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Energy Technology Roadmaps

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The GEN IV Roadmap:
The Way Towards Sustainable Development of Nuclear Energy

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INTRODUCTION

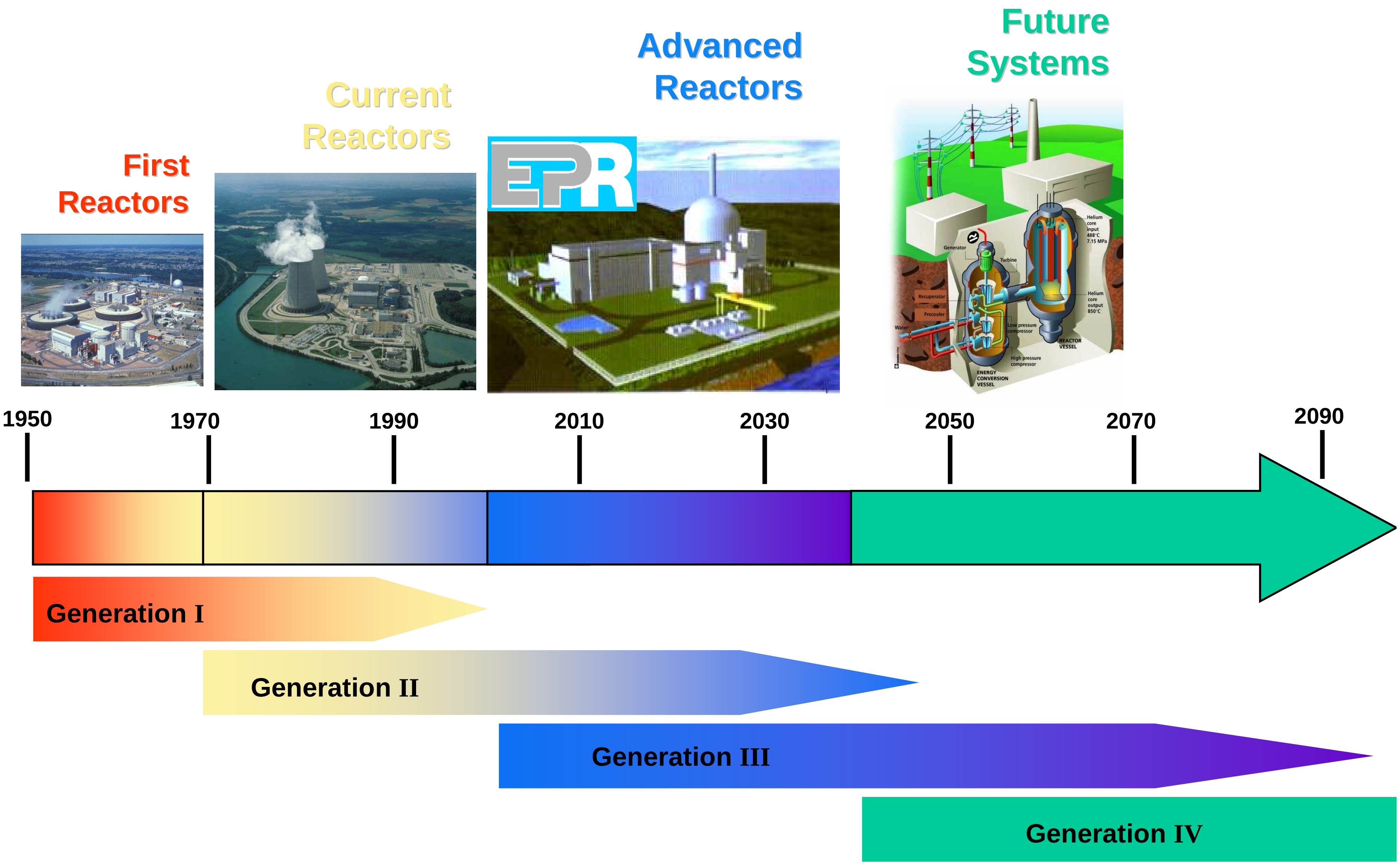
- Energy needs are still increasing,
- Oil and gas are becoming scarce and expensive,
- Climate change due to CO_2 emissions is a concern

The world needs nuclear energy

- Nuclear installed capacity could be multiplied by a factor 3 to 4 by 2050 (1500 - 2000 GWe) : It may be possible with LWRs.
- These reactors will have a minimum lifetime of 60 years, the corresponding needs will lead to an increase of uranium cost and countries will have to take into consideration uranium supply issues
- There is a need for a clear and proved vision of waste management

Generation IV nuclear systems

Nuclear Reactor Generations



Generation I : Early Prototypes

Reactors built in the fifties and sixties

- **Many prototypes all around the world**

- **Various types of thermal and fast neutron reactors**

- **For most of the countries, a main limitation due to the use of natural uranium**

  -**> graphite or heavy water moderated cores**

- **Development of the first light water reactors for naval propulsion**

- **First production of electricity in ARCO (Idaho) 1951, with a fast neutron reactor**

Generation II : Current Power Plants

Reactors built from the end of the sixties to the nineties

- **An industrial development accelerated by the first oil shocks**
- **A large domination of light water reactors : PWR – BWR**
- **Some countries made other choices: CANDU – AGR – RBMK**
- **An expansion stopped in many countries after the TMI and Chernobyl accidents**

Status of existing power reactors connected to the grid (2005):

Type	Nb of units	Capacity (GWe)
PWR	267	241
BWR	93	83
PHWR	41	21
GCR	22	11
LWGR	16	11
FBR	2	1
Total	441	368

Generation III : Advanced Reactors

Near term deployment of industrial reactors

- A new generation of reactors benefiting from the large experience of Gen II plants and from TMI lessons;
- Main objective: new improvements in safety while keeping economic competitiveness
- Mitigation of severe accident consequences is a major step

A large industrial offer

Advanced Pressurized Water Reactors: AP 600, AP 1000, APR1400, APWR+, EPR

Advanced Boiling Water Reactors: ABWR II, ESBWR, HC-BWR, SWR-1000

….

The market prospective

- The capacity could grow from 400 GWe to 1000 - 1500 GWe by 2050.
- Most of the new NPP will be Gen III systems.

Generation IV International Forum (GIF)

➢ **New requirements for sustainable nuclear energy**

- Gradual improvements in :
  - ✓ **Competitiveness**
  - ✓ **Safety and reliability**
- Concepts with breakthroughs
  - ✓ **Minimization of wastes**
  - ✓ **Preservation of resources**
  - ✓ **Non Proliferation**

➢ **Systems expected to reach technical maturity by 2030**

➢ **Assets for new markets**

- **hydrogen production**
- **direct use of heat**
- **sea water desalination**

➢ **An internationally shared R&D**

New Requirements for Sustainable Nuclear Energy

- Competitiveness: - Overnight cost 1000$ / installed kWe
  - Production cost limited to 20$ / kWh

- Safety/Reliability: - At least as good as GenIII Reactors

- Waste Minimization/Resource Preservation/Non Proliferation :
  Most GenIV Systems=Fast Neutron Reactors associated to a Closed Fuel Cycle, in which Minor Actinides are burnt

➔ 50 to 100 times more electricity produced with the same amount of uranium, from transformation of U238 into fissile Pu239

➔ In turn, multiplication by 100 of available world primary fissile resources

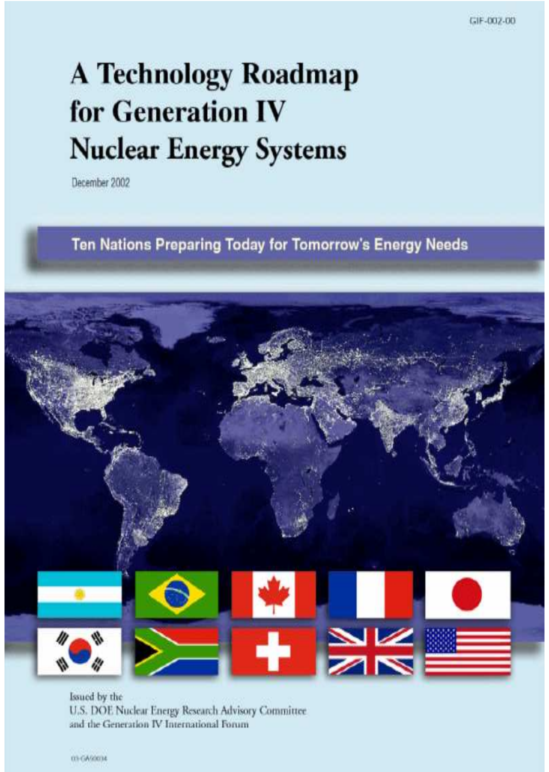
➔ Also, the waste is reduced to fission products, which reduces the radiotoxicity by several orders of magnitude (a few 100 years, instead of several 100000 years)

➔ Proliferation Resistance is enhanced, as Pu is mixed to MA, thus more difficult to handle

- Physical Protection: increase of extrinsic measures based on monitoring and international controls

The GEN IV Technology Roadmap

- Two-year effort by 100 international experts finding the most promising nuclear systems and contributing to the R&D planning
- Six systems were selected:
    - Gas-Cooled Fast Reactor (GFR)
    - Lead-Cooled Fast Reactor (LFR)
    - Molten Salt Reactor (MSR)
    - Sodium-Cooled Fast Reactor (SFR)
    - Supercritical-Water Reactor (SCWR)
    - Very High Temperature Reactor (VHTR)



High Temperature Reactors

A new path for both electricity and hydrogen productions

- **Direct use of heat for industrial applications, including possible hydrogen productions by chemical processes, requires temperatures in the range 800 – 1000 °C.**

- **Gas cooling is the only solution and among gases helium is the most practical choice.**

- **A first attempt to develop that technology took place in the 70s (Fort St Vrain in the US, THTR in Germany) after some early prototypes.**

- **Small experimental reactors have been built more recently in Asia (HTTR in Japan, HTR 10 in China).**

- **New projects are considered in the frame of Gen III (PBMR in South Africa) or Gen IV (NGNP in the US).**

HTR : The challenges

1 – The fuel : Small particles with carbon and SiC coatings; particles embedded in graphite; two options:

- compacts (FSV, GT-MHR)

- pebbles (THTR, PBMR)

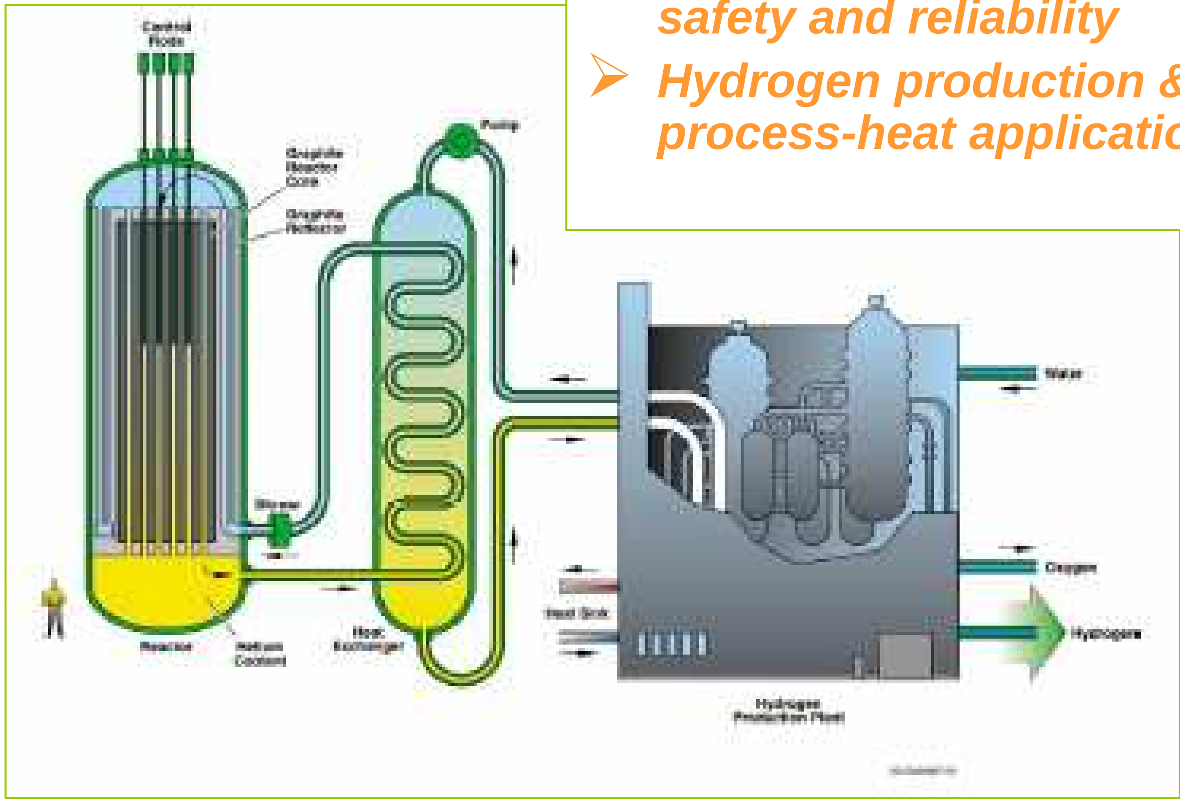
2 – Structural materials : Graphite is the basic material inside the core;

3 – The cooling system : helium loops with direct conversion (Brayton cycle) or indirect conversion through heat exchangers.

4 – Reactor power : limited by low power density and high gas pressure; still more limited in the pebble option by the control of core reactivity.

VHTR Very High Temperature Reactor

- *Thermal spectrum, once-through uranium cycle*
- *Prismatic block or pebble bed fuels*
- *Highly ranked in economics & in safety and reliability*
- *Hydrogen production & other process-heat applications*



Fast Neutron Reactors

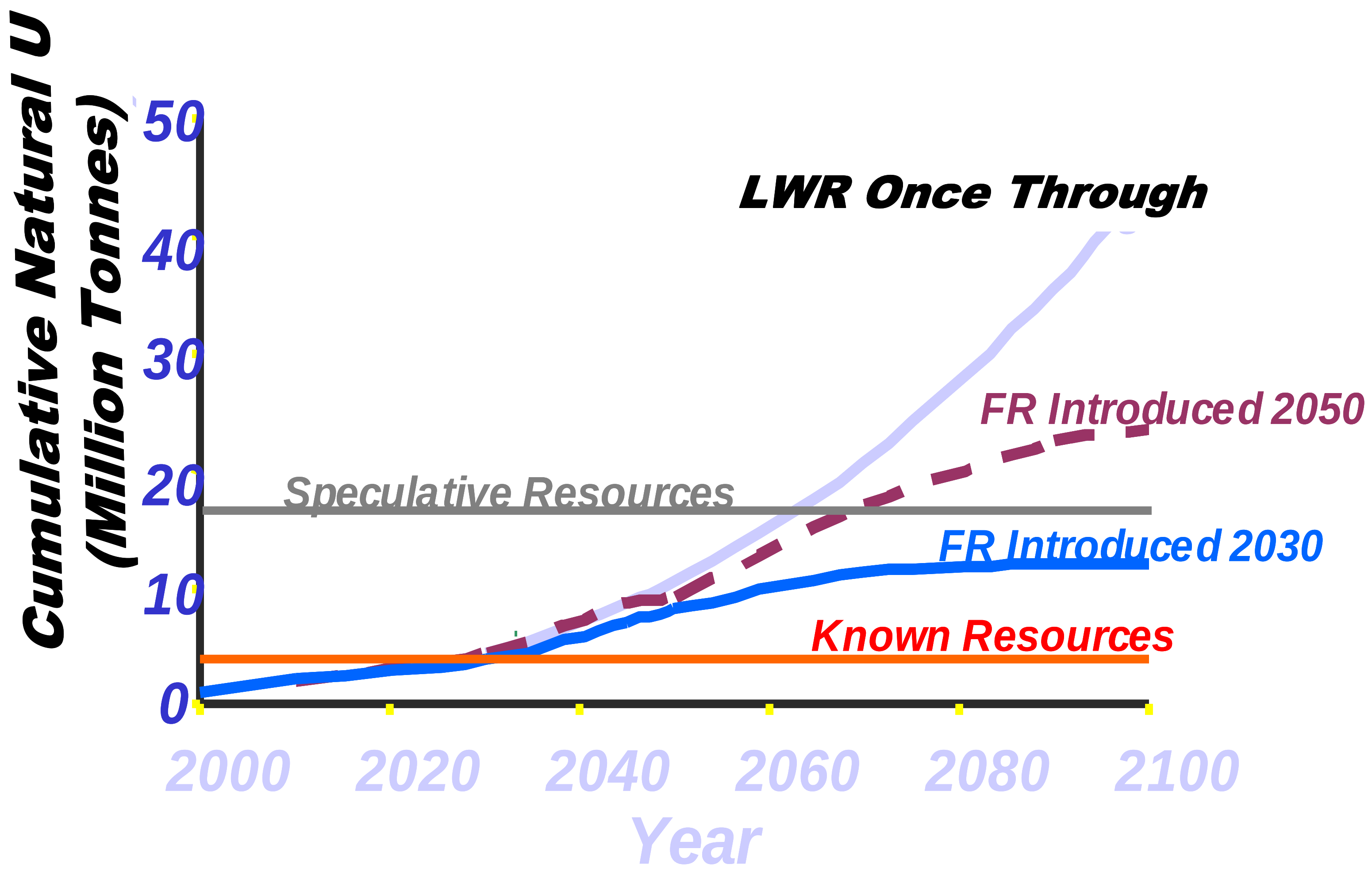
A solution for both an optimized use of resources and waste minimization

- **Fast neutrons allow a more efficient burning of actinides because the ratio of fission/capture cross sections is higher than with thermal neutrons.**

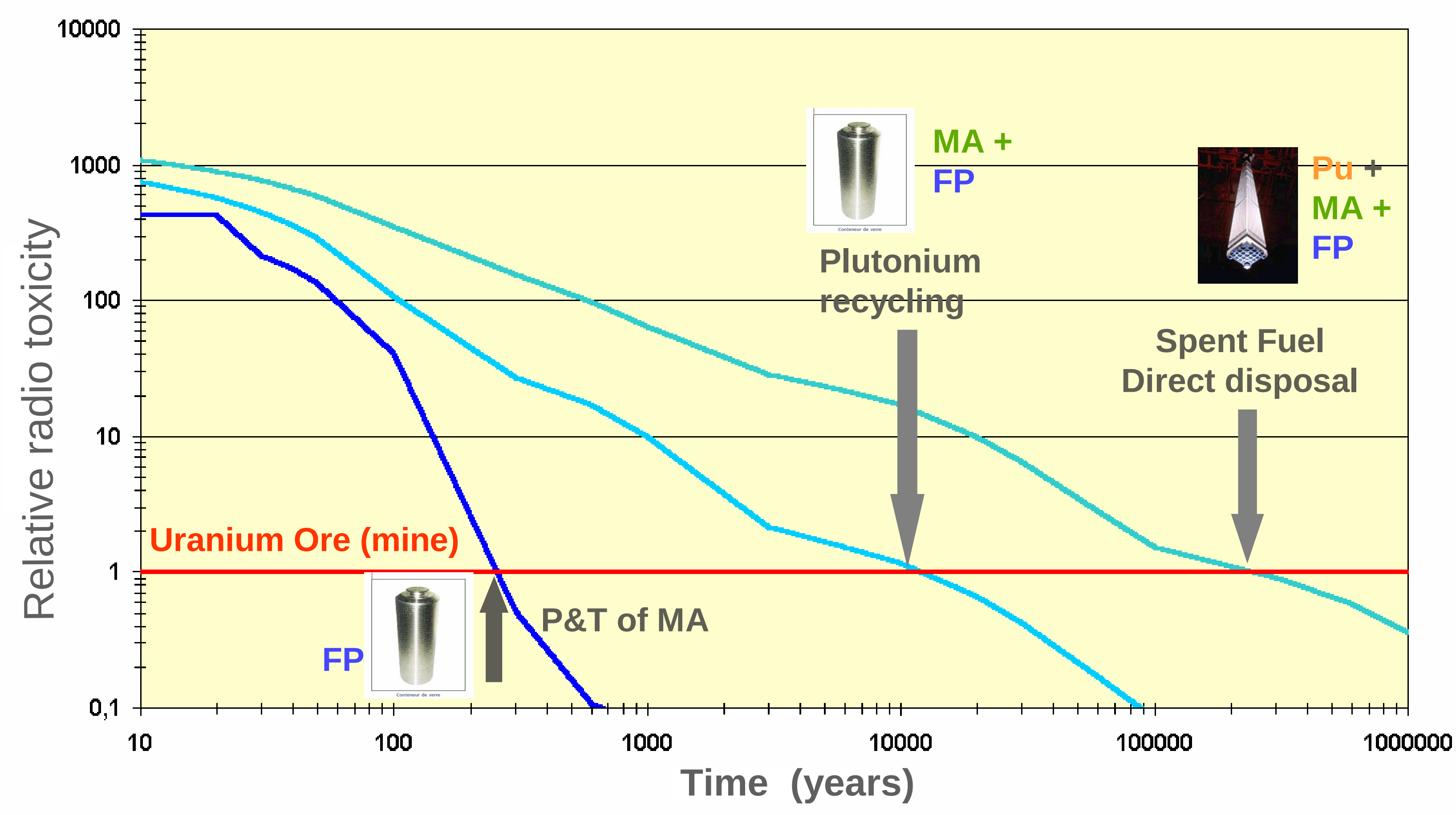
- **The first consequence is the possibility of positive breeding gains which allows to burn all the uranium through conversion of Uranium 238 in Plutonium 239.**

- **Another interesting feature is the possibility of burning all the actinides produced in the fast reactors themselves or in light water reactors by continuous recycling, thereby reducing considerably the long term radioactive potential of waste.**

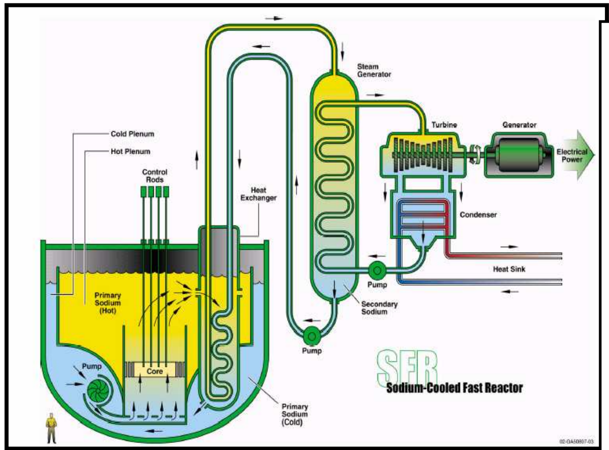
Fast Reactors : Resources optimization



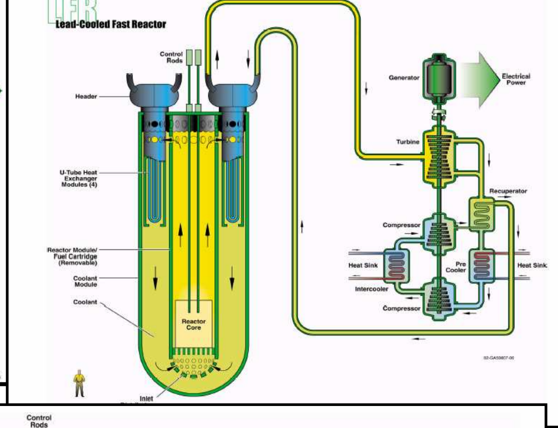
Fast Reactors : Waste minimization



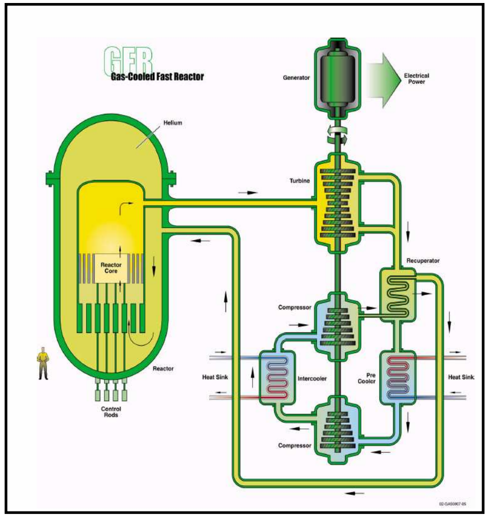
Six Concepts Selected



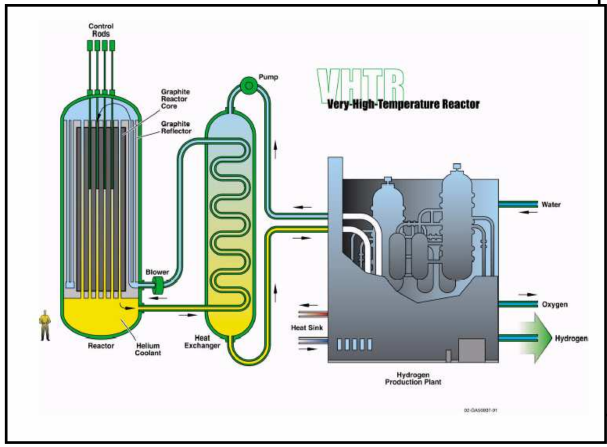
Sodium Fast Reactor



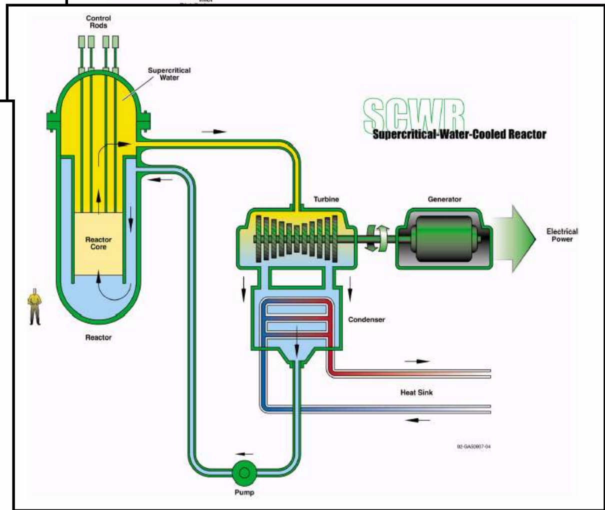
Lead Fast Reactor



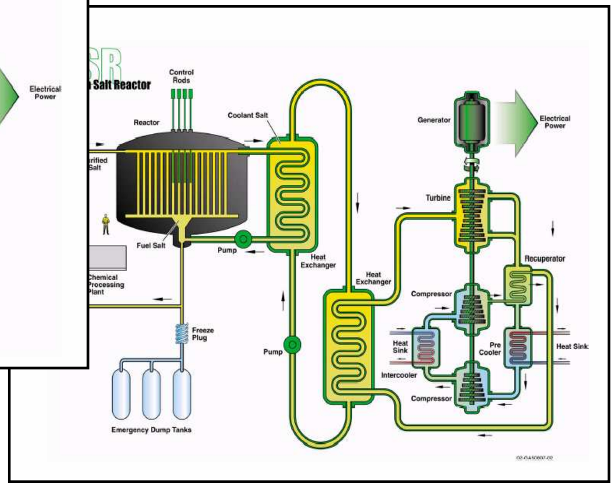
Gas Fast Reactor



Very High Temperature Reactor (Gas)



Supercritical Water Reactor



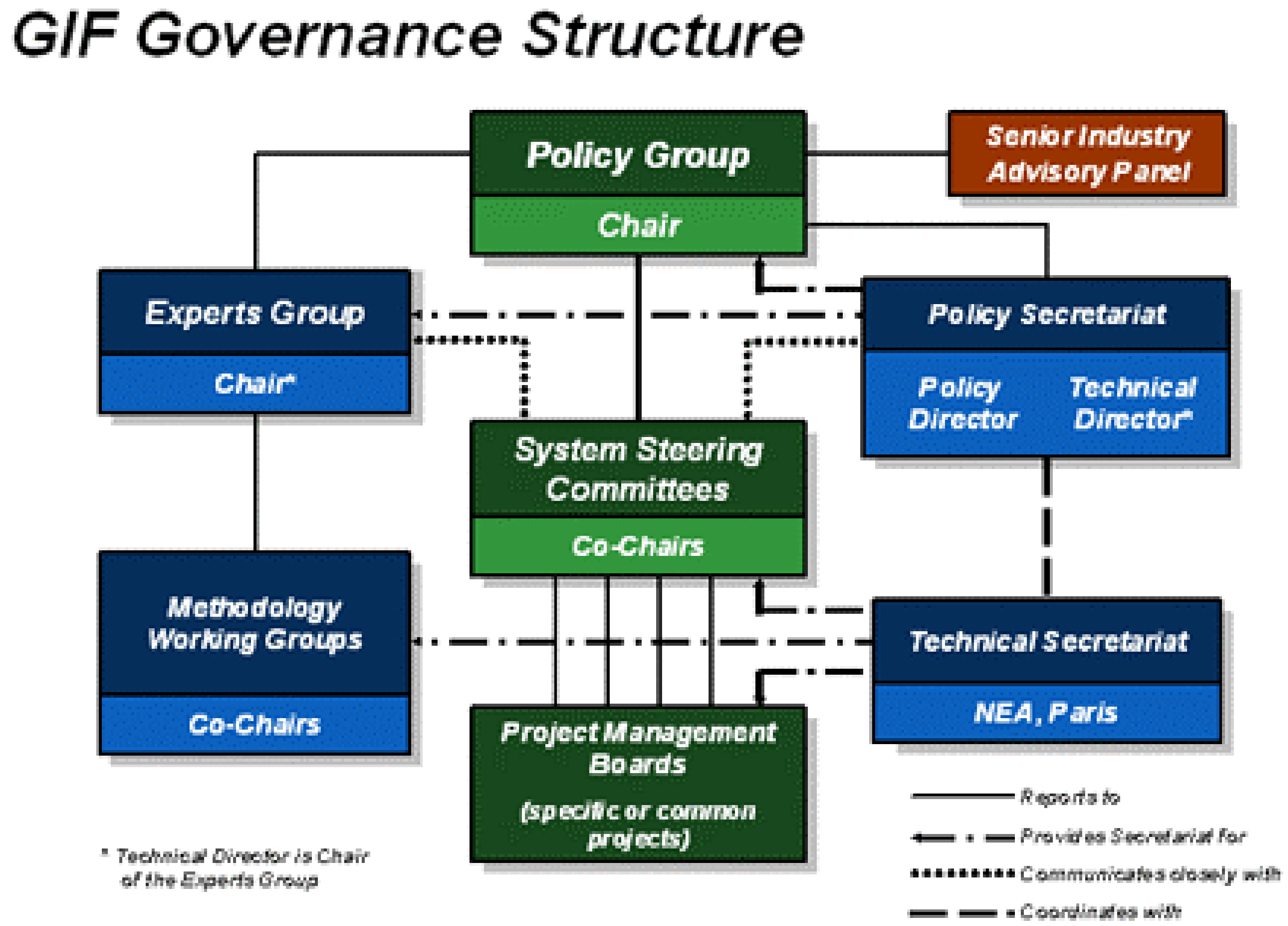
Molten Salt Reactor

SUPERPHENIX

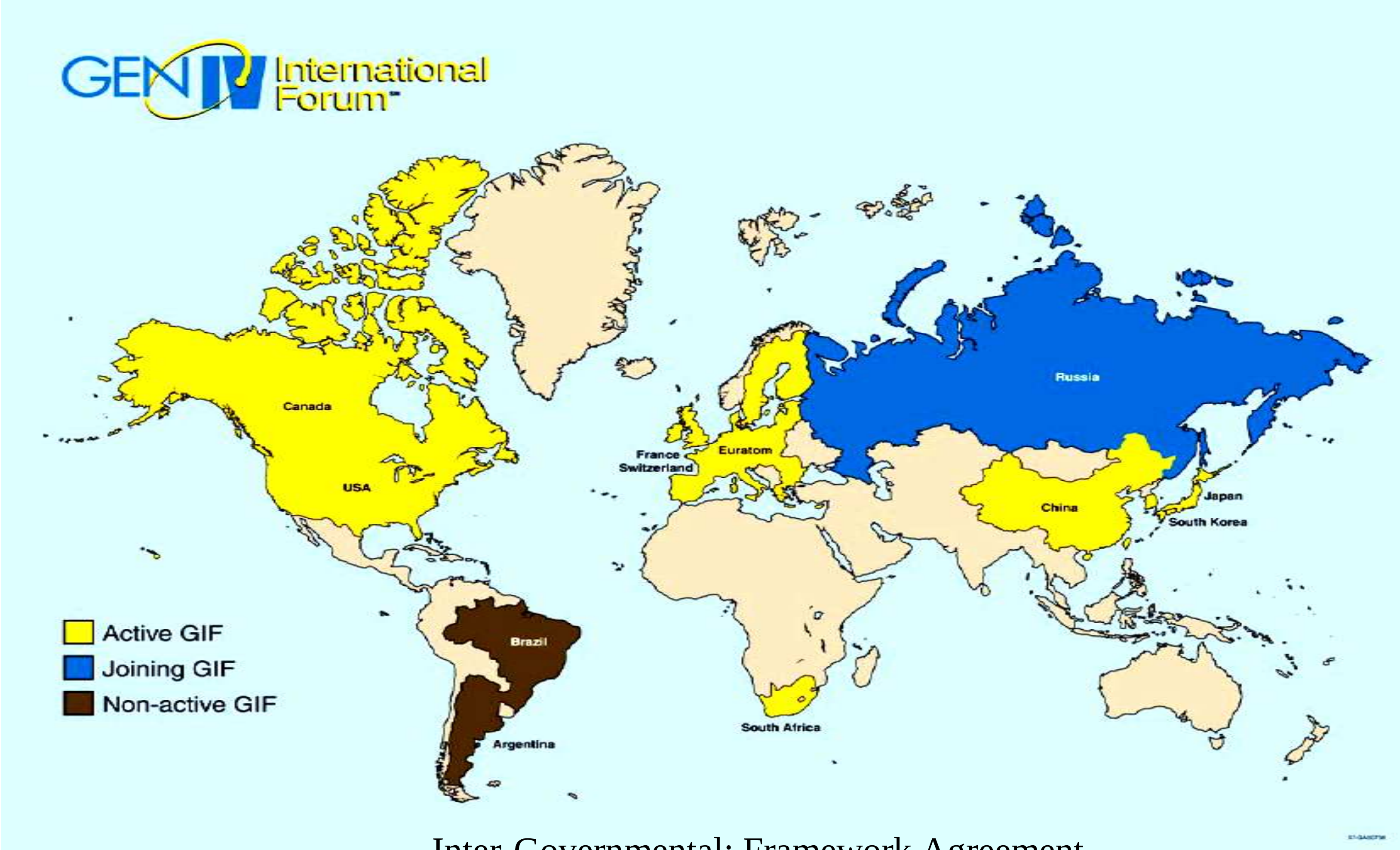
A 1200 MWe plant built at Creys-Malville (France)
First criticality: 1985; Shutdown: 1997

GEN IV International Forum

The GIF Organization



Multilateral R & D within the GIF



3 Levels of Agreement:

- Inter-Governmental: Framework Agreement
- Inter-Ministerial or Interagency: System Arrangements
- Project Arrangements: no restriction on Signatories

System Partners

Apr 2008

	NRCan	JRC	CEA	JAEA, ANRE	MEST, KOSEF	PSI	DOE	CAEA, MOST	DME
VHTR	◆	◆	◆	◆	◆	◆	◆	◆	◆
GFR		◆	◆	◆		◆			
SFR		◆	◆	◆	◆		◆	◆	
SCWR	◆	◆		◆					
LFR		◆		◆					
MSR		◆	◆						

Partners: NRCan JRC CEA JAEA, ANRE MEST, KOSEF PSI DOE CAEA, MOST DME

ANRE – Agency for Natural Resources and Energy (JP)
CAEA – China Atomic Energy Authority (CN)
CEA – Commissariat à l'Énergie Atomique (FR)
DME – Department of Minerals and Energy (ZA)
DOE – Department of Energy (US)
JAEA – Japan Atomic Energy Agency (JP)
JRC – Joint Research Centre (EU)
KOSEF – Korean Science and Engineering Foundation (KR)
MEST – Ministry of Education, Science and Technology (KR)
MOST – Ministry of Science and Technology (CN)
NRCan – Natural Resources Canada (CA)
PSI – Paul Scherrer Institute (CH)

VHTR – Very-High-Temperature Reactor
GFR – Gas-Cooled Fast Reactor
SFR – Sodium-Cooled Fast Reactor
SCWR – Supercritical Water-Cooled Reactor
LFR – Lead-Cooled Fast Reactor
MSR – Molten Salt Reactor

Research Plans and Activities

- System Steering Committees each create a System Research Plan
- Four systems have finalized plans
  - SFR, SCWR, VHTR and GFR
- LFR is under development
- MSR is planned in the future
- Each creates several projects
  - Project participants make binding commitments for the scope, schedule and resources for their contribution.
  - Legal issues: protection and allocation of intellectual property, protection of business-confidential information, dispute resolution, …
  - Universities, industry and even countries outside the GIF may participate, with the approval of the Steering Committee