DE LA RECHERCHE À L'INDUSTRIE

Why recycling the actinides is a key step towards sustainability ?

… *A French perspective*

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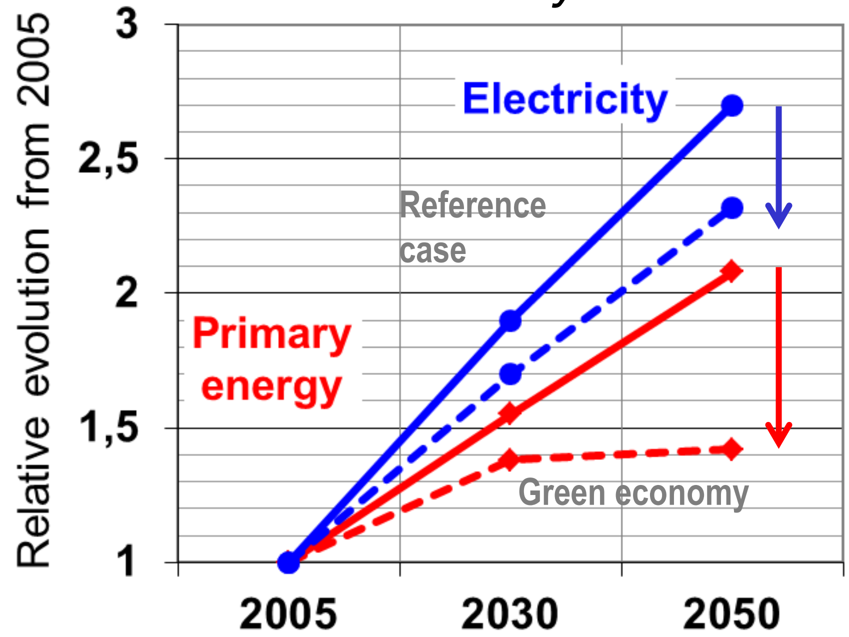
The energetic challenge of the XXIth century

❶ Energetic needs will at least double

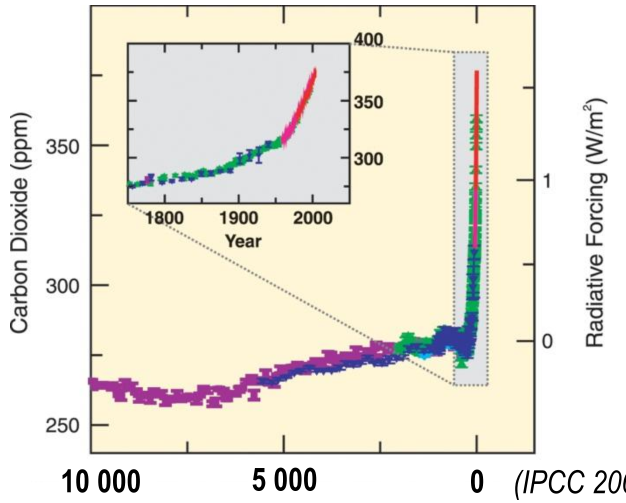
↗ *Population*

↗ *economy*

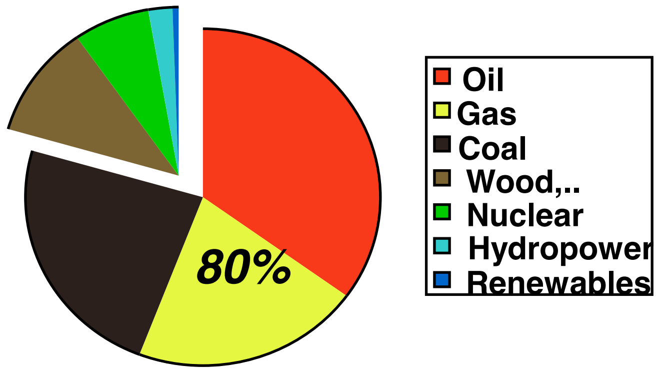


World Energy Outlook, AIE 2008

❷ Mitigating the Global Climate Change ➔ Low-carbon energy



(IPCC 2007)

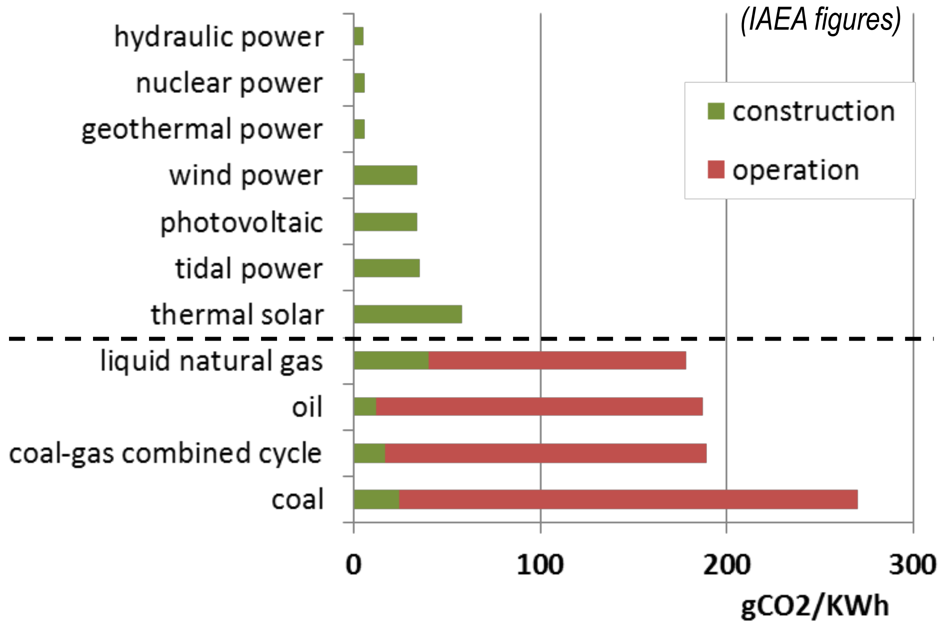


80% of the current primary energy = fossile

Limit the temperatures increase ~ 2°C ⇔ decrease GHG emissions by a factor of 2 ⇔ ↗GHG-free energies

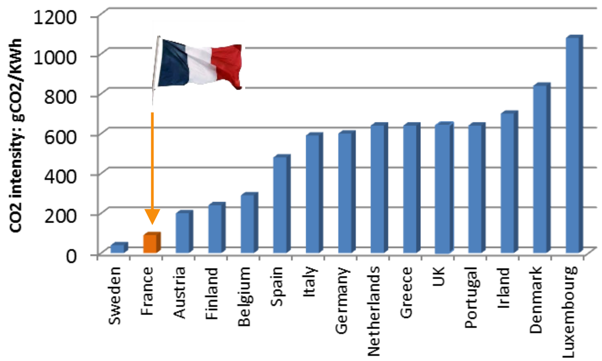
Promoting the low-carbon energies

GHG emissions in Eq.CO_2 for the whole lifetime of the plant



Comparison of CO_2 intensity in Europe

(EUROSTAT, 2009)



- low-GHG energies to be developed
- Nuclear energy can help to meet the future energy challenge
  - Low-carbon energy
  - Efficient for electricity base-load production
  - Available and world-around dispersed resource
- Societal debate following the Fukushima crisis reminded the need for a global assessment and decision-making process for any energy sources:
  - Future energy systems will only develop if they meet the sustainability criteria

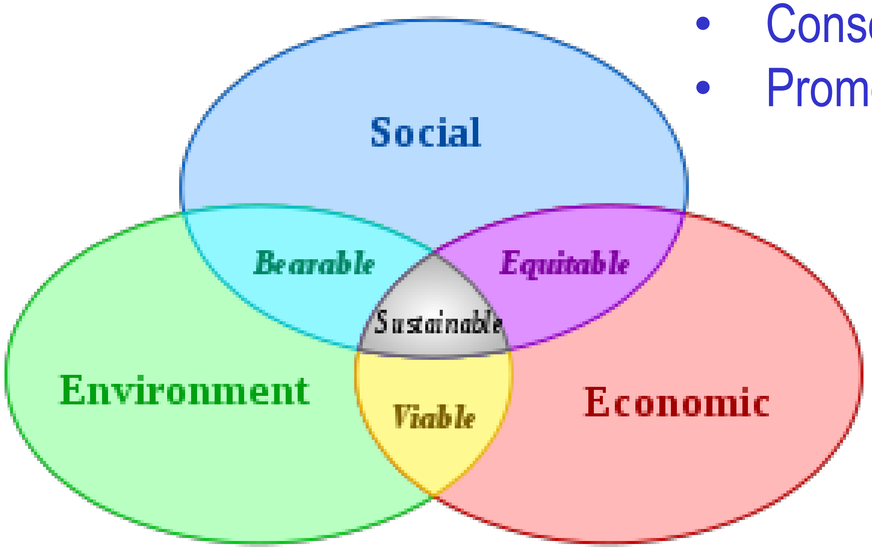
Towards sustainable future energy systems

« Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (…) »

(Bruntland's commission, 1987)

3 main drivers to consider

- Highest level of safety and reliability
- Consensual choice of the society
- Promote the international stability



- GHG-free energy
- Preservation of natural resource
- Low environmental footprint

- Predictable, stable and limited energy cost
- Economic stability through energetic independence

Outlook of the presentation

1. What are the respective relative benefits of the current fuel cycles?
   1. The relative waste burden in the current fuel cycles
   2. What about the different cycles relative environmental footprint?

2. The environmental drivers:
   1. How to efficiently preserve the natural resource for future generations?

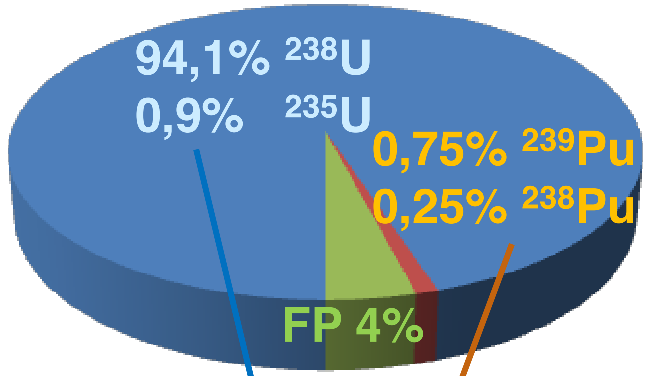
3. The societal drivers
   1. How to increase the societal acceptance?

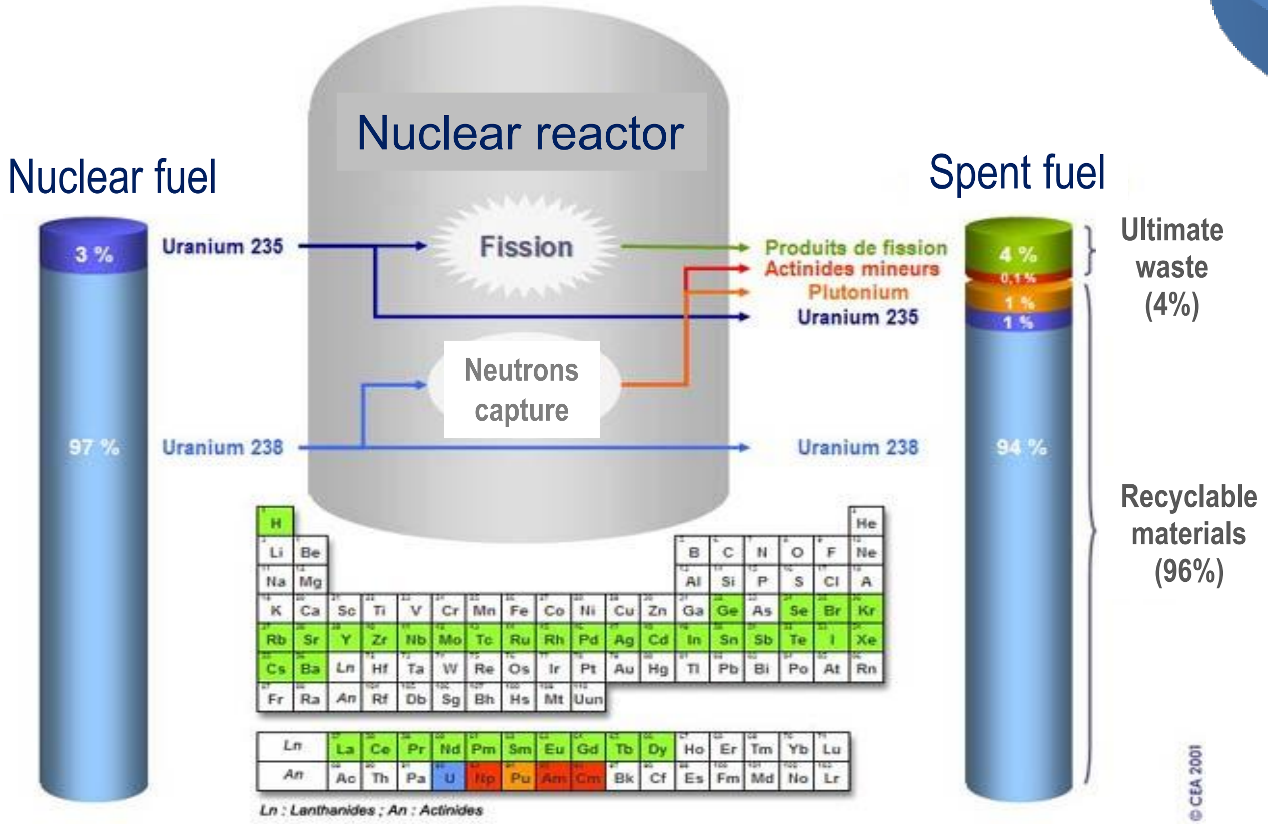
4. A few words about economic drivers

5. Conclusions: towards sustainable fuel cycles

1. Current fuel cycles: Fuel transformation in reactors

Evolution of the composition during the ~4y. irradiation

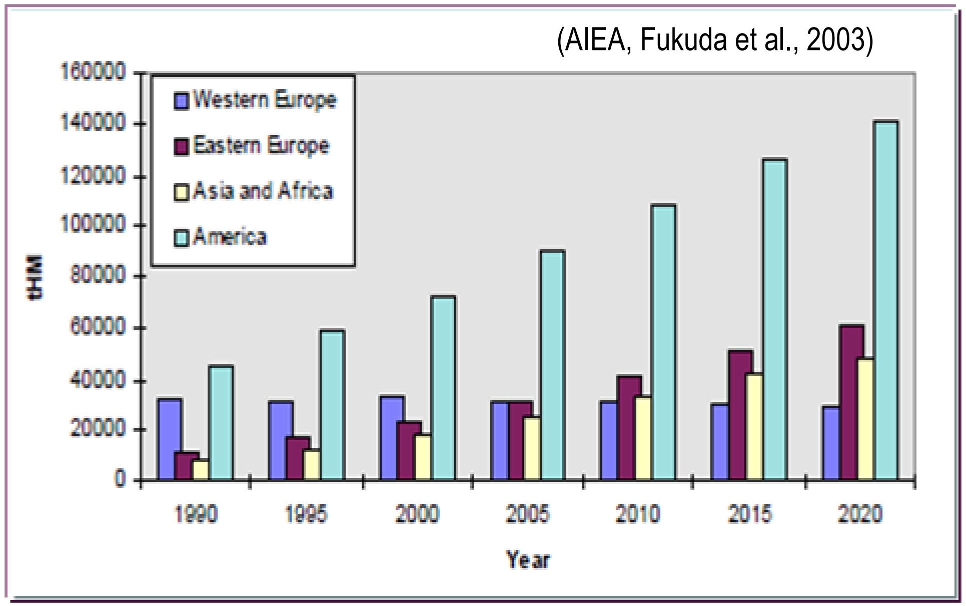


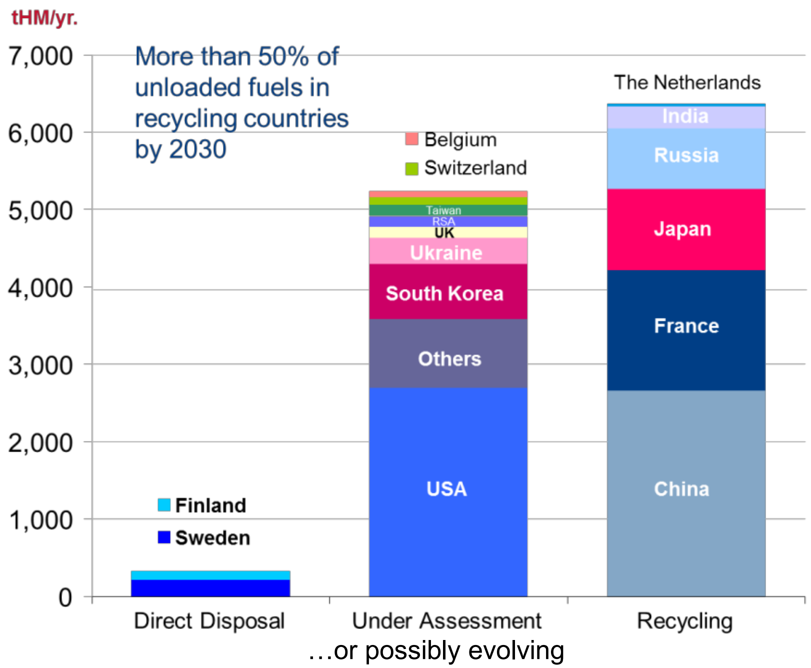


Key issue: Should SNF be recycled or considered as a waste?

What is the current fate of SNF worldwide?

- Most of the discharged SNF are temporarily stored
  - Significant burden towards future generations, residual risk
- Very few countries definitively chose SNF direct disposal
  - Still an open issues for many countries
  - Strongly linked to the far-future – see later

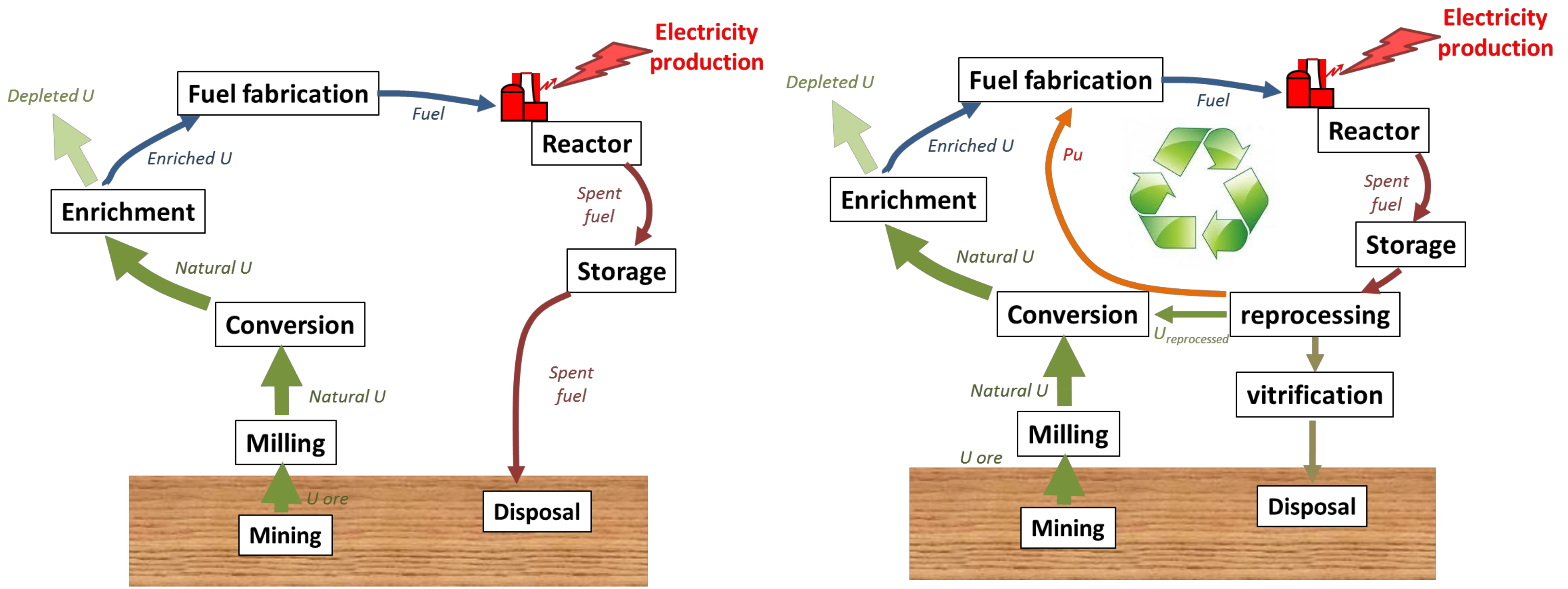




Current nuclear fuel cycles are of two types

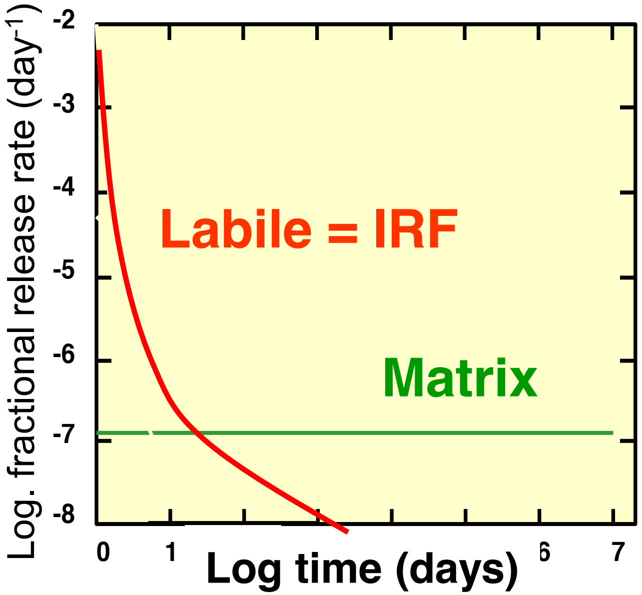
Once-through cycle
SNF= waste

Twice-through cycle
SNF = valuable material to recycle



➢ How do they meet the sustainability criteria and to improve their respective values?

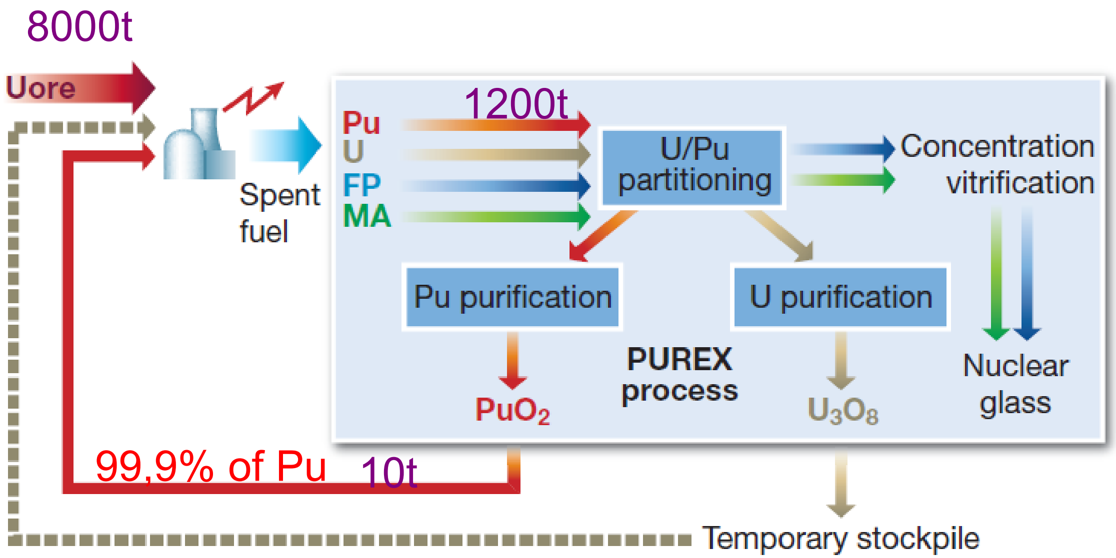
(1.2) Waste burden: the direct disposal of hte once-through back-end

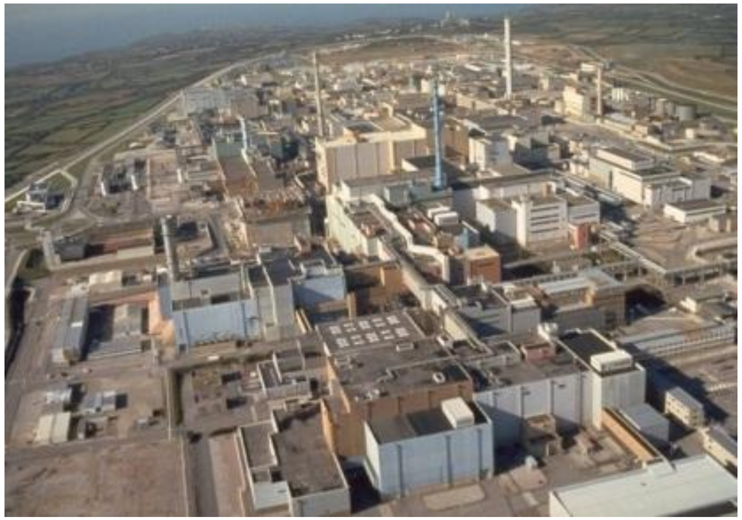


Adapted from Johnson et al., 1988

- Chosen by countries
  - Having low number of reactors
  - That do not want to handle Pu-material
  - Which anticipate to phase out nuclear energy
- Require to extend storage as long as repository is not available
- RN release from SNF in repository governed by
  - Rapid release of unbonded and mobile RN: IRF
    - Thick container to avoid any early release (e.g. Cu-container in Sweden)
  - Potentially slow release of RN trapped in the U oxides,
    - Necessity to ensure reducing conditions

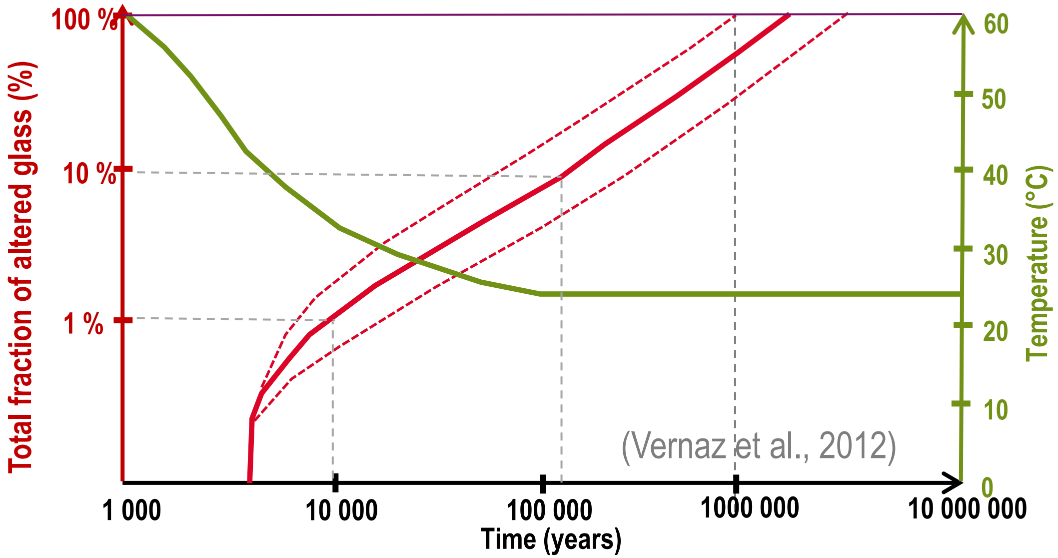
Twice-through back-end: the recycling in MOX

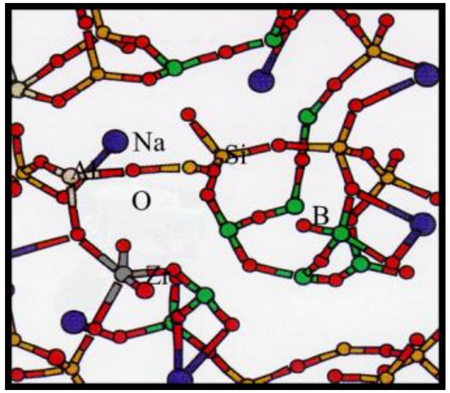


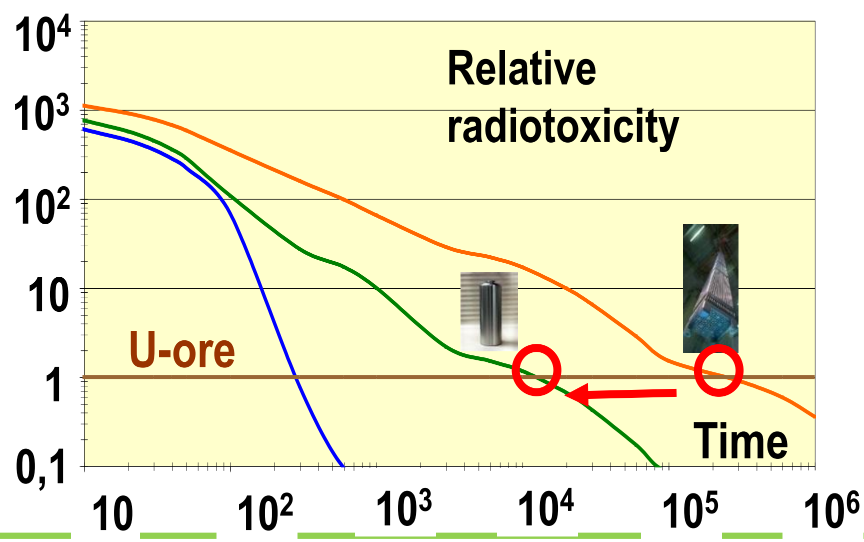


- Liquid/Liquid extraction process
  - Continuous process with a very positive industrial feedback
    - La Hague plants, >27 kt reprocessed
  - Very large efficiency through the repetition of several steps
    - > 99.9 % Pu recovered
- Pu recycled in MOX fuels
  - Powder blending technology
  - Pu content ~8-10%,
  - 22 PWR in France
- U recycled in URE fuels
  - 4 PWR in France

Recycling (U,Pu) from SNF improve the waste issue

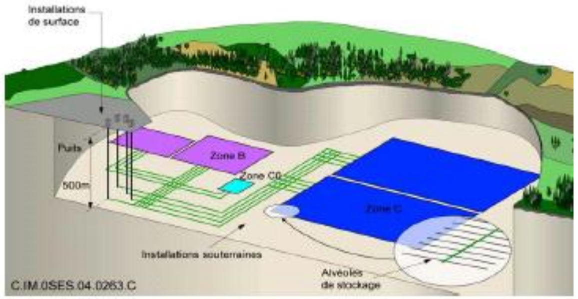




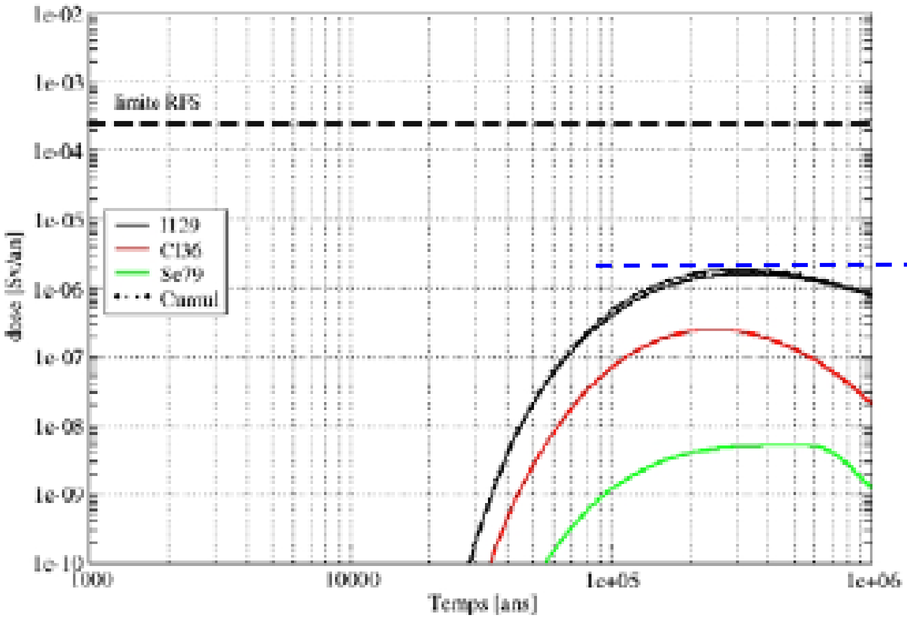


- Allows efficient conditioning of High Level Waste
  - No IRF anymore ➔ significant gain for the repository
  - Lifetime demonstrated to be > 500ky in clay-type repository
- Allow a significant decrease of waste burden:
  - No Pu in waste anymore
  - Lifetime / radiotoxicity / volume decreased by one order of magnitude

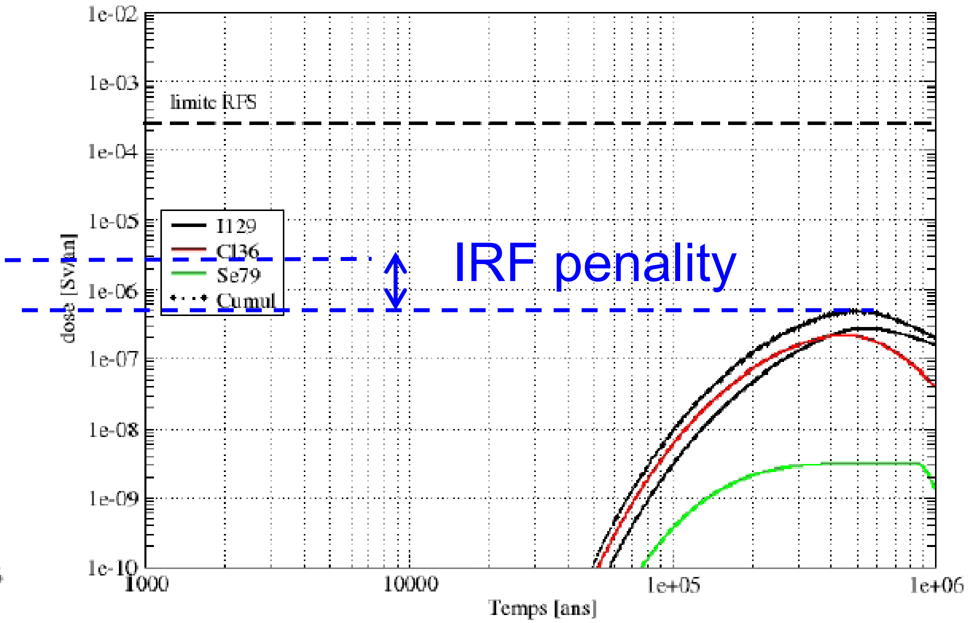
Respective performances of SNF and glass



- Still a controversial issue
  - IRF is a significant penality for SNF
    - In particular for any incidental scenario where wasteform is of great significance
  - Performance of the SNF matrix is good as long as the environmental remains reducing



Spent nuclear fuel
(considering solubility-controlled dissolution)



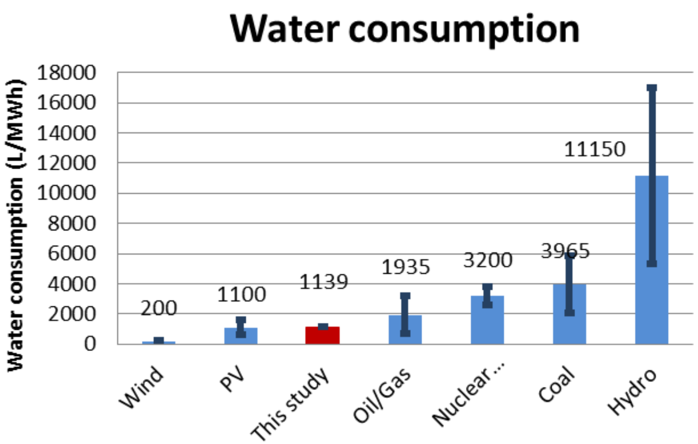
Nuclear glass

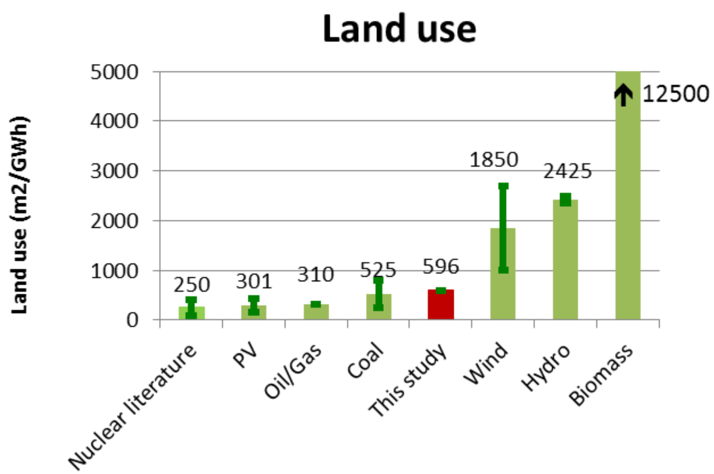
(1.2) What about the environmental footprint of the current fuel cycles?

- Based on the current French fuel cycle by PCA method: Once-through cycle derived from French current fuel cycle *(Poinssot et al., in prep.)*

	Once-through	Twice-through	Difference
Land-use (m²/KWh)	596	542	-9%
Water consumption (L/MWh)	1139	1132	-1%
Repository surface (m²/TWh)	471	163	-65%

	Once-through	Twice-through
GHG (gCO_{2eq}/KWh)	1.7	1.86
NOx (g/MWh)	0.47	0.47
SOx (g/MWh)	<	<
Particles (g/MWh)	0.06	0.06





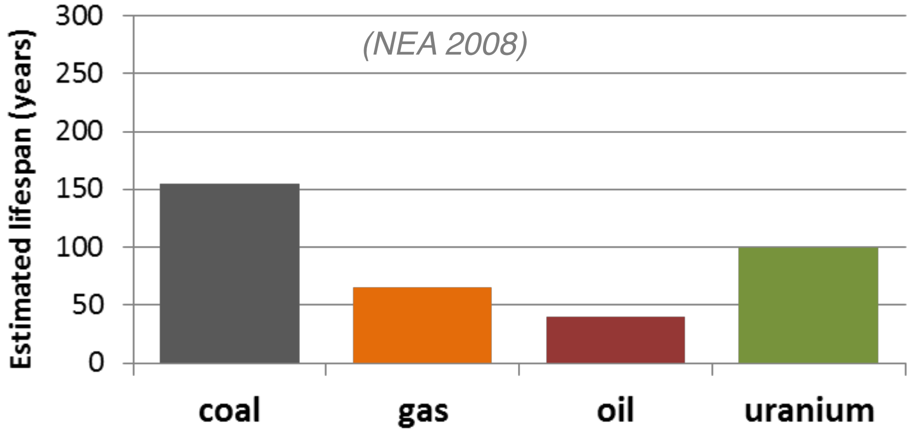
Main results on environmental specific release

- **Significant evolution of the type of release:**
  - Diminution of the nuclear waste inventory.
    - Diminution of the HLW inventory ⇔ 96% total waste radioactivity
    - Increase of ILW / LLW inventory ⇔ low radioactivity inventory, negligible impact
  - Correlated to an increase of the off-gas release at the processing plant which does not yield to any significant impact :
    - 93% is due to rare gases which are not incorporated.
    - The overall radiological impact is negligible ~1% of natural radioactivity (~2.4 mSv/y)

Actual impact demonstrated to be in unsignificant ~17-25 µSv/y (refers to Rare gases / Tritium)

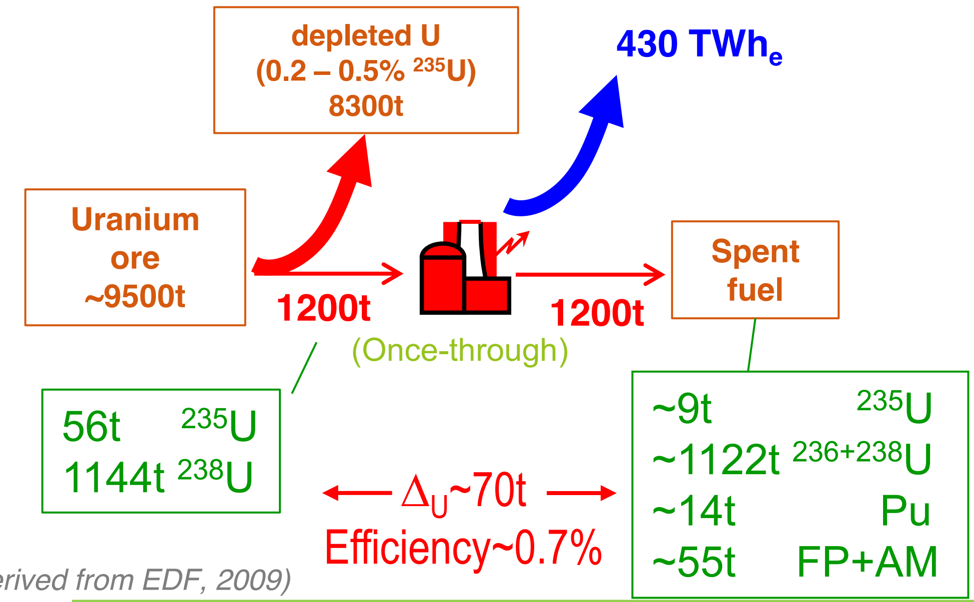
	Once-through	Twice-through	Difference
Gas release (µSv/KWh) [Overall inventory]			
- Rare gases	0.01	59	X 590
- Tritium	1.4	4	+ 186%
Liquid effluents (kg/GWh)	396	356	-10%
Nuclear waste (m^3/TWh)	69289	61133	-12%
- Very Low Level (VLL)	69270	61106	-12%
- Low-Level Waste (LLW) (0.1%Rad)	18	26	+44%
- Intermediate Level Waste (ILW) (3.6% Rad)	0.06	0.93	+1450%
- High-Level waste (HLW) (96%Rad)	1.17	0.3	-74%

(2) Environmental drivers: what about the preservation of natural resource?



- Uranium conventional resource
  - Limited for the far-future at a reasonable price (130$/kg U)
    - 5,5 Mt identified
    - 7,5 Mt estimated *(IAEA/NEA, 2010)*
  - Lifespan ~1-2 centuries *(current consumption 75kt/y)*

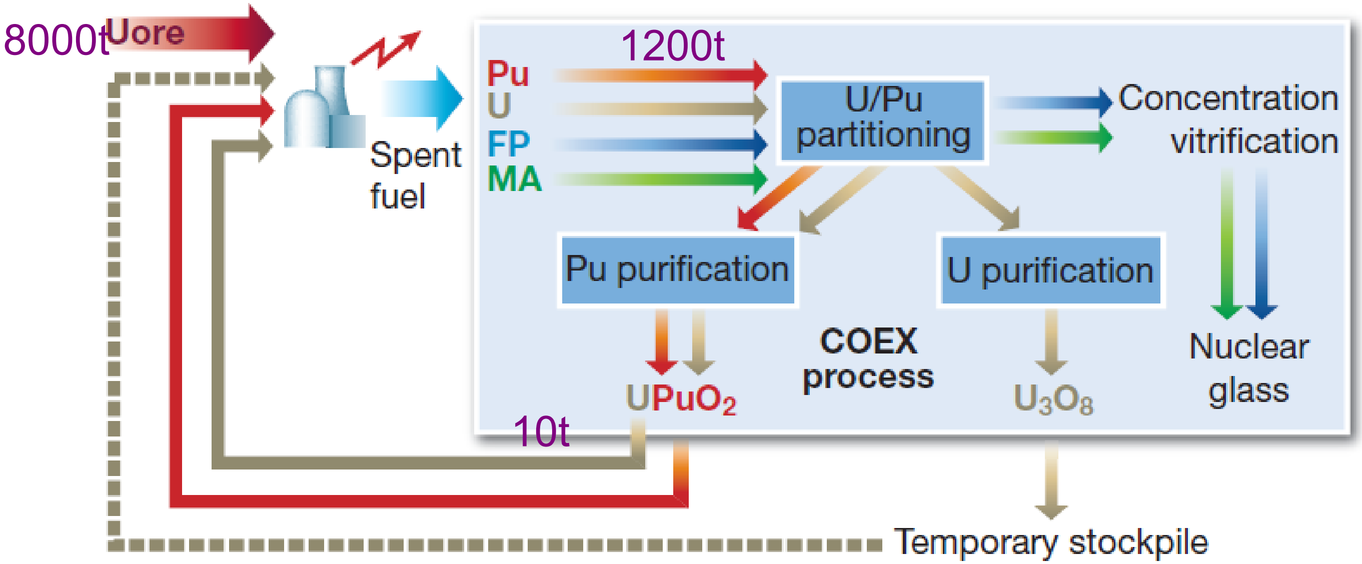
Rough estimates derived from French Fuel cycle assuming no recycling

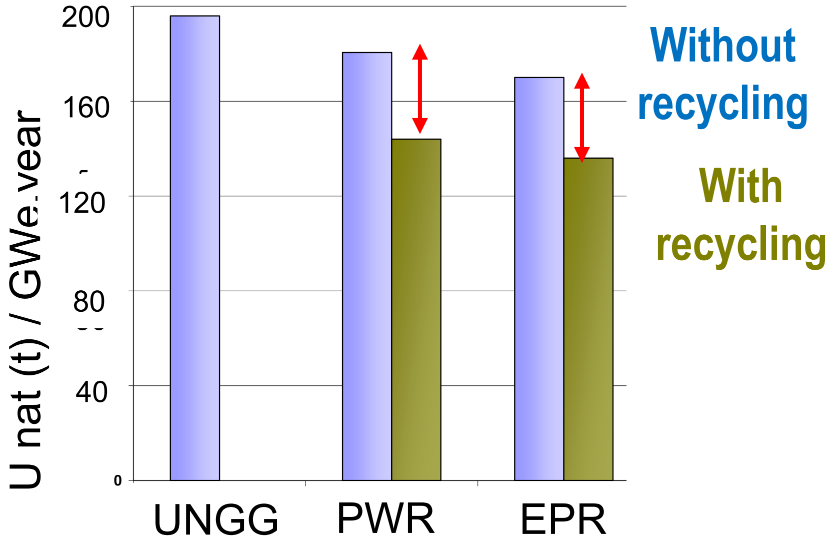


(derived from EDF, 2009)

- However, global efficiency is currently very low: ~0.7%
  - Only ~70t from the initial ~9500t of U is effectively used
- Sustainability requires
  - better consuming natural resource
  - preserving it for future generations

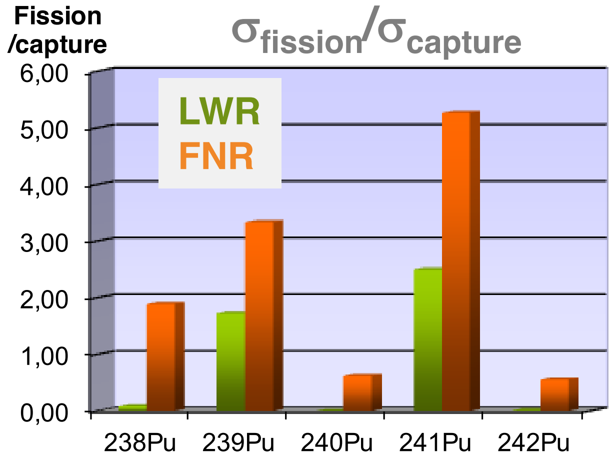
1st step towards sustainability: the Pu mono-recycling

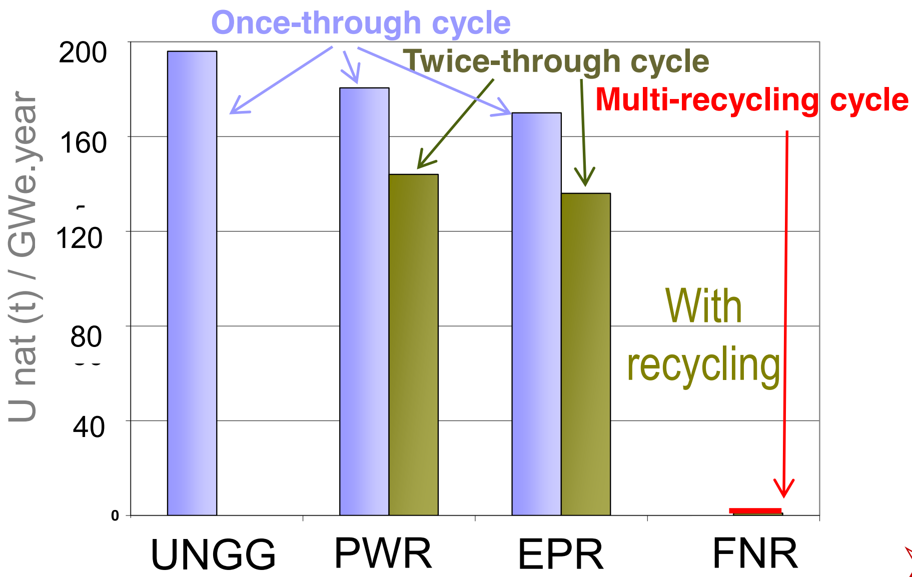




- Mono-recycling already allows saving 17% of U natural resource!
- However, MOX fuels can't be easily recycled
  - Increase of non-fissile even isotopes ➔ significant penality for the neutrons balance
  - Low consumption of U through captures
- Necessity to shift to higher neutrons energies

Increasing efficiency requires shifting towards fast neutrons





1t/yr of ^{238}U is sufficient to produce 1 GWe

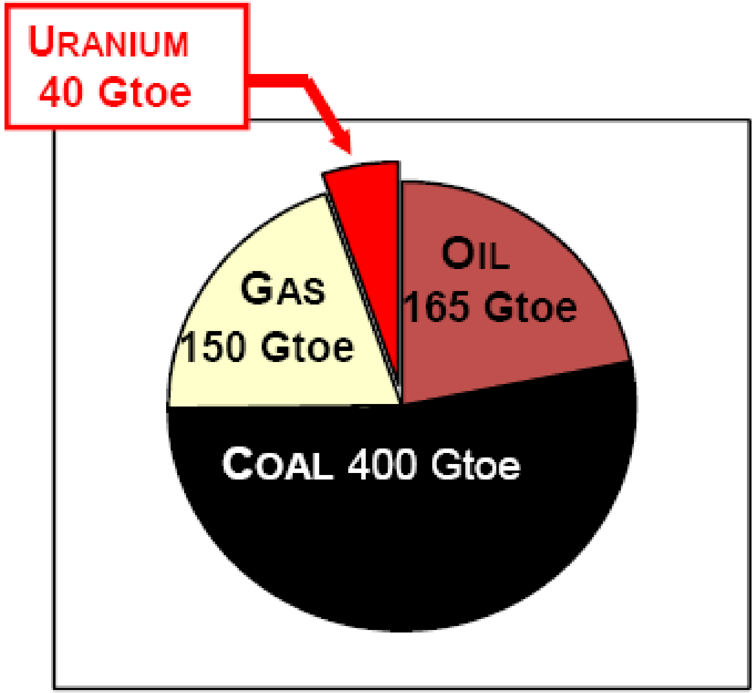
- Neutrons with higher energies allow a better use of U and Pu
  - Promote the fission of every Pu isotopes limiting the formation of MA (=waste)
  - Promote the neutron capture of ^{238}U to produce fissile Pu isotopes (^{239}Pu)
- Fast neutron spectrum reactors
  - Pu can be indefinitely recycled
  - Could be operated with the Pu stockpile from PWR and
    - Stockpile of $U_{depleted}$, $U_{reprocessed}$ (250 000t in France)
    - No need for additional natural U resource

➔ Significant improvement for environmental footprint (no mines) and for proliferation-resistance (no enrichm.)

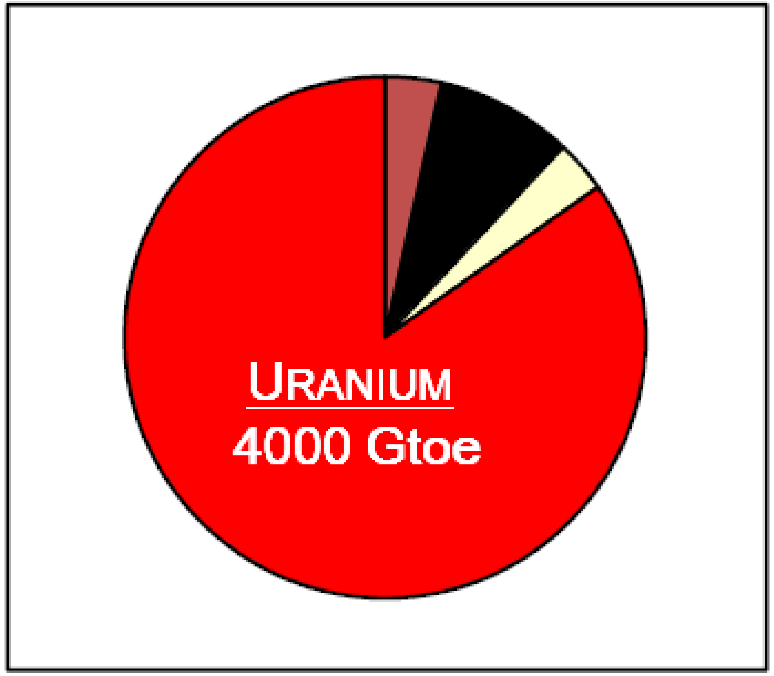
- Very significant efficiency increase: from 0.7 to > 80%

A very significant improvement with respect to natural resource

Comparison of the lifespan of natural resource as a function of reactor types

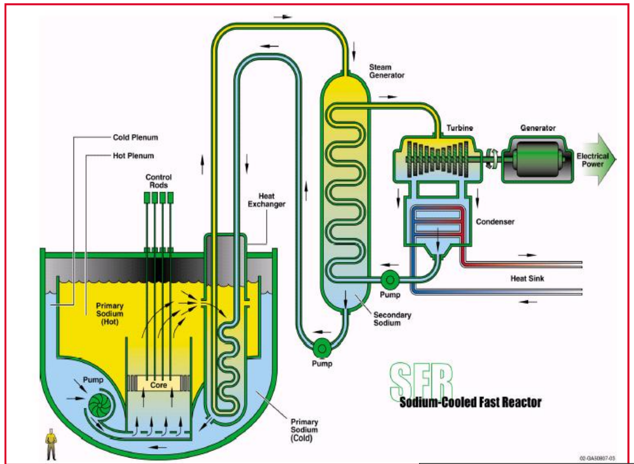


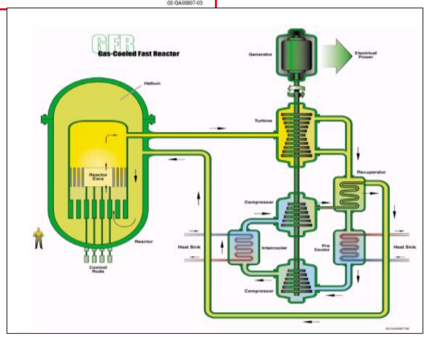
Uranium use in current reactors



Uranium use in 4th generation reactors

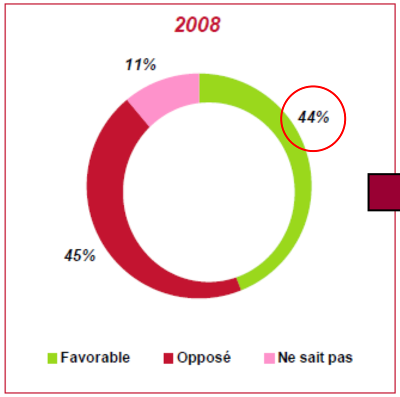
Gen.IV systems

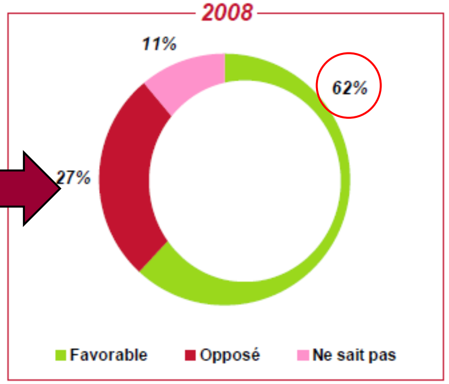




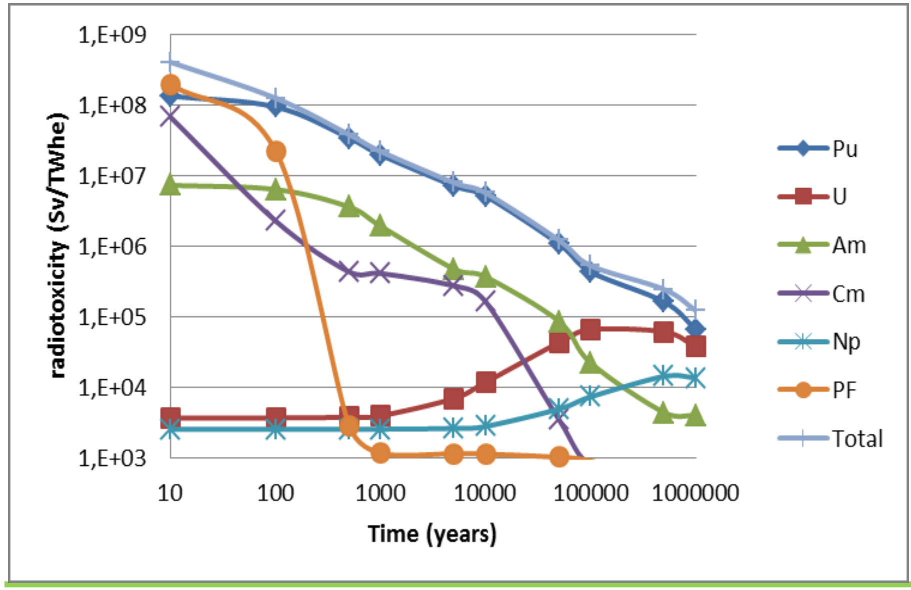
- GEN4 reactors developed in the framework of the Generation IV International Forum (GIF)
- France focused on 2 fast-reactor types
  - Sodium-cooled fast reactors (SFR):
    - Large experience (Phenix, SuperPhenix …) ➔ mid-term perspective
    - Significant improvement under study towards safety and inspections
    - Prototype ASTRID planned to be in operation by 2023 (French WM Act of 2006)
  - Gas-cooled Fast Reactors (GFR):
    - Key issues regarding materials behaviour in such high-T°C conditions ➔ long-term perspective
- No major breakthrough regarding the fuel cycle: (U,Pu) COEX process to be implemented ➔ MOX. R&D required to optimise the whole process

3. The societal drivers: Improving the social acceptance



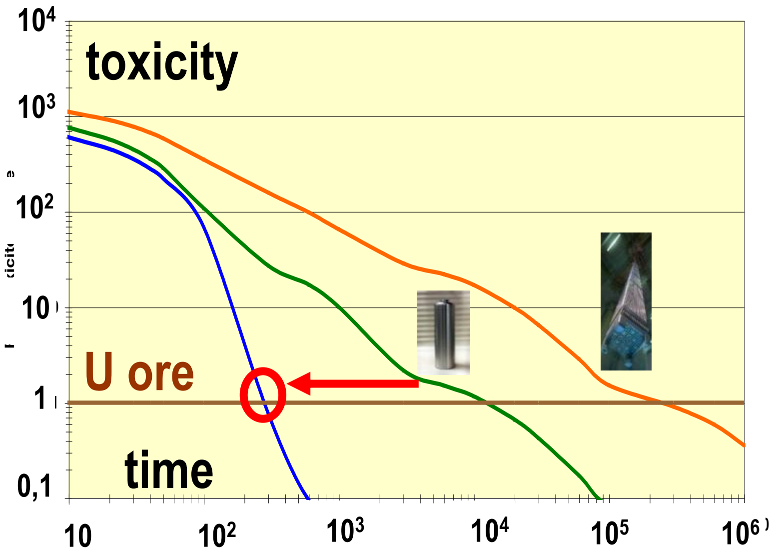


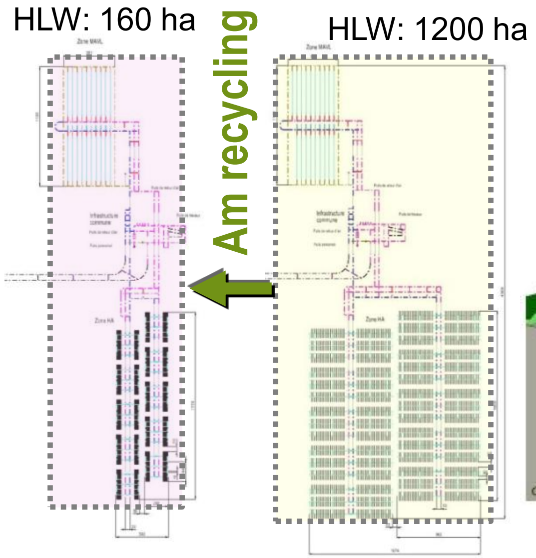
Eurobarometer 2008: % of EU citizens supporting nuclear energy with/without a permanent and safe solution for the HLW

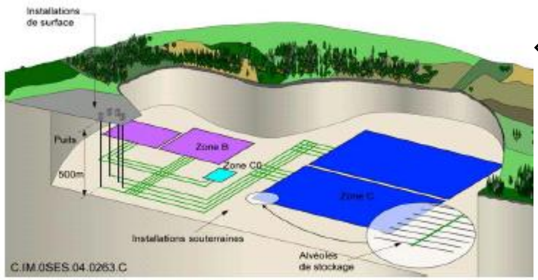


- Safety is to be kept at the highest level: continuous upgrading
- Waste management is perceived as the key issue to be solved for the acceptance of nuclear energy
  - Nuclear waste is considered as the Achille's heel of nuclear energy, mainly because of the long lifetime
  - Decreasing the waste lifetime may improve the social acceptance
- Recycling Pu already yields a very significant benefit
- MAs are the main contributor after Pu to long-term toxicity:
  - recycling them will allow to reduce the waste burden towards the future generations

Recycling the minor actinides, a key contribution for decreasing the waste burden

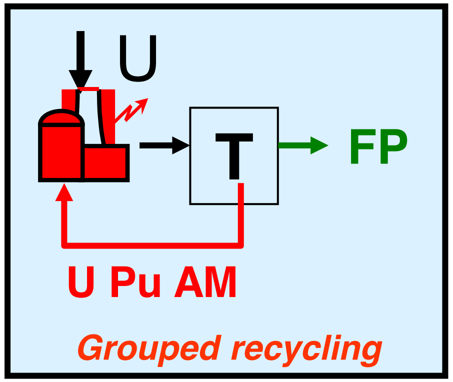


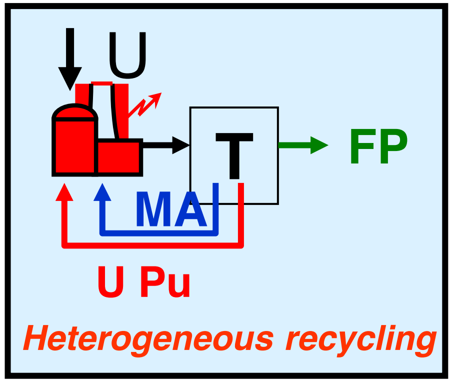




- Allows decreasing the waste lifetime and toxicity
- Stabilization of MA inventory in the whole fuel cycle
- Allows decreasing the waste heat power ➔ save repository resource
  - With Am recycling, reduction of the repository volume by roughly order of magnitude
  - ⇔ very significant increase of the repository "lifespan"
  - ⇔ repository = resource to preserve for future

Two main Minor Actinides multi-recycling options

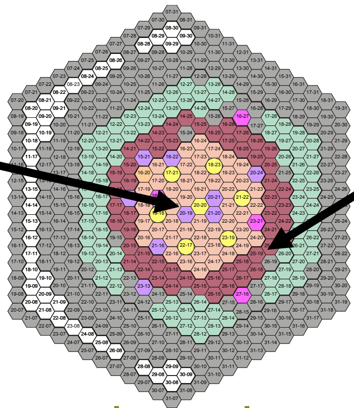




Homogeneous recycling ➔ grouped recycling ➔ GANEX processes

Heterogeneous recycling ➔ enhanced partitioning ➔ DIAMEX/SANEX processes

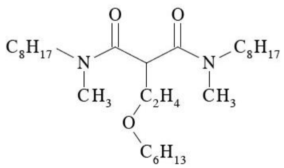
MA concentration ~1%, diluted in standard fuel in the whole core

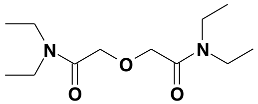


Moderated core target or blanket in periphery of the core with MA content ~10-20%

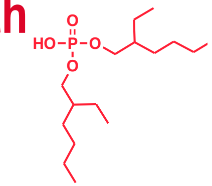
Specific extraction processes have been developed and qualified

Example: recycling the sole Am through the EXAm process



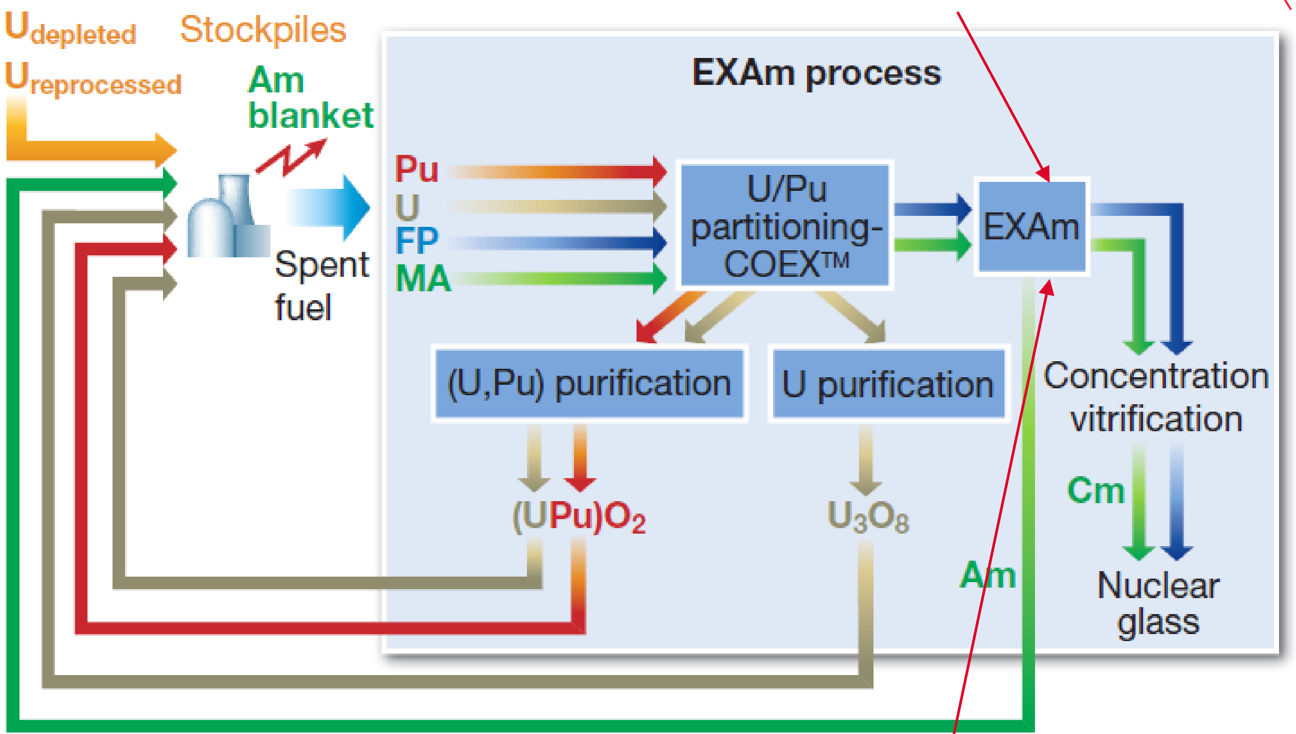


1- Co-extraction Am and light Ln (III) with DMDOHEMA + HDEHP + TEDGA in aqueous phase



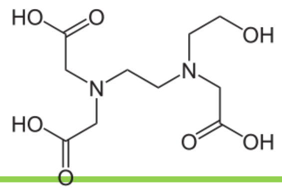
Efficiency demonstrated with hot test performed in Atalante

in 2010 on ~5kg spent fuel



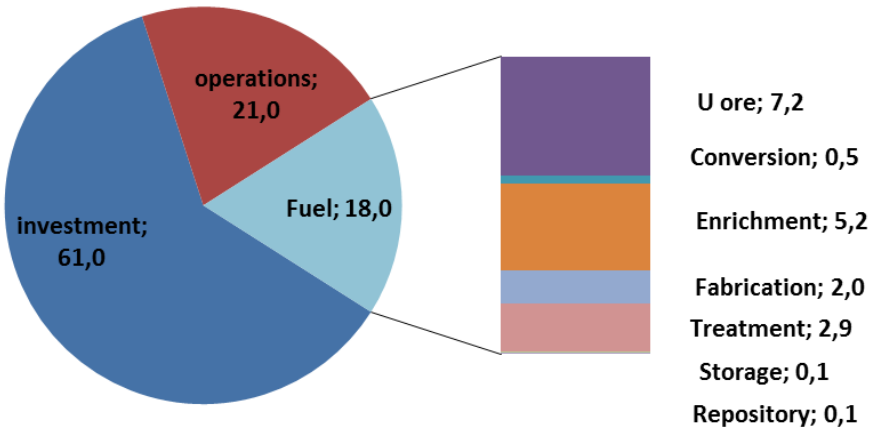
> 98.5% Am

FD(Cm) = 500



2- Stripping of Am with HEDTA + Citric acid (pH=3-4)

4. Economic drivers: What about the economic cost of both current fuel cycles?



	Once-through	Twice-through
Specific costs	• Mining/milling capacities increased by ~17% • Interim storage capacity X 6 • Cost of repository X 4	• Treatment and recycling plants to fund

- Economy is not a systematic driver
- Recent exhaustive assessment of the current and future costs of the nuclear energy in France by the French General Accounting Office
  - Most of the costs are due to the initial investment, fuel cycle has a limited influence
- Compare investment costs
- ➔Although controversial, costs are in the same order of magnitude
- However, indirect positive economic effects of the recycling
  - ↘ used U resource ⇔ ↗ economic independence and cost stability
  - Recycling activities : 16% of the nuclear direct employment (~20'000) in France (PWH, 2011), 0.1% of French GDP.
- For GEN4, costs ∈ R&D targets

Outlook: the rationale of the future nuclear fuel cycles

1980 | 2000 | 2200 | 2040 | 2060 | 2080 | 2100

Dates are purely indicative

TOWARDS INCREASING SUSTAINABILITY

Gen. II & III ***Pu-monorecycling***

Gen. IV ***Pu-multi-recycling***

Gen. IV ***…+ MA recycling***

Pu-mono-recycling
- LWR reactors
- Pu-recycling in MOX fuel
- from PUREX to COEX™

Breakthrough=reactors

Pu multi-recycling
- Fast-Reactors (FR)
- Pu multi-recycling
- COEX™ process

Breakthrough=cycle

Pu+MA multi-recycling
- Fast Reactors (FR)
- Pu multi-recycling
- MA burning
- MA specific separation processes

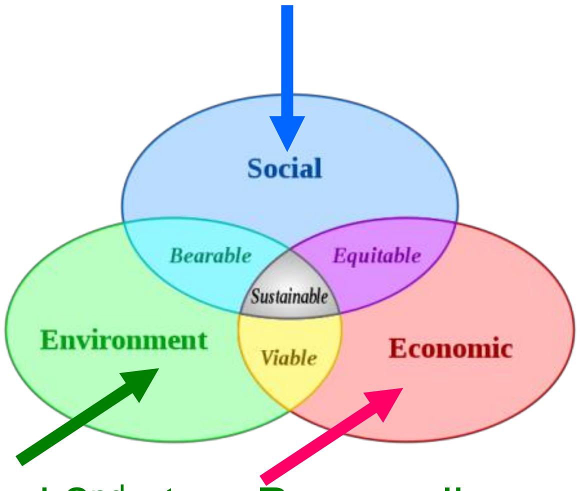
Main incentives
- 1st step towards U resource saving
- Efficient waste conditioning

Main incentives
- Major resource saving
- Energetic independence
- Economic stability

Main incentives
- Decrease of waste burden,
- Optimisation of the disposal
- Public acceptance

Conclusion: on the sustainability of fuel cycles …

3rd step: MA recycling to decrease burden to future generations and increase acceptance



1st and 2nd step: Pu recycling to increase natural resource saving and promote stable and predictable energy costs

- None of the current fuel cycle is fully sustainable regarding the saving of the uranium resource for future generations
  - However, twice-through cycle already allows saving 17% natural uranium
    - For a similar economic cost
    - With a quite limited radiologic impact
    - With a positive impact in terms of waste volume, lifetime and long-term performances
- Improving sustainability would require
  - Improving uranium resource preservation
    - ^{238}U consumption with Pu-multi-recycling through fast reactors,
    - reduced need for any U-mining activities
  - Decreasing waste burden towards future generations
    - Minor actinides transmutation
- Recycling the actinides is the cornerstone of any sustainable fuel cycle