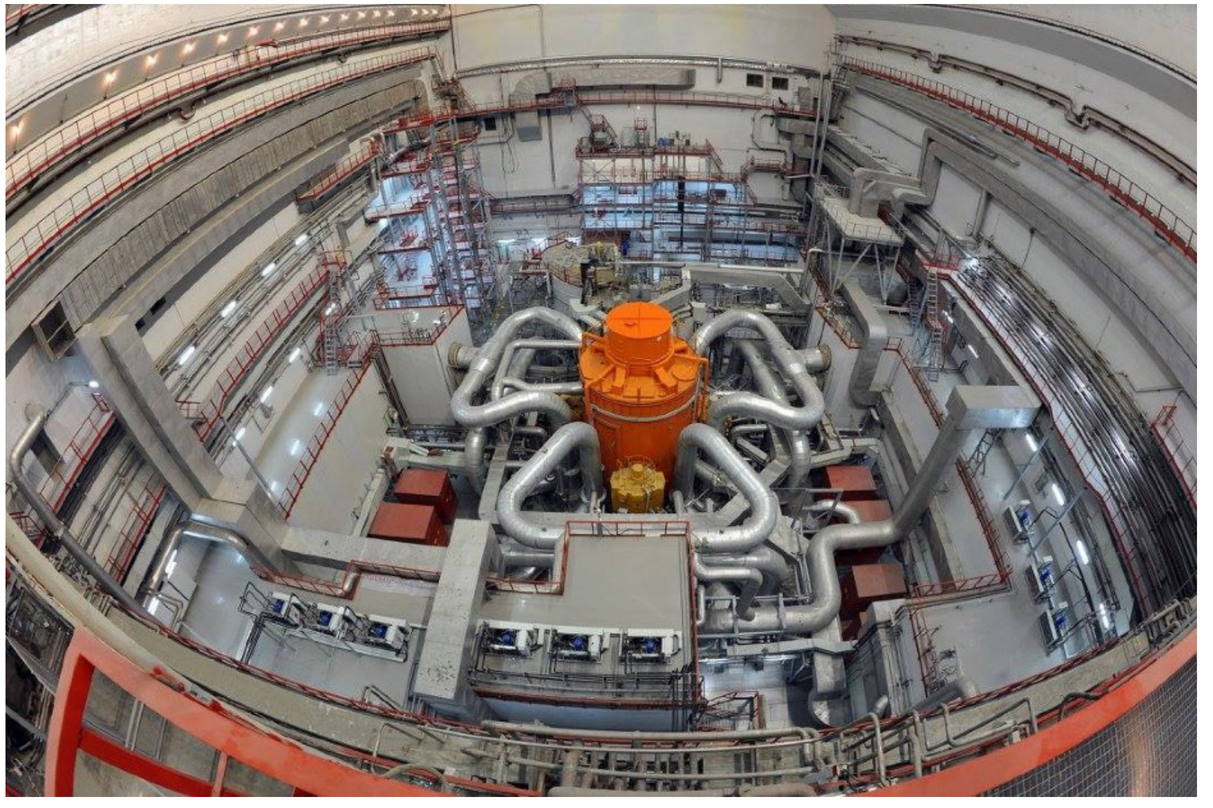
Physics of breeding



Janne Wallenius

Nuclear Engineering, KTH

Intended learning outcomes

Generation IV reactors are intended to

Increase fuel resources by a factor > 100 by breeding of fissile fuel from ^{238}U or ^{232}Th.

After today's meeting and associated home assignment, you will be able to

- **Evaluate the capacity of a reactor to breed fissile fuel from fertile nuclides**
- **Assess the impact of power density, fuel composition and coolant on breeding**
- **Develop unconventional approaches to breeding**

Why do we need breeding?

- Inventory of easily recoverable fissile nuclide is limited
- Fissile nuclides may be produced by neutron capture in “fertile” nuclides:
- $n + {}^{238}U \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \nu + e^- \rightarrow {}^{239}Pu + \nu + e^-$
- $n + {}^{232}Th \rightarrow {}^{233}Th + \gamma \rightarrow {}^{233}Pa + \nu + e^- \rightarrow {}^{233}U + \nu + e^-$
- Natural uranium consists of 99.3% ^{238}U
- Easily recoverable thorium resources ≈ twice of uranium resources

- How long may the world rely on nuclear fission power?
- Where do these fuel resources reside?

What is breeding, more exactly?

- **PURPOSE**
- The intention of breeding is to reload a nuclear reactor with its own spent fuel, adding only ^{238}U or ^{232}Th as top-up. Any surplus fuel may be collected to start additional reactors.

- **DEFINITION**
- The sum of reactivity changes during burn-up and subsequent cooling, reprocessing and re-fabrication of the fuel should be larger than zero.

Mathematical formulation

Instantaneous in-pile conversion ratio:

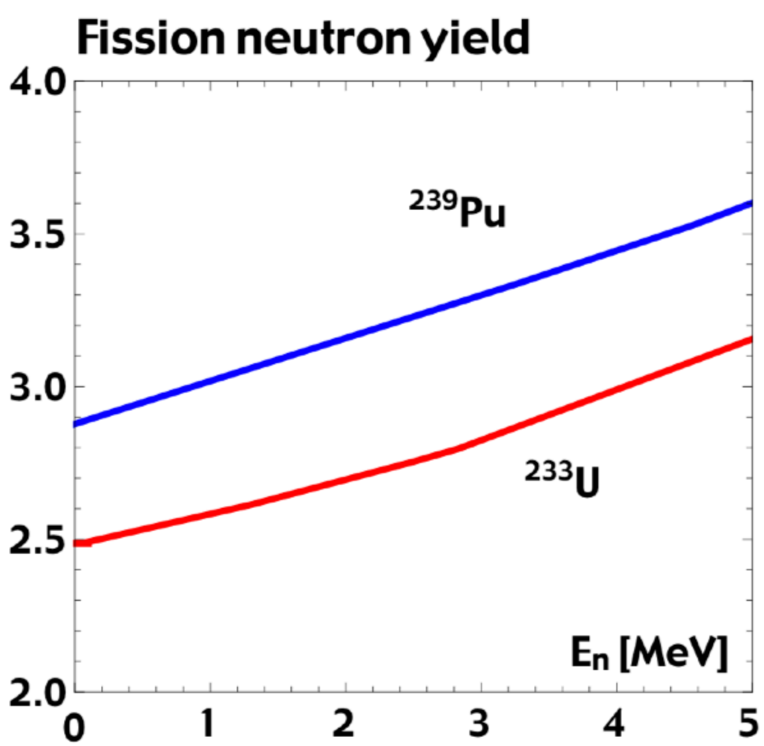
$$CR_{ip} = \frac{\sum_{A,m} \sigma_c({}^m A)C({}^m A)\eta({}^{m+1}A')}{\sum_{A,m} \sigma_f({}^m A)C({}^m A)\eta({}^m A)},$$

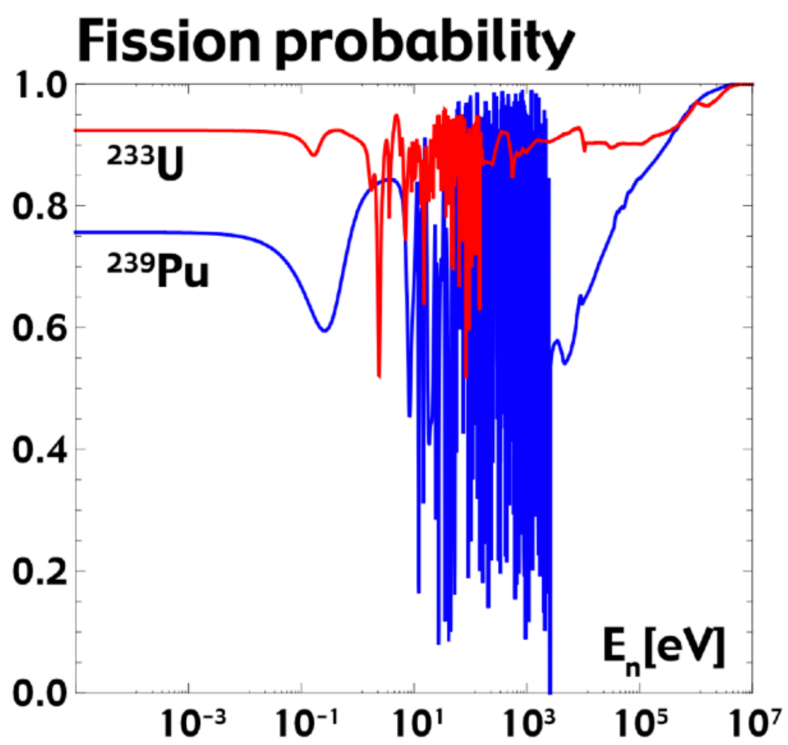
$$\frac{\text{Reactivity produced by capture}}{\text{Reactivity destroyed by fission}}$$

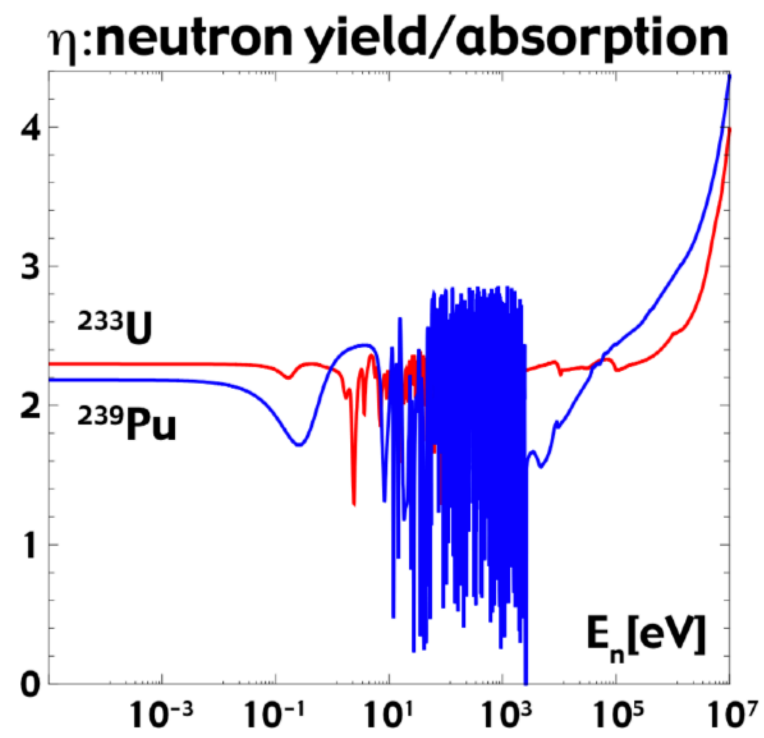
η-value

Average number of neutrons produced in an absorption

$$\eta = \nu \frac{\sigma_f}{\sigma_a} \simeq \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$







Thermal spectrum reactors

In a thermal spectrum reactor, we have

$\sigma_f\,(\text{fertile}) \approx 0$

$\eta\,(\text{fertile}) \approx 0$

$$CR_{ip} = \frac{\sigma_c(fertile) \times C(fertile) \times \eta(fissile)}{\sigma_f(fissile) \times C(fissile) \times \eta(fissile)} = \frac{\sigma_c(fertile) \times C(fertile)}{\sigma_f(fissile) \times C(fissile)}$$

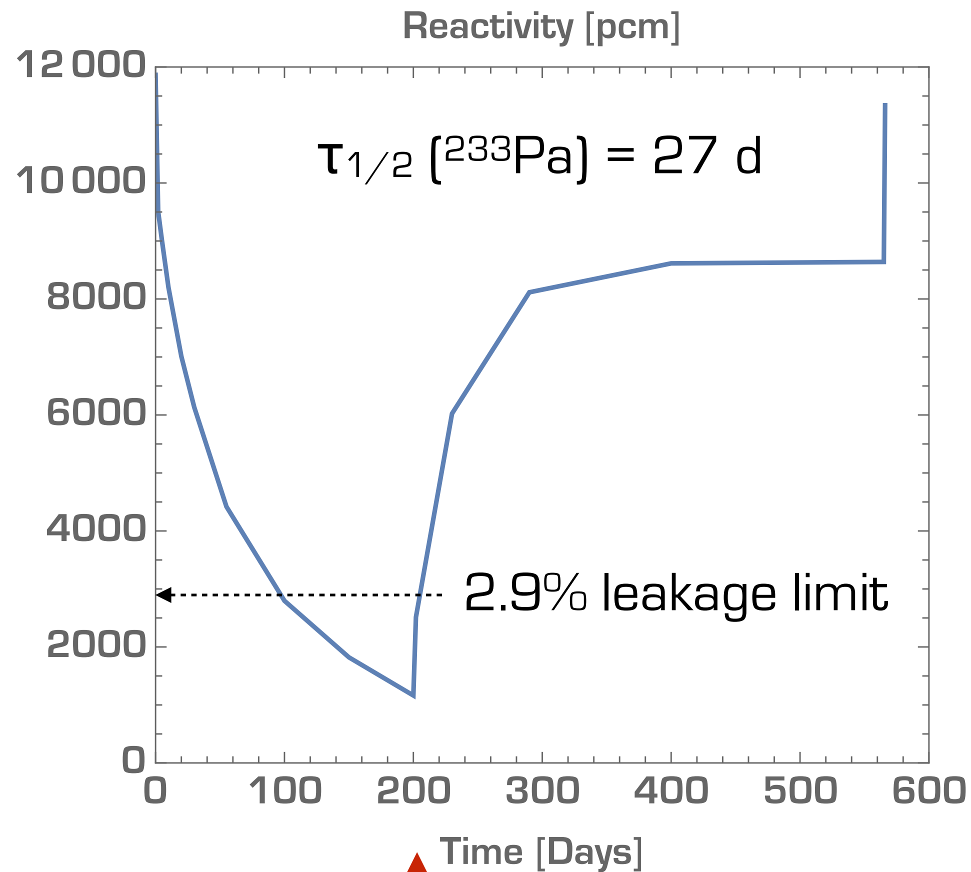
Independent of η!

Example: CANDU reactor

Cross sections for capture & fission

Cross section	Value
σ_c (^{232}Th)	1.84 b
σ_f (^{233}U)	118 b

- Which is the maximum concentration of ^{233}U permitted to obtain $CR_{ip} > 1.0$?



Maximum achievable burn-up ≈ 0.7%!

Fast spectrum reactors

In fast rectors, all nuclides have a significant probability for fission.

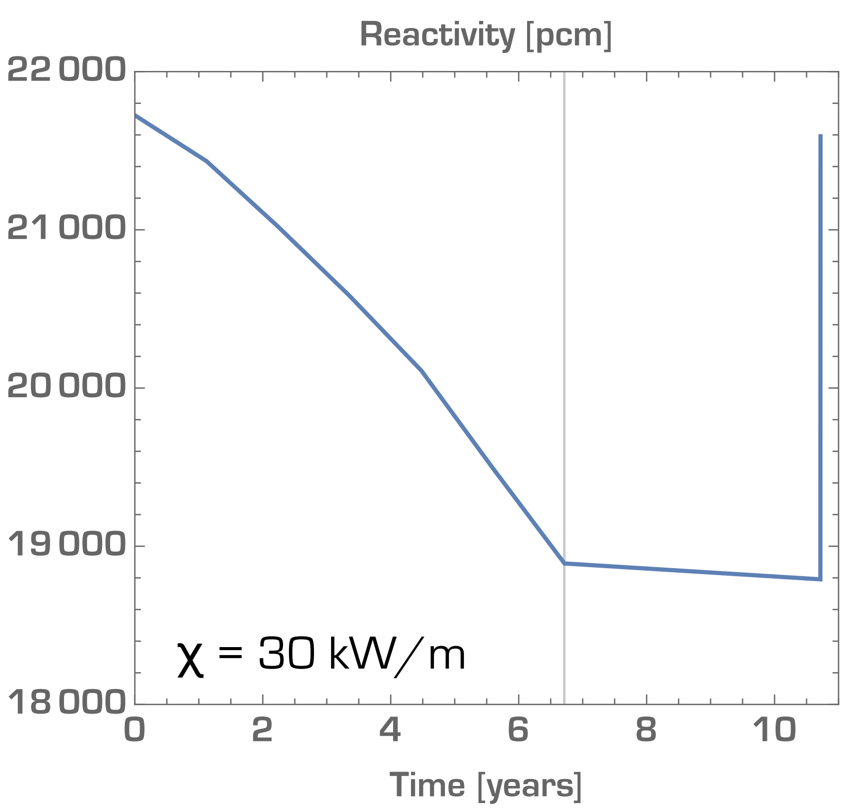
Sodium cooled rod lattice with (^{238}U,^{239}Pu)O_2 fuel

Nuclide	σ_c [b]	σ_f [b]	$\sigma_f/(\sigma_f+\sigma_c)$	η
^{238}U	0.25	0.04	0.14	0.38
^{239}Pu	0.40	1.68	0.81	2.37
^{240}Pu	0.43	0.35	0.45	1.38

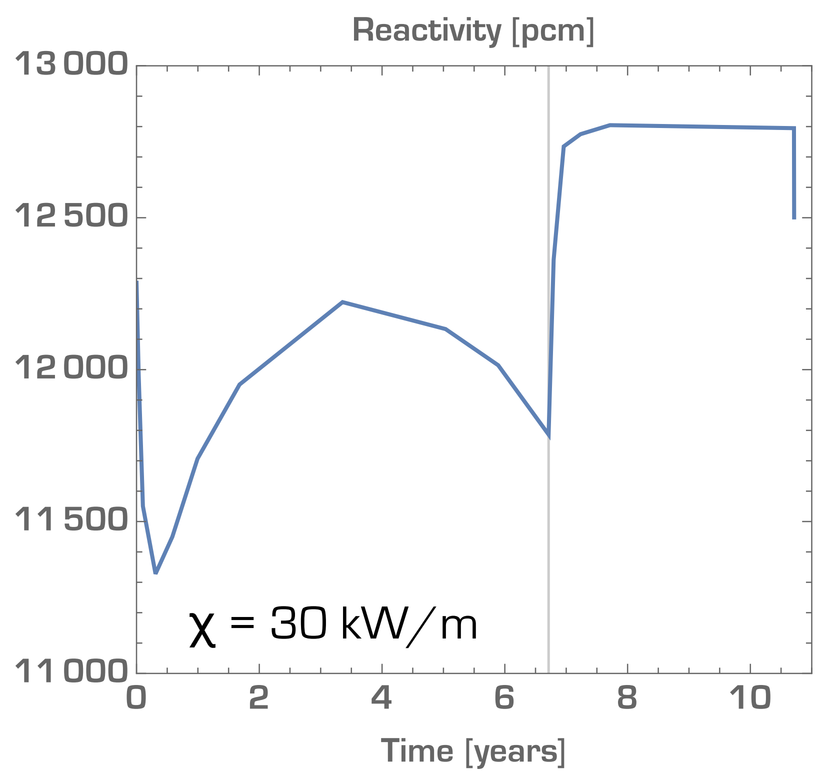
In-pile conversion rate $CR_{ip} > 1.0$ if C(^{239}Pu) < 14.3%

Breeding and burn-up

- Better neutron economy makes breeding with high burn-up possible
- Burn-up limited to ≈ 10% by damage dose to fuel cladding, not by reactivity
- U-Pu cycle features better reactivity margin
- Fissile mass at EoL < BoL! (contradicts conventional definition of breeding)



$({}^{238}U_{0.895},{}^{239}Pu_{0.105})O_2$



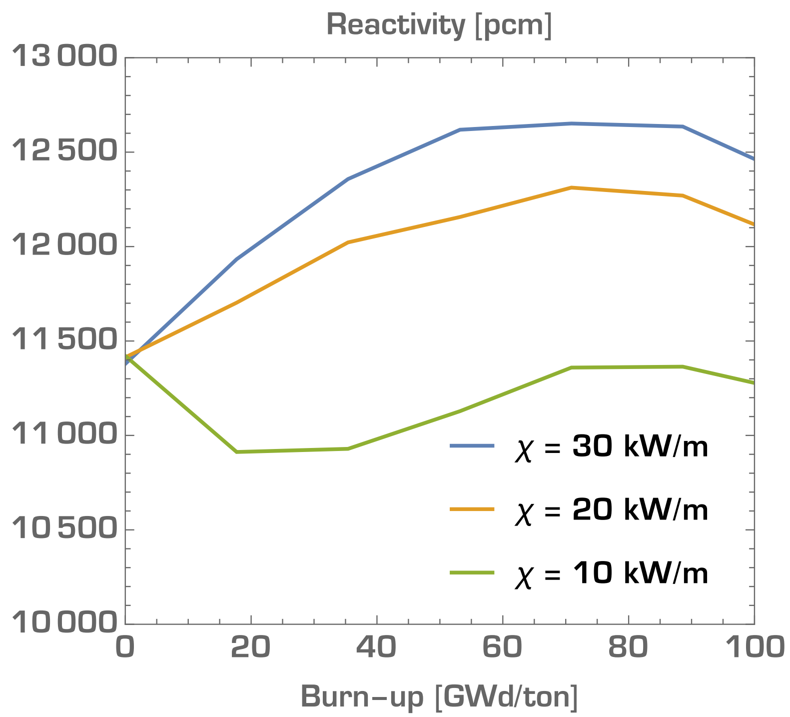
$({}^{232}Th_{0.908},{}^{233}U_{0.092})O_2$

Power density and breeding

- Starting a fast reactor, Pu from spent LWR fuel would be used
- Contains ^{241}Pu with half-life of 14 years ($^{241}Pu \rightarrow {}^{241}Am + \beta$)
- Decay of ^{241}Pu occurs both during irradiation and cooling

Nuclide	Fraction
^{238}Pu	0,035
^{239}Pu	0,519
^{240}Pu	0,238
^{241}Pu	0,129
^{242}Pu	0,079

Pu from spent PWR fuel



$(^{238}U_{0.875}, Pu_{0.125})O_2$

Reducing power density reduces conversion ratio

Fuel composition

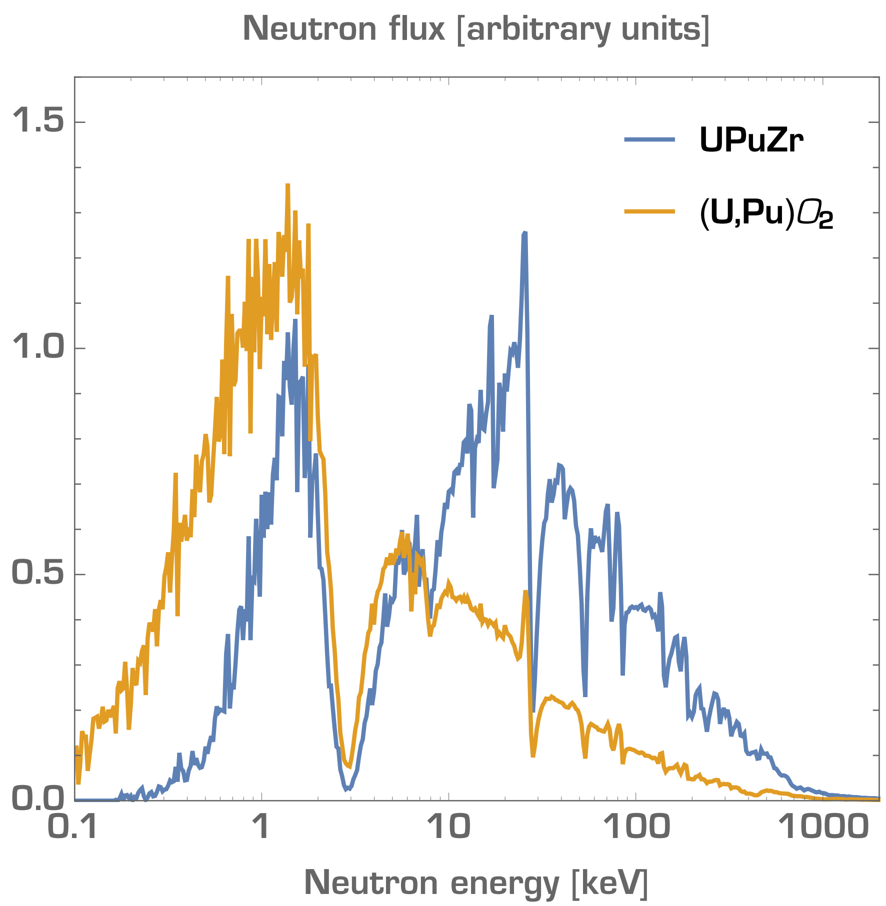
- "High density" fuels feature higher density of actinides & higher reactivity
- Carbides, nitrides and metal alloy fuels have been used in fast reactors
- Fewer light atoms in fuel leads to harder neutron spectrum

Fuel	Oxide	Carbide	Nitride	Metal alloy
σ_c [^{238}U]	0.29	0.26	0.25	0.20
σ_f [^{239}Pu]	1.80	1.73	1.68	1.61
σ_c [^{238}U]/σ_f [^{239}Pu]	0.16	0.15	0.15	0.12

Fuels with U/Pu ratio = 7/1

Harder spectrum **reduces** conversion ratio!

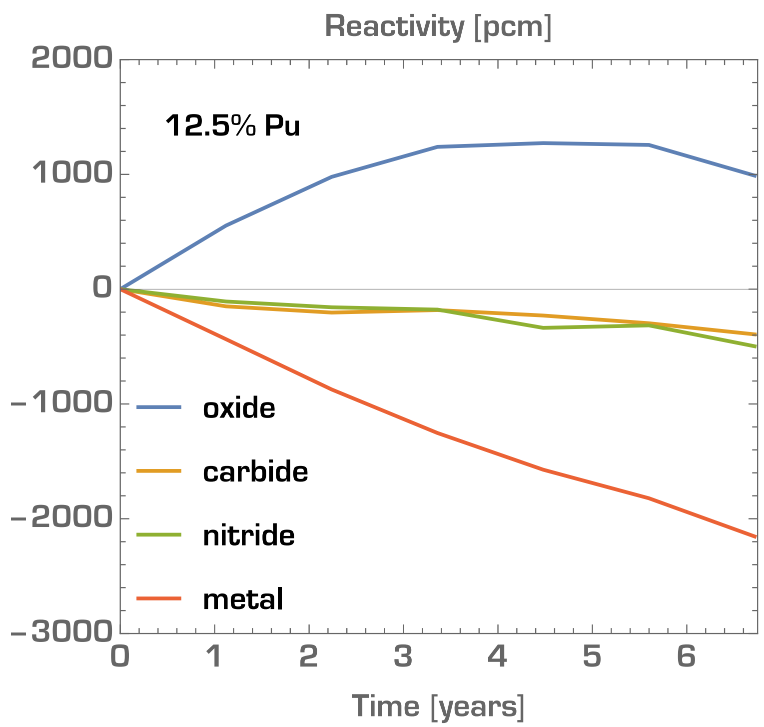
Spectrum hardening

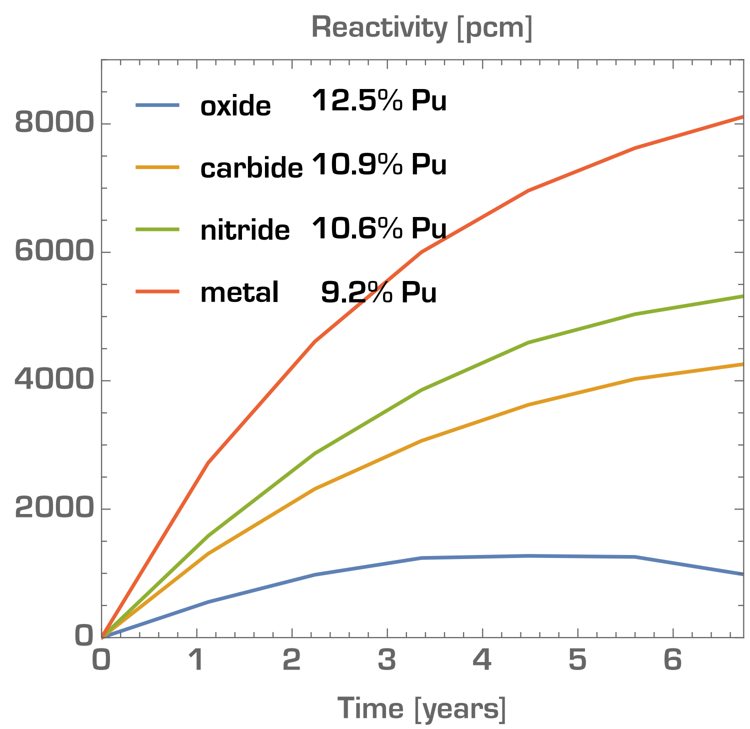


- Lower density of light atoms results in less slowing down of neutrons in elastic collisions.
- Average neutron energy increases
- Spectrum averaged capture cross section decreases
- Fewer neutrons reach energies below the sodium resonance at 3 keV

High density, high conversion rate fuels

- The higher actinide density permits to reduce Pu fraction in fuel
- Raises conversion ratio!





Reactivities normalized to zero at BoL

Coolant and breeding

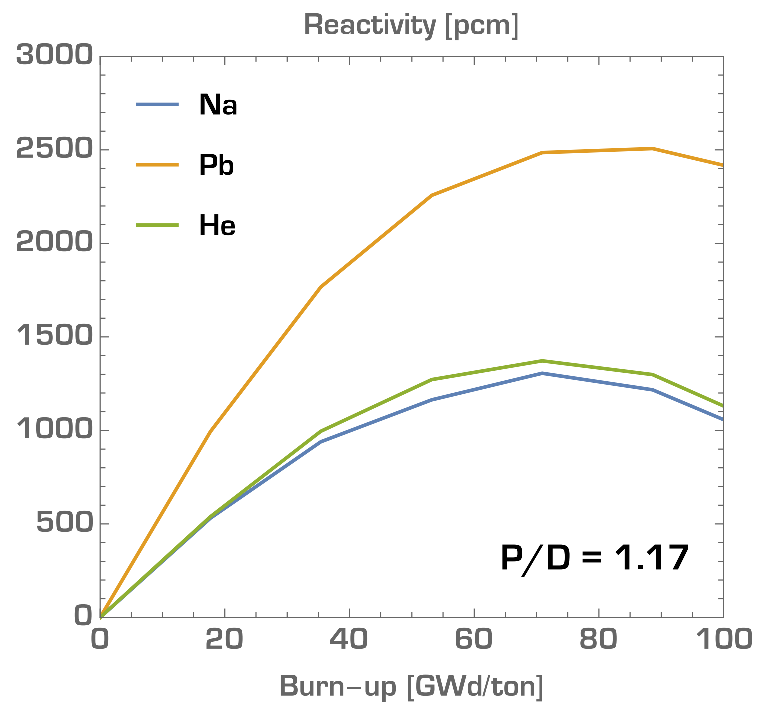
- Lead coolant will be used in the next fast reactor built in Russia (BREST)
- Helium coolant is considered for the ALLEGRO project in central Europe
- Neutron spectrum might be affected by choice of coolant

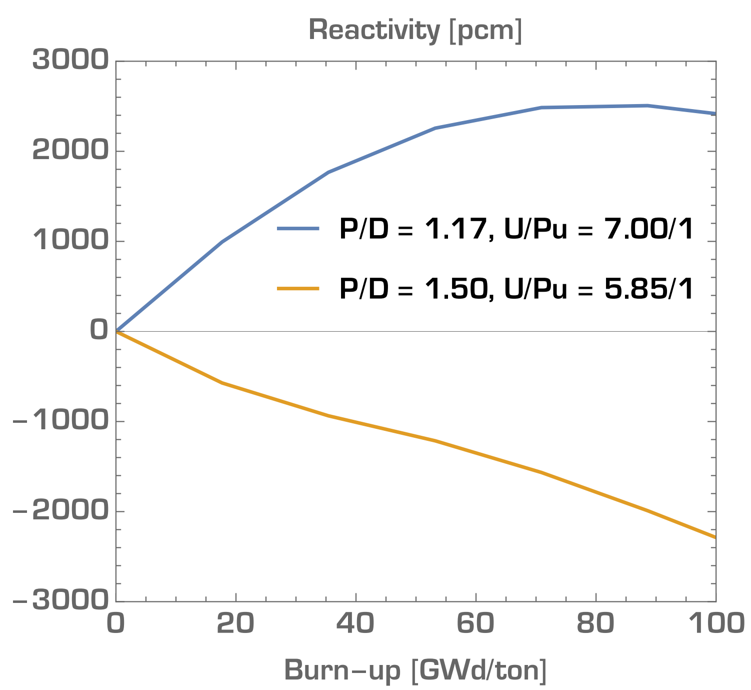
Na, Pb & He cooled rod lattices with $(^{238}U,Pu)O_2$ fuel & P/D = 1.17

Fuel	Sodium	Lead	Helium
$\sigma_c\,(^{238}U)$	0.29	0.29	0.28
$\sigma_f\,(^{239}Pu)$	1.80	1.73	1.73
$\sigma_c\,(^{238}U)/\sigma_f\,(^{239}Pu)$	0.16	0.17	0.16

- Reduced fission rate for lead coolant, due to in-elastic scattering
- For same P/D, Pb provides the highest conversion ratio!
- Sodium and helium yield similar conversion ratios

Fuel rod pitch & spectrum softening

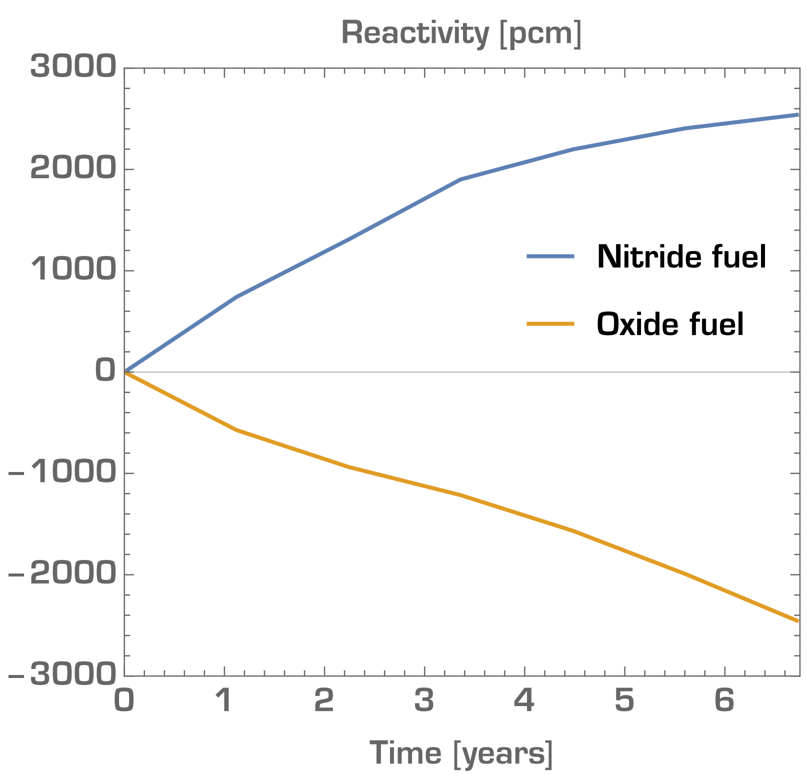




- Velocity of lead limited to 2 m/s by erosion concerns
- Rod pitch must be increased to achieve same cooling rate (power density)
- In lead-cooled reactors with power density of 30 kW/m, P/D ≈ 1.5
- Spectrum softens, requiring to increase Pu fraction in fuel.
- Conversion ratio more sensitive to Pu fraction than to spectrum.
- $CR_{ip} < 1.0$ for lead coolant with oxide fuel

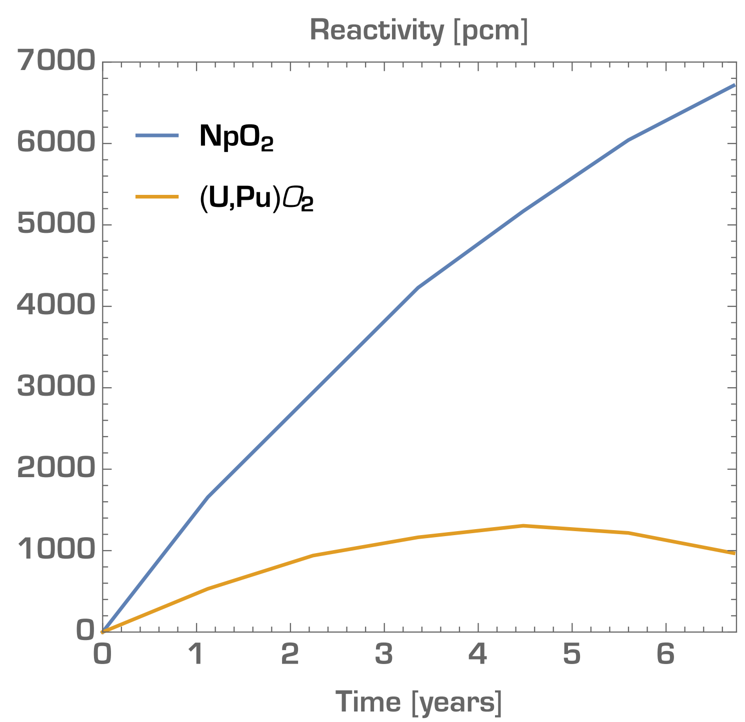
Conversion ratio > 1 with Pb coolant

- In order to achieve $CR_{ip} > 1$ with Pb coolant a dense fuel is required
- Metal alloy fuel is not compatible with liquid lead.
- Mixed nitride fuel selected for BREST project



Unconventional breeding cycles

- Fertile nuclides not available in nature are present in spent fuel
- ^{237}Np breeds into ^{238}Pu and eventually ^{239}Pu
- η-value for $^{237}Np > 1.0$, may be used as fuel without fissile support!



Sodium cooled rod lattice with $^{237}NpO_2$ fuel

Nuclide	σ_c [b]	σ_f [b]	$\sigma_f/(\sigma_f+\sigma_c)$	η
^{237}Np	0.80	0.57	0.42	1.21
^{238}Pu	0.27	1.32	0.83	2.55

$\eta > 2.0$ not a requirement for breeding!

Summary

- Breeding with high fuel burn-up achievable in a fast neutron spectrum
- Conversion ratio is affected by power density, fuel composition, choice of coolant and coolant volume fraction.
- Sodium coolant & metal alloy fuel maximizes conversion ratio
- Lead coolant requires dense fuel (e.g. nitride) to provide for $CR_{ip} > 1.0$
- Neptunium fuel features conversion ratio > 1.0, in spite of $\eta < 2.0$.

Home assignment 1

- Calculate cross sections for capture and fission, and neutron production, for the relevant nuclides in the U-Pu cycle, using Serpent. Adopt Pu from spent PWR fuel.
- Calculate the instantaneous in-pile conversion ratio at beginning-of-life, using

Group No	Sodium	Lead	Helium
Oxide	1	5	9
Nitride	2	6	10
Carbide	3	7	11
Metal alloy	4	8	

  - Do the calculation as function of P/D for P/D = 1.15 to 1.50 and adjust the ^{238}U fraction so that the reactivity in an infinite rod lattice = 0.10, corresponding to 10% leakage in a finite reactor core.
  - Which is the maximum P/D for which a conversion ratio larger than 1.0 is attainable in each case?
  - Discuss how the cross sections depend on the coolant volume fraction.