- **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 – Operation during 21st century
- **A transition scenario between LWRs and Fast Neutrons Systems**



R&D needed to support GenIII fuel cycle

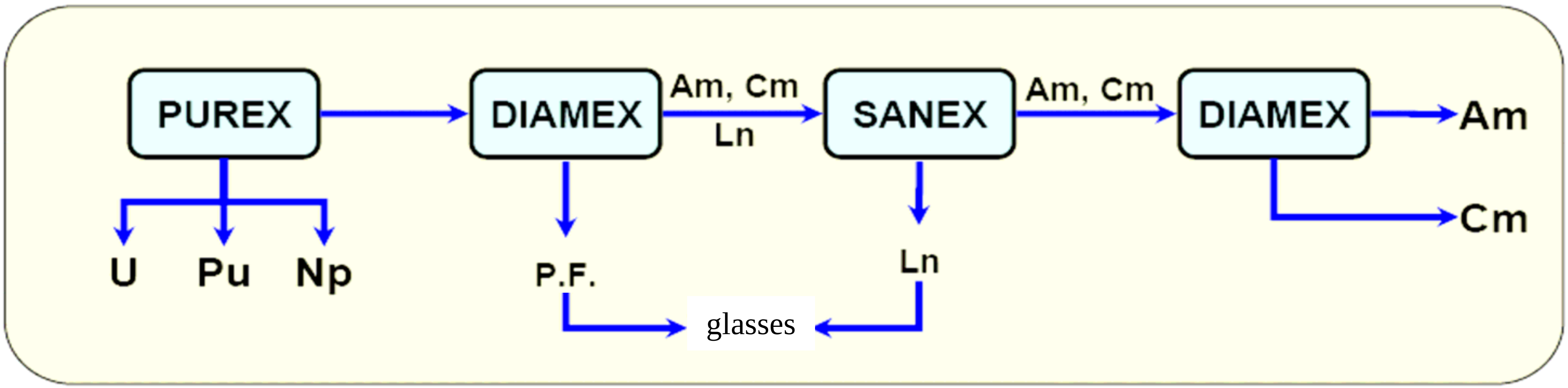


- **1- *RECYCLE INTO GEN3 LWRs !***
  - **Necessity *to avoid spent fuel accumulation* when world-wide *« nuclear renaissance »* is there!**
  - **Today's technology as an efficient basis, possibly improved by *uranium-plutonium co-management* (*COEX process*, *no « pure plutonium stream »*)**

R&D on fuel cycle : 2005 results

→ advanced partinioning in the « 1991 act » framework

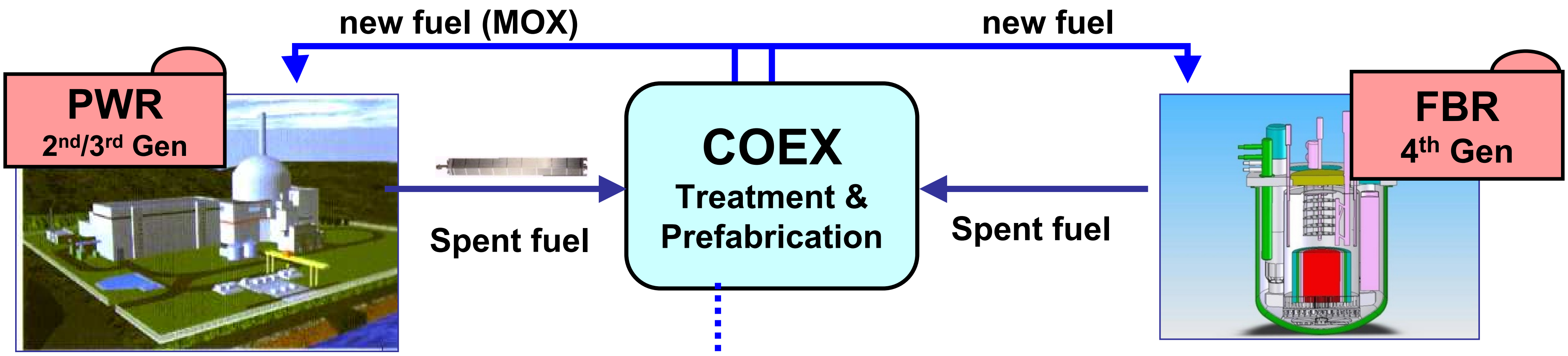
→ 2005 results in ATALANTE hot labs on 15 kg spent fuel : separation ~ 99,9 %

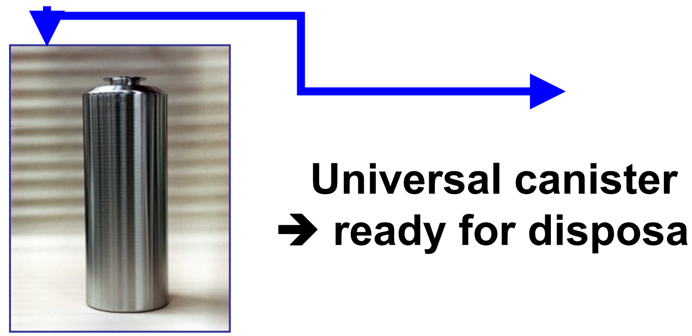


→ Proven processes and technologies which can be applied to other partinioning schemes

Example of a Generation III processing facility

The COEX plant

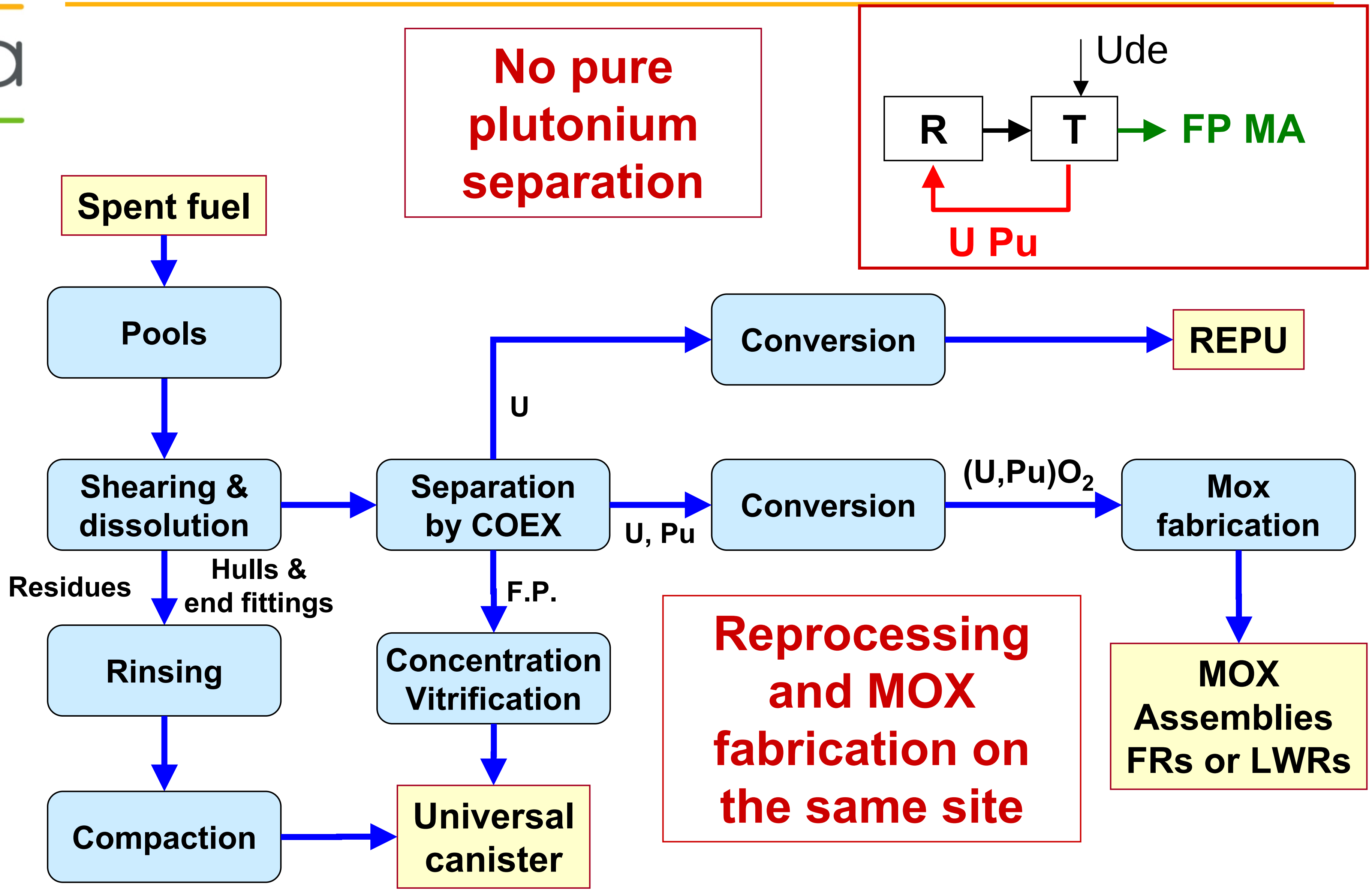




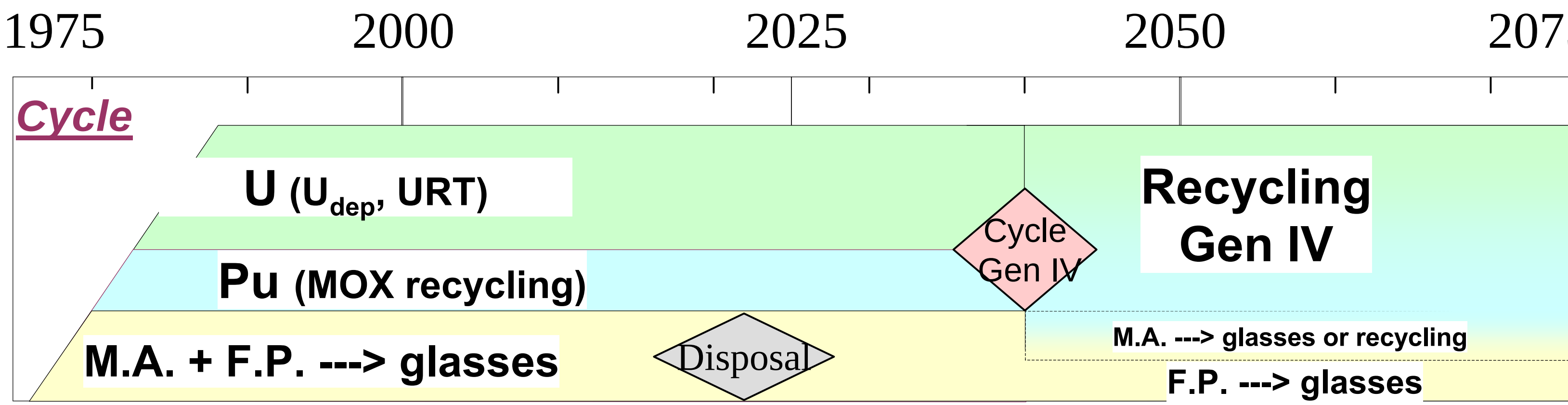
Consistency with Generation III/III+ reactors
Full U & Pu recycling (sharply decrease the repository impact)

➔ **Treatment & Recycling competitiveness**
Resistance to Proliferation (<u>Integrated Plant</u>, <u>no Pu alone</u>)

COEX general flowsheet



R&D needed to support Gen IV fuel cycle



2 - LONG TERM SUSTAINABILITY: RECYCLE INTO *FAST REACTORS* !

Recycle *minor actinides ?*

MANY STILL OPEN QUESTIONS, MANY *STILL OPEN OPTIONS*!

All-actinide ? All-together?

Hogeneously or with dedicated devices ?

What kind of fuel?

Nuclear Fuel Cycle Goals and options

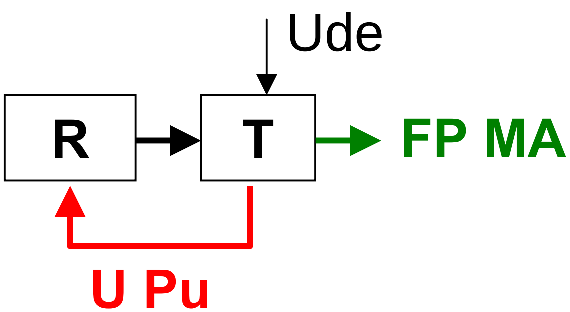
→ **Natural resources conservation**

→ **Waste minimisation**

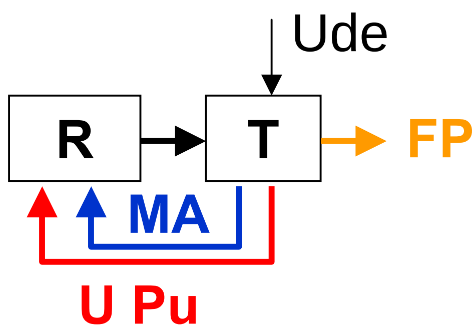
→ **Proliferation resistance**

To produce **50 times** more electricity
With the same uranium amount

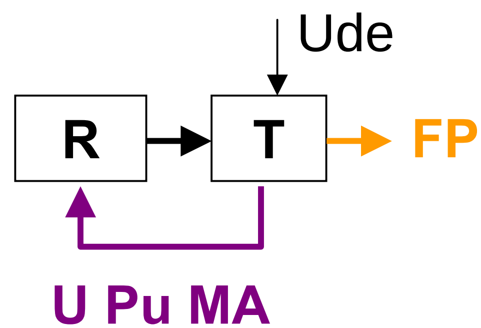
All paths should be kept available, **they could be used in a sequence.**



U & Pu recycling



Heterogeneous recycling

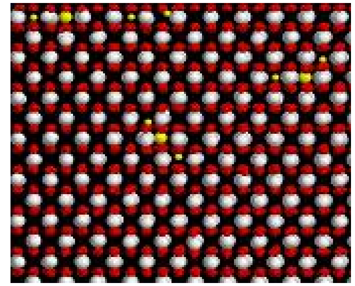


Homogeneous recycling (GenIV)

Actinide science, a key domain for the future of nuclear energy

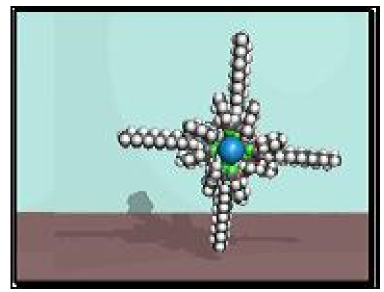
- **Fuel Development and Safety**

UO_2 radiation damage
UO_2 microstructural evolution



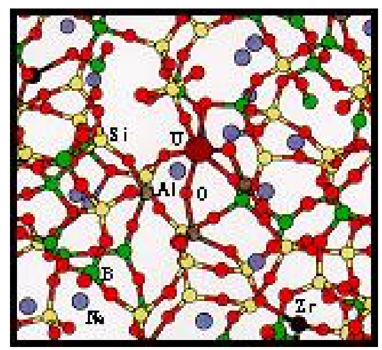
- **Spent Fuel Processing**

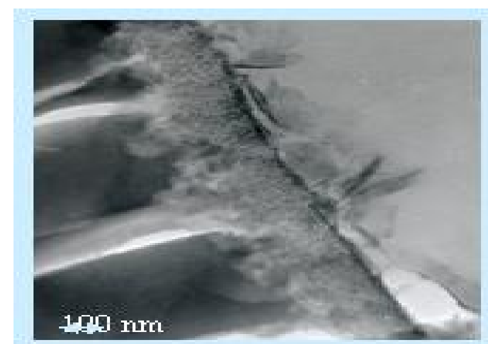
Micelle of DMDOHEMA + water
ATALANTE facility



- **Radioactive Waste Disposal**

Glass reticular structure with U
Glass alteration by water



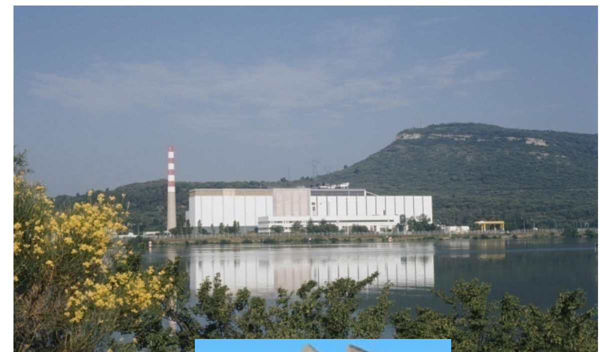


Some recent exemples in PHENIX reactor:

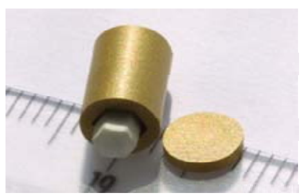
- **CAMIX – COCHIX** experiments
  - Demonstration of transmutation with Am-bearing targets

- **FUTURIX Programm** (CEA - DoE - ITU - JAEA)
  - FTA : dedicated fuels with M.A. compounds
  - Concept : nitride and carbide fuels
  - MI : inert materials for GFR structures

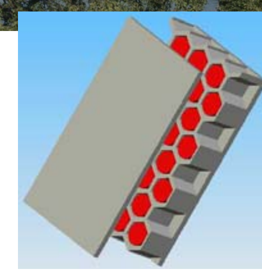
➔ ***2009***



UPuN / TiN



UPuC / SiC



Waste management : what options for the future ?

Axe 1

Advanced Partitioning

Transmutation

Separation

Resource preservation
Radiotoxicity reduction
Heat reduction

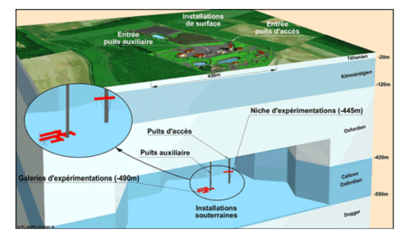
Axe 3

Volume reduction
Package performance

Conditioning

Storage

Axe 2



Disposal

French nuclear policy news 2005 - 2006 context : public debates & new bills

- **Sept 05-Jan 06** : Public Debate on **High Level Long Lived Radioactive Waste** (CEA responsible for Research on Partitioning/Transmutation and Long Term Disposal):

- **Oct 05-Feb06** : Public Debate on **the decision to build a first-of-a-kind EPR in Flamanville**.

***January 2006* : President Chirac announced**

*- the construction by 2020 of **a GEN IV prototype***

*- the creation of **a safety and transparency in nuclear affairs Authority***

***June 2006* : *a new waste management bill* adopted by French Parliament**

About the new law on waste management

- **A national plan** (PNG-MDR) **on radioactive materials and radioactive waste management** (up-grading by Parliament every three years)

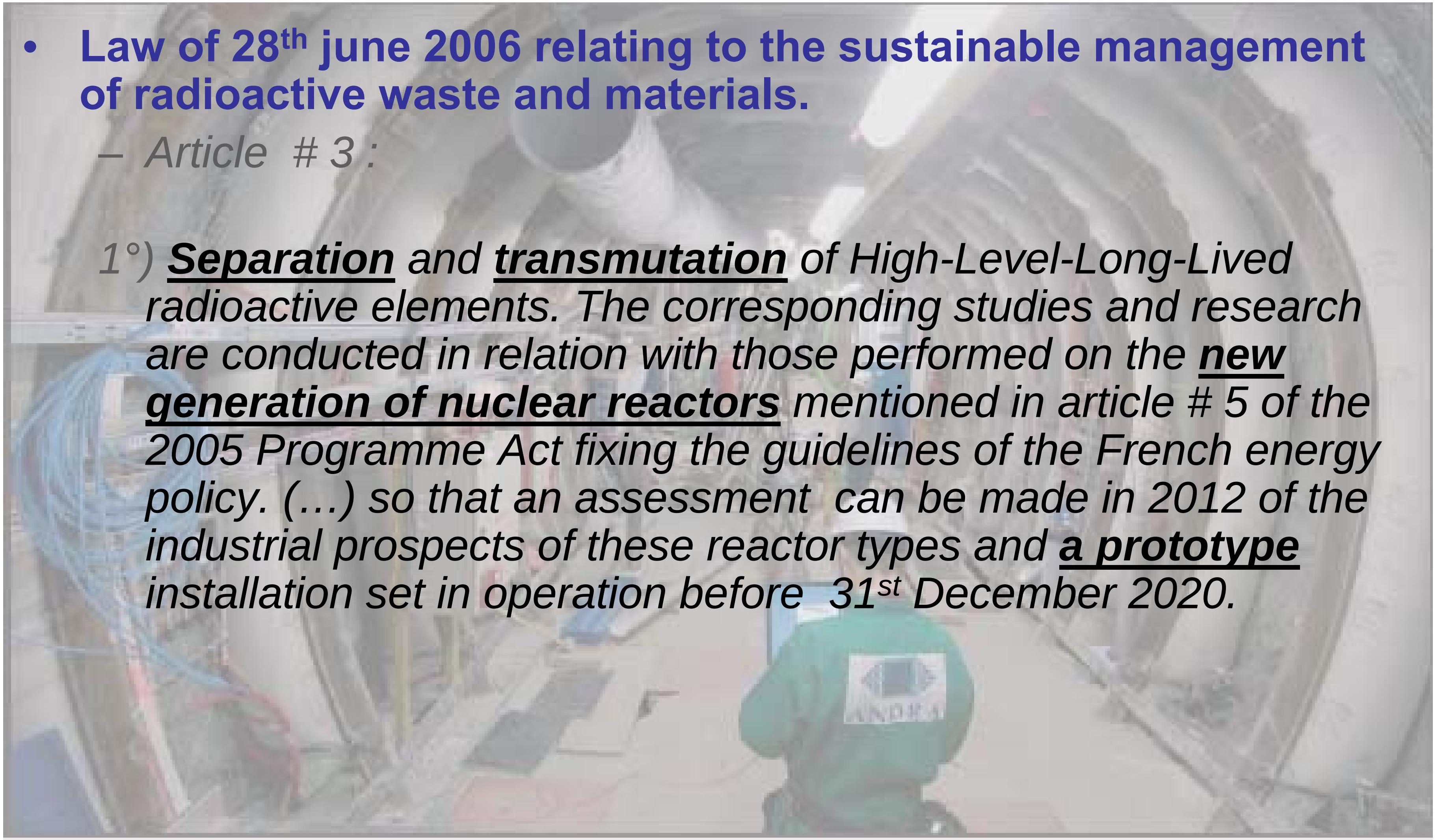
- **A step by step programme of HLLL waste management, including the complementarity of 3 solutions :**

  - **Partitioning-transmutation :**
    - **2012 : evaluation IV[th] Generation reactors / ADS**
    - **2020 : building of a prototype**

  - **Geological disposal for the final HL waste :**
    - **2015 : authorisation**
    - **2025 : operation**
  - **Intermediate storage :**
    - **creation of new industrial facilities in 2015**

- **A secured financing of radioactive waste management and R & D** (Dedicated fund)

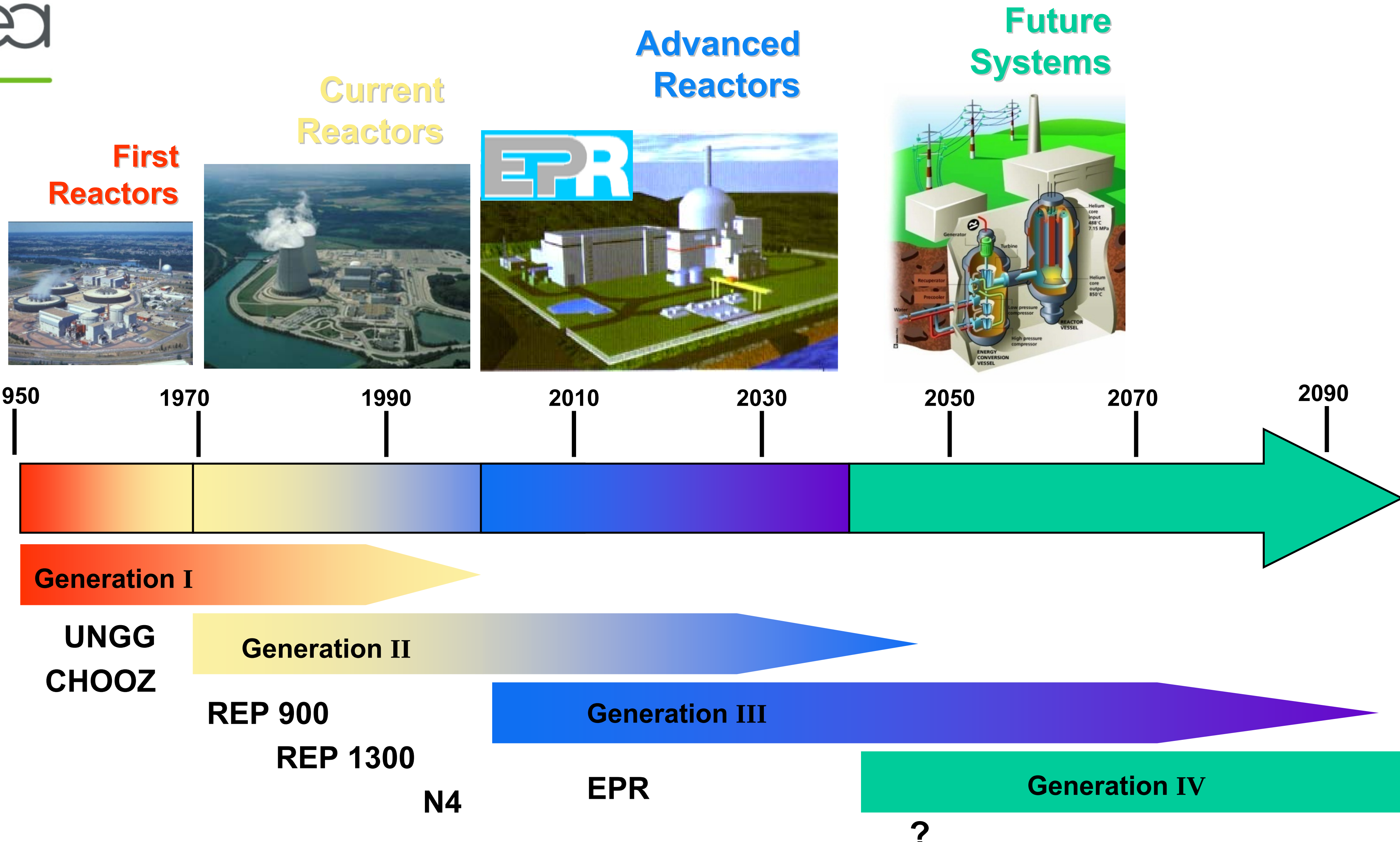
Nuclear Waste & Reactors : consistency between R&Ds



- **Law of 28th june 2006 relating to the sustainable management of radioactive waste and materials.**
  - *Article # 3 :*

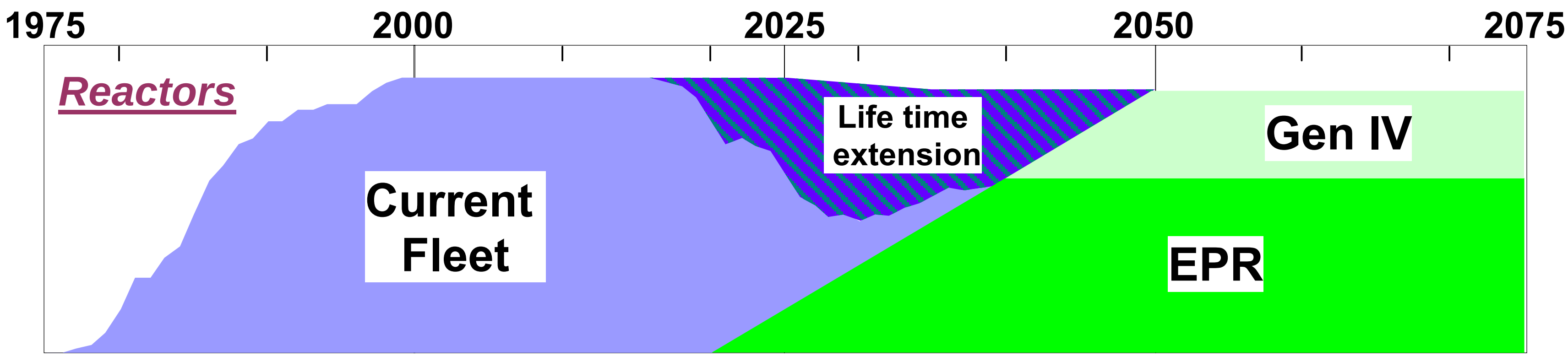
*1°) **<u>Separation</u>** and **<u>transmutation</u>** of High-Level-Long-Lived radioactive elements. The corresponding studies and research are conducted in relation with those performed on the **<u>new generation of nuclear reactors</u>** mentioned in article # 5 of the 2005 Programme Act fixing the guidelines of the French energy policy. (…) so that an assessment can be made in 2012 of the industrial prospects of these reactor types and **<u>a prototype</u>** installation set in operation before 31st December 2020.*

The Evolution of Nuclear Power



R&D needed to support **3 power plants generations**

- **Plant life time management & extension**
- **Gen 3 evolution, Fuel performance & safety,**
- **innovative fuel & material HTR & Gen 4**



Source : EDF, ENC 2002

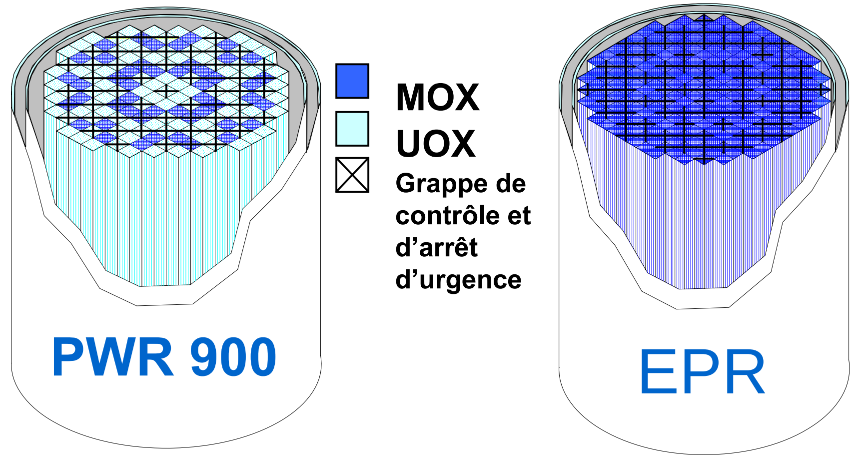
Prepare the Generation III reactor, EPR

-A matured concept, based on experience feed-back of current PWRs
- Significant improvements in safety

- Under construction in Finland at Olkiluoto (TVO)

- April 07: License application of Flamanville EPR Plant

Capacity to load up to 100% MOX Core

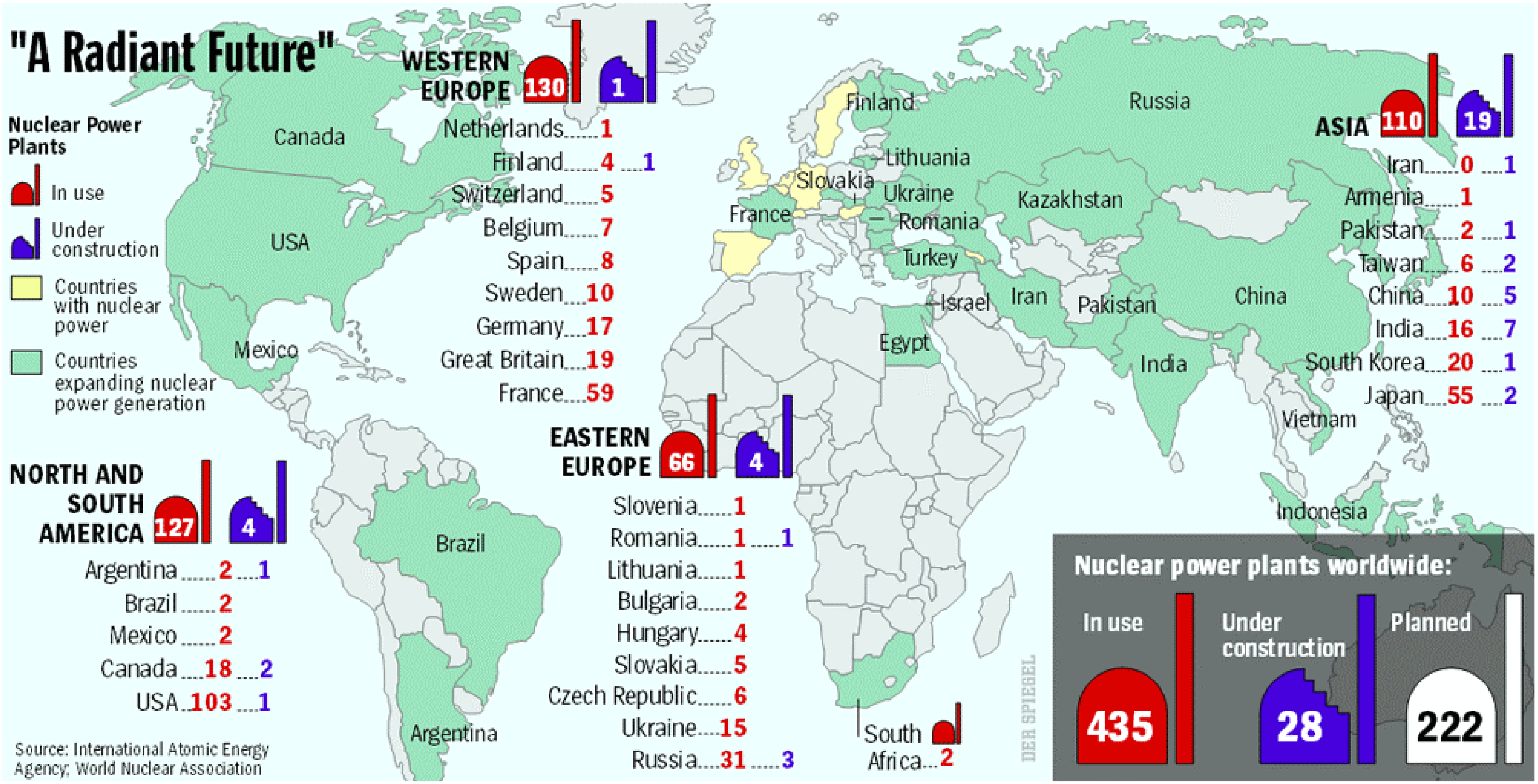


An enhanced capacity to burn Plutonium

Plutonium annual balance
Kg Pu/year

- REP 900 UO_2 : + 200
- REP 900 MOX : 0
- EPR 100% MOX : - 670

An increasing world nuclear electricity demand ...



Increasing share of nuclear electricity planned up to 50% by 2050

What could be the future?

Through a responsible spent fuel managment

Nuclear energy for the 21st century

RENAISSANCE

3rd generation reactors with best available technologies (EPR, COEX…)

SUSTAINABILITY

?

GEN IV : What is at stake in the future nuclear systems ?

New goals for sustainable nuclear energy

Continuous progress :

- Economically competitive
- Safe and reliable

Break-throughs :

- Waste minimisation
- Natural resources conservation
- Proliferation resistance

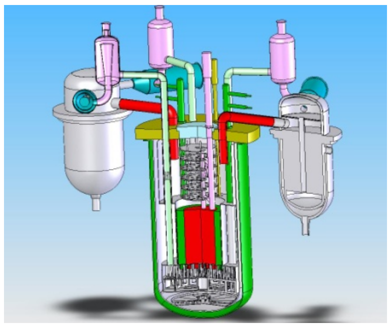
Systems marketable from 2040 onwards

True potential for new applications

Hydrogen, potable water, heat

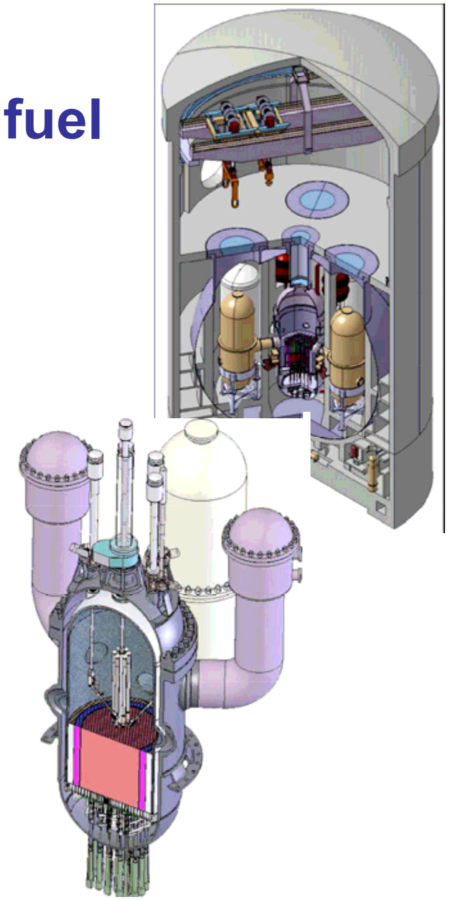
Internationally shared R&D

1 – Development of Fast Reactors with closed fuel cycles, along 2 tracks:



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

→ ***Industrial deployment around 2040***



2 –Hydrogen production and very high temperature process heat supply to the industry

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

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

French strategy for fast reactors

➔ *Two options studied simultaneously, in line with the French priorities in the international Gen IV forum*

- As reference, the Sodium Fast Reactor

- Very strong experience in the world

➔ **The most mature of Fast Reactor concepts**

- but significant improvements with respect to SPX and EFR are searched for

- As alternative, the Gas Fast Reactor

- Interesting features like transparent and inert coolant

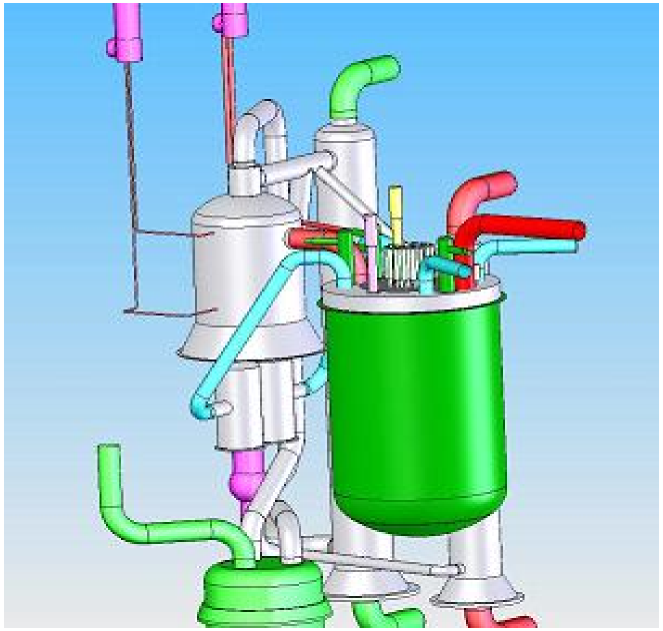
- capability to reach high temperatures (sustainable version of VHTR)

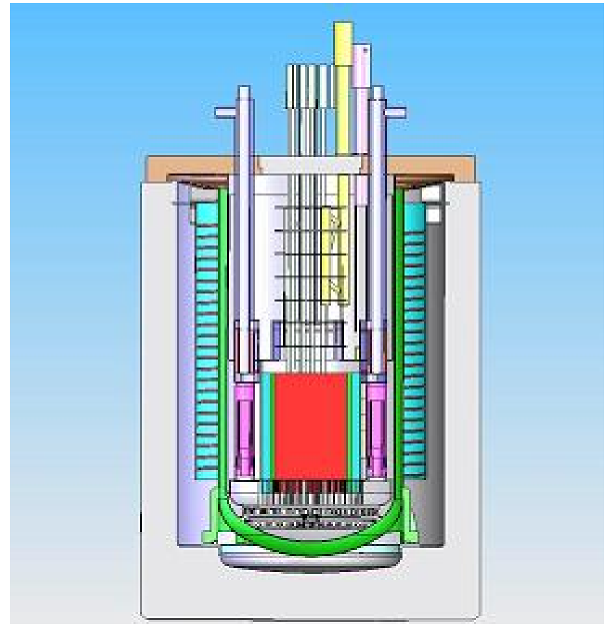
➔ **Need some technology breakthroughs but gives access to both "fast spectrum" and "high temperature"**

The SFR main stakes

- **Competitiveness**: some progress still needed to compare with 3rd generation water reactors
- **Safety**: implementation of design measures and innovative technologies to compensate for sodium and fast reactor specificities
- **Operability**: fuel handling and ISIR are still to be improved for more efficiency

System studies





CEA proposed to characterized two SFR pre-conceptual designs to evaluate the various options in coherent systems

➔A loop reactor without intermediate circuit and with a gas energy conversion system

➔A pool reactor with a compact intermediate circuit and a fluid avoiding the risk of sodium-water reaction

Energy conversion

Stakes are :

- **Improvement of safety** (sodium water reaction suppression)

- The **investment cost reduction**

- While **keeping or improving the system efficiency**

➔This orientates the design

- On **gas conversion systems without intermediate Na loop**

- Or on a **compact intermediate loop** with a **fluid compatible with both the sodium and water**

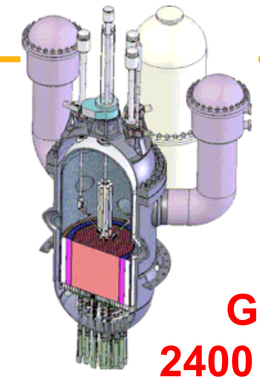
Favorable features of the core and the system :

- **Core resistance to compaction**,
- Favorable **reactivity effects balance**,
- Efficient core control and monitoring
- Diversified means in degraded situations :
  - . Neutron leakage,
  - . Natural circulation,
  - . Decay heat removal,
  - . Local melting management by design measures…

Core melt accident :

- **Exclusion by design of sequences leading to large energy release**
- Design of an adequate recuperator

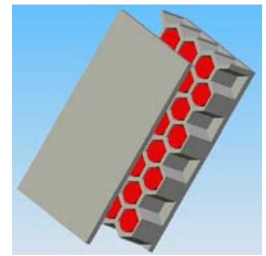
R&D on Gas Fast Reactors

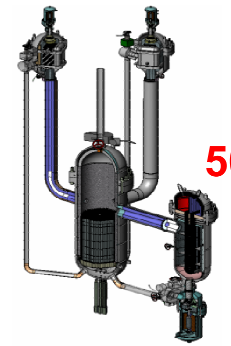


- Alternative FNR path with inert and transparent coolant

- Unlocking :

- nuclear fuel
- residual power management
- materials





- High power GFR feasibility

- Experimental and Technical Demonstration Reactor (ETDR) design studies

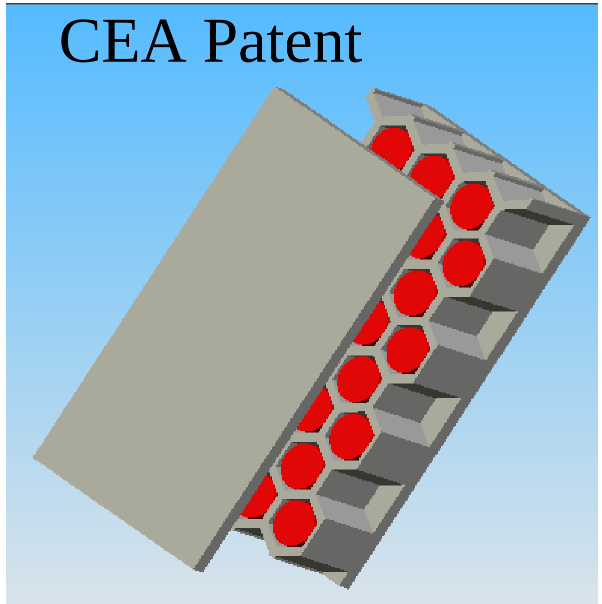
- global design, consistent with GFR
- safety assessment report (SAR)

Gas Fasr Reactors : nuclear fuel (1/2)

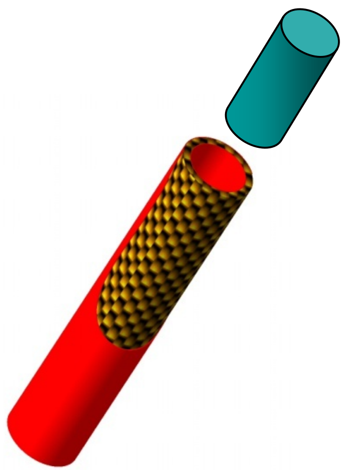
2004 – Preliminary choice of the reference (plate) and alternative (rod) concepts

Nuclear Fuel Plate

- *Parallelepiped plate 7x120x200 mm*
- *Actinide carbide pellets in honeycomb (SiC)*
- *SiCf-SiC lower and upper plates*



Fuel plate



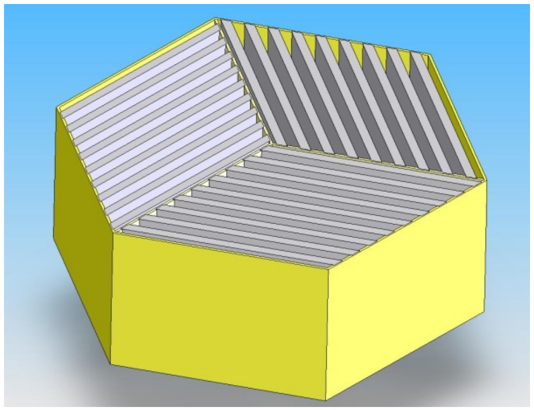
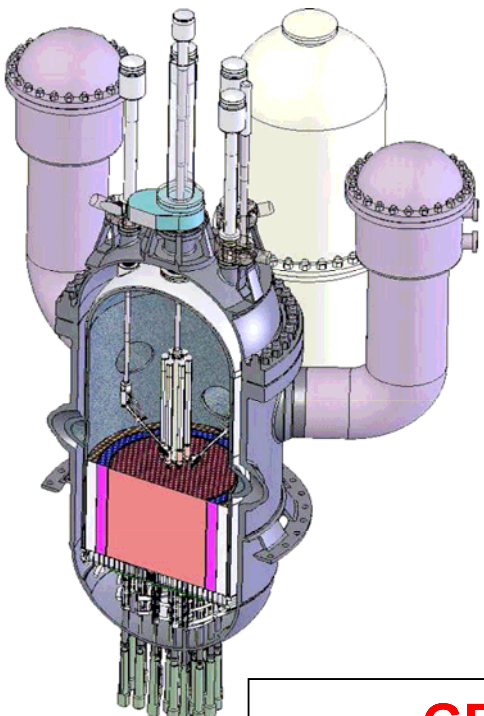
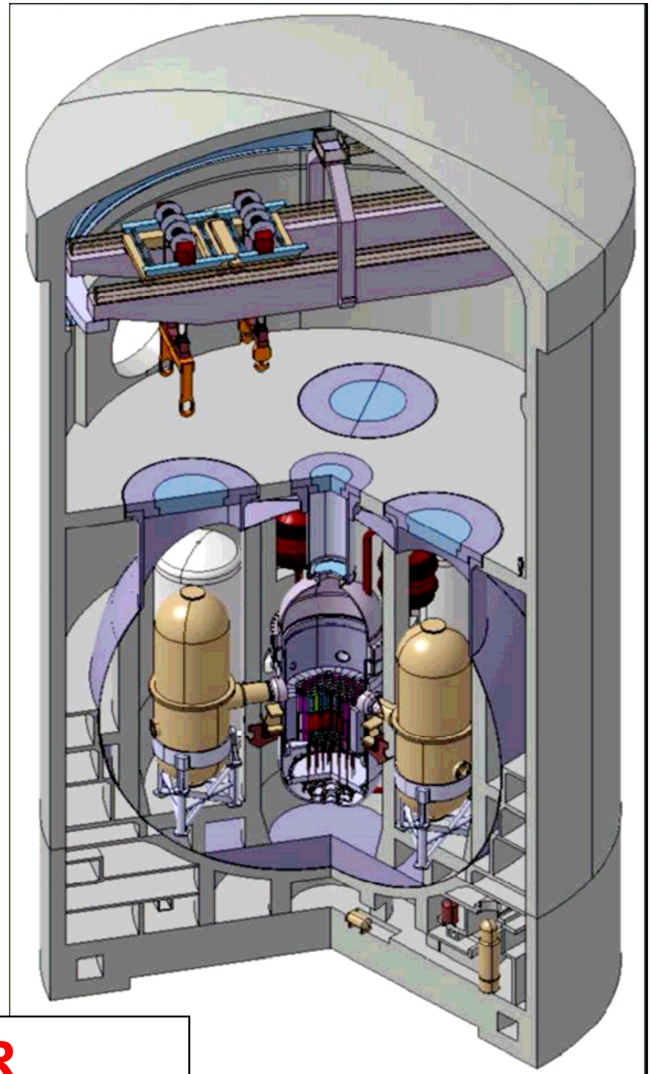


Plate assembly

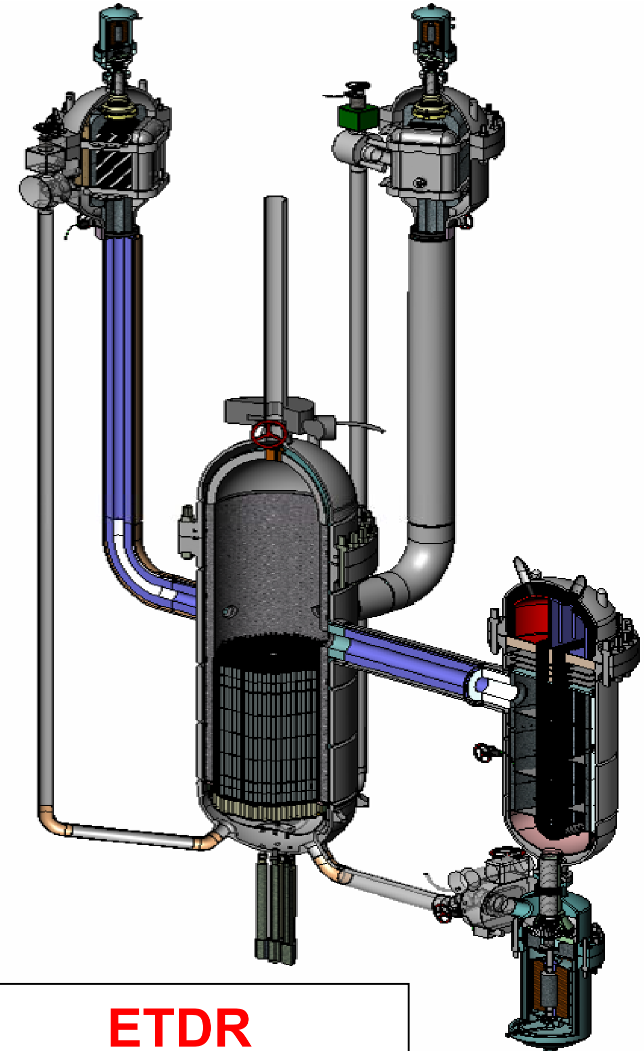
[1]**Alternative Fuel Rod*****: under studies***

ETDR and 2400 MWth GFR Sketches





GFR
2400 MWth



ETDR
50 MWth

A prototype reactor in 2020

President Chirac statement :

« 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.

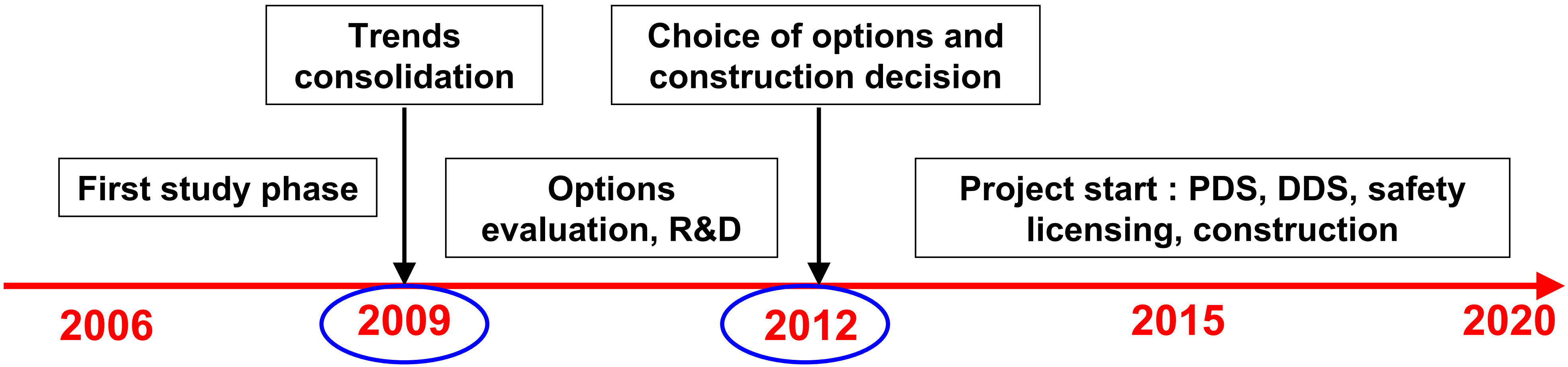
We will naturally welcome industrial or international partners who would like to get involved… »

A common schedule for the two options

The bill requires to « **provide by 2012 an assessment of the industrial prospects of those systems** » (of which Gen IV ones)

➔A 6 year period for R&D to gather technical elements necessary to decide the next step and propose the specifications for the prototype

➔This nevertheless does not mean that all the options for nuclear systems to be deployed after 2040 have to be decided at that time



The Sodium Fast Reactor prototype

- To be demonstrated, stakes need a prototype with its energy conversion system with a power in the 250-600 MWe range, the size choice being an optimisation between costs, risks, representativity

- Resource saving : materials recycling with increased levels of safety and proliferation resistance

- Waste management
    - Pu multi recycling (from used PWR MOX fuel)
    - MA recycling : progressive evaluation and technical-economic demonstration

➔ Associated cycle facilities are needed
    - MOX core (few tons year)
    - Minor-Actinides beared fuels (few 10Kg per year)

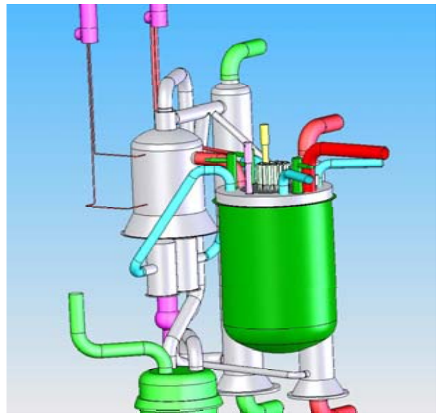
A comprehensive programme

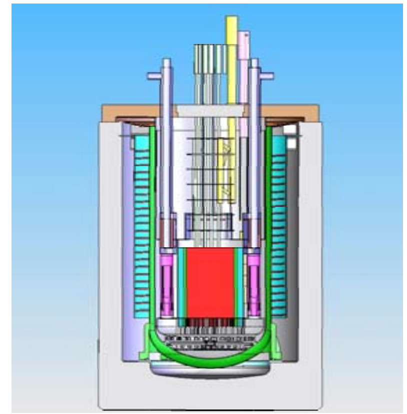
➔6 Pre-conceptual design studies to prepare 2012 decisions

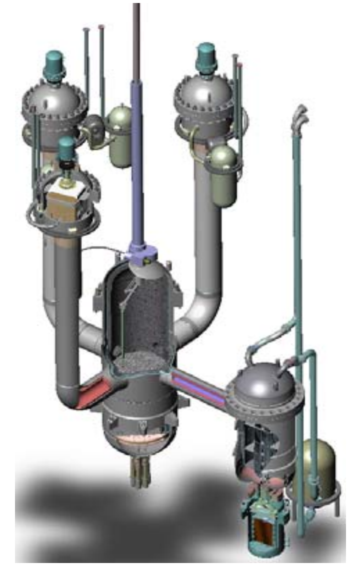
Pilot for MOX fabrication

MAs micro-pilot

2 SFR pre-conceptual studies







ETDR pre-conceptual studiy

With the associated main R&D tracks

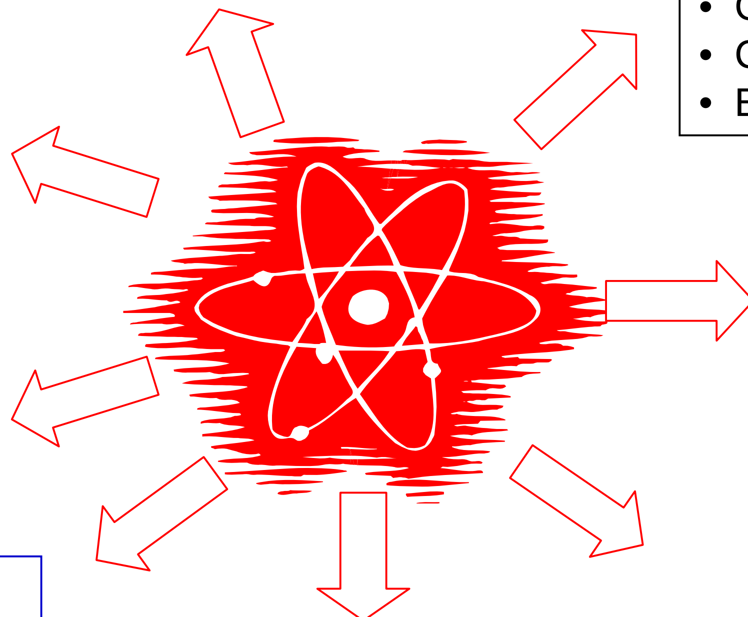
- SFR core studies and the safety improvement
- SFR in-core and secondary circuit materials
- Components for the SFR energy conversion
- Sodium technology and instrumentation (handling, ISIR, …)
- GFR challenges (fuel, safety) and viability assessment
- Fuel cycle processes

Few applications of industrial heat supply

Paper manufactories
- Paper Mill
- Heating

Oil-producing
- Refining
- De-sulfurisation d'huiles lourdes
- Gas production
- Coal gasification
- Extraction of bitumen

Cement works
- Production of cements
- Production of lime



Iron industries
- Steel Production

Electricity
- Production of electricity

Chemical industries
- Production of hydrogen
- Production of ethylen
- Production of styren
- …

Other industries
- Production of other metals (aluminium, …)
- Glass manufacturing

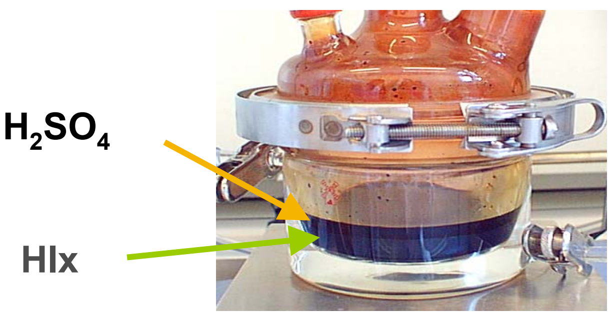
Others
- Sea water desalination
- Heating

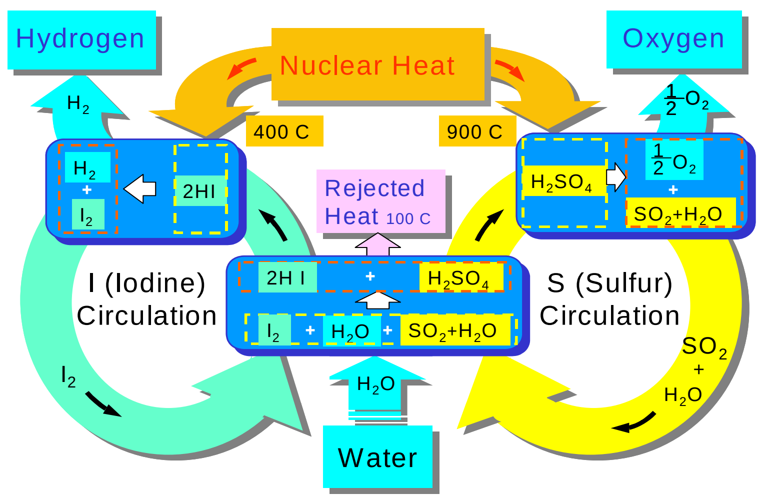
R&D on hydrogen production

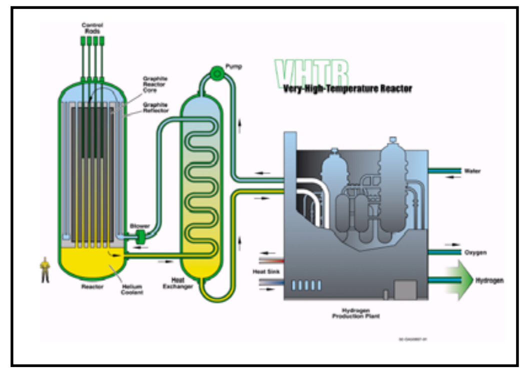
- **2 main processes , 4 fields**
    - iodine/sulfur cycle
    - high temperature electrolysis
    - process evaluation
    - Plant design and coupling with nuclear plant
- **A first step in 2008 :** feasibility and comparison of performances

many collaborations : Europe, Gen IV, USA, Japan

Reactor (B0)



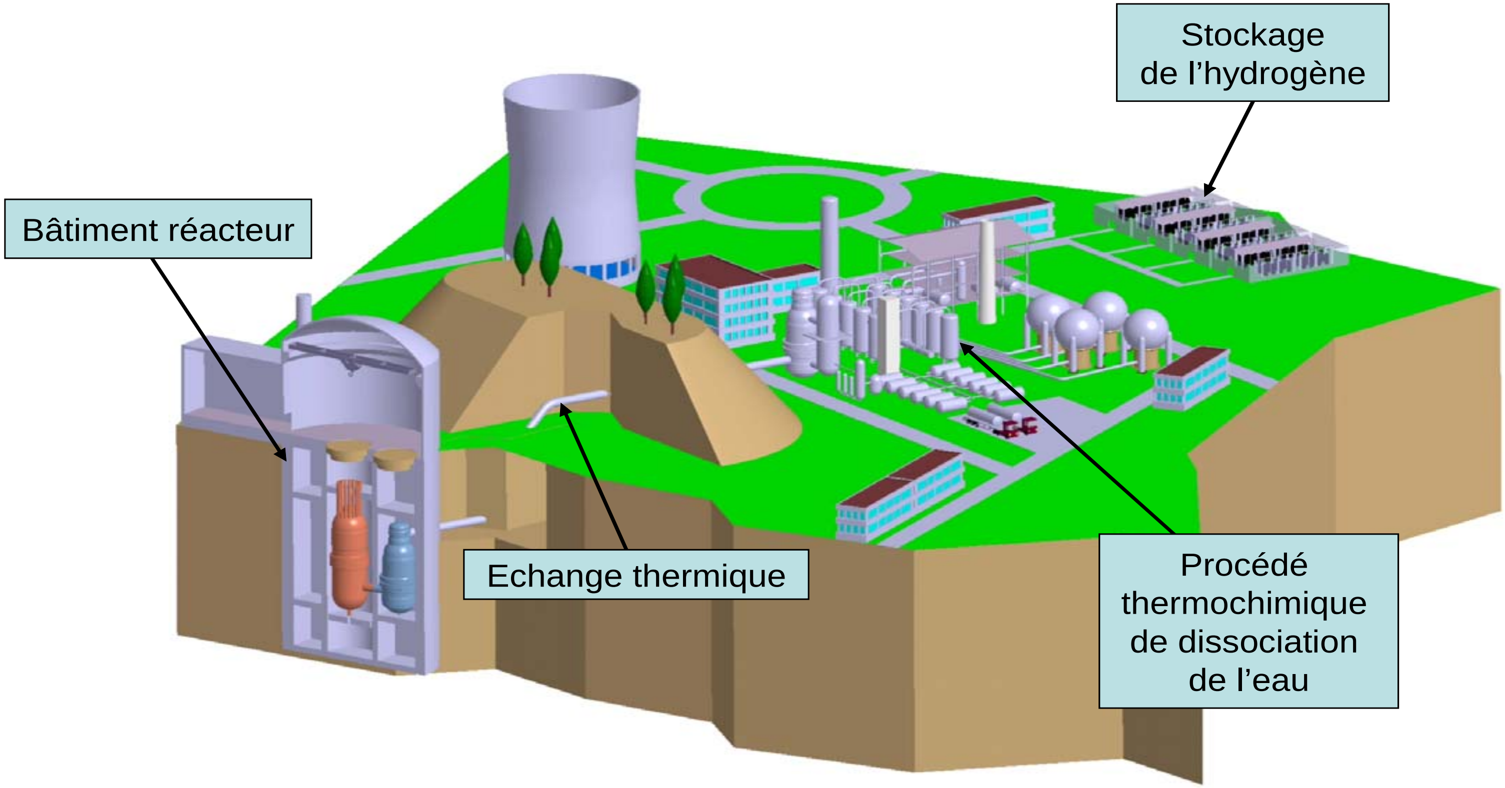




Very High Temperature Reactor

Coupling with a nuclear power plant

- A dedicated 600 MWth VHTR and the iodine/sulfur process
- Electricity coming from the grid (100 MWe)
- Hydrogen production of about 80 000 m^3/h
- Safety and hydrogen risk studies



Syngas enrichment in H2 so as to reach the best conversion of $C_{Biomass}$ into fuel

$$C_6H_9O_4 + 2H_2O + 5.5\ H2 \rightarrow 6\ \text{-CH2-} + \text{eau}$$

BIOMASS + HYDROGEN → BIOFUEL

$C_6H_9O_4$ + eau

5.5 H2

6 -CH2-

Means for a nuclear renaissance

- **Advanced irradiation tools**
- **R& D programms shared by international partnership**
- **A capability to build demonstration reactors (prototypes)**
- **A large international cooperative framework**

Three Categories of Reactors

- « Material Testing Reactors » : MTR

- pool reactors : for irradiation purpose

JHR 2014

- Experimental Reactors (anticipating new systems)

- 10 to 100 MW th → fuel type, coolant, safety and control systems.
- with no energy conversion system
- example : Rapsodie (FNR sodium, 40 MWth)

ETDR 2020

- Demonstration Reactors (prototypes)

- fully integrated system with energy conversion,
- scalable up to commercial needs
- technical and economical performances
- front-end and back-end industrial inputs (fuel fabrication, SNF reprocessing, etc...).
- example : Phénix (600 MWth, 250 MWe)

ASFR 2020

PGFR 2025

JHR : A new material testing reactor in Europe

• **JHR Project** : an international facility

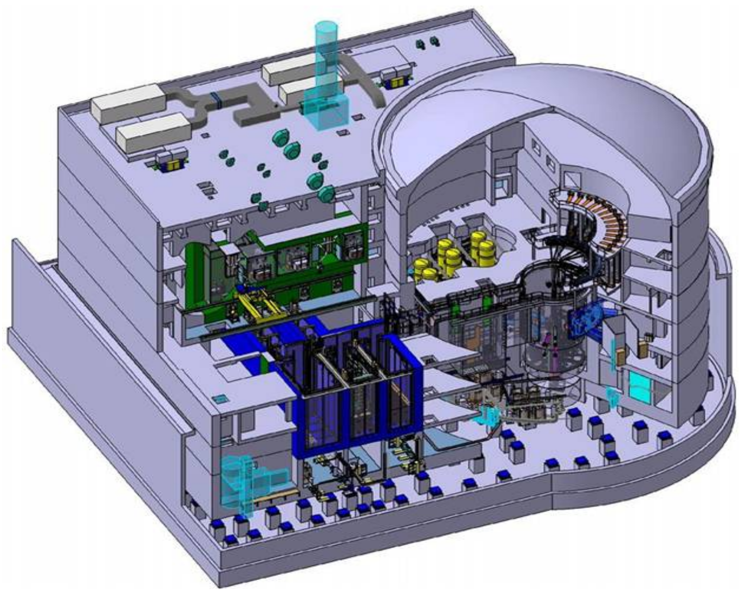
a high performance and flexible reactor (2014)

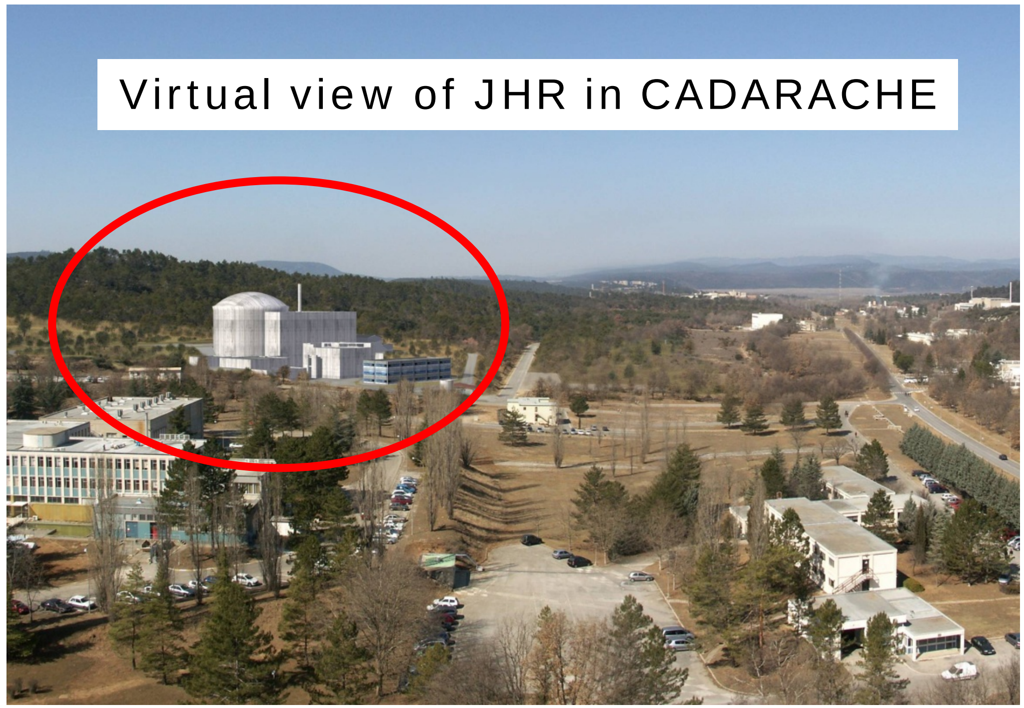
-behaviour of structural materials and fuels

-High level neutronic flux

-Increasing instrumentation

-Capability to simulate different environments





Irradiation tools for future system development

- **JOYO** and **PHENIX** (➔2009)

- **MONJU** :

global actinide management (2010-2020)

CEA engineer currently on-site in Monju

- **JHR Project** :

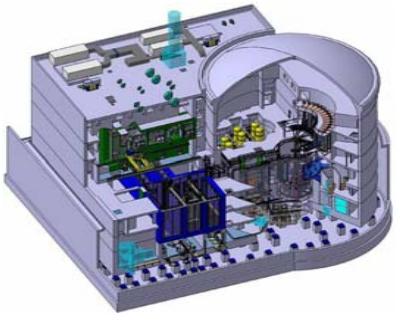
a high performance and flexible reactor (2014)

-behaviour of structural materials and fuels

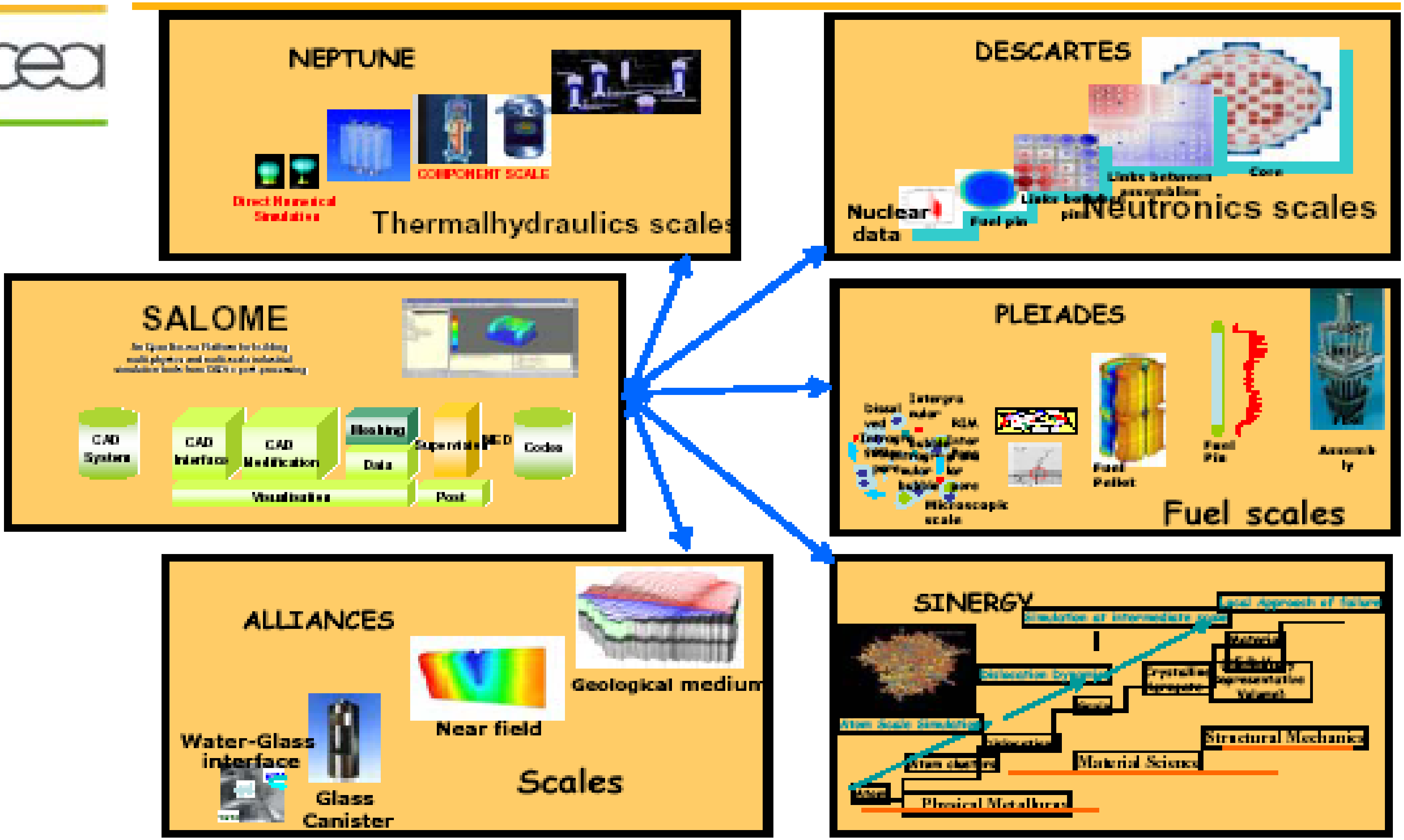
-High level neutronic flux

-Increasing instrumentation

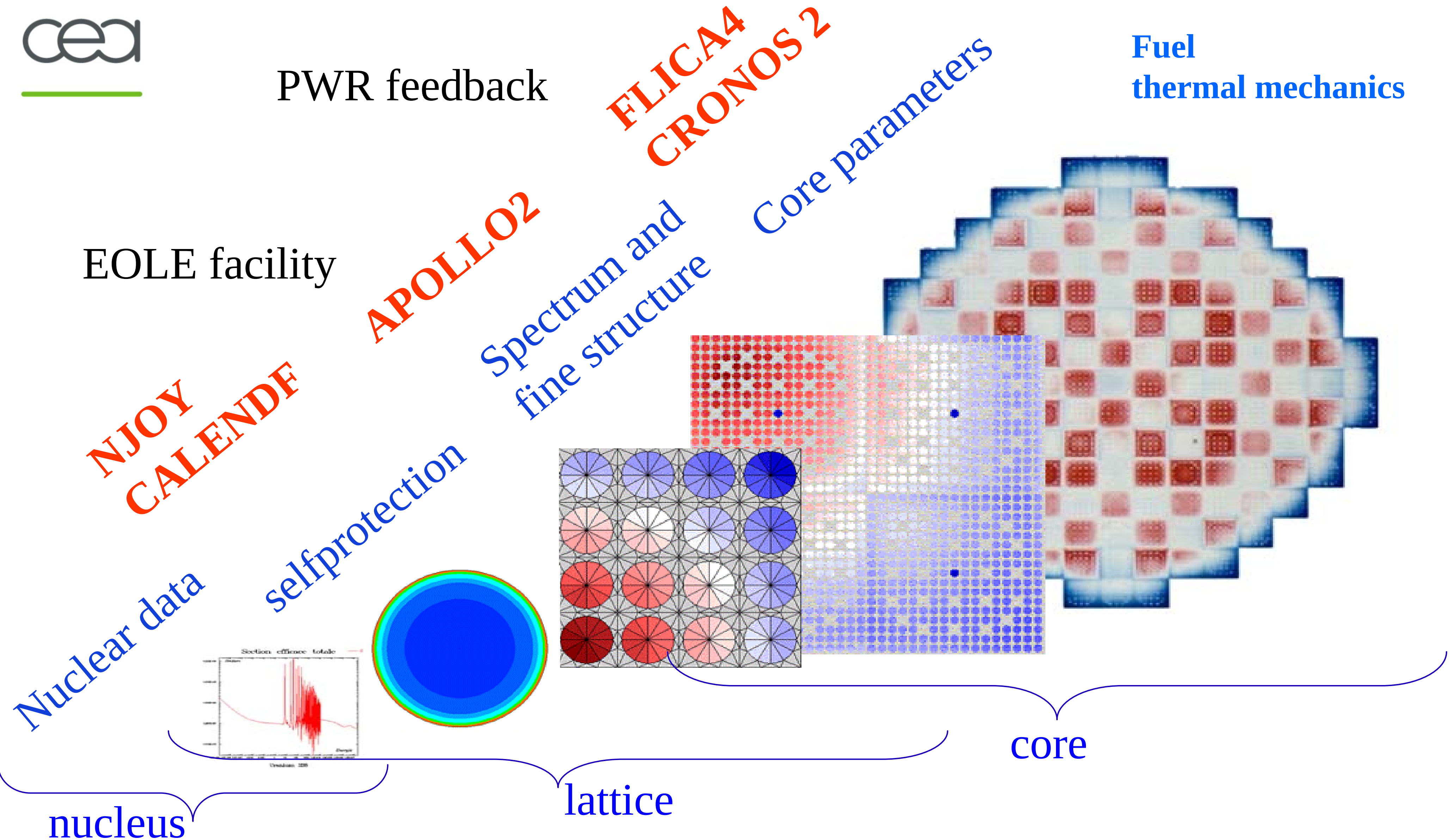
-Capability to simulate different environments



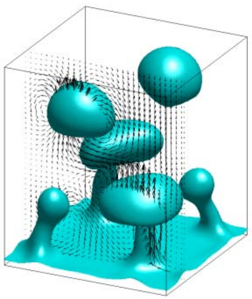
Multiscale and multiphysics approach



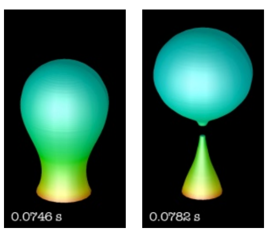
SAPHYR : example : LWRs



Multiscale scope of ThermalHydraulics

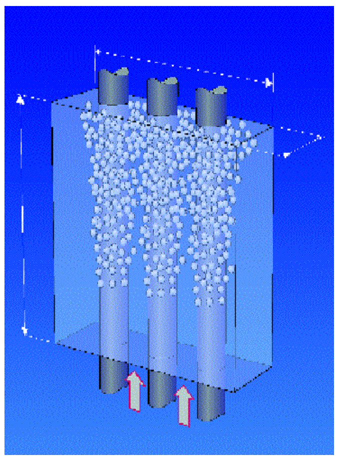


MICROSCOPIC SCALE



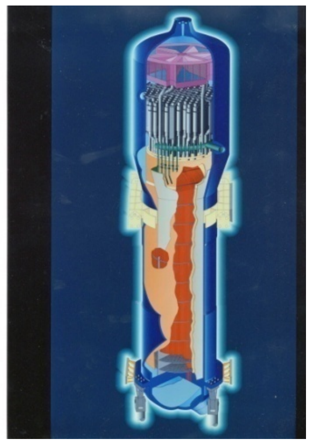
DNS SCALE
(TRIO-U)

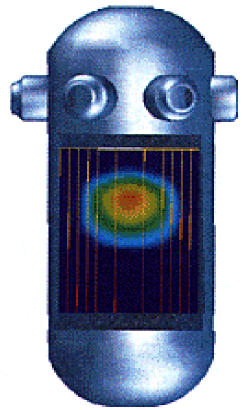
MESOSCOPIC SCALE



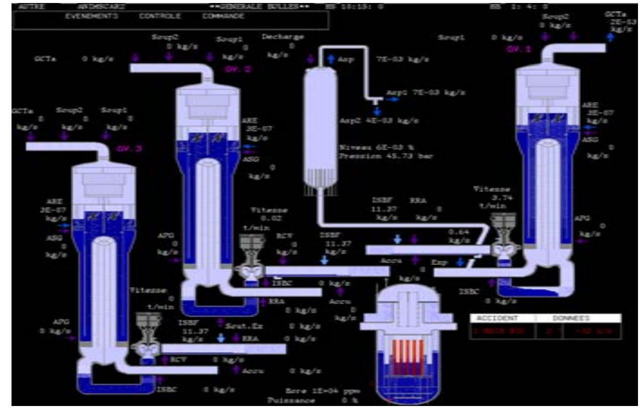
CFD IN OPEN MEDIA

MACROSCOPIC SCALE





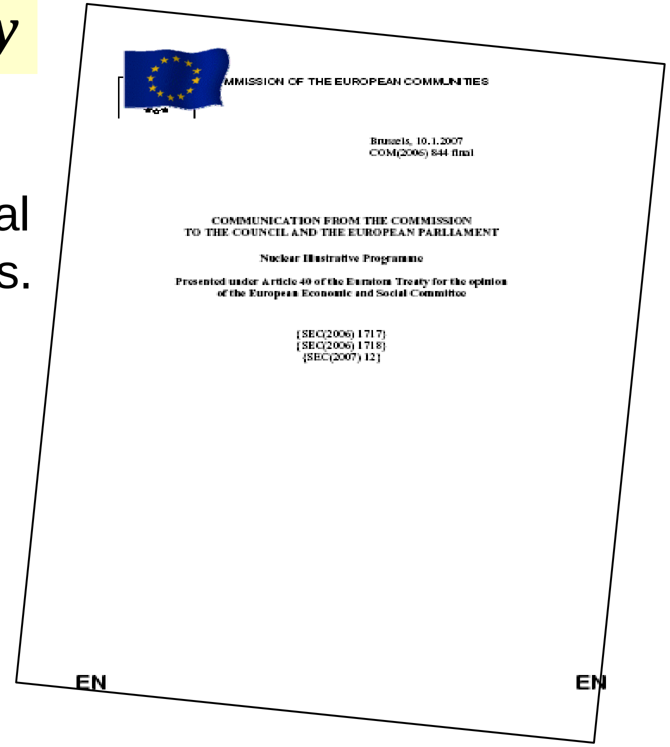
CFD IN POROUS MEDIA
(FLICA-GENEPI-THYC)



SYSTEM SCALE
(CATHARE)

THE NEPTUNE PROJECT
(CEA-EDF-AREVA-NP-IRSN)

A new perspective on the nuclear energy


MMISSION OF THE EUROPEAN COMMUNITIES

Brussels, 10.1.2007
COM(2006) 844 final

COMMUNICATION FROM THE COMMISSION
TO THE COUNCIL AND THE EUROPEAN PARLIAMENT

Nuclear Illustrative Programme

Presented under Article 40 of the Euratom Treaty for the opinion
of the European Economic and Social Committee

{SEC(2006) 1717}
{SEC(2006) 1718}
{SEC(2007) 12}

EN EN

" …/…

Nuclear energy, essentially free of CO_2 emissions, makes **an important contribution** to mitigation of global climate change as a result of greenhouse gas emissions.

…/…

Globally, demand for nuclear generation is expanding. **The EU is a leading industrial actor in nuclear energy**.

This creates business opportunities for European companies and brings potential advantages to the EU economy, thereby contributing to the Lisbon agenda.

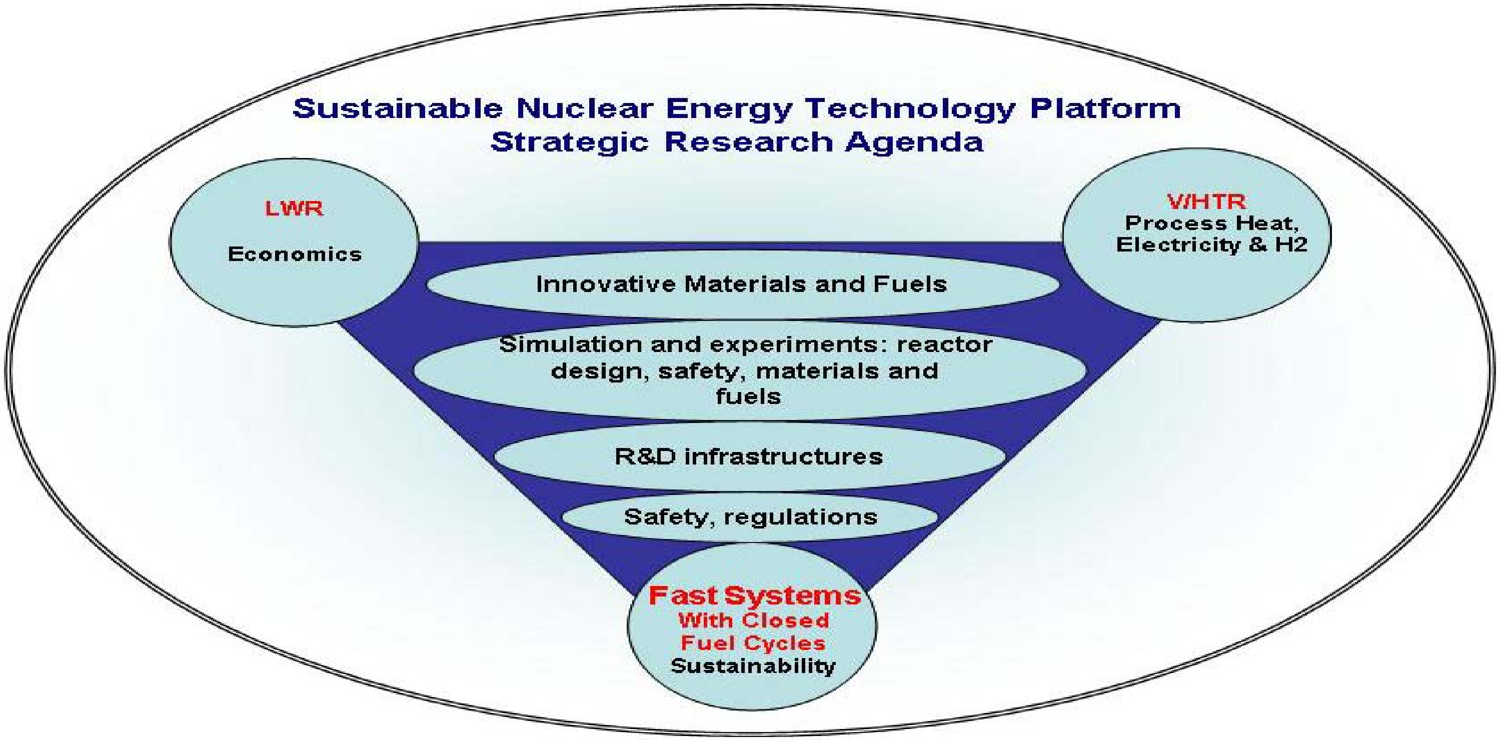
…/…

Development of nuclear energy will need to be governed in line with the rest of EU energy policy in accordance with the principle of subsidiarity, should be based on the technology's own competitiveness and should be **one component of the energy mix..** …/…"

Excerpt §7 final report COM(2006) 844

- **SNE-TP: Sustainable Nuclear Energy Platform**

(to be launched in september 2007)



Aim: ***to give priorities, to prepare / to launch R&D projects for nuclear fission in Europe (strategy, infrastructures…)***

SNE-TP : a shared approach

"Ensuring the place of nuclear energy in the EU's Energy Mix"

NUCLEAR ENERGY : *TWO MAINSTAYS*

Nuclear energy for the 21st century

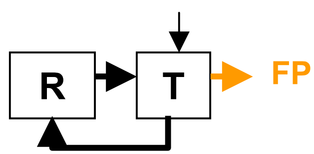
RENAISSANCE

avoid spent fuel accumulation!

3rd generation reactors with advanced recycling proven technologies

SUSTAINABILITY

Preserve resources



4th generation reactors with appropriate fuel cycle options

Towards a responsible renaissance

Adapted initiatives taking into account the best available technologies, towards the emerging economies

↓

to enlarge the access to the nuclear energy in terms of

- **electricity production without green gas emission (up to 40-50% in 2050),**
- **natural ressources conservation,**
- **waste minimisation,**
- **potential for new applications (hydrogen, desalination, heat…)**

RENAISSANCE

Spent fuel

new fuel (MOX)

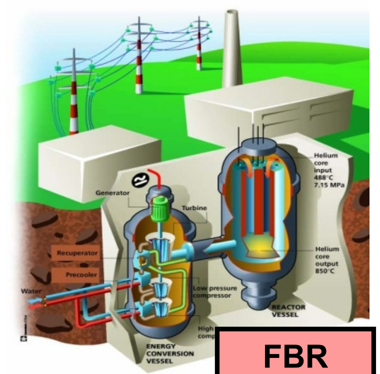
BRIDGING TECHNOLOGIES

Proven advanced recycling technologies

Spent fuel

new fuel

SUSTAINABILITY



FBR 4th Gen

Renaissance...

& Sustainability

Nuclear energy

L'énergie nucléaire

up to you !