

Definition of Breeding Gain for the Closed Fuel Cycle

Application to Generation IV Gas Cooled Fast Reactor

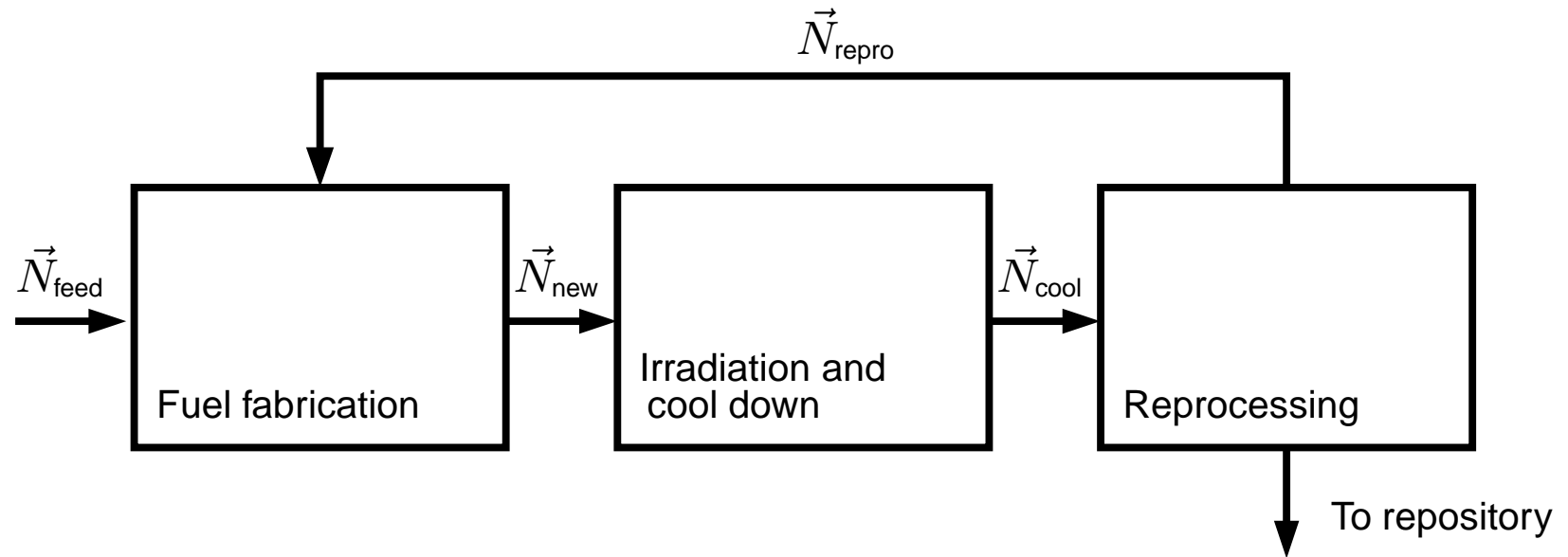
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Contents of this talk

- The closed fuel cycle, and a corresponding definition of Breeding Gain
- Some (new) definitions: reactivity weight and fuel performance
- Nuclide perturbation theory to estimate the effect of initial fuel composition on BG
- Application to a Generation IV GCFR closed fuel cycle
- Conclusions

The closed nuclear fuel cycle



- Only Fission Products to repository, all TRansUranic (TRU) material is recycled
- Add only fertile feed material to reprocessed fuel to make new fuel
- Performance ('reactivity') of newly made fuel is function of fuel at beginning of previous irradiation

Breeding Gain: Differential vs. Integral

Breeding Gain is measure of 'reactivity' ('fissileness') of fuel batch $i + 1$ compared to fuel batch i . If $BG = 0$ fuel cycle can be closed.

- *Integral* definition: use fuel inventories at two times t_1 and t_2 , compare performance. Advantage: easy definition. Disadvantage: requires solving entire irradiation history.
- *Differential* definition: use difference of reaction rates at time t_0 to estimate BG . Advantage: depends on composition at time t_0 only. Disadvantage: only applicable during irradiation.

Both integral and differential definitions of BG require a 'reactivity weight', quantifying how each nuclide contributes to the overall reactivity of the reactor.

Mathematical model

If reactivity weights can be defined, the performance parameter for BG can be written as a scalar product:

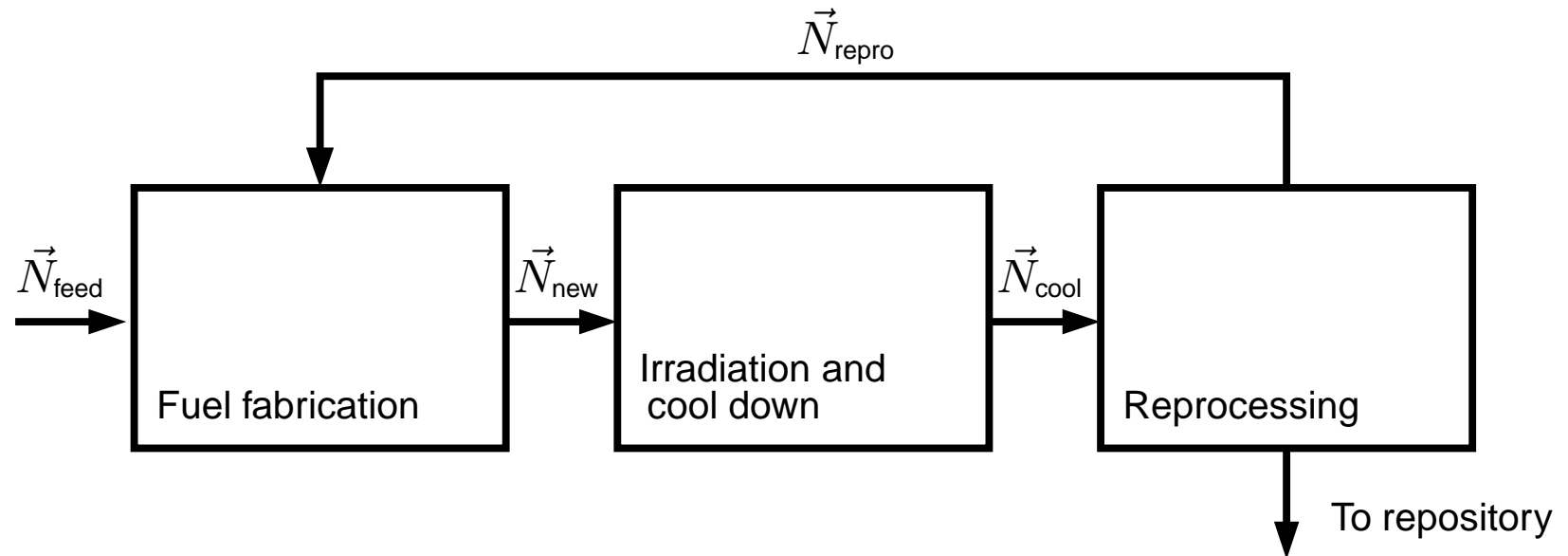
$$R(t) = \langle \vec{w}, \vec{N}(t) \rangle$$

The reactivity weight for nuclide i , w_i , is defined by considering the change of the reactivity of the reactor upon a change of density of nuclide i :

$$w_i \equiv \frac{\Delta \rho}{\Delta N_i} = \frac{\langle \phi_0^*, [\lambda_0 \frac{\partial P}{\partial N_i} - \frac{\partial L}{\partial N_i}] \phi_0 \rangle}{\langle \phi_0^*, P_0 \phi_0 \rangle}$$

(!) Note that this definition implies that w_i is a function of the reactor composition and layout.

Breeding Gain for closed fuel cycle



- Closed fuel cycle: calculate BG between fuel at BOC of batch $i + 1$ and BOC of batch i
- Fuel batch $i + 1$ depends on final composition of fuel batch i , after irradiation, cool down and reprocessing
- For optimization we want to calculate the performance of batch $i + 1$ as a function of the initial composition of batch i

Nuclide perturbation theory

Nuclide evolution is calculated with the transmutation equation:

$$\frac{d\vec{N}}{dt} = \underline{M}\vec{N} + \vec{Q} \quad (1)$$

For a response R defined as $R(t) = \langle \vec{w}, \vec{N}(t) \rangle$, the change of response (ΔR) due to changes in initial condition $\Delta\vec{N}(0)$, source term $\Delta\vec{Q}$ and nuclear data appearing in \underline{M} can be shown to be:

$$\Delta R = [\vec{N}_0^*(t=0)\Delta\vec{N}_0]_{\neq t} + \int_0^{t_f} \vec{N}_0^*[\Delta\vec{Q} + \Delta\underline{M}\vec{N}_0]_x dt$$

If only initial condition is changed, only the first term on RHS remains.

Recipe to calculate changes of BG

- Calculate forward irradiation and cool down of fuel mixture (transmutation equation)
- Calculate composition after reprocessing, and calculate composition of new fuel
- Calculate R_i , R_{i+1} , and $BG = \frac{R_{i+1}}{R_i} - 1$
- Calculate adjoint transmutation problem
- Calculate ΔR_{i+1} as a function of (hypothetical) changes of the initial density of nuclide i , $\Delta N_i(t = 0)$, and calculate the new BG .

For this research, an adjoint capable transmutation program was written based on the ORIGEN-S formalism: LOWFAT, *Like Origen With Forward and Adjoint Transmutation*,

GFR600: Generation IV GCFR

Theoretic framework was derived for application to GFR600, a 600 MWth Generation IV GCFR researched in European GCFR STREP.

- Helium cooled fast reactor, high temperature operation, using direct Brayton cycle
- Generation IV goal: sustainability. Closed fuel cycle, adding only U-238 to recycled material
- Plate fuel, UPuC fuel in SiC matrix, clad with SiC
- Reference fuel: UC / PuC fuel, 84% uranium, 16% Pu, low quality Pu (twice recycled in LWR)
- Delft University contribution: possibilities of adding extra MA to fuel for transmutation

BG for reference fuel and MA fuel

Breeding Gain was calculated for reference fuel (84% U, 16% Pu) and a fuel with 79% U, 16% Pu and 5% MA (Np-237, Am-241, Am-242, Cm isotopes).

	GFR 600 (ref)	GFR600 (5% MA)
R_{ini}	1.02	1.15
R_{irrad}	1.01	1.29
R_{cool}	0.932	1.22
R_{repro}	0.923	1.21
R_{feed}	-0.109	-0.097
R_{new}	0.813	1.11
BG	-20.2 %	-3.56 %

MA fuel has better overall *BG*, because reactivity increase during irradiation compensates losses in cool down and reprocessing.

Perturbations of initial conditions

Improve Breeding Gain: either add extra fissile material, or add extra fertile material to have higher R of the new fuel. Starting point is fuel with 5% MA.

<i>Extra fissile material</i>		<i>Extra fertile material</i>	
R_{ini}	1.27	R_{ini}	1.11
R_{irrad}	1.36	R_{irrad}	1.28
R_{cool}	1.29	R_{cool}	1.21
R_{repro}	1.28	R_{repro}	1.20
R_{feed}	0.09	R_{feed}	0.048
R_{new}	1.19	R_{new}	1.15
BG	- 6.42%	BG	+ 3.71 %

Conclusion: extra fertile material improves BG (as expected)

Long term evolution of the fuel

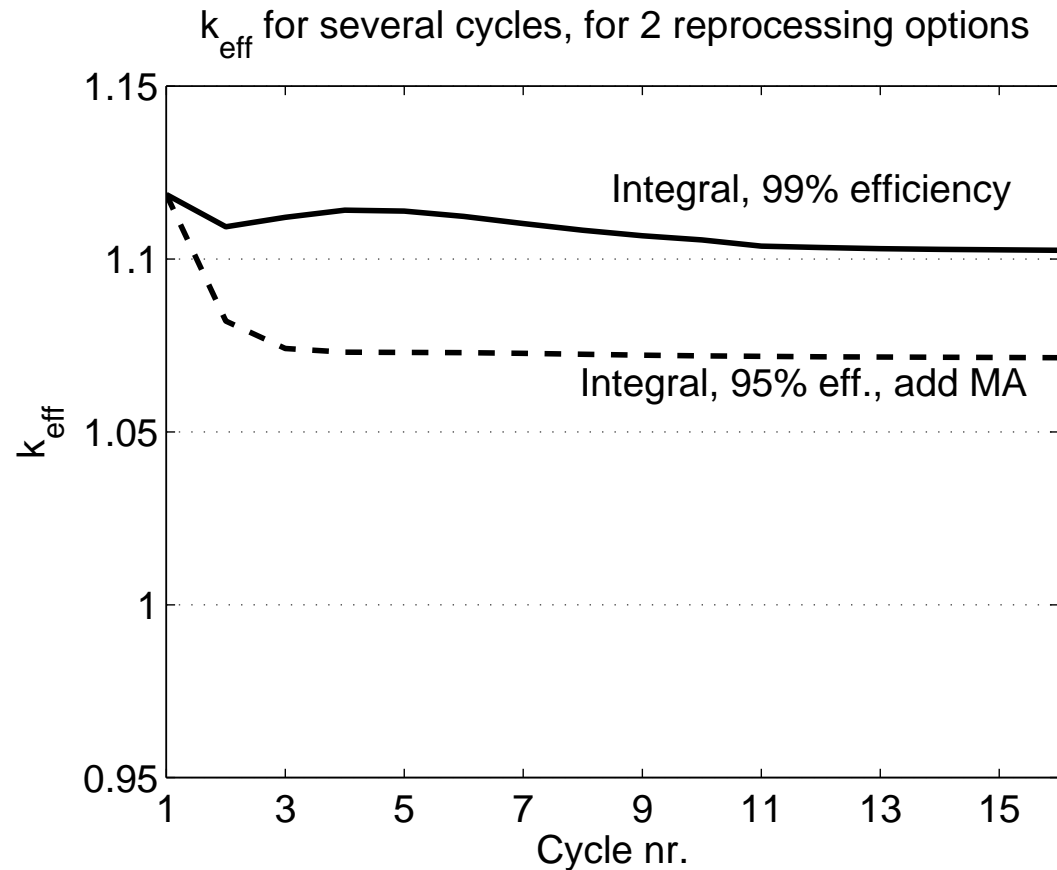
A calculation was done over several irradiation cycles. Two fuel cycle options are explored:

- Integral reprocessing, retrieving 99% of all TRU, adding only ^{238}U to make new fuel
- Integral reprocessing, retrieving 99% of all TRU, adding ^{238}U and 10% MA (Np, Am, Cm) to the fuel

Option 1 is a truly closed fuel cycle. Option 2 is explored because there are no existing integral reprocessing technologies, so their reprocessing efficiency is not known. Reactivity is lost due to reprocessing losses, which can be offset by adding extra MA to the fuel.

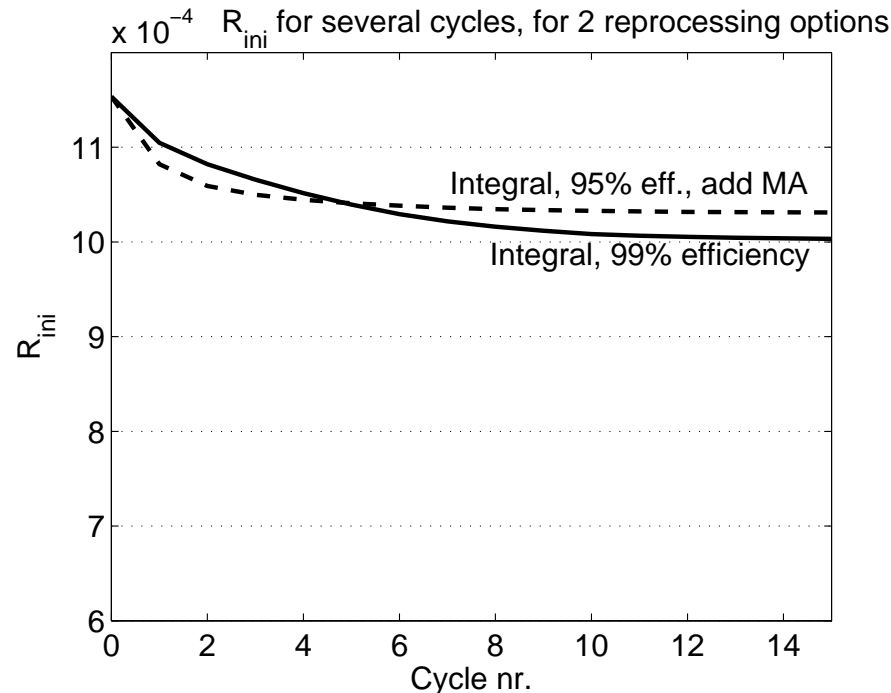
Evolution of k_{eff}

The value of k_{eff} from cycle to cycle for both reprocessing options



Evolution of R

The value of R for the fresh fuel from cycle to cycle



For both options, k_{eff} from cycle to cycle is the same. BG is also almost the same from cycle to cycle. Thus the proposed definition of BG does in fact yield $BG = 0$ if k_{eff} is equal from cycle to cycle.

Conclusions

- In the closed fuel cycle, Breeding Gain has to be defined taking into account irradiation, cool down and reprocessing
- The required reactivity weights can be defined using an eigenvalue perturbation approach
- Using nuclide perturbation theory an efficient method is found relating changes of initial fuel composition to the performance of the closed fuel cycle
- GFR600: reference fuel has negative Breeding Gain, adding some MA improves this and enables closed fuel cycle
- Truly closed fuel cycle is possible if reprocessing is highly efficient. For lower efficiency, adding small amounts of MA to the fuel can give $BG = 0$
- The proposed definition of BG does in fact yield $BG = 0$ if in the initial k_{eff} of the fuel is the same from cycle to cycle

Questions?

Time for questions, if you have any.

Acknowledgement

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