Closing the fuel cycle

^{238}U

(U, Pu,MA)N

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Intended learning outcomes

One may achieve a fully closed nuclear fuel cycle by combining

1. recycle of Pu in LWRs and/or fast neutron Gen-IV reactors
2. burning of minor actinides in fast neutron Gen-IV reactors

+ Repository requirements are alleviated

- The cost of producing nuclear power increases

After this lecture you will be able to:

- **Assess the impact on a geological disposal from closing the fuel cycle**
- **Optimise a reactor fleet with respect to cost/volume/inventory objectives**

Minor actinide production in LWRs

LWR UO_2 assembly

Unit: kg/TWh_{th}

Cooling time	4 years	30 years
Pu	8.51	7.89
Np	0.54	0.57
Am	0.44	1.17
Cm	0.04	0.03
Σ MA	1.02	1.77

LWR MOX assembly

Unit: kg/TWh_{th}

Cycle	1st (MOX)	5th (MOX-UE)
Pu		-22
Np	0.0	0.0
Am	4.1	4.0
Cm	0.8	1.1
Σ MA	4.9	5.1

- MA production rate in LWR fleet depends on cooling time before recycle
- Pu from LWRs may be recycled as mixed oxide (MOX) fuel in LWRs
- Safety manageable if manufactured with up to 4% enriched U (MOX-UE)
- Zero net production of Pu when fraction of MOX-UE assemblies is 28%
- Average MA production rate in LWR fleet: 2.1- 2.7 kg/TWh_{th}

Minor actinide production in fast reactors

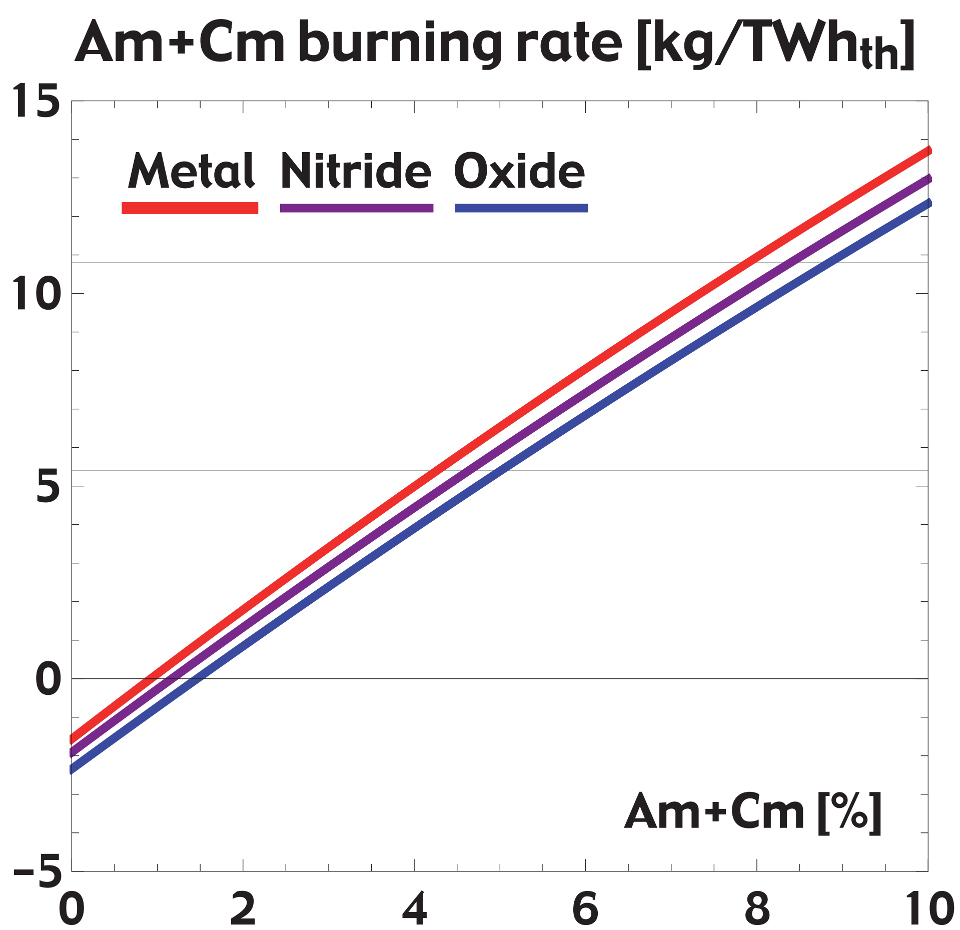
SFR $(U_{0.87},Pu_{0.13})O_2$ assembly, CR ≈ 1.0

Unit: kg/TWh_{th}

Burn-up	50 GWd/ton	100 GWd/ton
Pu	≈ 0.0	≈ 0.0
Np	0.12	0.17
Am	1.94	1.80
Cm	0.08	0.25
Σ MA	2.14	2.22

- Minor actinide production rate in fast reactor MOX fuel is < 1/2 of that in LWRs, in spite of higher Pu concentration in fuel. Why?
- Starting fast reactors on Pu from LWRs, reduces MA production in a nuclear fleet
- Higher burn-up results in higher specific production rate of Cm

Minor actinide burning rate in fast reactors



- For given MA fraction, metal alloy fuels provide the highest burning rate.
- > 1.0 - 1.5% BoL inventory required for net MA burning to occur.
- 4% BoL inventory yields burning rates of 4 - 5 kg/TWh_{th}
- 8% BoL inventory yields burning rates of 10 - 11 kg/TWh_{th}
- Which fraction of fast reactors is required to achieve net zero production of MA in nuclear fleet?

Closed fuel cycle scenario example

^{235}U

- Pu recycle as MOX-UE in 28% of LWR assemblies
- 83% of fleet power

MOX-UE

$(U,TRU)O_2$

^{235}U

- MA feed from LWRs to FR with CR = 1.0
- 17% of fleet power

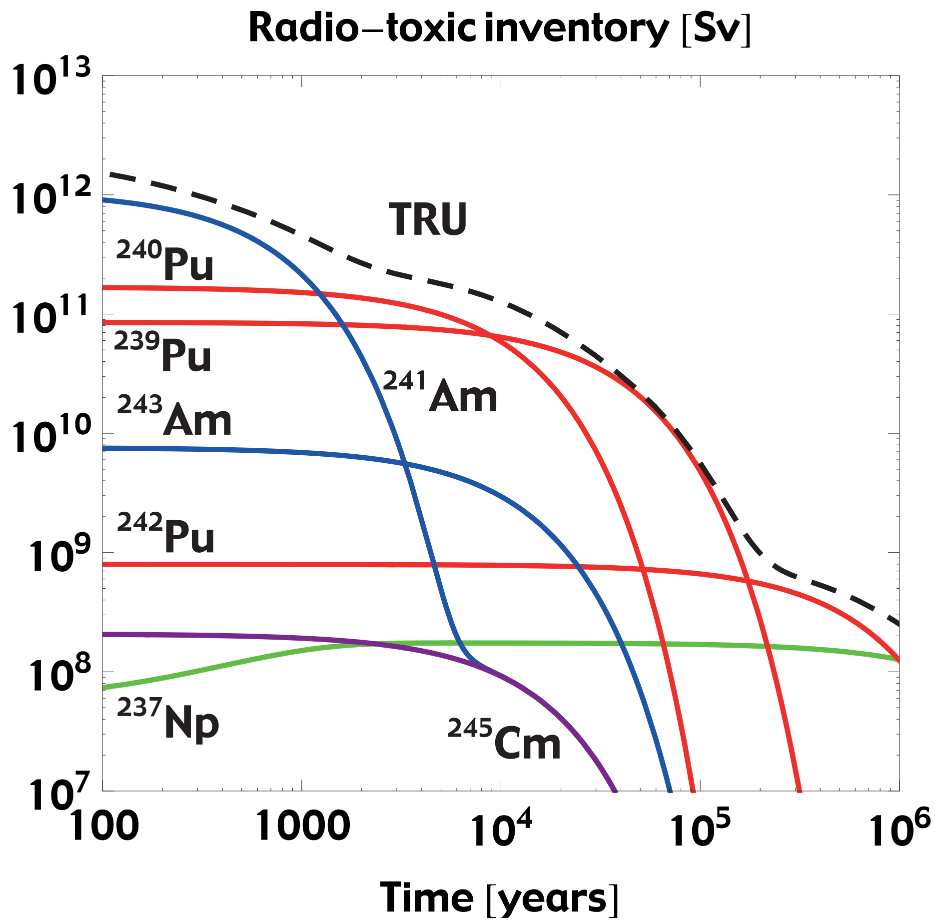
MA

^{238}U

(U, Pu,MA)N

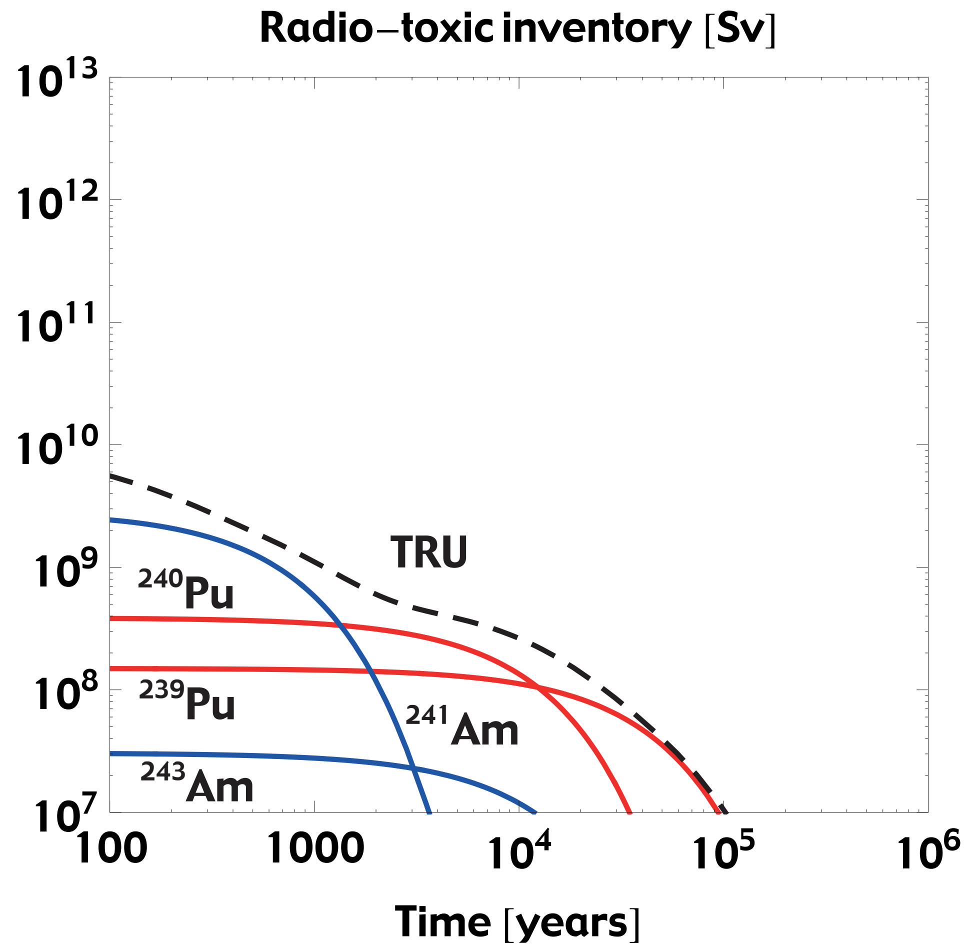
Radiotoxic inventory in geological repository

120 y of 10 GWe LWR fleet
with direct disposal



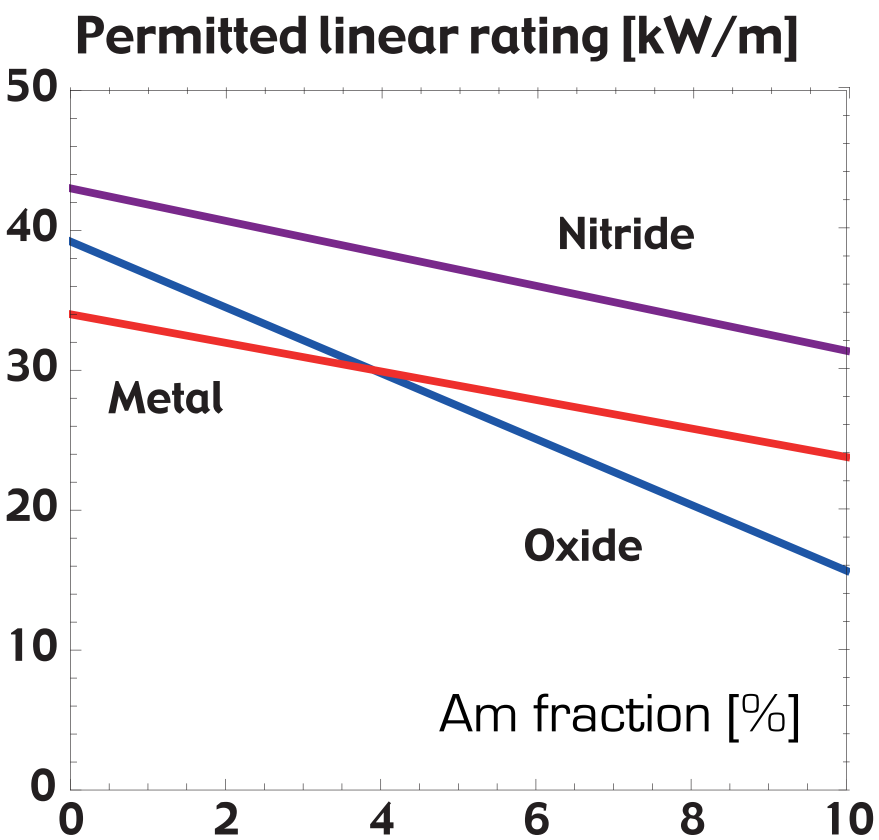
1 GSv inventory: 200 000 years

120 y of 10 GWe closed fuel cycle
with 0.1% reprocessing losses



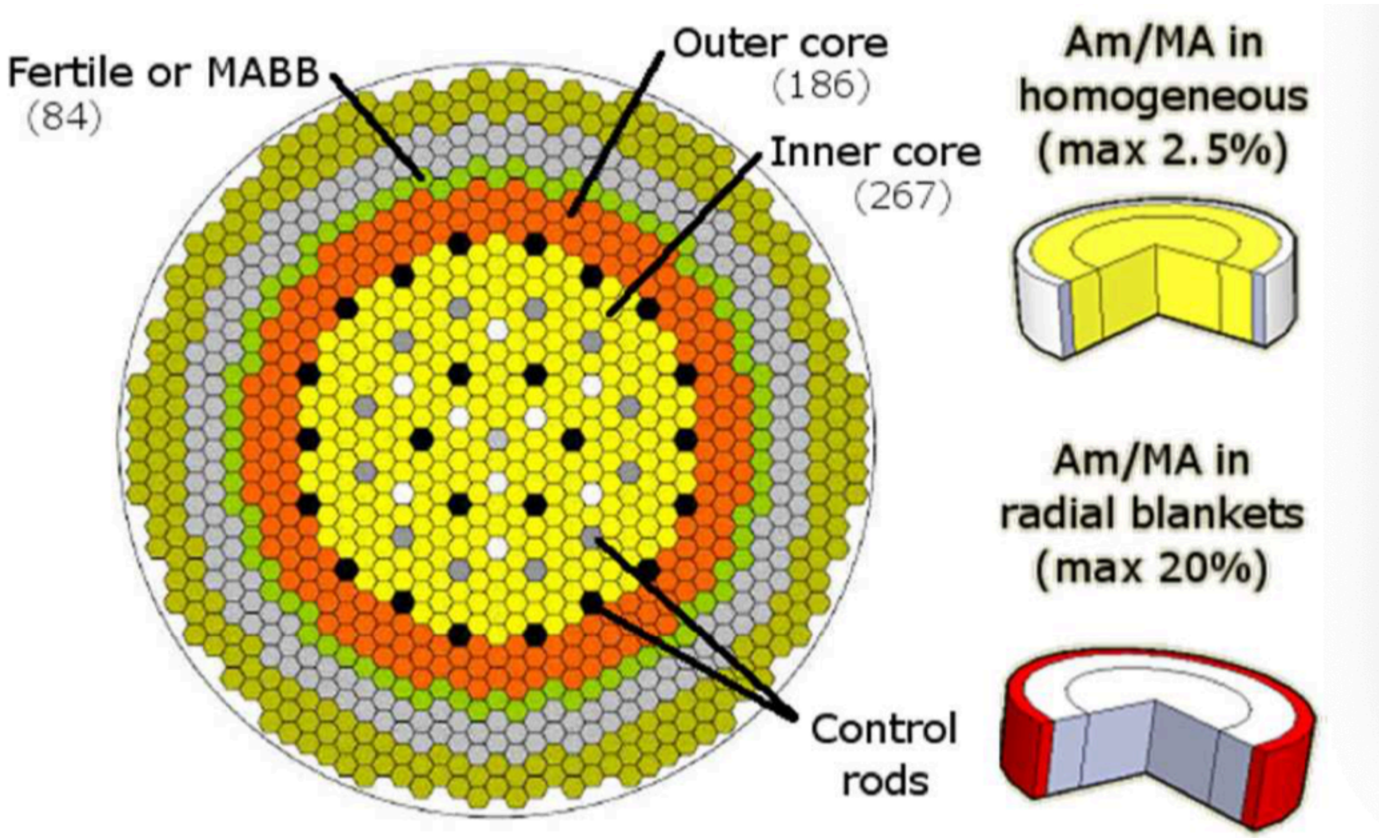
1 GSv inventory: 1000 years

Cost penalty



- For 4% Am fraction, the permitted power density in a reactor with oxide or metal fuel is 75% of that in a reactor with nitride fuel
- At 8% fraction the oxide fuel reactor may operate at 60% of the power of the nitride fueled reactor.

French solution: Minor actinide burning blanket



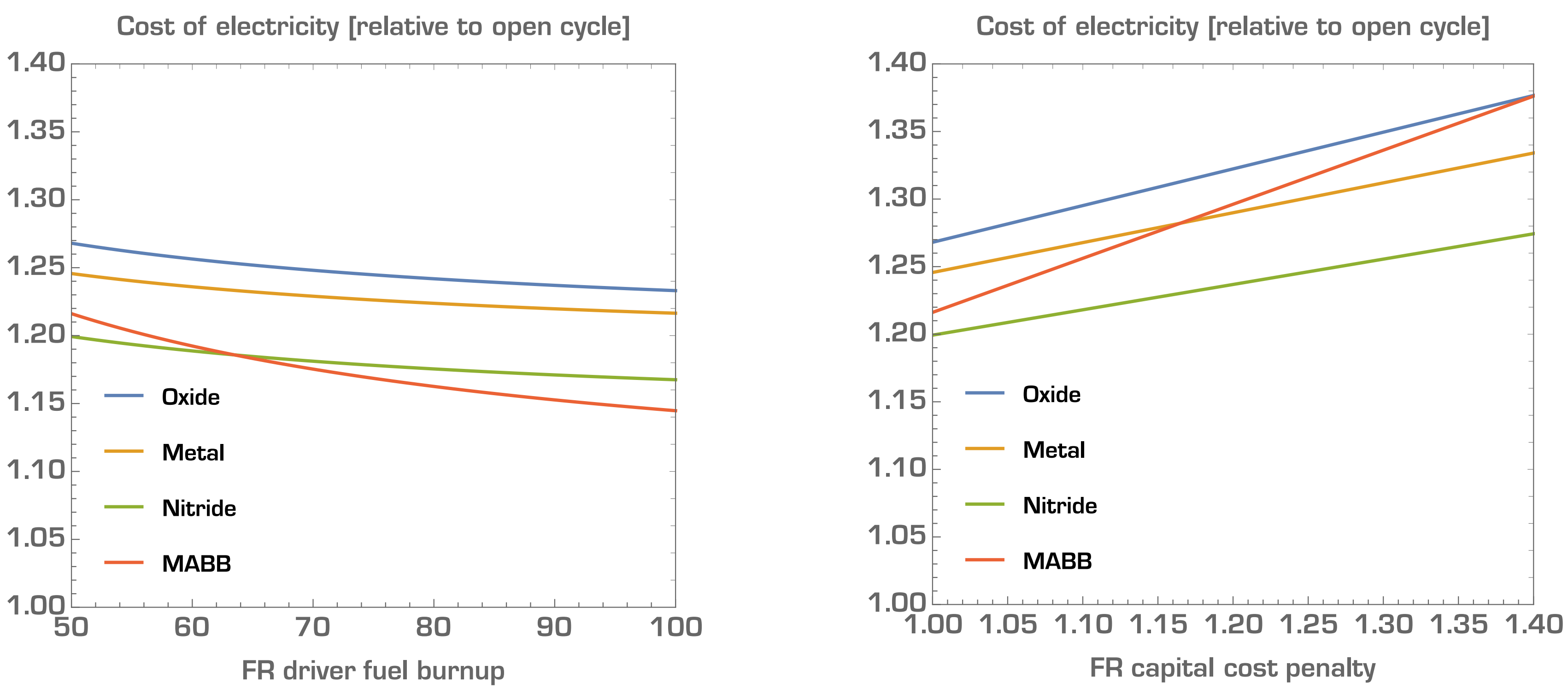
- Placing Am in the radial blanket of a fast reactor with $(U,Pu)O_2$ fuel, the detrimental impact on safety parameters is minimized
- $(^{238}U_{0.8},Am_{0.2})O_2$ is considered feasible to manufacture on industrial scale and has sufficiently low decay heat at EoL to be managed in air.
- Burning rates are reduced due to lower flux in blanket vs driver fuel.
- Larger fraction of FRs required

Cost/benefit analysis

- **ASSUMPTIONS:**
  - LWR MOX fuel cost: USD 12000/kg
  - Gen-IV fuel cost: USD 9000/kg (why would it be cheaper?)
- Specific capital cost for building a fast reactor is the same as for a light water reactor,
- Conversion efficiency from thermal to electrical power is 42% in the fast reactor,
- Average cost for producing electricity in an LWR is 0.05 €/kWh.
- Average fuel burn-up in the fast reactor is 50 GWd/ton,
- Fuel related cost penalty in fast reactors is the same for MA in driver fuel and in blankets.

MA transmutation route	FR-oxide	FR-metal	FR-nitride	MABB
Fraction of thermal power	0.20	0.16	0.18	0.40
Fast reactor power penalty	0.72	0.74	0.95	1.0
Closed fuel cycle CoE penalty	27 %	24 %	20 %	22 %

Sensitivity of penalty to assumptions



- Increasing burn-up in fast reactor reduces penalty slightly
- Largest benefit for MABB case
- Increasing fast reactor capital cost increase penalty significantly
- Largest penalty for MABB case

Concluding questions

- What are the potential benefits of fully closing the fuel cycle?
- What is the cost driver for implementation of Gen-IV reactors?
- How can costs be minimised?
- What is the ideal fraction of Gen-IV reactors in the nuclear fleet?