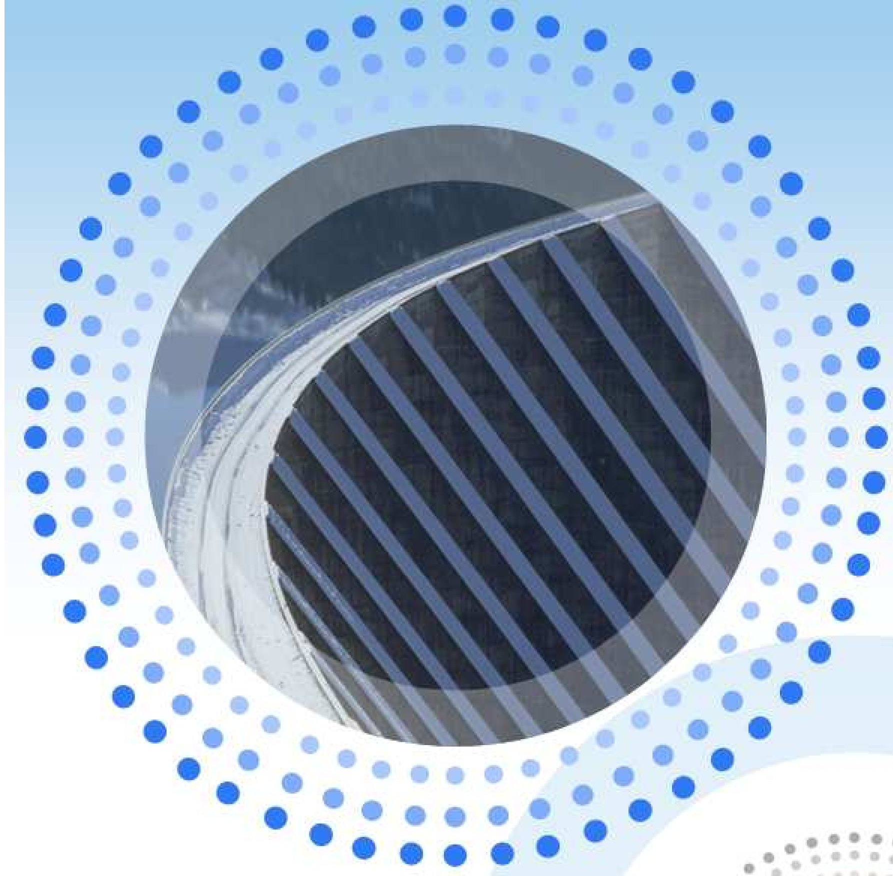


French Fuel Cycle Strategy and Transition Scenario Studies

Frank Carré
Jean-Michel Delbecq

Outlook

- What are scenario studies?
- World scenario studies
- French scenario studies
  - The French fuel cycle
  - French strategy for nuclear energy
  - Scenario studies
- The French R&D programme

Scenario studies : to do what?

- Scenario studies **help actors to take decisions** in an uncertain future

- Consistent study of the implementation of technical **assumptions** relative to reactors, fuel cycle, front end, back end,…
    - To identify potential critical points
    - To evaluate and compare different strategies
    - To define R&D orientations

- A scenario is attached to a geographic domain : World, Region, Country

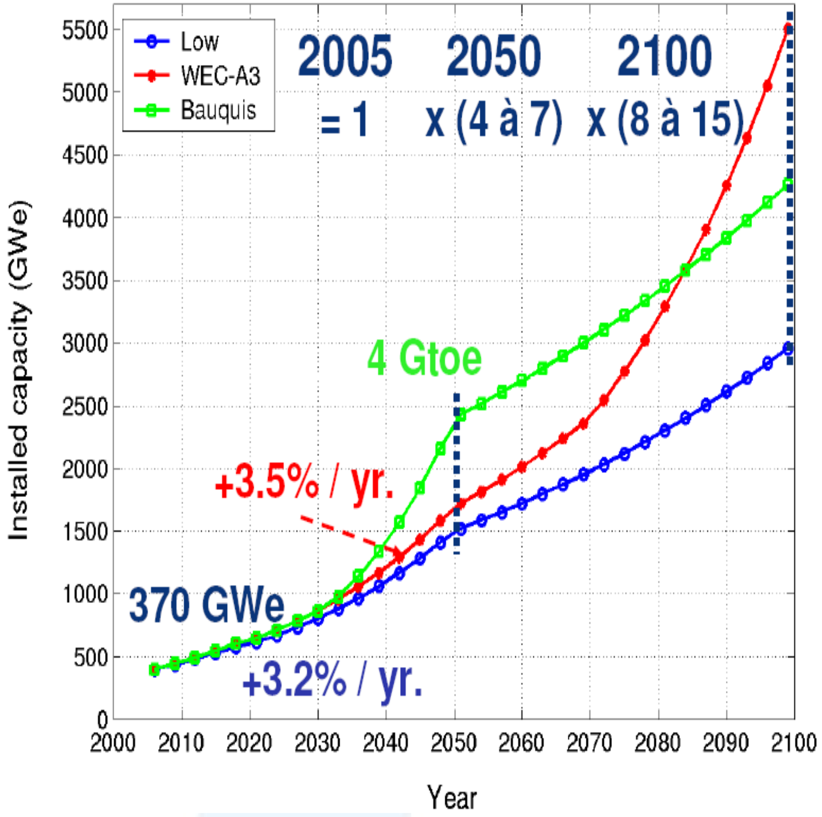
    - World scenarios : world energy mix, total installed nuclear power, uranium consumption, comparison open fuel cycle/closed fuel cycle, fast reactors deployment, etc.

    - Regional and National scenarios : transition between current fleet and future fleet taking into account local conditions (economic, societal, technical), plutonium availability, storage capacities, spent fuel treatment capacities, waste management,…

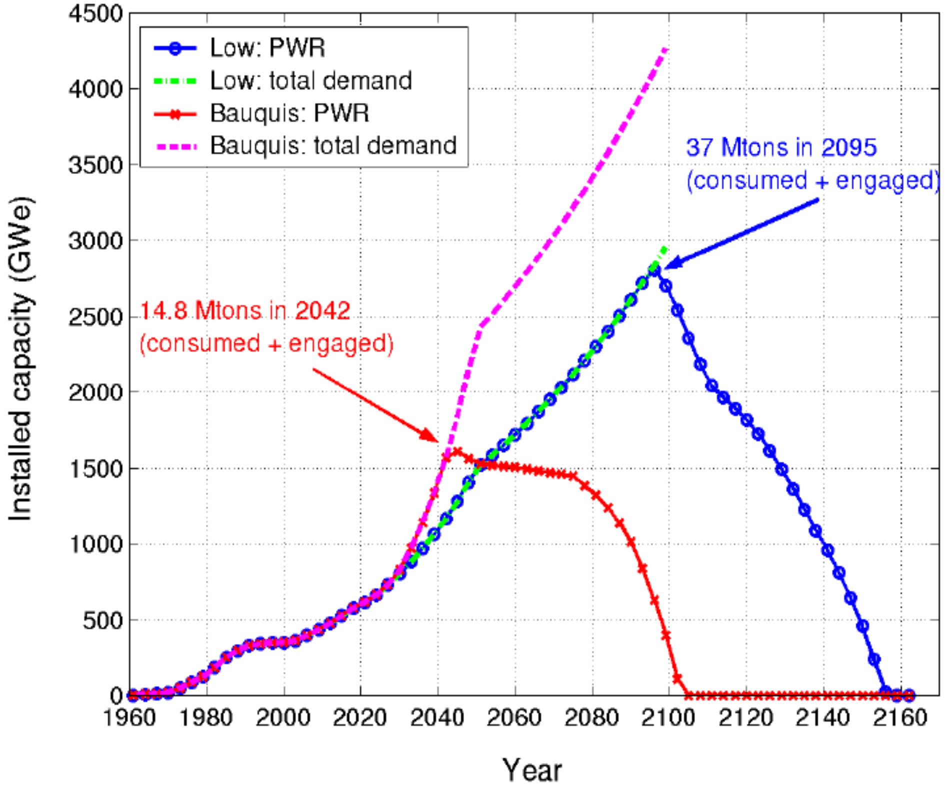
- Equilibrium (direct study of the final equilibrium state / to assess the scientific feasibility of an option) and Dynamic studies (transients study of the whole cycle, from mines to storage / to assess the technological feasibility of an option)

- In all cases, the exploitation of these results needs to define **a set of criteria** for the comparison between different scenarios : environmental and radiological impacts in all the facilities, thermal loads on waste disposal and disposal surface area, economic costs of the cycle, etc.

World deployment of nuclear energy



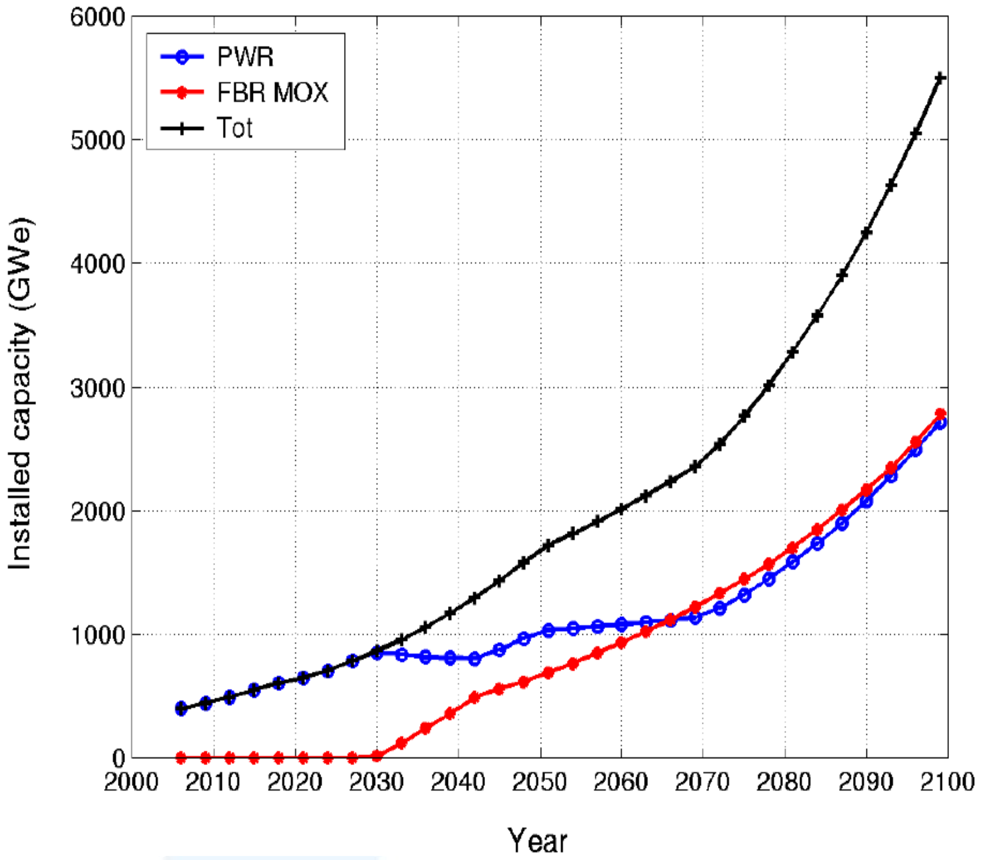
Scenarios for nuclear energy



Unat consumption with PWRs (open cycle)

After 2042 (Bauquis scen.) or 2095 (Low scen.), the PWR capacity is decreasing as a function of their age

FRs deployment in WEC-A3 scenario



2005 World fleet modeled by PWR

New reactors between 2005-2030 : PWR EPR-type (4,9% ^{235}U, BU 60 GWd/tHM, 60 yrs lifetime)

As early as 2030, MOX-fueled FRs are deployed at a pace dependent on the Pu availability for the fresh MOX fuel fabrication. Pu is issued from PWR and FR SNF reprocessing. If a Pu lack appears (it is the case after 2045), new PWRs will be deployed but the highest priority is given to FRs all along the century

FR = Na –cooled EFR with BG = 0.2, $T_{\text{core+SNF cooling+ ageing}}$ =6+2+2 yrs

Scenario (Mt)	Low	WEC-A3	Bauquis
PWR-Only	23 (+14.1)	31.7 (+30.8)	32.7 (+19.3)
PWR + FR MOX	11.0 (+2.5)	17.6 (+15.0)	17.1 (+2.3)

Cumulative U consumption (+ engaged) in 2100

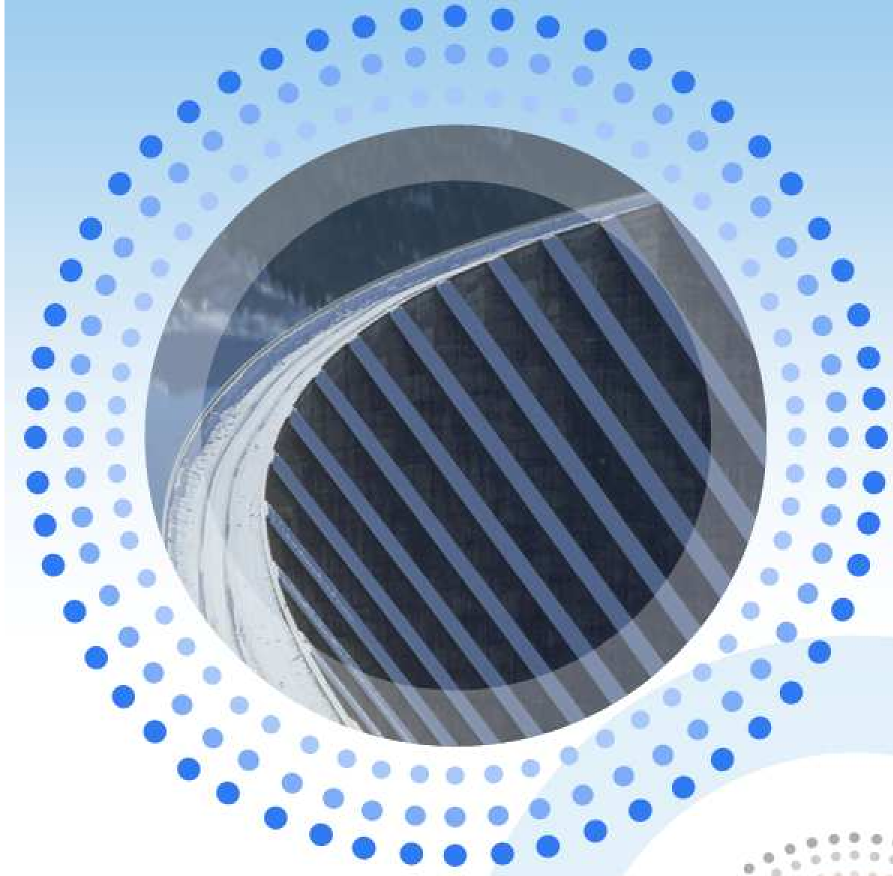
Factor 2 to 3 saving with FR

Some conclusions relative to World scenarios studies

- **Open cycle with LWRs** : a strong increase of installed capacity could be limited due to uranium scarcity. Waste management could be a societal issue.
- **Pu (once) recycling in LWRs**
  - **up to 10% saving in Unat consumption;**
  - **HLLL (FP+MA) are vitrified**
  - **MOX SNF are stored : reduction by 7 of volume storage; Pu stock for future FR deployment; to smoothen future needs in SNF treatment** (~ 5 times more Pu in MOX SNF than in UOX SNF)
- **Pu multi-recycling in FRs**
  - **U resources 100 times better used**
  - **But Pu availability?**
- **LWRs will remain during the 21st century. The reason to deploy FRs is uranium scarcity,** waste management could be improved (still tb demonstrated)
- There is also room for more sustainable LWRs in a symbiotic fleet, if one can prove that it's an industrial option (after 2030).

Interest and limits of World scenarios studies

- These studies are well fitted to the evaluation of uranium consumption and they allow to assess the interest of the introduction of sustainable nuclear systems
- But such studies are geographically global and don't take into account local situations: in particular, there is a great disparity in plutonium stockpile in the nuclear world and it induces very different situations regarding the introduction of FRs.
- **These studies are insufficient and have to be completed with regional or local scenarios studies**

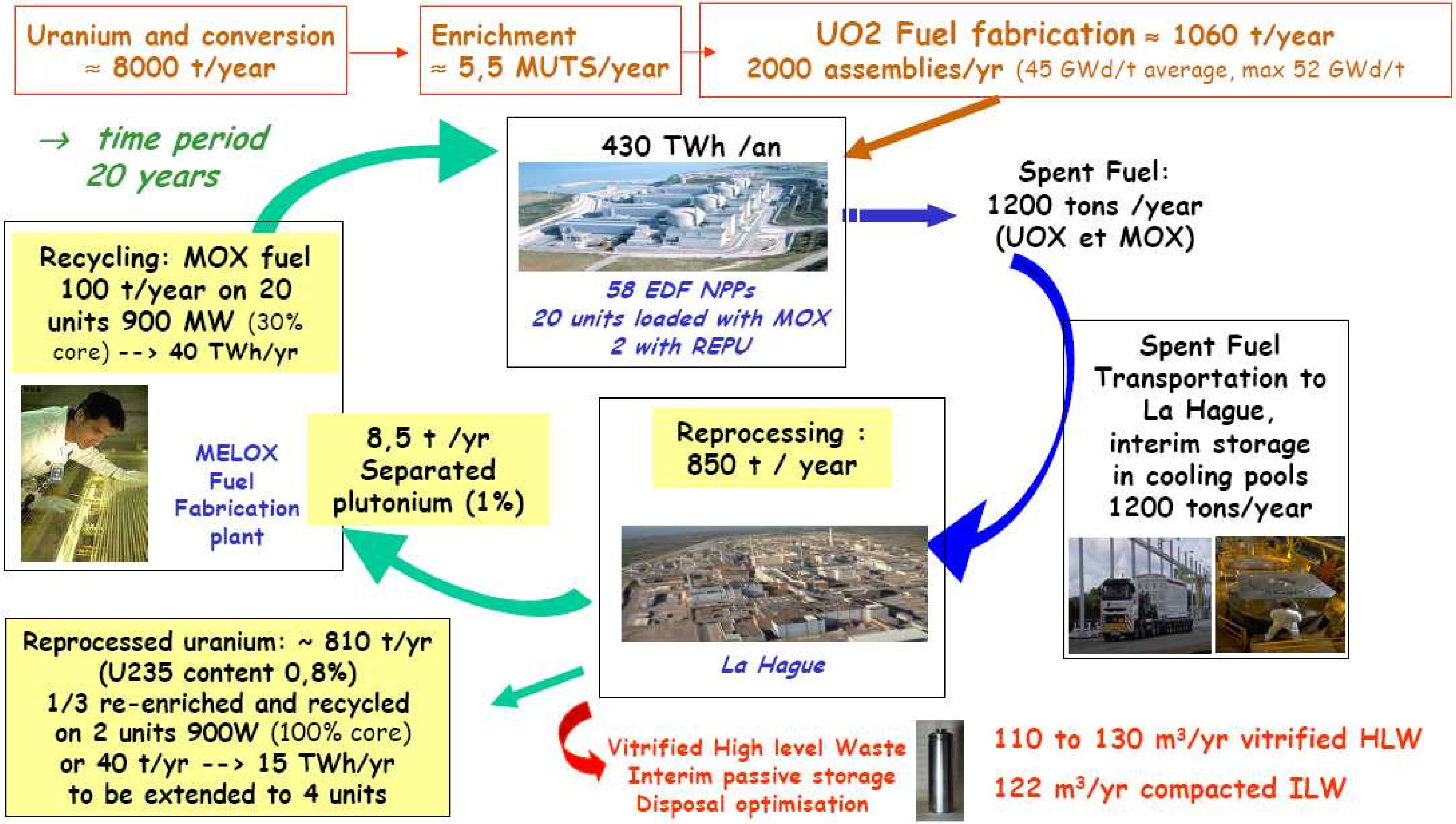


French scenario studies

In the framework of the Act of June 28, 2006

cea EDF R&D

In France, to-day, a mature fuel 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)

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

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

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

The renewal of the nuclear fleet : EDF strategy

- Mid-term: two strategic complementary lines
  - Extending the existing reactors lifetime beyond 40 years
  - Preparing the fleet renewal beyond 2020 with the launching of a FOAK EPR reactor (FLA 3 in 2012)
- Long term: a two-step flexible and robust approach
  - To initiate this renewal (~2020) with earlier tested Gen III (EPR)
  - To pursue with fast reactors Gen IV by 2040, **if needed**, in a worldwide context resulting in an increased appeal to nuclear energy (sustainability)
    - Another scenario could be : Gen IV deployment by 2080

A sustainable management of nuclear materials & waste: the Act of June 28, 2006

- **National Plan for managing *nuclear materials and radioactive waste***
- **Guarantees for *long term funding* of radioactive waste management**
- **Stepwise program for *Long-Lived Waste (High and Medium Activity)* management along various approaches:**
  - → ***Partitioning & Transmutation:***
    - ✓ *2012: Assessment of Fast Reactors / ADS*
    - ✓ ***2020: Fast reactor Prototype***
  - → ***Retrievable Geological Repository:***
    - ✓ ***2015: Authorization decree***
    - ✓ ***2025: Beginning of operation***
  - → ***Interim storage:***
    - ✓ ***Creation of new facilities in 2015***

Scenario studies in the framework of the Act of June 28, 2006

- To assess the industrial perspectives of FRs and ADS for the transmutation of HLLL waste

  - The assessment is made by comparing different scenarios of evolution of the French nuclear fleet Gen II → Gen III → Gen IV (w or wo ADS) to the reference scenario, i.e. Pu only recycling in FRs in the future.

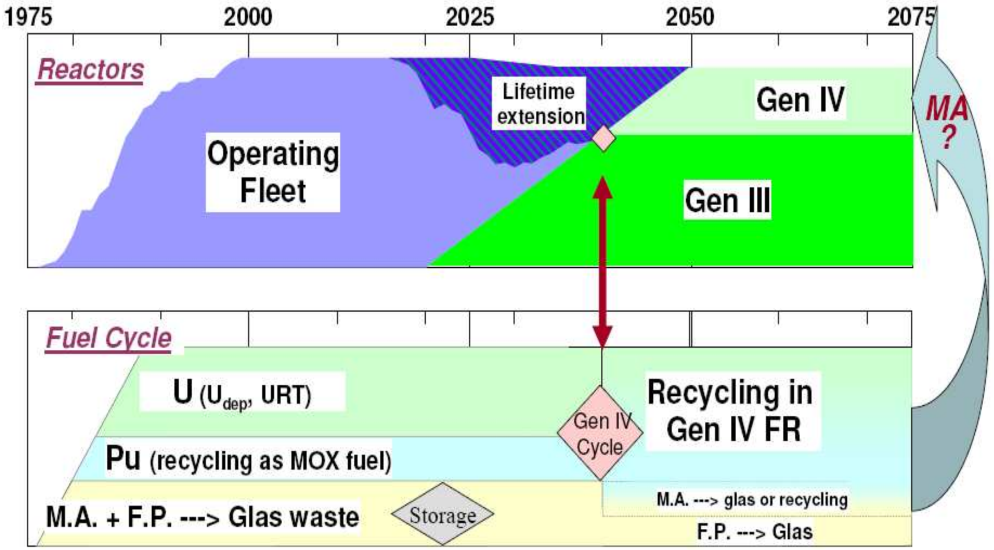
  - Various criteria are evaluated when comparing the different scenarios: their selection is an important phase of the study. They may be country-dependent as waste management is a societal issue: nuclear materials inventories, disposal surface area, waste radiotoxicity, disposal environmental impact, radiological protection of workers in the whole nuclear cycle, induced costs (investment, operation, etc.), etc.

  - The results presented in the following slides are issued from previous studies. A complete set of new scenarios, described in next slides, will be studied by 2012 to provide a report to the French Parliament.

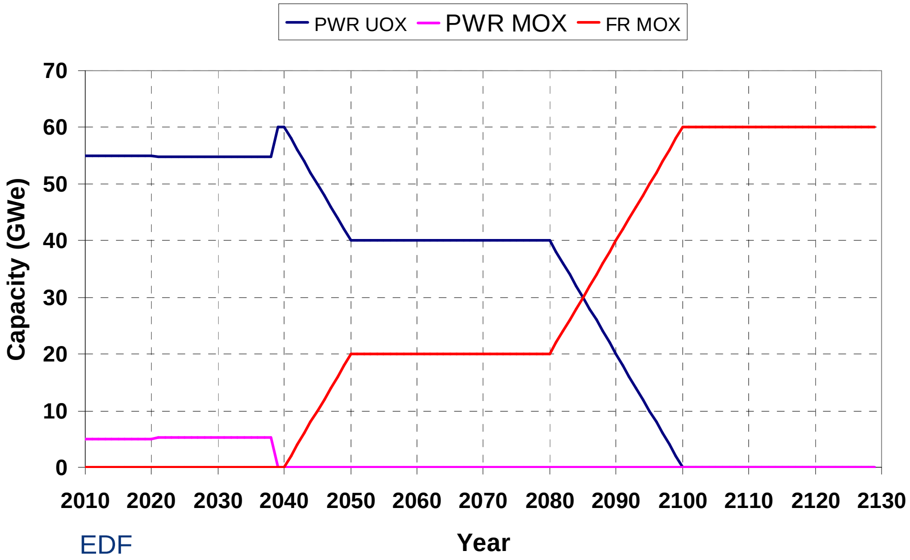
.

An illustration of these scenarios

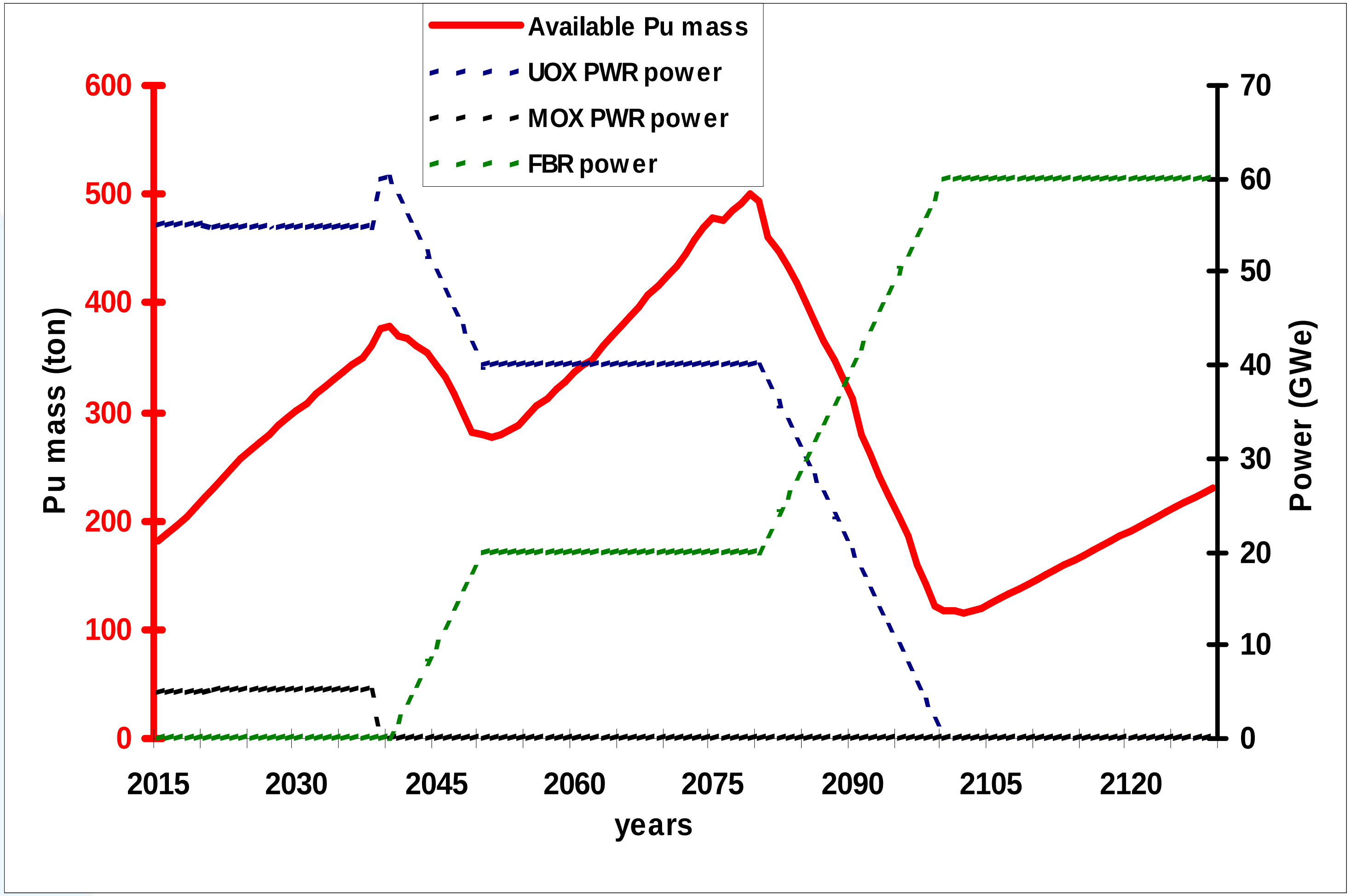
Source : EDF, ENC 2002



Scenario F4 : Installed capacity (GWe)



Pu stock available for FBR-MOX fabrication



FR BG = 0.07
(SFR V0 – 2006)

With BG = 0, other things being equal, only 56 GWe of SFR could be deployed because of lack of Pu

Cumulated amount of TRU disposed

For 1 TWhe (Net Prod.« cycle » Pu and MA, TRU [= Pu +MA] to waste in kg)

PWR UOx BU 60 GWd/t

Pu : 26
MA : 3
TRU : 29

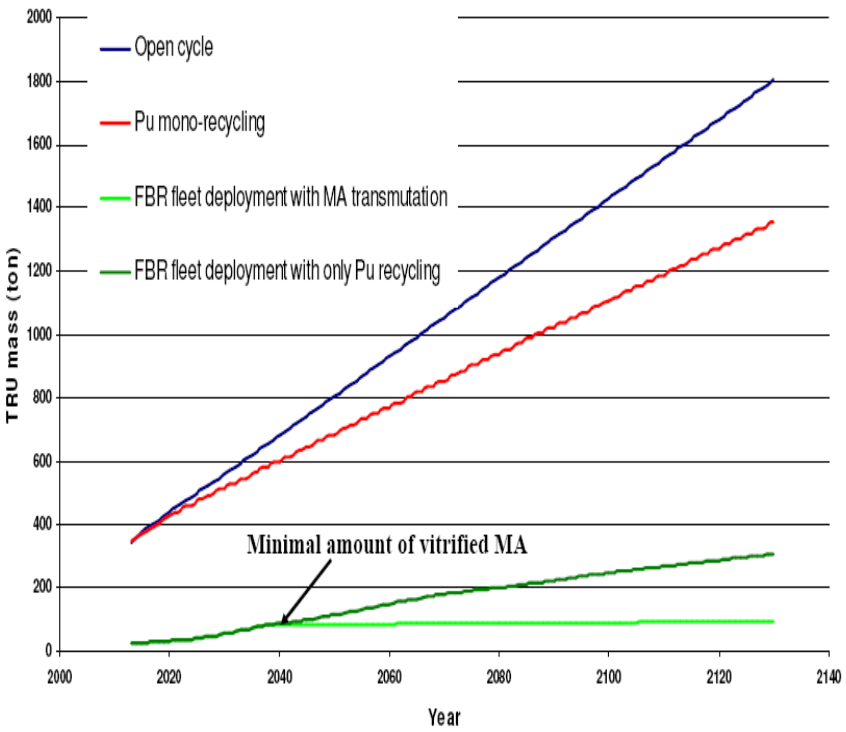
PWR UOx - MOx BU 45 GWd/t

Pu : 16
MA : 6
TRU : 22

EFR iso equilibrium w.o. MA recyc. / * w. MA recyc.

Pu : 0
AM : 4/*0
TRU : 4/*0,15

Cumulated amount of TRansUranics put in the disposal for 3 scénarios of French fleet evolution (60 GWe, ~410 TWhe)

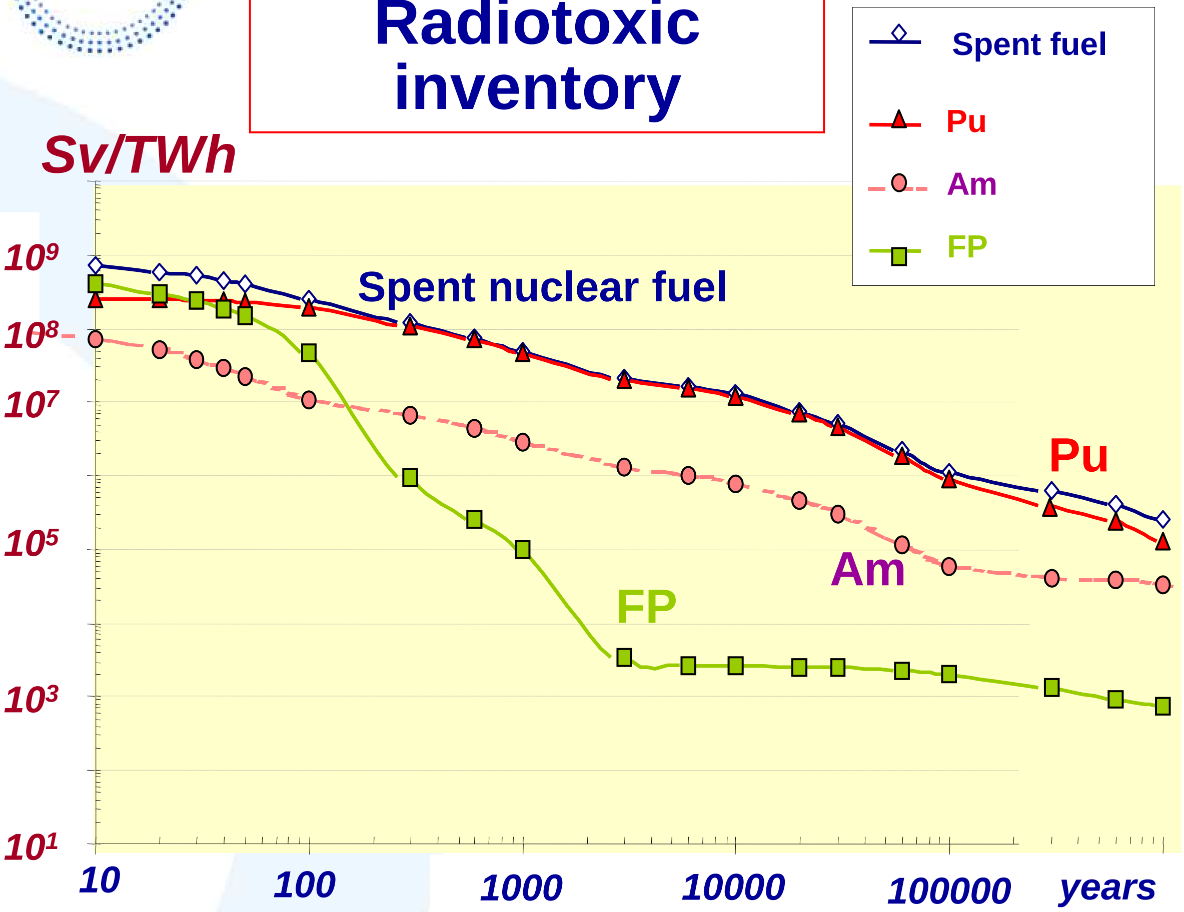


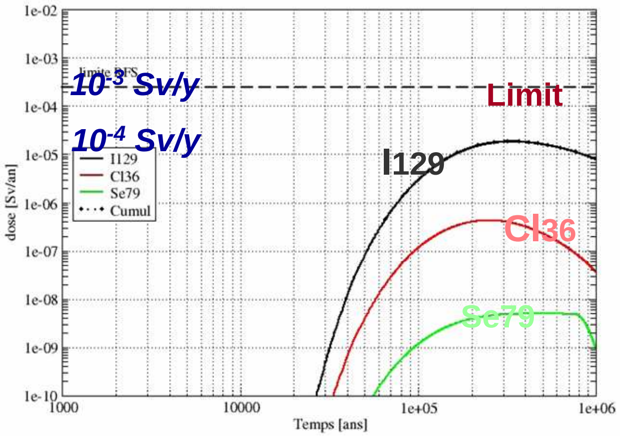
A factor 200 at equilibrium,

A factor 20 in 2130 in the dynamic scenario

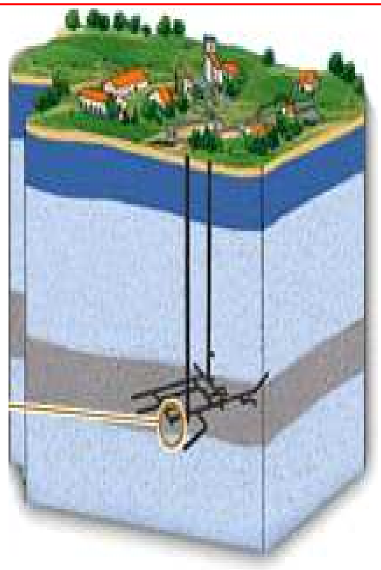
Long term radiotoxic inventory

Radiotoxic inventory





Radioactive releases by SNF, Saulx (Andra, « Clay » report, 2005)

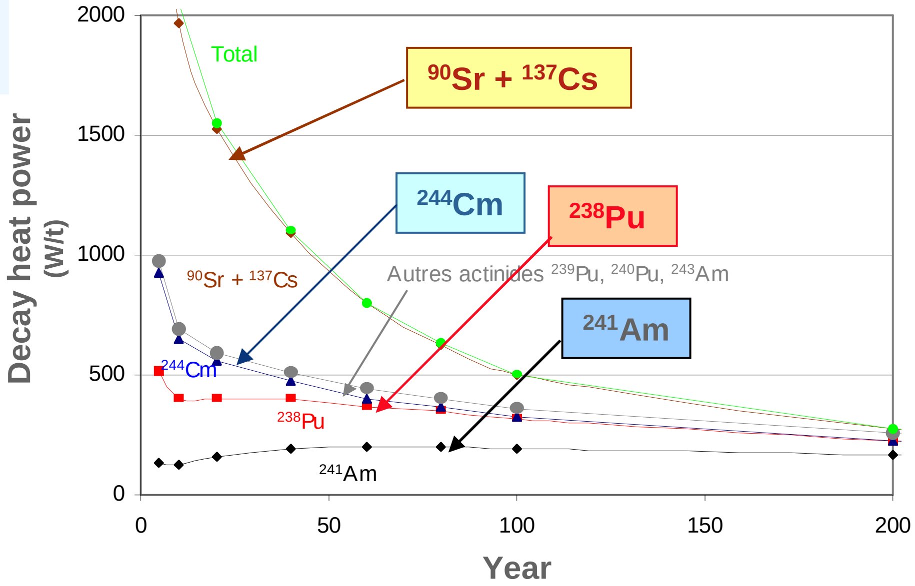


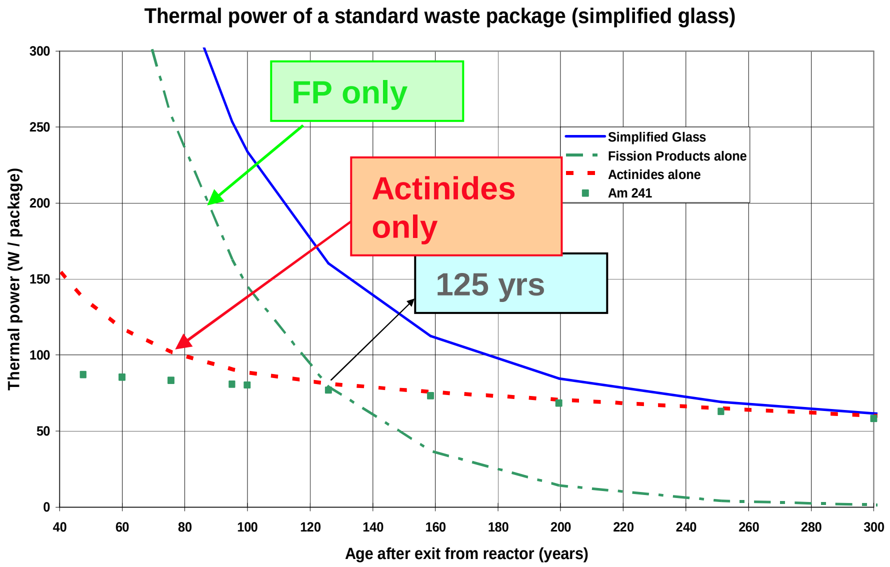
Long term radiotoxic inventory:

Pu >> minor actinides >>> FP

But radio-toxicity release is driven by LLFP

Decay heat of waste packages





TRU and FP contribution to decay heat power for a UOX 50 GWd/t

Thermal load evolution of a glass package from UOX 50 GWd/t treatment

Short term decay heat dominated by short lived FP (^{90}Sr, ^{137}Cs) and ^{244}Cm

Middle term decay heat dominated by ^{238}Pu and ^{241}Am

The age « 125 yrs » would be reduced to less than a century if FR SNF is considered – To be studied precisely in the future

Impact of transmutation on surface area of waste disposal

- Thermal load reduction can be managed by the waste inventory (nature and quantity) but also by the storage duration before disposal
- Two modes of waste management are considered here:
  - Partitioning and transmutation: ^{241}Am ($T_{1/2}$: 430 yrs)
  - Storage: ^{244}Cm ($T_{1/2}$: 18 yrs) ^{90}Sr, ^{137}Cs ($T_{1/2}$: 30 yrs)

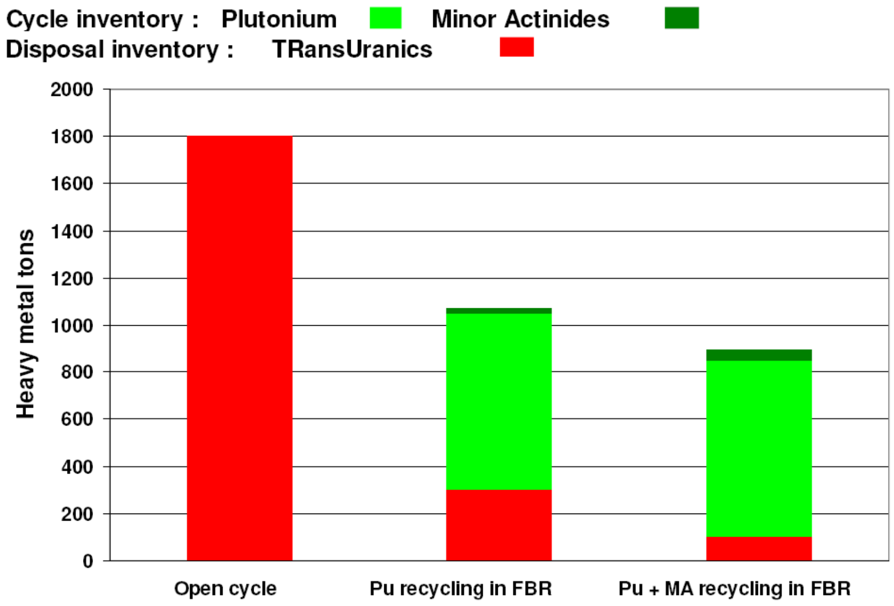
	Storage		
	50 – 60 yrs	100 yrs	150 yrs
CU UOX **FP + Pu + MA**	**100 Reference**	**90**	**55**
Current glass **FP + MA**	**33**	**17**	**12**
« MA-light » glass **FP**	**~ 25**	**~ 10**	**2 à 8**
« Ultra-MA-light » glass **FP – {Cs, Sr}**	**7**	**-**	**-**

Note that the glasses considered here are UOX glasses and not MOX FR glasses. For the latter glasses, MA heat load dominates sooner : their transmutation should allow to reduce strongly the disposal thermal load..

Waste disposal surface area reduction

Some limits of transmutation strategy are to be considered

- MA transmutation efficiency is potentially limited by :
  - The amount of minor actinides vitrified before the implementation of the transmutation (~90 t in 2040 in France)
  - The amount of transuranics (mainly Pu) to be disposed at the end of nuclear industry (or at a chosen date to compare the different strategies) **(the green part in the TRansUranics inventory in cycle and in disposal in 2130**

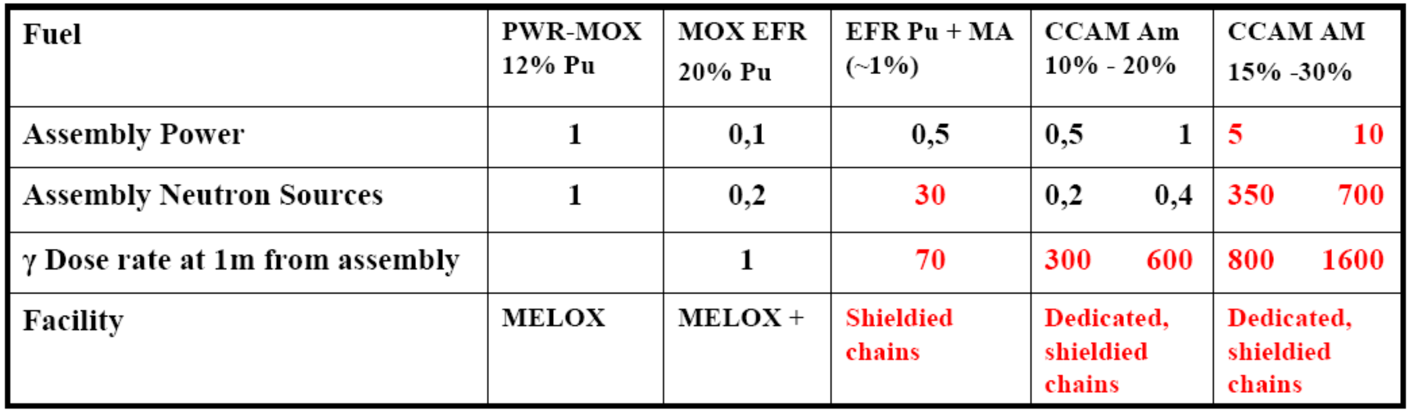


Reduction factor of TRU compared to open cycle

Calculation hypothesis	Only Pu recycling	Pu + AM recycling
Equilibrium state, TRU in disposal	7	200
In 2130, TRU in disposal	6	20
In 2130, total TRU (disposal + cycle)	1,6	2

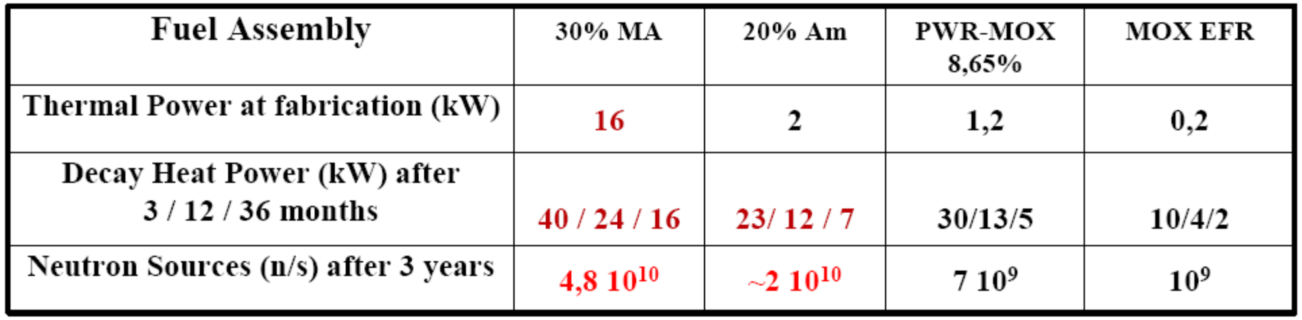
So the nuclear phase-out study is a part of scenario studies to assess the efficiency that can realistically be expected from MA recycling options

Other impacts on fuel cycle facilities



Fuel	PWR-MOX 12% Pu	MOX EFR 20% Pu	EFR Pu + MA (~1%)	CCAM Am 10% - 20%	CCAM AM 15% -30%
Assembly Power	1	0,1	0,5	0,5 1	5 10
Assembly Neutron Sources	1	0,2	30	0,2 0,4	350 700
γ Dose rate at 1m from assembly		1	70	300 600	800 1600
Facility	MELOX	MELOX +	Shieldied chains	Dedicated, shieldied chains	Dedicated, shieldied chains

Impact of MA recycling on fuel fabrication facility

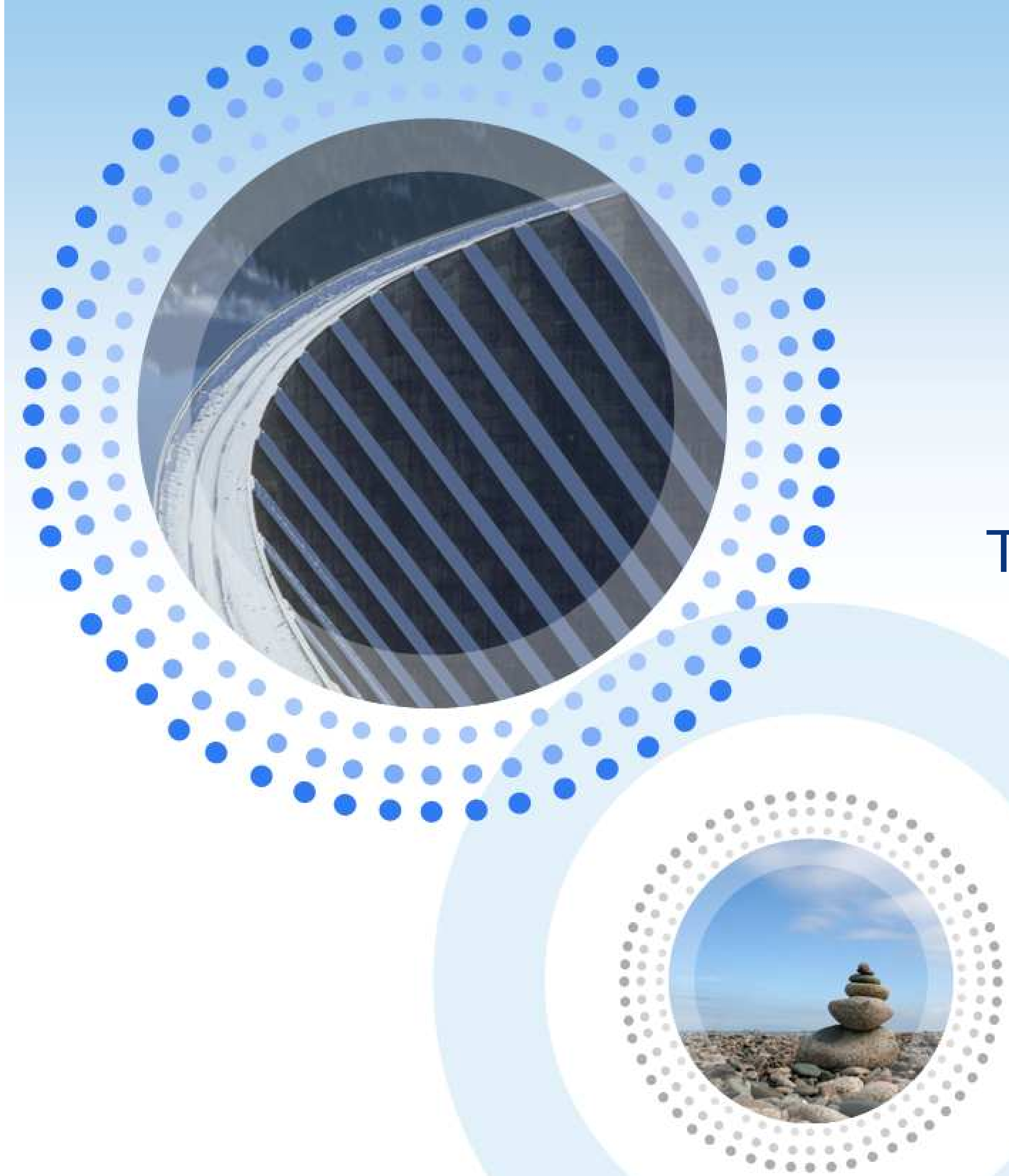


Fuel Assembly	30% MA	20% Am	PWR-MOX 8,65%	MOX EFR
Thermal Power at fabrication (kW)	16	2	1,2	0,2
Decay Heat Power (kW) after 3 / 12 / 36 months	40 / 24 / 16	23/ 12 / 7	30/13/5	10/4/2
Neutron Sources (n/s) after 3 years	$4,8\ 10^{10}$	$\sim 2\ 10^{10}$	$7\ 10^{9}$	10^{9}

Impact of MA recycling on fuel handling and transportation

MA recycling assessment

- MA recycling is very challenging and the impacts on all the facilities have to be assessed. For instance:
    - Shieldied fabrication facilities? Remotely operated facilities? Which constraints on treatment facilities?
    - Ageing of MA SNF in storage (α activity of Cm)
    - Transportation cask design (fuel clad temperature and dose rate)
    - Fuel handling in reactor: time before unloading and transportation (thermal load), impact on plant availability; iImpact on reactor safety impact (void coefficient in particular)
- The potential benefit of MA recycling on proliferation resistance will be also evaluated (strengthening of radiation barrier against diversion of nuclear materials; easier detection of nuclear materials;…)
- One of the main important criteria is, of course, the industrial feasibility of MA recycling and its cost (direct costs at every step of the whole fuel cycle, including disposal and reactors and indirect costs such as the plants availability), compared to the cost of reference option.
- Societal criteria will also be assessed in a more qualitative way (acceptability)
- The report assessment will be provided to the French Parliament in 2012.
- Of course, a strong R&D programme accompanies these scenario studies to develop Gen IV Frs and the associated fuel cycle.



The French R&D programme

The French Gen IV R&D programme

Towards an industrial, safe and competitive Gen IV FR around 2040….

Atomic Energy Committee meeting on December 20, 2006

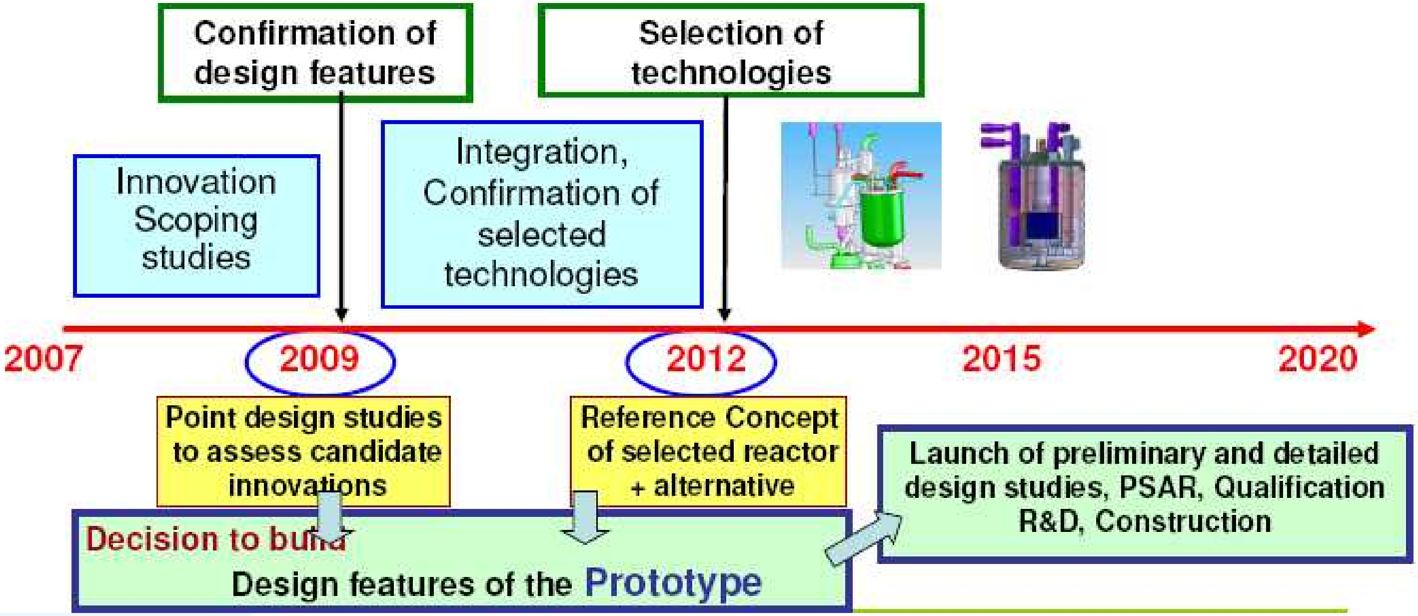
→ Two types of Fast Reactors studied in parallel

1 – Sodium Fast Reactor, reference type for a Prototype by 2020 in France

→ *Search for significant innovations*

2 – Gas Fast Reactor, alternative Fast Reactor type

→ *Active collaboration in Europe towards an experimental reactor?*



Confirmation of design features

Selection of technologies

Innovation Scoping studies

Integration, Confirmation of selected technologies

2007

2009

2012

2015

2020

Point design studies to assess candidate innovations

Reference Concept of selected reactor + alternative

Decision to build

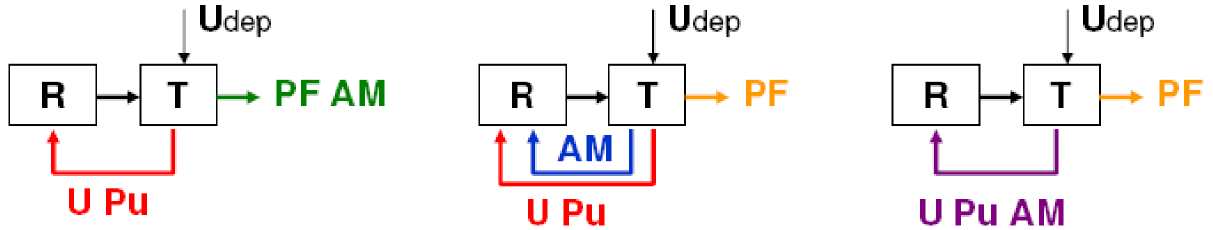
Design features of the Prototype

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

The French Gen IV R&D programme

Towards an industrial, safe and competitive Gen IV FR around 2040….and the associated fuel cycle

3 different options



Recycling U Pu only

Heterogeneous recycling

Homogeneous recycling (GenIV)

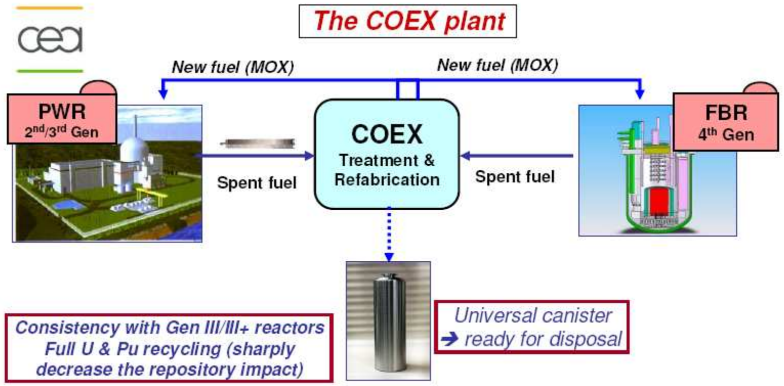
→ Keep options open for R&D and demonstrations in 2020s + assess ways for a stepwise implementation

R&D

- **Separation** *(UPu, Np, Am, Cm)*
- **MA bearing fuels** *(Fab, Recy)*

The French Gen IV R&D programme

Example of a Generation III processing facility



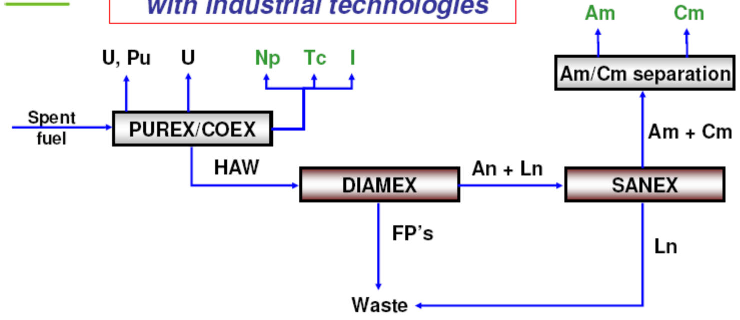
Consistency with Gen III/III+ reactors Full U & Pu recycling (sharply decrease the repository impact)

Universal canister
➔ ready for disposal

Treatment & Recycling competitiveness
Resistance to Proliferation *(Integrated Plant, no Pu alone)*

Advanced separation processes of actinides

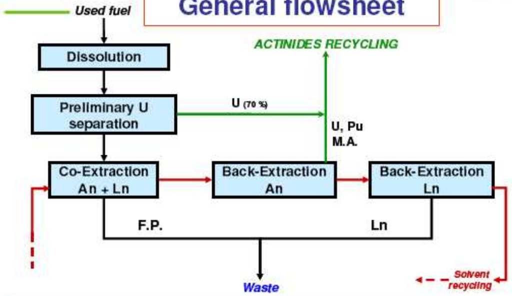
Demonstration test in 2005 on 15 kg of spent fuel with industrial technologies



Processes such as **UREX+/Talspeak** or **NEXT/Todga** are other viable options

R&D on spent fuel separation processes

GANEX
General flowsheet



- **Demonstration of GANEX in 2012**
- **Experience from the R&D performed on HL radioactive waste management**

Co-conversion of actinides through the solgel process

Beads of U(VI)-Pu(IV) hydroxide gel

Oxalic co-precipitation of actinides

(U,Np,Pu,Am) 78/1/20/1

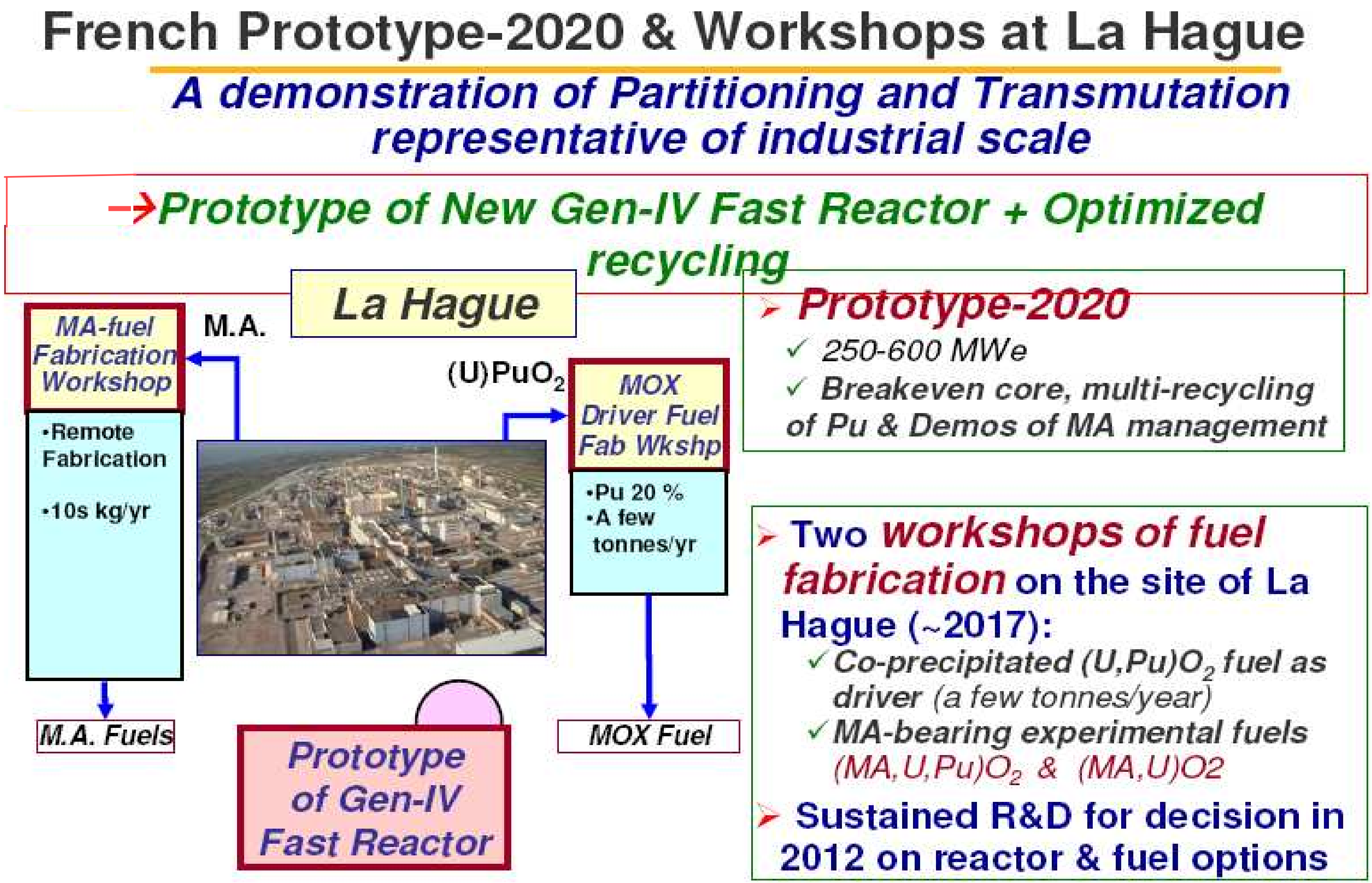
TRU fuel tests in Phenix & Superphenix

	SUPERPHENIX		PHENIX	
	Homogeneous	Heterogeneous	Homogeneous	Heterogeneous
Np	NACRE UO_2,PuO_2 + 2% Np Fabricated Not irradiated		SUPERFACT pins UO_2 + 2% NpO2	SUPERFACT pins UO_2 + 40% NpO_2 METAPHIX Metal Np, Am, Cm
Am Cm	Few pins with 1% Am		SUPERFACT pins UO_2 + 2% AmO2	SUPERFACT pins UO_2 + 20% AmO_2 ECRIX AmO_2 + MgO CAMIX/COCHIX Oxide *FUTURIX FTA*

🟩 Completed
🟦 On-going (2003-2009)

+ **PROFIL** *(nuclear data)*
+ **ANTICORPS** *(transmutation of Tc)*

The Gen IV prototypes planned in France



French Prototype-2020 & Workshops at La Hague

A demonstration of Partitioning and Transmutation representative of industrial scale

→***Prototype of New Gen-IV Fast Reactor + Optimized recycling***

La Hague

MA-fuel Fabrication Workshop

- Remote Fabrication
- 10s kg/yr

M.A.

(U)PuO$_2$

MOX Driver Fuel Fab Wkshp

- Pu 20 %
- A few tonnes/yr

M.A. Fuels

MOX Fuel

Prototype of Gen-IV Fast Reactor

➢ ***Prototype-2020***

✓ *250-600 MWe*

✓ ***Breakeven core, multi-recycling of Pu & Demos of MA management***

➢ **Two *workshops of fuel fabrication* on the site of La Hague (~2017):**

✓***Co-precipitated (U,Pu)O$_2$ fuel as driver*** *(a few tonnes/year)*

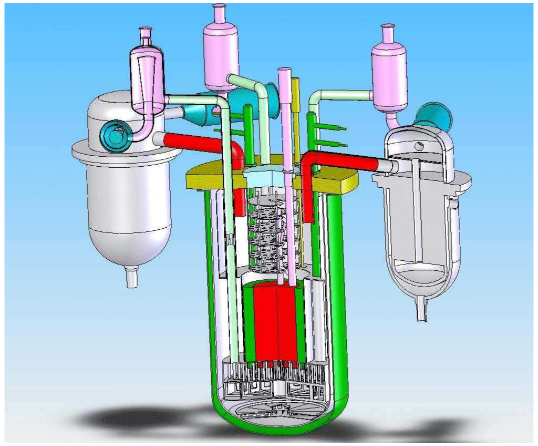
✓***MA-bearing experimental fuels*** *(MA,U,Pu)O$_2$ & (MA,U)O2*

➢ **Sustained R&D for decision in 2012 on reactor & fuel options**

Conclusions and perspectives

- Nuclear energy is a worlwide issue as one of the solution for the energy security of supply, in the context of climate change. Scenario studies are key to prepare strategic decisions on the transition between the current nuclear fleets and the future fleets.
- A set of various criteria is to be defined to assess the different scenarios. These criteria and the criteria ponderation are locally dependent.
- Nuclear fuel (re-)cycle is a worldwide issue. Different options of closed fuel cycle are studied: Pu only recycling, MA (homogeneous, heterogeneous with some variants) in FRs, MA in ADS. Scenario studies are a powerful tool to compare these options.
- Towards a joint phased development of reactor and spent fuel treatment industrial technologies
- Crucial need to federate current national initiatives as well as longer term R&D and demonstration programs into a consistent international technology roadmap
  - Reactors (Gen IV, prototypes, harmonized safety standards, ..) and nuclear fuel cycle
  - Fundamental and seed research, sharing complementary experimental equipment, large international demonstration,..

Thank you for your attention !



Complementary slides

The set of scenarios

- Main options
  - New technologies introduced in 2040 or in 2080
    - Gen IV FRs (Pu recycling or Pu+MA recycling) or
    - Gen IV FRs (Pu recycling) and ADS (MA recycling)
  - No new technologies, ie Gen II and Gen III reactors, open cycle or MOX once recycling (MA not recycled)
- 4 families of scenarios = ~ 12 study cases
  - Pu recycling in Gen IV FRs
  - Pu+MA recycling in Gen IV FRs (SFR or GFR)
    - Homogeneous
    - Heterogeneous (with or without Cm)
  - MA recycling in ADS (inert support)
  - LWR in open cycle (MOX recycling in LWRs stopped in 2030)
- Separation and transmutation introduced either in 2040 or in 2080
- All these scenarios are completed with an « end of life transient » (phase-out) to take

Other impacts on fuel cycle facilities

- MA recycling induces at the different stages of the fuel cycle (fabrication, treatment, reactor – fuel handling in particular, transportation, storage, disposal) :
  - Higher thermal power
  - Higher γ emissions
  - Higher neutron emissions

MA Content	1% Np	1% Am	1%Cm
Thermal Power	X 1	+ 30%	X 10
γ emission	X 2	X 30	X 200
n emission	X 1	+ 15%	X 700

Impact at fuel fabrication stage of the addition of 1% of each MA type in a standard FR MOX fuel assembly

Ass.	**PWR MOX**	**FR Pu**	**FR Pu+MA** (homogeneous)	**CCAM – Am** (heterogeneous)	**CCAM – AM** (15%) (heterogeneous)	**ADS**
Pu	**8,7% (<12,5%*)**	**15-20%**	**15-20%**			**40%**
Am	**0,1% (<3%Pu*)**	**0,15%**	**0,8%**	**10-20 %**	**10-12%**	**45%**
Cm	**0**	**0**	**0,2%**		**2-3 %**	**10%**
Np	**0**	**0**	**0,2%**		**1-2%**	**5%**

TRU abundance in fuel assembly

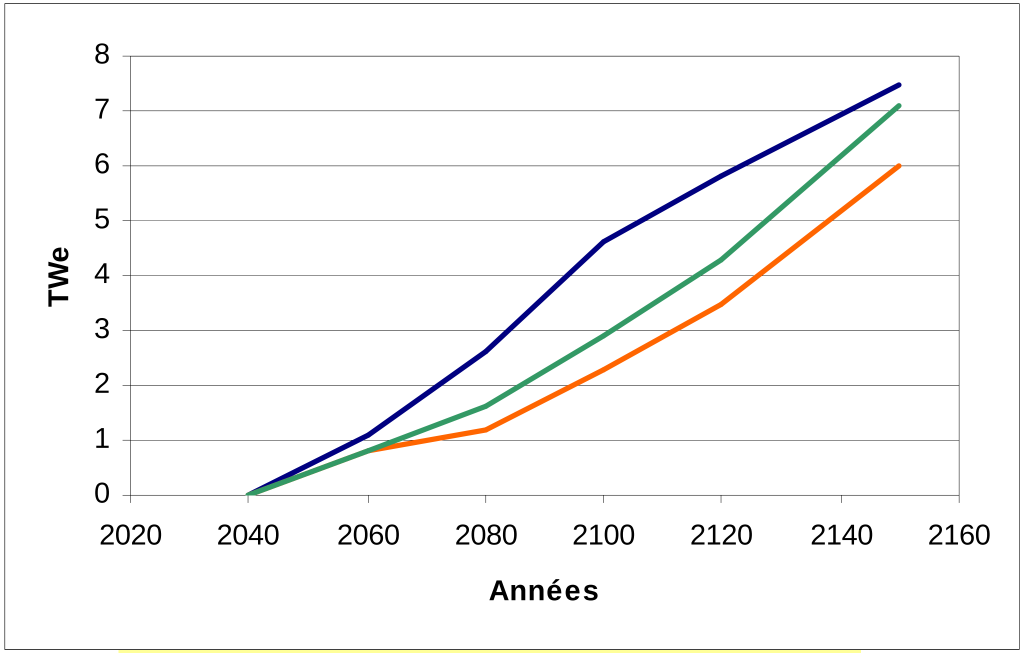
Plutonium availability

FRs deployable with available Pu (Bauquis scenario)

— Total installed power from 2040 (TWe)

— FRs Power max. BG = 0.3

— FRs Power max. BG = 0

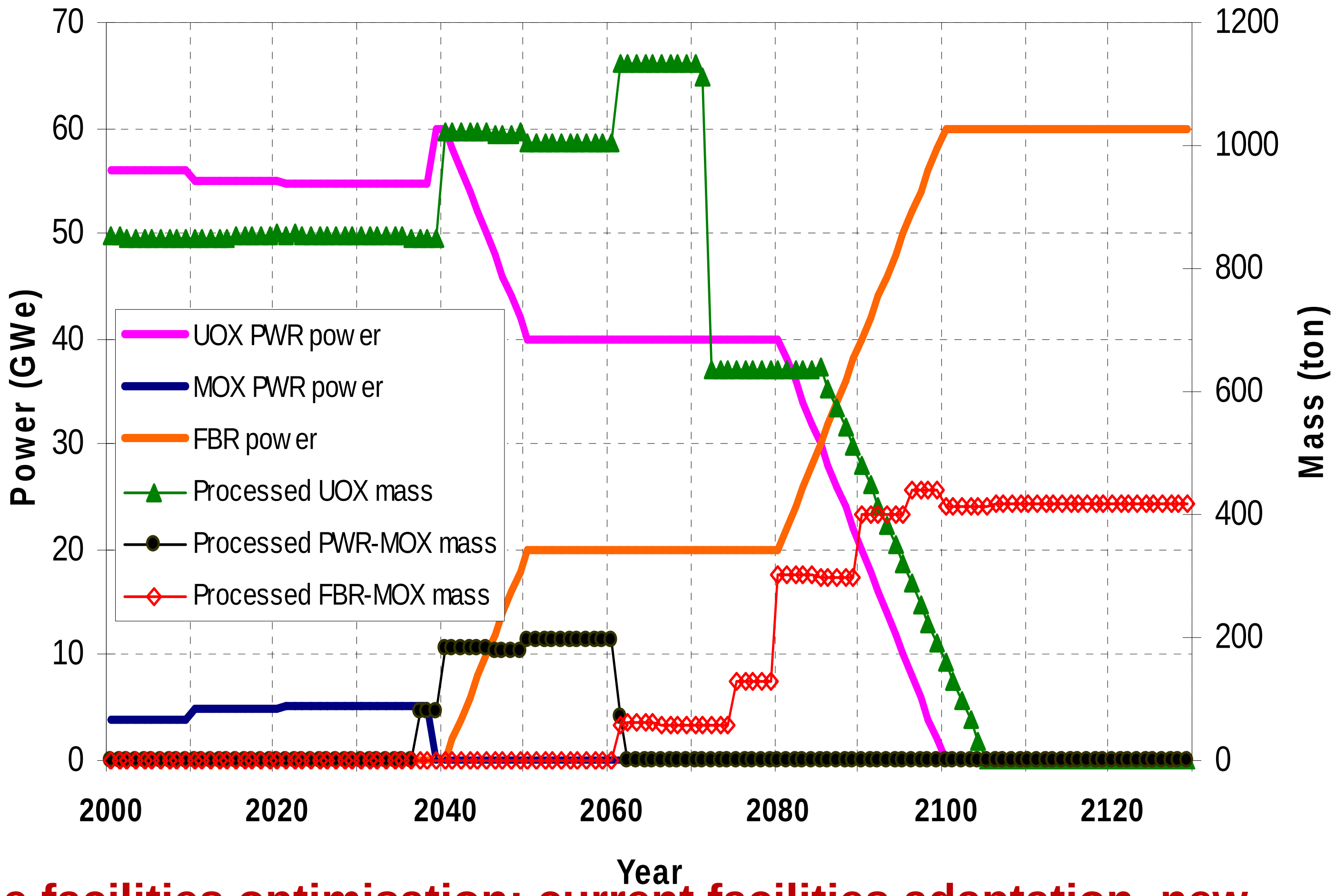


J-L. Carbonnier CEA – SFEN March 2008

- With FR technology available from 2040 and spent fuel treatment sufficient capacities, the amount of available Pu doesn't allow to deploy only FRs.

- This result is a world average and covers strong regional variations: Pu gap will be all the more big as nuclear power is young in a region.

Impact on used fuels processing capacity requirement



Fuel cycle facilities optimisation: current facilities adaptation, new facilities size, load factor to manage at the best the transition PWR➔FR