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Advanced fuel cycles and final disposal of radioactive waste: mutually exclusive or useful allies?

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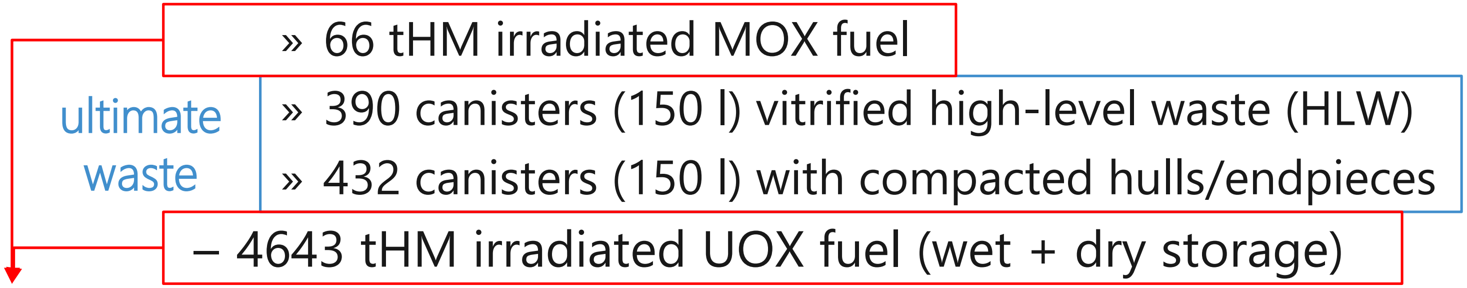
Outline

- Spent fuel in Belgium
- Why advanced partitioning?
- Disposal options currently considered by NIRAS/ONDRAF
- Results from EC project Red-Impact (generic)
- Application to Belgian situation
- Additional considerations
- Take-home messages and reflections

Spent fuel in Belgium

- Since 1975: nuclear energy in Belgium
  - 7 PWR reactors: 4 at Doel NPP, 3 at Tihange NPP
  - Irradiated nuclear fuel
    - < 1993: Reprocessing + reuse of Pu (and REPU) as MOX-fuel
    - > 1993: No more reprocessing
    - Projections at reactor EOL:
      - – 630 tHM irradiated fuel reprocessed



        - » 66 tHM irradiated MOX fuel
        - » 390 canisters (150 l) vitrified high-level waste (HLW)
        - » 432 canisters (150 l) with compacted hulls/endpieces
      - – 4643 tHM irradiated UOX fuel (wet + dry storage)

- What to do with spent fuel?

→ Management option has direct influence on amount and radiotoxicity of final radioactive waste streams

Spent fuel management options

- Composition of SF after irradiation
  - still high amount of fissile/fertile materials
    - 93,6% U
    - 1,0% Pu
    - 0,08% Np
    - 0,18% Am
    - 0,002% Cm
  - Rest: ~5% fission and activation products

Table 3.1: Mass content in the Belgian irradiated fuel inventory in 2035.

U (t)	**Pu(t)**	**Minor Actinides**			
U (t)		Np (t)	Am (t)	Cm (t)	FP (t)
		3.72	8.01	0.26	
4768	54.94	12.00			23.67

- Management options
  - Direct disposal
  - Classical reprocessing (partial or full)
  - Reprocessing with **advanced partitioning**

Why partitioning?

2 applications

1

- Partitioning of (activation- and) **fission products** for transmutation (**P&T**) or (interim) storage and conditioning in tailored matrices (**P&C**)

Emphasis on reduction of RN lifetime

- **Long-lived**: ^{99}Tc (214ky), ^{126}Sn (230ky), **^{79}Se** (356ky), ^{93}Zr (1.53My), ^{135}Cs (2.3My), ^{107}Pd (6.5My) and **^{129}I** (16.1My)

→ only ^{99}Tc en ^{129}I are theoretically fit for transmutation, but efficient transmutation is hard to achieve

determine dose impact in case of geological disposal

Emphasis on optimisation of repository footprint

- **Heat producing**: ^{137}Cs (30y) and ^{90}Sr (29y)
- Removal of Mo and noble metals → higher glass loading

Why partitioning?

2 applications

2

- Separation of **actinides** to recycle/transmute
  - At industrial level: in advanced reactor types with fast neutrons

To make optimal use of fissile resources

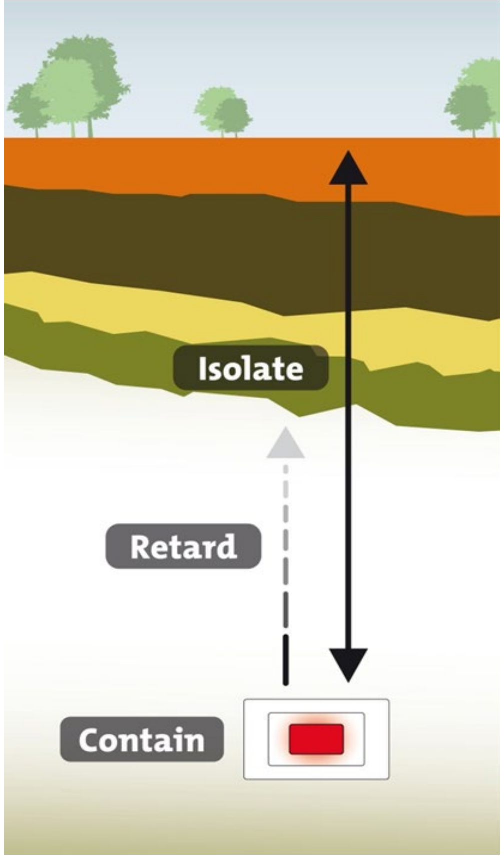
- Generation IV reactors: **critical** reactors

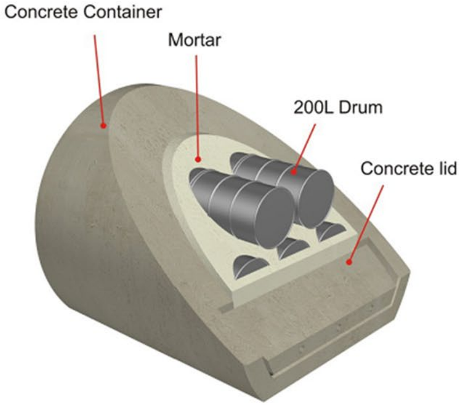
To reduce radiotoxicity

- ADS (Accelerator Driven Systems): **sub-critical** reactors

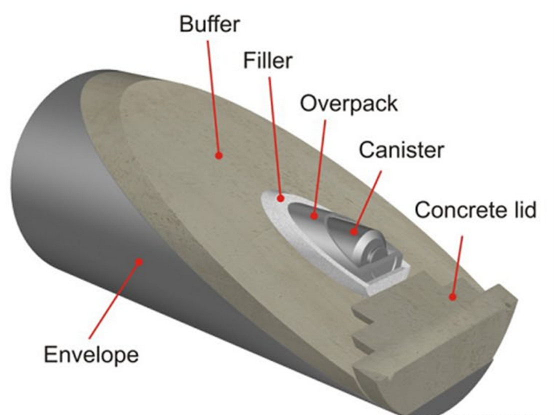
ONDRAF/NIRAS disposal concept LILW-LL, HLW, SF

- Geological co-disposal of category B (LILW-LL) & category C (=heat emitting) waste



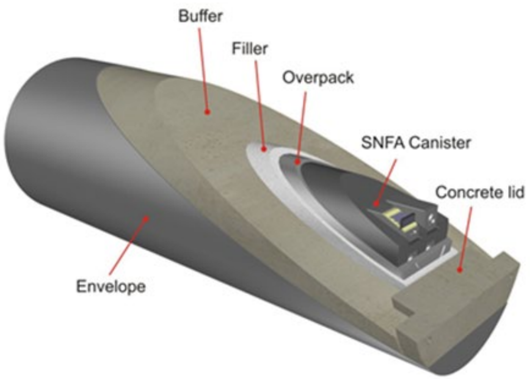


Monolith (Category B)

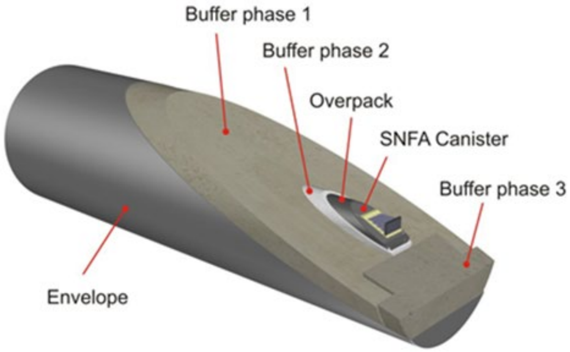


Figures by ONDRAF/NIRAS

Supercontainer (HLW)



Supercontainer (UOX)



Supercontainer (MOX)

Advanced fuel cycles and waste management

Red-Impact comparative study

Industrial fuel cycles

open cycle

- **A1:** reference “once through” cycle in PWRs
  UOX spent fuel

partially closed cycle

- **A2:** mono-recycling of Pu as MOX in PWRs
  V-HLW, ILW, MOX spent fuel
- **A3:** multi-recycling of Pu in (Na-cooled) FRs
  V-HLW, ILW

Innovative fuel cycles

closed cycle

- **B1:** multi-recycling of Pu and MA in (Na-cooled) FRs
  V-HLW, ILW
- **B2:** double strata cycle of PWR’s en ADS
  V-HLW (UOX, MOX, ADS), ILW (MOX, ADS-pyro, ADS-oper)

All of these are ‘equilibrium’ scenarios

Impact of advanced fuel cycles on
natural U use

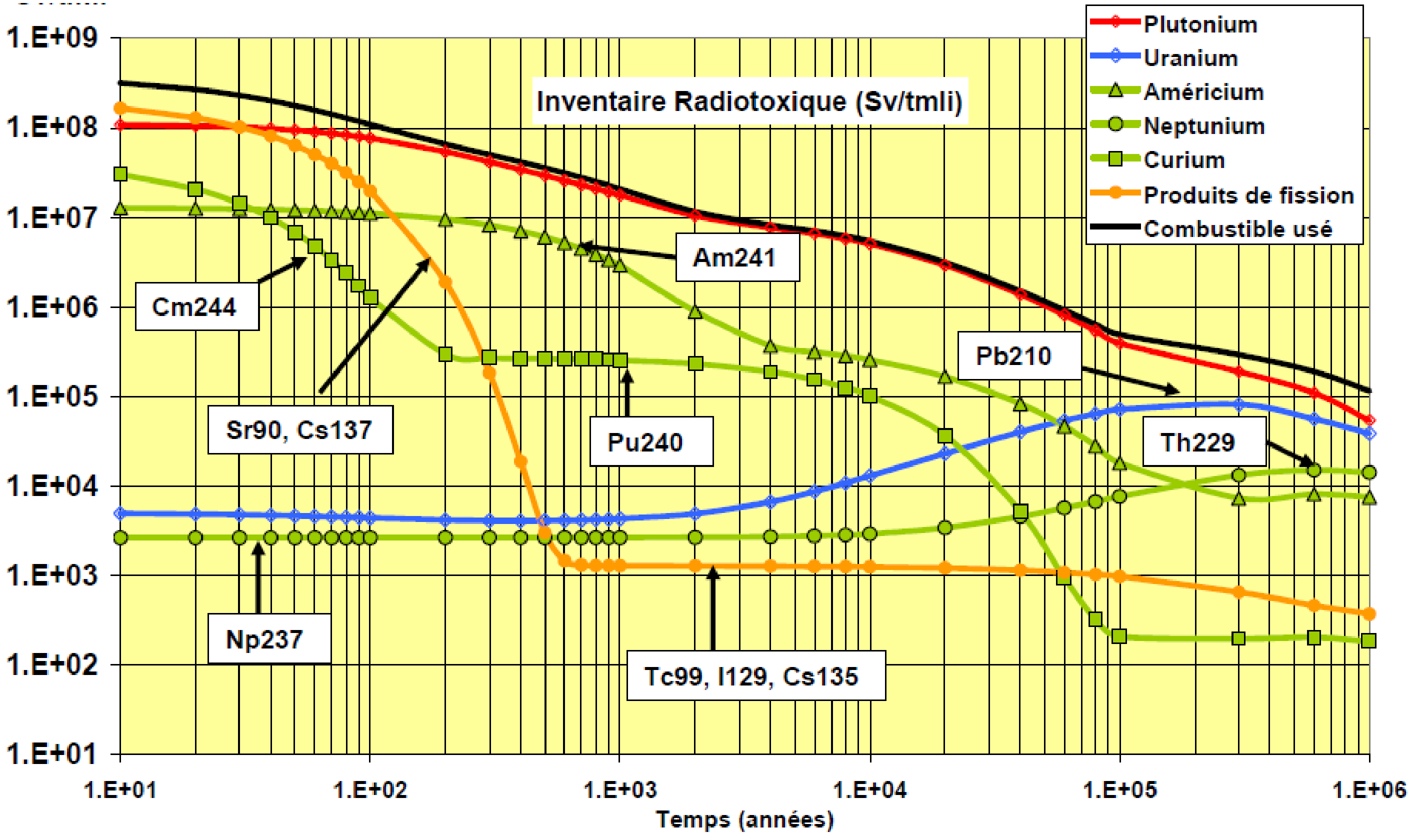
- Natural U use for production of 1 TWh(e):

Fuel cycle		A1	A2	A3	B1	B2
Nat. U consumption	kg/TWh(e)	20723	18448	986	106	15766
normalised		**1**	**0.89**	**0.048**	**0.0051**	**0.76**

A1: open cycle PWR with UOX fuel
A2: mono-recycling of Pu as MOX in PWRs
A3: multi-recycling of Pu in Na-cooled FRs
B1: multi-recycling of Pu and MA in Na-cooled FRs
B2: double strata cycle of PWR's and ADS

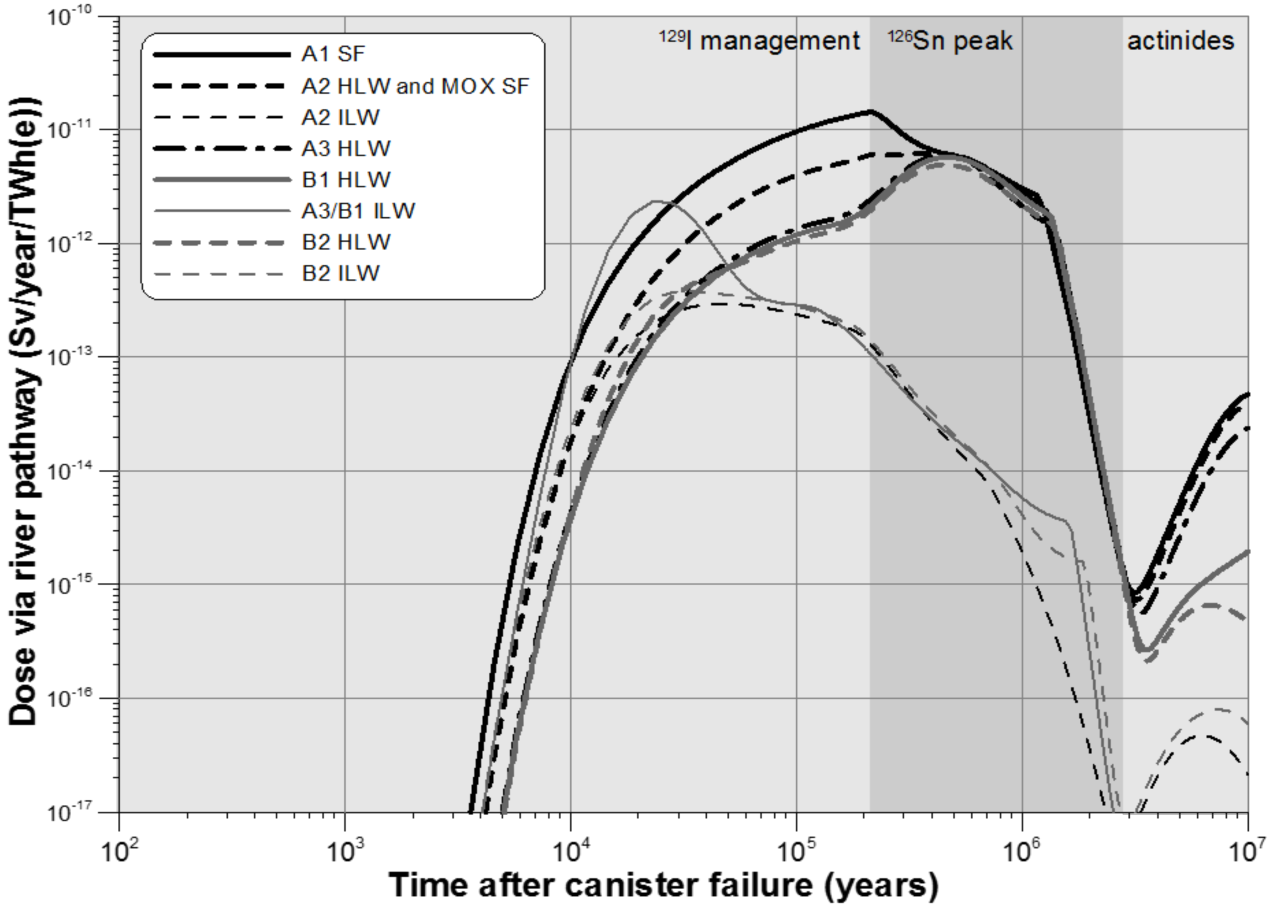
- **B2**: 25% more efficient w.r.t. U consumption
- Fast reactors (**A3/B1**): efficiency x 100 and more through use of natural or depleted U in MOX instead of enriched U

Impact of advanced fuel cycles on **radiotoxicity (activity × dosefactor ingestion)**



- Radiotoxicity /10 if Pu is recycled (multi-recycling)
- Radiotoxicity /100 if Pu and MA are recycled

Impact of advanced fuel cycles on
long-term dose of geological disposal of SF in clay



- Typical bimodal shape: actinides are very well sorbed in clay host rocks
- Differences mainly due to fate of I-129, and amounts of ILW produced

Impact of advanced fuel cycles on **waste volumes**

- Dimensions of waste packages as in Red-Impact (basically not much more than an overpack)

Fuel cycle		A1	A2	A3	B1	B2
TOTAL HLW	(m^3/TWhe)	3.86	2.13	1.27	1.21	1.41
relative TOTAL HLW	**(-)**	**1.00**	**0.55**	**0.33**	**0.31**	**0.37**
TOTAL HLW + ILW	(m^3/TWhe)	3.86	4.62	6.57	6.50	4.75
relative HLW +ILW	**(-)**	**1.00**	**1.20**	**1.70**	**1.68**	**1.23**

- Dimensions of waste packages as proposed by ONDRAF/NIRAS (monoliths and supercontainers)

Fuel cycle		A1	A2	A3	B1	B2
TOTAL HLW	(m^3/TWhe)	27.01	22.85	15.82	14.96	17.53
relative TOTAL HLW	**(-)**	**1.00**	**0.85**	**0.59**	**0.55**	**0.65**
TOTAL HLW + ILW	(m^3/TWhe)	27.01	27.25	25.19	24.33	23.44
relative HLW +ILW	**(-)**	**1.00**	**1.01**	**0.93**	**0.90**	**0.87**

Impact of advanced fuel cycles on
repository footprint (HLW only)

- Red-impact: only HLW considered (no ILW)
- Theoretical maximum disposal density:
  decay heat calculations versus near field temperature criterion <100°C

Fuel cycle		**A1**	**A2**	**A3**	**B1**	**B2**
TOTAL HLW	(m^2/TWhe)	711	464	174	94	145
relative	**(-)**	**1.00**	**0.65**	**0.24**	**0.13**	**0.20**

Factor ~10

- Variants of B1: Impact of separation of ^{137}Cs and ^{90}Sr:
  - Hypotheses:
    - Cs and Sr streams are individually vitrified (waste loading 60%)
    - 100 years decay storage

Fuel cycle		**B1.1 (40FP-60Cs-60Sr)**	**B1.4 (60FP-60Cs-60Sr)**
TOTAL HLW	(m^2/TWhe)	21.86	21.95
relative	**(-)**	**0.031**	**0.031**

Factor ~30

Potential size reduction for Belgian geological repository
needed gallery length (km)

	No further reprocessing	Full reprocessing	MA+FP P&T case
	Disposal gallery length (km)	Disposal gallery length (km)	Disposal gallery length (km)
fuel cycle dependent			
UOX spent fuel	15.43	-	-
MOX spent fuel	0.79	-	-
V-HLW future	-	6.39	1.23
Total C waste	16.22	6.39	1.23
CSD-C future	-	1.40	2.07
Total B&C waste	16.22	7.79	3.30
relative	**1.00**	**0.48**	**0.20**
fuel cycle independent			
historic waste	5.74	5.74	5.74
V-HLW existing	0.79	0.79	0.79
CSD-C existing	0.14	0.14	0.14
GRAND TOTAL	**22.90**	**14.47**	**9.98**
relative	**1.00**	**0.63**	**0.44**

MA+FP P&T case based on extrapolations from Oigawa et al. 2006

Potential size reduction for Belgian geological repository

needed repository footprint (km²)

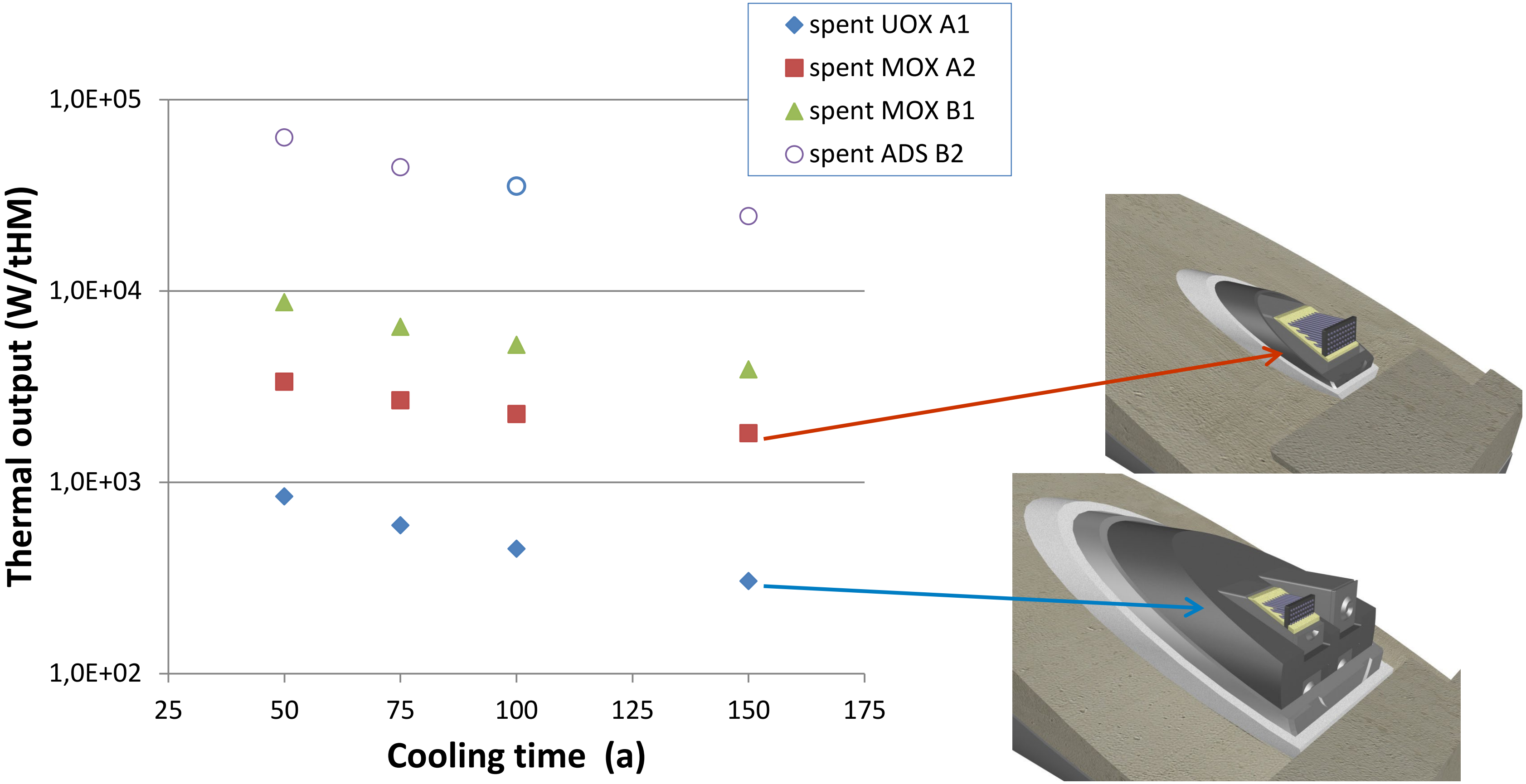
	No further reprocessing	**Full reprocessing**	**MA+FP P&T case**
	footprint (km^2)	**footprint (km^2)**	**footprint (km^2)**
fuel cycle dependent			
UOX spent fuel	1.85	-	-
MOX spent fuel	0.10	-	-
V-HLW future	-	0.32	0.06
Total C waste	1.95	0.32	0.06
CSD-C future	-	0.07	0.10
Total B&C waste	1.95	0.39	0.17
relative	**1.00**	**0.20**	**0.08**
fuel cycle independent			
historic waste	0.29	0.29	0.29
V-HLW existing	0.04	0.04	0.04
CSD-C existing	0.01	0.01	0.01
baseload non-waste footprint	1.30	1.20	1.18
plugs	*0.14*	*0.04*	*0.02*
shaft and access gallery zones	*1.16*	*1.16*	*1.16*
GRAND TOTAL	3.58	1.92	1.68
relative	**1.00**	**0.54**	**0.47**

Other considerations
research needed

- Materials science
  - Reactor materials
    - High neutron fluxes in FR : strong activation e.g. ^{14}C
      → (further) development of low-activation materials
  - Waste matrices
    - P&T/P&C: separation of fission products, new types of waste streams
      → waste conditioning requires new types of waste matrices, with at least comparable durability in disposal conditions as spent fuel as such
- Process research
  - Reprocessing
    - High BU of the fuel/new fuel types: need for new reprocessing techniques (advanced PUREX, pyro-reprocessing)
  - ADS as actinide burner
    - High efficiency only after several irradiation cycles, requiring **long times (~100y)**
    - P&T should ideally be embedded in a regional (e.g. European) approach
      - U, Pu → recycle / to market
      - See EC projects PATEROS/ARCAS for estimates of #EFIT's needed to reduce MA stock

Other considerations
Heat output of FR and ADS spent fuel

- reactor shutdown (at EOL or unforseen circumstances)
  - Spent fuel from FR and ADS



Take-home messages

- Geological disposal is needed in every scenario considered.

- The time needed for isolation & confinement in geological disposal is equal in all scenarios, because it depends on impact of mobile fission and activation products, which are not targeted in any P&T scenario

- **Partitioning** helps to reduce repository size
  - Full reprocessing: ↓ needed gallery length with **factor 2**
  - FP Partitioning (Cs/Sr decay): ↓ needed gallery length with **factor 5**

- **Transmutation** helps to reduce the waste's radiotoxicity
  - Pu multi-recycling: ↓ radiotoxicity with **factor 10**
  - Pu multi-recycling + MA transmutation: ↓ radiotoxicity with **factor 100**

Reflections

- Radiotoxicity is not an indicator for a potential exposure situation
  - Trade-off between hypothetical doses in far future and actual doses to workers in nuclear facilities

- Difficulties with translating waste streams from fuel cycle scenarios into
  - #waste packages
  - inventory per waste package

  due to uncertainties on
  - conditioning matrix: glass, cement, other?
  - waste loading?
  - secondary waste streams?
  - waste classification? (category C → B; category B → A)

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