Development Program of Innovative Reactor Systems in the World

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OUTLINE

SOME PERSPECTIVES FOR SUSTAINABLE NUCLEAR ENERGY ?

PRESENT STATUS AND PROJECTIONS WITH THE 3rd GENERATION

WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED ?

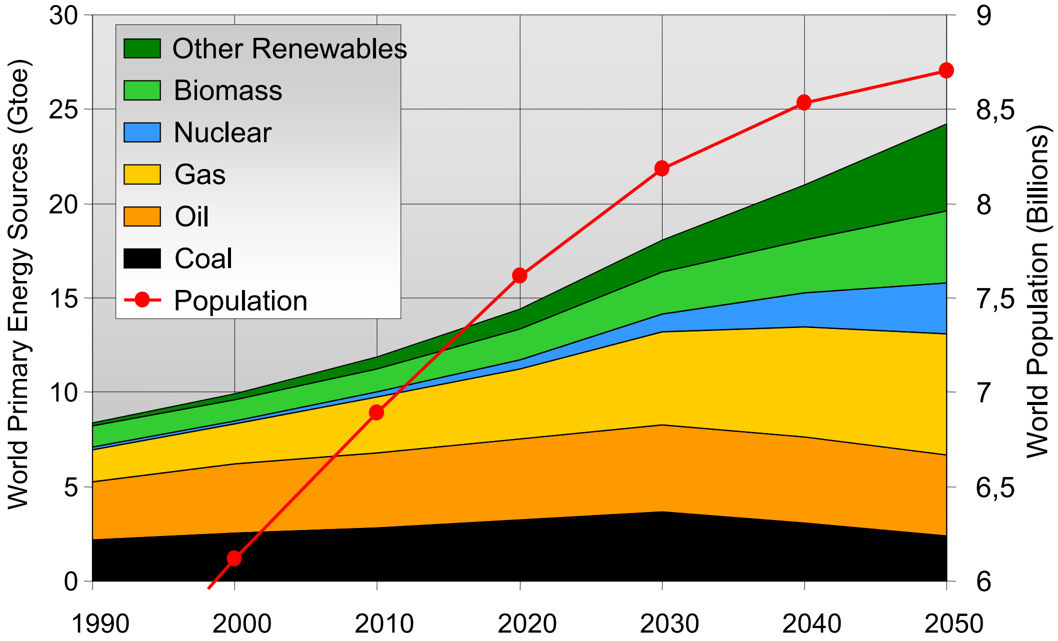
THE GENERATION IV INTERNATIONAL FORUM

THE STRATEGY IN FRANCE AND EUROPE

R&D ISSUES AND HIGHLIGHTS:
- FAST NEUTRON SYSTEMS AND CLOSED FUEL CYCLE
- HIGH TEMPERATURE REACTORS AND APPLICATIONS

TOOLS, INFRASTRUCTURES, EDUCATION & TRAINING

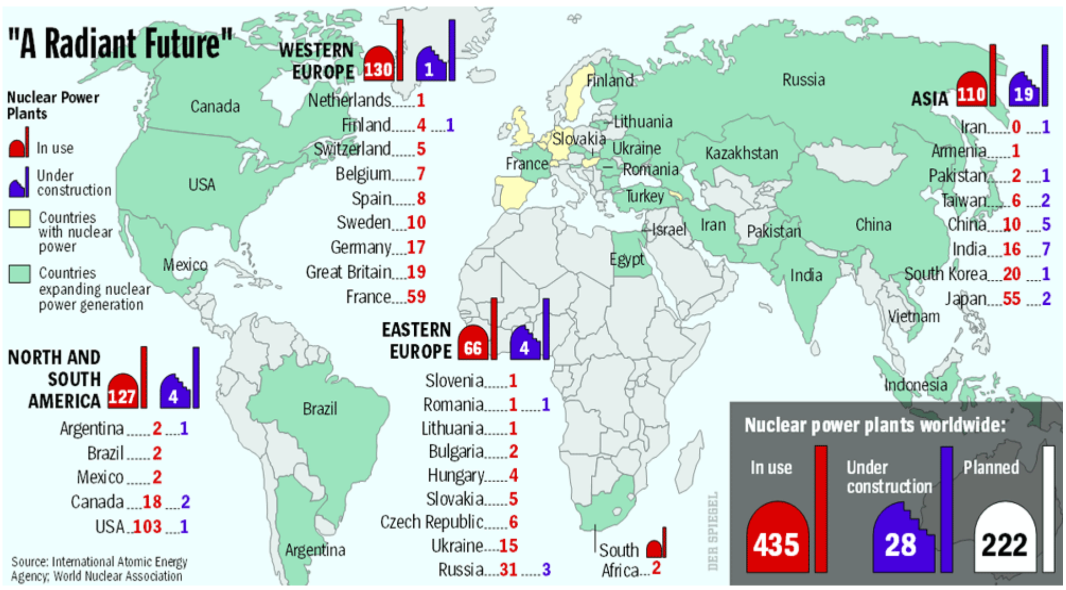
Sustainable energy development scenario (IEA - 2003)



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

Many published scenarios predict a significant increase of the share of nuclear in the energy mix by 2050

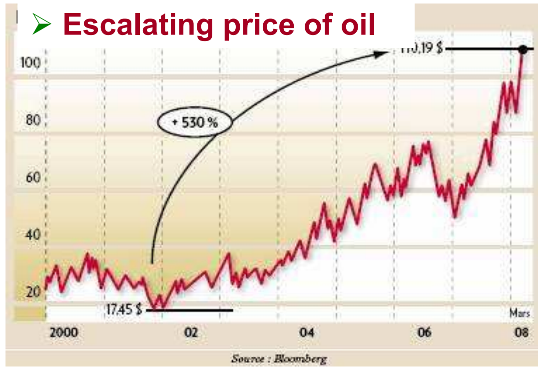
An increasing world nuclear electricity demand ...

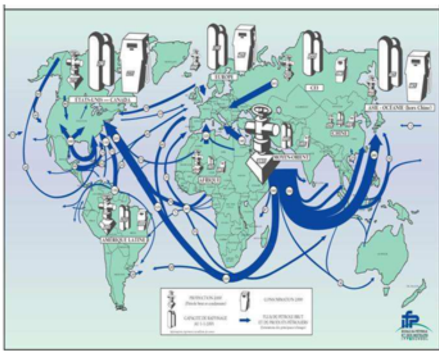


Installed nuclear power increased by a factor 3-5 by 2050 ?

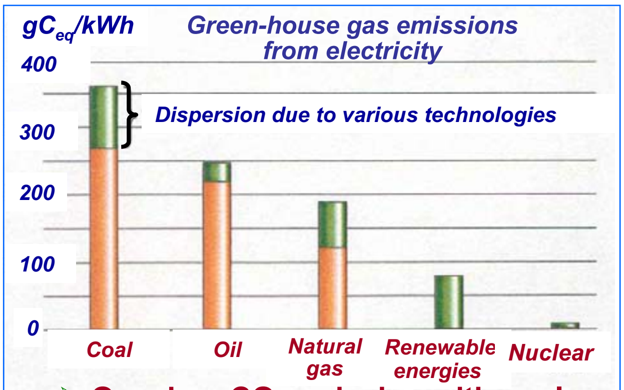
Assets of nuclear power

- **Economic competitiveness**
  ~ 28 vs 36 €/MWh *(gas, coal)*
  [DGEMP-DIDEME Study 2003]
- **High safety level and steady improvements**



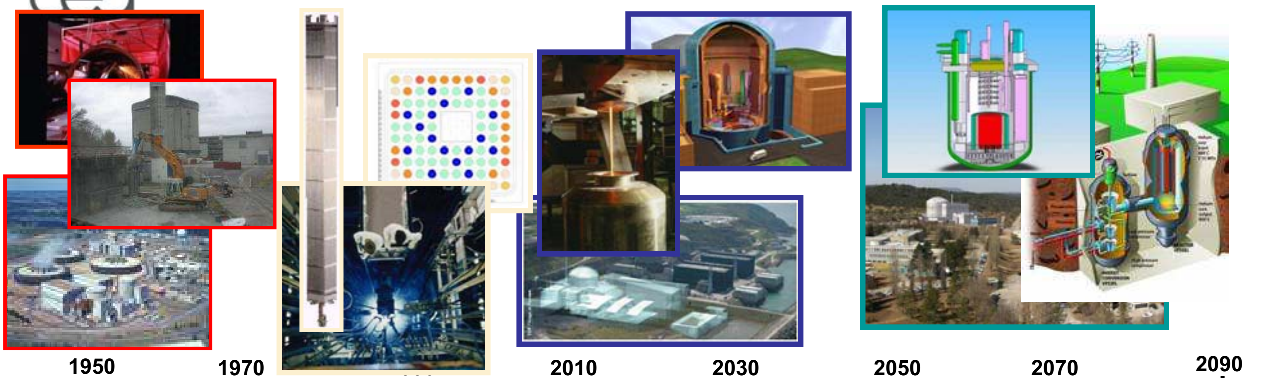


- **Energy security**



- **Quasi no CO_2 emission with nuclear**

Generations of Nuclear Power Systems



1950 | 1970 | 2010 | 2030 | 2050 | 2070 | 2090

1st generation DISMANTLING
UNGG
Magnox

2nd generation OPERATION
REP 900
REP 1300
N4 (1450)

3rd generation OPTIMIZATION
EPR (1600), **AP1000, ABWR, ESBWR**
COEX

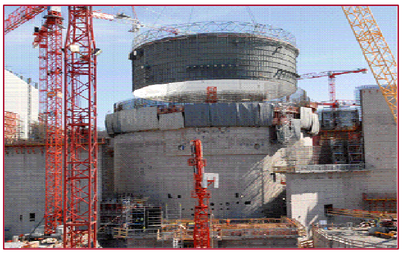
4th generation DESIGN and R&D
Prototypes 2020-25
DIAMEX/SANEX, GANEX

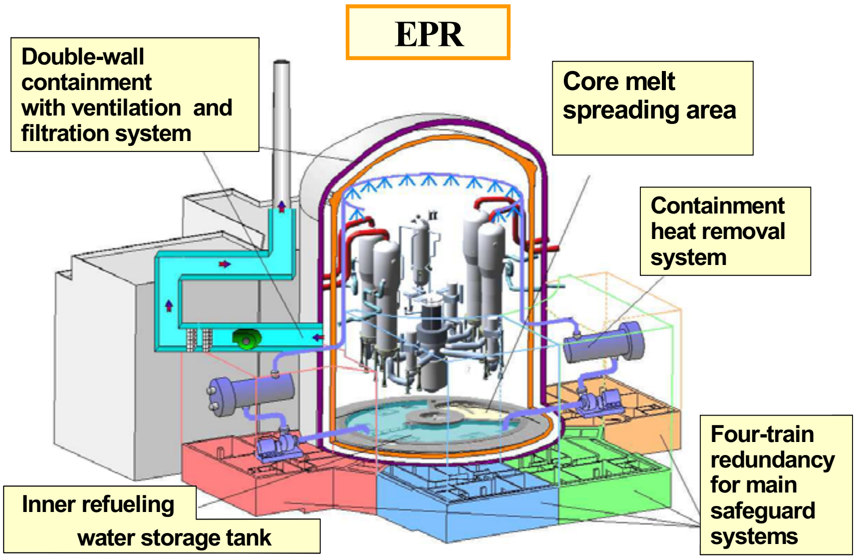
EPR: European Pressurized Reactor

PWR 1600 MWe, 60 years, K_D~91%

EPR Flamanville *(2012)*

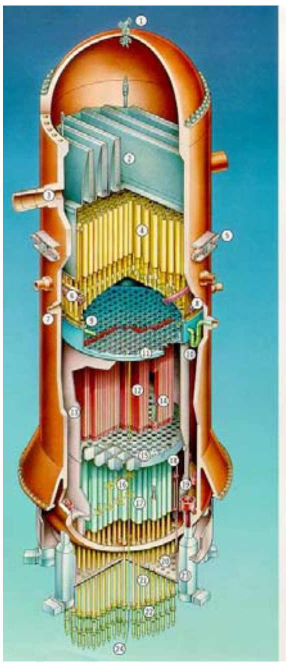
EPR Olkiluoto *(2011)*

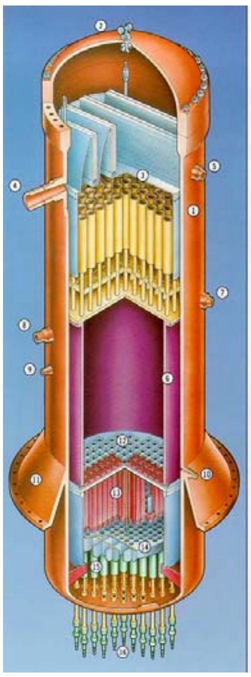


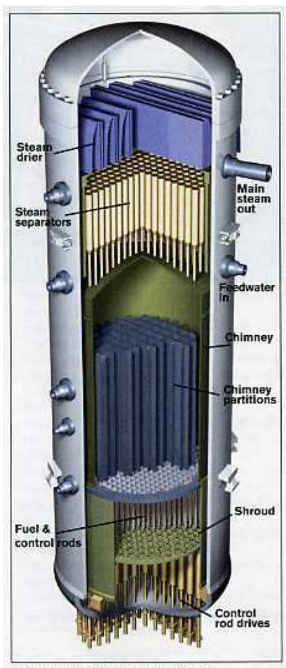


Reinforced safety features and economic competitiveness

Advanced BWRs : GE ABWR and ESBWR







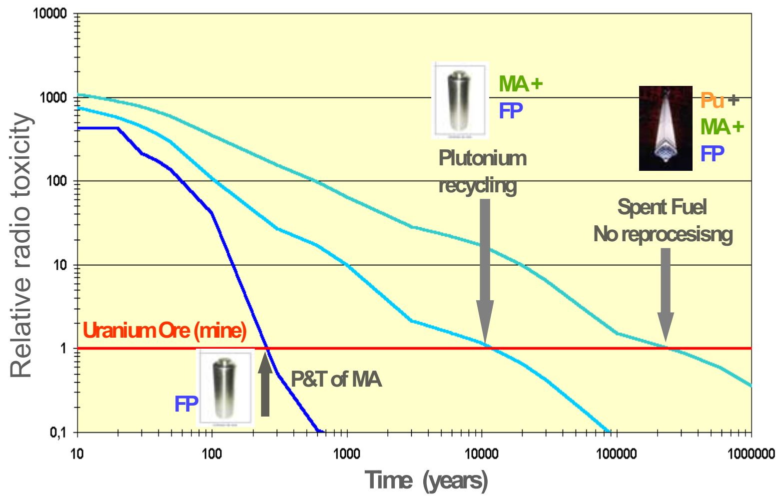
ABWR (~1300 MWe) **SBWR (670 MWe)** **ESBWR (~1500 MWe)**

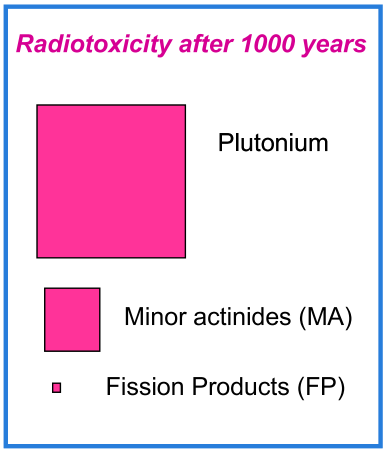
Minimizing waste with advanced actinide recycling

- Plutonium has a high energetic potential

- Plutonium is the major contributor to the long term radiotoxicity of spent fuel

→ ***Plutonium recycling***





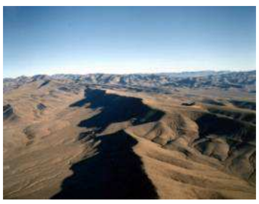
- After plutonium, MA (Am, Cm, Np) have the major impact to the long term radiotoxicity

→ ***MA transmutation***

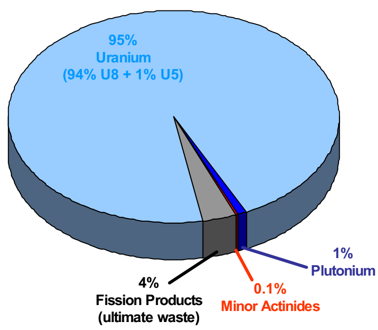
Open cycle or closed cycle

❑ Some countries (USA, Sweden, Finland) have made the choice of « open cycle ».

No fuel processing, nuclear spent fuel stored into repository



Yucca Mountain site



→ Valuable materials U et Pu are lost, the potential radiotoxicity and the volume of nuclear waste to repository is significant.

❑ In France, spent fuel is recycled.

U and Pu are recovered, stored and used (partially) for fresh fuel fabrication. Fuel treatment and recycling save Unat and minimize the volume and radiotoxicity of nuclear waste.

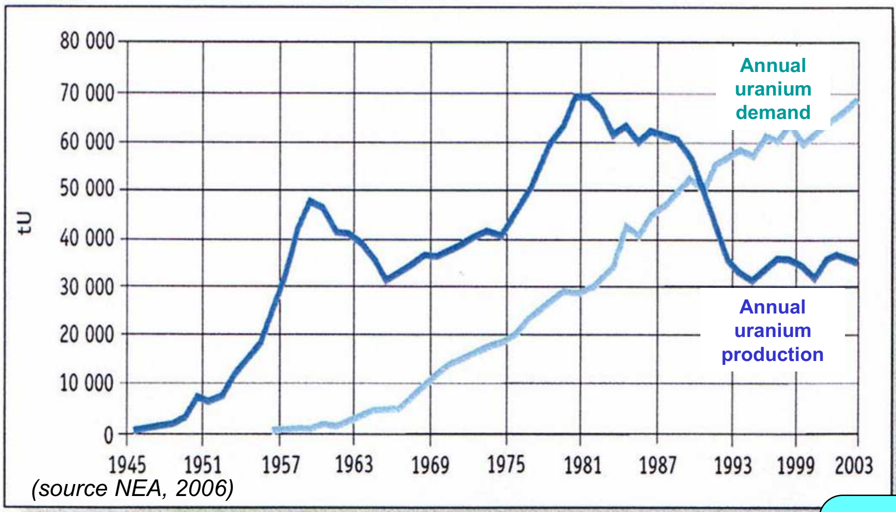
La Hague plant

Japan is promoting the same strategy

Uranium demand is larger than natural uranium production

→ *Complementary resources have been engaged (Pu, recycled U, MOX)*

Annual production of uranium and needs for nuclear reactors (1945-2003)



Conventional resources (identified,< 130 US$/kg) 4.7 MtU

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

Open fuel cycle in LWRs

Utilization of uranium ore for 1 GWe x year

200 tons U_{nat}

99.3% ^{238}U + 0.7% ^{235}U

E →

20 tons U 5% → R →

- 1 t → W + PF
- 0.2 t Pu
- 18.8 ton U_{rep}

180 tons U_{dep}

Fast neutron reactors need only 1 ton U238 (U_{dep} & U_{rep}) that is converted into plutonium and burned in situ *(regeneration → breeding of fissile fuel)*

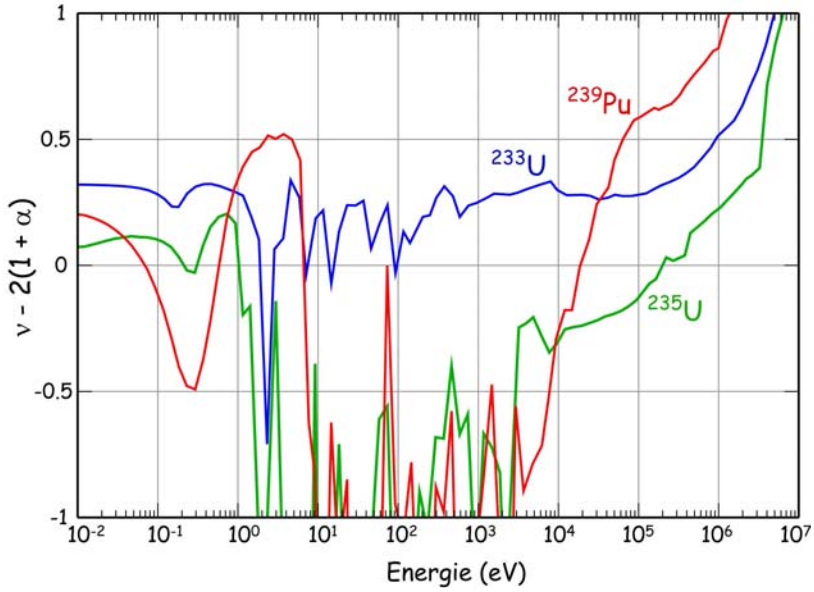
→ U_{dep} generated by a LWR over a 50 year lifetime is worth > 5000 years of the same power output with fast reactors

Why should we do better than the 3rd generation ?...

- The large scale development of 3rd generation reactors challenges uranium resources : identified conventional resources (at a cost < 130 $ /kg) represent 160 years of today’s consumption (only about 0.5% of natural uranium is used)
- The management of nuclear wastes will have to be further improved
- Having in mind a perspective of fossil fuel shortage, nuclear technology should get prepared to answer other needs than electricity supply: hydrogen, process heat, desalination,…
- Larger spreading of nuclear power needs proliferation resistance

→ New types of nuclear reactors must be designed in order to ensure energy supply in a context of sustainable development

Fast neutron reactors have the best capability for breeding and transmutation



	Thermal	Fast
isotopes	$\alpha=\sigma_c/\sigma_f$	
^{235}U	0.22	0.29
^{238}U	8.3	7.5
^{239}Pu	0.58	0.3
^{240}Pu	396.6	1.6
^{241}Pu	0.40	0.19
^{242}Pu	65.5	1.8
^{237}Np	63	5.3
^{241}Am	100	7.4
^{243}Am	111	8.6
^{244}Cm	16	1.4
^{245}Cm	0.15	0.18

Conditions for breeding… more precisely

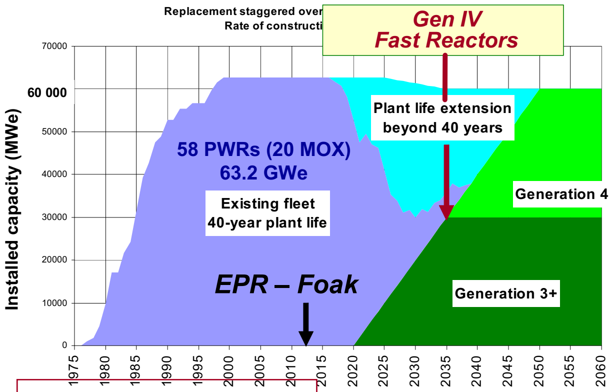
$$N_a = \nu - 2(1+\alpha)$$

$$N_a > 0 \rightarrow \eta > 2$$

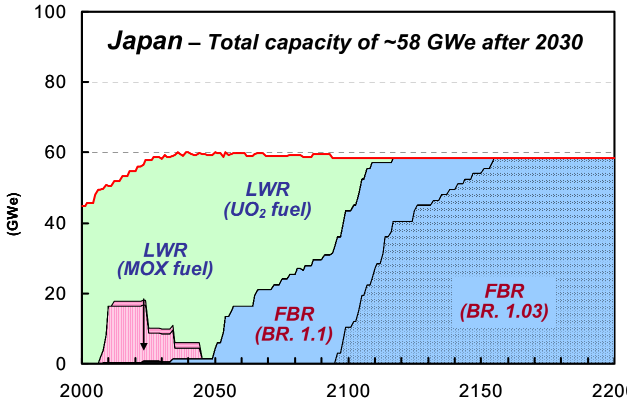
The ratio α = capture/fission is favourable to MA fission in fast neutron spectrum

Scenario for the renewal of nuclear reactors in France and in Japan

Major role of LWRs over the 21st century…



Source : EDF (ENC 2002)



…Transition from PWRs to Gen IV fast neutron systems by 2035

…Transition to fast neutron systems (breeders, FBRs) > 2050

Closed fuel cycle is an industrial reality in France and in Japan

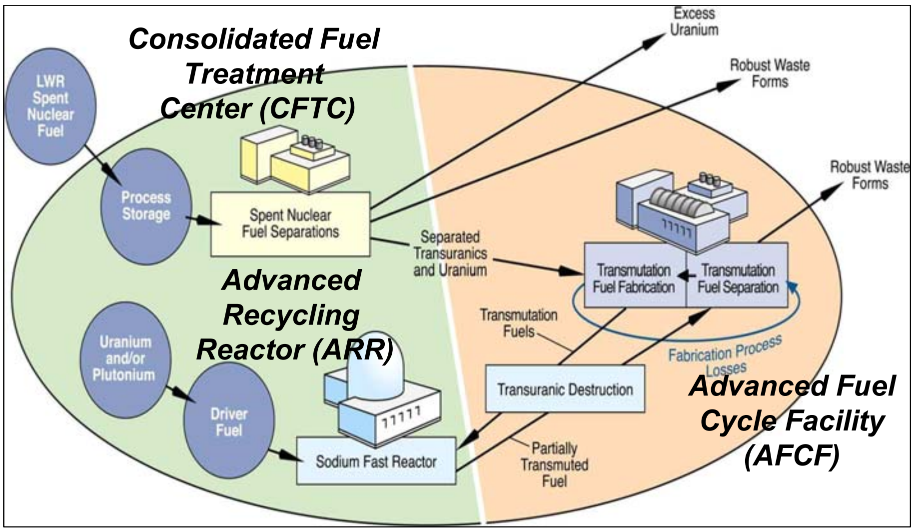
Rokkasho reprocessing plant

The GNEP initiative

The recognition of the benefit of treatment/recycling strategies

G. Bush, January 2006

- Expand use of nuclear power
- Minimize nuclear waste
- Demonstrate recycle technology
- Demonstrate Advanced Burner Reactors
- Establish reliable fuel services
- Demonstrate small, exportable reactors
- Enhanced nuclear safeguards technology



GNEP key program elements and supporting facilities (ARR, AFCF, CFTC)

A renewed vision of nuclear fuel cycle in USA → Major change in the Carter doctrine with regards to fuel reprocessing

A considerable feedback on fast neutron reactors…

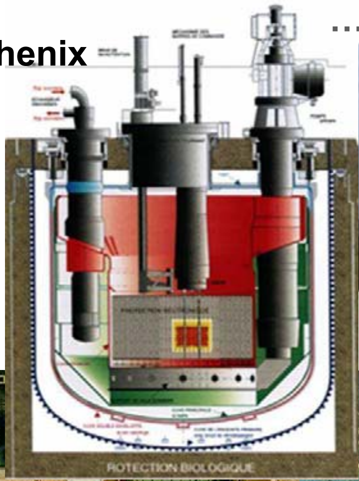
…in Japan

The choice of the loop-type design

Joyo (50 MWt)

Monju (280 MWe)
(shutdown in 1995, to be restarted in 2008)

Phenix



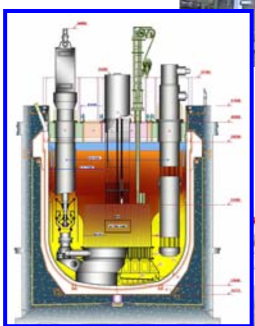
…and in France

Phenix (Marcoule)

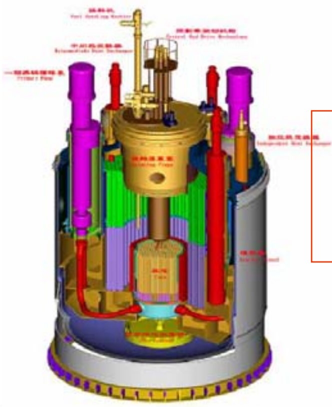
Superphenix (Creys-Malville)

Superphenix: an industrial prototype (1200 MWe), shutdown in 1998

India and China are building Sodium Fast Reactors…



PBFR (India)
500 MWe (2010)



CEFR (China)
65 MWt, 20 MWe (2010)

…The construction of BN 800 has been initiated in Russia

Nuclear is a CO_2-free option for sustainable energy

New requirements for sustainable nuclear energy

Search innovative solutions for:

Waste minimisation

Natural resources conservation

Proliferation resistance

***Perform continuous progress on*:**

Competitiveness

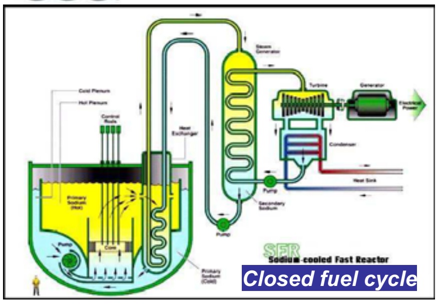
Safety and reliability

Develop the potential for new applications:

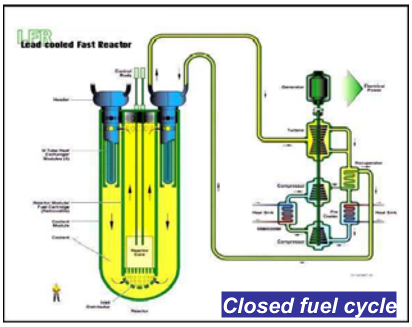
hydrogen, syn-fuels, desalinated water, process heat

➔ ***Systems marketable from 2040 onwards***

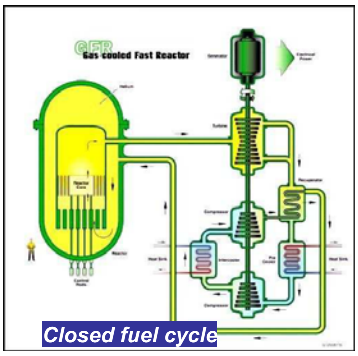
GIF selection of 6 nuclear systems



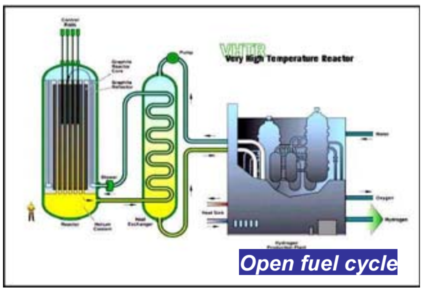
Sodium Fast Reactor



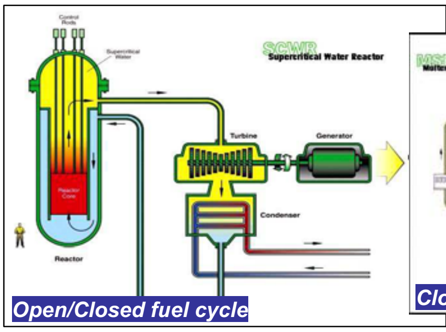
Lead Fast Reactor



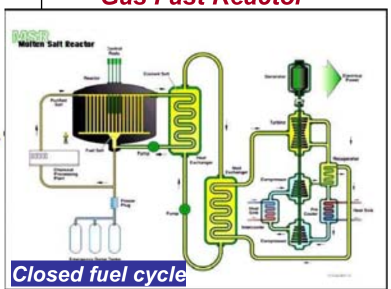
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

The recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissil regeneration) and waste minimization (minor actinide burning)

Interest shown by GIF members for each of the 6 concepts

Update on Participation in System Arrangements (status July 2007)

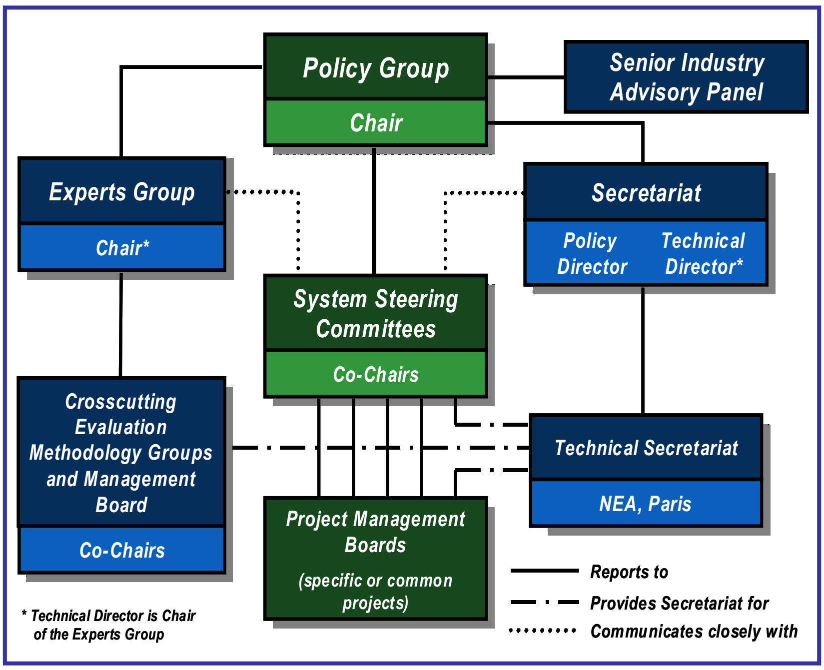
	GFR	LFR(a)	MSR(a)	SCWR	SFR	VHTR	Total
Canada				X		X	2
China (b)					X	X	2
Euratom	X	X	X	X	X	X	6
France	X		X	X	X	X	5
Japan	X	X		X	X	X	5
Korea					X	X	2
Russia (b)					X		1
Switzerland	X					X	2
USA					X	X	2
Total	4	2	2	4	7	8	

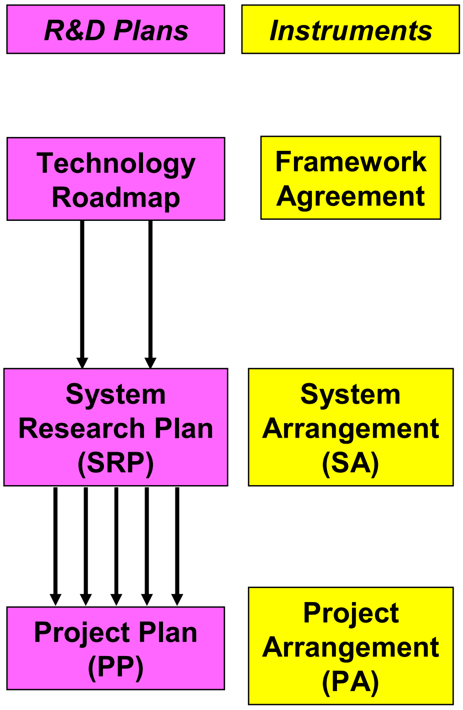
a: SA not yet negotiated

b: Not yet acceded to Framework Agreement

The GIF Management

What are SRPs, SAs, PMBs, PPs, PAs ?

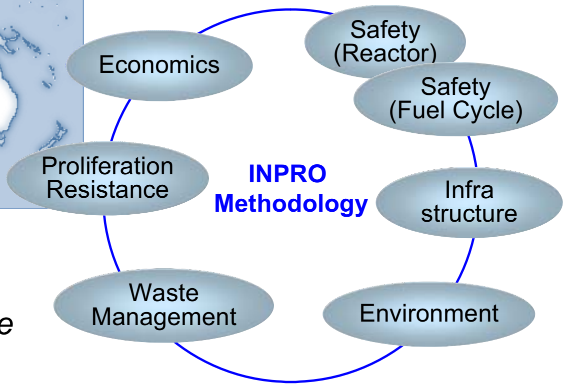




INPRO

A unique forum for the development of nuclear energy in IAEA affiliated countries, strengthening the cooperation between Technology "Holders" & "Users"

27 MEMBER STATES (status July 2007)

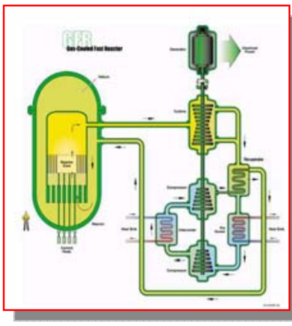


INPRO Methodology

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

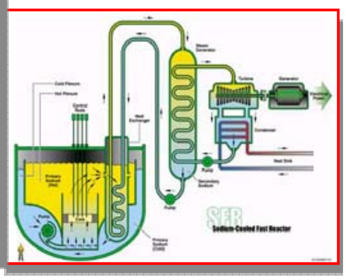
R&D Strategy of France for Future Nuclear Systems

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



Gas Fast reactor

Sodium Fast Reactor



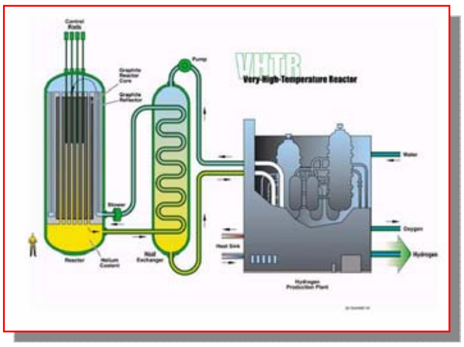
1 - Development of Fast Reactors with a closed fuel cycle:

- *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)*
- *Water splitting processes for hydrogen, synthesis of hydrocarbon fuels, process heat…*

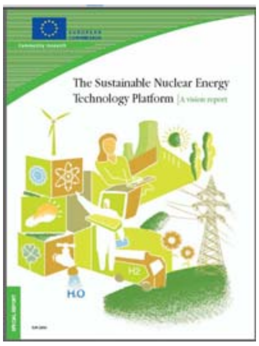
3 - Innovations for LWRs *(Fuel, Systems…)*



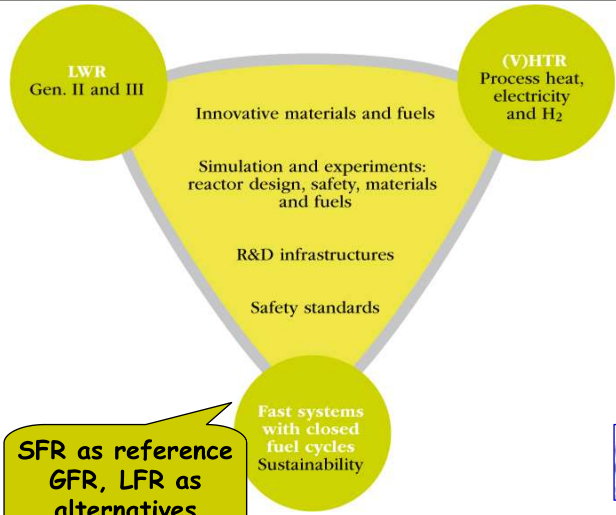
Very High Temperature Reactor

Sustainable Nuclear Energy Technology Platform (SNE-TP) Objectives & organization: 3 main areas

The involvement of industry and safety organizations together with research institutes and universities



SNE-TP vision report (September 2007)



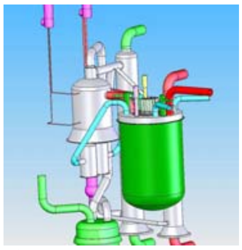
SFR as reference GFR, LFR as alternatives

A renewed approach for nuclear energy in Europe, consistent with the global vision of reactors + closed fuel cycle

Draft Strategic Research Agenda (SRA) to be issued end 2008

In the French strategy, 2 options of fast reactors are examined concurrently

- **A reference option: the Sodium Fast Reactor (SFR)**
  - Considerable experience world-wide
  - ➔ **The most mature of Fast Reactor concepts**
  - Major improvements are sought with respect to SPX and EFR

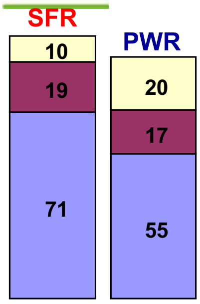


SFR prototype (250-600 MWe)

2020

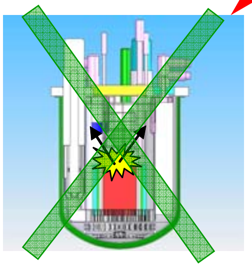
- **An alternative, the Gas Fast Reactor (GFR)**
  - Attractive features such as transparent and inert coolant
  - Capable of reaching high temperatures (sustainable version of VHTR)
  - ➔ **Requires some technological breakthroughs, but provides access to both a fast neutron spectrum and high temperatures**

Demonstration reactor (ALLEGRO, 50-70 MWt)



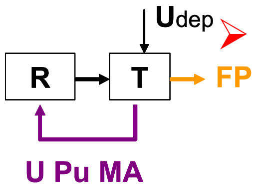
➢ Competitive economics relative to Gen III LWRs

- Reduction of *investment cost* (design simplification, increased compactness)
- Optimization of *operation* in order to alleviate possible constraints associated with a metallic coolant (in-service inspection, maintenance, repair)



➢ Enhanced safety

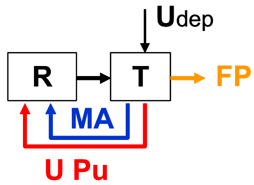
- Decrease or suppression of *risks of sodium/water interaction*
- Practical exclusion of large energy release in case of *severe accidents* (reactivity effects, reliability of passive systems)



➢ Closure of the fuel cycle

- U/Pu closed cycle
- Flexible strategy for MA transmutation

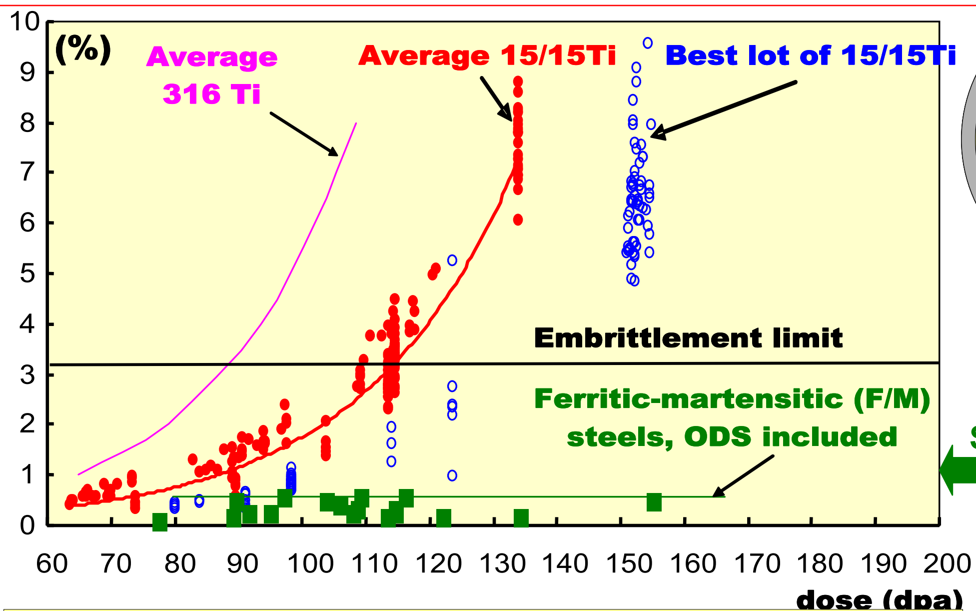
(← homogeneous, heterogeneous →)

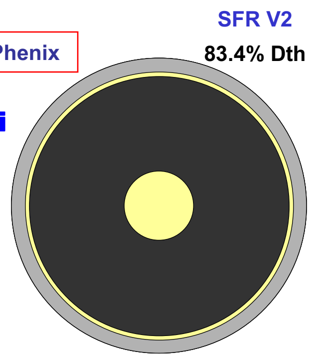


- large diameter pins
- high burn up (dose > 200 dpa)

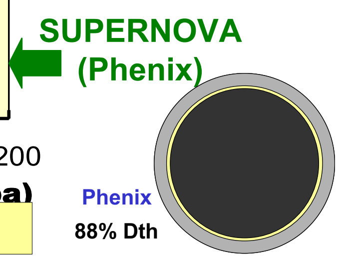
→ clad without swelling

Swelling of advanced austenitic steels and ferrito-martensitic steels used as fuel cladding in Phenix





Large-diameter pins, small-diameter spacing wire

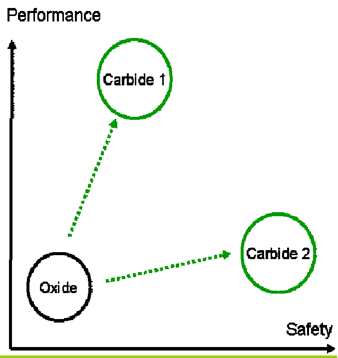


Advanced fuel cladding: 316 Ti → 15-15 Ti → F/M ODS

Potential of progress with dense ceramics

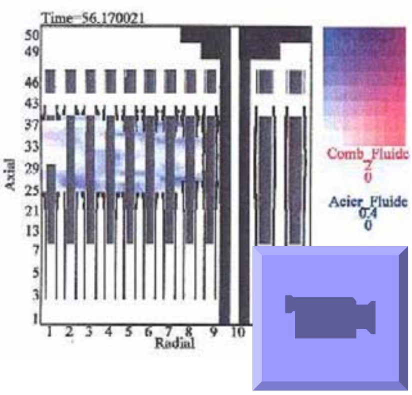
Pu/(U+Pu) = 0.2	Carbide $(U,Pu)C$	Nitride $(U,Pu)N$	Oxide $(U,Pu)O_2$	Metal $(U,Pu)Zr$
Heavy atoms density (g/cm^3)	**12.95**	**13.53**	**9.75**	**14**
Melting point (°C)	**2420**	**2780**	**2750**	**1080**
Thermal conductivity (W/m/K)	**16.5**	**14.3**	**2.9**	**14**

Carbide (and nitride) have an **increased margin to melting** which can benefit
- **either to increase power density (economy, HM inventory)**
- **or to improve safety (accident prevention)**

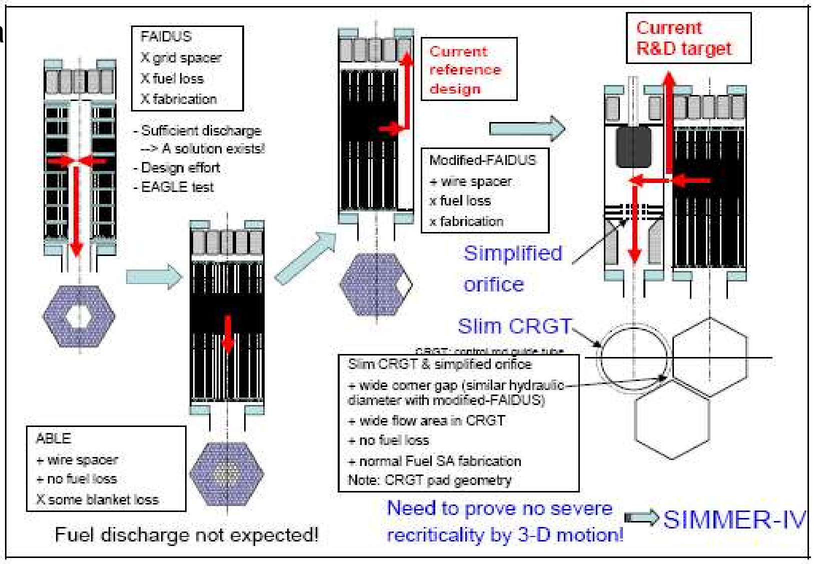


A strategy for severe accident management

Provisions for mitigating the core melting risk and, in the event of a core meltdown, for preventing high-energy accident sequences



Simulation of *BTI in Phénix (SIMMER-III code)**

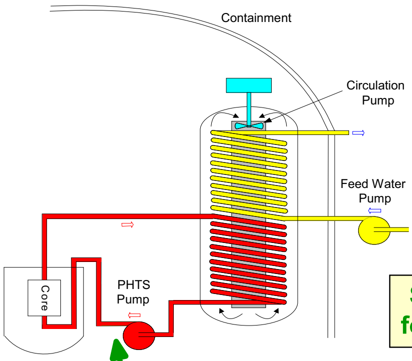


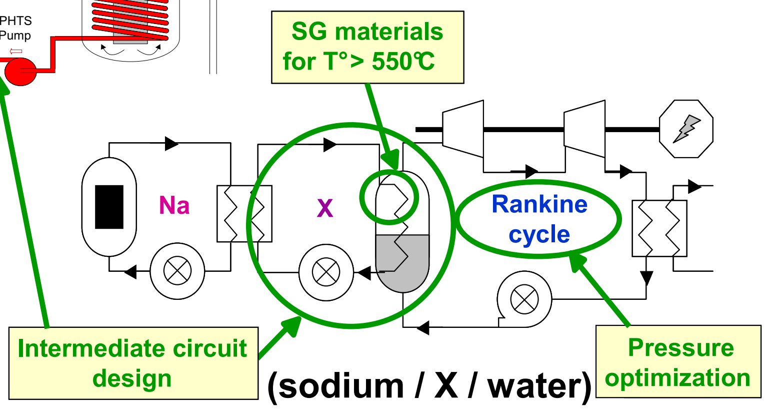
Passive devices for corium channeling (FAIDUS, Japan)

*BTI: Total Instantaneous Blockage of a fuel assembly

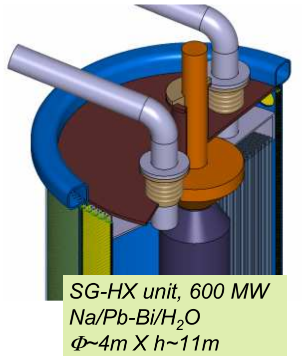
Several options under investigation for energy conversion

- Gas cycle conversion (N_2, supercritical CO_2)
- Water/steam (Rankine cycle)
  → Simplification of intermediate circuit and avoidance of sodium/water interaction





« Ultra-compact » 3-fluid component (SG-HX)

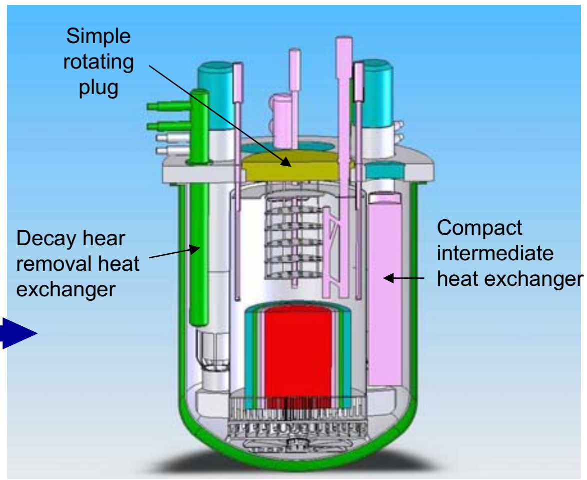


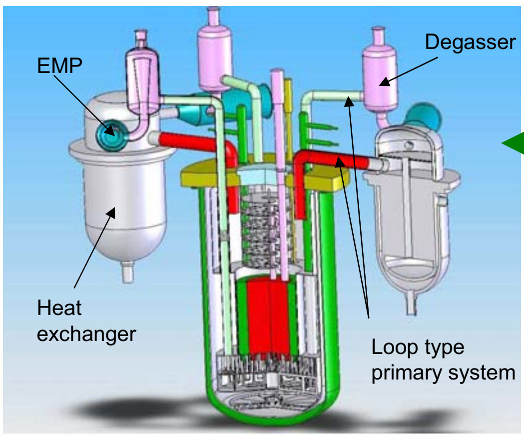
Pool or Loop ?

- **Large pool-type concept (1500 MWe)**
- **Design optimisations**

→ core vessel diameter reduced by ~ 30% compared to EFR (17 m)

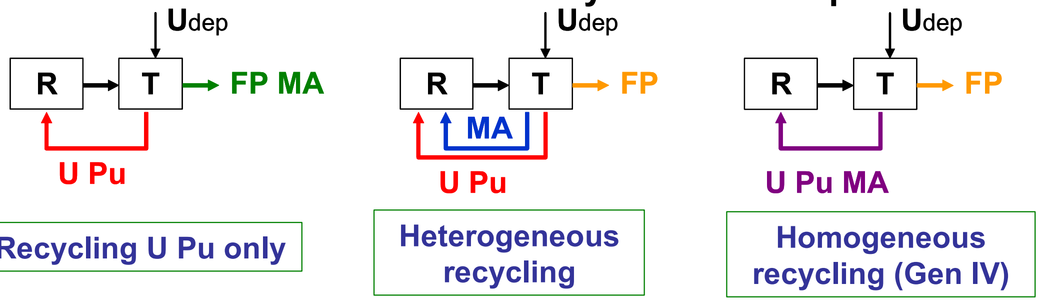
- **3 compact intermediate loops**





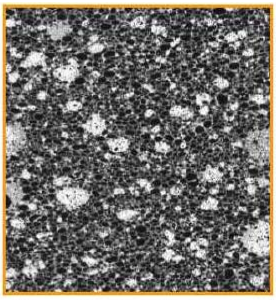
- **Modular concept (500 MWe) with gas conversion system (no intermediate circuit)**
  - Transportable core vessel (~ 7 m)
  - Nitrogen energy conversion system (2 loops), sodium/nitrogen heat exchanger
  - Core outlet temperature > 600 ℃

Fast neutron reactor closed fuel cycle: several options

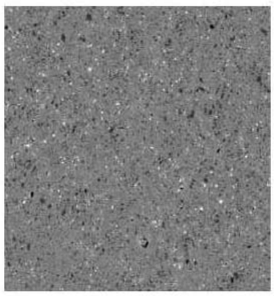


All options should be kept available, they could be used in a sequence

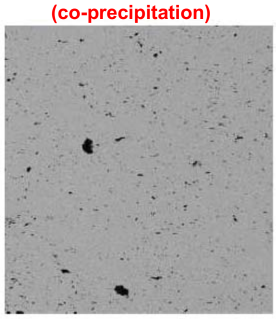
UPuO2 MIMAS
11 % Pu

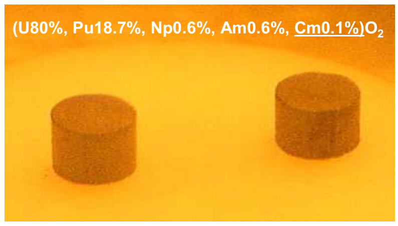


(U,Pu)O2
6% Pu (COCA)



$(U,Pu)O_2$
27.5 %Pu
(co-precipitation)

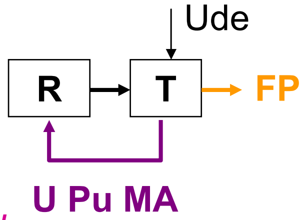




MA-bearing (Np, Am, Cm) fuel samples manufactured in ATALANTE

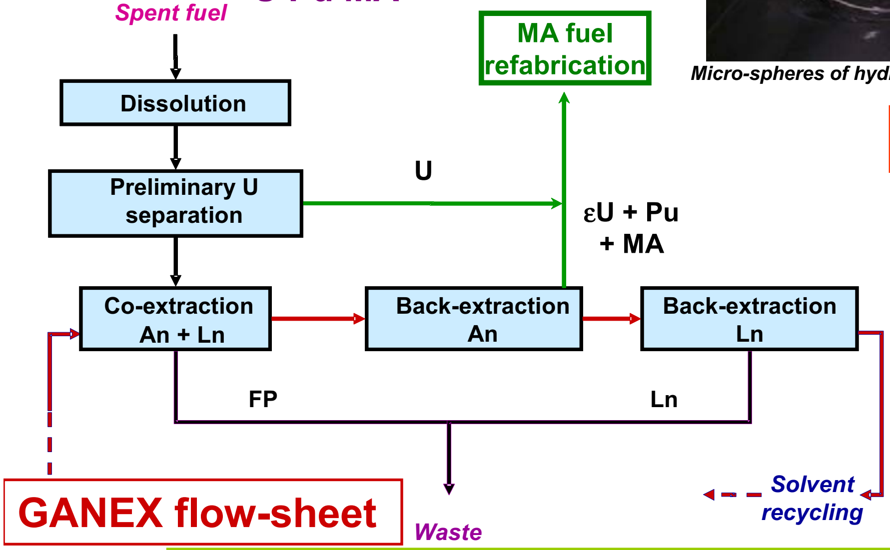
X-ray micrography of MOX microstructure

Grouped actinide partitioning and refabrication (SFR & GFR)

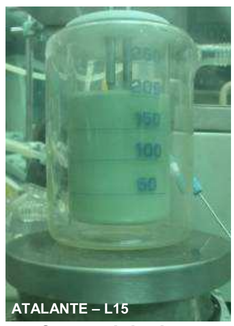


Sol-gel actinide co-conversion

Micro-spheres of hydroxyde U(VI)-Pu(IV)



Oxalic co-precipitation of actinides



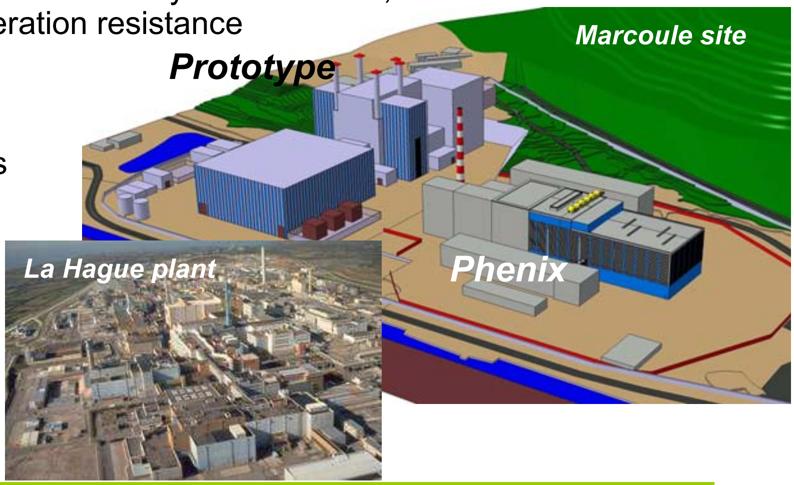
Co-precipitation (U, Np, Pu, Am) 78/1/20/1

A SFR prototype under operation by 2020

1. **Electricity producer prototype (power range 250-600 MWe)** to demonstrate the promising technologies for the commercial SFR (including ECS, ISIR, …); size choice will be the result of an optimization/compromise between costs, risks and representativity
2. **Convincing demonstration of the improvements proposed against the weak points of past SFRs**
3. **Resources saving:** operation with recycled materials, while reinforcing safety and proliferation resistance

4. Waste management: progressive evaluation and demonstration of Minor Actinides recycling

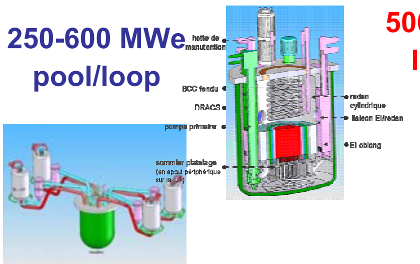
5. Need for associated fuel cycle facilities: MOX fuel for the starting core and irradiation capabilities at the fuel S/A level (advanced fuels, MAs bearing fuels)



Harmonisation of prototypes

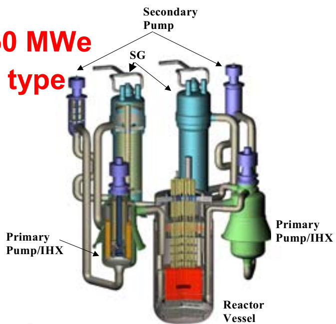
France, Japan and USA plan SFR prototypes by 2020-2025

250-600 MWe
pool/loop



French prototype

500-750 MWe
loop type



Japanese prototype (JSFR)

250-2000 MWt
pool type

American prototype (ARR)

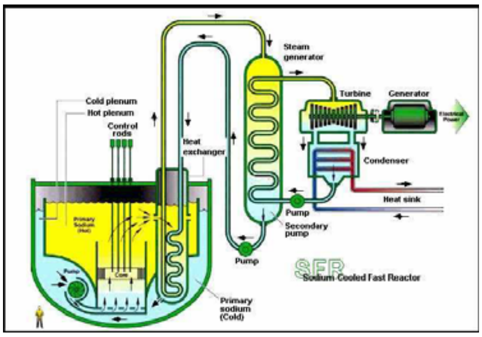
An approach aiming at international harmonisation is underway :

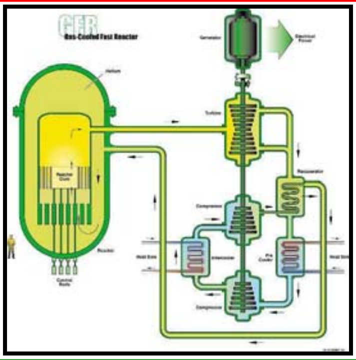
- Assure complementarity of prototypes (objectives, options,…)

- Optimize related infrastructures (including fuel fabrication facilities)

SFR	GFR
The reference option (significant past experience and innovation objectives) → Reduction of investment cost → Safety level comparable to 3rd generation LWRs → Improved operation techniques (ISIR,…)	**An alternative track based on:** → Benefits from helium as a coolant → Robust fuel *(including severe accident conditions)* → Potential for high temperature applications

A common concern : the potential for integral recycling of actinides





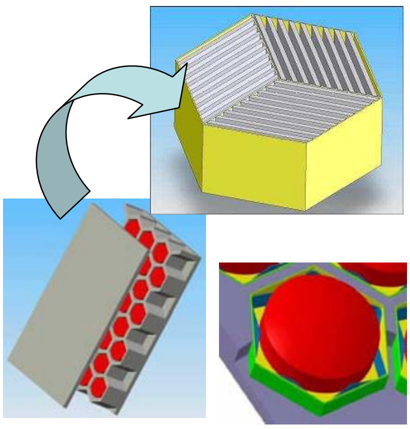
Milestone 2020: prototype (250-600 MWe)

Milestone 2020: experimental reactor *(ALLEGRO, 50-70 MWt)*

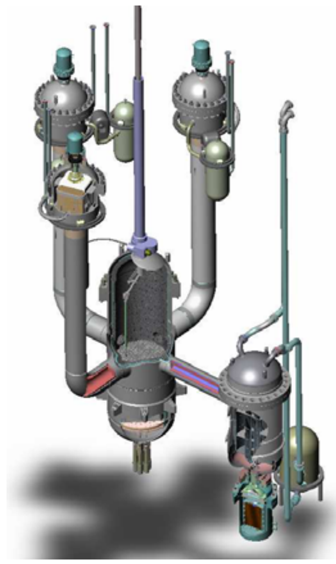
A first consistent design for a 2400 MWt GFR

Robust decay heat removal strategy (passive after 24hrs)

GFR preliminary feasibility report issued January 2008



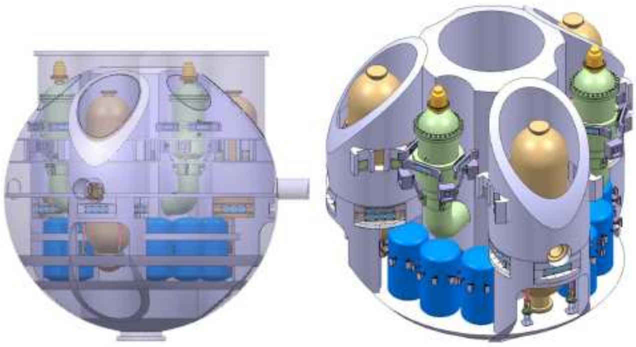
Innovative fuel



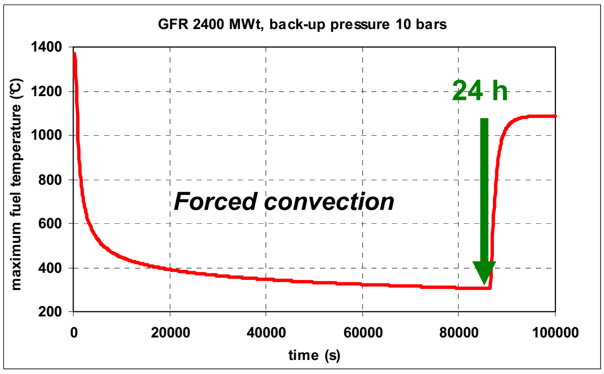
GFR 2400 MWt (1100 MWe) reference concept

ALLEGRO (50-70 MWt)

Analysis of GFR fast depressurization accident



GFR guard containment
(metallic sphere 33 m diameter)
+ gas injection tanks



Confirmation of DHR system performance (LOCA) with CATHARE

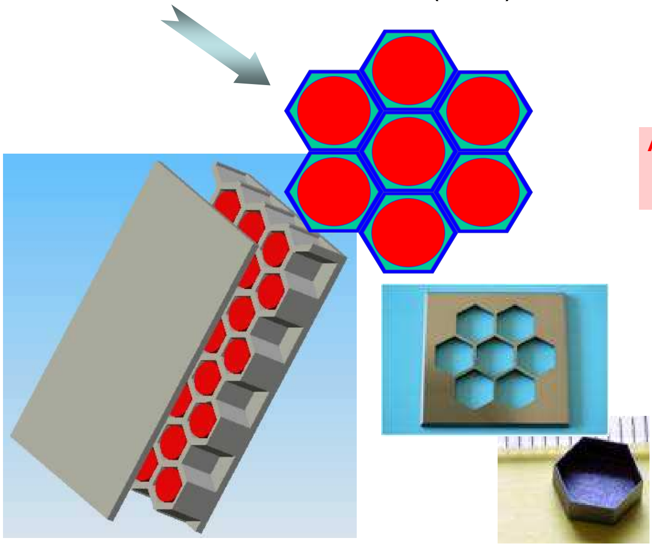
Efficiency of DHR systems and control of fuel temperature < 1600°C

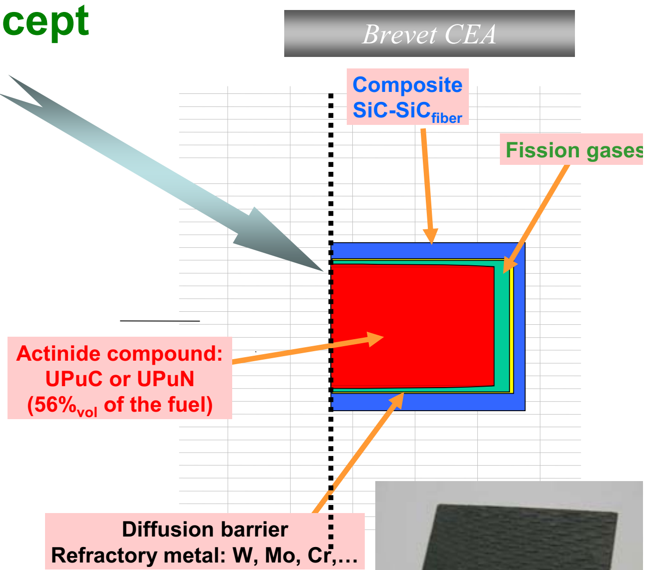
- **24 hr in forced convection (small pumping power ~ 10 kWe)**
- **For longer term, natural circulation at 1.0 MPa**

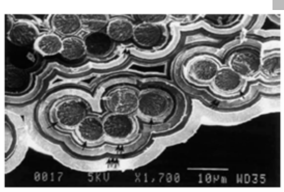
GFR innovative fuel concept

Axial gap: closed at beginning of life (BOL) for homogeneous thermal behaviour

Radial gap: retention of fission gases and helium, closure at end of life (EOL)

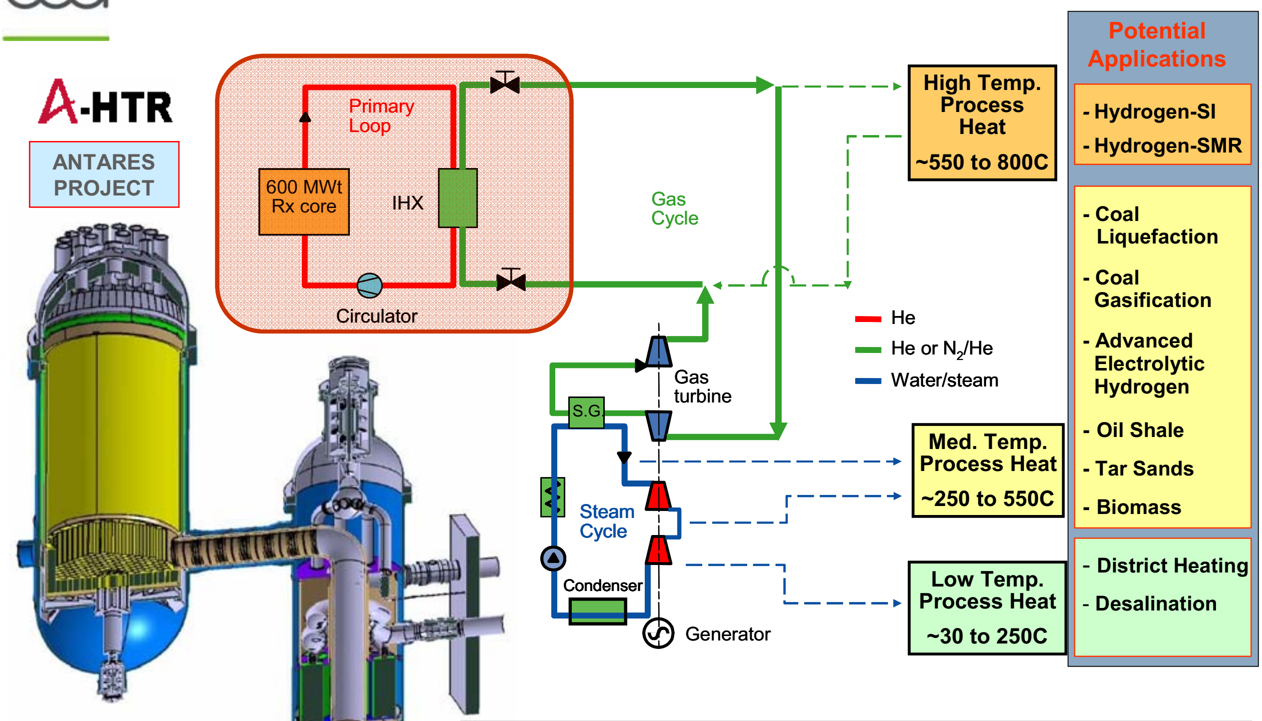






SiC/SiC$_f$ plate

Behaviour under irradiation (FUTURIX in Phenix, IRRDEMO in BR2)



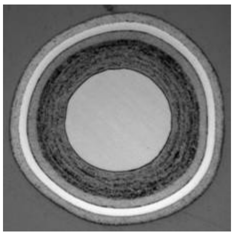
ANTARES concept (600 MWt, 850°C)

The interest to VHTR is essentially driven by its potential for a large scope of process heat applications

HTR/VHTR: the R&D challenges

1. Manufacturing of particle fuel

Requirement on kernel sphericity ($\varnothing_{max}$ / $\varnothing_{min}$) fulfilled at 90% (November 2007)

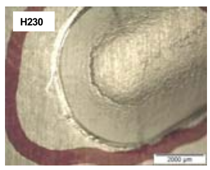


UO_2 TRISO particles (natural uranium) fabricated in GAIA (Cadarache)

2. High temperature gas-gas IHX and materials

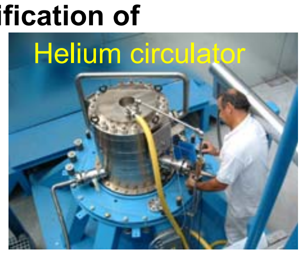
Different plate concepts appear as good candidate technologies

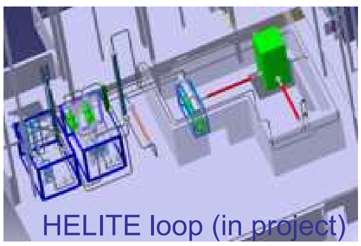
Plate Stamped Heat Exchanger (PSHE) (temperature ~ 850°C)



3. Helium technology

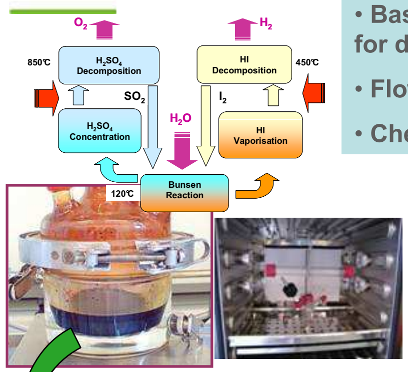
Development and qualification of helium technology and components





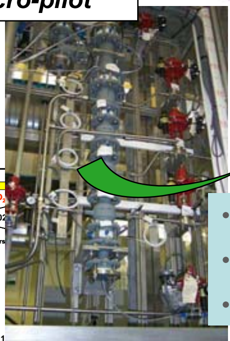
Helium Technology Platform (Cadarache)

Hydrogen production: thermo-chemical cycles (Sulfur/Iodine)

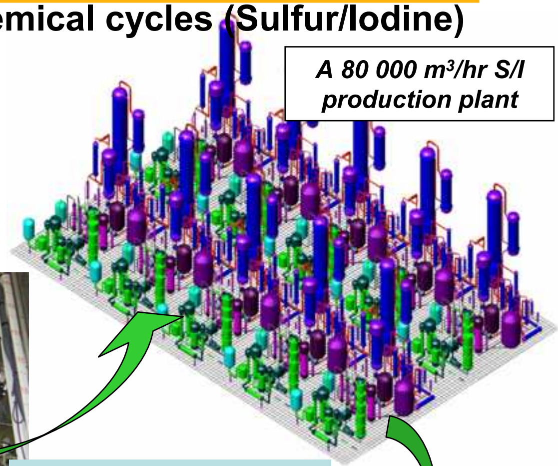


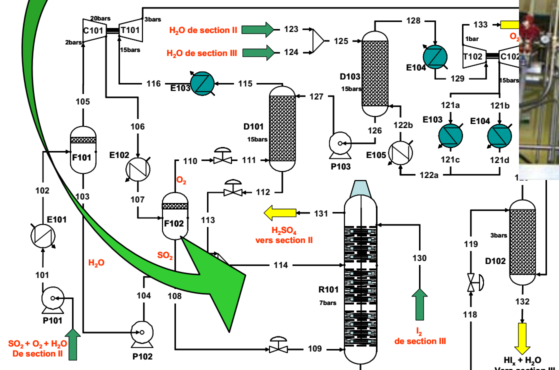
- Basic measurements for data acquisition
- Flow-sheet optimization
- Chemical engineering

200 l/hr S/I micro-pilot



A 80 000 m³/hr S/I production plant





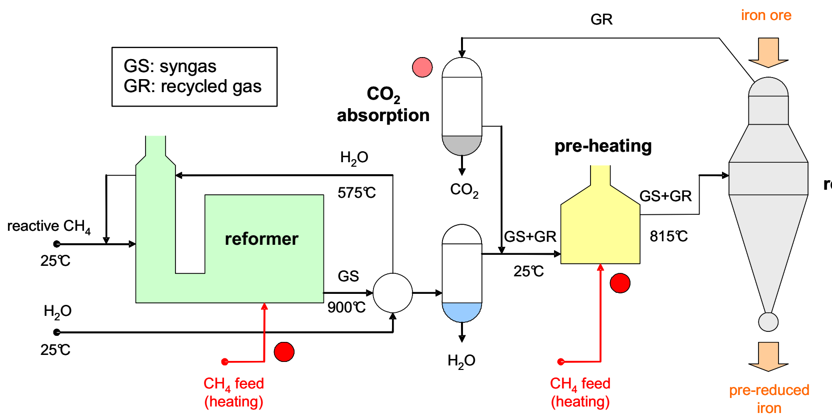
Bunsen section

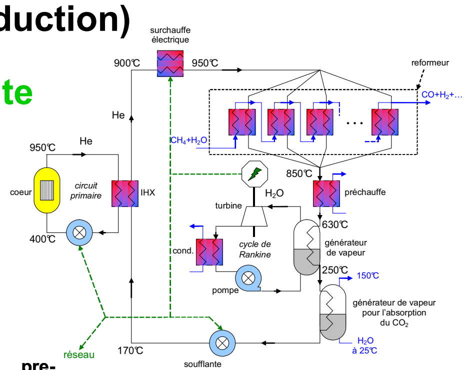
- Components design
- Plant safety
- Cost estimates

In cooperation with ArcelorMittal

Coupling of a nuclear reactor (VHTR) with steel factory (iron pre-reduction)

➔ A low CO_2 steelmaking route with possible CO_2 recovery





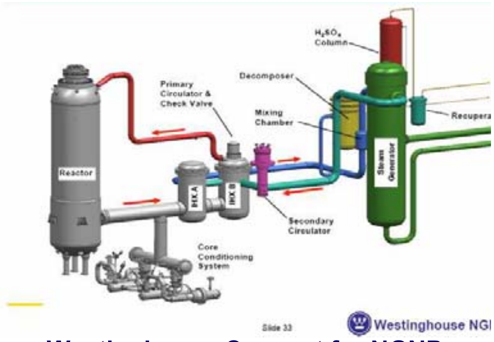
Thermodynamic optimization of the coupling (CYCLOP tool)

A VHTR (600 MWt) operated in cogeneration can feed a pre-reduction unit producing 6000 tons / day of pre-reduced iron (~ 2 standard units)

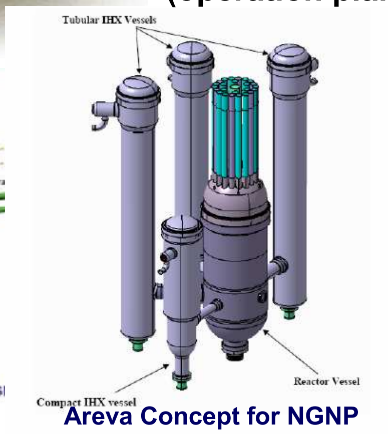
NGNP: Next Generation Nuclear Plant (US DOE)

Enables commercialization of High Temperature Gas-Cooled Reactor technology to provide process heat

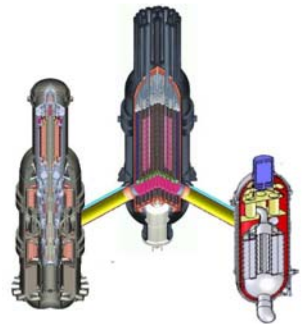
Completed pre-conceptual design studies for 3 different vendor concepts led by Areva NP, GA and Westinghouse (operation planned 2018)



Westinghouse Concept for NGNP



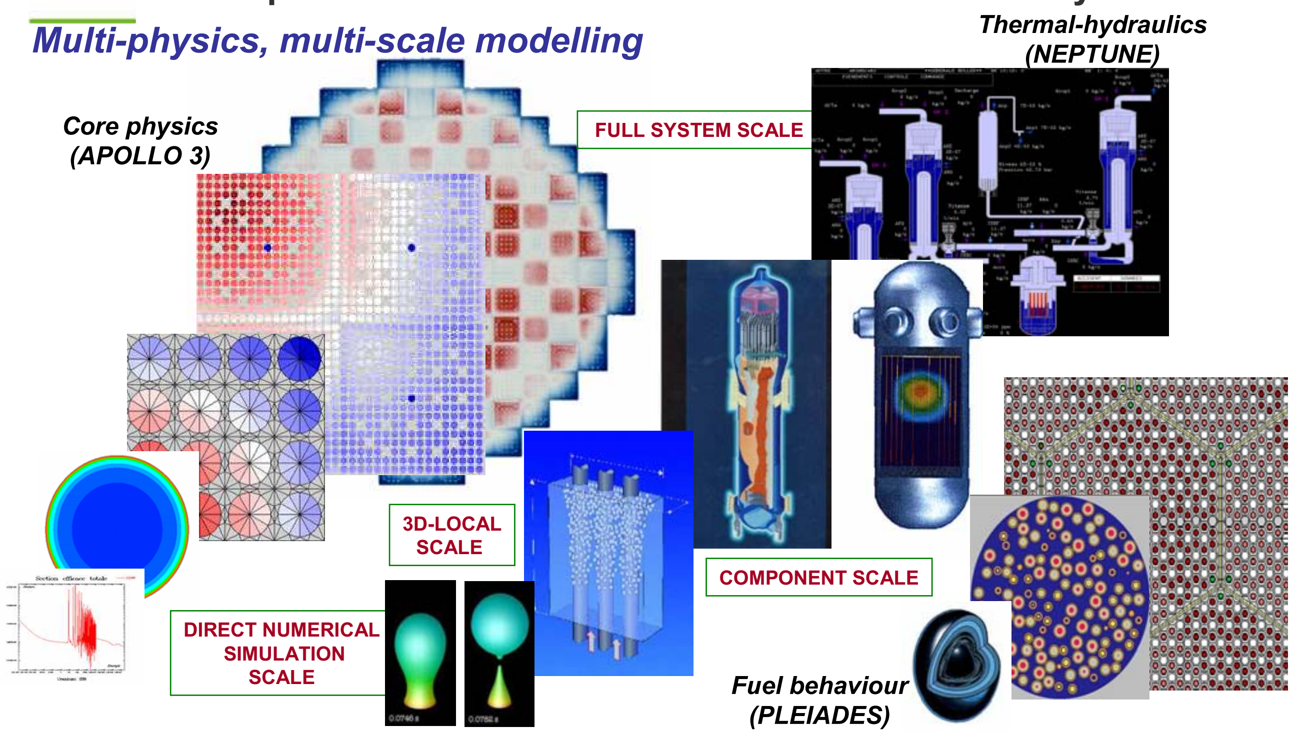
Areva Concept for NGNP



GA Concept for NGNP

Computational tools for current and future nuclear systems

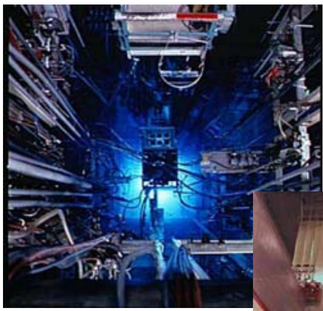
Multi-physics, multi-scale modelling

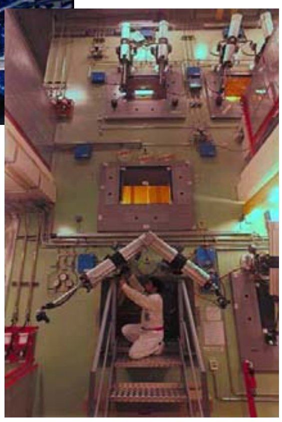


Joint development of numerical platforms (CEA-EDF-AREVA

Research Reactors

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

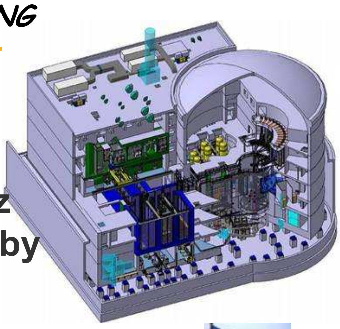




Hot labs

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

JHR (Jules Horowitz Reactor): a new MTR by 2014 in Cadarache



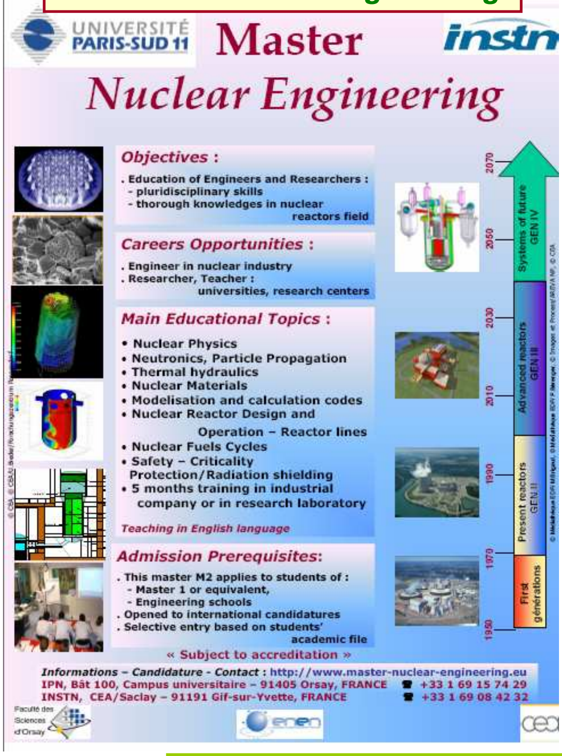
International partnership

E.U.

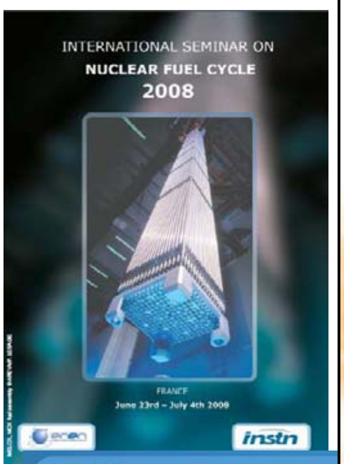
- CEA, EDF, AREVA
- EU, Belgium, Czech Republic, Finland, Spain, India, Japan, Sweden…

Japan

Master in Nuclear Engineering



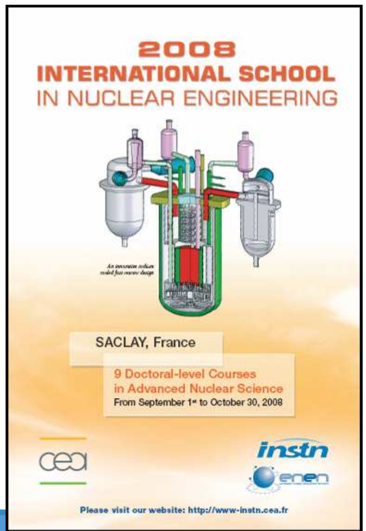
Training courses & technical visits



VISITS

- Fuel fabrication plant (FBFC – FRAMATOME ANP)
- Uranium refining and conversion plant (COMURHEX)
- Uranium enrichment plant (EURODIF)
- MOX fuel fabrication plant (MELOX)
- Na – FNR (PHENIX)
- La Hague spent fuel reprocessing plant (COGEMA)
- Storage site for low radioactivity waste (ANDRA)

Doctoral school



Summary and conclusions

- A clear trend towards a global vision of energy production and waste management, involving the need of nuclear technologies preserving uranium resources and minimizing nuclear wastes.

- The recognition of the essential role of fast neutron systems with closed cycle technologies. SFR considered the reference option in many countries (France, Japan, USA, Europe,…), with regard to considerable past experience. GFR and LFR are evaluated as alternative options in Europe.

- Market opportunities envisioned for cogeneration applications (H_2, synfuels, steel fabrication,…). HTR/VHTR offer the best potential.

- International cooperation on future nuclear systems (Gen IV, INPRO…). Harmonization of the approach at international level (innovation R&D, simulation tools, infrastructures, prototypes).

- Training a young generation of scientists in nuclear engineering