Long term trends in nuclear production technologies

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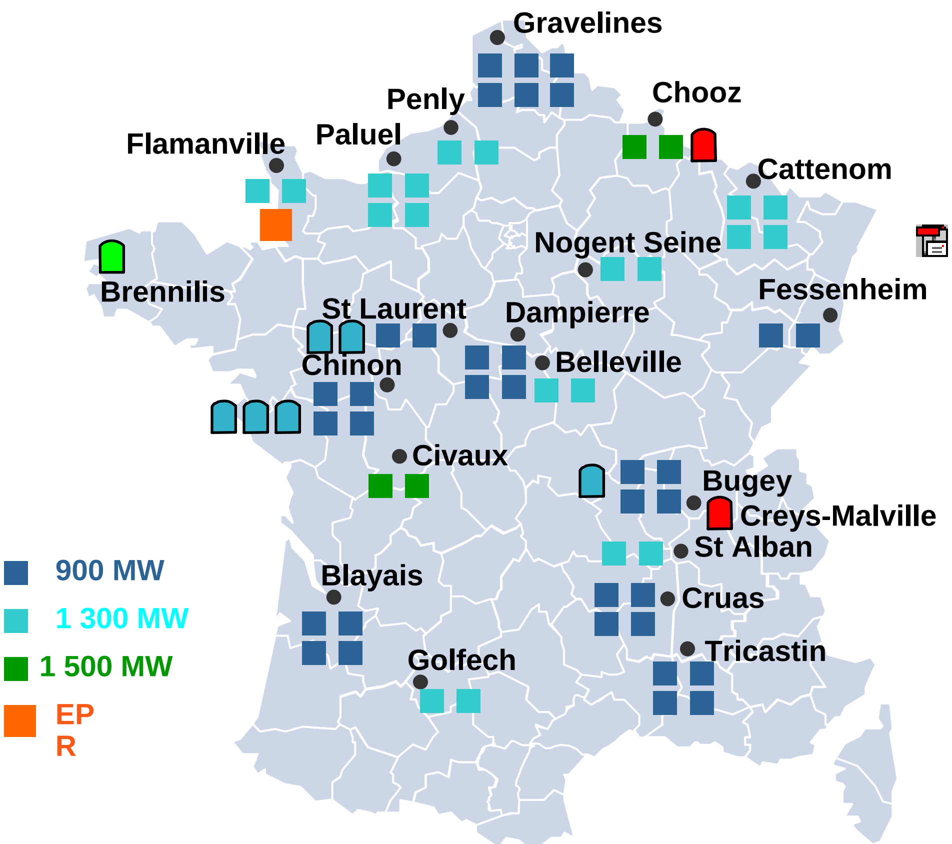
Generation and Engineering Direction

EDF NUCLEAR FLEET IN FRANCE

Nuclear electricity production plants



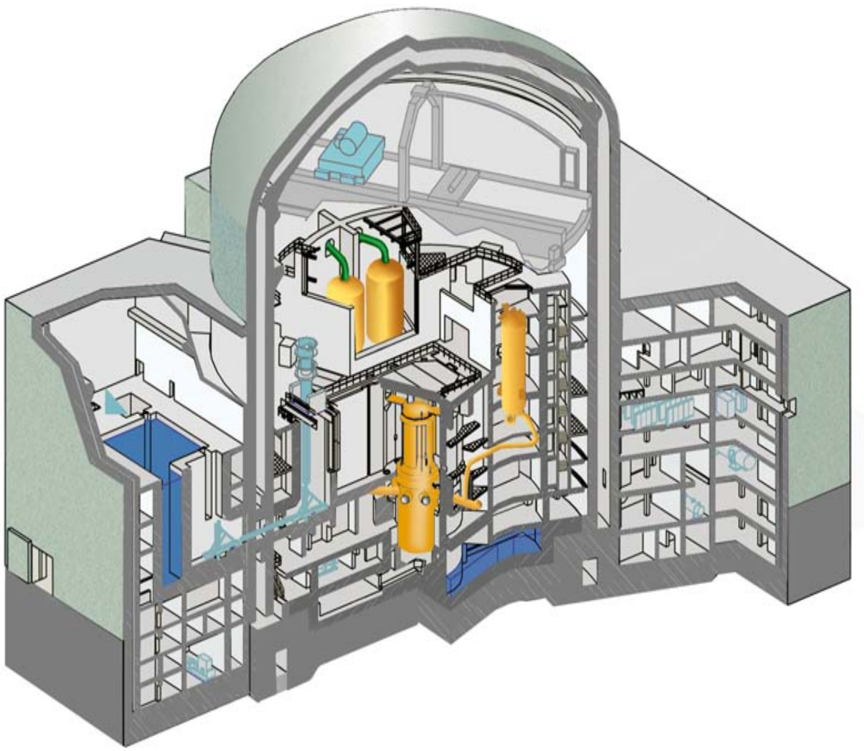
Largest fleet in Europe,

Homogeneous and concentrated

- **58 reactors in operation**
- **spread across 19 sites**
- **single technology :PWR (Pressurised Water Reactor)**
  - **3 series :**
    - **900 MW : 34 units,i.e 31 GW**
    - **1 300 MW : 20 units, i.e 26 GW**
    - **1 500 MW (N4) : 4 units, i.e 6 GW**

- **9 reactors being currently decommissioned**
- **1 reactor under construction**

The EPR project



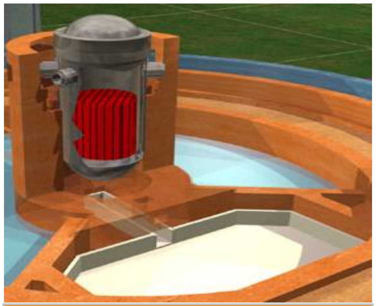
EPR Reactor

- Net Electric Power : **1 600 MW**
- Technical lifetime at design **60 yrs**
- Availability factor **91%**
- Investment **3,3 Md€$_{2005}$**
- Generation cost for the first of a kind : **46 €$_{2005}$/ MWh**
- Industrial Commissioning : 2012
- EDF takes part in 10 EPR projects : USA, UK, China, South African Republic. (Progress differs according to the countries).

The Flamanville EPR project : safety breakthroughs

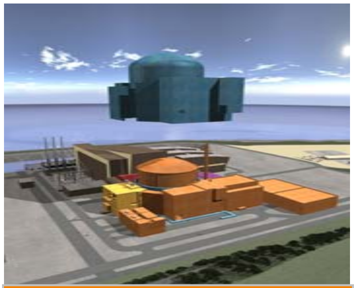
4 redundant safety systems

- Reduction of the likelihood of a major incident



Core catcher

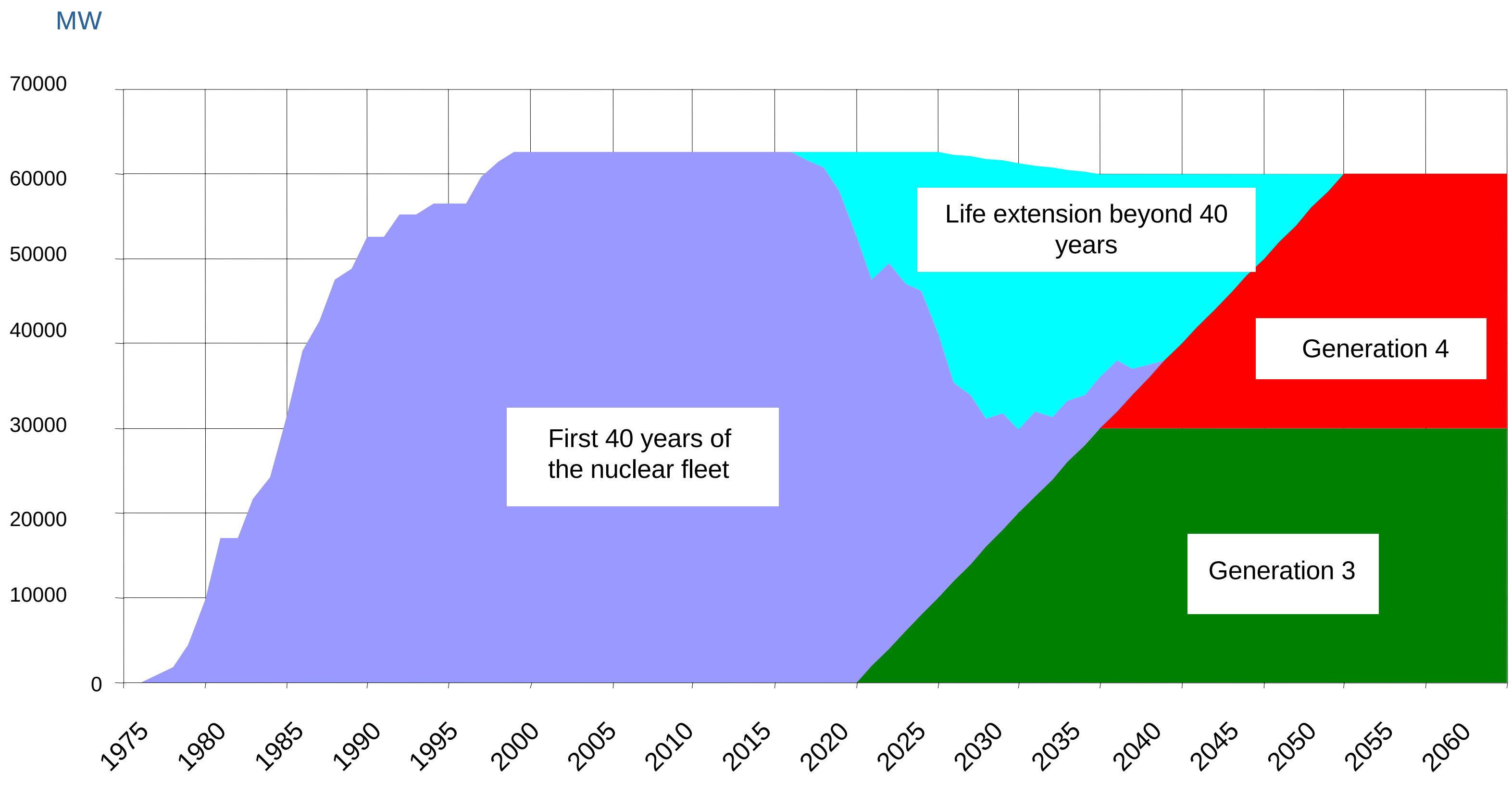
- Further protections against the consequences of such a major incident (core-catcher)



Larger concrete containment shell

- Design-based enhanced protection against hazards (fire, earthquake, flooding, extreme weather, plane crash …)

Preparing the future : the renewal strategy for the nuclear fleet



objectives for the lifetime of EDF's nuclear reactors : between 50 and 60 years

Beyond Generation III reactors : Generation IV

•long term, sustainable nuclear energy means

- Safety
- Economic Competitiveness
- Social acceptance of the back end of the fuel cycle (wastes)

•Generation IV and uranium resources

- OECD/NEA 2005 red book : 15 MT estimated resources could be “engaged” around 2050 if nuclear energy expands,
- OECD/NEA 2007 red book : ***Identified*** Resources increase beyond 5 Mt
- It does not basically change the long term problem (>2050)
- Generation IV nucelar systems with a closed U-Pu cycle would enable full use of uranium, and could emerge around 2050
- Such a time frame is coherent with the development of the technology

•Generation IV nuclear systems can help to facilitate acceptance of long lived radioactive wastes. Alone, they cannot solve the problem (2006 waste law).

Utility Requirements for Industrial Fast Breeder Reactors to be built by EDF

- **Safety:**

safety objectives = Gen 3 LWRs

similar quantitative probabilities for severe accidents, and more robust demonstrations.

physical protection = EPR

- **Sustainability and natural ressources utilization**

Breeding is an objective and a deployment criteria probably beyond 2040 in an expanding world nuclear fleet

minor actinides burning within the scope of the 2006 french waste law.

- **Operations**

Improve dramatically beyond levels of the preceding reactors : SuperPhenix 53 months of operations between 1986 and 1997 and European Fast Reactor EFR project (conceptual design)

Detailed specifications include materials selection, in service inspection and reparation, general Nuclear Island Outlay, components and core unloading, maintenance.

Utility Requirements for Industrial Fast Breeder Reactors to be built by EDF

- **Competitiveness and investment protection:**
  - capital cost and expected performance in operation = Gen 3 LWRs
  - design lifetime of components = 60 years or possible replacement

    limitation of risk of non-nuclear accidents leading to plant outage

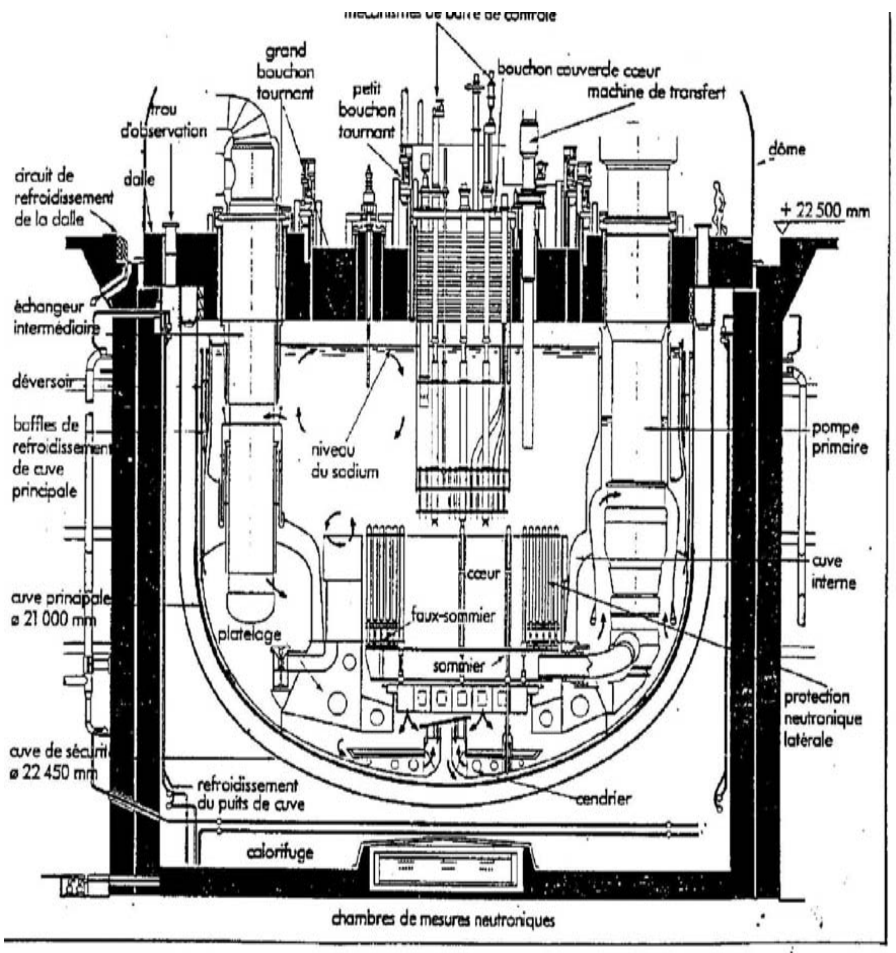
    low technological risk (availability vs. performance)
- **Non proliferation : increased safeguards**
  - For reactors
  - And for associated fuel cycle facilities
- **Physical Protection**
  - Same level as EPR

Utility Requirements for Industrial Fast Breeder Reactors – Generation IV Int. Forum design goals

GIF design goals		Gen 3 LWRs	former French SFRs
Sustainability	Resource Utilization	++	=
	Waste Minimization and Management	++	+
Economics	Life Cycle Cost	=	++
	Risk to Capital	+	++
Safety and Reliability	Operational Safety and Reliability	=	++
	Core Damage		+
	Offsite Emergency Response	=/+	++
Proliferation Resistance and Physical Protection	Proliferation Resistance	different	+
	Physical Protection	++ / =	++

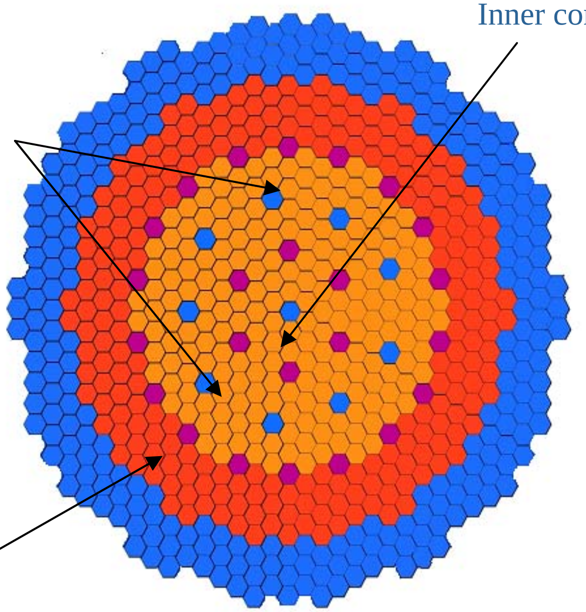
++: significant progress necessary; +: some progress needed; =: objective already met

The EDF R&D program (1/6)



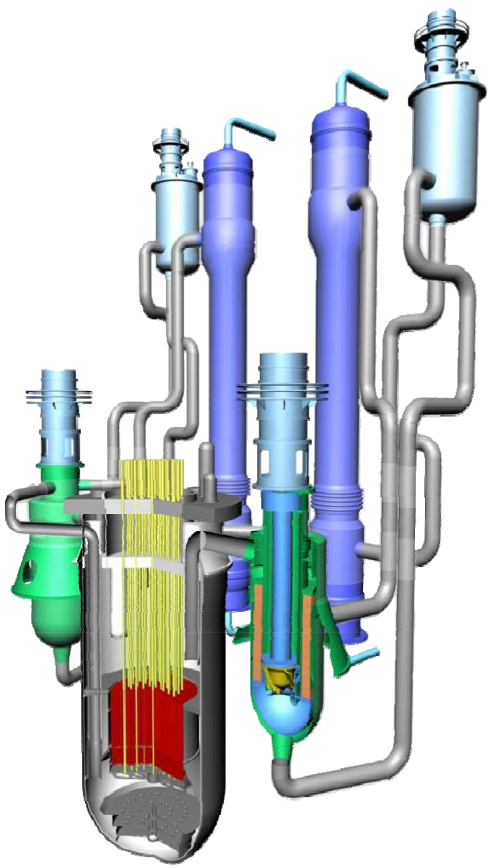
- •R&D on Sodium Fast Reactors : ~5% of EDF's Nuclear R&D budget
- •30 engineers mainly in the R&D Division
- • Utility's role, not a designer nor a vendor, nor a government R&D center
- •Fast Reactors and System Studies
- •Materials
- •Deployment scenarios, Inventories
- •Fuel cycle
- •Participation to the french program with CEA and AREVA (EDF ~4 M€/yr)

The EDF R&D program – Core physics (2/6)



- Basic reactor physics shows that fast reactors are « more reactive » than thermal water reactors
- Neutron lifetime 10^{-6}s vs $2x10^{-5}$s
- Neutronics studies to improve the core design with respect to the European Fast Reactor (EFR)
- Decrease the void coefficient, improve the prompt temperature coefficient
- Maintain a capability to answer safety questions related to neutronics and fuel design questions
- G. Mignot et al. « Studies on french SFR advanced core desings » in Proceedings ICAPP Conference June 2008 (joint AREVA/CEA/EDF paper)

The EDF R&D program Safety (3/6)



EPR levels of safety for severe core accidents and off site releases

EPR levels are compatible with the European Utitlity Requirements (EUR).

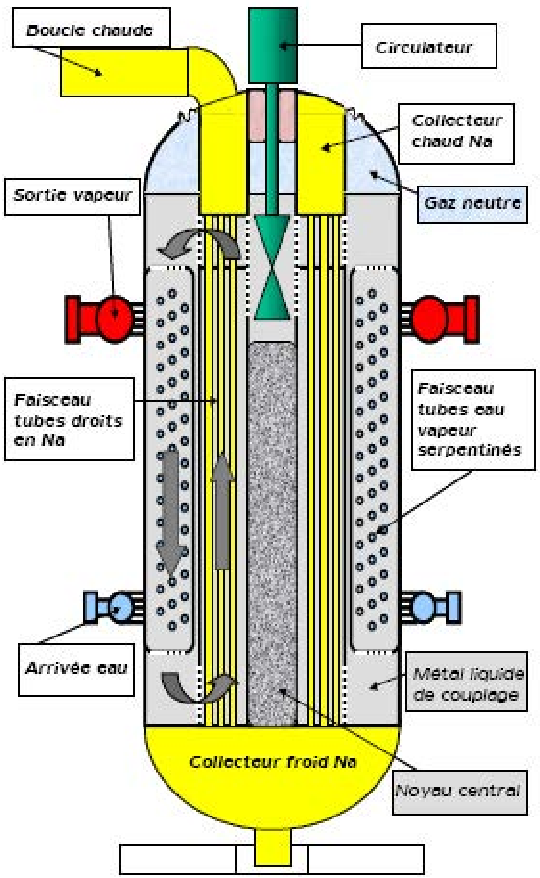
Probability of severe core accidents < 10^{-5}/ry, all initiators

Probability of severe accidents with off site releases requiring emergency, delayed or long term measures < 10^{-6}/ry.

1st phase : improve the core designs, hold internal safety technical reviews, launch safety R&D projects, prepare methodology discussions with the regulators

More details : see ICAPP 2008 joint paper Ch. Clément et al. « Drafting and implementation of a practical elimination approach for Gen IV nuclear reactors ».

The EDF R&D program Technology Innovations (4/6)



Integrated Heat Exchanger for loop type reactors

One Heat exchanger instead of 2 in SPX design

Heat Exchange and Steam Generation integrated in one component

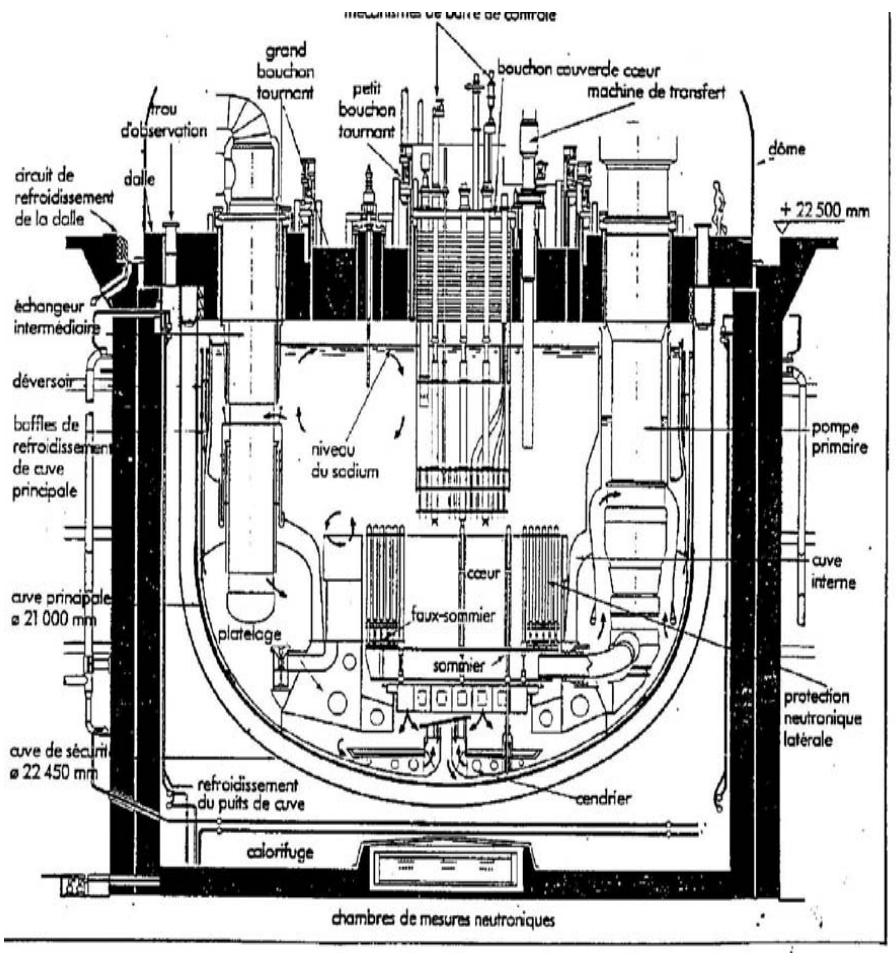
Physically separates Sodium and Water at the cost of a liquid metal coupling fluid

Liquid metal flow thermo hydraulics calculations

Chemical compatibility studies between liquid metals and materials

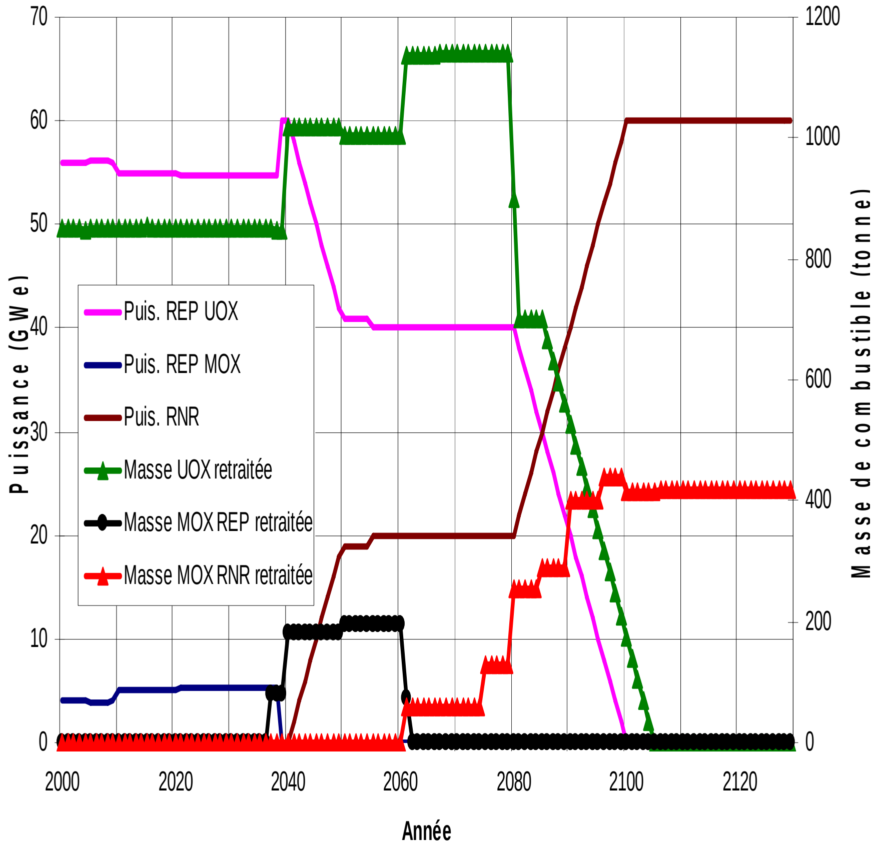
No technological construction capability within EDF

The EDF R&D program (5/6) Materials



- New materials associated to core designs and fuel assemblies : Oxide Dispersed Strengthened (ODS) steels (European collaborations)
- With large LWR expertise, avoid steel and alloy weaknesses which impaired operations in SPX (fuel handling section of the plant in 1987)
- Confirm 316 LN Steel for reactor vessels
- Other piping materials for primary circuits
- Up to date materials for secondary circuits

Deployment Scenarios : LWR'S and Fast Reactors Total Power Level of 60 GW (6/6)



- Starting a 20 GW fleet of fast reactors in 2040 requires 300 tons of Pu.
- 300 tons of Pu will be provided by the LWR fleet, with accumulated LWR MOX fuel being processed at La Hague between 2035 and 2060.
- In the actual Purex process, LWR MOX and UOX fuels are processed together (dilution).
- FBR MOX fuel will be reprocessed in a new plant commissioned after 2050
- Benchmark of models (on particular fleets) between ANL/INL, CEA and EDF

Prototypes and the french R&D program

•A fast reactor prototype has been announced by the government and confirmed by the parliament for operations in 2020.

•For EDF, what role for the 2020 prototype ?

- Research Reactor for concept validations and/or transmutation physics
- Or demonstration reactor with industrial capabities, derived from our utility requirements (smaller scale)
  - Safety
  - Operations
  - In service Inspection
  - Reparation
  - Maintenance
- The trilateral R&D program and engineering studies have to bring answers to this question by 2012.

National and International collaborations in Gen IV R&D

- **Trilateral R&D program with AREVA, CEA.** Impetus on Sodium Fast Reactors, small EDF effort on Gas Fast Reactors
- **Limited participation to the US/DOE Global Nuclear Energy Partnership (GNEP)**
  - Utility Advisory Panel set up by the Consortium led by AREVA which promotes Advanced Recycling Reactors, a Consolidated Fuel Treatment Center, an R&D fuel cycle facility.
  - EDF's contributions : R&D on Fast Reactors as outlined above, industrial experience of a closed fuel cycle with 22 reactors licensed for MOX
- **Bilateral R&D agreement with Japanese JAEA**
  - Joint technical reviews of the Japan Sodium Fast Reactor design (JSFR)
  - Operations of Sodium Fast Reactors, (Monju vs Superphenix)
  - Other technical topics
  - Education and Training

Supplementary Slides

Answers to question and comments during the debate

▪1-Load follow with nuclear units

intra day load follow is done on an industrial basis with the (french) nuclear fleet. For instance, a nuclear unit can vary its load from 100 % nominal power down to 30 % nominal power. However, this takes time, and is done over a 10-12 h period under normal conditions. This rate is not compatible with wind intermittency and a large percentage of the mix produced by wind turbines.

•**2-The 46 €/MWh EPR Flamanville 3** generation cost takes into account : investments costs (including financial costs and dismantling costs), Operations and Maintenance Costs, Fuel Costs.

•**3-The french situation concerning intermediate storage** of used fuel on site is different from the american one. It is felt that it would cause acceptance problems, and the 2006 waste law has prescribed a reference solution : reversible geological disposal. Very long term intermediate storage (above 120 years) has been studied, but not kept in the law as an acceptable definitive solution.

Nuclear fuel cycle industry in France
A Closed Cycle

Uranium and conversion
≈ 8000 t/year

Enrichment
≈ 5,5 MUTS/year

UO2 Fuel fabrication ≈ 1060 t/year
2000 assemblies/yr (45 GWd/t average, max 52 GWd/t

→ *time period 20 years*

430 TWh /an

58 EDF NPPs
20 units loaded with MOX
2 with REPU

Spent Fuel:
1200 tons /year
(UOX et MOX)

Spent Fuel Transportation to La Hague, interim storage in cooling pools 1200 tons/year

Recycling: MOX fuel
100 t/year on 20 units 900 MW (30% core) --> 40 TWh/yr

MELOX Fuel Fabrication plant

8,5 t /yr
Separated plutonium (1%)

Reprocessing :
850 t / year

La Hague

Reprocessed uranium: ~ 810 t/yr
(U235 content 0,8%)
1/3 re-enriched and recycled on 2 units 900W (100% core)
or 40 t/yr --> 15 TWh/yr
to be extended to 4 units

Vitrified High level Waste
Interim passive storage
Disposal optimisation

110 to 130 m^3/yr vitrified HLW

122 m^3/yr compacted ILW