EDF research scenarios for closing the Plutonium cycle

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Introduction - Framework of the study

- French Act on « a sustainable management of nuclear materials and radioactive waste » (2006)

  ➔ EDF long term objective is to fully close the plutonium fuel cycle

  - Optimizing the use of the various available resources: natural, reprocessed and depleted uranium, plutonium
  - Assessing Fast Breeder Reactors potentialities with respect to:
    - fuel cycle flexibility and fissile material management
    - while minimizing the High Level Waste production
  - Assessing the potentialities of other reactors

- EDF studies the main strategies conceivable
  - A full Sodium cooled Fast Reactors (SFRs) fleet is deployed from 2040
  - SFRs deployment remains partial and the French fleet is composed of SFRs and PWRs
  - SFRs availability being delayed, advanced PWRs with high conversion ratio are deployed from 2040

1. General scenario assumptions

Reactor assumptions

- EPR : Industrial design
- HCPWR : CEA hexagonal design HCPWR-HEXA
- SFR : CEA low void effect (SFR-CFV) design modified to create a 3600 MWth core

Characteristics	EPR		HCPWR	SFR
Thermal power	4500 MWth		4250 MWth	3600 MWth
Net electrical power	1550 MWe		1450 MWe	1450 MWe
Net yield	34.4 %		34. %	40.3 %
Load factor	81.81 %		81.81 %	81.81 %
	UOX	MOX		
Core management	4 * 366.6 EFPD	3 * 366.6 EFPD	4 * 369 EFPD	5 * 400 EFPD
^{235}U enrichment	4.5 %			
Average Pu content (% of fissile assembly)		~ 9 %	~ 21 %	~ 24 %
Average Pu content (tons/Gwe)		6.8	14.5	8.7
FIR		0.7	0.86	>1.
Fuel average burn-up	55 GWd/t	46 GWd/t	45.2 GWd/t	121 GWd/t

1. General scenario assumptions

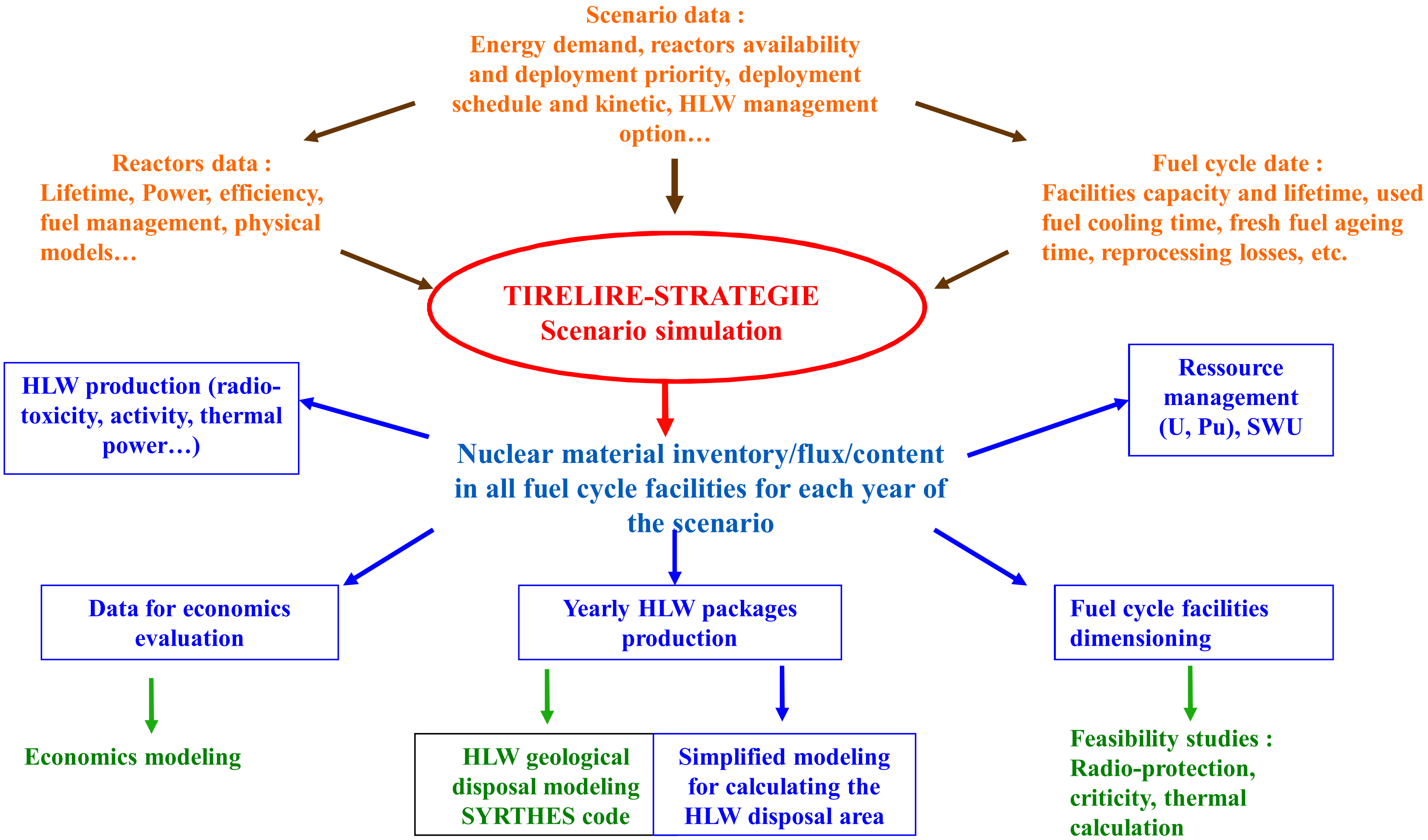
- Simulation of French fleet with constant installed power: 60 GWe
  - Current fleet ➔ Generation III+ (EPR) ➔ SFR-CFV / HCPWR
  - Scenarios are compared to « business as usual » : mono-recycling of plutonium in EPR

- Fuel cycle assumptions
  - MOX for EPRs is produced from mono-recycling of PWR-UOX and depleted uranium
  - MOX for SFRs and HCPWRs is produced from any type of recycled Pu and reprocessed uranium

  - Two-year minimum fabrication
  - Five-year minimum cooling time after irradiation

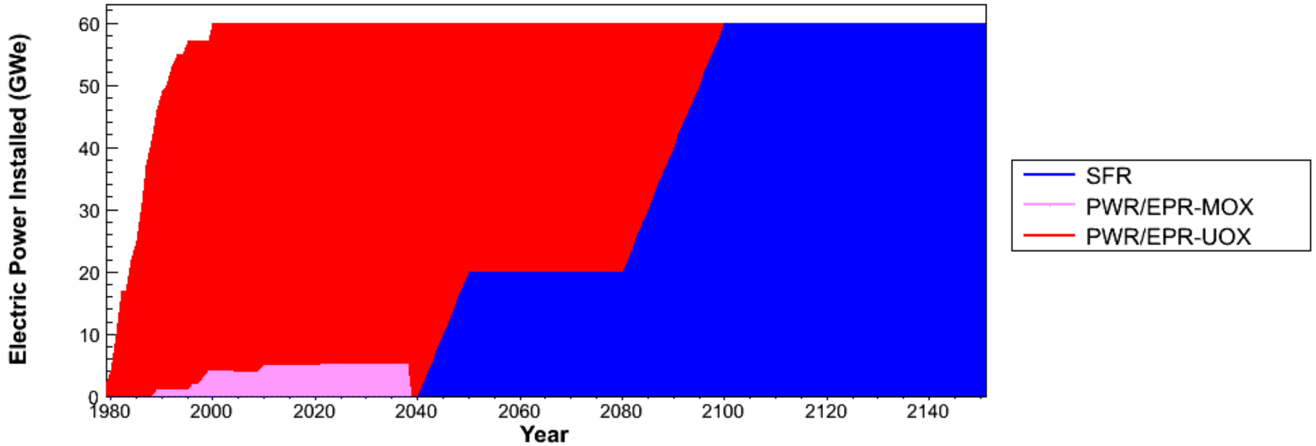
  - The reprocessing unit is an evolution of the current reprocessing plant of AREVA NC at La Hague:
    - Hydro-chemical reactions
    - Assemblies have to be cleaned and transported before reprocessing
    - 0.1 % loss of actinide during reprocessing
    - FP and MA not transmuted are gathered in glass canisters (CSD-V)
    - The rest of the assembly is compacted in other canisters (CSD-C)

2. Calculation tool : TIRELIRE-STRATEGIE



3. Plutonium fuel closure - scenario S_1

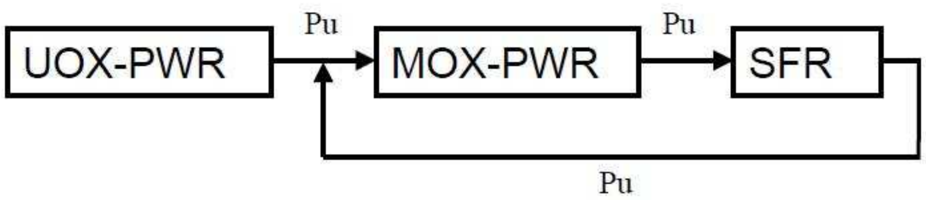
- Deployment of a full SFR-CFV fleet
  - From 2040, every PWR/EPR decommissioned is replaced by SFR-CFV
  - Requires the use of all fertile blankets during transition phase



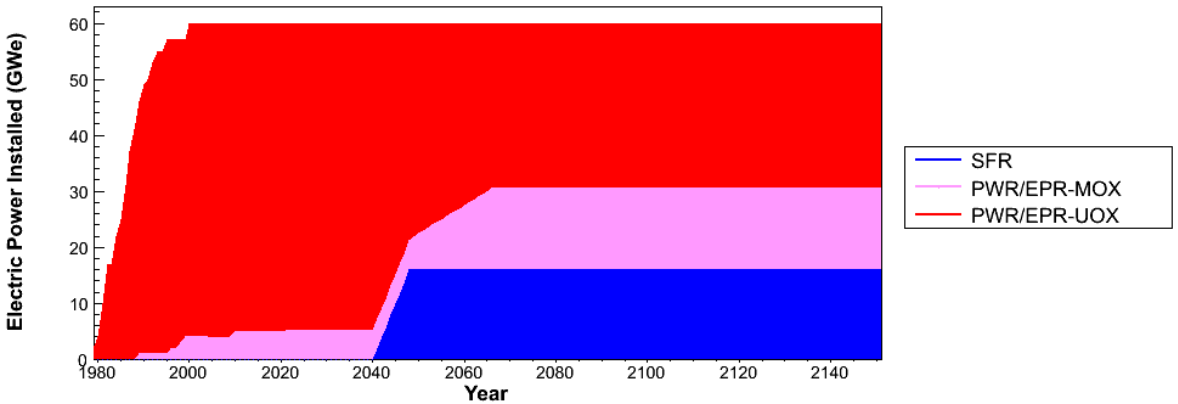
  - All objectives of generation IV deployment are met :
    - Plutonium can be multi-recycled
    - From 2100, no more natural uranium consumption
    - Americium transmutation is possible
  - Scenario extremely challenging

3. Plutonium fuel closure - scenario S_2

- Multi-recycling of plutonium with a partial SFR-CFV fleet
  - We use all fertile blankets of SFR-CFV in order to create more plutonium for EPR-MOX.
  - SFR improve plutonium quality
    ➔ SFR spent fuel is reprocessed and used in EPR-MOX



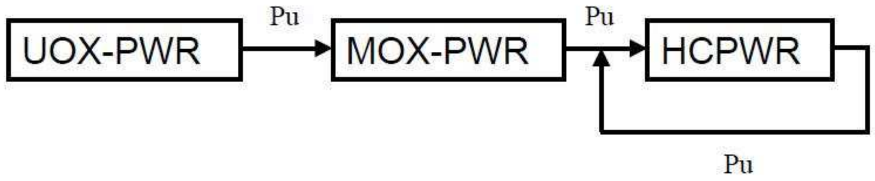
- Equilibrium state :
  - PWR-UOX 29.5 GWe
  - PWR-MOX 14.5 GWe
  - SFR-CFV 16 GWe



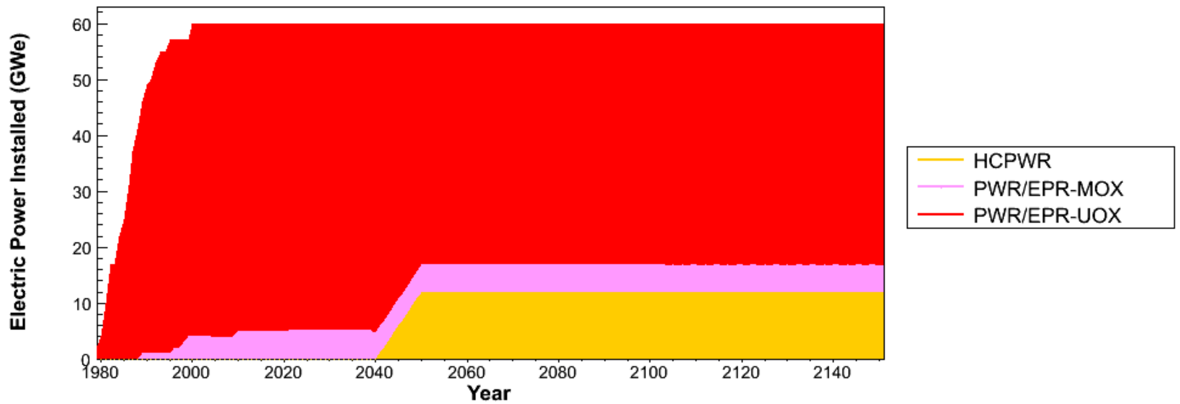
3. Plutonium fuel closure - scenario S_3

- Multi-recycling of plutonium with a partial HCPWR fleet
  - Technological or economical requirements for SFR-CFV industrial deployment are not met in 2040

    ➔ HCPWR is a roundabout solution to plutonium fuel closure
  - HCPWR does not improve plutonium quality



- Equilibrium state :
  - PWR-UOX 43.2 GWe
  - PWR-MOX 4.8 GWe
  - HCPWR 12 GWe



4. Results: Uranium consumption

Natural uranium consumption	Scenario S_1	Scenario S_2	Scenario S_3	Scenario S_BAU
2100 (10^3 tons)	741	731	822	915
2150 (10^3 tons)	741	927	1,109	1,209
Consumption at equilibrium (10^3 tons/year)	0	3.91	5.74	7.26

- Full generation IV fleet is the most efficient in term of natural uranium consumption

- If we consider the mass of uranium preserved per GWe of advanced reactor :
  - S_1 : 120 tons/year/GWe of SFR
  - S_2 : 210 tons/year/GWe of SFR
  - S_3 : 125 tons/year/GWe of HCPWR
- Symbiotic scenarios make better use of advanced reactors

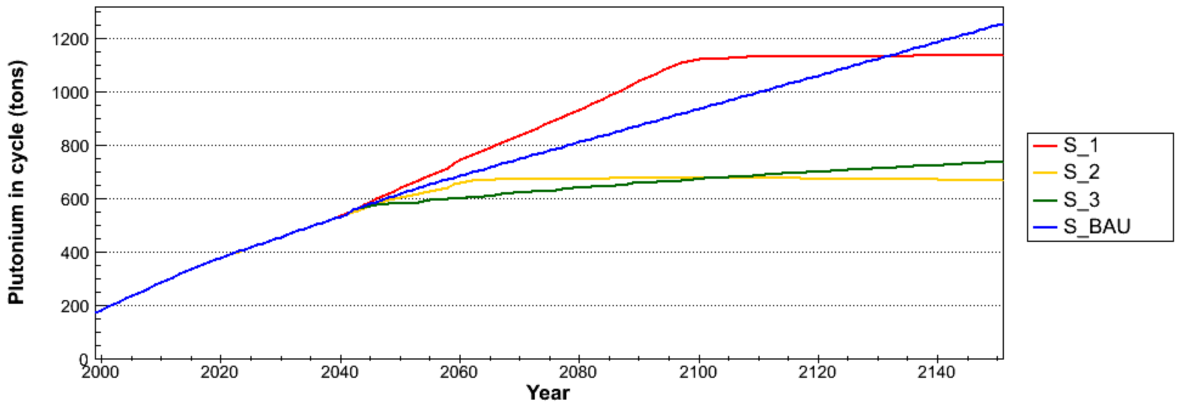
4. Results: Plutonium inventory

- Scenarios S_1 and S_2 are at equilibrium soon after deployment
- Scenario S_3 fleet does not evolve after 2065 but the plutonium inventory continues to grow (equilibrium is 800 tons)

  ➔ plutonium quality is decreasing

- Scenario S_1 inventory is of the same magnitude as S_BAU one century after deployment

  ➔ The benefits on plutonium inventory are significant only after a long period



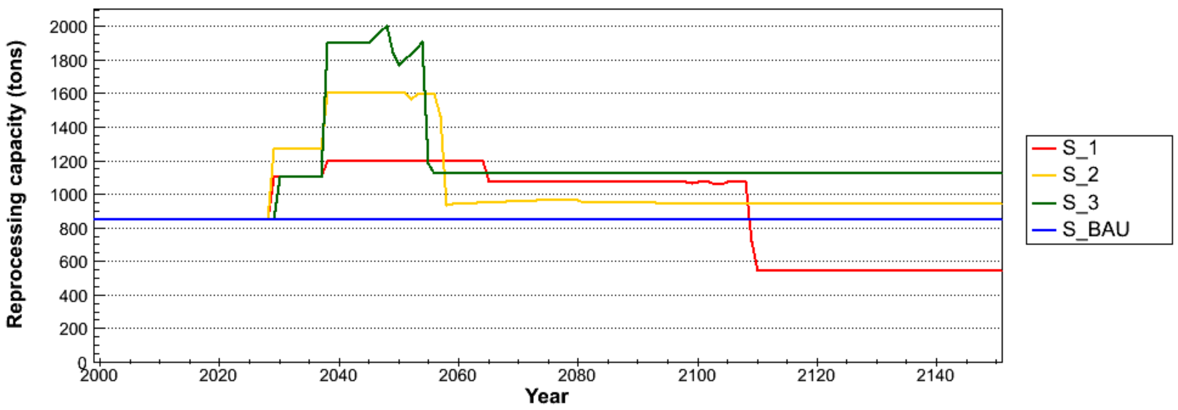
4. Results: Spent Fuel processing

- Spent fuel processing is driven by the need of Pu for assembly fabrication
  - Deployment of advanced reactors requires a lot of plutonium
  - Scenario S_3 and S_2 need a high reprocessing capacity during a short period

    ➔ not industrially realistic

- Plutonium content of scenario S_1 spent fuel is higher at equilibrium

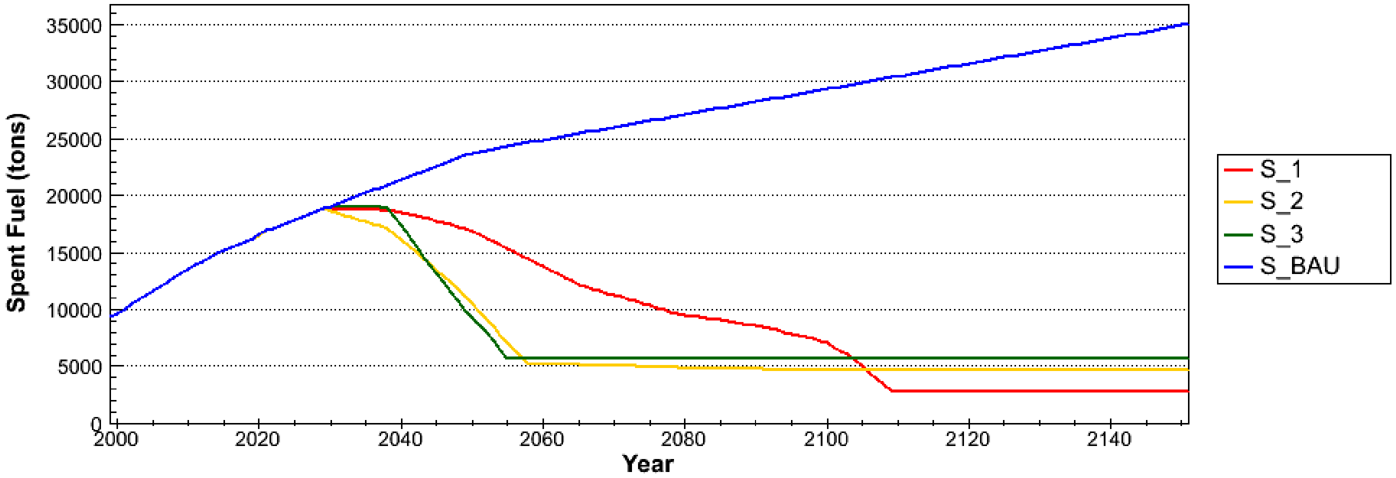
  ➔ the capacity of the plant is lower but it can be more challenging



4. Results: Spent Fuel storage

- Current limit in France: 19 000 tons
  - All scenarios that reprocessed MOX spent fuel permit to limit the spent fuel storage
  - At equilibrium, the storage needed is really low compared to the current state

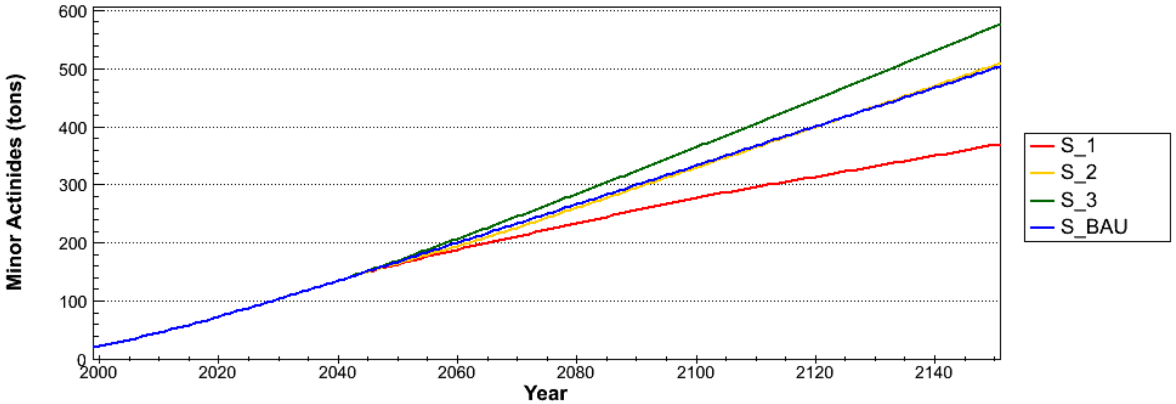
- Scenarios S_1 and S_2 have to use sodium cooling pools before spent fuel washing which is technologically more advanced than current water pools.



4. Results: Waste fluxes and minor actinides inventories

- HCPWRs create more HLW than SFRs
  - PWRs net yield is below SFRs one ➔ more fission products
  - Epi-thermal spectrum favors capture over fission compared to fast spectrum ➔ more minor actinides production in HCPWR

	PWR-UOX	PWR-MOX	HCPWR	SFR-CFV	S_1	S_2	S_3
Neptunium	1.70	0.39	0.45	0.38	0.38	1.05	1.35
Americium	1.54	14.83	26.40	3.90	3.90	6.95	7.58
Curium	0.22	2.81	2.05	0.20	0.20	0.98	0.79
MA	3.46	18.04	28.90	4.48	4.48	8.99	9.71



Conclusion

- There are various solutions to plutonium fuel closure

- Natural uranium consumption is reduced
  - Full generation IV fleet is obviously the most efficient
  - Symbiotic fleet makes a better use of its advanced reactors

- Plutonium inventory reaches an equilibrium between 700 tons and 1150 tons.
  - The multi-recycling of spent MOX fuel must be a long term solution in order to reduce significantly the plutonium inventory

- Spent fuel storage is reduced when MOX spent fuel are reprocessed but sodium pools are challenging

- Fast reactors are not the only solution to use MOX spent fuel
  - HCPWR is a roundabout solution
    - the reduction of natural uranium is limited
    - the high level waste production is high
    - The reprocessing plant capacity must be increased during deployment phase

    ➔ R&D must be continued to improve HCPWR design

More about generation IV transition scenario by EDF R&D:

- Industrial research for transmutation scenarios
  - CAMARCAT et al, Comptes Rendus Mécanique, Volume 339, Issue 4, pages 209-218, April 2011.
- A prospective scenario of the French Nuclear fleet growth based on sodium cooled fast reactor technology
  - GARZENNE et al, GLOBAL 2011, Japan.
- A calculation scheme to optimize the high-level waste geological disposal: an application to a transition scenario from PWR to FR
  - LEROYER et al, GLOBAL 2011, Japan.
- Impact of the Deployment of Fast Breeding Reactors in the Frame of the French Act for Nuclear Materials and Radiactive Waste Management
  - LE MER et al, ICAPP 2012, Chicago, Illinois, USA.
- Scenario of a symbiotic nuclear fleet composed of PWRs and SFRs
  - LEMASSON et al, ICONE 2012, Anaheim, California, USA.

Thank you for your attention.

Any question ?

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