Advanced Fuel Cycles and Fast Reactor Flexibility

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Introduction

Fast neutron reactors can meet a wide range of needs → **breeding** fissile material (basic mission of FRs), **burning** TRUs and/or MAs for any Pu vector, MA content or MA/Pu ratio

Breeders → Sustainable development of nuclear energy and waste minimization by means of the introduction of FRs with appropriate breeding performance to replace LWRs

Burners with low conversion ratio → Drastic reduction of spent fuel TRU inventories

Fast reactor flexibility can also be exploited to revert a burner FR into a breeder FR, and vice-versa

A lesson drawn from the CAPRA international Program (90's) → a fast reactor core can be reverted from 'burner' (CR<1), to 'breeder' (CR>1) → burning dedicated machines should not be necessarily new

Aim of the study

The FR flexibility has been underlined in two very different scenarios:

- **'Global' transition scenario** (OECD-NEA Expert Group) → the increasing worldwide energy demand is met with the deployment of LWRs at first, and successively of FRs.
  The FR optimum breeding capabilities have been investigated, in order to meet the energy demand without reducing the U resources down to a critical limit

- **'Regional' European scenario** (EU project and OECD-NEA Expert Group) → a so-called "double strata" fuel cycle strategy is examined: **low conversion ratio (CR) critical fast reactors** are deployed to eliminate the TRU inventories in countries with stagnating or phasing-out nuclear energy, while stabilizing the MA inventories in other countries further developing nuclear energy in the same "region".
  The comparison of low CR critical FRs with ADS has been performed

Fast Reactor Cores Assessment

A wide range of fast core models have been developed by means of the ERANOS deterministic code system (with JEF2.2 nuclear data) and the effective neutron reaction rates transferred to the COSI6 scenario code. The following fuel vectors have been considered:

(U-TRU)O_2 fuel - **MA/Pu ~ 0.1**			
5-years cooled LWR spent fuel Av. discharge burnup=50 MWd/kg			
Isotope	(wt.%)	Isotope	(wt.%)
Np237	4.8	Am241	3.4
Pu236	0.0	Am242	0.0
Pu238	2.3	Am243	1.5
Pu239	47.9	Cm242	0.0
Pu240	22.5	Cm243	0.0
Pu241	10.6	Cm244	0.5
Pu242	6.5	Cm245	0.0
Pu	**89.8**	**MA**	**10.2**

(U-TRU)O_2 fuel - **MA/Pu ~ 1.2**			
30-years cooled LWR spent fuel Av. discharge burnup=45 MWd/kg			
Isotope	(wt.%)	Isotope	(wt.%)
Np237	8.8	Am241	41.0
Pu236	0.0	Am242	0.1
Pu238	1.7	Am243	8.8
Pu239	21.2	Cm242	0.0
Pu240	15.6	Cm243	0.0
Pu241	1.8	Cm244	1.6
Pu242	5.4	Cm245	0.6
Pu	**45.7**	**MA**	**54.3**

Global Transition Scenario towards Fast Reactors

Fast ‘Breeder’ and ‘Isogenerator’ Cores Assessment

A ‘**Breeder**’ core has been defined with UO_2 loaded radial and axial blankets

Fuel type	**$(U\text{-}TRU)O_2/UO_2$**
MA/Pu ratio	**~ 0.1**
HM Inventory (Tons) Fissile Ax. Blanket Radial Blanket	 35.3 12 38
Pu content (% wt.)	15.8/21.2
Power (GWth)	1.4
Conversion ratio	**~ 1.45**
Av. Burnup (GWd/tHM)	85.6

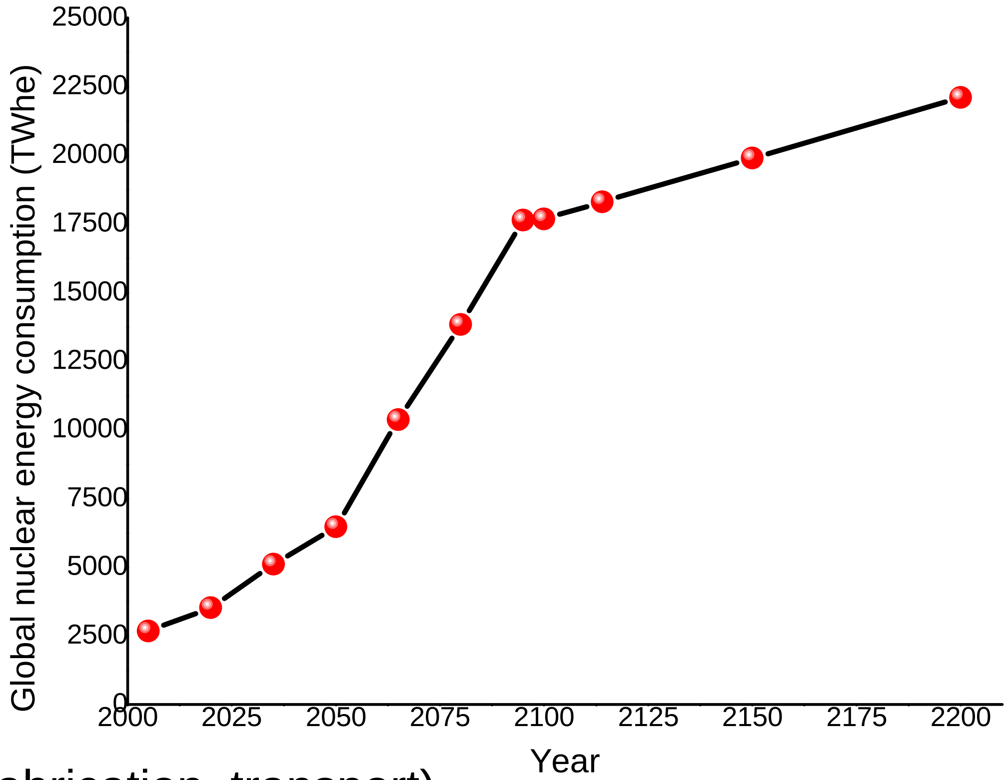
An ‘**Isogenerator**’ core (**EFR like**) with UO_2 loaded axial and radial blankets

Fuel type	**MOX**
MA/Pu ratio	**~ 0.1**
HM Inventory (Tons) Fissile Ax. Blanket Radial Blanket	 41.4 18 35
Pu content (% wt.)	22.21
Power (GWe)	1.45
Conversion ratio	**~ 1**
AV. Burnup (GWd/tHM)	136

Global World Transition Scenario towards Fast Reactors
Nominal case: homogeneous approach

- Objective: to replace from 2050 the entire thermal fleet by FRs as soon as possible

- Pu stock drives the rate of FR deployment



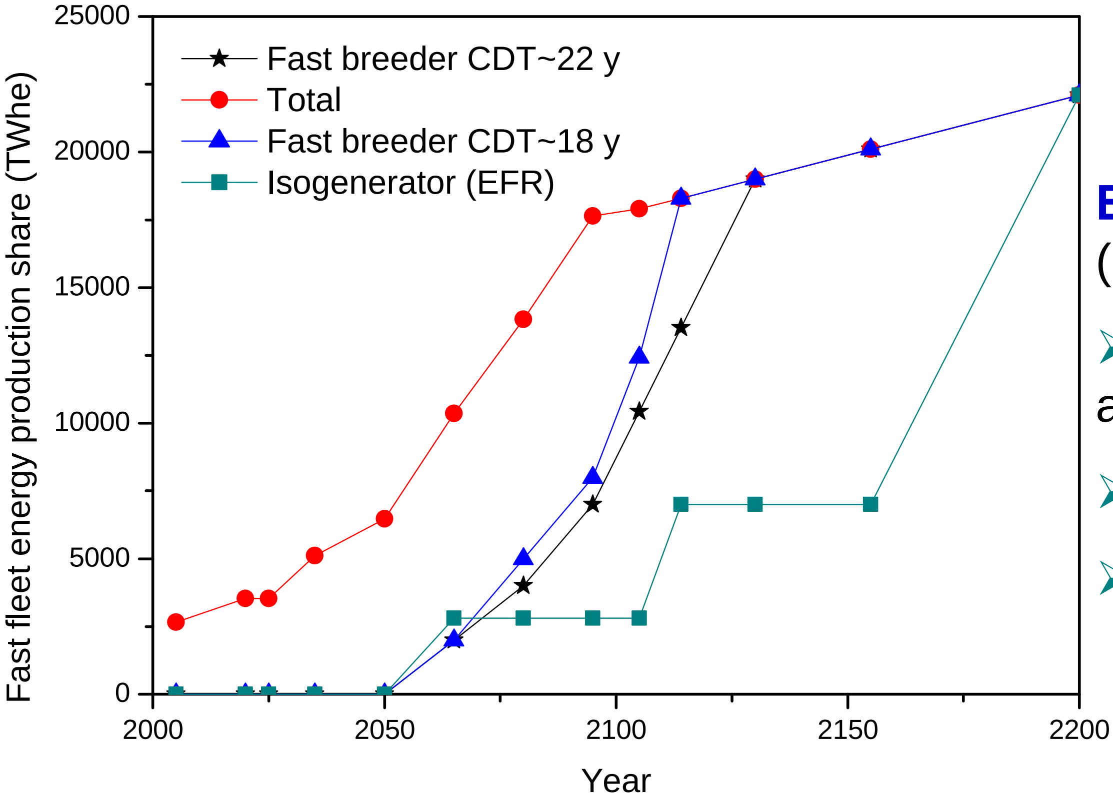
- **Key parameters**

- Imposed energy growth rate
- Spent fuel available to be processed
- Reprocessing capacity
- FR breeding gain
- Ex-core lag time (cooling, reprocessing, fabrication, transport)

Global Scenario

Overall nuclear energy production envelope and reactor shares

- **Fast reactors: FBR, EFR**



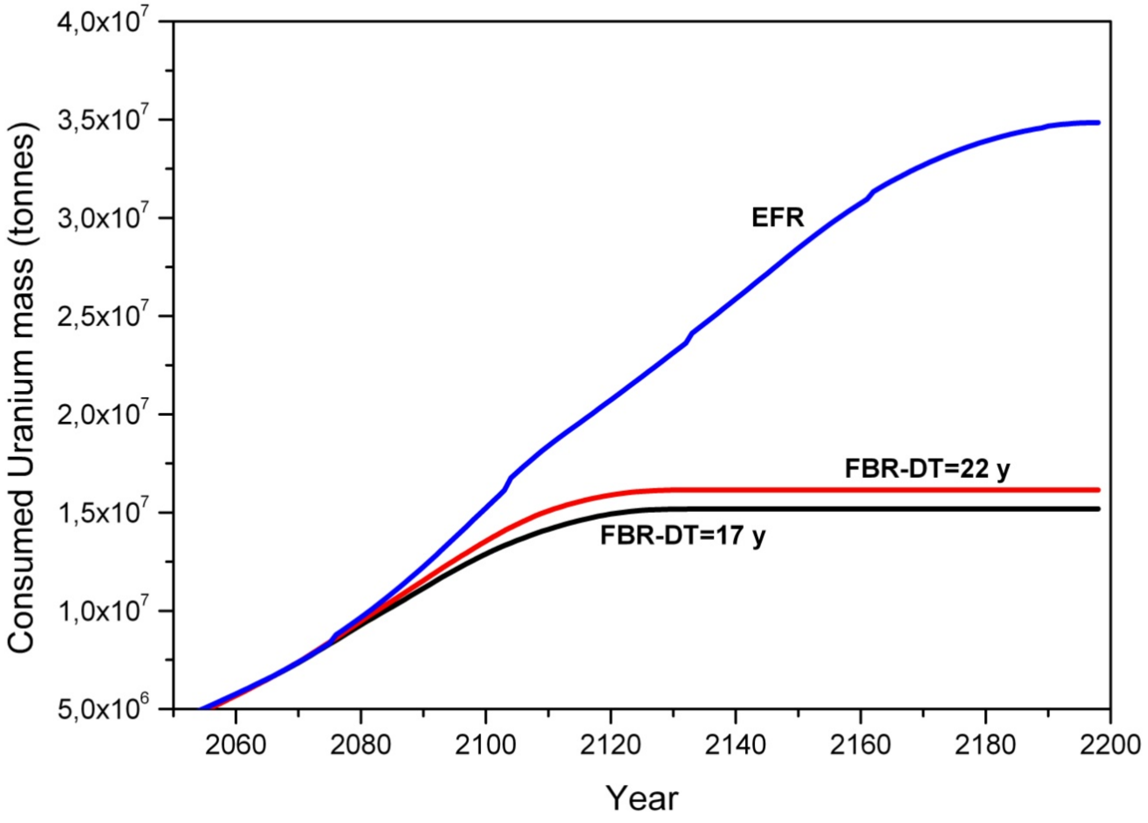
Breeder FBR and "isogenerator" (EFR) defined previously:

- **FBR** Breeding Gain=**0.47 (CR~1.45)** and doubling time: **17 or 22 y**
- **EFR** Breeding Gain **0.022 (CR~1)**
- Fuel cooling time: **5 years**

FR will meet the full overall demand in **2200** for EFR,
2130 for FBR with DT 22y, **2114** for FBR with DT 17 y

Global Transition Scenario
Cumulative masses of consumed natural U

- Impact of **breeder** deployment versus **“isogenerator”** deployment on U savings: 12 % in 2100, 45 % in 2150 and 55 % in 2200



Regional Scenario - 'Burners' Reactor Cores Assessment

'**Burner**' cores with conversion ratios **~0.5** and **~0.8** have been modeled by employing $(U\text{-}TRU)O_2$ fuel with **MA/Pu** ratio **~0.1** and **MA/Pu** ratio **~1.2**

Parameter	Fast Reactor Burner		ADS/EFIT
Fuel type	**$(U\text{-}TRU)O_2$**	**$(U\text{-}TRU)O_2$**	**TRU-MgO**
MA/PU	**~0.1**	**~1.2**	**~1.2**
Conversion ratio values	**0.73/0.46**	**0.75/0.55**	0.0
Cycle length (EFPD)	353/326	353/326	320
TRU/(TRU+U) content (% wt.)	27.1/40.0	41.2/50.1	100
Power (GWth)	1.0	1.0	0.384
Average discharge burnup (GWd/t)	149/205	117/143	78
Reactivity Loss/cycle (%Δk/k)	2.7/4.8	-0.9/~0.0	~0.0

Performance of critical 'Burners' (CR~0.5) and ADS Reactor Cores

	'Burner' MA/PU~0.1	'Burner' MA/PU~1.2	ADS EFIT
Total Pu (kg/TWh)	-26.0	-3.82	-2.0
Total MA (kg/TWh)	-1.1	-25.59	-39.9
Total (kg/TWh)	-27.1	-29.33	-41.9

Total consumption rates of the fast 'burner' cores are ~70% of the ADS EFIT one

Performance of 'Burners' (CR~0.5) Fast Reactor Cores

Karlsruhe Institute of Technology

The flexibility of a critical fast reactor allows employing low CR cores for both TRU or MA burning for different missions:

- A low (e.g. CR<0.5) critical FR with a MA/Pu~0.1 fuel can be apt to burn TRUs from LWRs
- A low (e.g. CR<0.5) critical FR with MA/Pu~1 or more can be used within a double-strata type of strategy → reduction and successive stabilisation of MA stocks. In this case, ADS can also be attractive.
- If the decision is made to shift progressively to a different energy mix, with a sharply decreasing share of nuclear energy → low CR fast reactors with a MA/Pu<0.1 fuel can be employed to reduce drastically the TRU inventory legacy from a previous development of nuclear energy based e.g. on fast reactors

Key issues: an appropriate MA/Pu ratio in the fuel and an as low as possible CR

Regional Scenario - Description

GROUP A →

Countries with no reprocessing facilities and with a stagnant or a nuclear energy phasing-out policy.

The goal: elimination of waste legacy by the end of the century (Belgium, Czech Republic, Germany, Spain, Sweden and Switzerland)

GROUP B →

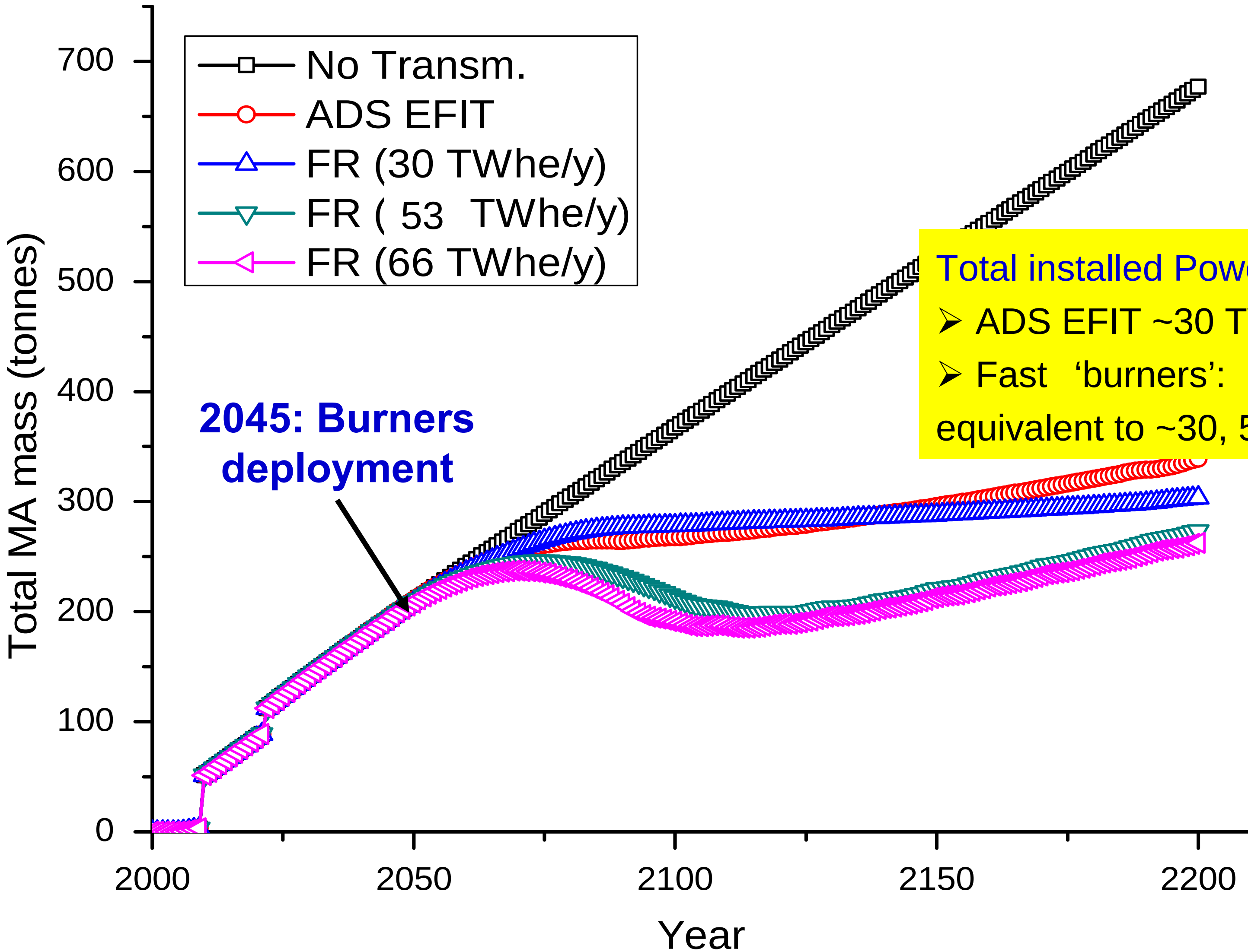
A nation in a continuation scenario, i.e France, with incoming delayed deployment of FRs

The goal: MAs inventory stabilization by the end of the century

The scenario considers the time period up to year 2200 and the **deployment of dedicated burners starting in 2045.**

Purpose of the scenario is providing countries B with a transmuter able to burn MA (and not Pu) with the **ADS EFIT** or with a **critical FR with CR ~0.55 and MA/Pu ~1.2** (corresponding to the ADS EFIT system)

Regional Scenario – Results: Total MA mass vs. time



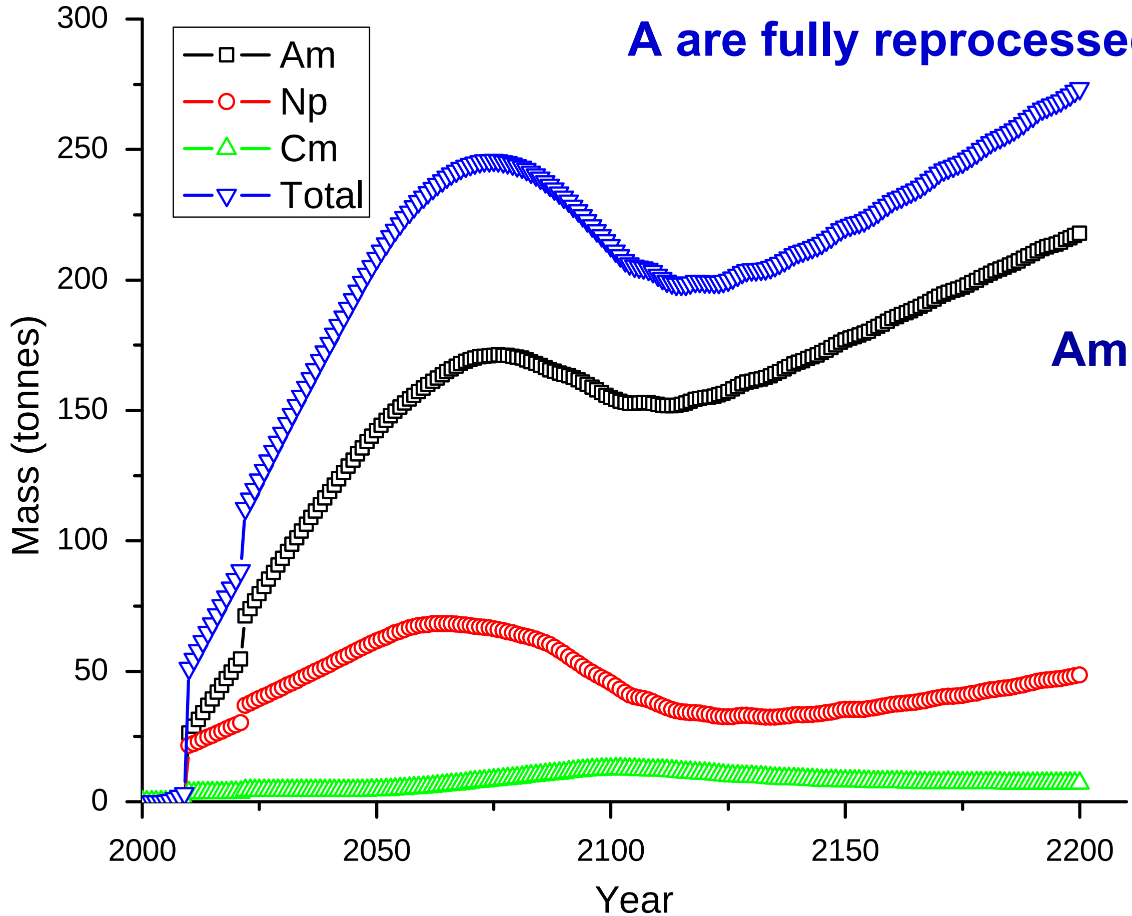
Total installed Power associated to burners:

- ADS EFIT ~30 TWhe/y
- Fast 'burners': three cases considered equivalent to ~30, 53 or 66 TWhe/y

Stable level of MA is reached rather soon in all cases (well before the end of the century) to the level of 250-350 tonnes/y, according to the transmuter power deployed

Regional Scenario - Results : MA inventory vs. time

In all cases TRU stocks of countries of Group A are fully reprocessed by ~2075 in all cases



Am↑ due to Pu^{241} decay

The goals of the scenario can be met by employing both FR 'burners' with low conversion ratio or ADS

Transmuters power share in the full energy producing fleet can be limited to ~ 5-10 %

Conclusions

- Several neutronics fast reactor models have been assessed in order to provide practical demonstrations of great flexibility associated to FRs

- This unique characteristic was tested by performing scenario analyses where FRs ‘breeder’, ‘isogenerator’ and ‘burner’ have been deployed with very different missions

- Breeders: the requirements of sustainability can be dealt with appropriate design choices (e.g. fuel type) in order to reduce the doubling time (e.g. below 10 years)

- Burner FRs: easily adaptable to the assigned mission within a specific national or regional policy such as a reduction and successive stabilization of MA inventories by drastically reducing legacy inventories of TRU, resulting from a previous deployment of nuclear energy in the extreme cases of both a LWR-only or FR-only power fleet deployment