Technical Workshop on Fuel Cycle Simulations
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# Overview of KIT activities on fuel cycles options for phase-out and regional scenarios

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# Nuclear fuel cycle and transmutation studies at KIT

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The KIT (IKET/TRANS group) is involved in fuel cycle and transmutation studies since long time. An overview of the main projects and findings is reported in the following slides.

The activities have been grouped as follows:

- Activities related to the CAPRA / CADRA Project (assessment of Pu burner system)
- Activities related to the FP6 – PATEROS Project (P&T on regional scenario studies)
- The German P&T study (2012-2014)
- Activity (on-going) on burner systems characterizations for waste minimization

The KIT (IKET-TRANS group) is participating to the OECD/NEA EG in Advanced Fuel Cycle Scenario studies.

The code used at KIT for scenario studies is COSI6 code (CEA). For each system considered, reactor-dependent libraries are generated at KIT (IKET-TRANS group) by means of ECCO/ERANOS code.

# The CAPRA / CADRA Project

# The CAPRA / CADRA Project

The joint European CAPRA / CADRA program launched by CEA (France) in early ‘90s → investigations of critical reactors for transmutation and incineration of nuclear waste. The IKET-TRANS group was extensively involved in safety studies.

The CAPRA (Combustion Améliorée du Plutonium dans les Réacteurs Avancés) mainly deals with managing the plutonium stockpile and CADRA (Consommation d'Actinides et de Déchets dans les Réacteurs Avancés) is related to the burning/transmutation of MAs and LLFPs. The CAPRA / CADRA program comprises the development of advanced LWRs, FRs, with different coolants and ADS.

The originally designed CAPRA / CADRA core was planned to be the size of a conventional FR as the European Fast Reactor (EFR) core (1300 MWe).

Reversibility in this case meant that a plant, such as the EFR, may host core with BR>1 (reference EFR core) and CAPRA / CADRA core for burning plutonium and MAs during the life of the plant without requiring any changes to be made in plant design.

# The FP-6 PATEROS Project

# The FP-6 PATEROS Project

**The FP6 - PATEROS project (coordinated by SCK-CEN – 2006 -2008) → establishing a European vision for the deployment of P&T of Nuclear Waste, up to the level of industrial implementation → regional scenario.**

**The possibilities to share fuel cycle facilities have been investigated within the project. It is envisaged a concerted use of materials, in order to optimize the use of resources and investments in an enhanced proliferation resistant environment.**

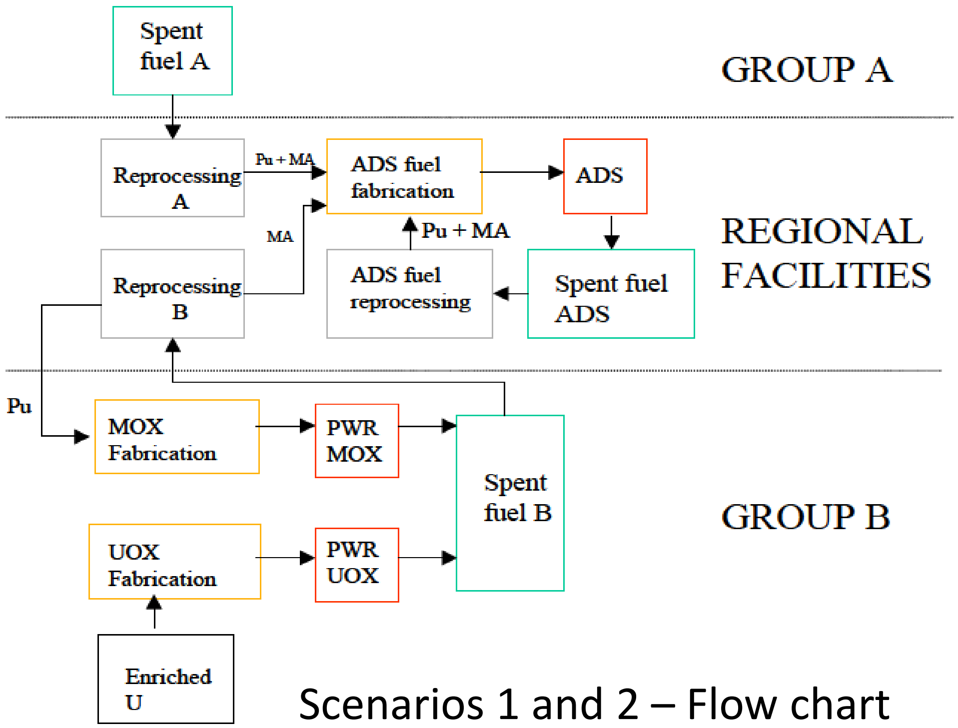
**European situation has been analyzed by considering four groups of countries:**

- **Group A is in a stagnant or phase-out scenario (e.g. Germany) for nuclear energy and has to manage his spent fuel, and especially the plutonium and the minor actinides.**
- **Group B is in a continuation scenario (e.g. France) for the nuclear energy and has to optimize the use of his resources in Plutonium for the future deployment of fast reactors or ADS.**
- **Group C (a subset of Group A), after stagnation, envisages a nuclear "renaissance".**
- **Group D, initially with no NPP, decides to go nuclear.**

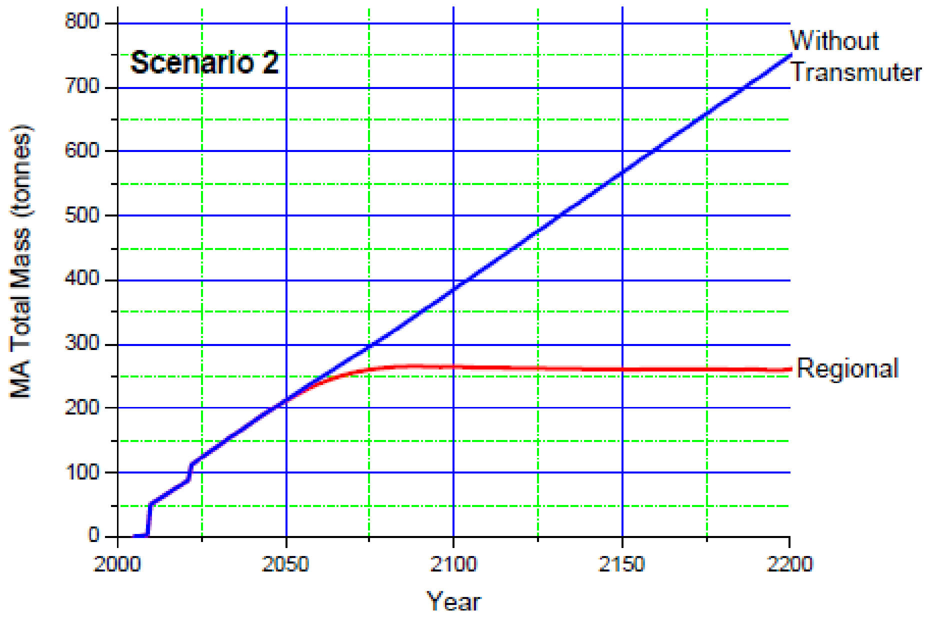
# The FP-6 PATEROS Project

**Mainly 3 scenarios have been selected and investigated:**

- **Scenarios 1 and 2 consider the deployment of a group of ADS-EFIT shared by countries A and B. The ADSs use the plutonium of Group A and transmute the Minor Actinides (MA) of the two groups.**
- **Scenario 3 considers the deployment of Fast Reactors in Group B. These Fast Reactors use the Pu of Groups A and B and recycle all MA.**




Scenarios 1 and 2 – Flow chart




**MOX in PWR**

# The German P&T study (2012-2014)

# The German P&T study (2012-2014)

**In order to identify potential advantages that P&T may offer for waste management strategy in Germany, the Federal Ministry of Economics and Technology (BMWi) and the Federal Ministry of Education and Research (BMBF) launched and granted in the period 2012-2014 an interdisciplinary research project, to support the decision on merit of P&T implementation.**

**Several scenarios in a nuclear phase-out context have been investigated:**

- ***Scenario 1*: no actions in support of P&T strategy**
- ***Scenario 2*: only R&D activities related to P&T (i.e. postponing the decision of P&T implementation)**
- ***Scenario 3*: Isolated application of P&T in a phase-out context.**
- ***Scenario 4*: Implementation of P&T in a regional (e.g. European) context.**

**Several technological options were considered:**

- **TRU in U-free matrix (MgO, Mo, …) → *ADS – EFIT-like***
- **TRU in U matrix → *Low CR FRs – ASTRID-like***

O. Renn, (2014), „Partitionierung und Transmutation. Forschung Entwicklung  Gesellschaftliche Implikationen (acatech STUDIE)“, München, Herbert Utz Verlag.

C. Fazio, et al. „Study on partitioning and transmutation as a possible option for spent fuel management within a nuclear phase-out scenario”, Proc. Int. Conf. GLOBAL 2013, 2013.

A. Rineiski, et al. „Options for Incineration of Trans-Uranium Elements from German Spent Nuclear Fuel”, Proc. Int. Conf. ICENES2013, 2013.

# The German P&T study (2012-2014)

- *Scenario 1*: no actions in support of P&T strategy
- *Scenario 2*: only R&D activities related to P&T

**SNF has been produced in Germany since 1969 (LWRs-UOX and LWRs-MOX systems). According to the German phase-out schedule (abrupt shut down of 8 LWRs after Fukushima accident) the operation of the remaining 9 units will be terminated latest in 2022.**

**Fine characterization of German wastes and SNF inventories has been performed in the study*.**

**Inventory (2075)**

| Amount given in tons | SNF | Vitrified Waste |
|---|---|---|
| U | 9710 | 0.7 |
| Fission Products (FPs) | 416 | 207.0 |
| Pu | 137 | 0.3 |
| MA | 38 | 4.0 |
| TRU (Pu+MA) | 175 | 4.3 |
| Total (U+FPs+TRU) | 10300 | 212.0 |

O. Renn, (2014), „Partitionierung und Transmutation. Forschung Entwicklung Gesellschaftliche Implikationen (acatech STUDIE)", München, Herbert Utz Verlag.

(*) A. Schwenk-Ferrero, "German Spent Nuclear Fuel Legacy: Characteristics and High-Level Waste Management Issues". In: Hindawi Publishing Corporation, Science and Technology of Nuclear Installations, Nr. 2013 ID 293792, 2013. URL: http://dx.doi.org/10.1155/2013/293792 [Stand: 23. 09. 2013].

# The German P&T study (2012-2014)

- ***Scenario 3 -4*: P&T implementation**

| | EFIT-like | | ASTRID-like | |
|---|---|---|---|---|
| Matrix | MgO | Nat. Mo | $UO_2$ | $UO_2$ |
| Pu/MA | 68/32 | 80/20 | 66/34 | 95/5 |
| TRU vol% | | | | |
| inner core | 21 | 22 | 33 | 25 |
| mid core | 27 | 28 | -- | -- |
| outer core | 31 | 32 | 36 | 27 |
| Power MWth | 400 | | 1200 | |
| CR | 0 | 0 | 0.55 | 0.68 |
| | | | | |
| **Initial core inventory, kg** | | | | |
| TRU | 4133 | 4417 | 6580 | 5087 |
| Matrix | 4532 | 9544 | 11408 (U) | 12803 (U) |
| | | | | |
| **TRU transmutation rate (kg/TWhth) after 3 or 5 (EFIT or ASTRID) years of irradiation and 3 or 5 years cooling** | | | | |
| Pu | -21 | -35 | -4 | -13 |
| MA | -24 | -9 | -15 | 0 |
| | | | | |
| **kg of burned TRUs / kg loaded TRUs after 3 or 5 years of irradiation (in EFIT or ASTRID) and 3 or 5 years cooling** | | | | |
| | -0.11 | -0.10 | -0.14 | -0.13 |
| **Safety-related parameters: Doppler Constant and coolant void effect (in EFIT core or in ASTRID core and Na Plenum above), pcm** | | | | |
| $K_D$ | -208 | -267 | -272 | -571 |
| Void effect | 3033 | 3054 | -88 | -1138 |

**Consequently, the EFIT and ASTRID designs have been adapted to the needs of the actual German phase-out.**

**EFIT-like and ASTRID-like systems have been defined able to transmute both MAs and Pu. In particular with respect to the original systems, the fuel composition, power, and core height values have been adapted.**

**The scenarios have been compared by quantifying different indicators.**

**They have been then used in applying the Delphy method for assessing social opportunities and risky of P&T.**

F. Gabrielli, et al. „ASTRID-like Fast Reactor Cores for Burning Plutonium and Minor Actinides", Proc. Int. Conf. INES-4,2013.

O. Renn, (2014), „Partitionierung und Transmutation. Forschung Entwicklung Gesellschaftliche Implikationen (acatech STUDIE)", München, Herbert Utz Verlag.

# Burner systems characterization for waste minimization

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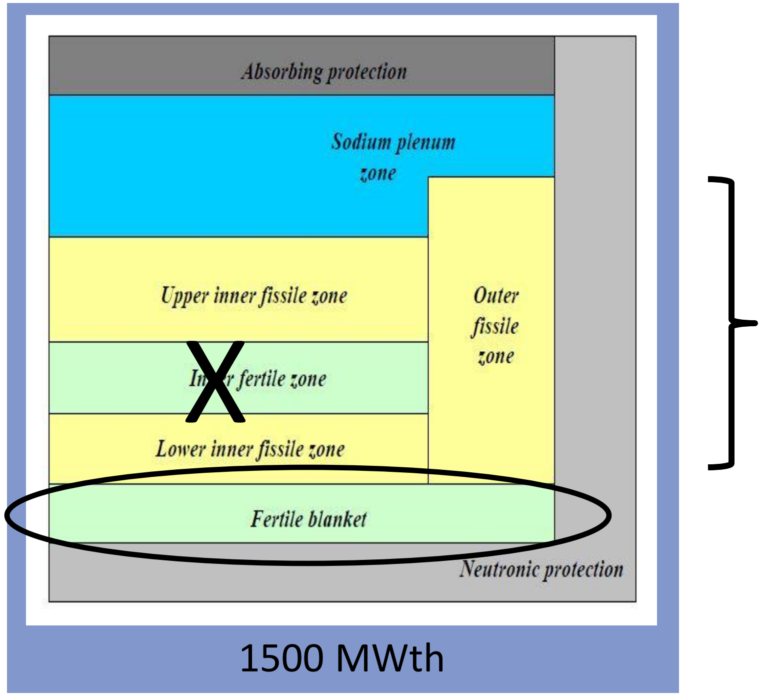
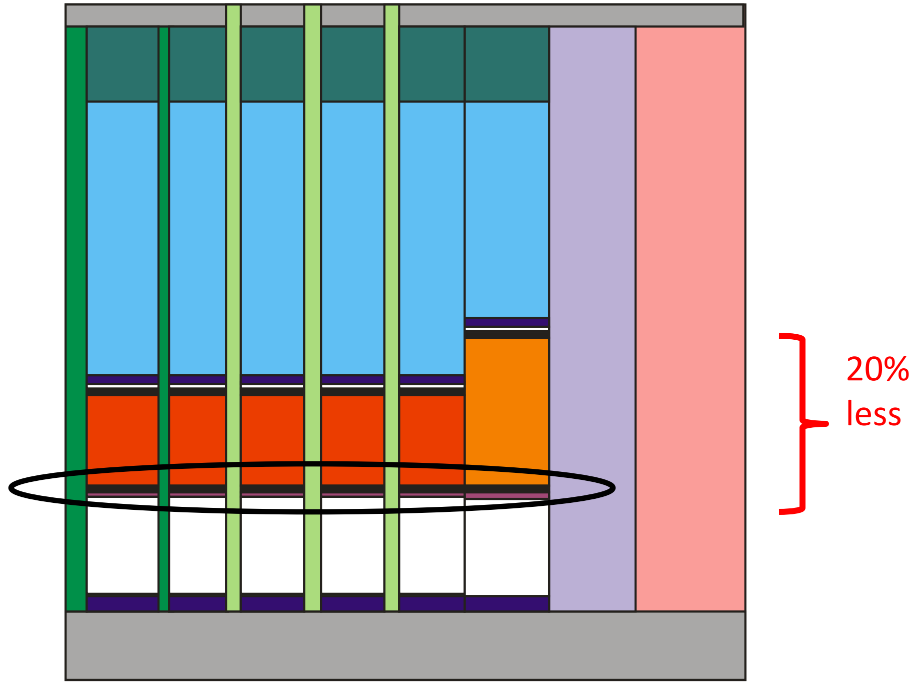



ASTRID design (J.P. Grouiller, FR13)




1200 MWth

ASTRID-like burner (F. Gabrielli, Energy Procedia 71, 130 – 139, 2015)

Power: 1500 MWth → 1200 MWth (20% less)

Active height: reduced by 20%

Internal fertile blanket: removed

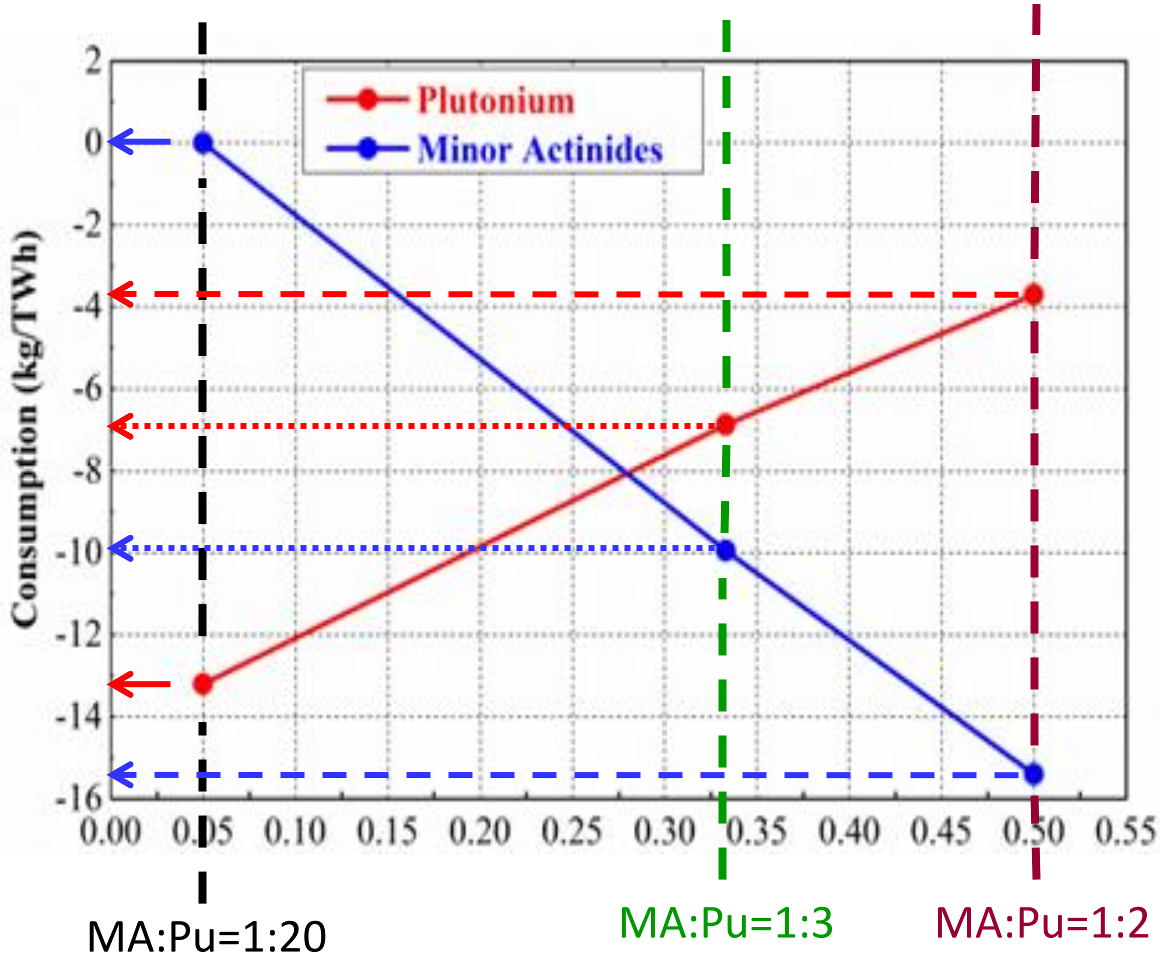
Lower fertile blanket: reduced to 2 cm

High TRU content
→ CR 0.6-0.7
(originally CR = 1)

MA:Pu contents adjusted to get the required burning rates

# Burner systems characterization for waste minimization

**System flexibility → same geometry, same power (1200 MWth) → different fuel compositions (MA:PU ratio) → target: MA/TRU burning rates to meet specific scenario needs.**




**MA:Pu=1:20**

→ Pu burner

→ Phase-out scenarios

(Pu main component to TRU inventory, radiotoxicity, .. to be reduced at first)

**MA:Pu=1:2**

→ mainly MA burner

→ On-going/regional scenarios

(need to stabilize MA inventory)

Large MA content (ca. 12%) in fuel → Safety coefficients remain acceptable but deteriorate.

**MA:Pu=1:3**

→ mainly MA burner

→ On-going/regional scenarios

Lower MA content (ca. 8%) in fuel → Better safety behavior

# Burner systems characterization for waste minimization

## Safety performances:

| | MA:Pu=1:20 | | MA:Pu=1:2 | | MA:Pu=1:3 | |
|---|---|---|---|---|---|---|
| Parameter | BOL | EOC3 | BOL | EOC3 | BOL | EOC3 |
| $\beta_{eff}$(pcm) | 331 | 328 | 275 | 272 | 331 | 328 |
| $\Lambda$(μs) | 0.66 | 0.63 | 0.42 | 0.47 | 0.61 | 0.63 |
| $K_D$(pcm) | -571 | -540 | -275 | -272 | -352 | -361 |
| | | | | | | |
| Reactor Condition | Δρ($) | | Δρ($) | | Δρ($) | |
| Voided core | 3.1 | 4.0 | 5.9 | 6.1 | 4.3 | 4.6 |
| Voided core + plenum | -3.4 | -2.6 | -0.3 | -0.6 | -1.2 | -1.1 |

*(F. Gabrielli, et al., Energy Procedia 71, 130 – 139, 2015)*

Considered in regional scenarios

**Neutron transport calculations performed by means of the ECCO/ERANOS code (VARIANT solver) assuming 3D (HEX-Z) models, effective XS in 33 energy-groups, JEFF3.1 nuclear data library.**

**Dedicated libraries for fuel cycle code COSI6 have been generated at KIT.**

**For checking the full procedure (from ERANOS to COSI6 core modeling) and before adding sources of "uncertainties" due to the scenario dynamic isotopic vector evolution, the same conditions used in ERANOS simulation have been applied to COSI6. The effect of different initial TRU vectors have also been considered.**

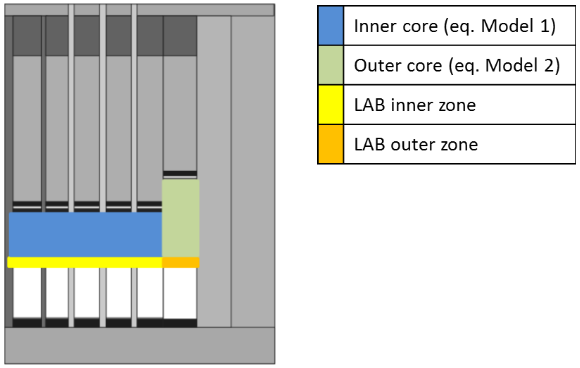
# Burner systems characterization for waste minimization

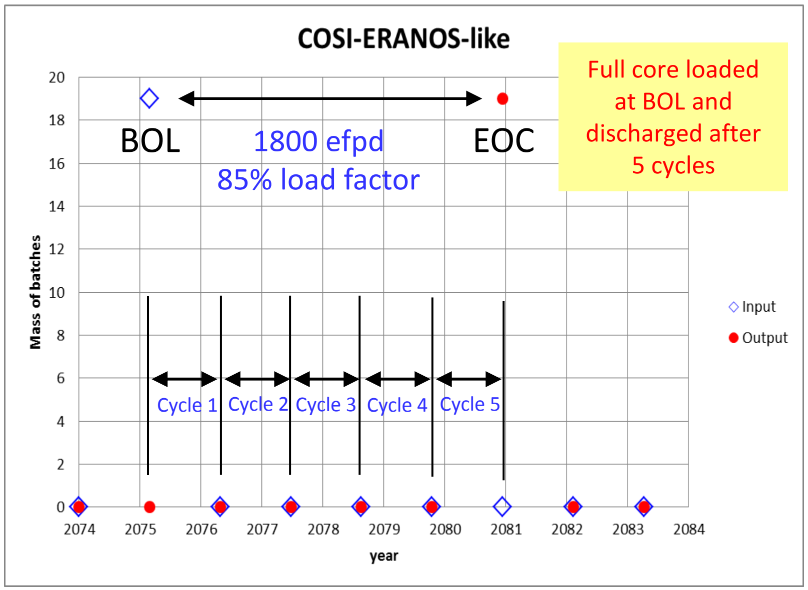
**Same conditions used in ERANOS simulation have been applied to COSI6:**

1. **Full core modeled.**
2. **No reshuffling.**
3. **A single irradiation step of 1800 efpd.**

**System modeled by 4 BBLs.**

**Fuel composition loaded in core calculated by the COSI itself using Pu239eq. and omega values (BOL) from ERANOS.**




| MA burner | | |
|---|---|---|
| U+TRU inventory | ERANOS | COSI6 |
| | kg | |
| BOL | 18601 | 19022 |
| EOC | 16413 | 16806 |
| ΔM | 2188 | 2216 |

Main difference from Pu241 burning rate

| MA burner | | | |
|---|---|---|---|
| Elements | ERANOS | COSI6 | |
| | | As ERANOS | In scenario (eq. batch) |
| | kg/TWhth | | |
| U | -23.5 | -24.2 | -23.7 |
| **Pu** | **-4.2** | **-3.3** | **-3.5** |
| Am | -16.80 | -17.32 | -17.44 |
| **MA** | **-14.7** | **-15.2** | **-15.5** |

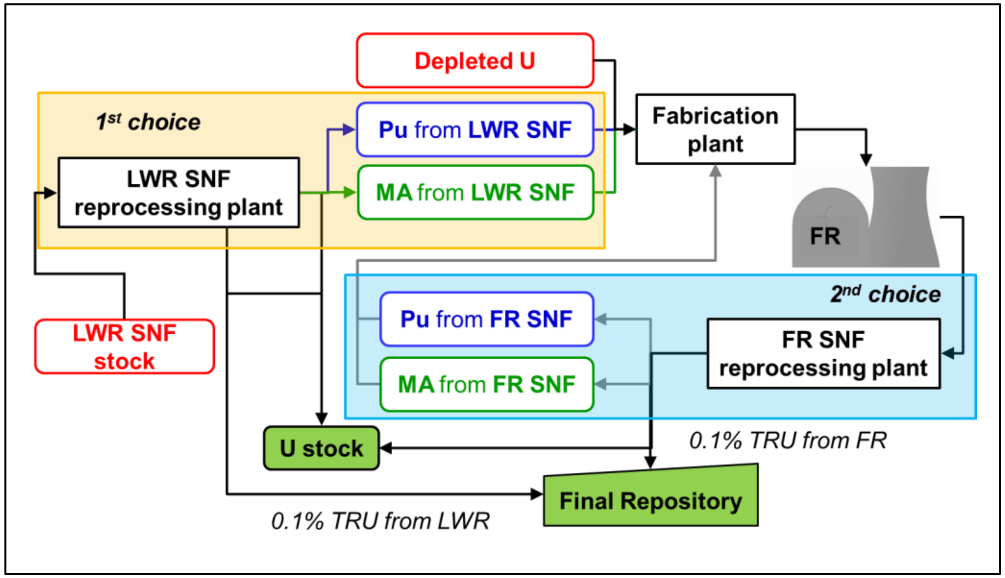
# Toward phase-out scenario studies

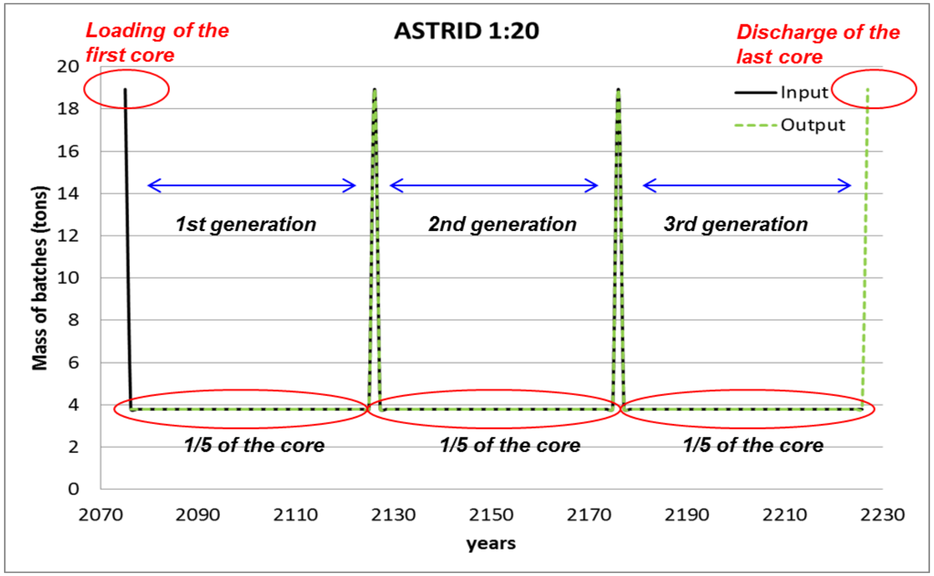
# Toward phase-out scenario studies

The **German accumulated TRU inventory** assumed **to be burned in about 150 years***.

**Starting from 2075 (date arbitrary chosen) three generations of burners (50 years lifetime each) assumed.**

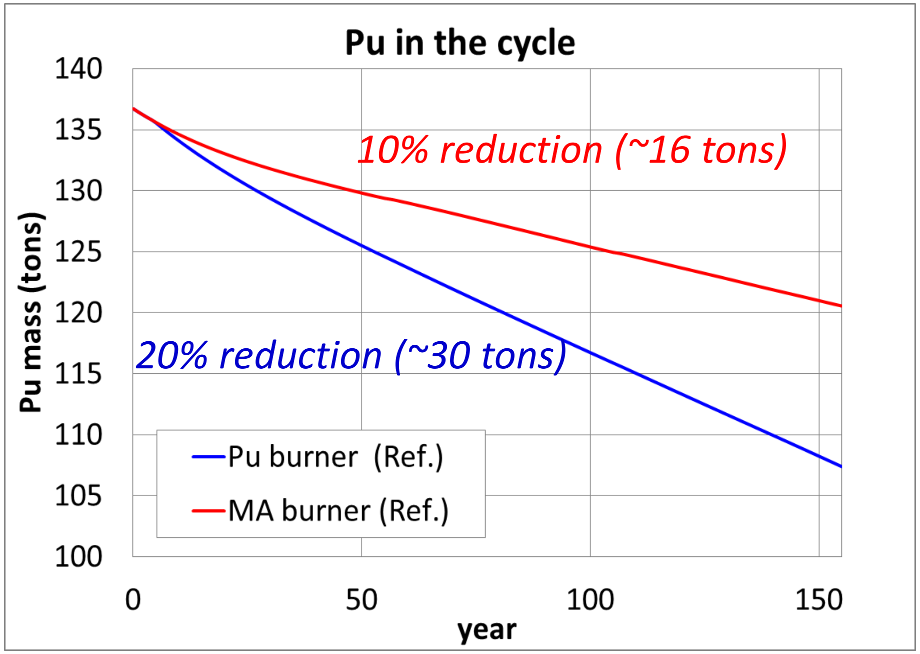
**Comparison: deployment of one single unit (Pu or MA burners) → analysis of burners behavior under dynamic conditions**.**

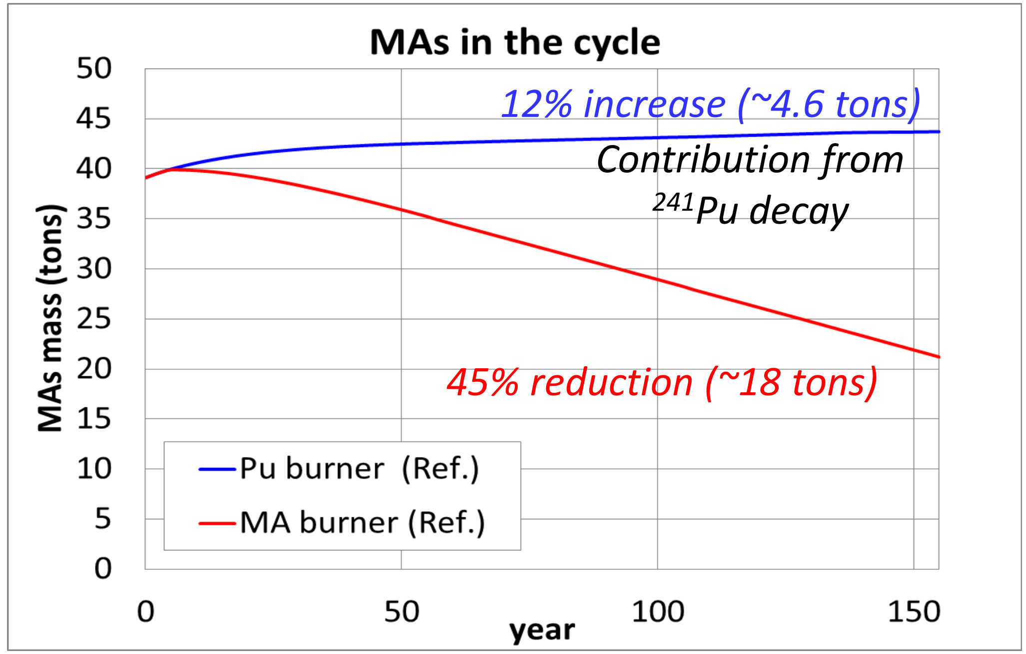



*O. Renn, (2014), „Partitionierung und Transmutation. Forschung Entwicklung Gesellschaftliche Implikationen (acatech STUDIE)“, München, Herbert Utz Verlag [conservative value adopted].
**B. Vezzoni, et al. „Minor Actinides Incineration Options using Innovative Na-cooled Fast Reactors: Impact on Phasing-out and On-going Fuel Cycles”, Progress in Nuclear Energy, Volume 82, Pages 58–63, July 2015.

# Toward phase-out scenario studies



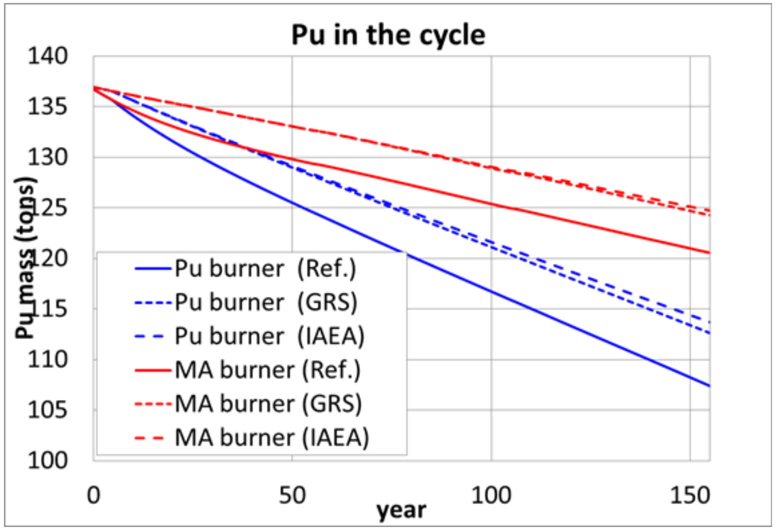




**After introduction of a single unit → large residual mass of TRU remains in the cycle.**

**The complete TRU burning may be achieved by a fleet of about 4 to 5 Pu burners and 2 MA burners (or 6-7 systems with intermediate characteristics) corresponding to an "effective CR" of about 0.62-0.65 → results confirm the conclusions of the German P&T study (P&T results based only on neutronics investigations).**

# Toward phase-out scenario studies

| Isotope | Ref. | GRS | IAEA |
|---|---|---|---|
| | Pu vector (wt. %) | | |
| Pu238 | 3.7 | 2.45 | 4.45 |
| **Pu239** | **46.4** | **52.49** | **57.17** |
| **Pu240** | **34.1** | **32.19** | **28.49** |
| **Pu241** | **3.8** | **0.9** | **0.6** |
| Pu242 | 11.9 | 11.97 | 9.29 |
| | MAs vector (wt. %) | | |
| **Am241** | **75.5** | **63.8** | **62.09** |
| **Am242m** | **0.3** | 0.1 | 0.04 |
| **Am243** | **16.1** | 10.7 | 8.62 |
| **Np237** | **3.9** | 24.4 | 28.53 |
| **Cm243** | **0.1** | 0.0 | 0.03 |
| **Cm244** | **3.0** | **0.5** | **0.30** |
| **Cm245** | **1.1** | 0.5 | 0.33 |
| **Cm246** | **0.1** | 0.0 | 0.05 |

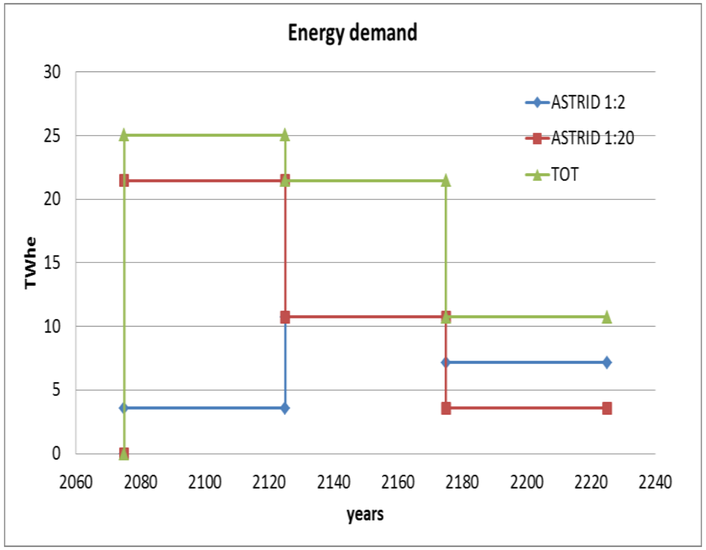


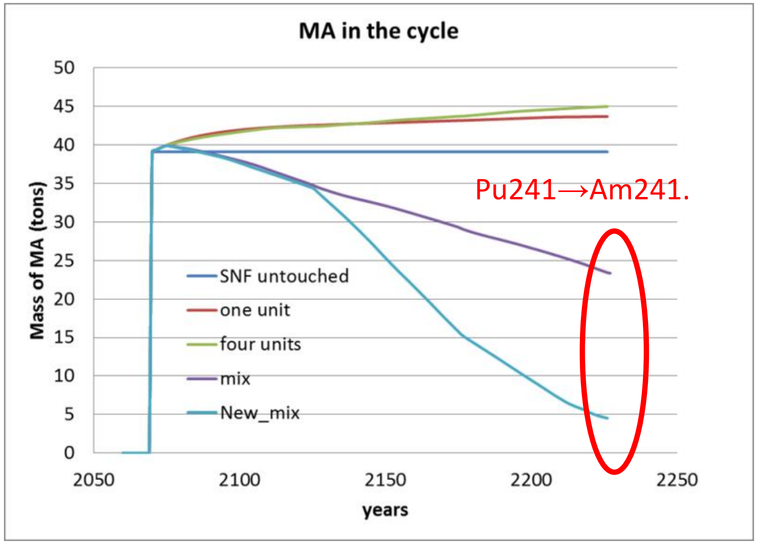

**The impact on the trends of the TRU vector associated to the LWR SNF has been analyzed.**

**Some steps toward scenario optimization**

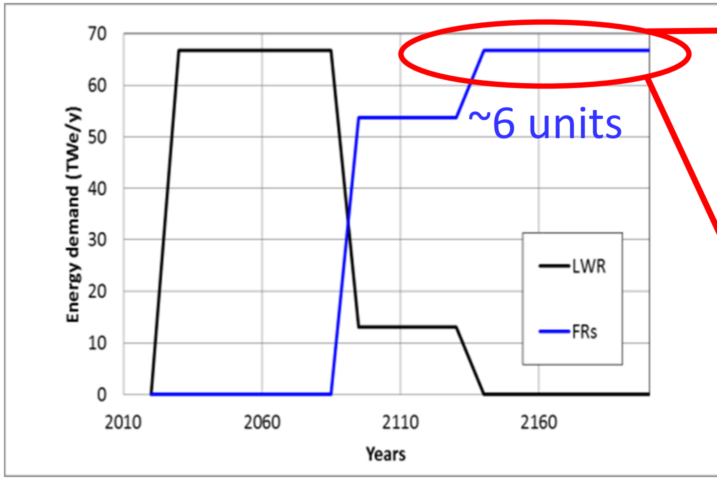
**NEW MIX**

**1st gen. :**
**1 unit MA burner, 6 units Pu burner**
**2nd gen.:**
**3 units MA burner, 3 units Pu burner**
**3rd gen.:**
**2 units MA burner, 1 unit Pu burner**



# Simplified on-going scenarios (test case)

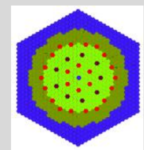



Within the CP-ESFR project, the ESFR system (3600 MWth) was extensively studied by the IKET-TRANS group.

**Focus on safety** - several measures for reducing the positive **sodium void reactivity effect** considered and a modified axial structure proposed – **transient behavior** confirm the better behavior of the optimized configuration with respect to the WH core.

## ESFR WH or ESFR CONF2

***Homogeneous loading***

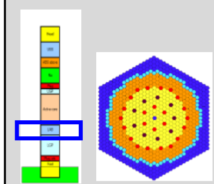


**MAs < 5%**

for limiting the impact on core safety parameters

***Heterogeneous loading***

***In axial or radial blankets***



**MAs < 20%**

less impact on safety

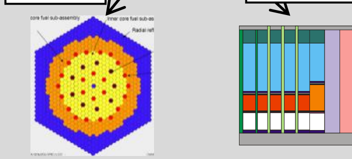
## ESFR WH + ASTRID-like MA burner

***Mixed fleet***

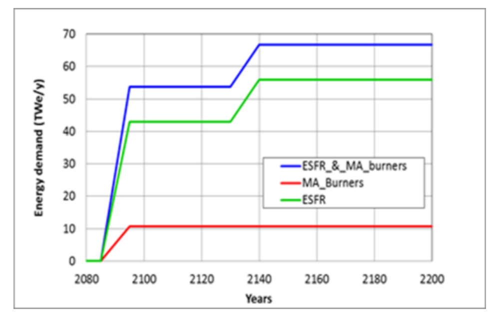
***ESFR + MA burners***

**Pu**

**Pu + MAs**



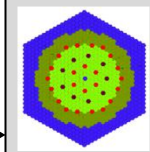
One ESFR unit → 3 MA burner units



# Simplified on-going scenarios (test case)

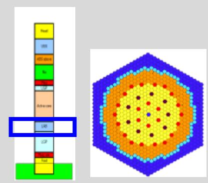
| Name | Type of System | Recycling | | | |
|---|---|---|---|---|---|
| | | Pu | Am | Cm | Np |
| LWR | Thermal | No | no | no | no |
| ESFR (**MOX**) | Fast core – No Blankets | yes | **no** | **no** | **no** |
| ESFR (**5 wt.% MAs in the core**) | Fast core – No Blankets | **yes** | **yes** | **yes** | **yes** |
| **ESFR-CONF2 (10 wt.% MAs in the blanket)** | Fast core | yes | no | no | no |
| | Lower Axial Blanket (30 cm, 10 wt.% MAs) | no | yes | yes | yes |
| **ESFR_&_MA burners** | ESFR Fast core – No Blankets | **yes** | **no** | **no** | **no** |
| | MA Burner Fast core | **yes** | **yes** | **yes** | **yes** |
| | MA Burner Lower Axial Blankets (2 cm, 10 wt.% MAs) | no | **yes** | **yes** | **yes** |

***Homogeneous loading***



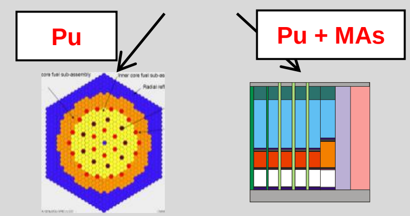
**MAs < 5%**
for limiting the impact on core safety parameters

***Heterogeneous loading***
***In axial or radial blankets***



**MAs < 20%**
less impact on safety

***Mixed fleet***
***ESFR + MA burners***

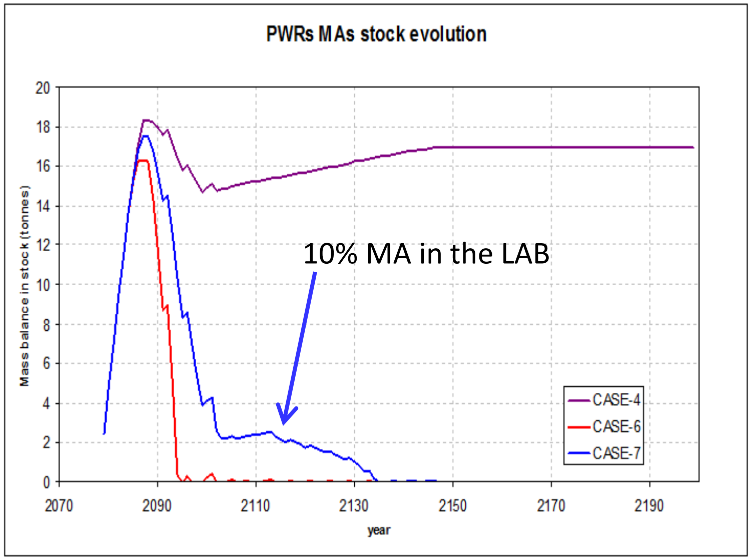


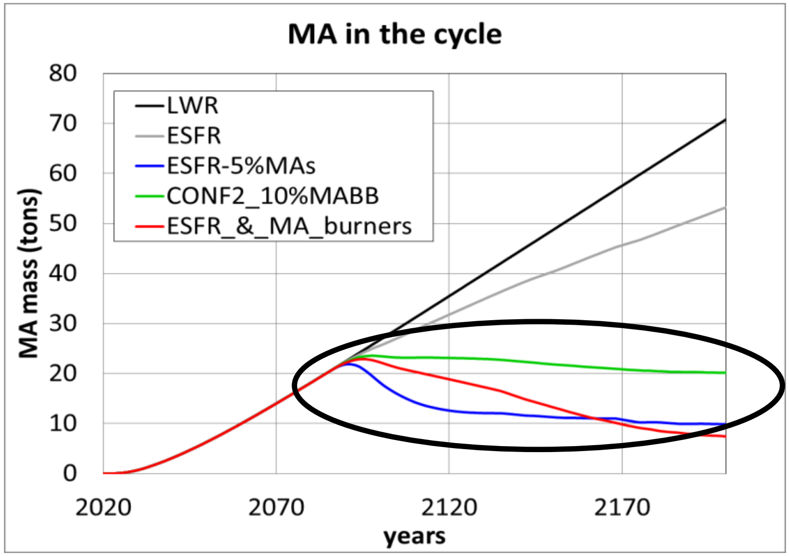

*B. Vezzoni, et al. „Innovative TRU burners and fuel cycles options for phase-out and regional scenarios", Proc. Int. Conf. 13th IEMPT, Seoul, Rep. Korea, Sep. 2014.

# Simplified on-going scenarios (test case)

Homogeneous and heterogeneous MA loading strategies have been compared.

Focus remains on safety*.




**Mixed fleet → more favorable from the safety point of view due to a lower Na void reactivity effect in burner systems (-0.3$) with MA-bearing fuels compared to larger ESFR-like ones (more than 4$). Heterogeneous loading (10% MA) on CONF-2 allows stabilizing MA but Pu in the cycle accumulates.**

**The specific activity (TBq/t) and the specific decay power (W/t) of the material in input to the fabrication plants remains comparable with the case of a full fleet loaded homogeneously with 5% MAs in the core*/**.**

*B. Vezzoni, et al. „Analysis of Minor Actinides incineration adopting an Innovative Fast reactor Concept”, Proc. Int. Conf. 12th IEMPT, Prague, Czech Rep., Sep. 2012.
**B. Vezzoni, et al. „Innovative TRU burners and fuel cycles options for phase-out and regional scenarios”, Proc. Int. Conf. 13th IEMPT, Seoul, Rep. Korea, Sep. 2014.

# Activities on-going

# Definition of the Regional Scenario

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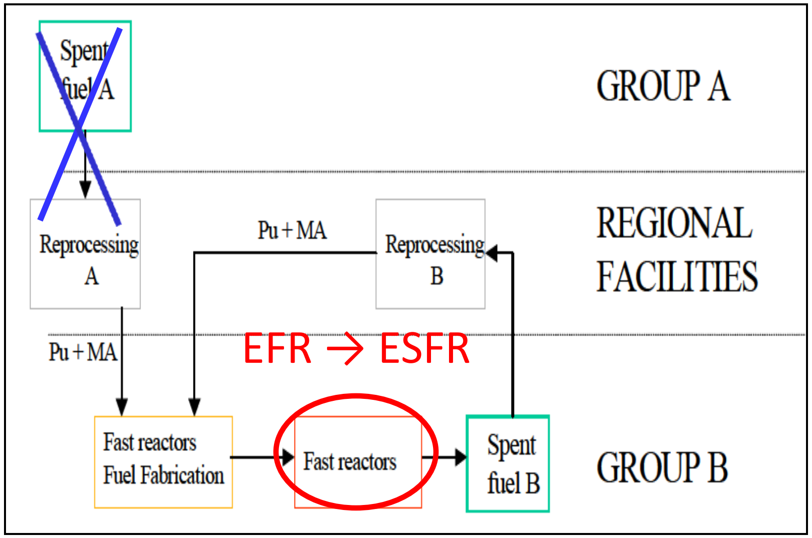


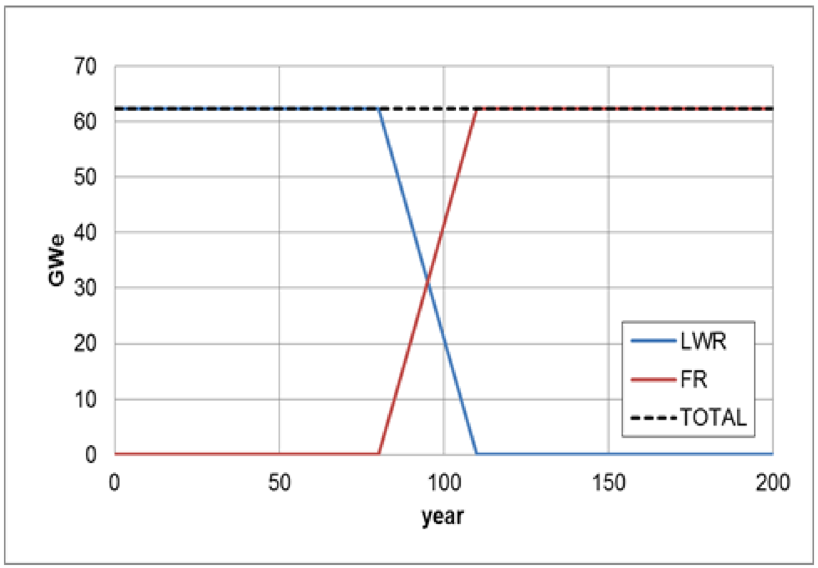


→ Modifications introduced with respect to PATEROS original scenario 3:

- The original FR design (EFR design) has been substituted by a more recent design: the European Sodium Fast Reactor Design developed within the FP7-CP-ESFR project,
- No external SNF inventory (simulating country in phase out) considered → neglected at first to focus mainly on reactor synergies → inserted in future studies.
- The overall transition scenario and energy demand considered in PATEROS has been kept.

ASTRID-like MA burners are introduced as component of the FR fleet (different shares see next slide)

# Definition of the Regional Scenario

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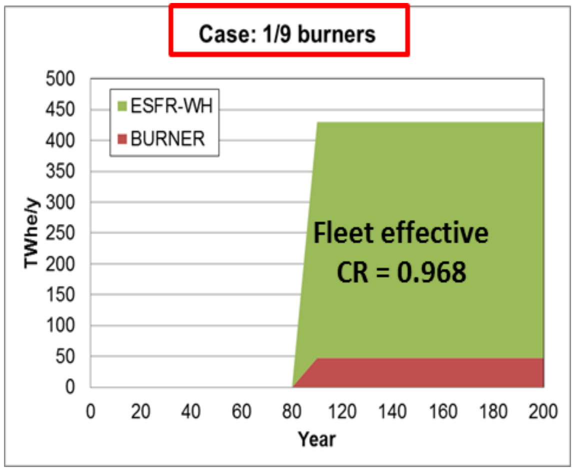
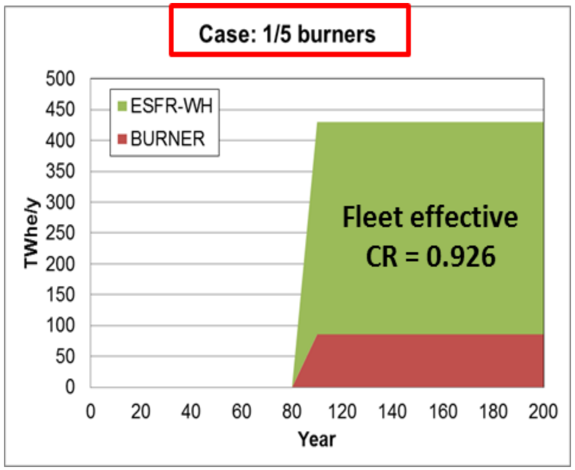
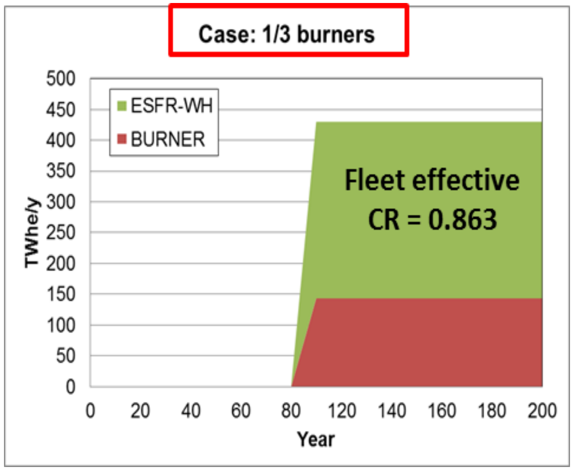
In combination with ESFRs



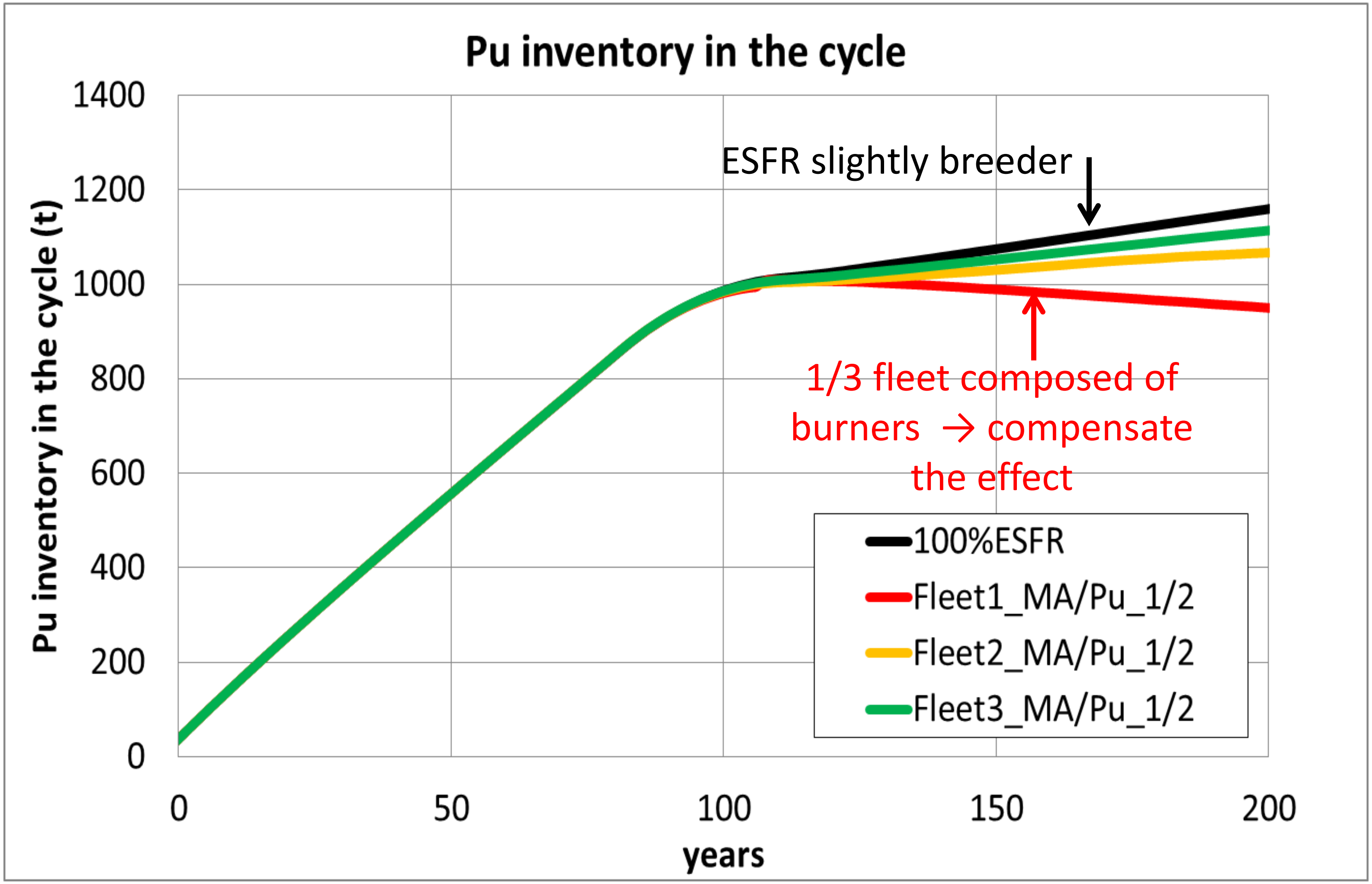




In combination with LWRs

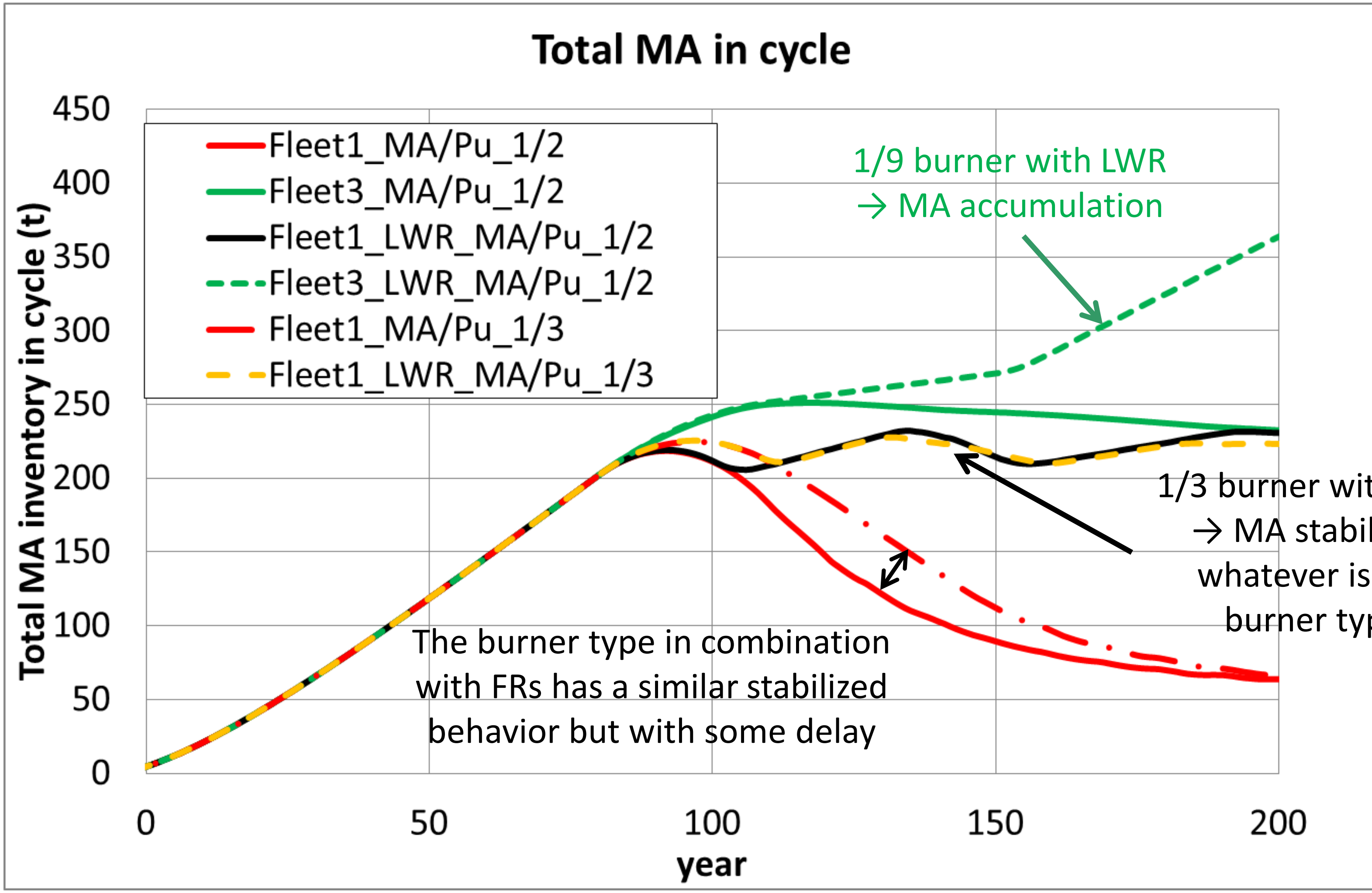
**In order to try to take into account the effect induced by an external SNF inventory, we have considered setting aside ESFR systems but using only MA burners → different shares of LWRs remain in operation also during the second part of the scenario**

| 1/9 fleet MA burners | 1/5 fleet MA burners | 1/3 fleet MA burners |
|---|---|---|

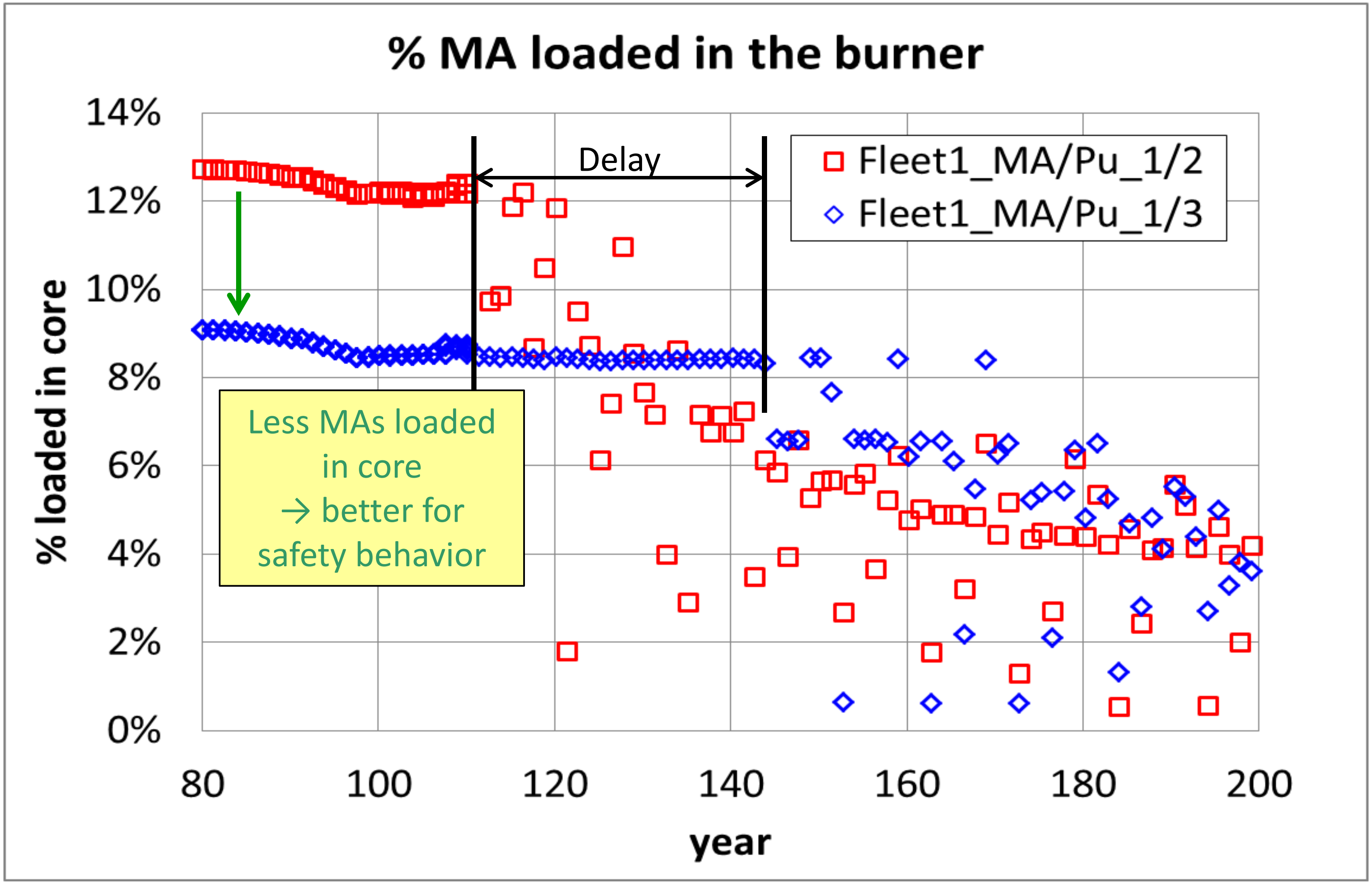
# Regional Scenario: some results



# Regional Scenario: some results



# Regional Scenario: some results



# Summary

# Summary

**The IKET-TRANS has been continuously involved in several national/international activities on fuel cycle scenarios.**

**Large experience has been acquired by the group. The fuel cycle COSI6 code has been extensively adopted at KIT since 2007. More than 10 different reactor types (LWR, ADS, SFR, LFR, Burners,..) have been considered in the studies. For each system dedicated libraries (BBLs) have been generated at KIT by means of ECCO/ERANOS codes for modeling the systems in COSI6.**

**Recently the group has been involved in the German P&T study by leading the scenario definition and comparison. The activity on going is about ASTRID-like burner systems to be implement in phase-out (regional) or on-going scenarios.**

**The activity on fuel cycle and scenario calculations for MA/TRU management has been always complemented by safety investigation of the systems considered in scenarios.**

**The IKET-TRANS group is contributing to present and future activities of the OECD/NEA EG-AFCS.**

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# Thank you very much for your attention

# The German P&T study (2012-2014)

- *Scenario 3 -4*: P&T implementation

| | **Reference system for German Scenario** | | **Comparative technological option** |
|---|---|---|---|
| | EFIT-like | | ASTRID-like |
| Fuel | (IMF, TRUs) | | (U,TRUs) |
| Matrix | MgO | Mo (natural) | $UO_2$ |
| Industrial experience | Limited | Limited | Wider |
| CR | 0 | 0 | (0.5 - 0.7) |
| Power (MWth) | 400 | | ~ 1200 |
| Pu/MA ratio | ~ 70/30 to -90/10 | | ~ 70/30 to -90/10 |
| Fuel Volume Fraction | ~ 20 -30 % | | 100 % |
| Initial heavy metal loading (tons) | 4-5 (TRUs) | | 18 (U +TRUs) |
| TRU Burning rates (kg/TWhth) | 40-45 | | 14-16 |
| TRU burned / TRU loaded | ~ 10% | | ~ 13% |
| Irradiation time (with 100% load factor[1]) | 3 y | | 5 y |
| Number of units | 7-8 units working for 150 y | | 7-8 units working for 150 y |
| Reprocessing (tons HM/y) | ~ 9-10 (TRU) | | ~ 24 (U + TRU) |
| TRU cumulative losses | ~ 1.7 tons | | ~ 1.7 tons |
| Variation of the amount of actinides and FPs in the storage | ca. 170 tons more | | ca. 510 tons more |
| Energy (TWhth) | ca. 4000 | | ca. 12000 |

# Definition of the Regional Scenario

**The following cases have been considered:**

| CASE ID | Burner | | | FR/LWR |
|---|---|---|---|---|
| | type | share | GWe | |
| **Fleet1_MA/Pu_1/2** | **MA:Pu=1:2** | **1/3** | 20.8 | 41.6 (**ESFR**) |
| **Fleet1_MA/Pu_1/3** | **MA:Pu=1:3** | | | |
| **Fleet1_LWR_MA/Pu_1/2** | **MA:Pu=1:2** | | | 41.6 (**LWR**) |
| **Fleet1_LWR_MA/Pu_1/3** | **MA:Pu=1:3** | | | |
| **Fleet2_MA/Pu_1/2** | **MA:Pu=1:2** | **1/5** | 12.5 | 49.9 (**ESFR**) |
| **Fleet2_LWR_MA/Pu_1/2** | | | | 49.9 (**LWR**) |
| **Fleet3_MA/Pu_1/2** | **MA:Pu=1:2** | **1/9** | 6.9 | 55.5 (**ESFR**) |
| **Fleet3_LWR_MA/Pu_1/2** | | | | 55.5 (**LWR**) |



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# The German P&T study (2012-2014)

| Indicators | No P&T | No P&T but R&D | Regional implementation of P&T | P&T in Germany |
|---|---|---|---|---|
| **Mass HLW (HM only)** | 212 t vitrified HLW<br><br>10500 t SNF at 2022 | 212 t vitrified HLW<br><br>10500 t SNF at 2022 | 212 t vitrified HLW<br><br>**2 – 3 t of HM due to reprocessing losses** | 212 t vitrified HLW<br><br>**3 – 4 t of HM due to reprocessing losses**<br><br>**3 t due to last transmuter** |
| **Thermal output after 50 y** | ~7.0×10$^{6}$ W | ~7.0×10$^{6}$ W | ~ 6.45×10$^{6}$ W | ~ 6.45×10$^{6}$ W |
| **Thermal output after 500 y** | ~ 2×10$^{6}$ W | ~ 2×10$^{6}$ W | **Reduced by 1-2 orders of magnitude** | **Reduced by 1-2 orders of magnitude** |
| **Radiotoxicity after 50 y** | ~1.4×10$^{12}$ Sv | ~1.4×10$^{12}$ Sv | ~1.4×10$^{12}$ Sv + relatively small contribution coming from 30-40 tons FPs due to transmutation | ~1.4×10$^{12}$ Sv+ relatively small contribution coming from 170 (ADS) or 525 (FR) tons FPs due to transmutation |
| **Radiotoxicity after 500, 10000, 1000000 y** | ~5.0×10$^{11}$ Sv<br>~7.0×10$^{10}$ Sv<br>~9.0×10$^{8}$ Sv | ~5.0×10$^{11}$ Sv<br>~7.0×10$^{10}$ Sv<br>~9.0×10$^{8}$ Sv | **Reduced by 1-2 orders of magnitude** | **Reduced by 1-2 orders of magnitude** |

# The German P&T study (2012-2014)

| Indicators | **No P&T** | **No P&T but R&D** | **Regional implementation of P&T** | **P&T in Germany** |
|---|---|---|---|---|
| **Secondary waste due to P&T** | Not applicable | Not applicable | Short-lived intermediate level waste due to operation<br>Long-lived waste due to reprocessing depends on the technologies used. **An increase of the order of 5-10 times if compared to No P&T can be estimated**<br>Waste from decommissioning slightly increased<br>Operational, reprocessing and decommissioning secondary waste can be shared in the regional scenario | Short-lived intermediate level waste due to operation<br>Long-lived waste due to reprocessing depends on the technologies used. An increase of the order of 5-10 times if compared to No P&T can be estimated<br>Waste from decommissioning slightly increased |
| **Facility capacity/number requirements** | Interim storage - geological repository for accommodating the above indicated quantities | Interim storage - geological repository for accommodating the above indicated quantities | Irradiation: **6-7 units for 30-40 years (e.g. 400MWth EFIT)**<br><br>Reprocessing and Fabrication:<br>If TRU elimination in ~30-40 y<br>**15 t HM/y for EFIT-like**<br>**if time span longer (~150 y)**<br><br>Geological repository in Germany for accommodating FP and losses | Irradiation: **7-8 units for 150 years (400MWth EFIT-like or 1200 MWth ASTRID-like)**<br><br>Reprocessing and Fabrication:<br>**9-10 t HM/y for EFIT-like or 24 t HM/y for ASTRID like**<br>Geological repository in Germany for accommodating FP and losses |
| **Facility requirements to comply with accepted dose limits** | Associated to interim storage | Associated to interim storage | At reprocessing, fabrication and irradiation plants ad hoc technological solution to limit the dose to workers can be considered as part of P&T additional costs | At reprocessing, fabrication and irradiation plants ad hoc technological solution to limit the dose to workers can be considered as part of P&T additional costs |

# The German P&T study (2012-2014)

| Indicators | **No P&T** | **No P&T but R&D** | **Regional implementation of P&T** | **P&T in Germany** |
|---|---|---|---|---|
| **R&D requirements** | Interim storage - geological repository | Interim storage - geological repository + specific R&D activities in international context to understand issues on P&T | Interim storage - geological repository + R&D on P&T: e.g. design of transmutation device and fuel, materials, thermal-hydraulics, safety, decommissioning reprocessing | Interim storage - geological repository + R&D on P&T: e.g. design of transmutation device and fuel, materials, thermal-hydraulics, safety, decommissioning reprocessing |
| **Uranium inventory** | 9710 t | 9710 t | 9710 t or less if recovered U is used by on-going countries | 9710 t |
| **Knowledge availability** | R&D Knowledge in all relevant technical area is presently available but it could be progressively lost | R&D knowledge in selected technical area should be developed | R&D knowledge in all relevant technical areas Design, construction, operational and decommissioning knowledge can be shared at EU level | R&D knowledge in all relevant technical areas as well as further design, construction, operational and decommissioning knowledge will be needed |