5) Closing the fuel cycle

Learning outcomes:

After working through this chapter, you will be able to:

1) Calculate the reduction in radio-toxic inventory and heat load of a geological repository resulting from an assumed fuel cycle scenario.
2) Assess the impact on geological repository from closing the fuel cycle
3) Optimise a reactor fleet for a given objective (cost/repository volume/inventory).

Background:

The second GIF criterion concerns waste minimisation. One may interpret that as reduced production of long-lived high level waste in power reactors and/or recycle of fissionable nuclides in spent fuel. In both of these aspects, fast spectrum Generation IV reactors can make a decisive contribution.

Let us first quantify the stream of long-lived high level waste resulting from current light water reactor fleets. Table 5.1 lists the mass of plutonium and minor actinides present in spent UO_2 fuel with an original enrichment of 4.1% and a burn-up of 50 GWd/ton. Since ^{241}Pu decays into ^{241}Am with a half-life of 14 years, and ^{244}Cm decays into ^{240}Pu with a half-life of 18 years, the values are provided for two different cooling times, corresponding to delays in reprocessing typical for a country with an established reprocessing industry, and one that decides to enter a closed fuel cycle strategy after several decades of nuclear power production.

Table 5.1: Pu and MA inventories in spent LWR fuel, in units of 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

Plutonium may be recycled in LWR or fast reactors. In the former case, single recycle as mixed oxide fuel (MOX) is industrial standard in France, Switzerland and the Netherlands. Multi-recycling of Pu in LWRs can be accomplished using minor modifications in the MOX fuel design, such as using enriched uranium, instead of depleted uranium, for manufacturing of the MOX fuel [Youinou 2005]. This is likely to be the cheapest and nearest term option for industrial plutonium management, but increases specific production rate of higher actinides in the LWR fleet. First generation MOX assemblies produce 4.1 kg Am and 0.8 kg Cm per TWh$_{th}$. When reaching equilibrium between plutonium production in UOX assemblies and Pu burning in MOX-UE assemblies, 28% of the power is produced in the latter [Delpech 1999], and the average production rate of higher actinides in the LWR fleet increases from 0.5 up to 1.8 kg/TWh$_{th}$. Out of this, 20% is curium [Wallenius 2011].

If instead, plutonium is used to start up a fleet of fast reactors, the production rate of minor actinides in the MOX fuels of such reactors is smaller than in the MOX fuel of LWRs. This is a consequence of fertile plutonium nuclides having a fission probability of about 0.5 in a fast spectrum (see Chapter 2). Table 5.2 displays plutonium and minor actinide production rates in a sodium cooled iso-breeder with $(U_{0.87},Pu_{0.13})O_2$ fuel, where the initial Pu vector corresponds to that of spent LWR fuel after four years of cooling (Table 5.1).

Data are provided for two burn-ups, corresponding to (a), the same value as for MOX fuel in an LWR, and (b) the target burn-up for MOX fuel in fast reactors (100 GWd/ton).

Table 5.2: MA production rates in the driver $(U_{0.87},Pu_{0.13})O_2$ fuel of an SFR, in units of kg/TWh$_{th}$. Values are given after four years of cooling.

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

From these numbers, we may conclude that for the same burn-up as in an LWR, the production rate of minor actinides is less than half of that in an LWR-MOX assembly. Moreover, the curium production rate is one order of magnitude lower. When doubling the burn-up of the fast reactor fuel, part of the latter advantage is lost.

Of course, an additional advantage pertaining to the introduction of fast reactors is the vastly improved resource utilisation (first GIF criterion), where this class of reactors enlarges the available fuel resource by two orders of magnitude. The corresponding multi-recycle of Pu in LWRs yields only a modest increase of 30% relative to the use of UO_2.

Heat production

Figure 5.1 shows the time evolution of heat production in one kilogram of spent LWR fuel [Wallenius 2011].

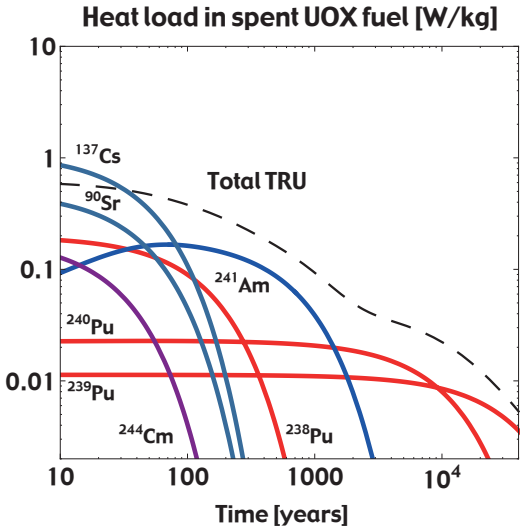

Figure 5.1: Evolution of heat load in spent UO_2 fuel from LWRs [Wallenius 2011].

After decay of the most highly active fission products, heating is dominated by ^{241}Am during the first 2000 years. Dimensioning of a geological granite or clay repository is determined by the requirement that the temperature of water saturated bentonite should not exceed 100°C after shutting down forced cooling systems in connection with closure of the repository. Consequently, there is a minimum distance between vertically placed spent fuel canisters in a granite repository concept of about nine meters [Von Lenza 2009].

If instead, americium and plutonium are recycled, high-level waste packages will contain fission products and losses of transuranium elements only. The distance between canisters may then be reduced to about two meters, and the volume of the entire repository by a factor of six. In the case of a clay repository with horisontal placement of canisters, the corresponding reduction in volume is estimated at a factor of three [Von Lenza 2009]. These improvements can obviously not be achieved if americium is not recycled.

Radio-toxicity

Closing the fuel cycle also reduces the long term radio-toxic inventory of the high-level waste repository. Figure 5.3 (left pane) illustrates the radio-toxic inventory of a geological repository accommodating the high level waste stream of an LWR fleet with a capacity of 10 GW that has been operating for 120 years, producing a total of 28 000 tons of spent UO_2 fuel [Zakova 2013]. Out of this, 270 tons constitutes plutonium, 20 tons neptunium, 40 tons americium and 0.7 tons of curium. 100 000 years after closure of the repository, americium and ^{240}Pu have decayed to less radio-toxic nuclides and the residual inventory is about 10 GSv. After 200 000 years, ^{239}Pu has decayed into ^{235}U, and the radio-toxic inventory has diminished to 1 GSv, or about 0.1% of the initial value.

Zakova and Wallenius calculated the inventory resulting from implementing a fully closed fuel cycle where plutonium from spent UO_2 fuel is recycled as MOX fuel (supported with enriched uranium), and all minor actinides are recycled in nitride fueled, lead-cooled fast reactors featuring a Pu conversion ratio equal to 1.0. The latter reactors produce 17% of the power of the entire fleet. The radio-toxic inventory of actinides ending up in the geological repository due to reprocessing losses is shown in the right pane of Figure 5.3. The calculation assumed that the losses of plutonium and minor actinides were equal to 0.1% in each reprocessing campaign.

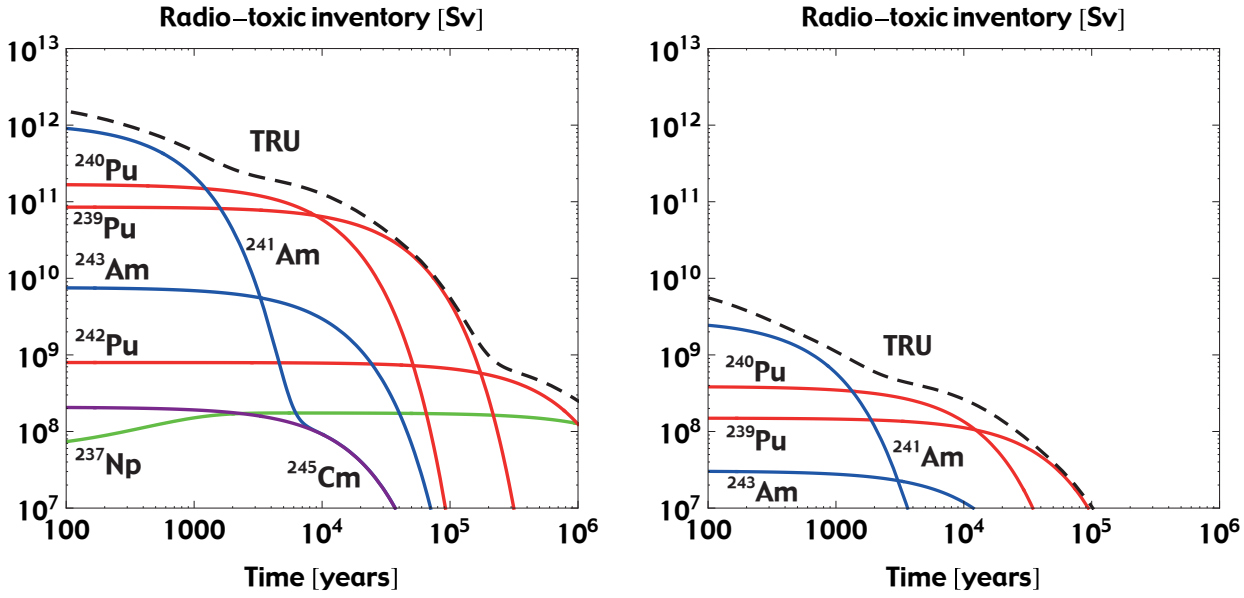

Figure 5.2: Left pane: Inventory of radio-toxicity in a geological repository accommodating spent UO_2 fuel from a 10 GW LWR fleet operating for 120 years. Right pane: Corresponding inventory for a scenario when Pu is recycled in LWRs as MOX fuel, and minor actinides are managed in lead-cooled fast neutron reactors with a Pu conversion ratio equal to unity [Zakova 2013]. In the latter case, the inventory consists of reprocessing losses.

In this case, the inventory is lower than 10 GSv already at closure of the repository and decreases to 1 GSv within 1000 years. One may argue that the time required for the repository to function as intended has been reduced by two orders of magnitude.

Here, one should recall that the inventory of plutonium and minor actinides that is present in the cores of the reactor fleet at the time of closing the (first) repository is considerably larger that that ending up in the same.

In order to reduce the remaining inventory, one may introduce actinide burners or accelerator driven systems with uranium free fuels [Dufek 2006, Fazio 2007, Wallenius 2019], which through a gradual reduction of the number of reactors may reduce the inventory in the nuclear power fleet to a magnitude similar to that in the first repository. This procedure would require another 100 years to be completed.

Cost penalty

Nuclear industry today believes that the capital cost of fast reactors may be of similar, if not even lower than for modern light water reactors designed for passive safety, i.e. of the order of 7000 USD/kWe installed capacity on US soil (the corresponding number in China is 3000 USD/kWe). Rosatom reported that the capital cost of building BN-800 in Russia was 3400 USD/kWe.

However, the use of plutonium and minor actinide bearing fuels would likely eliminate that advantage. Remote handling must be applied for MOX fuel fabrication, and adding americium to that may require industrial scale introduction of hot cells. Using numbers for the cost of reprocessing provided by OECD/NEA, the cost of LWR-MOX fuel can be estimated at 12 000 USD/kg (in 2019 dollars). Out of this, 10 000 USD/kg is the cost of reprocessing spent UOX fuel, and 2000 USD/kg is for manufacture of the MOX assembly [NEA 2002]. We may compare this to the 2019 market cost of 5% enriched UO_2 fuel (1000 USD/kg, see https://www.uxc.com/p/tools/FuelCalculator.aspx), and a UOX assembly manufacturing cost of 250 USD/kg [Boylan 2013]. Hence, if 30% of the fuel in an LWR constitutes of MOX assemblies, the fuel related cost of electricity from that reactor increases from about 0.3¢/kWh_e to 1.2¢/kWh_e.

In the same study, reprocessing of fast reactor driver MOX fuel was estimated to cost 2.5 times as much as reprocessing of LWR-UOX fuel. However, since the amount of fissile material in the spent fuel is the same as in next generation fresh fuel, the cost for the source material is about 4000 USD/kg, which is lower than for an LWR MOX fuel assembly. The cost of manufacturing a fast reactor MOX fuel assembly which includes minor actinides can be estimated at 5000 USD/kg of fuel. Hence, the total cost for a Generation-IV reactor fuel assembly is suggested to be 9000 USD/kg, or about eight times more expensive than an LWR-UOX assembly.

The energy released through fission in the latter assembly is 50-100 MWd_{th}/kg. Taking into account that fast reactors produce power with a conversion efficiency $\eta \approx 0.42$ results a fuel specific cost for Gen-IV electricity of 0.9-1.8 ¢/kWh_e.

Nuclear fleet composition.

We may now study how to compose a nuclear fleet that employed a fully closed fuel cycle. This means that its long-lived high level waste stream constitutes of fission products and reprocessing losses only. First, let us consider the case where all plutonium is recycled in LWRs using MOX fuel with support of enriched uranium. The minor actinide production rate of such LWRs is the average of that produced in UO_2 fuel assemblies (1.0 kg/TWh_{th}) and that of MOX-UE assemblies (2.2 kg/TWh_{th}). Since 28% of the latter is required to stabilise the plutonium inventory, the average MA production in the LWR fleet is 1.3 kg/TWh_{th}. We may now compare the cases of transmuting minor actinides in either the driver fuel or the blanket of Generation IV fast reactors.

Figure 5.3 shows the transmutation rates of higher actinides achievable in the driver fuel of an iso-breeding sodium cooled reactor. Data are provided for the case of oxide, nitride and metallic fuel. Note that the transmutation rate is zero for the equilibrium fraction of these elements, which varies between 0.8% and 1.6% for the three fuels in question. The highest transmutation rate is found for the metallic fuel, and the lowest for the oxide.

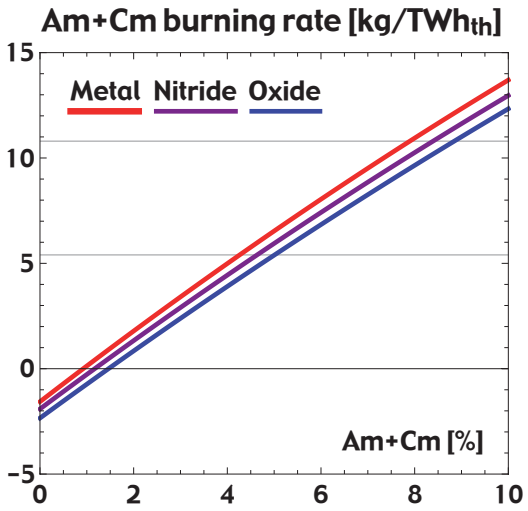

Figure 5.3: Higher actinide consumption rate in the driver fuel of Gen-IV fast reactors [Wallenius 2011].

As we have discussed in the previous chapter, the power density of passively safe fast reactors needs to be reduced when introducing minor actinides into the fuel, in order to maintain the margin to fuel and clad failure during un-protected over-power and loss-of-flow transients. Figure 5.4 displays the permitted linear rating of the three fuel candidates as function of americium content in the driver fuel [Zhang 2013].

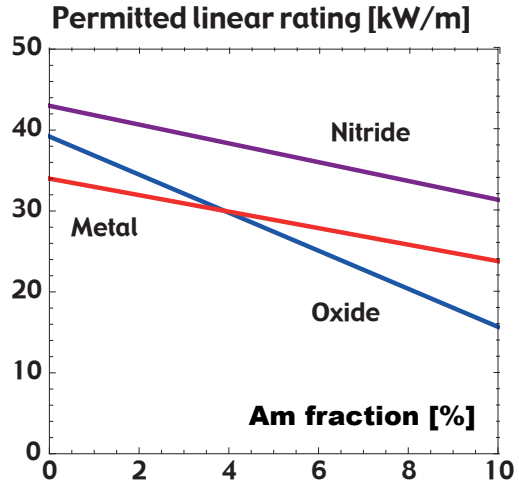

Figure 5.4: Permitted linear rating in Gen-IV sodium cooled fast reactors, as function of americium concentration in the driver fuel [Zhang 2013].

Due to a combination of high thermal conductivity and high failure temperature, the nitride fuel features the best performance. The metallic fuel is least affected by the introduction of americium, thanks to its higher axial expansion reactivity feedback.

We may now assess the cost penalty resulting from introducing fast reactors as minor actinide burners. The fraction of thermal power required to be produced in fast reactors in order stabilise the higher actinide inventory in the fuel cycle is given in Table 5.3, for a concentration of 5% of americium and curium in the driver fuel. Comparing to the case of heterogenous transmutation of these elements in a minor actinide bearing blanket, one finds that the homogeneous transmutation approach reduces the fraction of fast reactors in the nuclear fleet to less than half.

The second row shows the permitted operating power density of the fast reactor, relative to the MABB case, as derived from Figure 5.4. A value lower than 1.0 means that more fast reactors must be built to produce the same power. Finally, the third row displays the penalty on the cost of electricity produced by the fleet as a

whole (relative to that of a once through open cycle with 100% LWRs operating on UO_2 fuel), making the simplified assumptions that:

- the specific capital cost for building a fast reactor is the same as for a light water reactor,
- the conversion efficiency from thermal to electrical power is 42% in the fast reactor,
- the average cost for producing electricity in an LWR is 0.05 €/kWh.
- the average fuel burn-up in the fast reactor is 50 GWd/ton,
- the fuel related cost penalty in fast reactors is the same for MA in driver fuel and in blankets.

Table 5.3: Fraction of thermal power produced in fast reactors for the closed fuel cycle scenario where plutonium is multi-recycled in LWRs. The FR driver fuels are assumed to contain 5% higher actinides.

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 %

The cost of electricity in the closed fuel cycle, relative to the open cycle, is displayed in Figure 5.5, as function of driver fuel burn-up and fast reactor capital cost penalty. It may be observed that the MABB and the nitride fuel option have advantages with respect to the other alternatives, which mainly is related to the lower power penalty for operation of these cores. It should be noted that in the present model, LWR-MOX fuel is more expensive that FR-driver fuels, due to the much larger mass of spent UO_2 fuel from LWRs that must be reprocessed in the former case. We may recall that the specific amount of fissile nuclides in spent fast reactor fuel is at least a factor ten larger than in spent UOX fuel.

Here, an interactive graph can be inserted, where the reader can investigate the impact of uncertainties in penalties for fast reactor capital cost and fuel on the above conclusion.

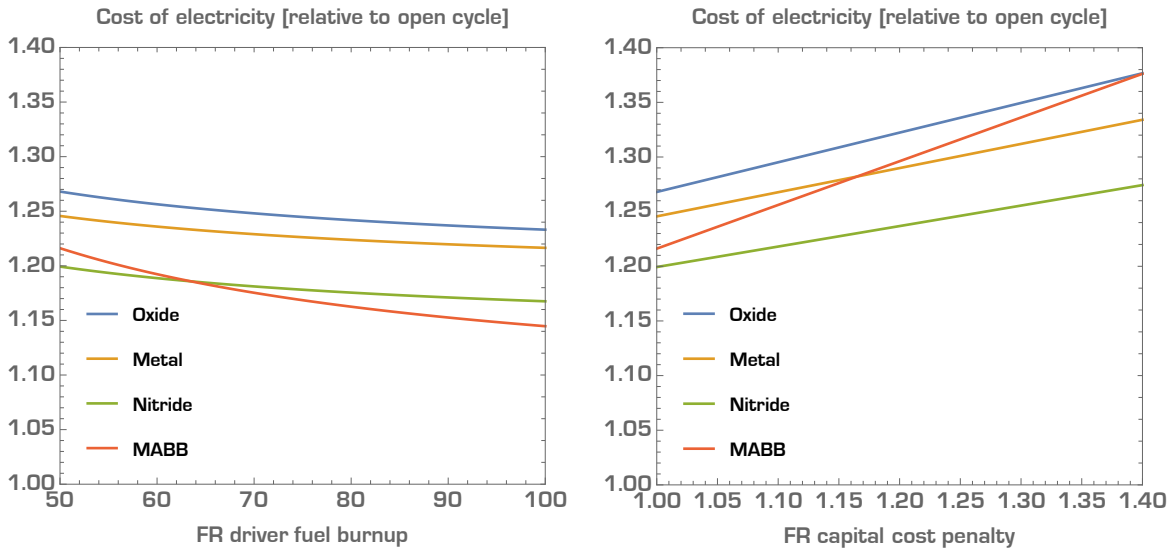

Figure 5.4: Estimated cost of electricity (CoE) in closed fuel cycles, where Pu is recycled as MOX in LWRs and MA is burned in fast reactors with CR=1.0. Left pane: CoE as function of fast reactor fuel burn-up, assuming that the capital costs of LWRs and FRs are the same. Right pane: CoE as function of fast reactor capital cost, relative to LWR capital cost, assuming an FR driver fuel burn-up of 50 GWd/ton.

Exercises:

1) Calculate MA burning rates in the driver fuel of a fast reactor
2) Calculate MA burning rates in the blanket of a fast reactor
3) Design a closed fuel cycle for a country with an existing LWR fleet

Questions:

1) How does one best achieve a reduction in radio-toxic inventory and heat emission of spent fuel?
2) What is the impact of closing the fuel cycle on repository related safety?
3) From a cost efficiency perspective, which reactors are suitable for Pu and/or MA management?

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