LEAD CONTAINING MAINLY ISOTOPE PB-208: NEW REFLECTOR FOR IMPROVING SAFETY OF FAST NUCLEAR REACTORS

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MEET THE PRESENTER

Dr. Evgeny Kulikov earned his PhD at the National Research Nuclear University MEPhI in Moscow in 2010 and is currently the associate professor at the Institute of Nuclear Physics and Engineering. His areas of professional interests include improving fuel burn-up, nuclear fuel cycle, non-proliferation, and fast reactor safety. Currently, his scientific research is supported by the Russian Science Foundation. He lectures on theoretical aspects of nuclear reactors and conducts laboratory works on experimental reactor physics. He is serving on the Gen IV International Forum Education and Training Task Force.

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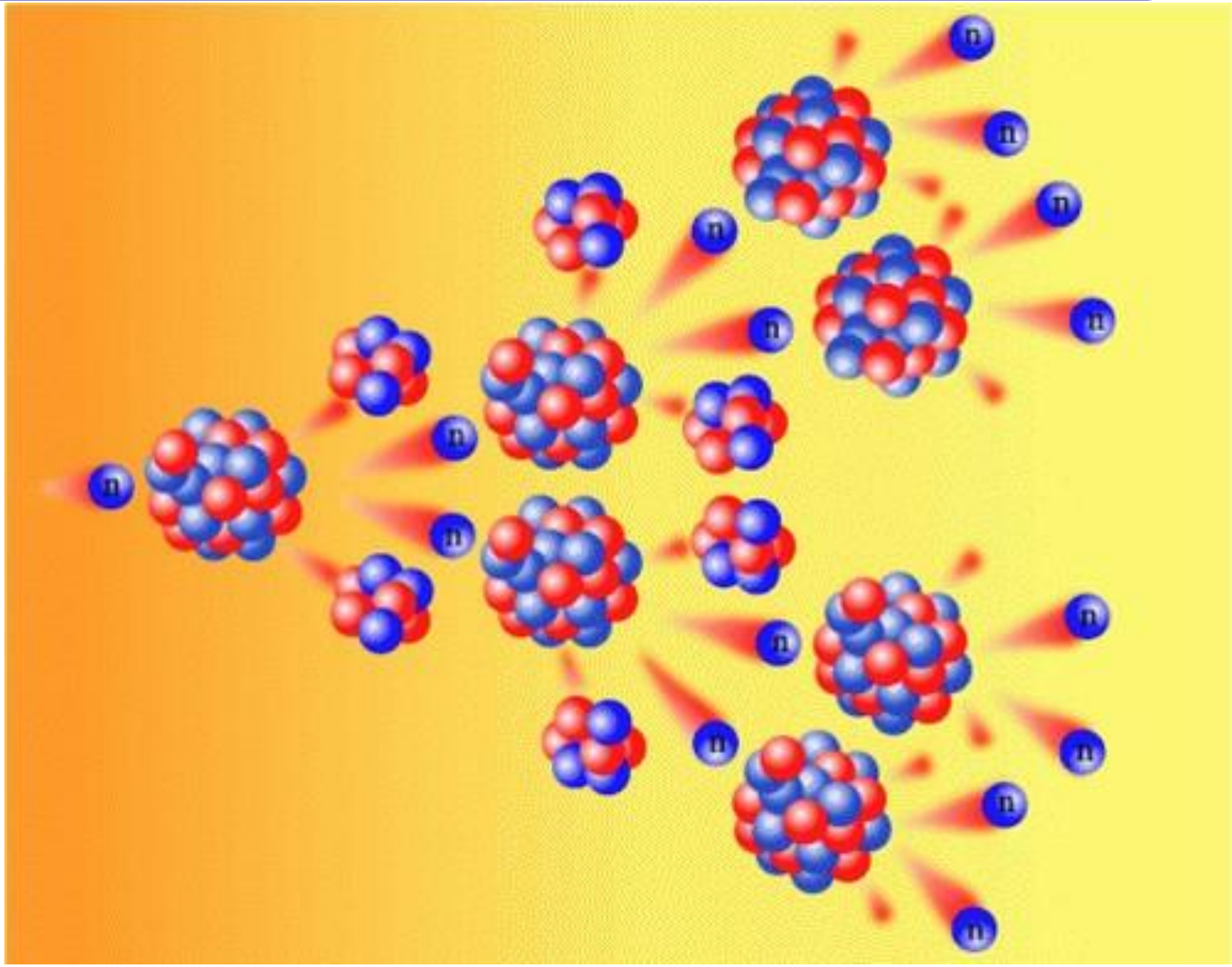
OUTLINE

1. How to slow down chain reaction?
2. Improved safety: kinetics
3. Improved safety: dynamics
4. Sources of ^{208}Pb

1 How to slow down chain reaction?



IDEA

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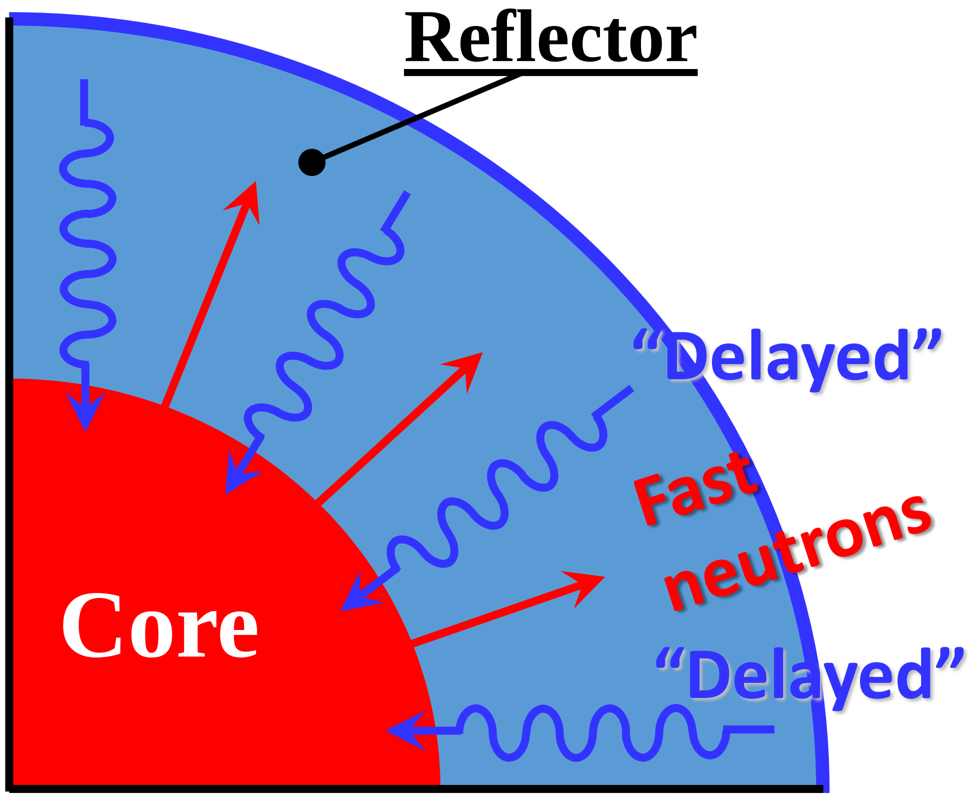
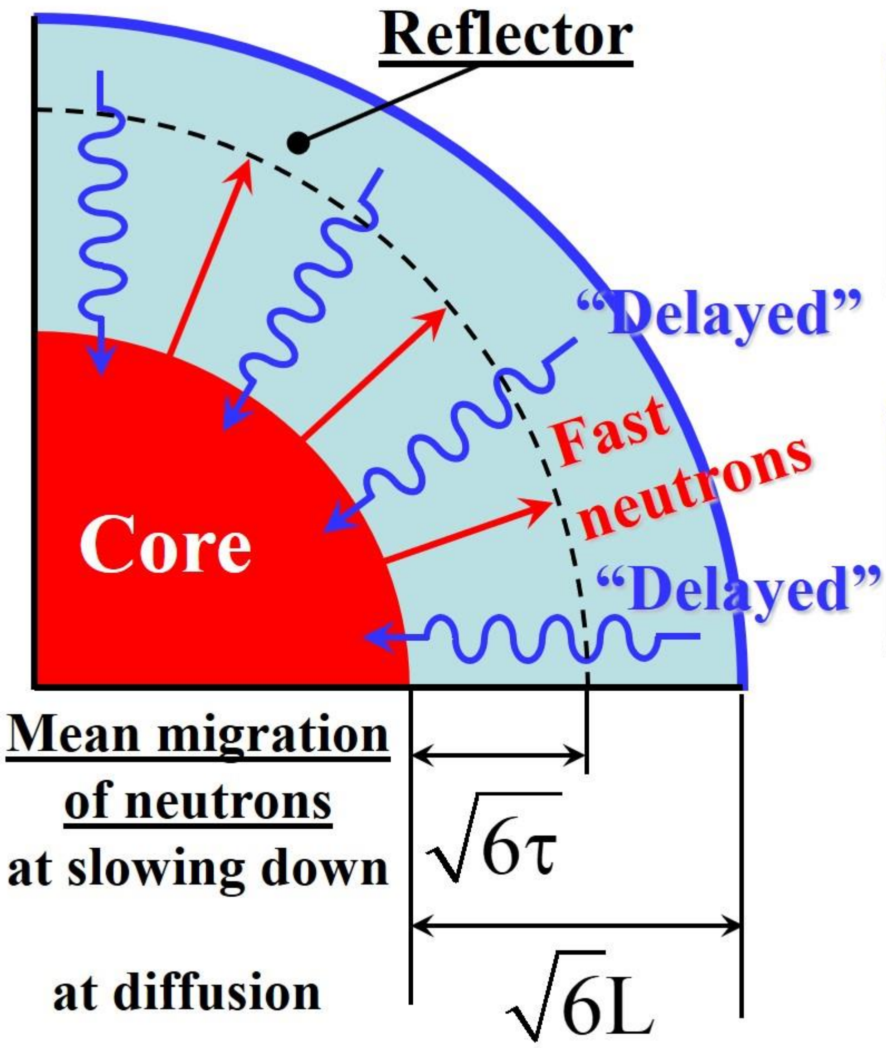


Reactor	Thermal	Fast
Λ	~ ms	~ μs
β	0.65%	0.36%

Safety improvement by slowing down chain reaction

- How we can slow down chain reaction
  - fast neutrons from the core should penetrate deeply into reflector
  - they should have high probability to return to the core as a result of diffusion (in some way "delayed" neutrons)

REQUIREMENTS TO SLOW DOWN CHAIN REACTION



1 "Penetrate deeply into reflector"
Neutron age τ ($E_{fis} \rightarrow E_{th}$)
as large as possible

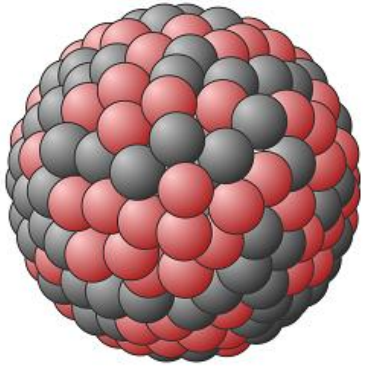
2 "High probability to return to the core"
Diffusion length L
larger than $\sqrt{\tau}$

CHARACTERISTICS OF CHAIN REACTION RATE

1 **Neutron age** $\tau(E) \sim A \int_{E_1}^{E_2} \frac{1}{\Sigma_s^2} \cdot \frac{dE}{E}$ $\tau \uparrow A \uparrow$

$\sqrt{6\tau}$ – **mean migration of neutrons at slowing down**

2 **Diffusion length** $L \sim \frac{1}{\sqrt{\Sigma_a^{th} \cdot \Sigma_s^{th}}}$ $L \uparrow \Sigma_a^{th} \downarrow$

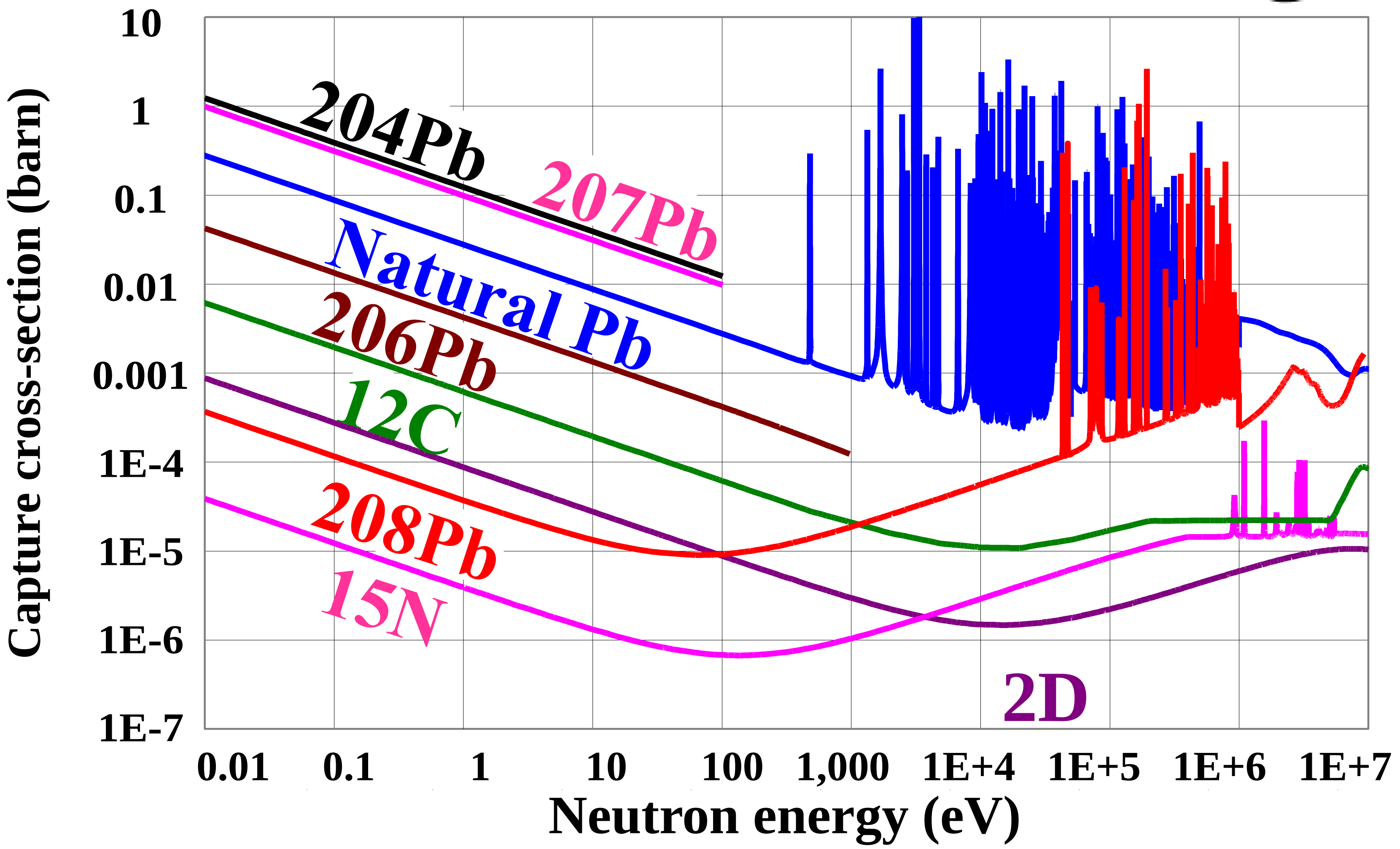


^{208}Pb

$\sqrt{6L}$ – **mean migration of neutrons at diffusion**

3 **Lifetime of thermal neutrons** $T_{th} \sim \frac{1}{\Sigma_a^{th}}$ $T_{th} \uparrow \Sigma_a^{th} \downarrow$

CAPTURE CROSS-SECTION

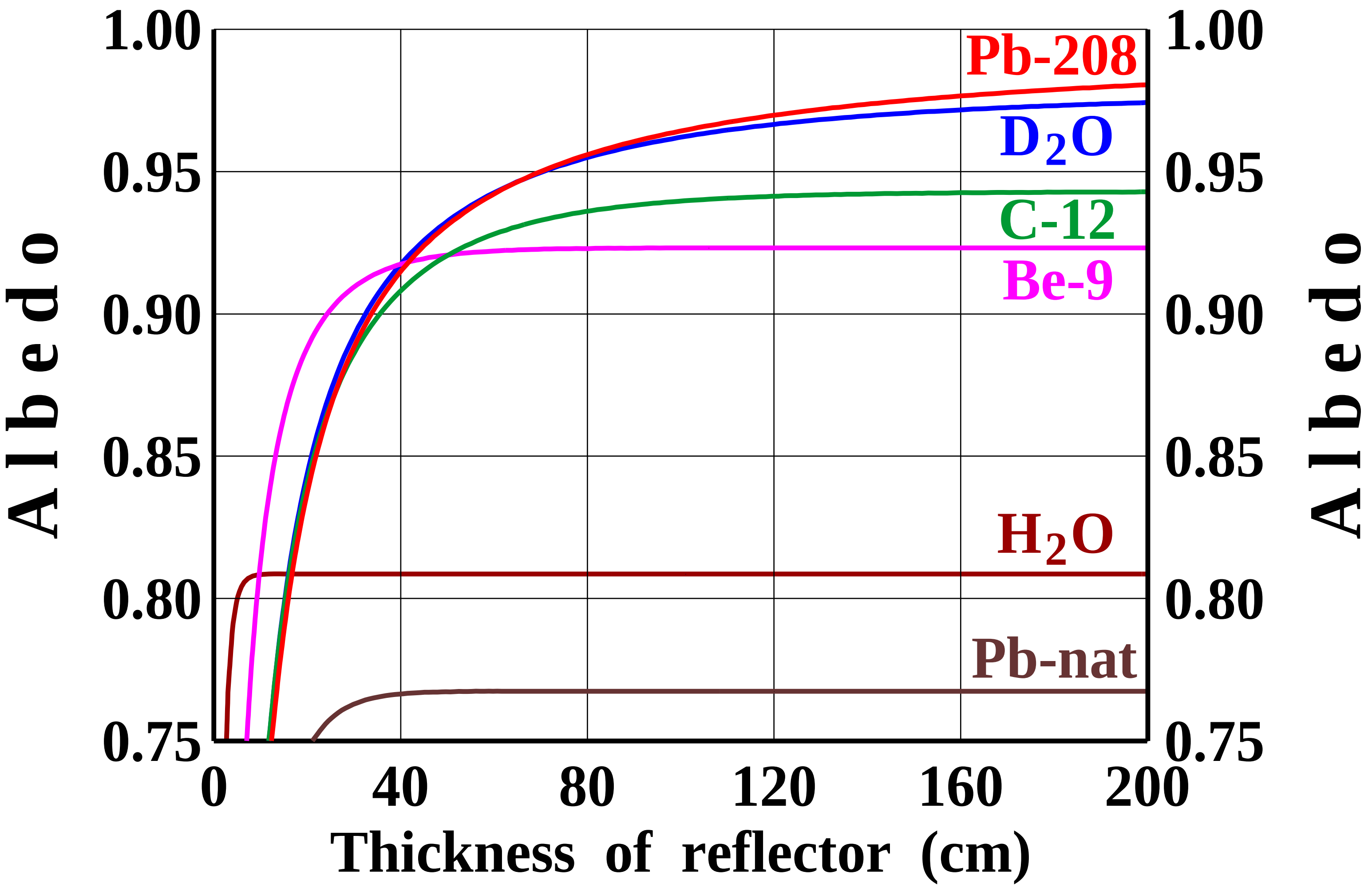


Extremely small capture of ^{208}Pb

REFLECTOR PROPERTIES

Material	$\sqrt{6\tau}$ (cm)	$\sqrt{6}L$ (cm)	Slowing down probability (2 MeV → 0.025 eV)	Lifetime of thermal neutrons (ms)
^{208}Pb	213	843 !	0.993	597 !
Pb_{nat}	213	33	0.304	0.9
Na	227	43	0.297	0.3
Bi	223	96	0.160	4.7
C	49	138	0.998	13

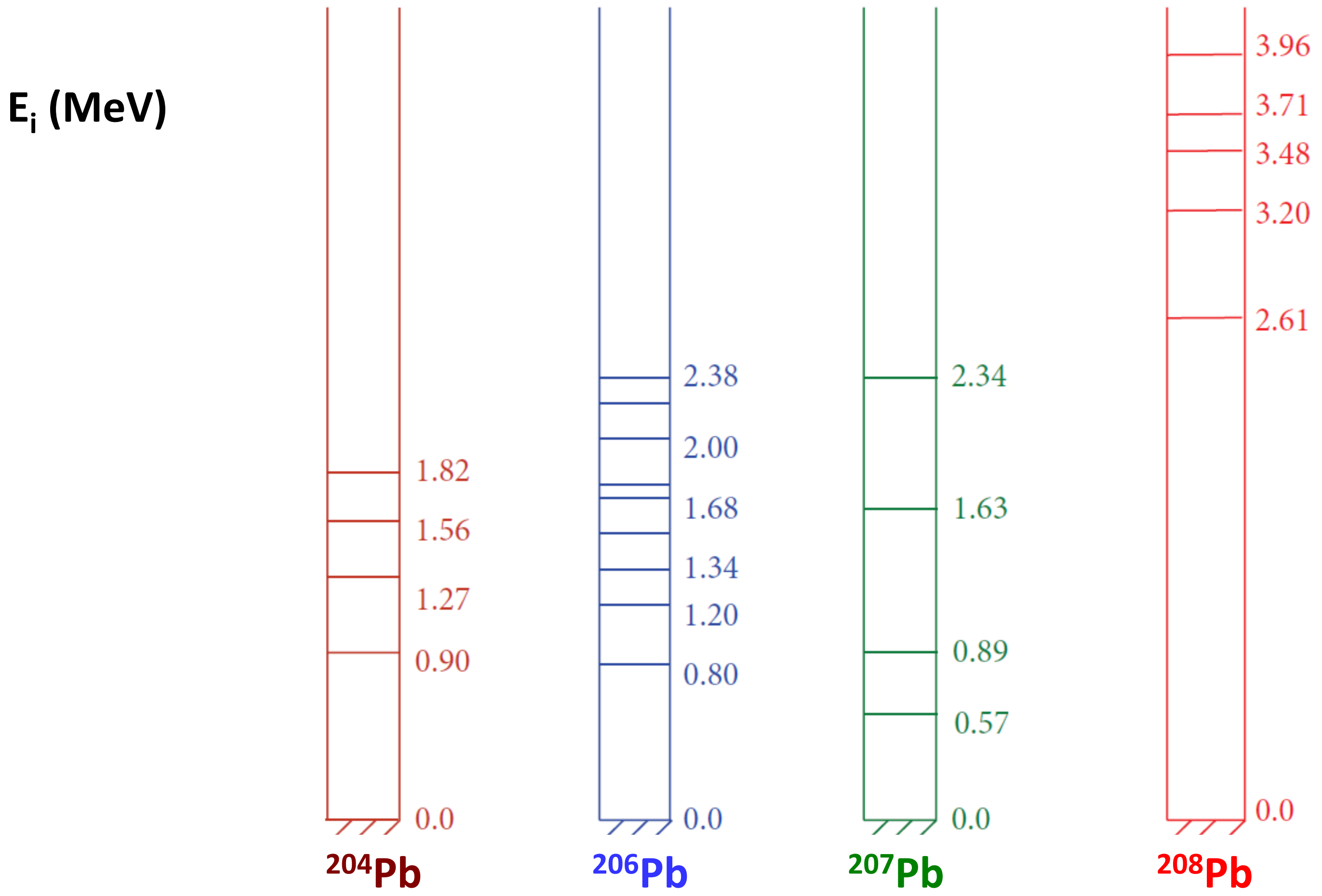
THERMAL NEUTRON ALBEDO

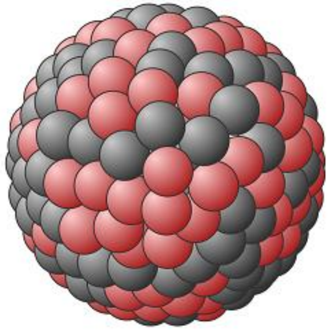


^{208}Pb is an effective reflector

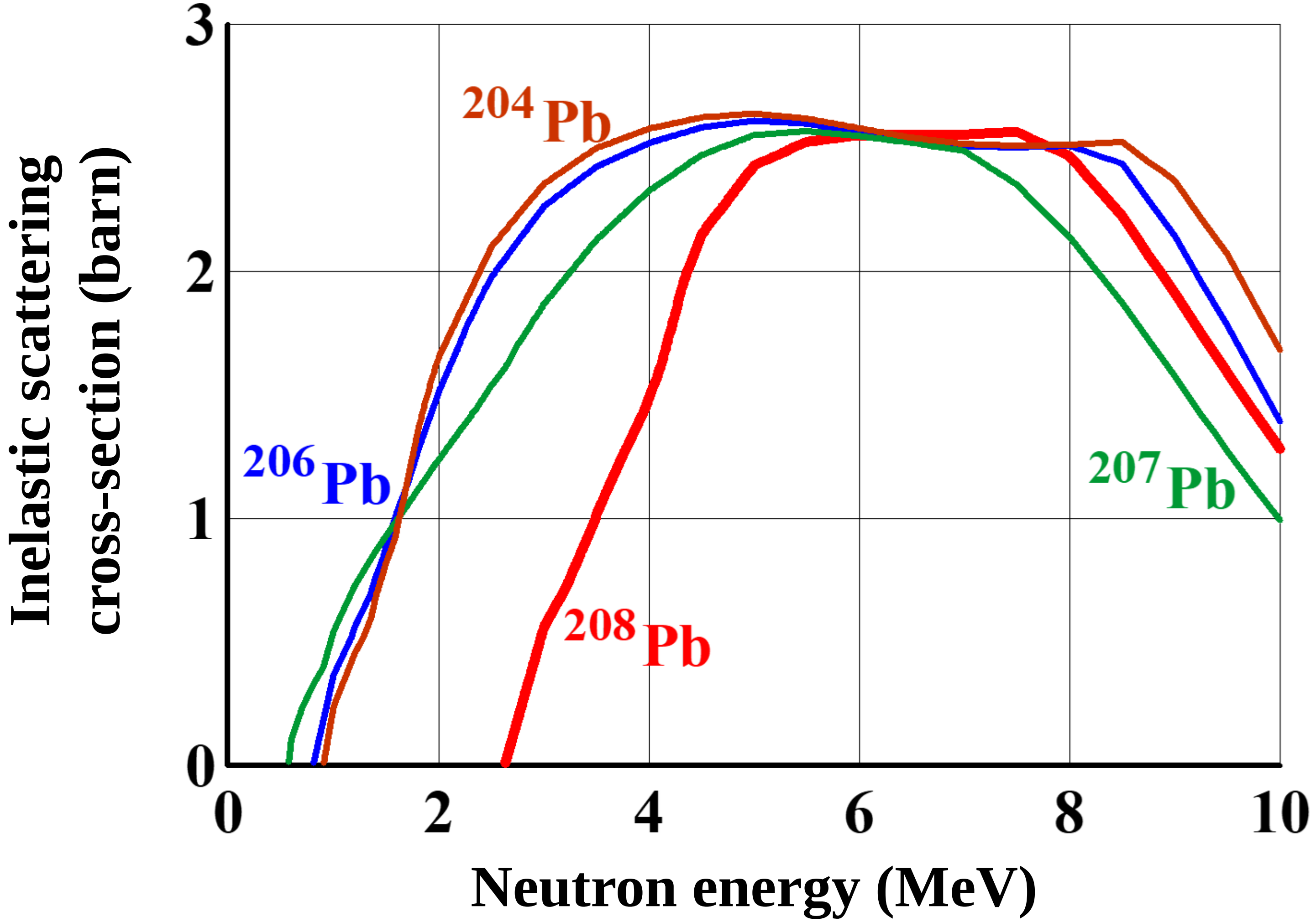
EXCITATION LEVELS OF LEAD ISOTOPES

$Pb_{nat} = 1.4\%\,^{204}Pb + 24.1\%\,^{206}Pb + 22.1\%\,^{207}Pb + 52.4\%\,^{208}Pb$





INELASTIC SCATTERING CROSS-SECTION



High threshold of inelastic scattering of ^{208}Pb

MODERATOR PROPERTIES

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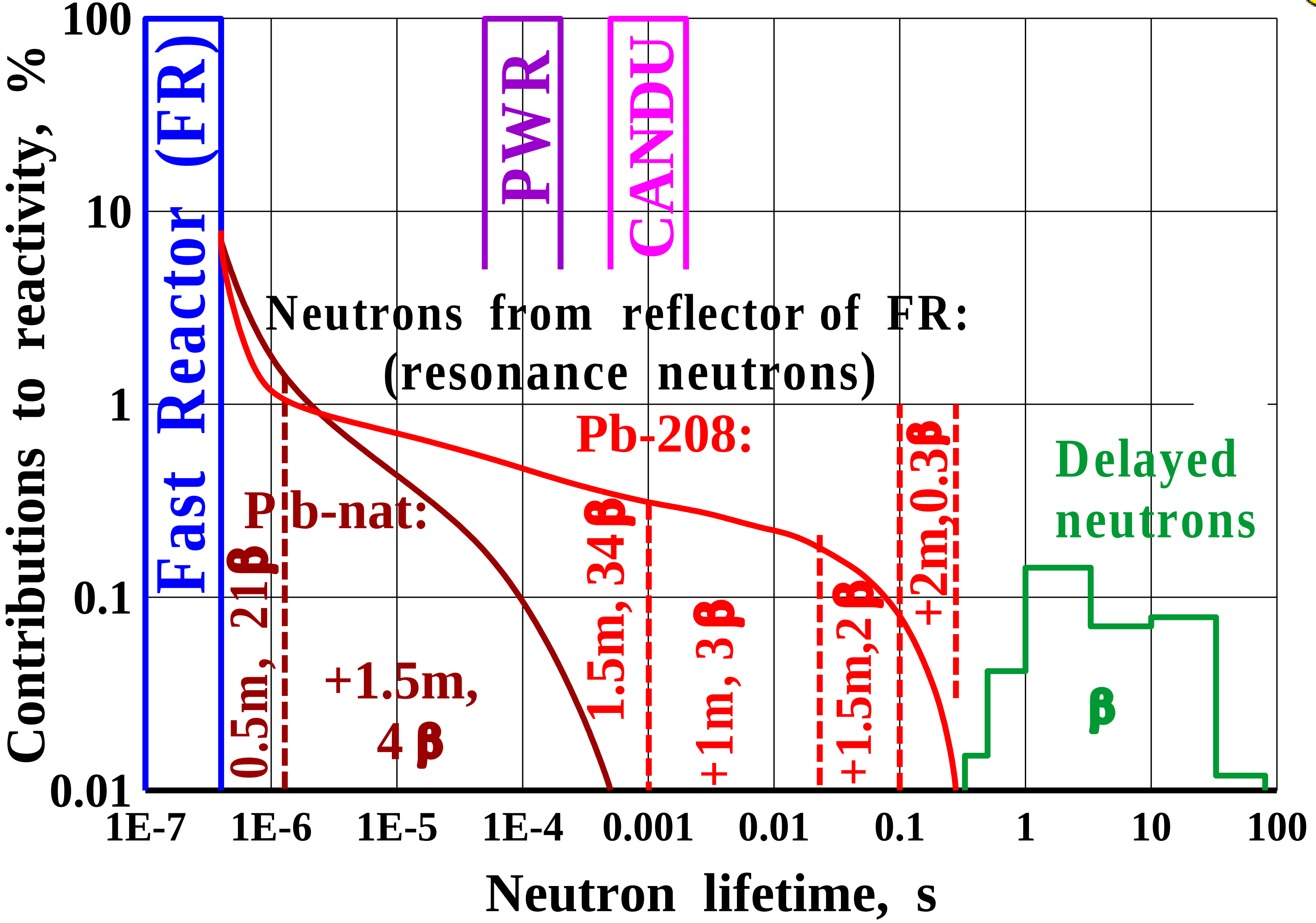
Material	Logarithmic energy decrement ξ	Moderating ability $\xi \cdot \Sigma_s$ (cm^{-1})	Moderating ratio $\xi \cdot \Sigma_s / \Sigma_a$
H_2O	0.95	1.39	70
D_2O	0.57	0.18	4590
BeO	0.17	0.12	247
C	0.16	0.063	242
Pb_{nat}	0.01	0.004	0.61
^{208}Pb	0.01	0.004	477

^{208}Pb is an effective moderator

2 Improved Safety: Kinetics

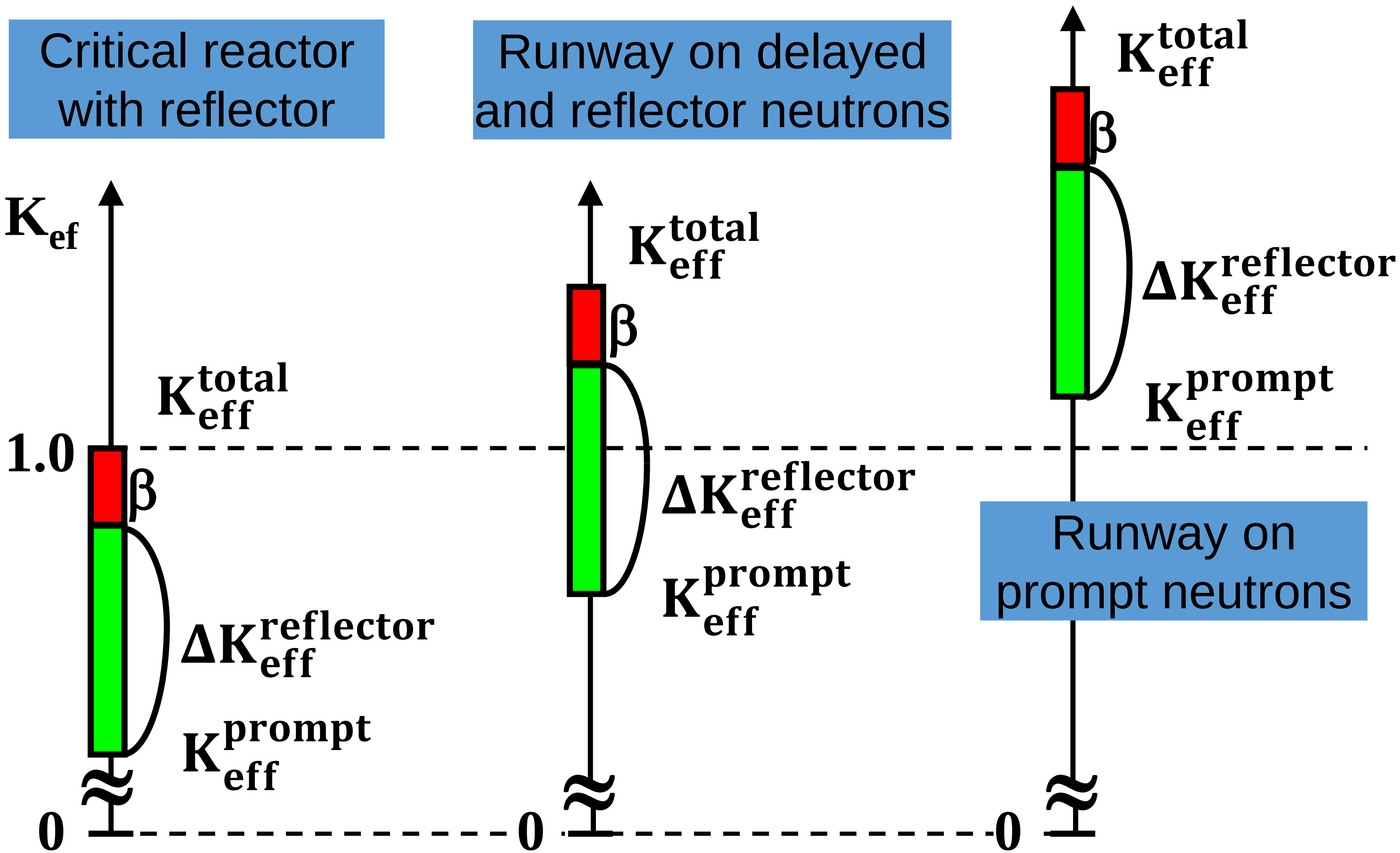
CONTRIBUTION OF NEUTRONS WITH DIFFERENT LIFETIMES INTO REACTOR CRITICALITY



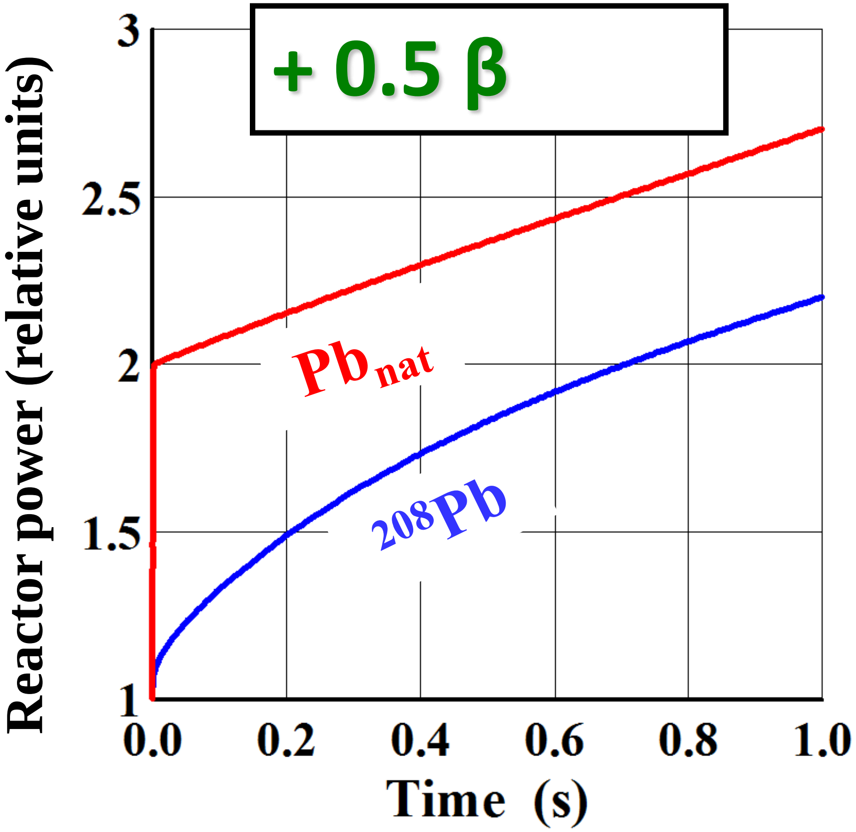
PECULIARITIES OF REFLECTOR NEUTRONS

Characteristic	Description
Origin	Prompt and delayed neutrons
Place of birth	Reflector
Fraction	<< prompt, but >> delayed
Lifetime	> prompt, but < delayed
Energy	<< prompt and delayed neutrons
Time of input into nuclear chain reaction	After returning to the core (there's a "dead" time)
Place of input into nuclear chain reaction	Mainly at the edge of the core
Forming	It's possible to change their fraction and energy by changing reflector
Role	Additional delayed neutrons

REACTOR RUNAWAY



FAST REACTOR RUNAWAY WITHOUT FEEDBACKS INDUCED BY STEP INSERTION OF REACTIVITY (β = 0.36%)



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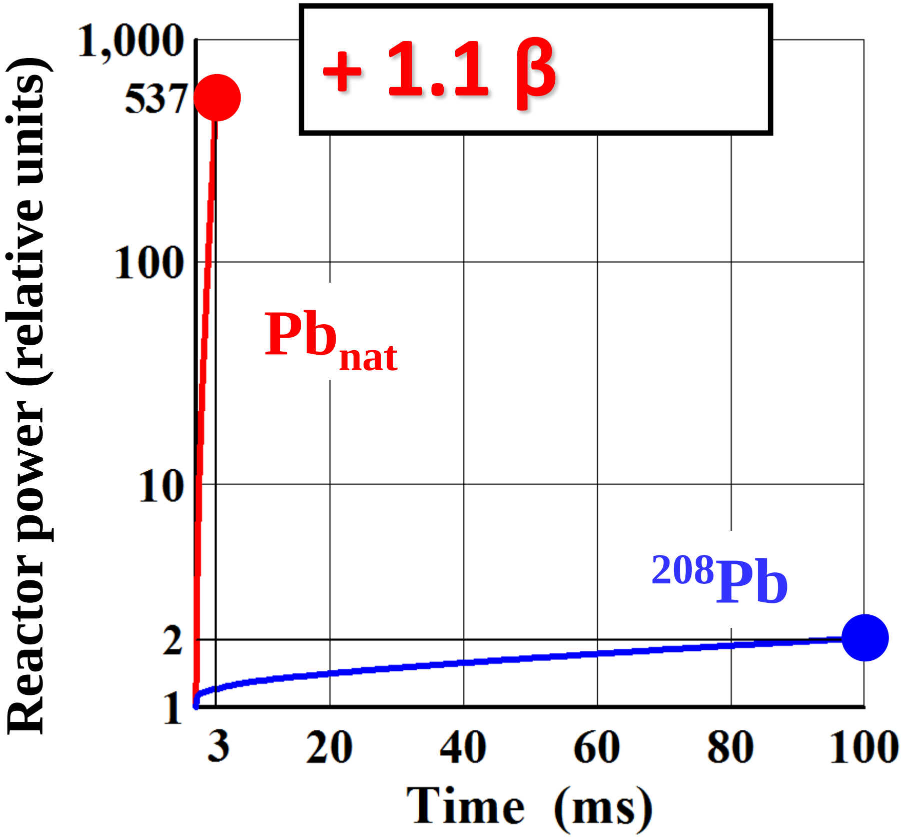
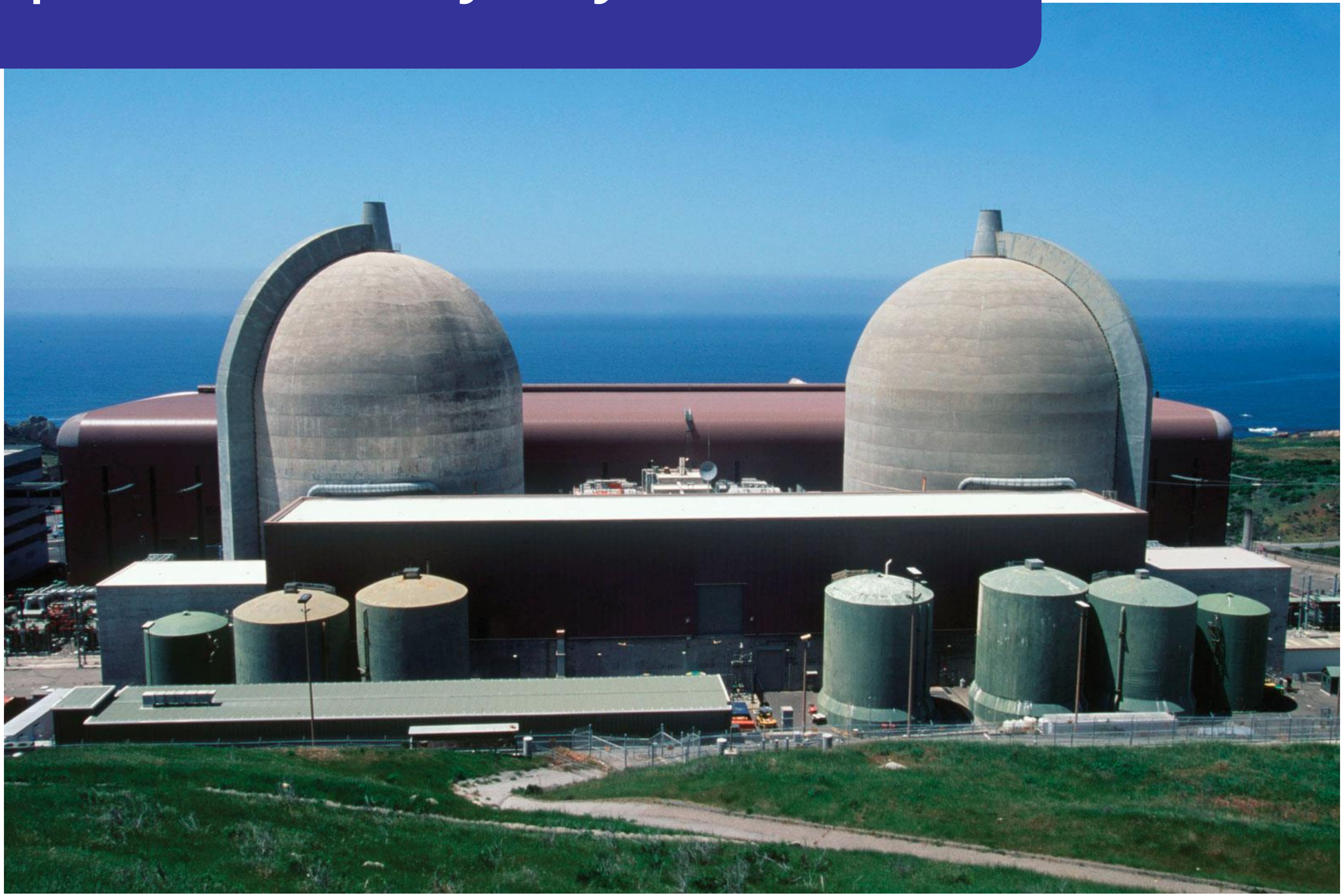


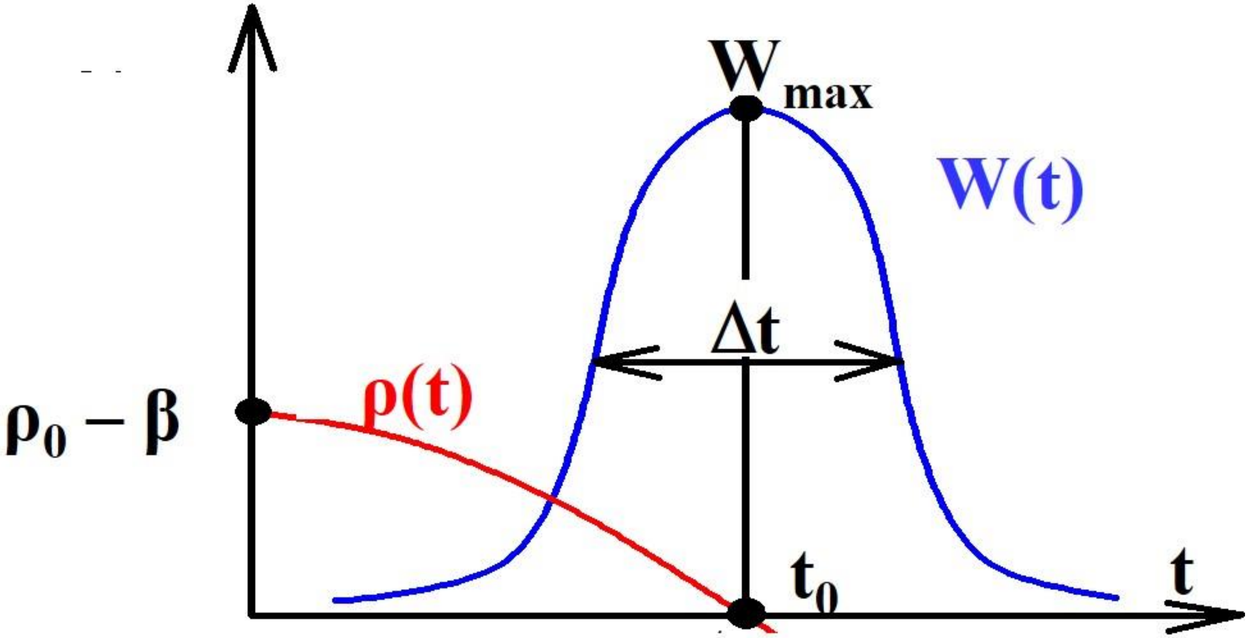
A big difference !

3 Improved Safety: Dynamics



MODEL OF NEUTRON FLASH (P0 > B)

- this is the state of prompt super-criticality
- heat does not have time to reach the coolant
- only Doppler effect has enough time to act
- duration of neutron flash $\Delta t \sim \Lambda$ neutron lifetime
- energy yield of neutron flash $Q \sim W_{max} \cdot \Delta t \neq f(\Lambda)$



SITUATION WHEN MODEL OF NEUTRON FLASH IS NOT CORRECT

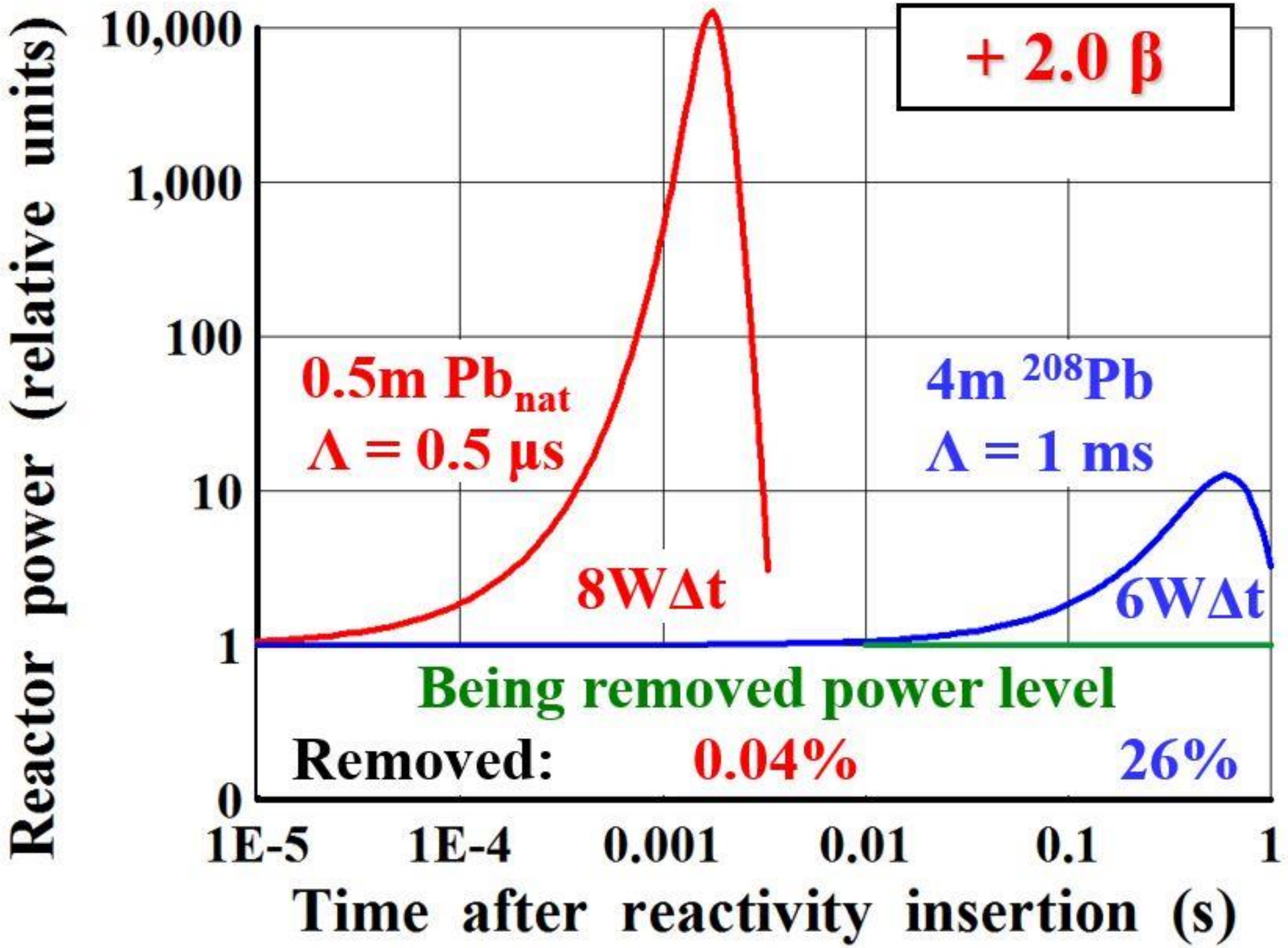
Model of neutron flash is correct in the case of Pb_{nat}

Reflector	Neutron lifetime Λ	Duration of neutron flash Δt at $\rho_0 = 2\beta$
Pb_{nat}	~ μs	0.5 ms
^{208}Pb	~ ms	1.1 s

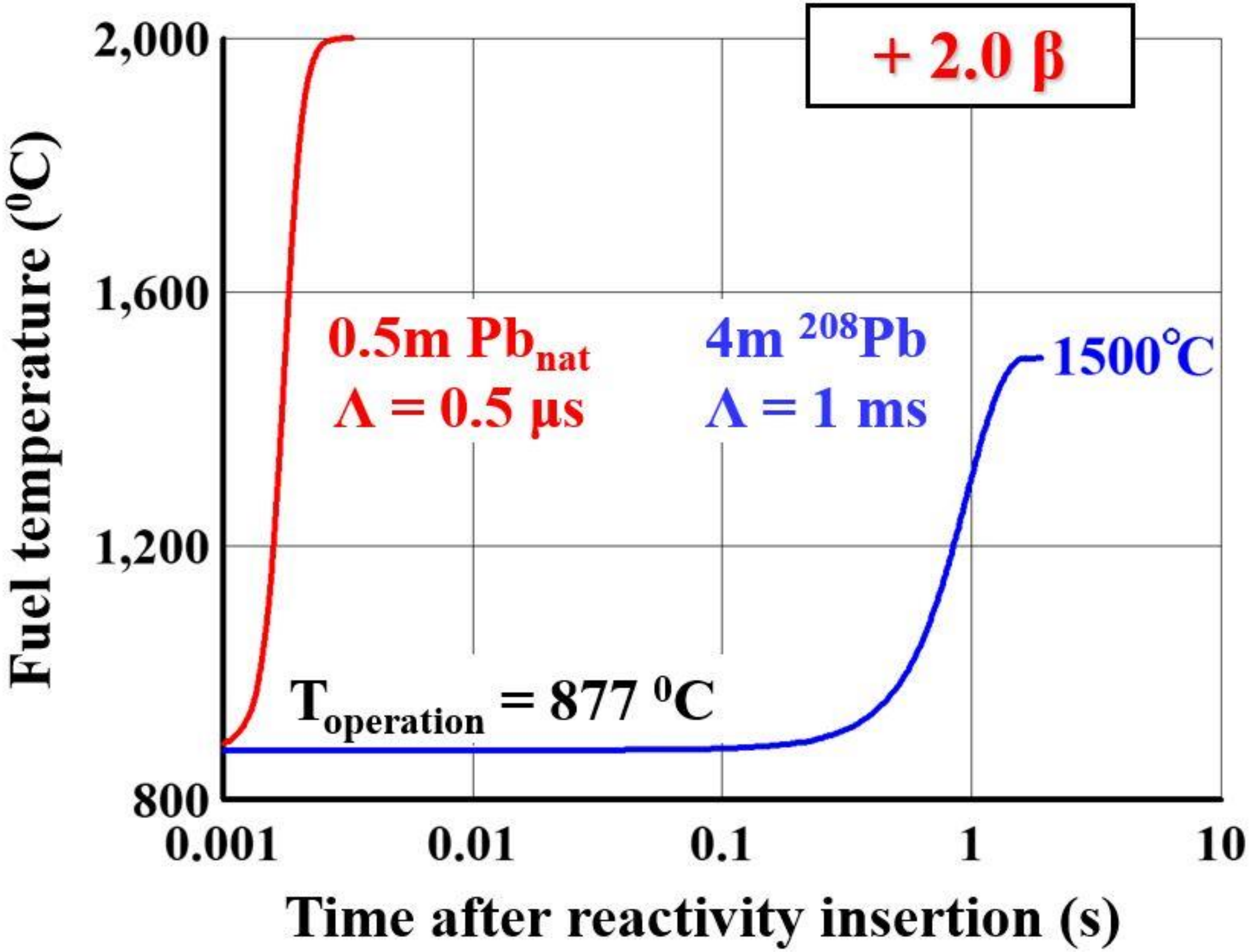
Time constant of fuel element τ_{th} ~ 0.1 s (metal) ÷ 1 s (oxide)
→ at $\Delta t \geq \tau_{th}$ part of the heat has time to reach the coolant
→ negative coolant feedback has enough time to act
(in addition to Doppler effect)

2 feedbacks in the case of ^{208}Pb

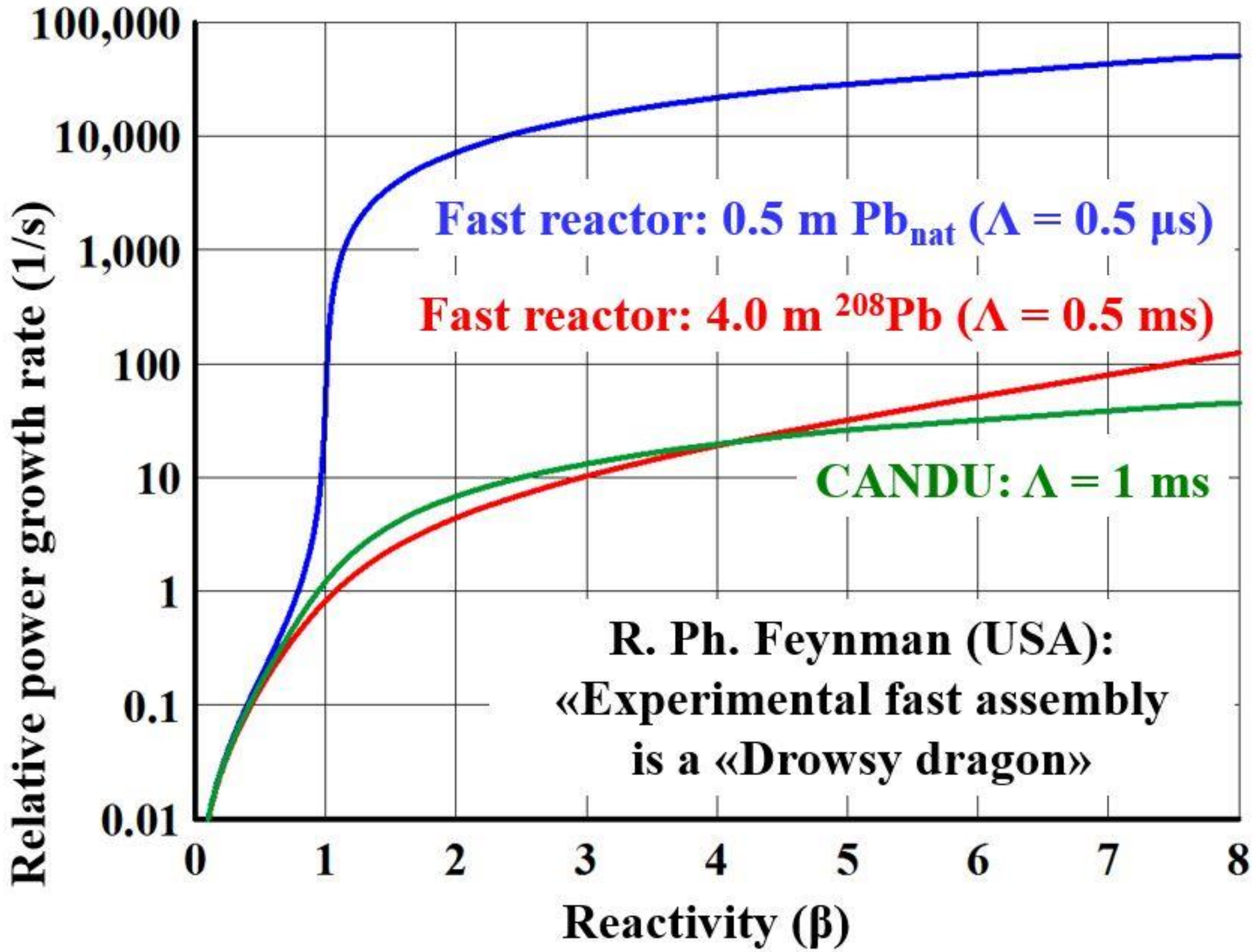
FAST REACTOR POWER AT THE NEUTRON FLASH



FUEL TEMPERATURE AT THE NEUTRON FLASH



ASYMPTOTIC PROCESS OF REACTOR RUNAWAY



4 Sources of ^{208}Pb

FROM WHERE CAN WE GET ^{208}PB?

$$^{232}\text{Th} \xrightarrow{\alpha} \underbrace{\overset{6\cdot\alpha + 4\cdot\beta}{\ldots\ \ldots\ \ldots}}_{\text{14.6 billion years}} \rightarrow {}^{208}\text{Pb}$$

$$^{235}\text{U} \xrightarrow{\alpha} \underbrace{\overset{7\cdot\alpha + 4\cdot\beta}{\ldots\ \ldots\ \ldots}}_{\text{0.7 billion years}} \rightarrow {}^{207}\text{Pb}$$

$$^{238}\text{U} \rightarrow \underbrace{\ldots\ \ldots\ \ldots}_{\text{4.6 billion years}} \rightarrow {}^{206}\text{Pb}$$

Relative content of lead isotopes in radiogenic lead depends on age of ore deposits and on admixture of natural lead

Pb_{nat} = 1.4%^{204}Pb + 24.1%^{206}Pb + 22.1%^{207}Pb + 52.4%^{208}Pb

From Th-ores and (Th-U)-ores

ORE DEPOSITS CONTAINING RADIOGENIC LEAD

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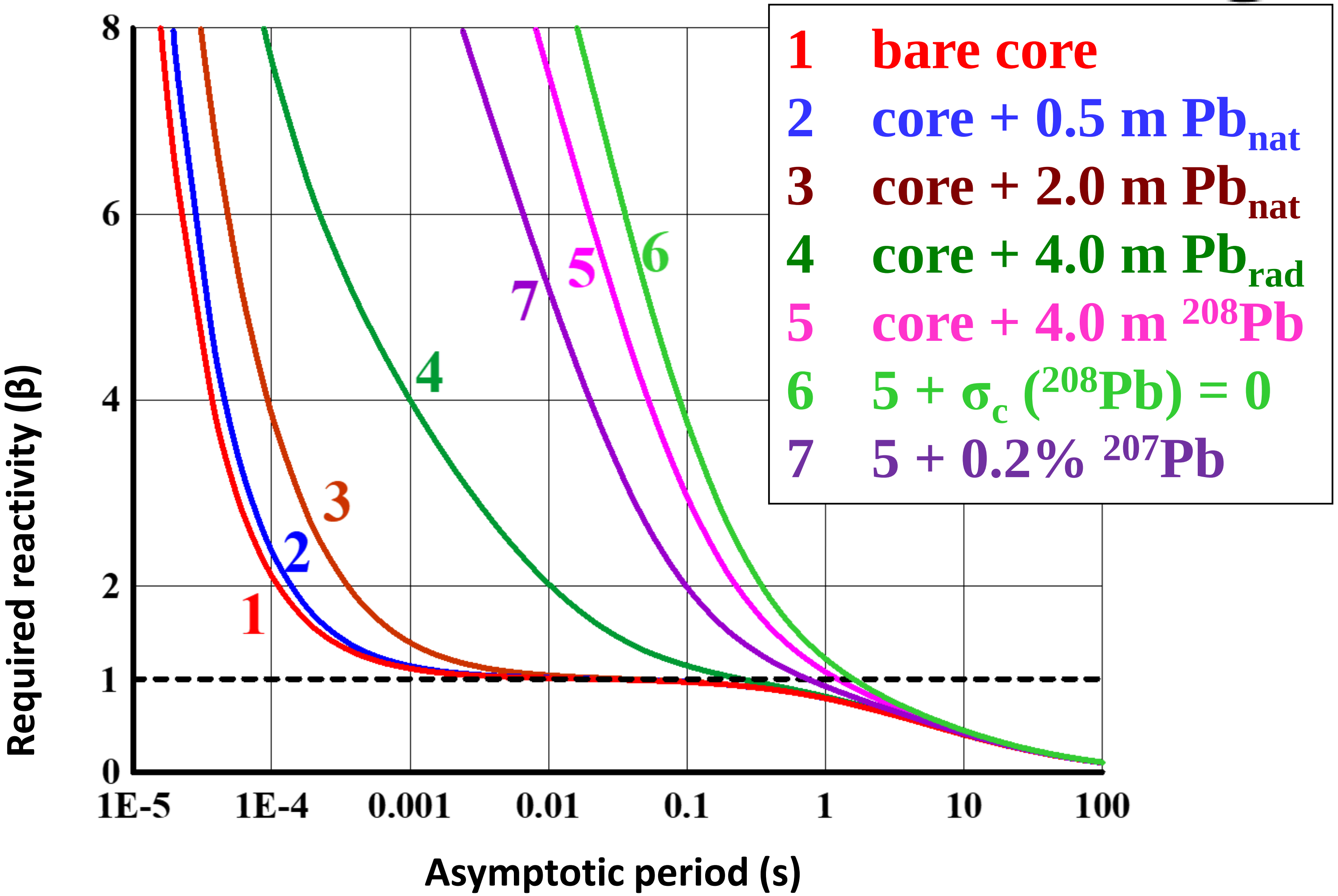
Ore	U / Th / Pb (% wt.)	^{204}Pb/ ^{206}Pb/ ^{207}Pb/ ^{208}Pb (% at.)
Monazite (Guarapari, Brazil)	1.3 / 59.3 / 1.5	0.005 / 6.03 / 0.46 / 93.5
Monazite (Manitoba, Canada)	0.3 / 15.6 / 1.5	0.010 / 10.2 / 1.86 / 87.9
Monazite (Mt. Isa Mine, Australia)	0.0 / 5.73 / 0.3	0.038 / 5.44 / 0.97 / 93.6
Monazite (Las Vegas, USA)	0.1 / 9.39 / 0.4	0.025 / 9.07 / 1.13 / 89.8
Monazite (South Bug, Ukraine)	0.2 / 8.72 / 0.9	0.010 / 6.04 / 0.94 / 93.0
Natural Lead	———	1.4 / 24.1 / 22.1 / 52.4

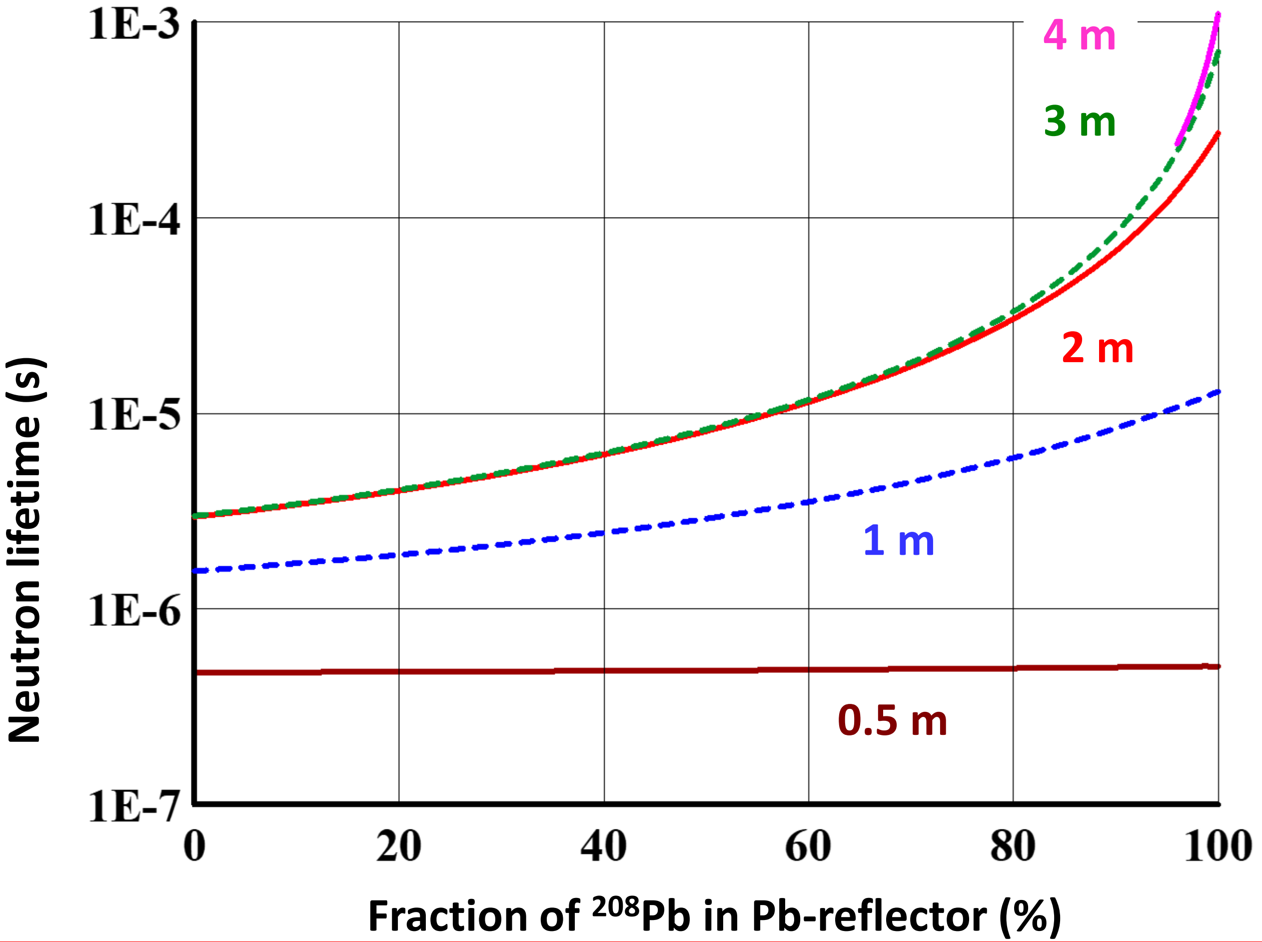
There are ores ~ 93% ^{208}Pb

DO WE NEED TO ENRICH LEAD?



It seems that we should enrich lead

NEUTRON LIFETIME IN A FAST REACTOR WITH DIFFERENT PB-REFLECTORS



It’s reasonable to use enriched lead of 2 - 3 m

CONCLUSION

1. The new approach is proposed to improve nuclear safety of fast reactors thanks to slowing down chain reaction

2. ^{208}Pb reflector in fast reactors can considerably prolong lifetime of prompt neutrons (by three orders of magnitude)

3. Long neutron lifetime and short time constant of fuel elements substantially improve nuclear safety even by insertion of reactivity > β

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Upcoming Webinars

25 September 2019	GEN IV Coolants Quality Control	Dr. Christian Latge, CEA, France
23 October 2019	Passive Decay Heat Removal System	Dr. Mitchel Farmer, ANL, USA
13 November 2019	Czech Experimental Program on MSR Technology Developments	Dr. Jan Uhlir, Research Center Řež, Czech Republic