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Fast Reactor Physics and Design: An Overview

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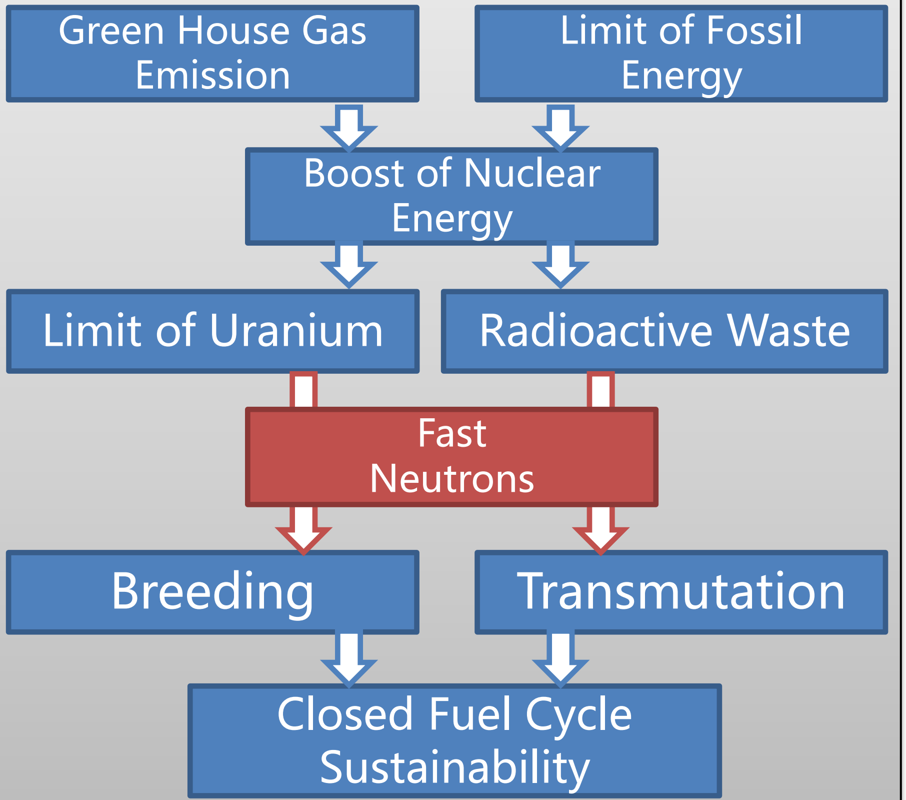
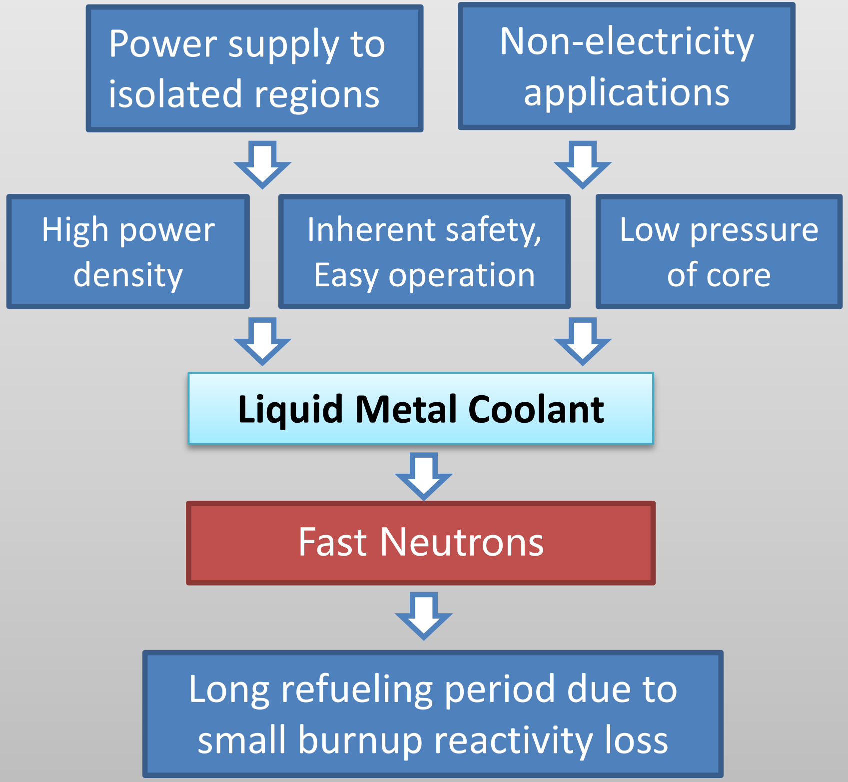
14 July 2026 Trieste, Italy

Why fast reactor?

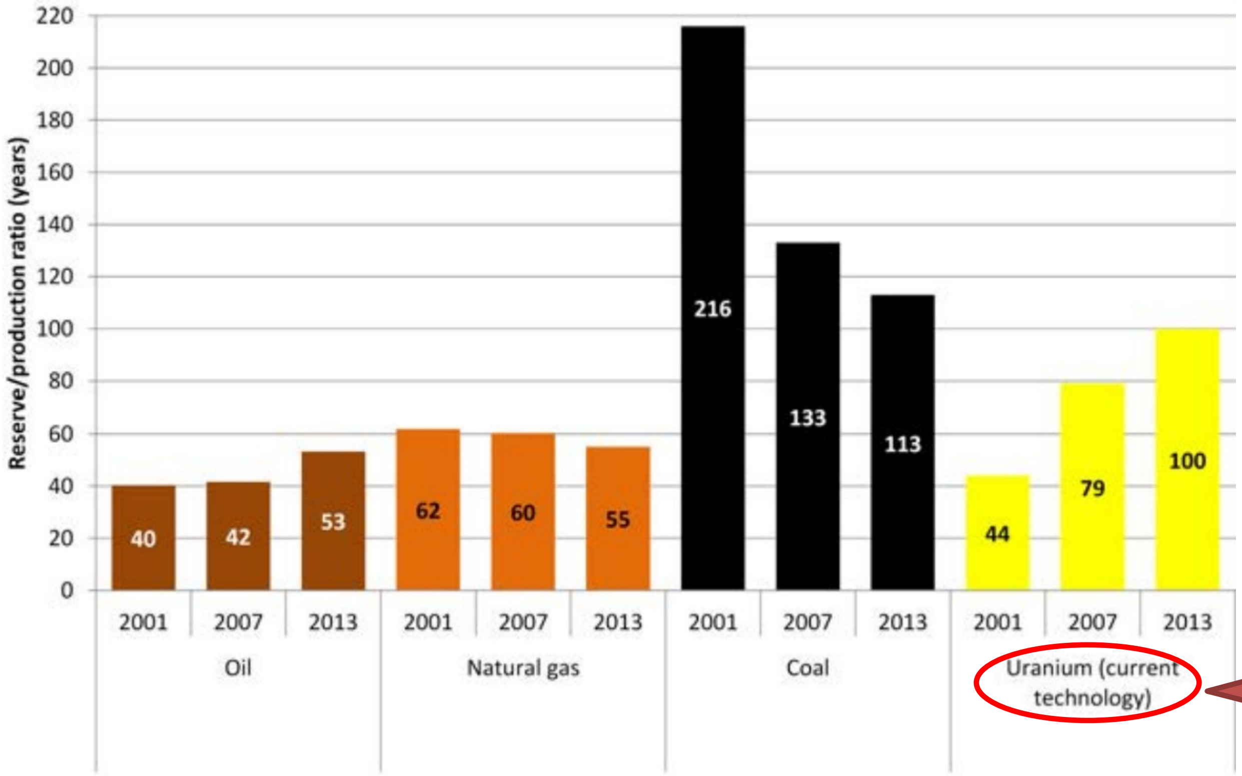
Answer for those who take nuclear as base-load:



Answer for those who take nuclear as supplement, such as by SMR:



Limit of Uranium Resources



Ratio of energy reserves to annual production

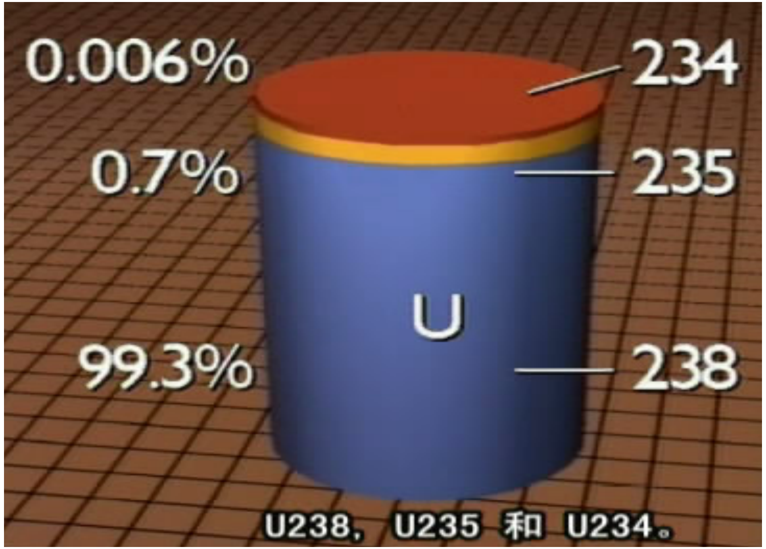
- **Uranium resources simply cannot meet human long-term energy needs.**
- **It seems nuclear energy cannot be counted on.**

The utilization rate of uranium resources is less than 1% with current technology!

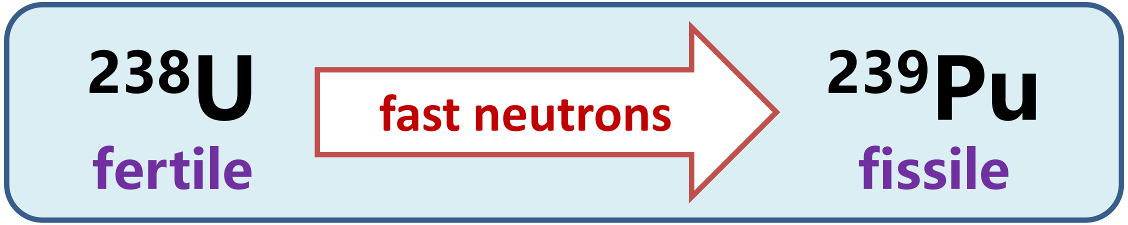
Reference: NUCLEAR POWER AND SUSTAINABLE DEVELOPMENT, IAEA, 2016

Importance of Breeding

- isotopes of the natural uranium:
  - ^{238}U, 99.284% (fertile)
  - ^{235}U, 0.711% (fissile)
  - ^{234}U, 0.0054% (fertile)
- fissile:
  - easy to fission
  - U-235, Pu-239, U-233
- fertile:
  - difficult to fission
  - U-238, Th-232
- breeding:
  - fertile to fissile



natural uranium isotopes



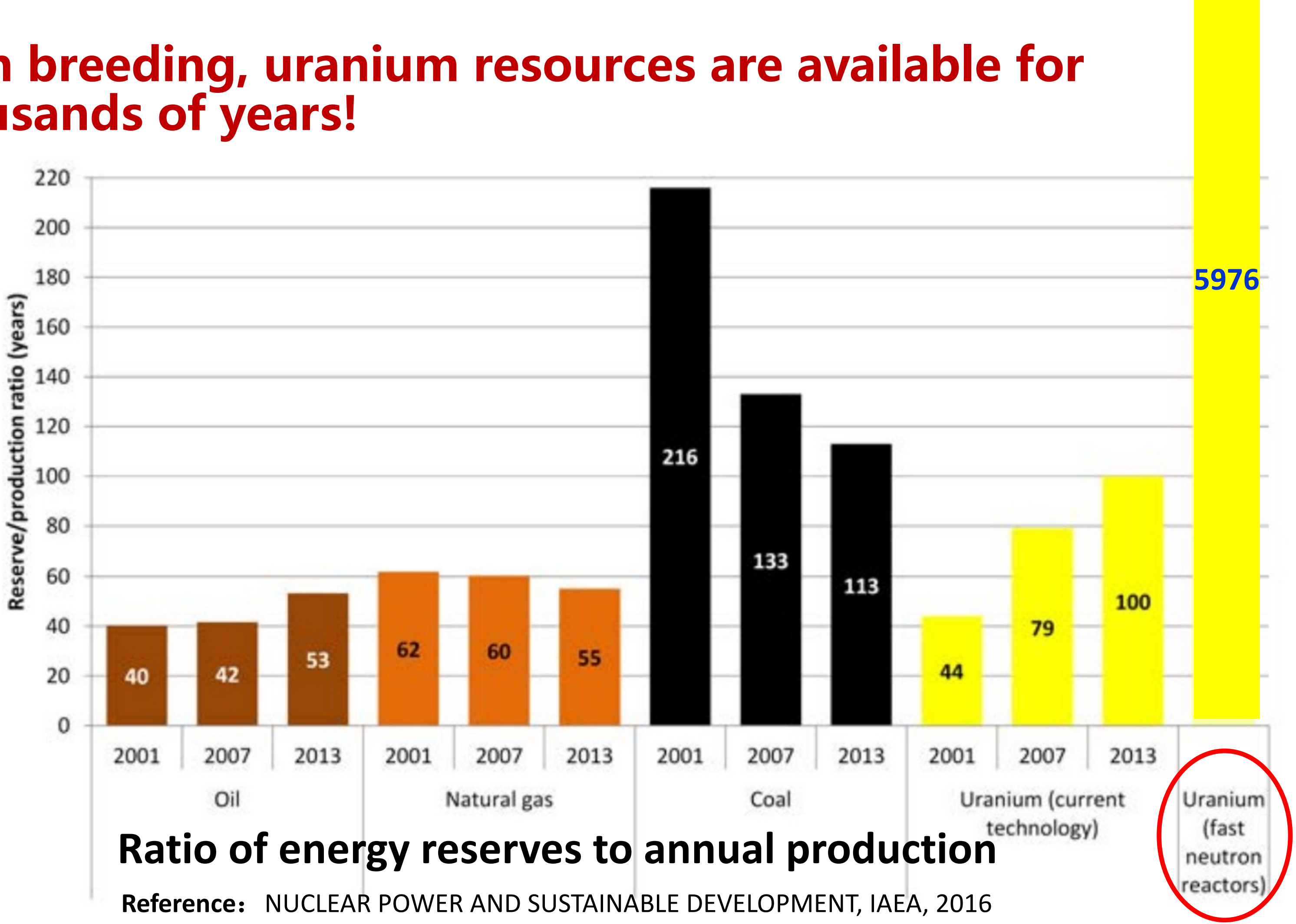
Importance of Breeding

- It has been widely accepted that the world's resources of U-235 would not be sufficient to meet the anticipated demand for nuclear fuel.
- Breeding is necessary if nuclear energy is taken as a main source of power, by converting abundant non-fissile materials, called fertile isotopes.
- As uranium-238 becomes usable, lower-grade uranium ores can be accepted, and economically mineable uranium resources will multiply many times over.

$$^{238}U(n,\gamma)\,^{239}U \xrightarrow[23.5\text{ m}]{\beta^-} \,^{239}Np \xrightarrow[2.35\text{ d}]{\beta^-} \,^{239}Pu$$

$$^{232}Th(n,\gamma)\,^{233}Th \xrightarrow[22.2\text{ m}]{\beta^-} \,^{233}Pa \xrightarrow[27.4\text{ d}]{\beta^-} \,^{233}U$$

With breeding, uranium resources are available for thousands of years!



Ratio of energy reserves to annual production

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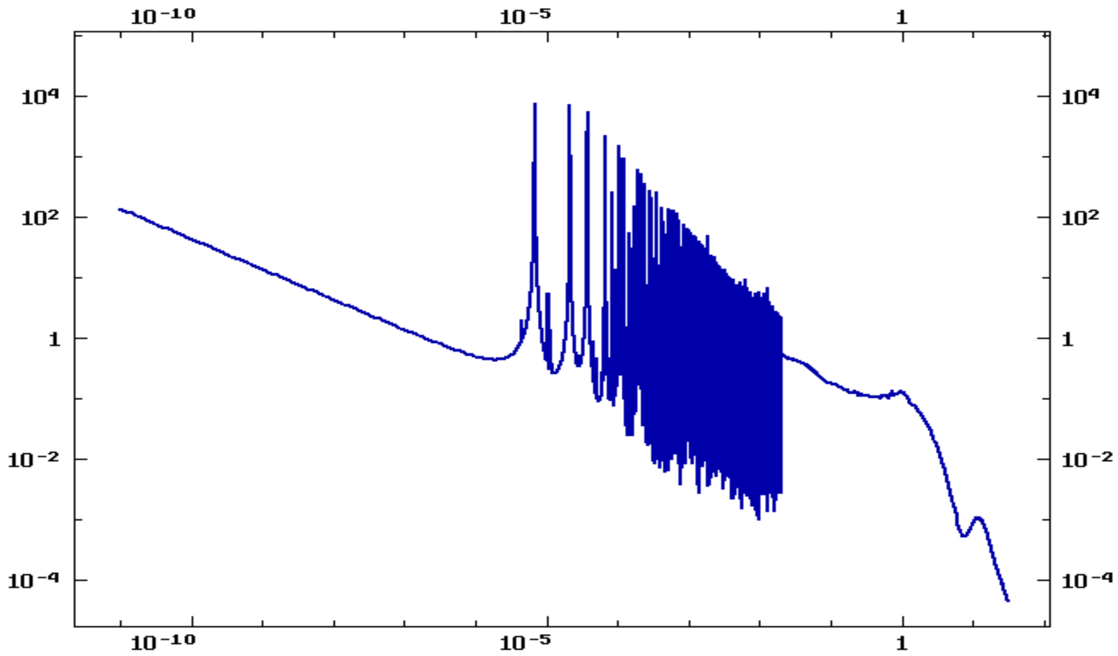
How to Achieve Breeding?

^{238}U → ^{239}Pu

fertile → fissile

- All neutrons can do the job. The slower, the easier!
- Breeding is initiated by the reaction radioactive capture (n, γ).

U-238(n,γ)U-239 Cross Section/barn



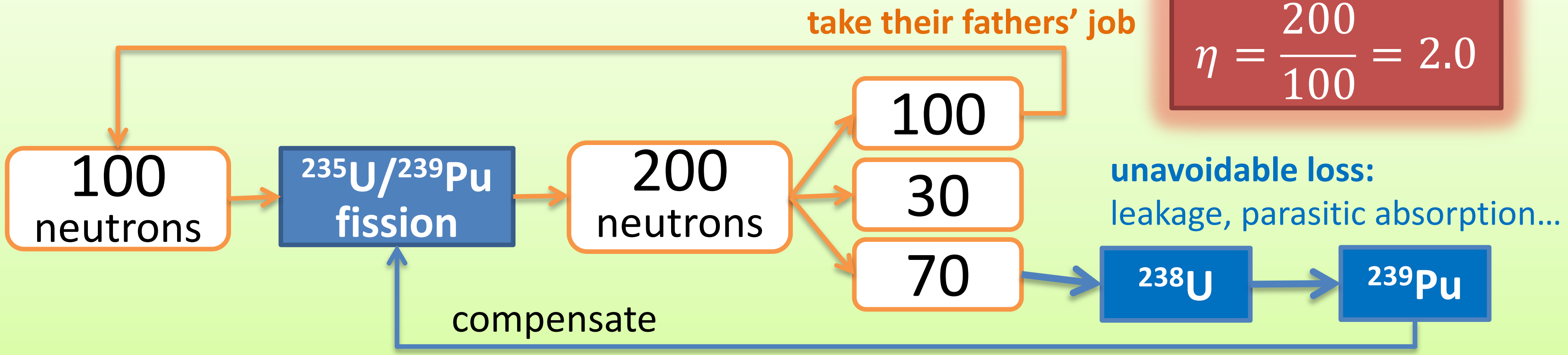
Neutron Energy/MeV

(from ENDF/B-VIII.0)

Thermal v.s. Fast: Key Difference in Neutron Balance

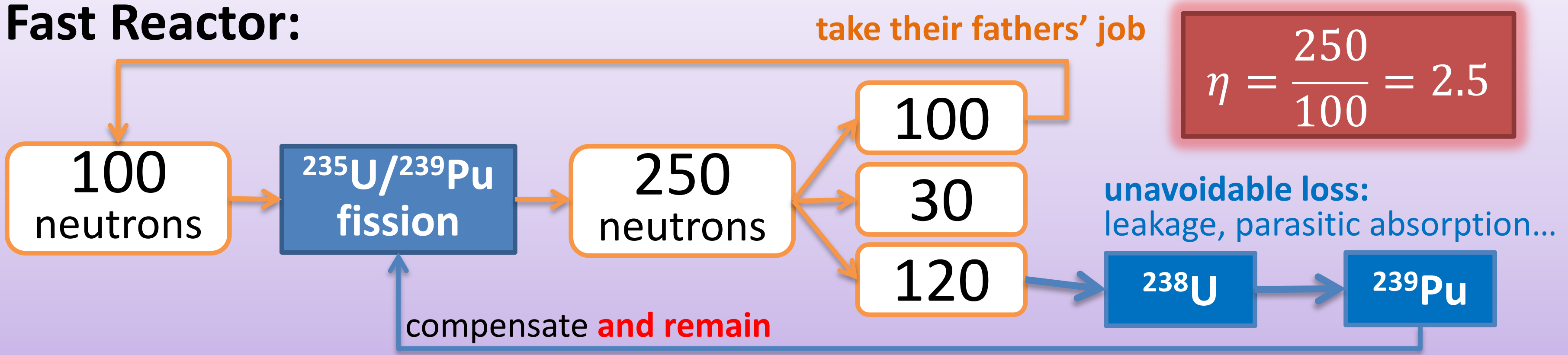
Thermal Reactor:

$$\eta = \frac{200}{100} = 2.0$$

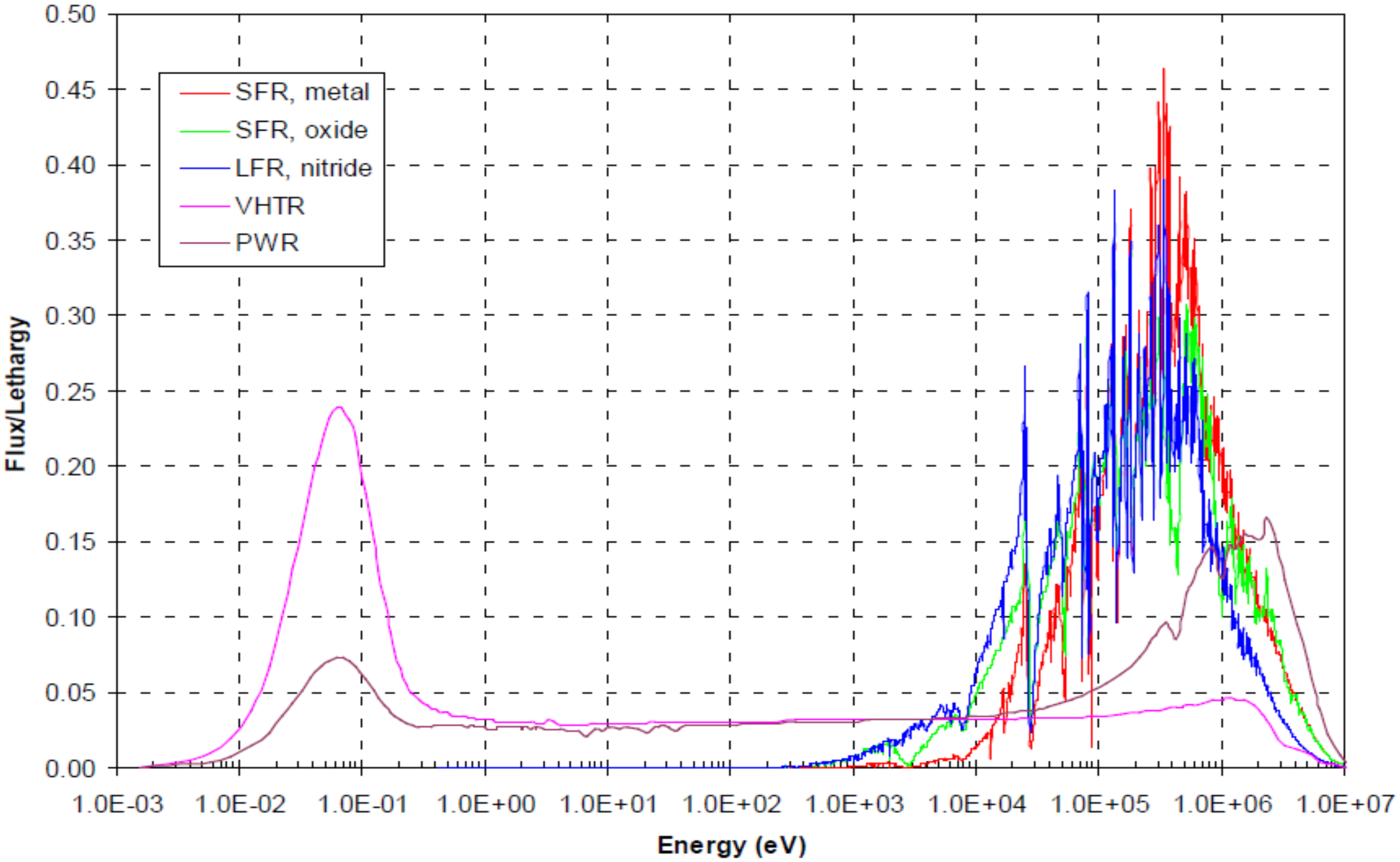


Fast Reactor:

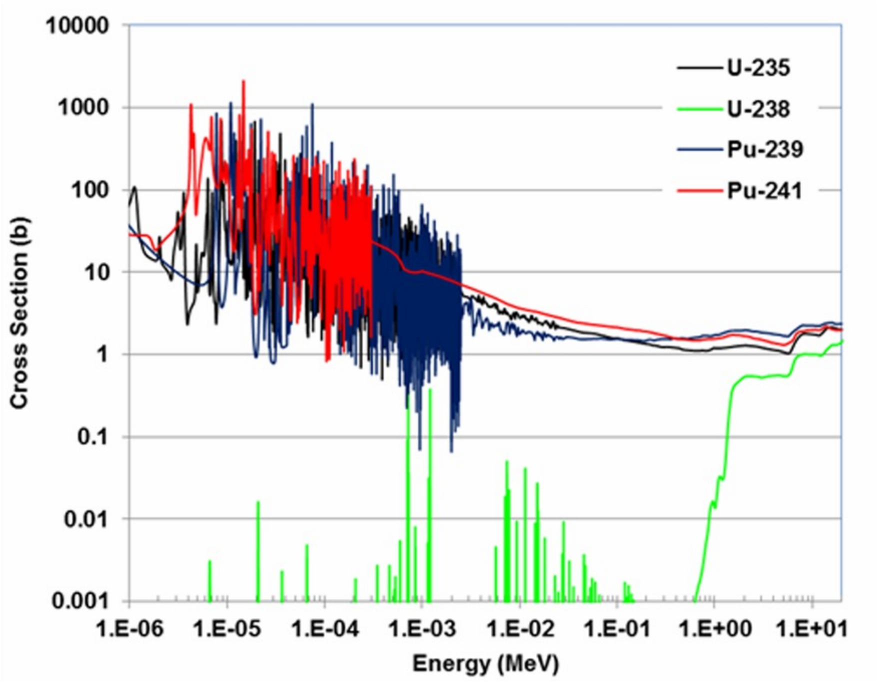
$$\eta = \frac{250}{100} = 2.5$$



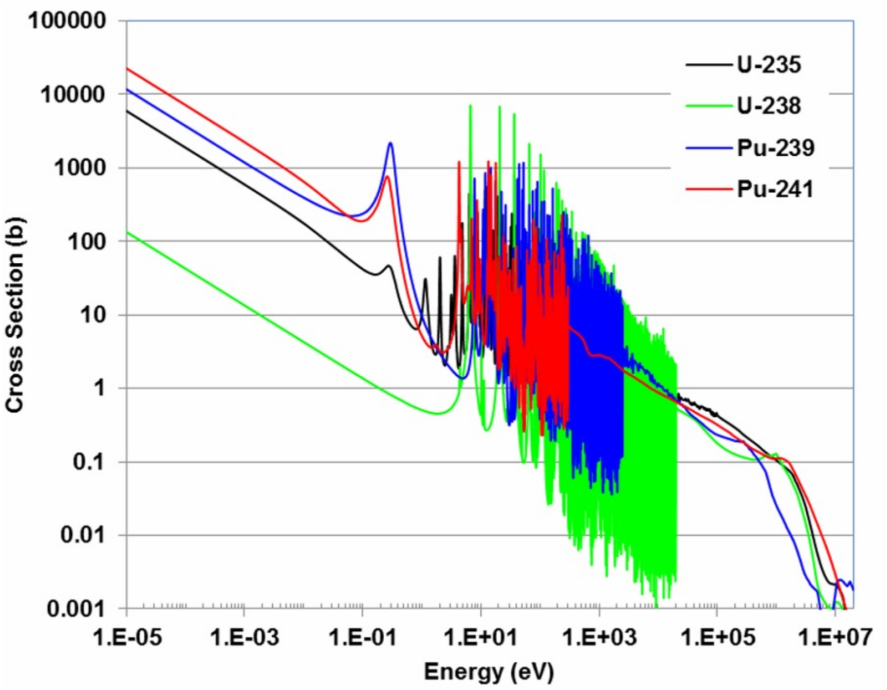
Neutron Spectra of Main Reactor Types



Fission Cross-section

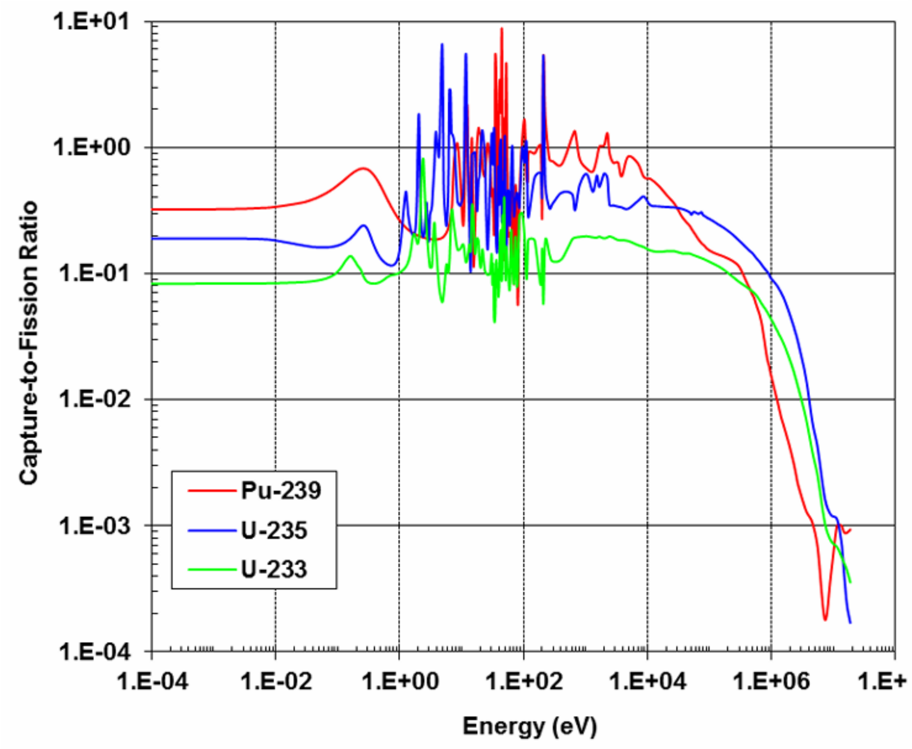


Capture Cross-section



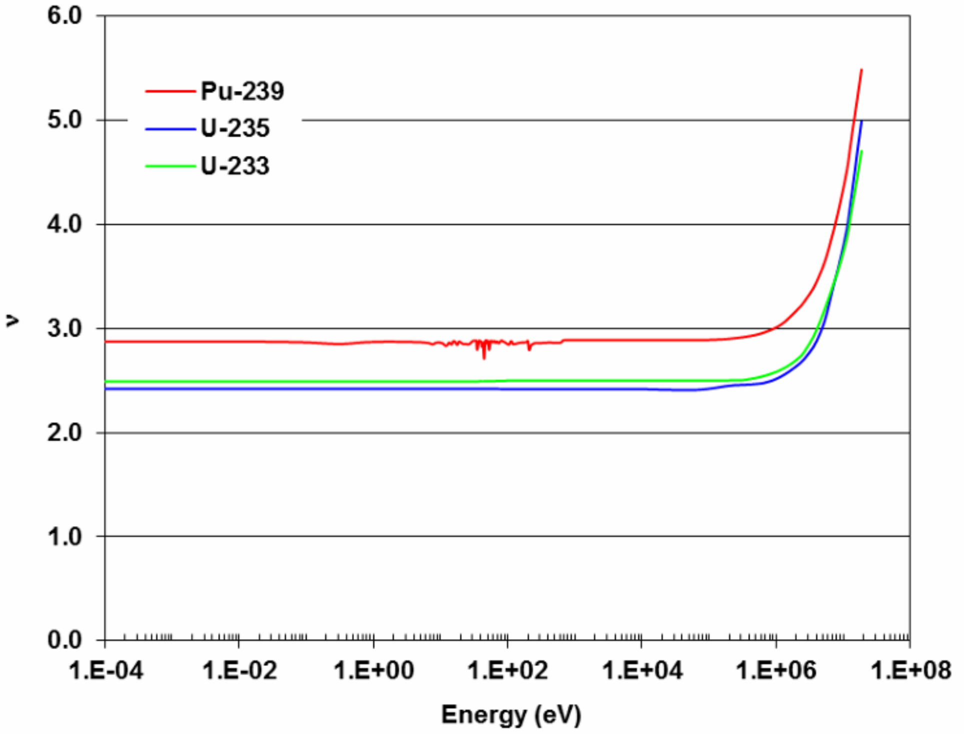
- Fission and capture cross sections are more than 100 times higher in thermal range.
- Fission cross sections are more or less constant in fast range.
- Capture cross sections decrease sharply in fast range.

Capture to fission ratio



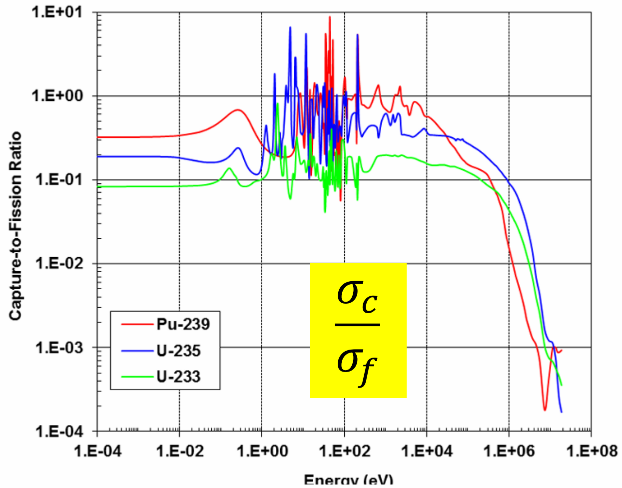
- Capture to fission ratio decreases rapidly at high energy.

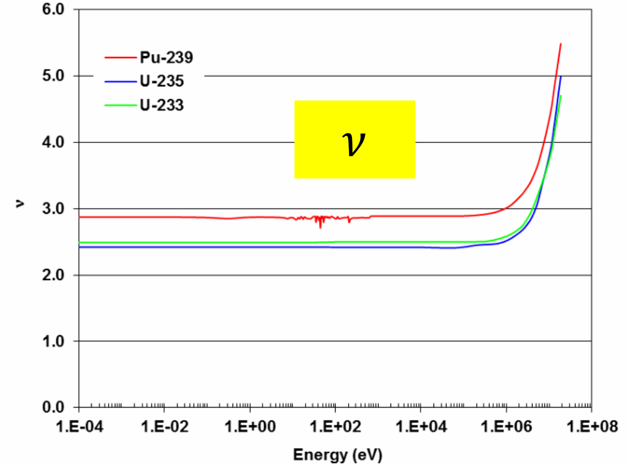
Neutron yield per fission

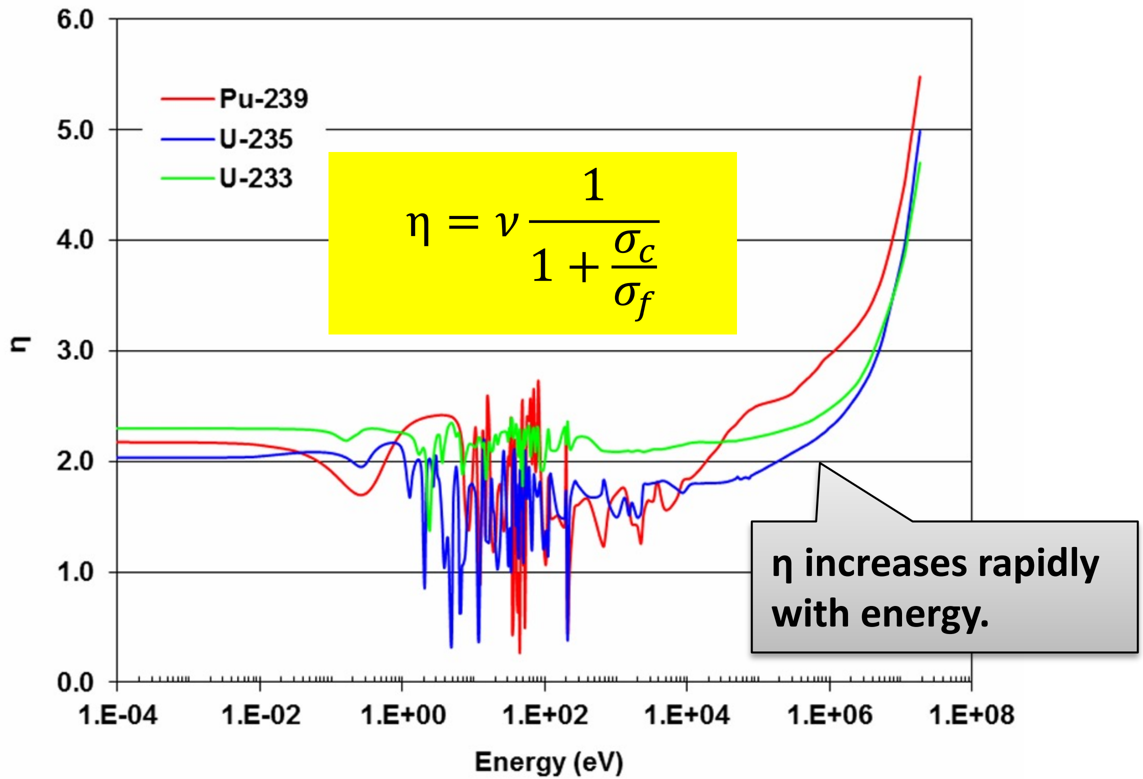


- Neutron yield per fission increases with energy.

Neutron yield per capture



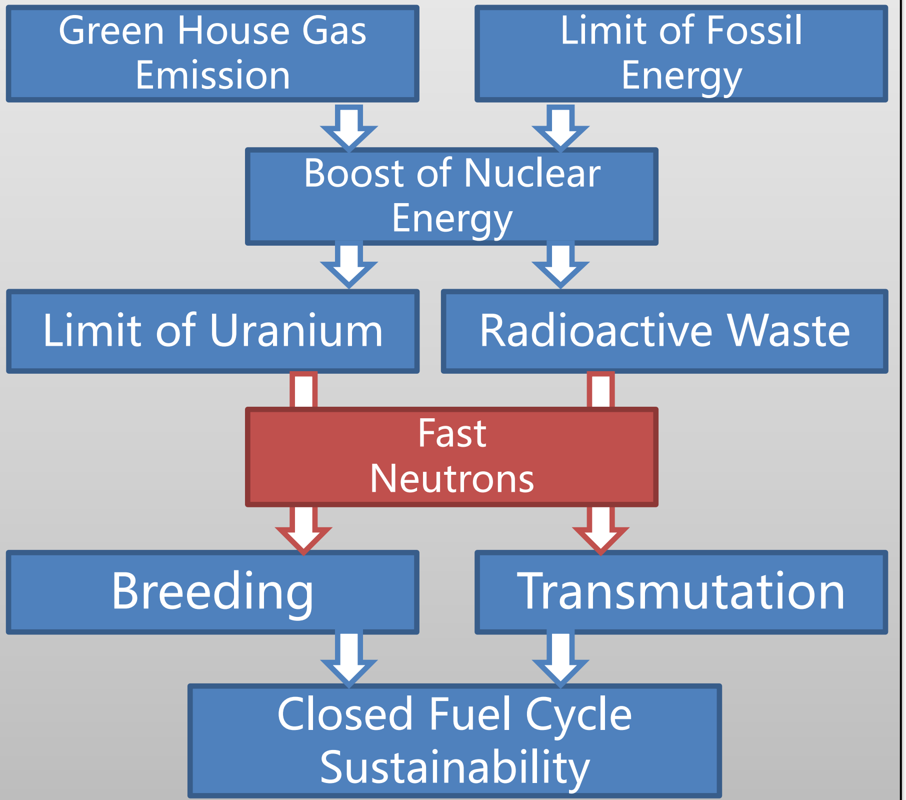




- ν is the number of neutrons produced per fission
- η is the number of neutrons produced per absorption
- $\eta = \nu \frac{\sigma_f}{\sigma_a} = \nu \frac{\sigma_f}{\sigma_{f+}\sigma_c} = \nu \frac{1}{1+\sigma_c/\sigma_f}$

Why fast reactor?

Answer for those who take nuclear as base-load:



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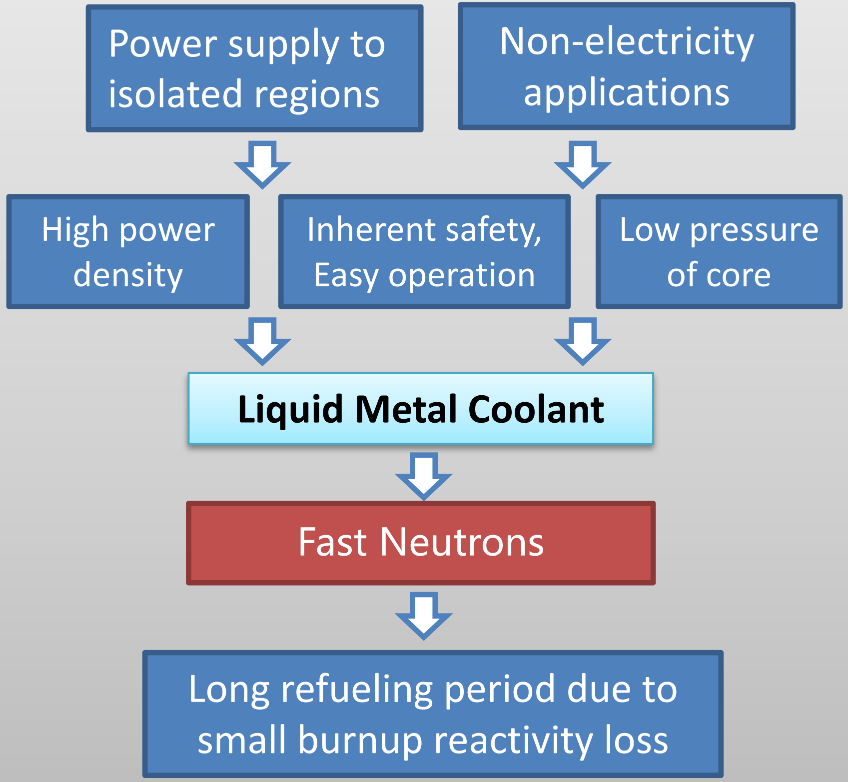
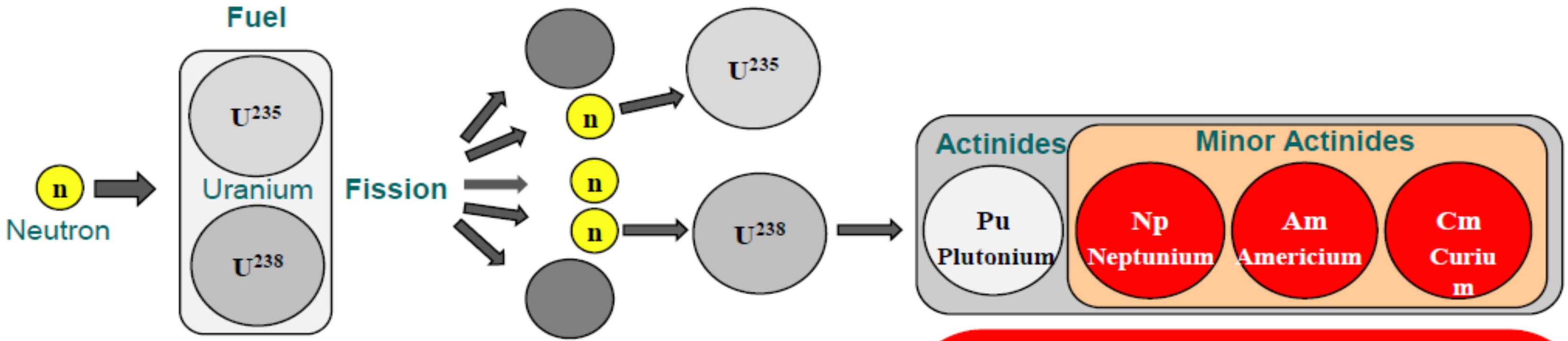
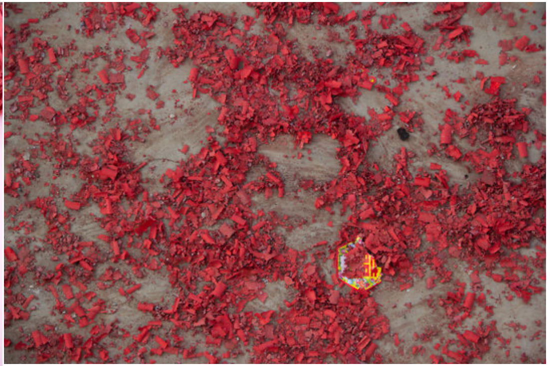


Main Radioactive Waste from Spent Nuclear Fuel:





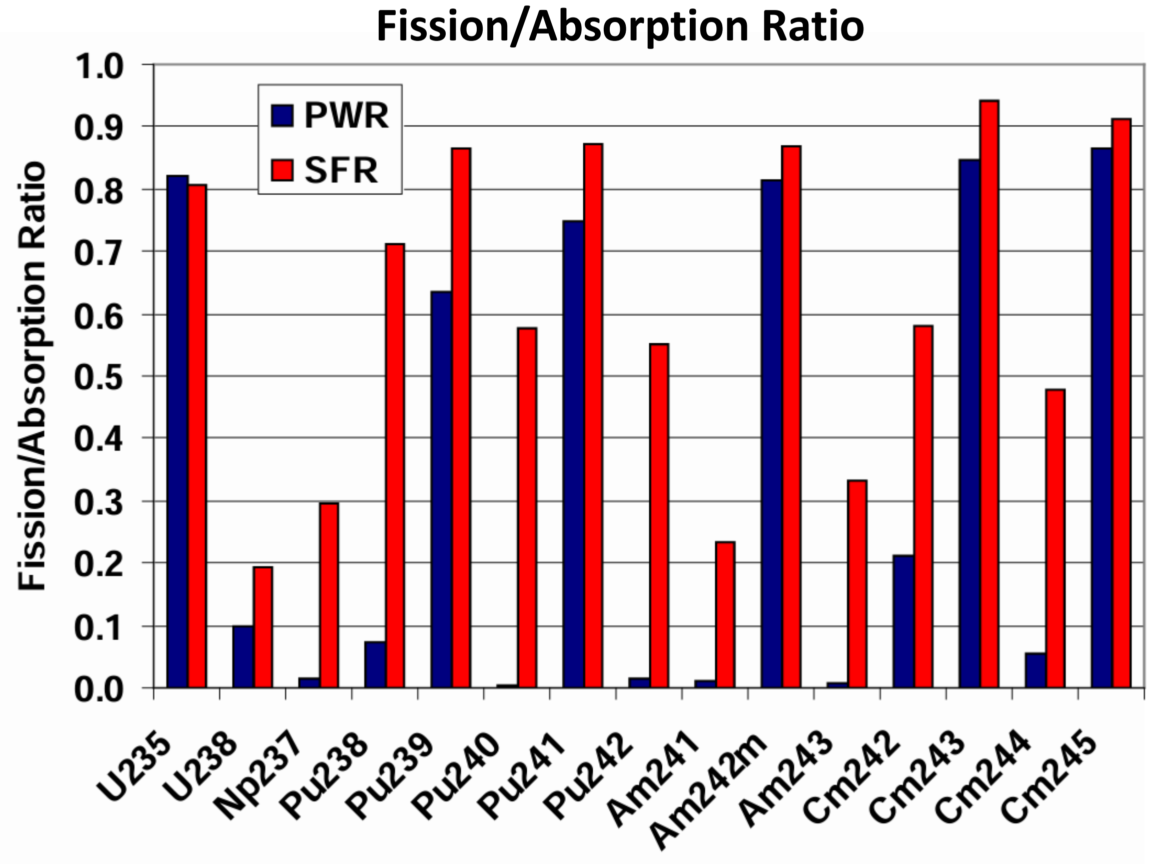
<u>Minor Actinides</u>

high radiotoxicity long lived waste that are difficult to store because:

- **Long lived (>1,000 years)**
- **Highly radiotoxic**
- **Heat emitting**

- Chinese firecracker: the unexploded ones are very similar to radioactive decay!
- The ideal way to deal with minor actinides is **fission**!

Fast Reactor has a higher fission/absorption ratio than thermal reactors:



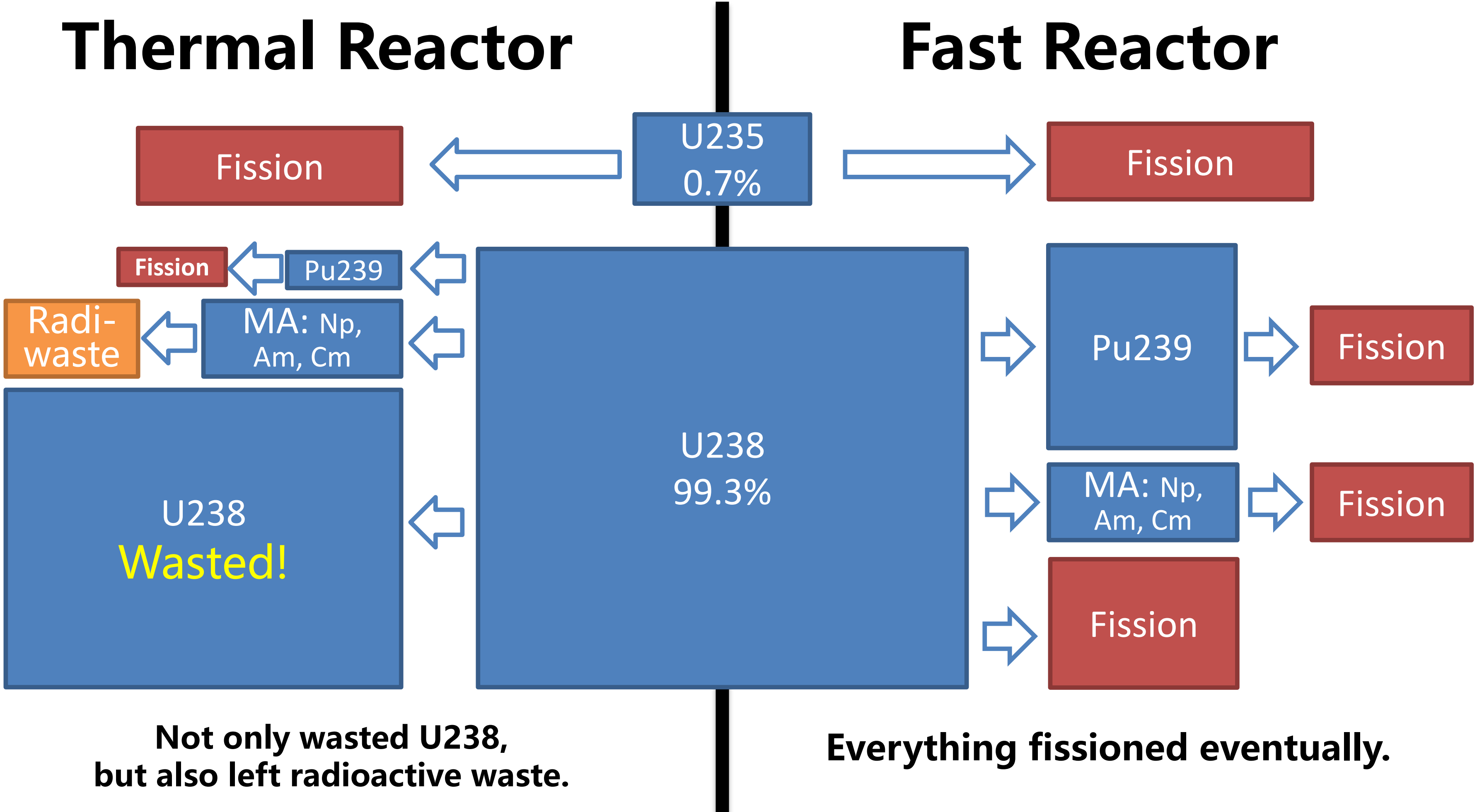
- Fissile isotopes are likely to fission in both thermal and fast spectra– **With higher fission fraction in fast spectrum.**
- Significant (up to ~60%) fission of fertile isotopes in fast spectrum.
- Transuranic elements are consumed efficiently in fast systems with less generation of higher actinides.

Fast Reactor has a higher fission/absorption ratio than thermal reactors:

Spectrum-averaged cross sections and capture-to-fission ratio for uranium and minor actinides

Nuclide	PWR spectrum			Fast neutron spectrum		
	$\bar{\sigma}_f$	$\bar{\sigma}_c$	$\alpha = \frac{\bar{\sigma}_c}{\bar{\sigma}_f}$	$\bar{\sigma}_f$	$\bar{\sigma}_c$	$\alpha = \frac{\bar{\sigma}_c}{\bar{\sigma}_f}$
^{237}Np	0.520	33.000	63.000	0.320	1.700	5.300
^{238}Np	134.000	13.600	0.100	3.600	0.200	0.050
^{238}Pu	2.400	27.700	12.000	1.100	0.580	0.530
^{239}Pu	102.000	58.700	0.580	1.860	0.560	0.300
^{240}Pu	0.530	210.200	396.600	0.360	0.570	1.600
^{241}Pu	102.200	40.900	0.400	2.490	0.470	0.190
^{242}Pu	0.440	28.800	65.500	0.240	0.440	1.800
^{241}Am	1.100	110.000	100.000	0.270	2.000	7.400
^{242}Am	159.000	301.000	1.900	3.200	0.600	0.190
^{242m}Am	595.000	137.000	0.230	3.300	0.600	0.180
^{243}Am	0.440	49.000	111.000	0.210	1.800	8.600
^{242}Cm	1.140	4.500	3.900	0.580	1.000	1.700
^{243}Cm	88.000	14.000	0.160	7.200	1.000	0.140
^{244}Cm	1.000	16.000	16.000	0.420	0.600	1.400
^{245}Cm	116.000	17.000	0.150	5.100	0.900	0.180
^{235}U	38.800	8.700	0.220	1.980	0.570	0.290
^{238}U	0.103	0.860	8.300	0.040	0.300	7.500

Final Destination of Uranium Resources

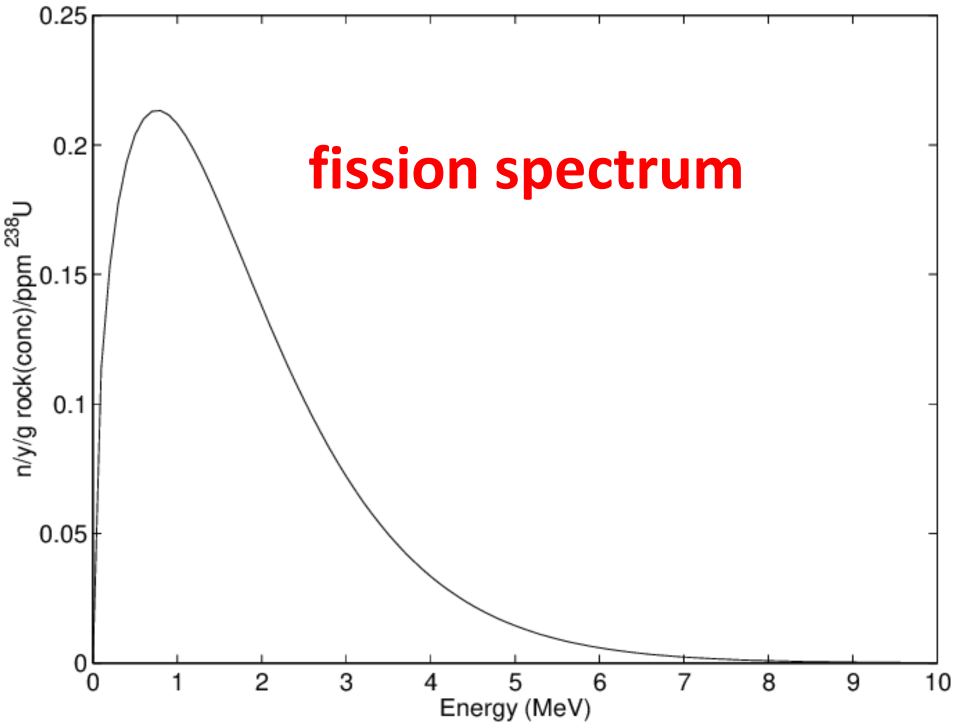


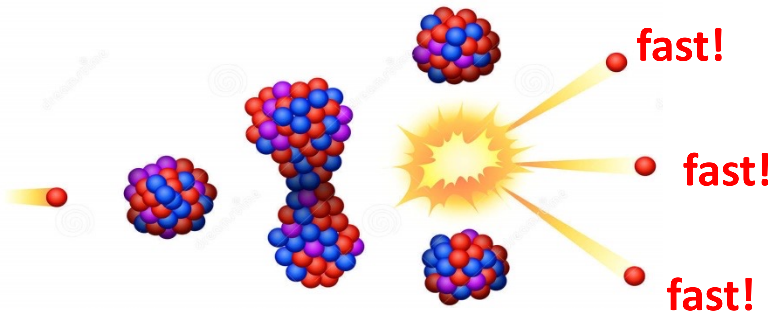
Not only wasted U238,
but also left radioactive waste.

Everything fissioned eventually.

How to achieve 'fast'?

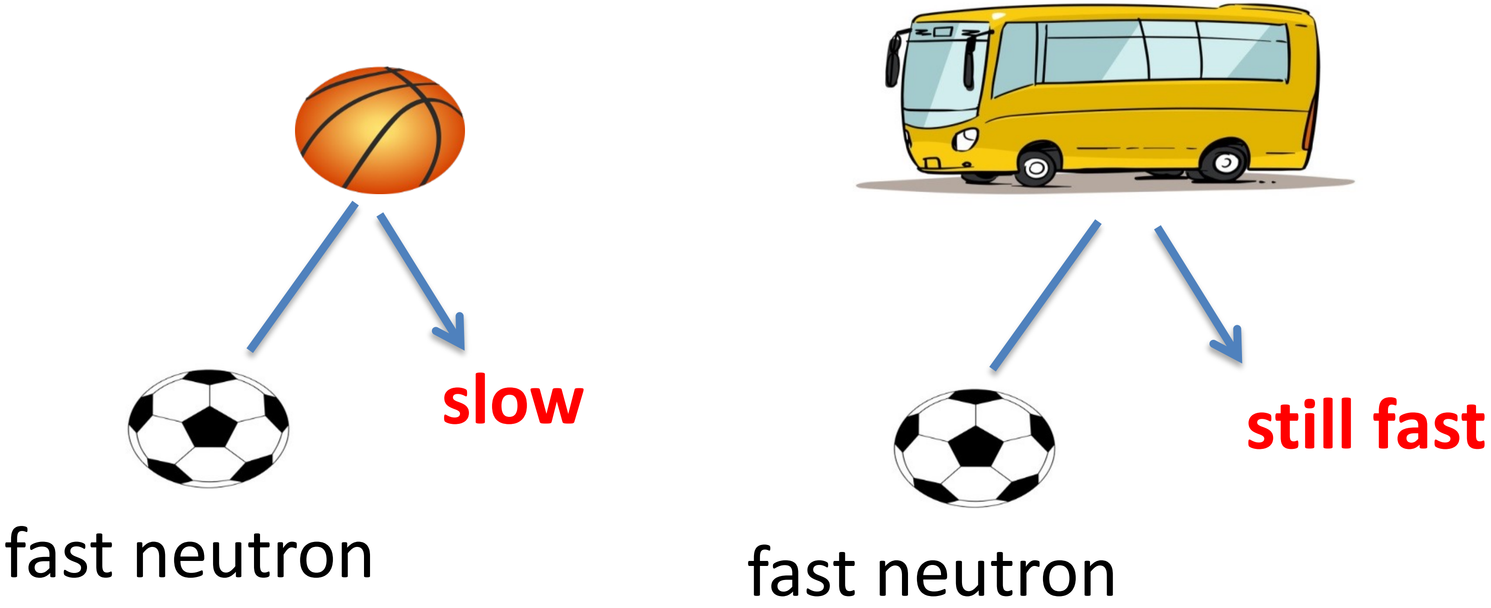
All **neutrons** are born **fast!**





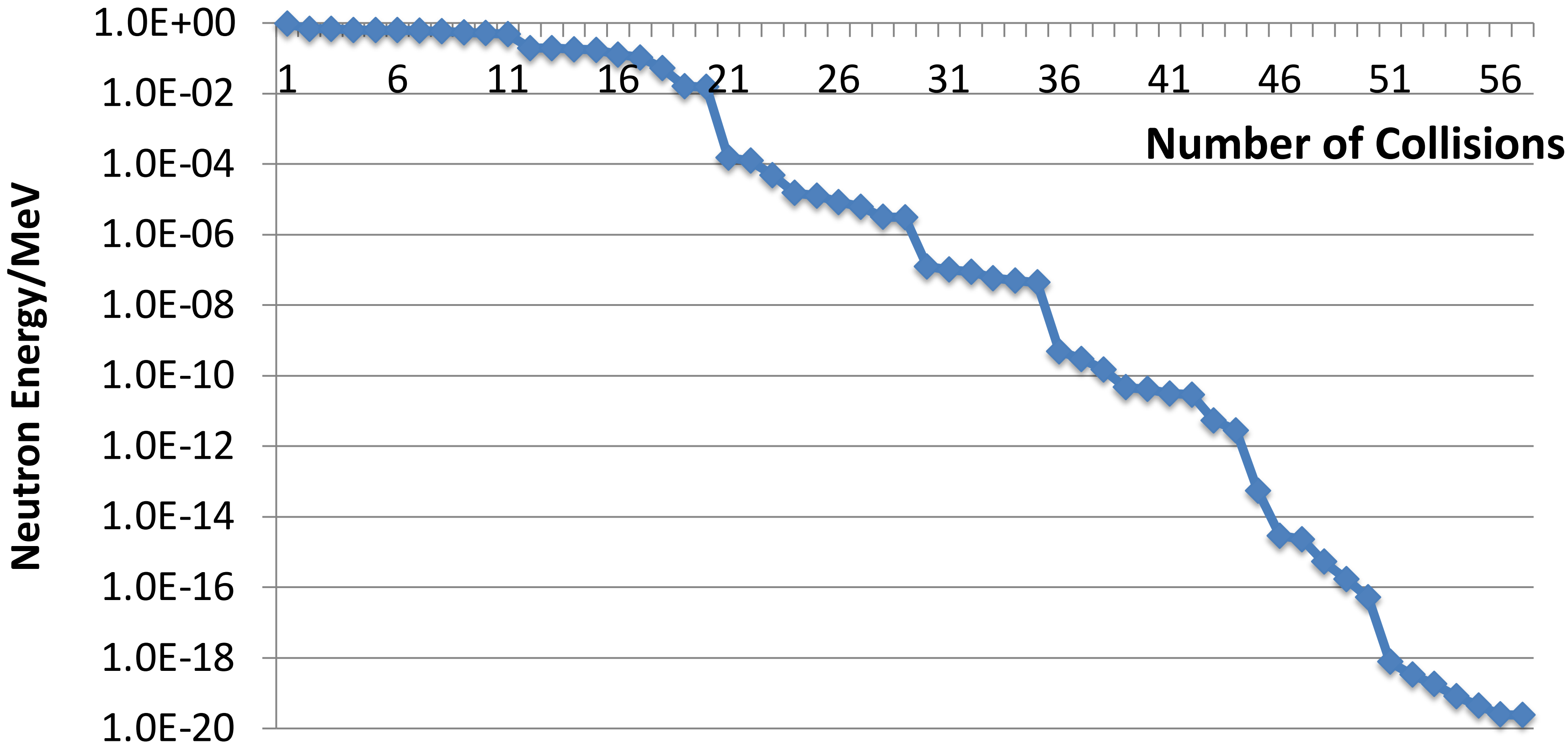
- Energy of neutrons newly born by fission:
  - Average: 2 MeV.
  - Most probable: 0.7 MeV
- Fast neutron by concept: > 0.1 MeV
- Neutron energy in thermal reactors: < 1 eV
- To build a fast reactor, just keep the original energy of neutrons as much as you can ...

How to achieve ‘fast’?



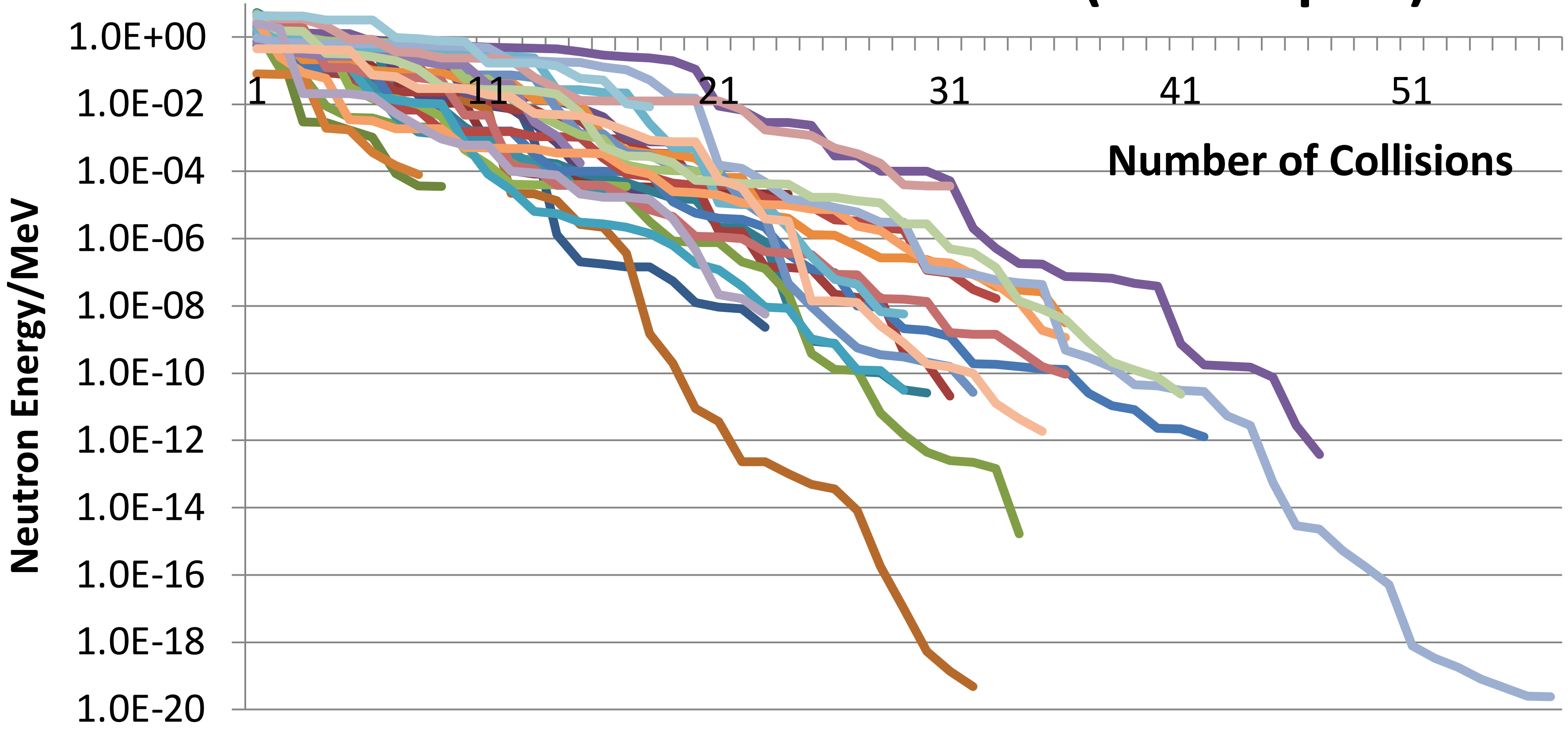
- To keep the speed/energy of neutrons: **The heavier the atom, the better!**
- In choosing coolants, just avoid light atomic-weight elements.

Neutron Moderation in PWR (one sample)



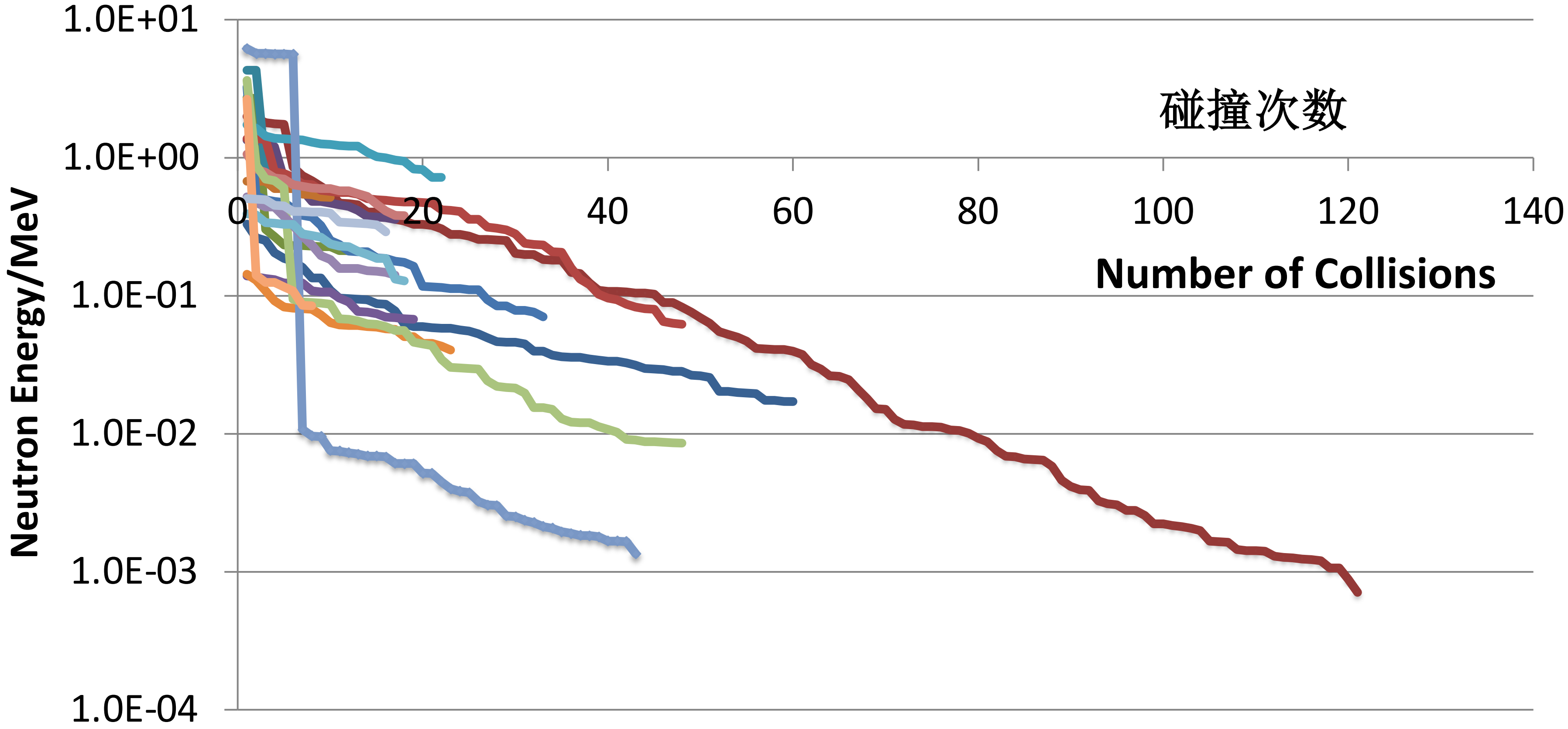
Attention: the simulation is carried out in an infinite material; therefore neutrons will not leak from the model but will eventually be absorbed. The simulation is only used to show the moderation speed by collisions.

Neutron Moderation in PWR (30 samples)



Attention: the simulation is carried out in an infinite material; therefore neutrons will not leak from the model but will eventually be absorbed. The simulation is only used to show the moderation speed by collisions.

Neutron Moderation in SFR (20 samples)



Attention: the simulation is carried out in an infinite material; therefore neutrons will not leak from the model but will eventually be absorbed. The simulation is only used to show the moderation speed by collisions.

How to achieve 'fast'?

To be a coolant of a reactor:

- It must be **liquid**!
- It must **flow** well!
- It must **transfers** heat well!
- It must be **stable** chemically!
- It must ...

Life is hard to a **coolant** of a **reactor**.

Life is much harder to a **coolant** of a **fast reactor**! Because it must also be **heavy**!

Available choices:

He Hg Na Na-K Pb Pb-Bi ...

Comparison of Fast Reactor Coolants

Coolants	Advantages	Disadvantages
Sodium	– Excellent heat transport properties – Low pressure system – Low pumping power requirements – Potentially high breeding ratio – Extensive sodium reactor experience	– Radioactivity (intermediate sodium loop employed) – Unfavorable coolant reactivity void coefficient – Chemical reactions with air and water – Nonvisible refueling procedure – Solid at room temperature
Helium	– No intermediate loop – Coolant not activated – Potentially high breeding ratio – Visible refueling/maintenance – Minimal void coefficient – Most compatible with materials – Utilization of thermal GCR technology – Potential for vented fuel – Potential for direct cycle – Flooding with H2O tolerable	– High pressure system – High pumping power requirements – Cladding roughening required – Emergency cooling provisions not established – Unproven high power density capability – Lack of fast spectrum reactor technology – Gas leakage difficult to control – High performance demands on pumps and valves

Reference: dan GABRIEL C. Handbook of nuclear engineering, Volume Ⅳ: Reactors of generation Ⅲ and Ⅳ[M]. [S. l.], Springer, 2010.

Comparison of Fast Reactor Coolants

Coolants	Advantages	Disadvantages
Lead	– Does not have the combustibility of sodium or other alkali metal coolants – Does not react vigorously with water, steam, air, or carbon dioxide – High boiling temperature – Excellent heat transport properties – Low pressure system – Slightly lower absorption of neutrons relative to sodium (permits derated core coolant volume to be increased, lowering pressure drop) – Acceptably low pumping power for derated core with opened lattice – High density provides sufficient net positive suction head to install primary coolant pumps in primary circuit hot leg in pool configuration – Significantly lesser amounts of 210Po by two to four orders of magnitude compared with Pb-Bi – High density limits coolant void growth following steam generator or heat exchanger failure and blowdown of steam or carbon dioxide into Pb	– Higher melting temperature relative to sodium or Pb-Bi – Thicker structures are required to support coolant weight – Thicker structures are required to resist forces during seismic events – Size of a pool reactor may be limited by need to accommodate seismic events – Opaque coolant – Solid at room temperature – Radioactive coolant (Dominant radiation is gammas from 207mPb having a half-life of 0.806 s)

Reference: dan GABRIEL C. Handbook of nuclear engineering, Volume Ⅳ: Reactors of generation Ⅲ and Ⅳ[M]. [S. l.], Springer, 2010.

Comparison of Fast Reactor Coolants

Coolants	Advantages	Disadvantages
Lead-bismuth	– Does not have the combustibility of sodium or other alkali metal coolants – Does not react vigorously with water, steam, or air – Reacts only weakly with carbon dioxide – Lower melting temperature compared with Pb – High boiling temperature – Excellent heat transport properties – Low pressure system – Slightly lower absorption of neutrons relative to sodium (permits derated core coolant volume to be increased, lowering pressure drop) – Acceptably low pumping power for derated core with opened lattice – High density provides sufficient net positive suction head to install primary coolant pumps in primary circuit hot leg in pool configuration – High density limits coolant void growth following steam generator or heat exchanger failure and blowdown of steam or carbon dioxide into Pb	– Neutron capture in 209Bi results in 210Po, which is an alpha emitter with a half-life of 138 days; exposure to moisture can result in volatile polonium hydride resulting in an airborn hazard – Thicker structures are required to support coolant weight – Thicker structures are required to resist forces during seismic events – Size of a pool reactor may be limited by need to accommodate seismic events – Opaque coolant – Solid at room temperature – Radioactive coolant (Dominant radiation is gamma from 207mPb with half-life of 0.806 s)

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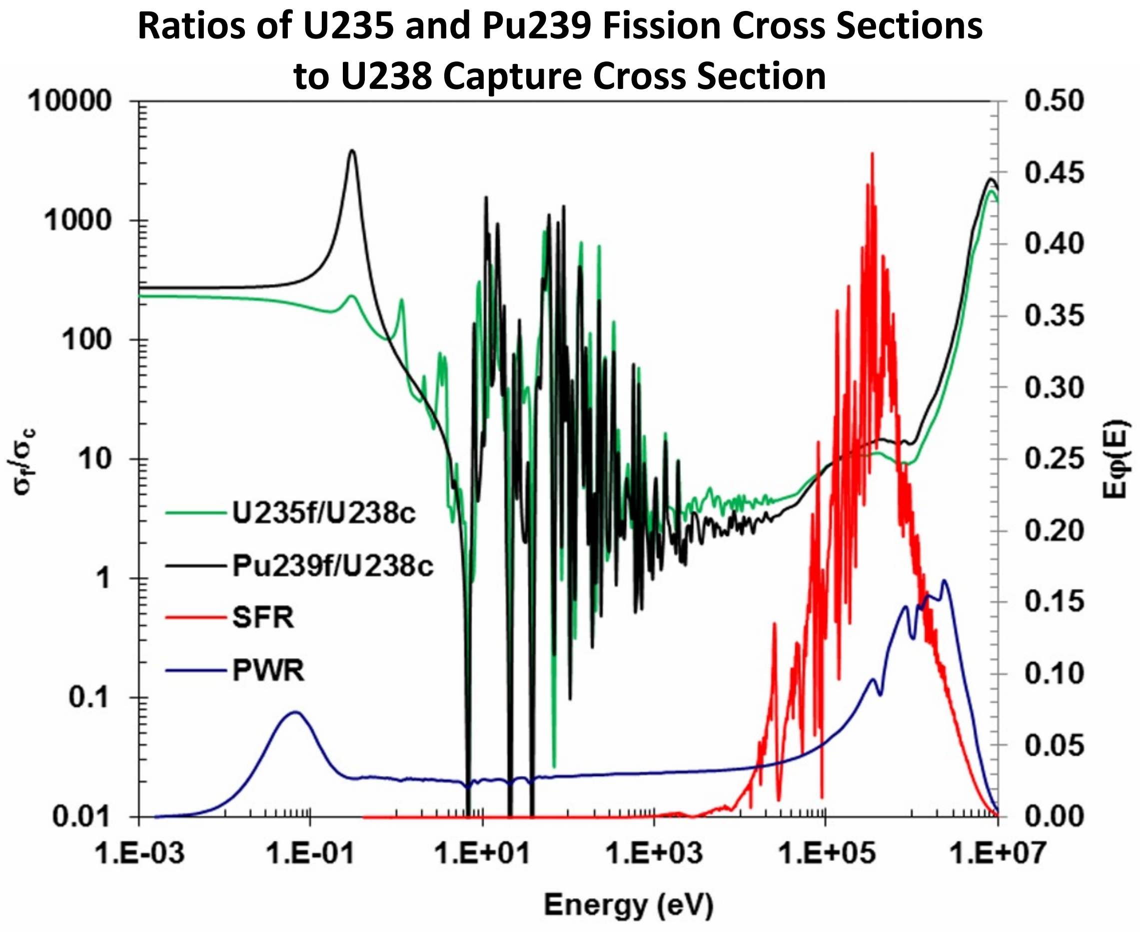
Special Engineering Issues of Fast Reactor

- Fast reactors have a higher enrichment.
- Fast reactors should increase the volume fraction of fuel.
- Fast reactor has two special reactivity feedback due to:
  - sodium void
  - subassembly deformation

Higher Enrichment is needed for fast reactor:

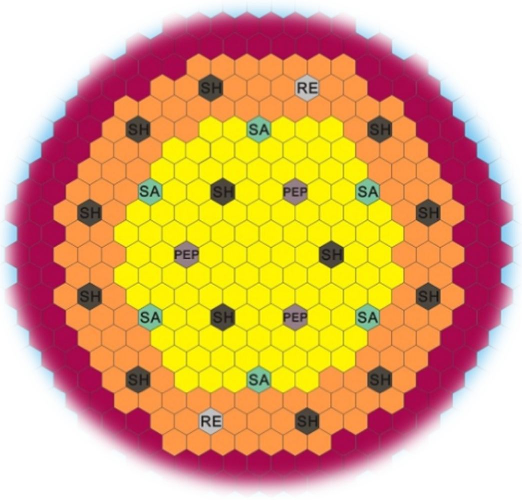


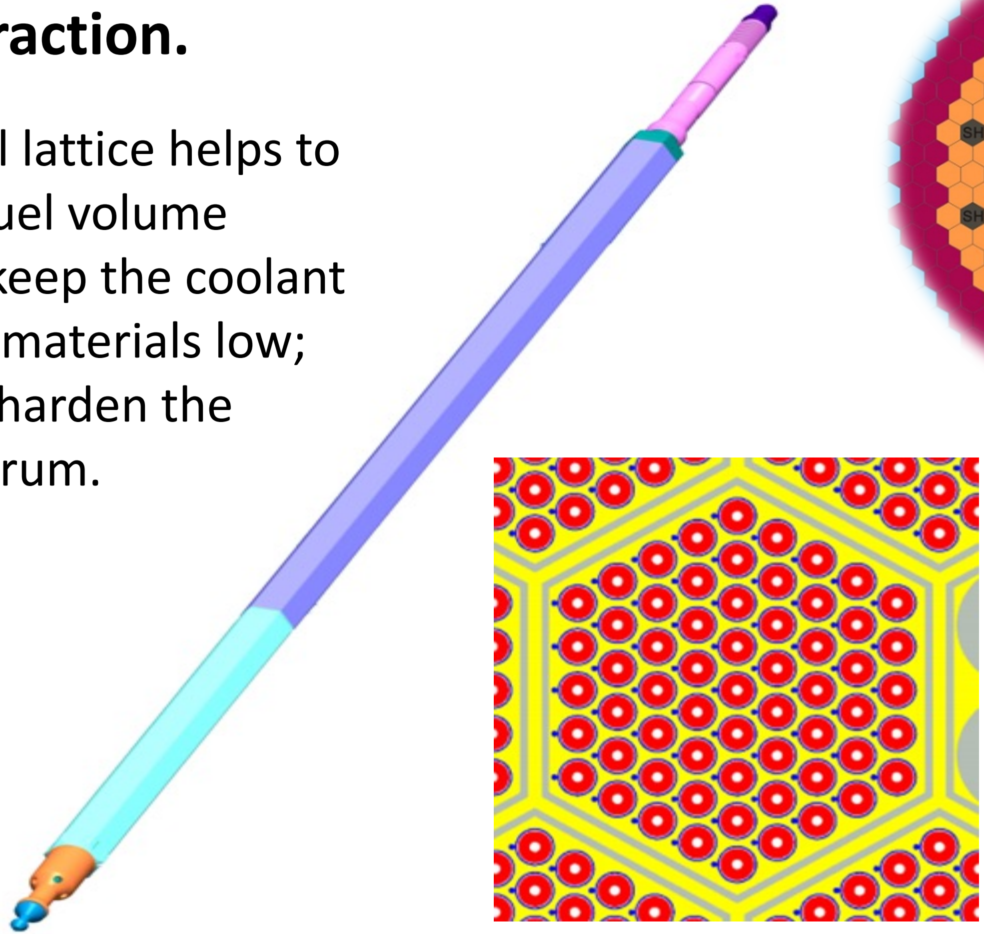
- The ratio is 200 ~ 300 in thermal region but only ~10 in tens and hundreds keV range
- A much higher enrichment is required to achieve criticality.

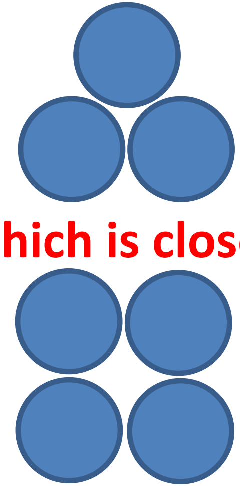
Reactor Type		Fissile Enrichment
Thermal	CANDU	0.7% (natural)
	PWR	3%~5%
Fast	Large	10%~25%
	Small	Up to 90%

Hexagonal lattice is adopted to optimize the fuel volume fraction.

- The hexagonal lattice helps to improve the fuel volume fraction, and keep the coolant and structure materials low;
- The goal is to harden the neutron spectrum.



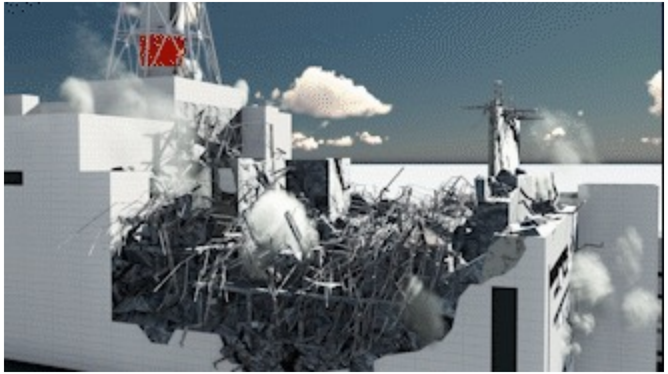


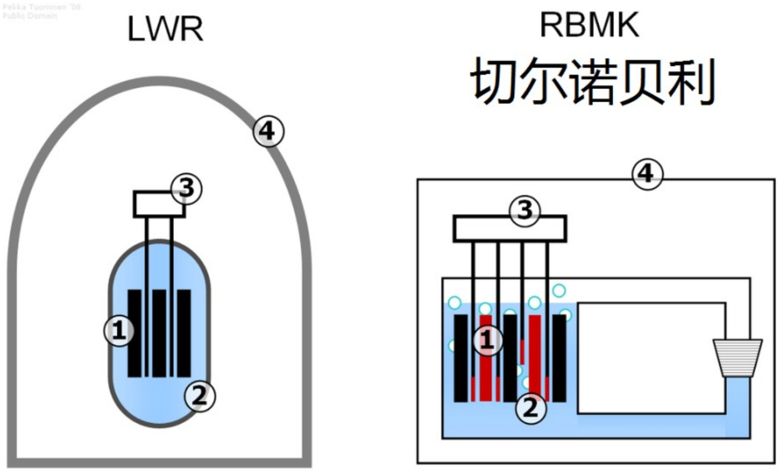


Which is closer?

Reactivity Feedback

The importance of reactivity feedback:



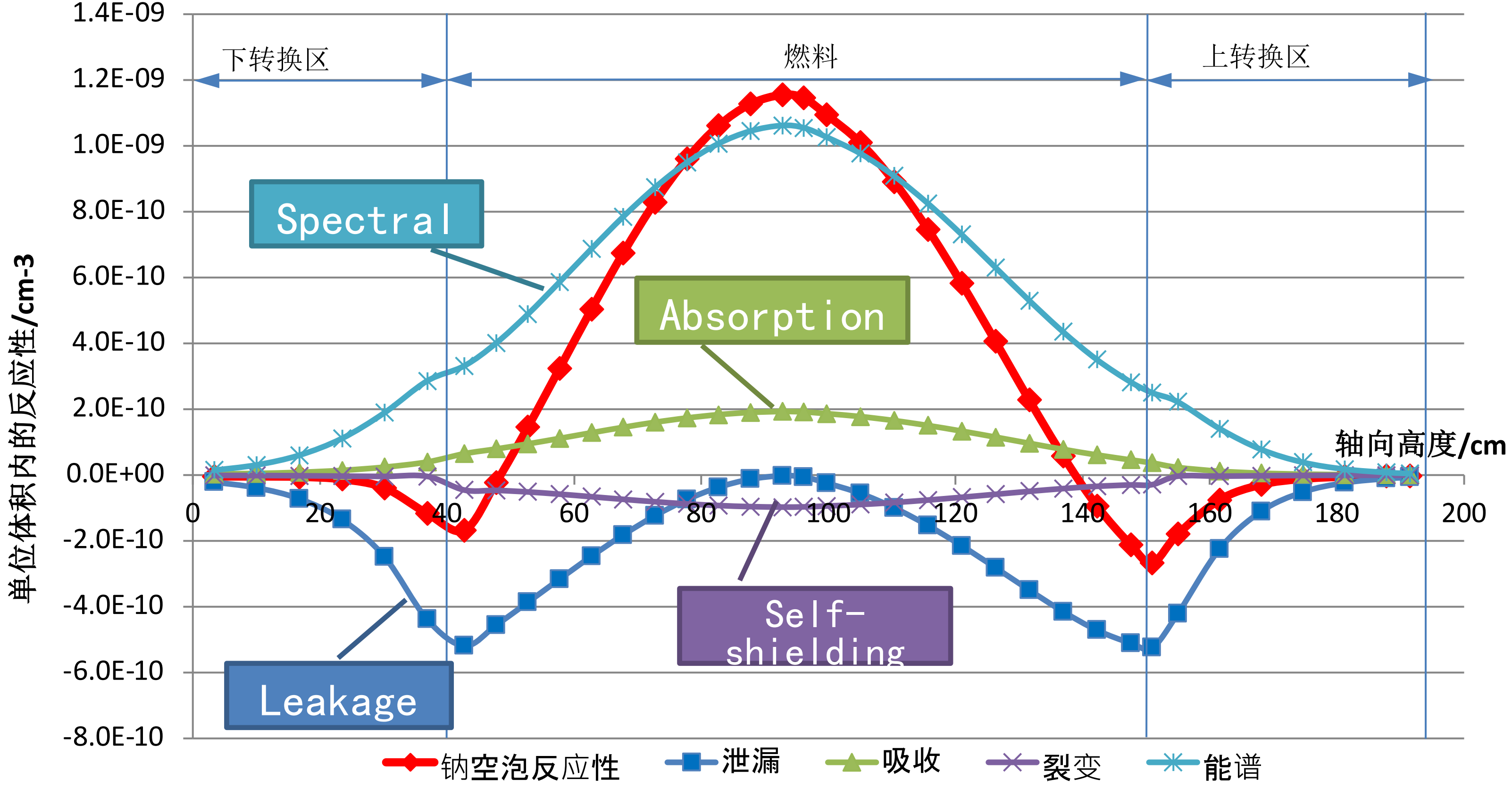


The main reason of Chernobyl accident indicated by INSAG-7 report in 1992 is:

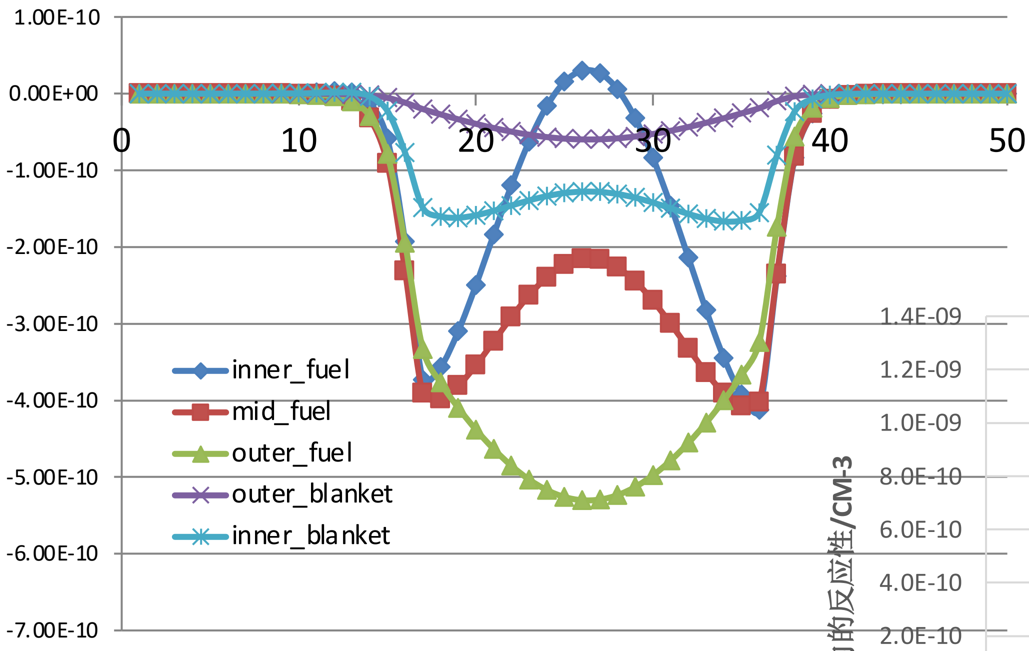
1. Positive void effect
2. Positive replacement effect of the tip of the control rod

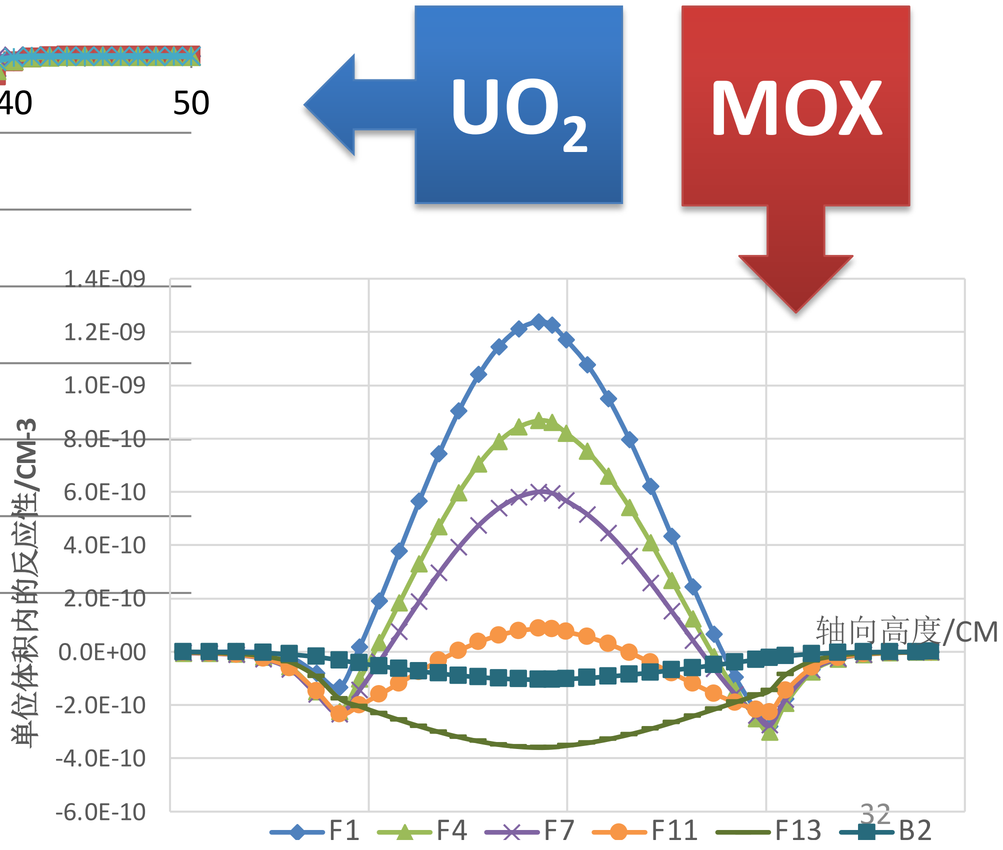
Reactivity Feedback

Physical Source of Sodium Void Reactivity



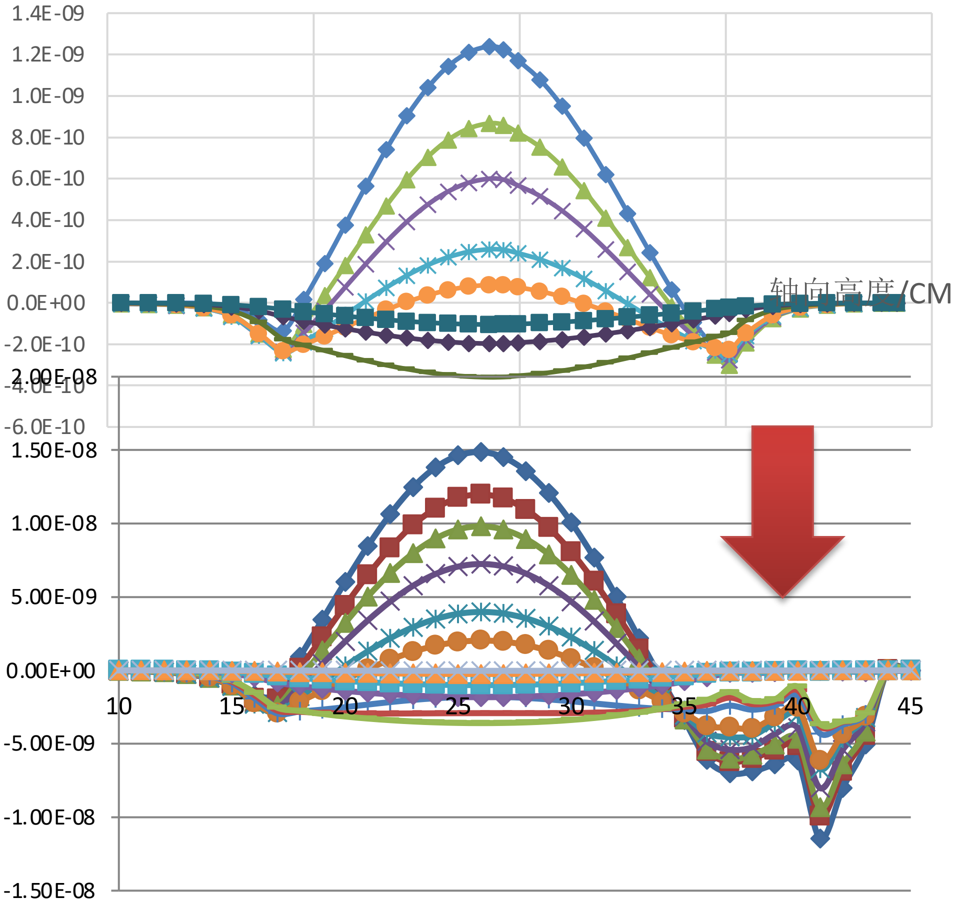
Reactivity Feedback

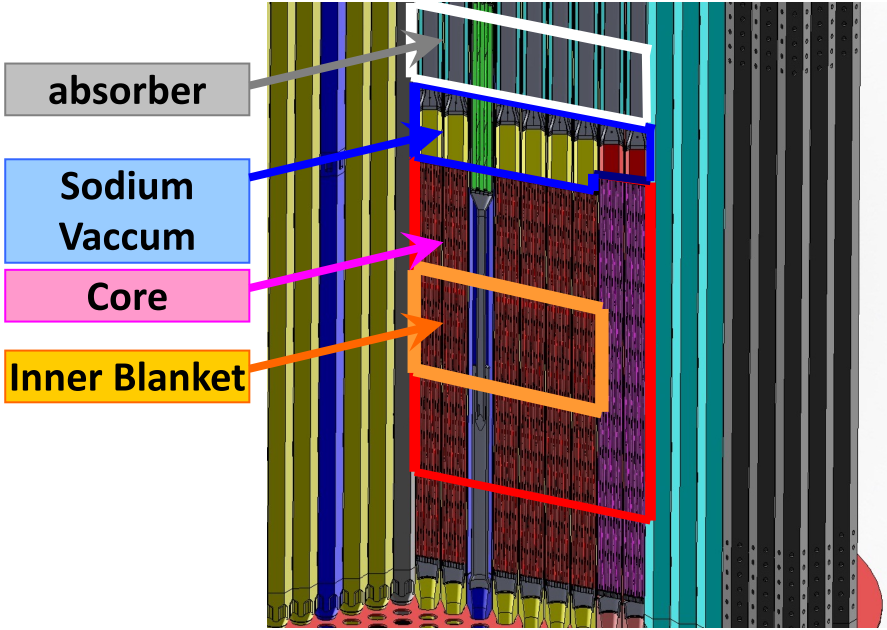




Spatial Distribution of Sodium Void Reactivity

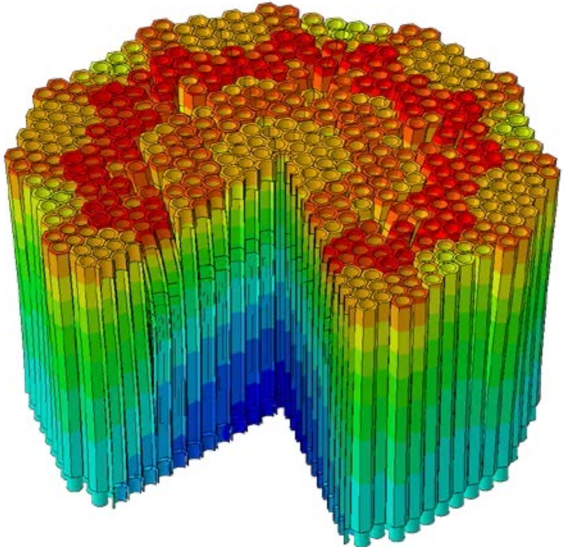
Reactivity Feedback

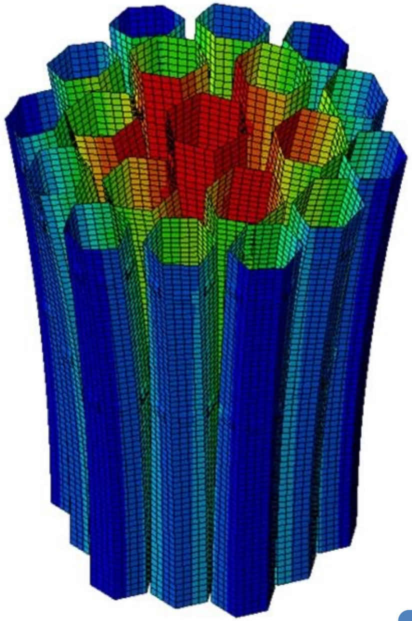


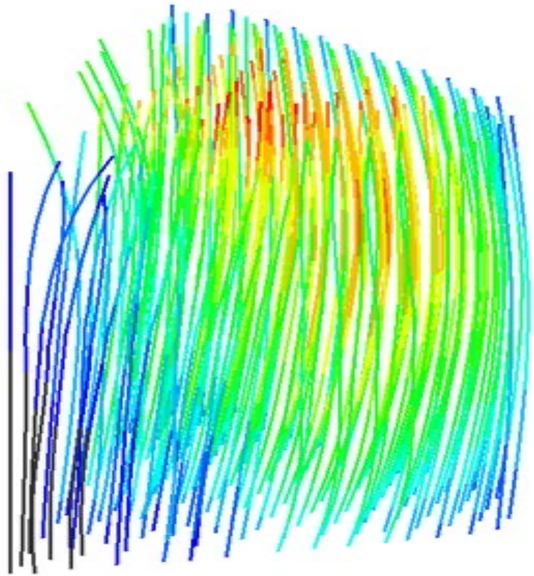


Low Void Effect Deisgn

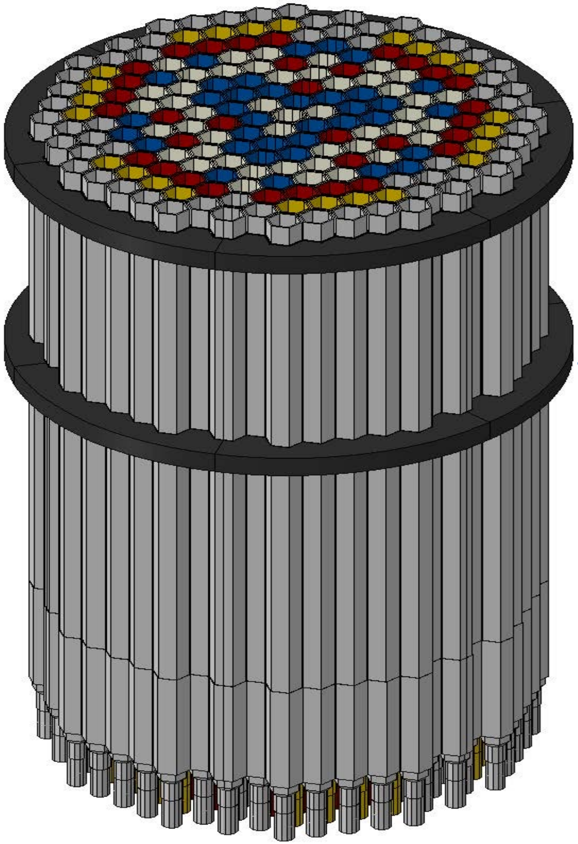
Reactivity Feedback







Reactivity Feedback



A special design to make negative bowing reactivity feedback!

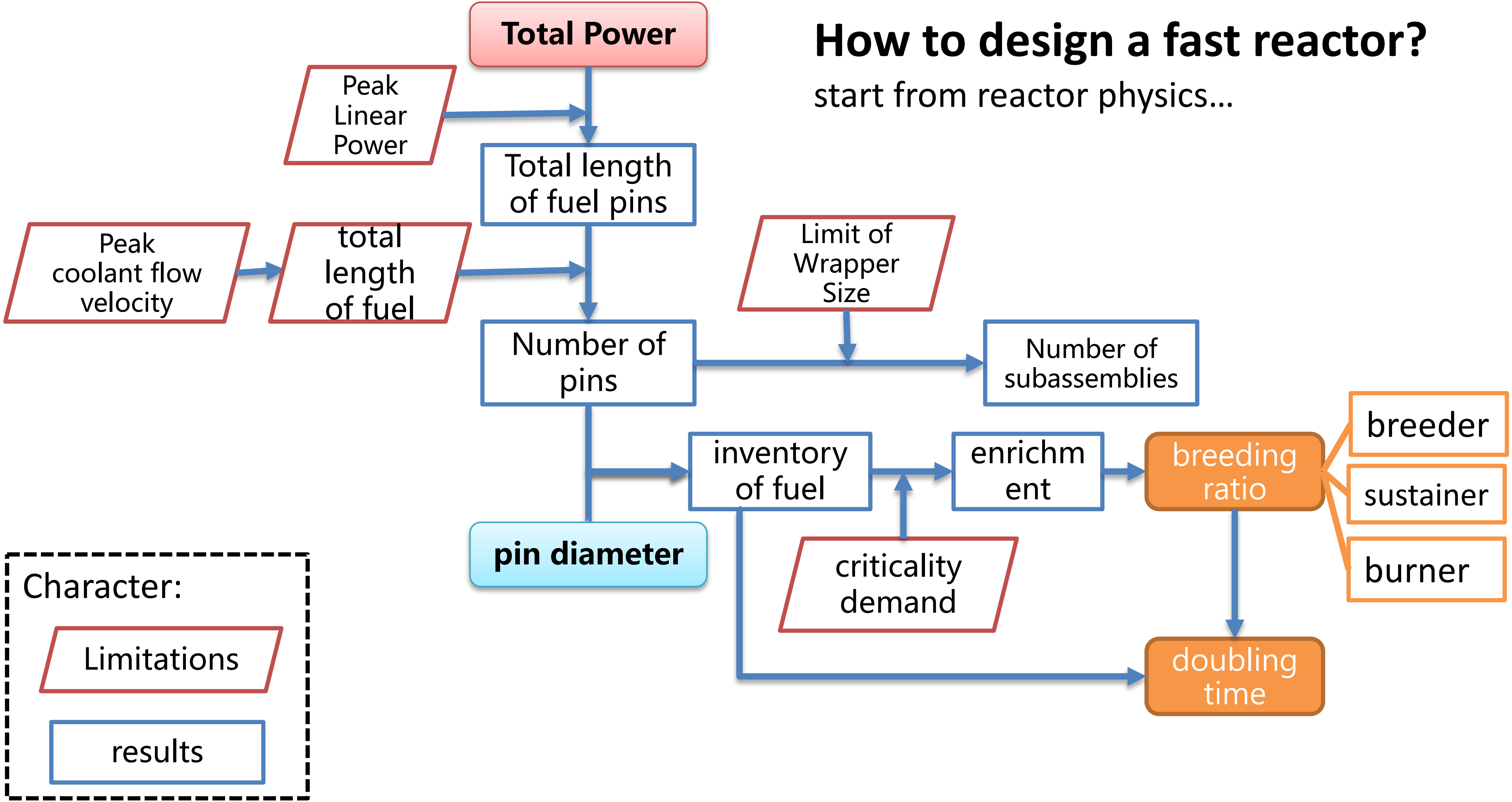
Reactivity Feedback

Sodium Void Reactivity of Typical SFR Design

Reactor	Reactivity/$	Fuel	Power	Country
SNR300	+2.9	MOX	327	Germany
PFBR	+4.3	MOX	500	India
CRBRP	+2.6	MOX	380	US
BN600	-0.3	UO2	600	Russia
BN800-MOX	+1	MOX	800	Russia
Super-Phenix	+5.9	MOX	1242	France
ASTRID-CFV	-0.3	MOX	600	France
CFR600-MOX	+3.5	MOX	600	China
CFR600-UO2	-2.3	UO2	600	China

How to design a fast reactor?

start from reactor physics…



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