Safety of fast spectrum Gen-IV reactors

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Course objectives

After this course, you will be able to make design choices making Gen-IV reactors sustainable, safe and reasonably economical. The objective is achieved if you show you are able to

- Calculate and analyse reactor safety parameters in fast neutron reactors
- Assess breeding performance for potentials fuels and coolants
- Select structural materials permitting high burnup in fast neutron spectra

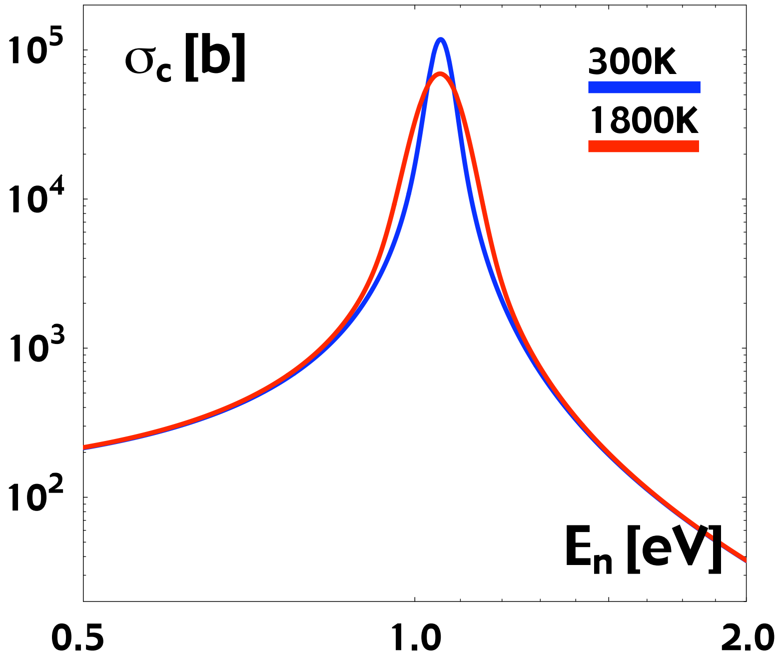
Outline

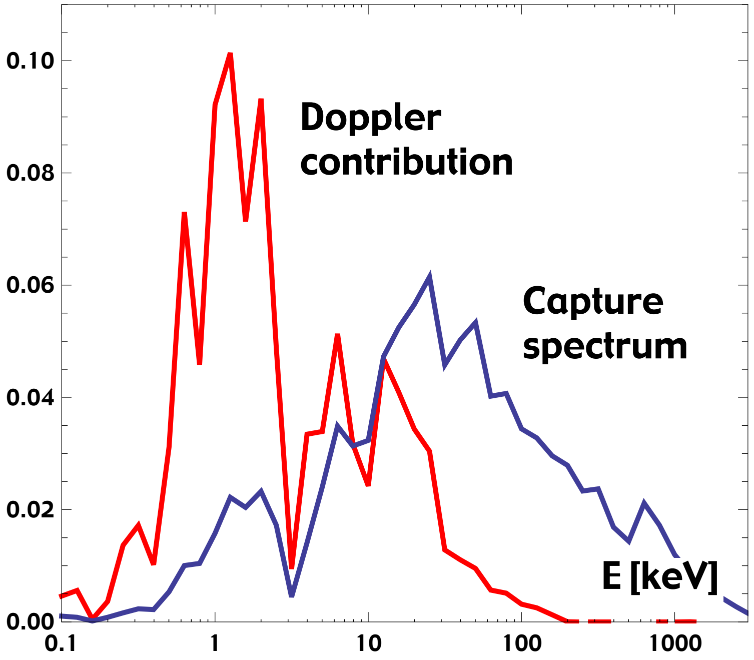
- How does americium affect the safety of fast neutron reactors?
- Doppler feedback
- Coolant temperature coefficient
- Effective delayed neutron fraction
- Coolant void worth
- Examples of fast reactor designs with full TRU recycling

Impact of americium on fast neutron reactor safety

- Gen-IV reactors should be able to recycle minor actinides from the waste stream of both Gen-IV reactors and LWRs
- Introduction of americium into the fuel of fast reactors leads to
- Reduction in Doppler feedback
- Increase in coolant temperature coefficient
- Reduction in effective delayed neutron fraction
- Increase in coolant void worth

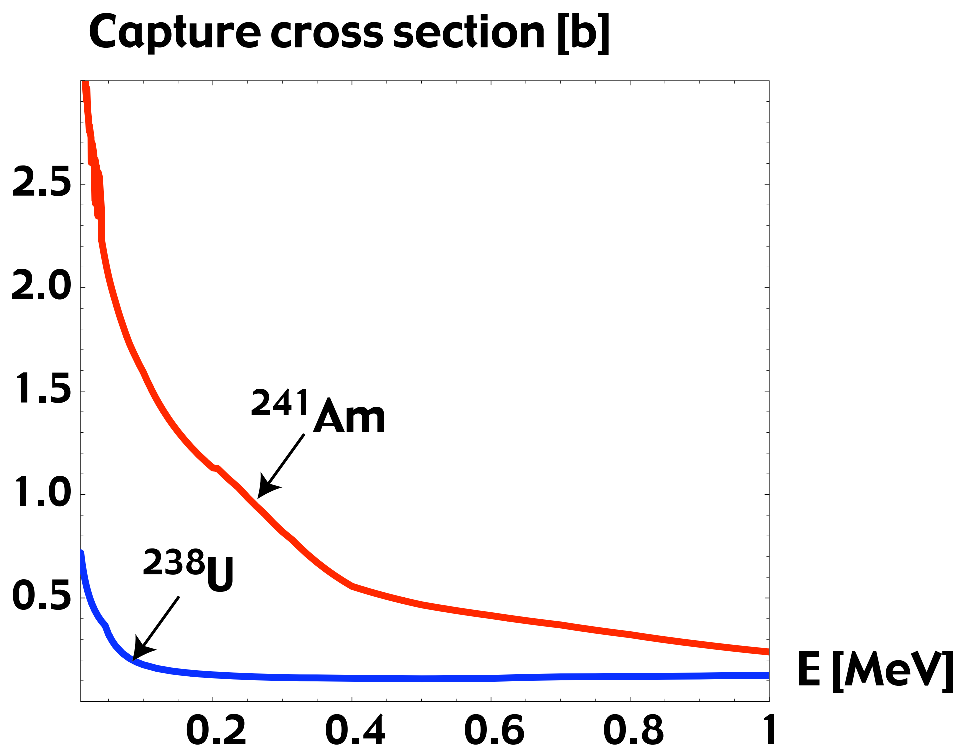
Doppler feedback: physics





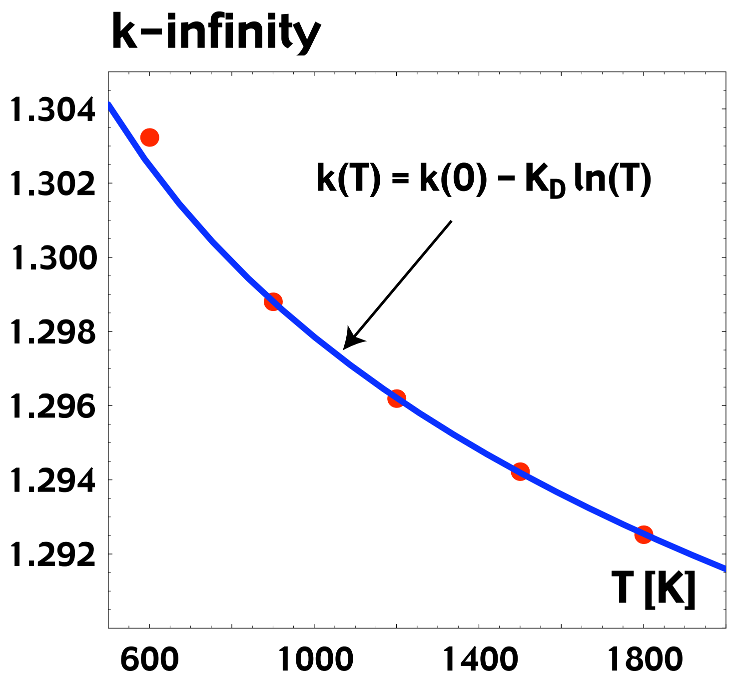
- Thermal oscillations of nuclei leads to Doppler broadening of resonances in the reaction cross sections.
- $\Delta T = 1000\text{K} \sim \Delta\Gamma = 0.1$ eV!
- Resonance “area” is conserved!
- Neutron spectrum is depleted on the high energy side of the resonance – neutron flux at the resonance peak is reduced.
- Doppler effect more efficient for low energy resonances
- Captures below 3 keV provide 60% of Doppler feedback in a sodium cooled FBR with oxide fuel, though constituting only 15% of captures!

Doppler feedback: impact of americium



- Capture cross section of ^{241}Am 5–10 times higher than that of ^{238}U between 10–500 keV.
- Am removes the soft tail of the neutron spectrum, and thus reduces Doppler feedback, even in the presence of ^{238}U!

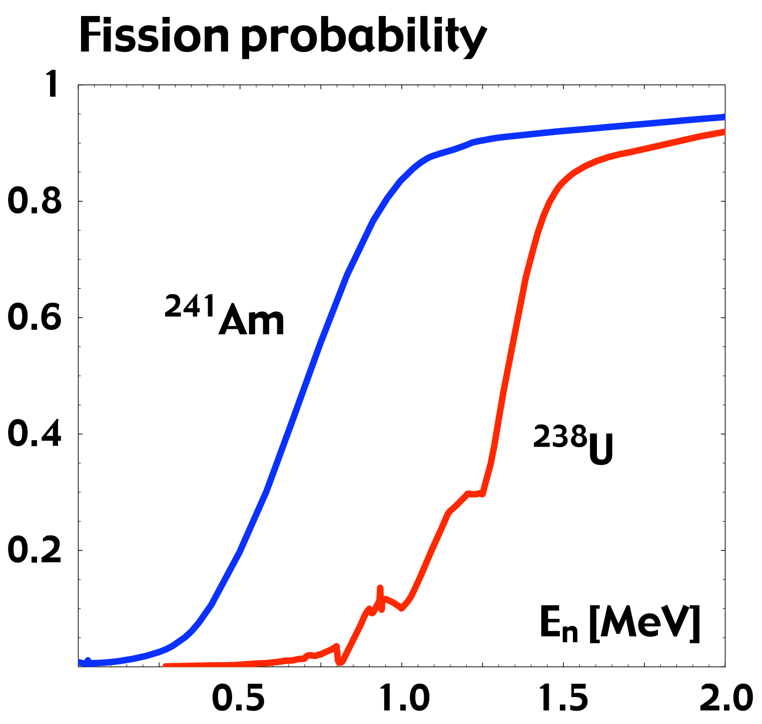
Doppler constant



Fuel	K_D
$(U_{0.8},Pu_{0.2})O_2$	570±20
$(U_{0.7},Pu_{0.2},Am_{0.1})O_2$	230±20
$(U_{0.6},Pu_{0.2},Am_{0.2})O_2$	60±10
$(U_{0.5},Pu_{0.2},Am_{0.3})O_2$	25±10
$(Pu_{0.2},Am_{0.3},Zr_{0.5})O_2$	5±10
$(Pu_{0.1},Zr_{0.9})O_2$	420±10

- In oxide fuel fast neutron reactors, reactivity decreases logarithmically with fuel temperature.
- Constant of proportionality = Doppler constant = K_D
- Small temperature changes: $d\rho/dT = -K_D/T$
- 10% Am reduces Doppler constant by a factor close to 3, even with 70% ^{238}U in the fuel!
- Specific Doppler feedback of fertile Pu isotopes stronger than that of ^{238}U!

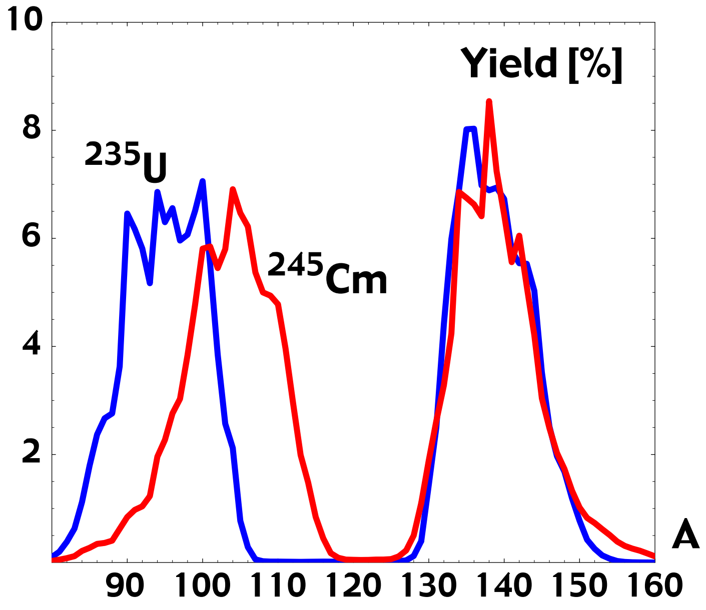
Coolant temperature coefficient



Fuel	α_{Na}
$(U_{0.8},Pu_{0.2})O_2$	+0.17
$(U_{0.7},Pu_{0.2},Am_{0.1})O_2$	+0.34
$(U_{0.6},Pu_{0.2},Am_{0.2})O_2$	+0.47
$(U_{0.5},Pu_{0.2},Am_{0.3})O_2$	+0.58
$(Pu_{0.2},Am_{0.3},Zr_{0.5})O_2$	+0.53
$(Pu_{0.1},Zr_{0.9})O_2$	−0.35

- Fission probability of ^{241}Am rises rapidly in the hard tail of the neutron spectrum
- Fission probability increases when coolant density decreases (mainly due to decrease in capture cross section): Spectral component
- Neutron leakage increases when coolant density decreases: Leakage component
- Small cores: Leakage dominates, α_{Na} is negative!
- Large cores: spectral effect dominates.
- With 10% Am in the fuel of medium sized core (1500MW$_{th}$), the void coefficient exceeds magnitude of Doppler feedback!

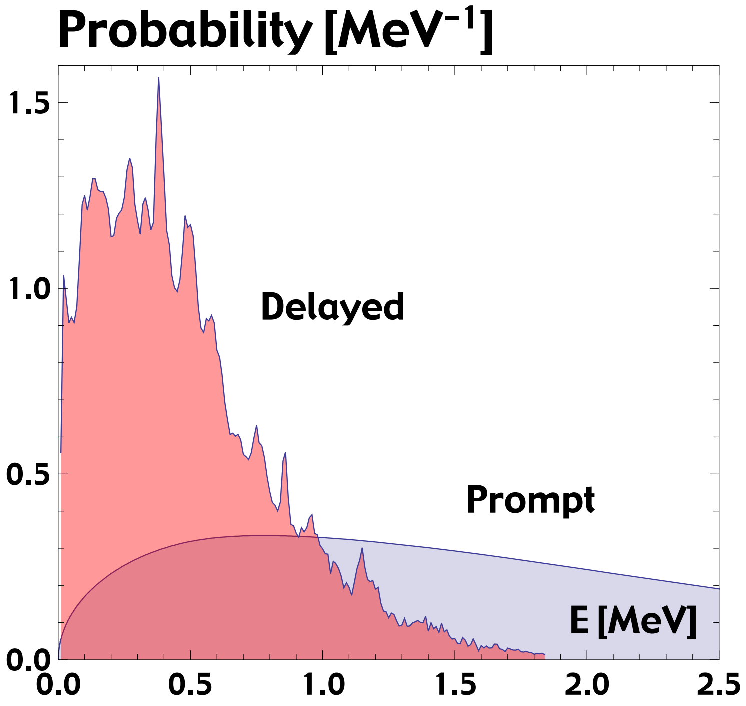
Delayed neutron fraction



Nuclide	ν_{tot}	ν_d/ν_{tot}
^{238}U	2.53	1.89%
^{239}Pu	3.02	0.22%
^{241}Am	3.37	0.13%
^{244}Cm	3.42	0.13%

- **Delayed neutrons are emitted by decaying fission products several seconds after the fission.**
- **^{235}U: β = 0.68%**
- **Yield of important delayed neutron emitters (Br-isotopes) decreases with increasing mass number**
- **Number of prompt fission neutrons (ν) increases with increasing mass number**

Effective delayed neutron fraction



Fuel	β_{eff}/β
$(U_{0.8},Pu_{0.2})O_2$	390/460
$(U_{0.6},Pu_{0.2},Am_{0.2})O_2$	270/390
$(U_{0.5},Pu_{0.2},Am_{0.3})O_2$	220/350
$(Pu_{0.2},Am_{0.3},Zr_{0.5})O_2$	160/260
$(Pu_{0.1},Zr_{0.9})O_2$	290/310

- **Fraction of neutrons inducing fission that were born as delayed neutrons: β_{eff}**
- **Delayed neutron spectrum softer than prompt spectrum**
- **β_{eff} smaller than β in a fast spectrum**
- **^{241}Am has a very high capture cross section at the peak of the delayed neutron spectrum**
- **β_{eff}/β = 0.6 with 30% americium in the fuel.**
- **β_{eff} < 220 pcm with 30% americium in the fuel.**

Coolant void worth

Fuel	W_{Na} / β_{eff}
$(U_{0.8},Pu_{0.2})O_2$	+1.8
$(U_{0.7},Pu_{0.2},Am_{0.1})O_2$	+7.2
$(U_{0.6},Pu_{0.2},Am_{0.2})O_2$	+13
$(U_{0.5},Pu_{0.2},Am_{0.3})O_2$	+19
$(Pu_{0.2},Am_{0.3},Zr_{0.5})O_2$	+25
$(Pu_{0.1},Zr_{0.9})O_2$	-17

Sodium void worth (in units of dollars) for a medium sized oxide fuel core with varying americium content

- Sodium boiling may lead to rapid voiding of the core
- Fission gas release or steam bubble introduction are potential sources of void
- Void worth increases rapidly with americium concentration
- Positive void worth of 3–4 dollars acceptable if a prompt negative temperature feedback of –0.5 pcm/K is available (Doppler, axial fuel expansion).
- Positive void worth of 7 dollars may not be acceptable with a Doppler feedback of –0.2 pcm/K

Fast reactors with enhanced Am recycling capabilities

- “Standard” sodium cooled FBR design allows for 2–3% Am in the fuel, enough to recycle its own production, but not for burning Am from LWRs.
- Generation IV fast neutron reactors may handle ~5 % Am in their fuel by means of innovative design:
- Dedicated Am & Cm target assemblies at the periphery of the EFR core (Europe)
- Metal alloy fuel with large axial expansion coefficient of the fuel: IFR (USA)
- Lead cooling with nitride fuel: BREST (Russia)
- Helium gas cooling: GCFR (France)

Summary