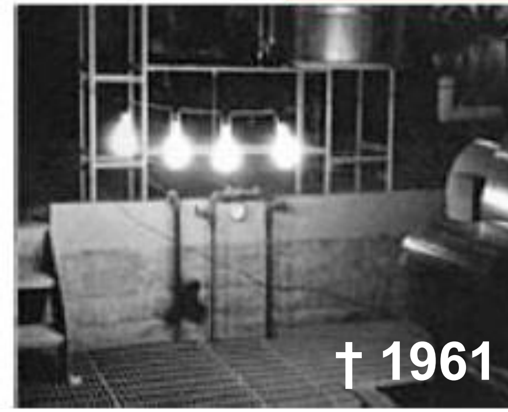
Broad topic	Lecture title
Basic principles of NPP	Introduction / Review of nuclear physics
	Interaction of neutrons with matter
	Nuclear fission
	Fundamentals of nuclear reactors
	LWR plants
Modeling the beast	The diffusion of neutrons - Part 1
	The diffusion of neutrons - Part 2
	Neutron moderation without absorption
	Neutron moderation with absorption
	Multigroup theory
	Element of lattice physics
	Neutron kinetics
	Depletion
Reactor Concepts Zoo	Advanced LWR technology
	Breeding and LFR
	AGR, HTGR
	Channels, MSR and thorium fuel
Review session	

THIS LESSON…

- Breeding, partitioning and transmutation
- Fast reactors using liquid metal coolants
- Technological aspects related to
  - Sodium Fast Reactors
  - Lead Fast Reactors
  - Accelerator Driven Systems

The *history of nuclear power* did not start with PWRs and BWRs:

- *Dec. 20, 1951: Launch of the Experimental Breeder Reactor EBR-1, **Idaho National Laboratory**, USA. It generated the first electricity ever.*



† 2.5.2002

- *June 26, 1954: A 5 MW_{el} channel type LWR (Chernobyl type) in Obninsk, Russia, delivered the first electricity to the grid.*

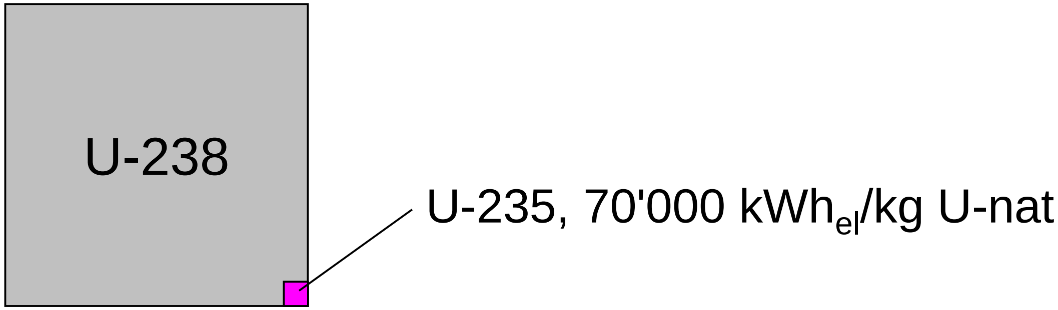
- *Aug. 27, 1955: The first commercial NPP, the gas-cooled reactor Calderhall 1 (50 MW_{el}) was connected to the public grid*

† 2003

There are nuclear power plants since more than 50 years

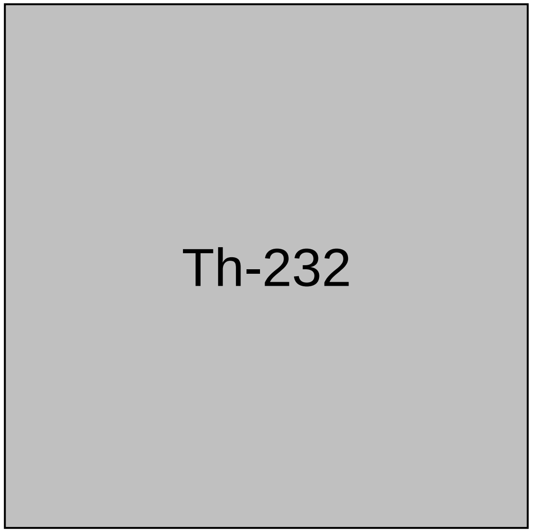
Power: 200 kW_{el}, 1400 kW_{th}
Coolant: NaK (T_M = -11 °C)

Natural uranium:



There is ~150 times more U-238 than U-235 in nature

Thorium:



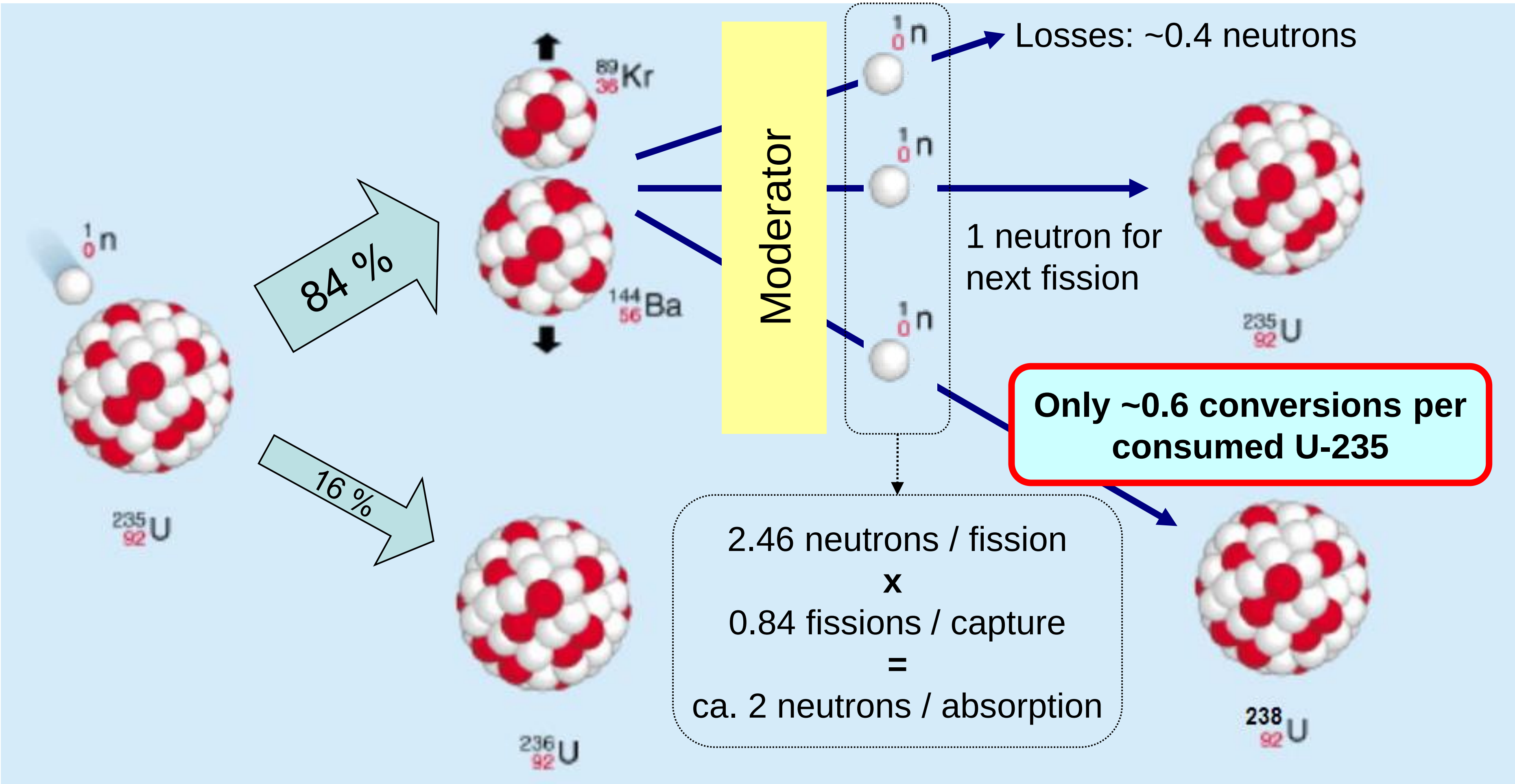
There is ~3 times more Th-232 than U-238 in nature

Attractive conversion processes:

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \xrightarrow{\text{23.5 min}} ^{239}_{93}\mathrm{Np} + \beta^{-} \xrightarrow{\text{2.35 d}} ^{239}_{94}\mathrm{Pu} + \beta^{-}$$

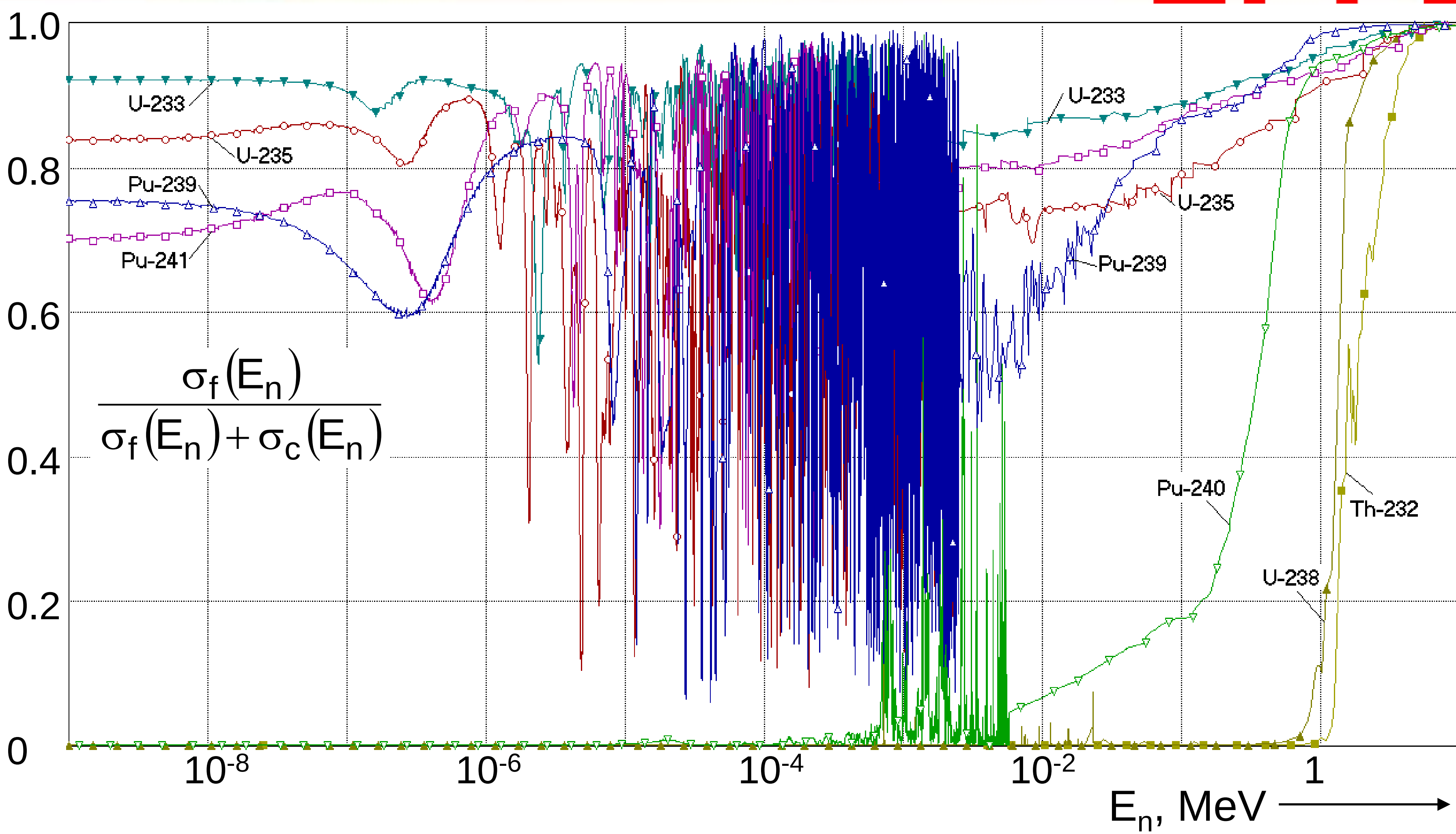
$$^{232}_{90}\mathrm{Th} + ^{1}_{0}\mathrm{n} \rightarrow ^{233}_{90}\mathrm{Th} \xrightarrow{\text{22.3 min}} ^{233}_{91}\mathrm{Pa} + \beta^{-} \xrightarrow{\text{26.967 d}} ^{233}_{92}\mathrm{U} + \beta^{-}$$

New fissile material

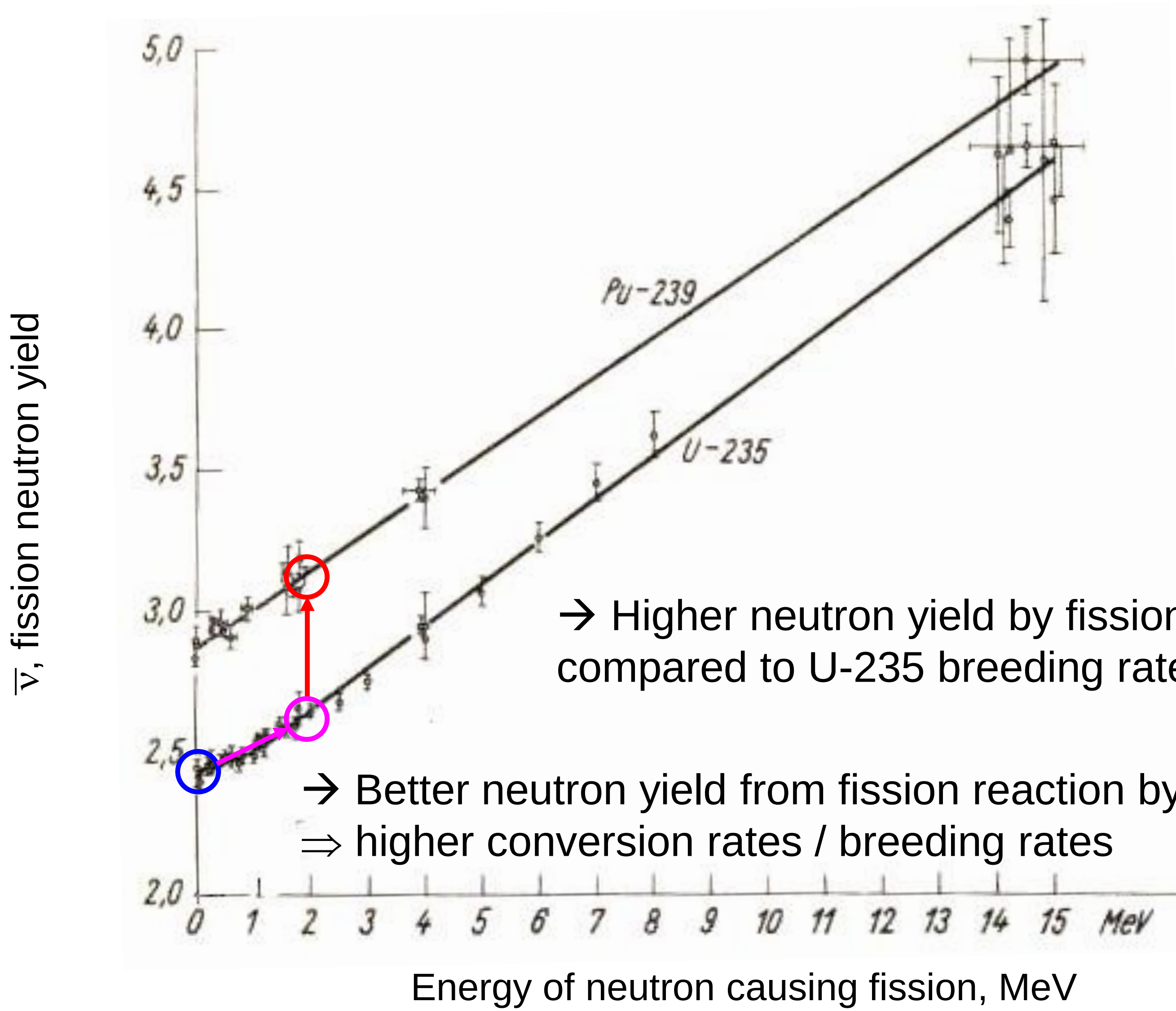


Thermal reactors using U-235 as fissile material

- not enough fission neutrons are left over for conversion
- generate less Pu-239 than they burn U-235



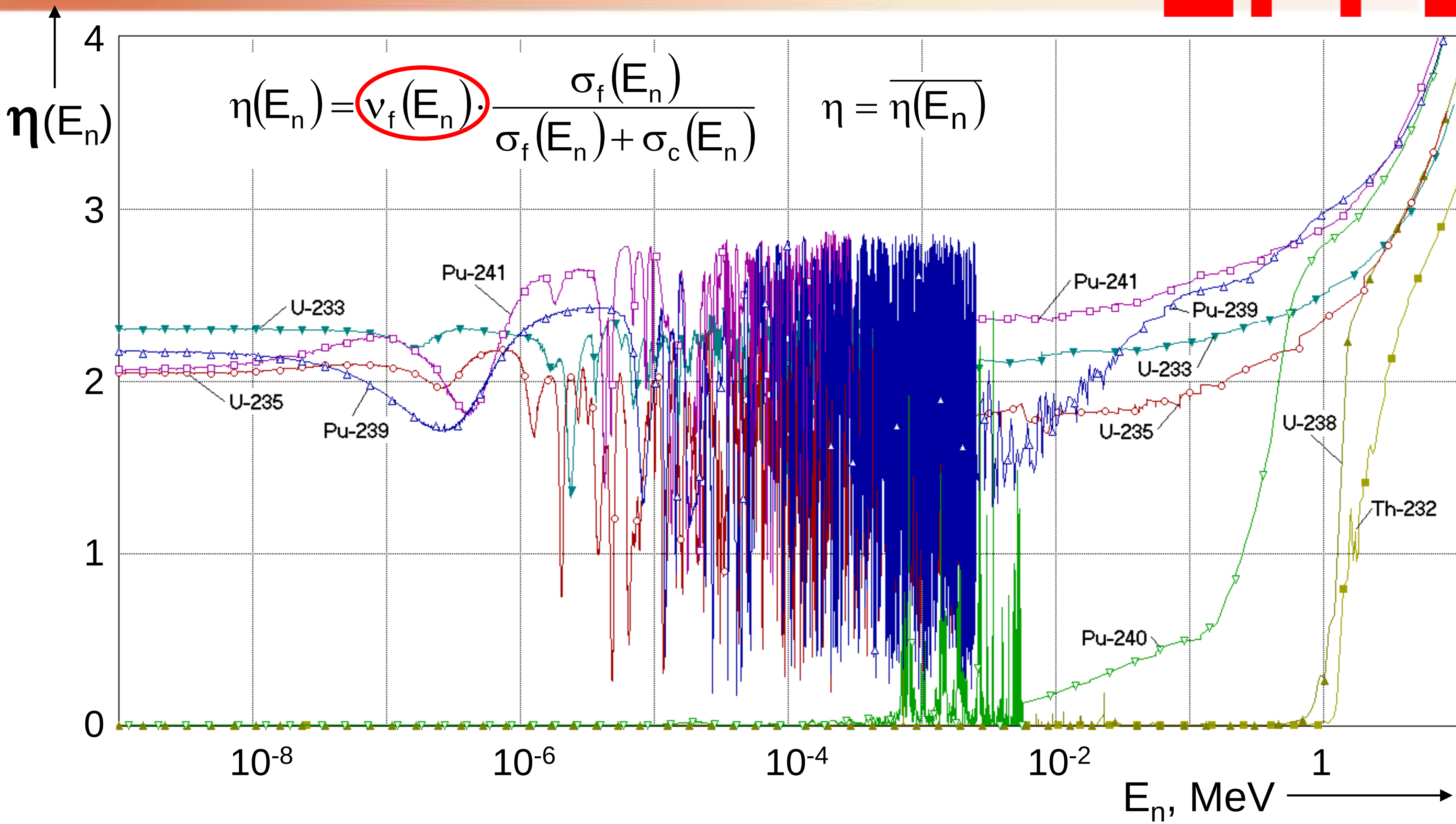
- Growing share of fissions with increasing neutron energy → fast breeders
- Pu-239 is slightly penalized by more parasitic neutron captures compared to U-235
- U-233 keeps overall record



→ Higher neutron yield by fission of Pu-239 compared to U-235 breeding rates

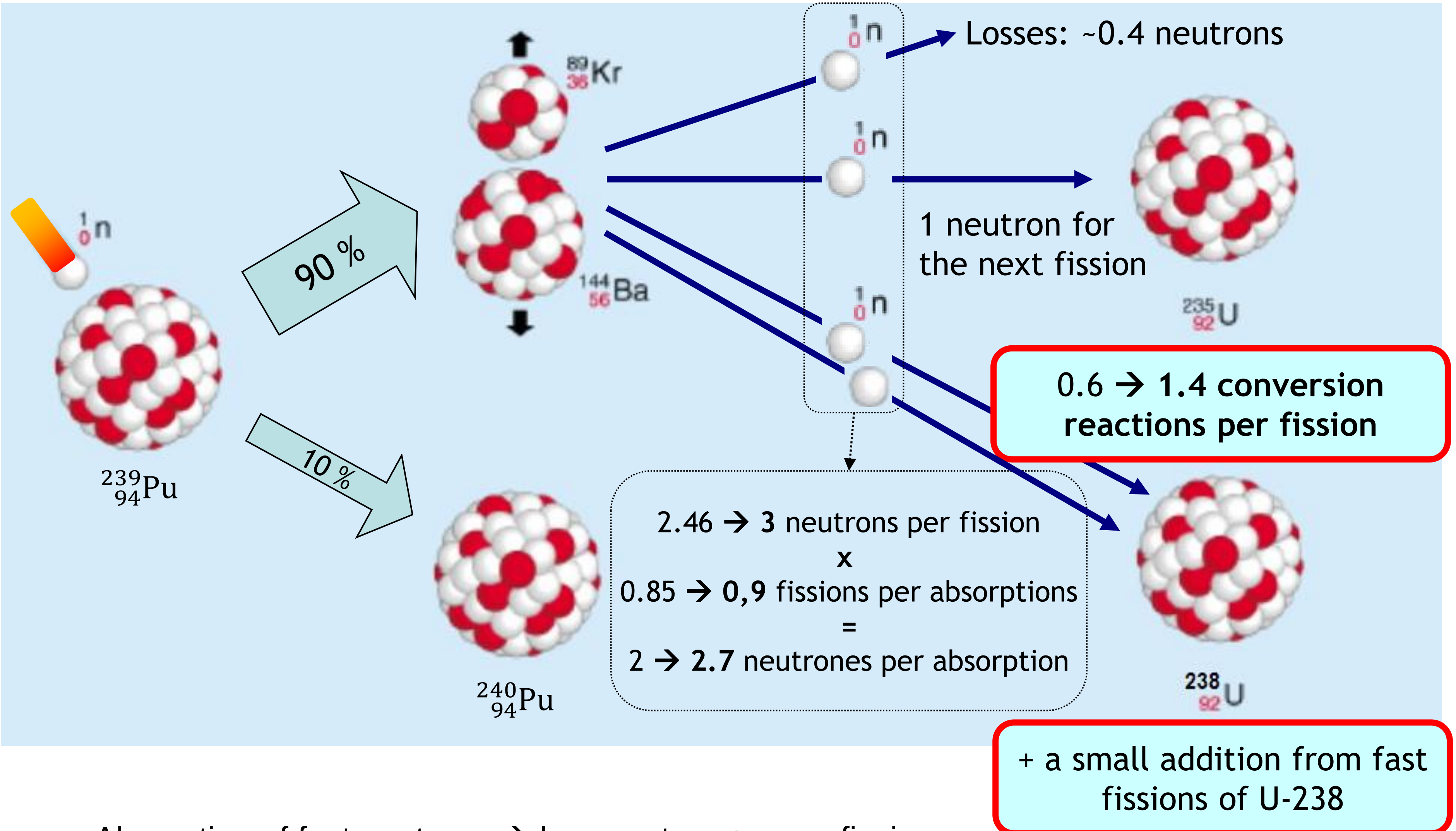
→ Better neutron yield from fission reaction by fast neutrons
⇒ higher conversion rates / breeding rates

$$\eta(E_n) = \nu_f(E_n) \cdot \frac{\sigma_f(E_n)}{\sigma_f(E_n) + \sigma_c(E_n)} \qquad \eta = \overline{\eta(E_n)}$$



- Growing reproduction factor with increasing neutron energy → fast breeders
- Pu-239 better than U-235 → feed Pu-239 - get Pu-239
- In thermal region: highest reproduction factor by U-233 → thermal thorium breeders

SUMMARY: SOURCES OF NEUTRON SURPLUS



- Absorption of fast neutrons → less capture + more fission
- Fission by fast neutrons → more activation energy → more fission neutrons
- Fission of Pu-239 instead of U-235 → more fission neutrons

Neutron balance and conversion (breeding) ratio.

- Neutron balance (static):
  $P = A + L$ [neutrons / s]

  $\eta_T A_{Fissile} = A_{Fissile} + A_{Fertile} + A_{Parasitic} + L$ [neutrons / s]

- Neutron absorption rate by fertile $A_{Fertile}$ = New fissile fuel generation rate [nuclei / s]

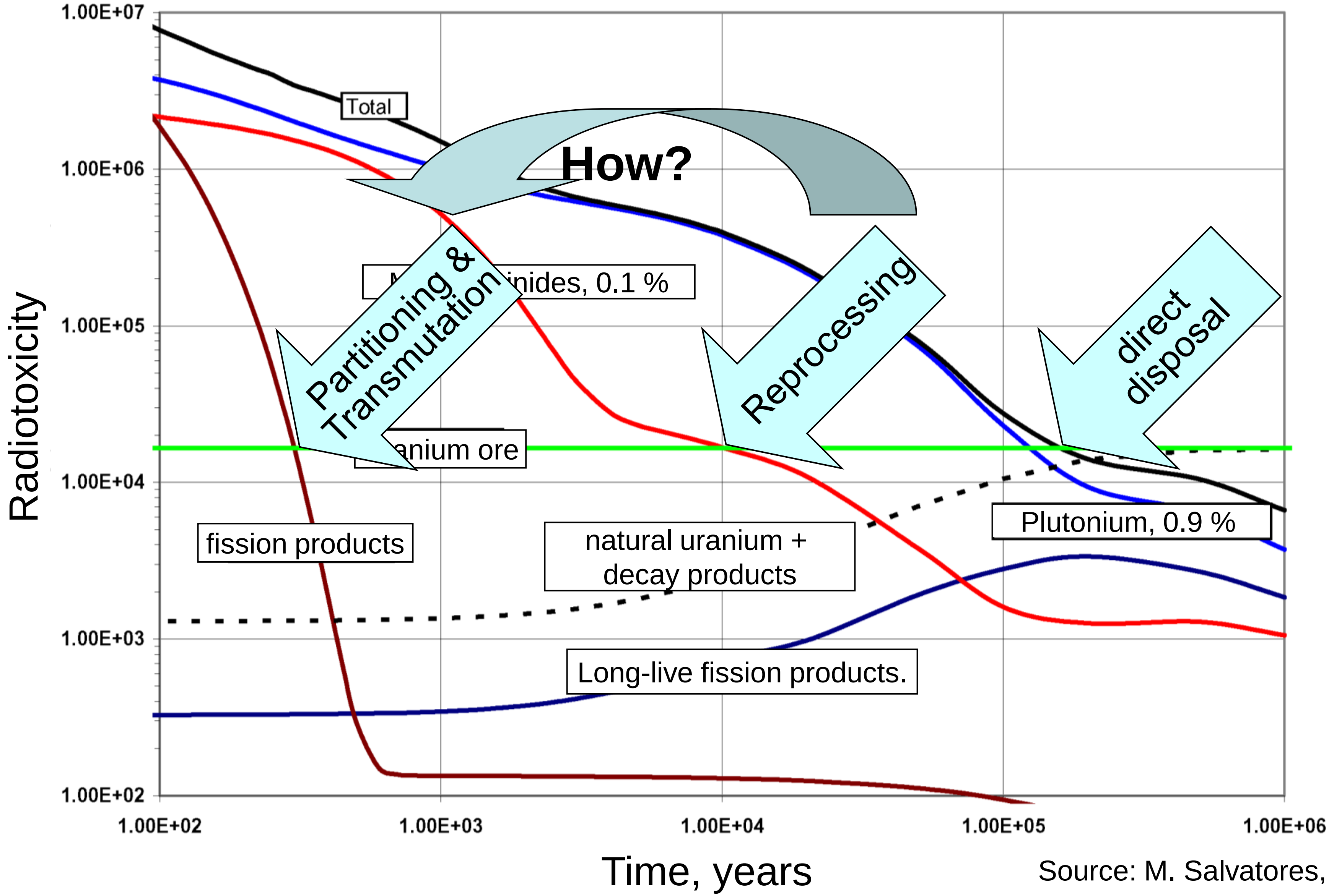
- Conversion (breeding) ratio:

$$C = \frac{\text{Rate of fissile fuel generation}}{\text{Rate of fissile fuel burning}} = \frac{A_{Fertile}}{A_{Fissile}}$$

- Decomposition of η_T factor:

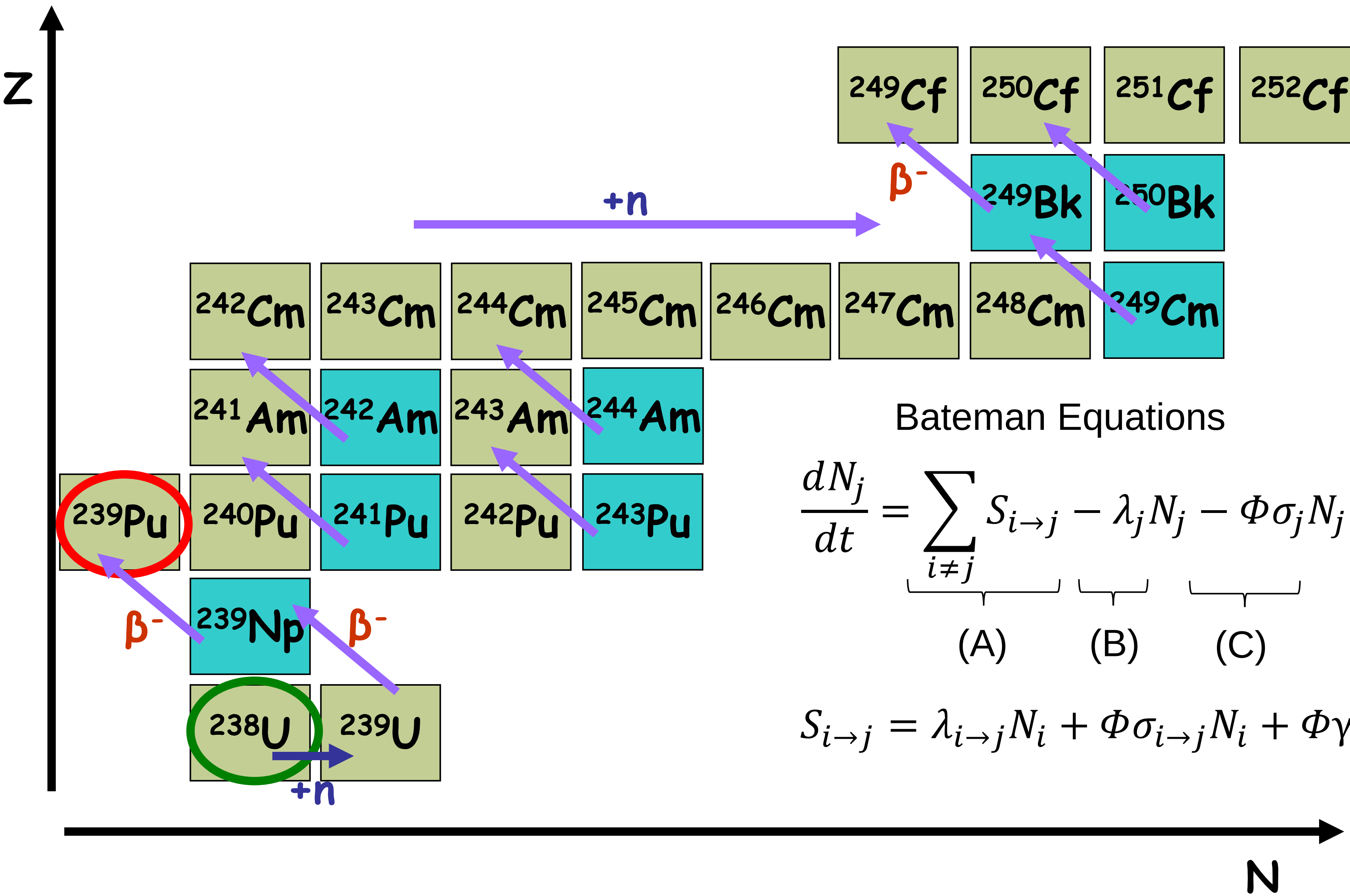
$$\eta_T = 1 + C + (A_{Parasitic} + L) / A_{Fissile}$$

Reduction of radiotoxicity in spent fuel



Source: M. Salvatores, CEA

Production of plutonium and minor actinides

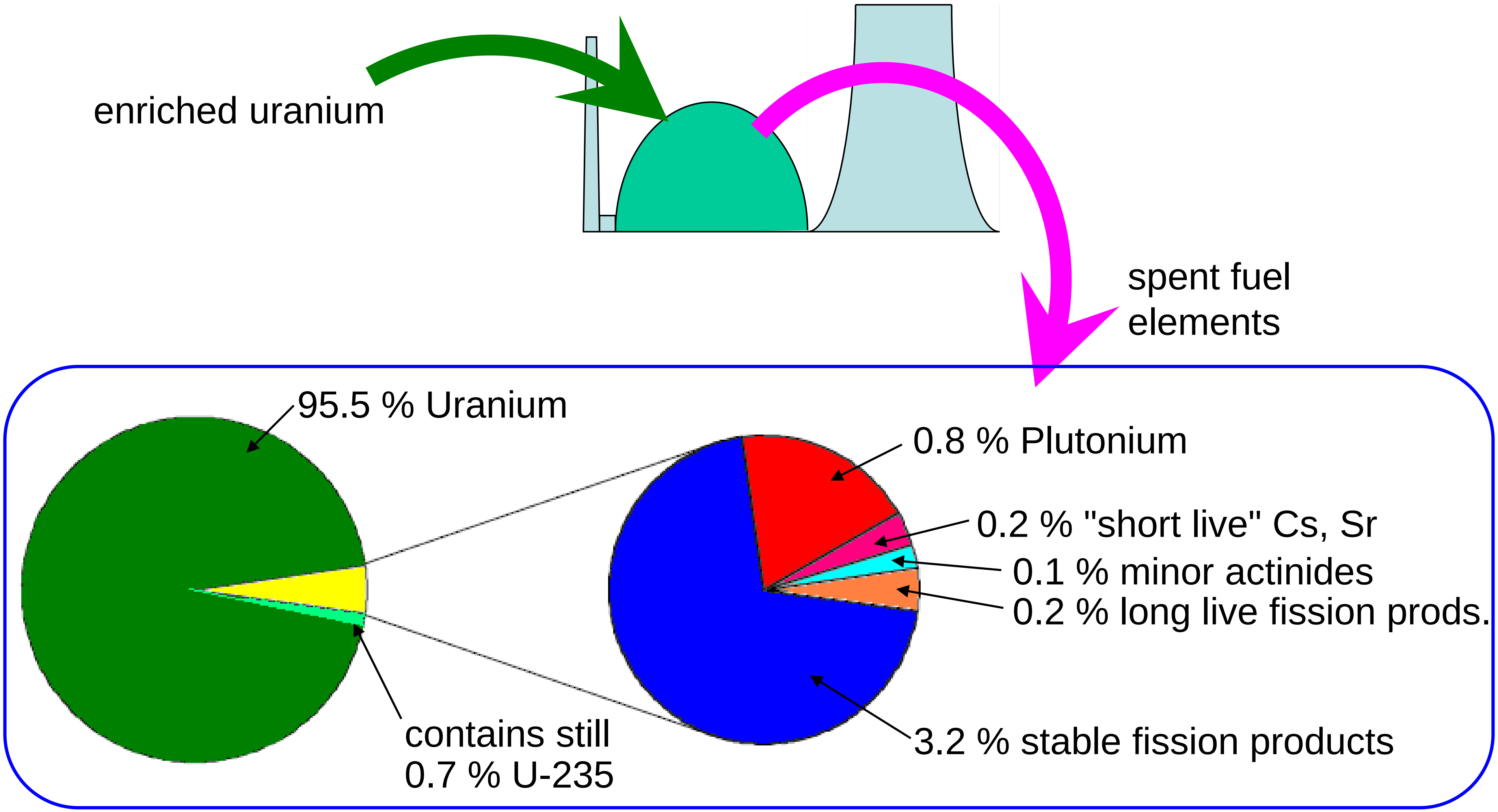


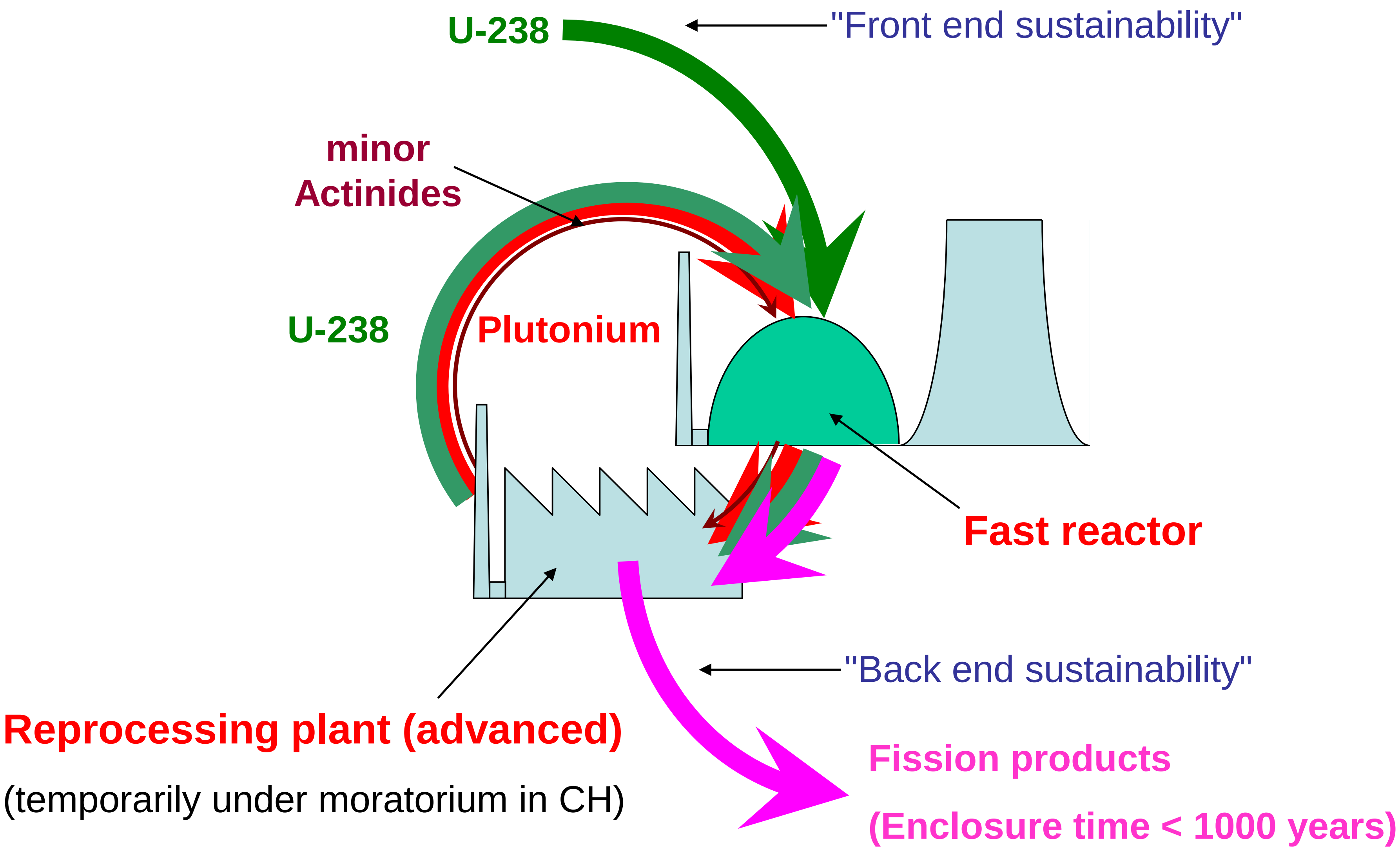
Bateman Equations

$$\frac{dN_j}{dt} = \underbrace{\sum_{i \neq j} S_{i \to j}}_{(A)} - \underbrace{\lambda_j N_j}_{(B)} - \underbrace{\Phi \sigma_j N_j}_{(C)}$$

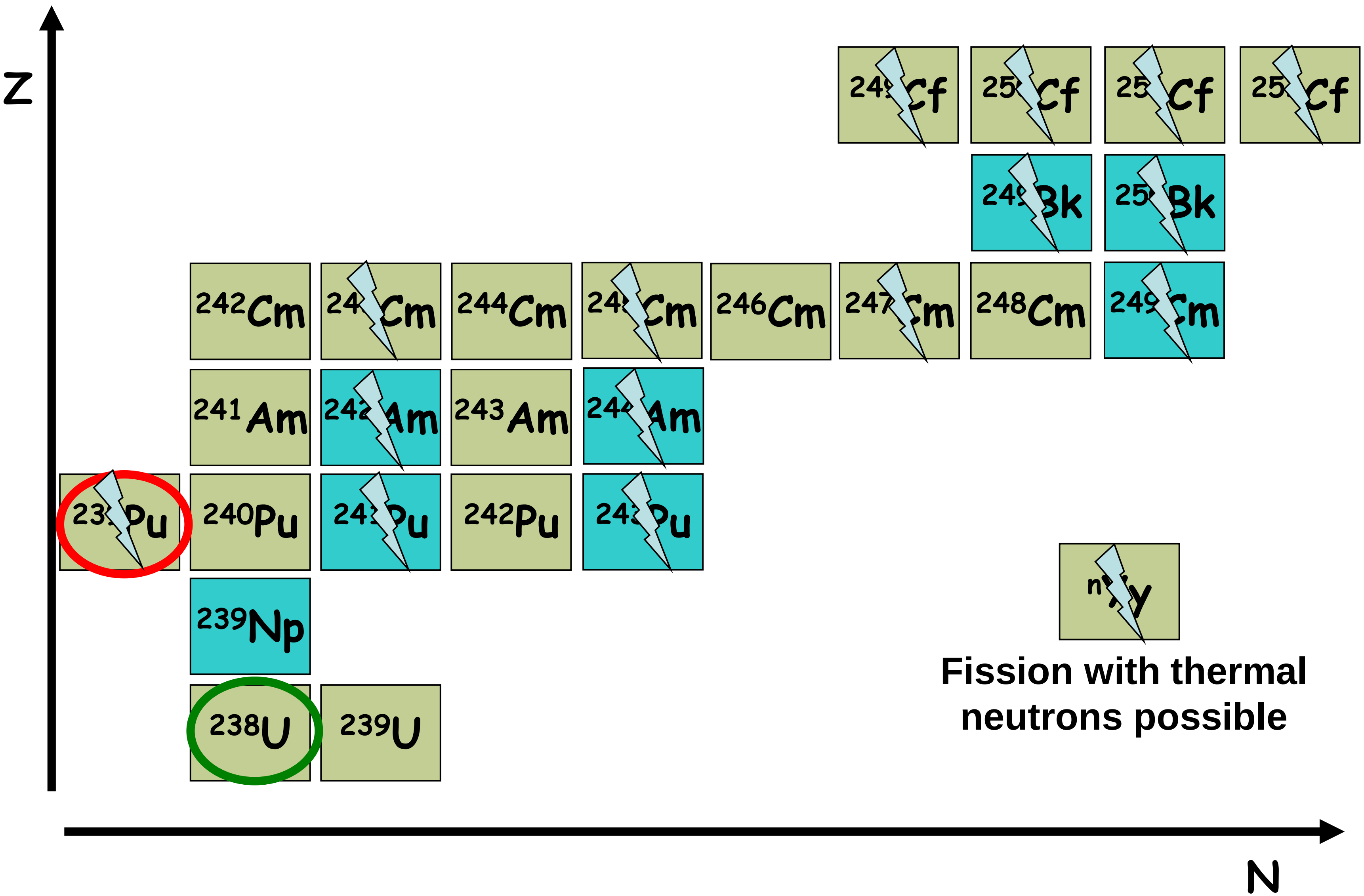
$$S_{i \to j} = \lambda_{i \to j} N_i + \Phi \sigma_{i \to j} N_i + \Phi \gamma_{i \to j} \Sigma_{f,i}$$

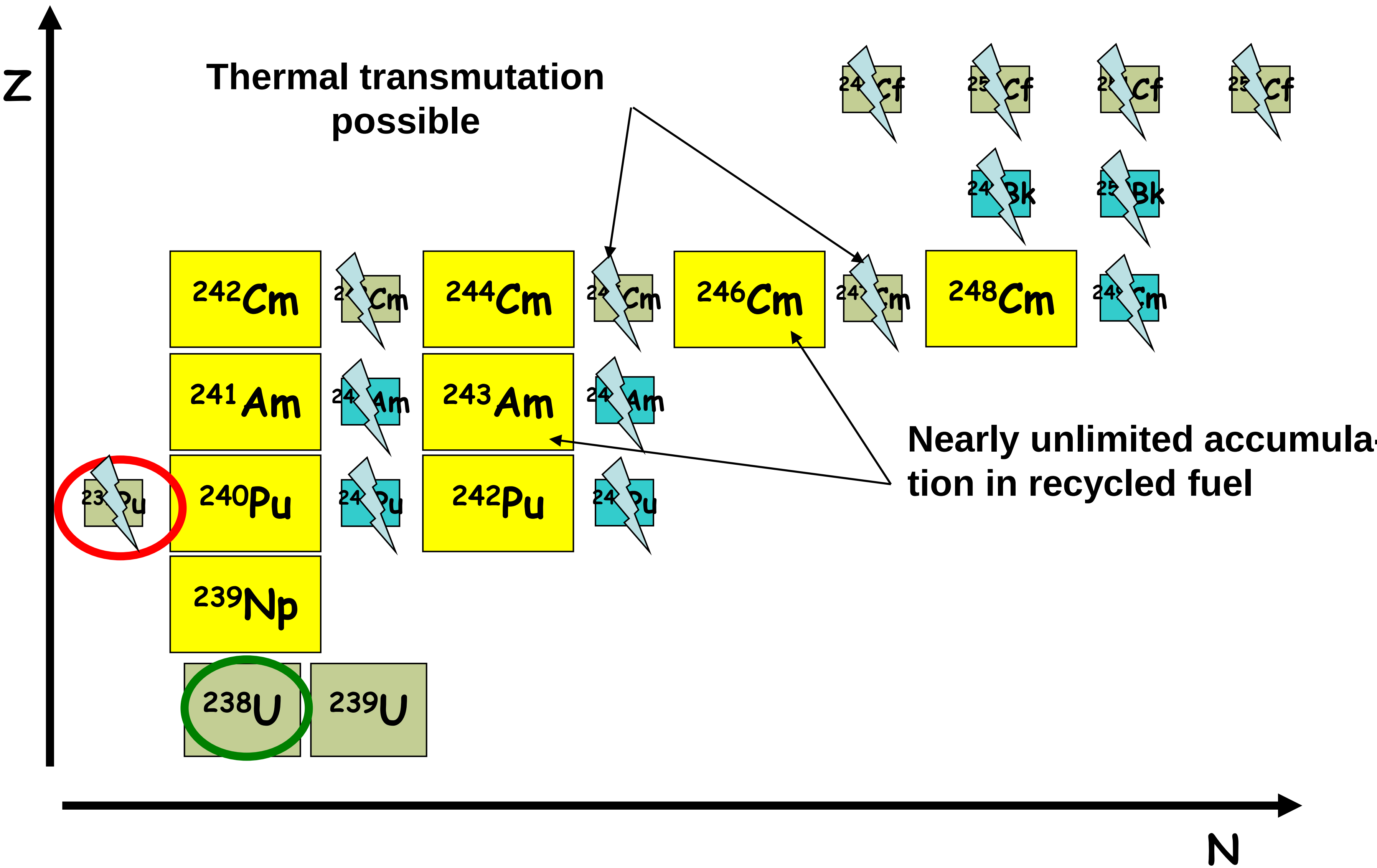
Open fuel cycle of Light Water Reactors

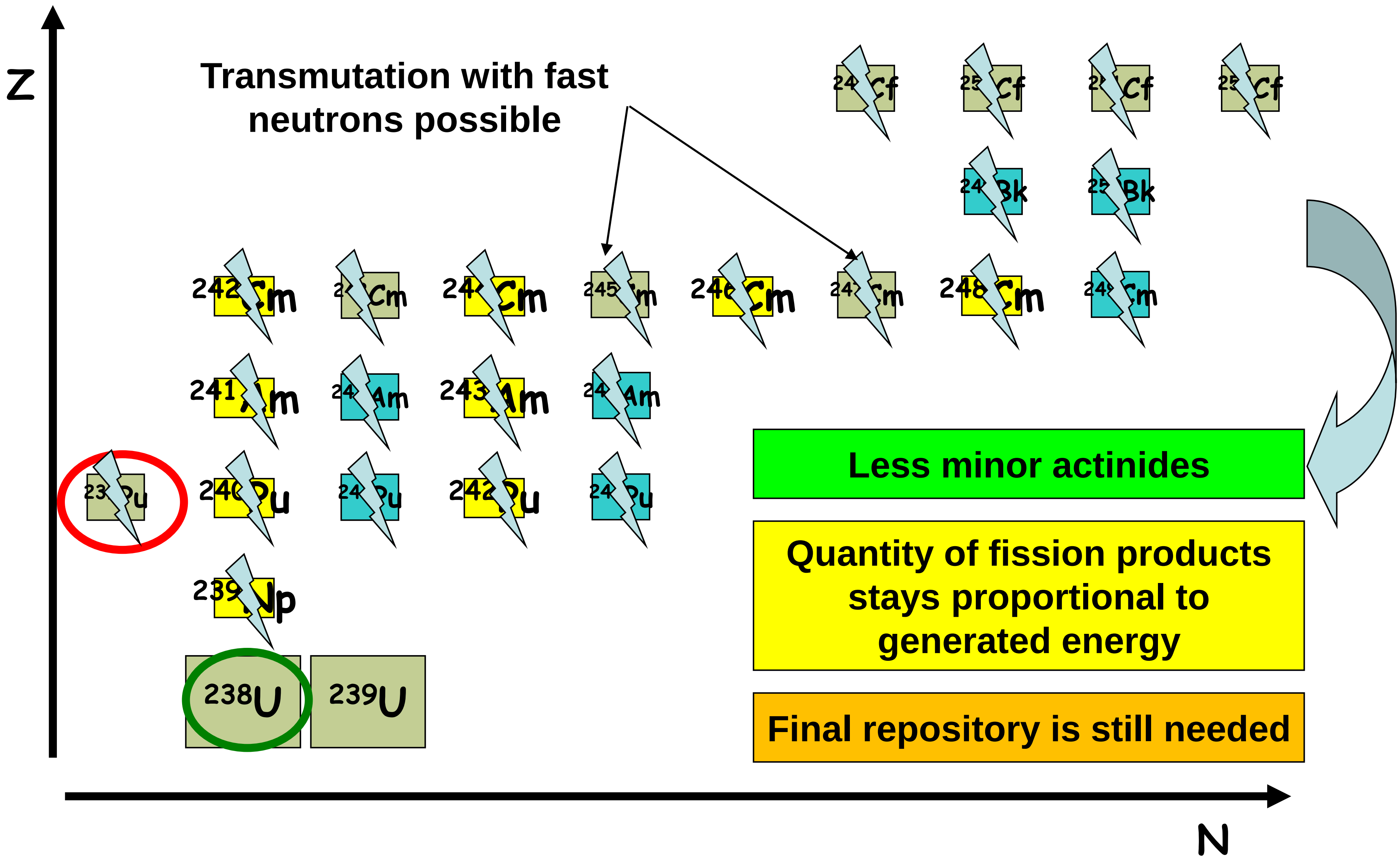



U-238
"Front end sustainability"
minor Actinides
U-238
Plutonium
Fast reactor
"Back end sustainability"
Reprocessing plant (advanced)
(temporarily under moratorium in CH)
Fission products
(Enclosure time < 1000 years)

Fissibility of minor actinides




Z
Thermal transmutation possible
242Cm
244Cm
246Cm
248Cm
241Am
243Am
240Pu
242Pu
239Np
238U
239U
Nearly unlimited accumula-
tion in recycled fuel
N



Less minor actinides

Quantity of fission products stays proportional to generated energy

Final repository is still needed

EPFL

Isotope	PWR Spectrum			Fast Neutron Spectrum			
	σ_f	σ_c	σ_c/σ_f	σ_f	σ_c	σ_c/σ_f	**Gain**
Np-237	0.52	33	63	0.32	1.7	5.3	**11.9**
Np-238	134	13.6	0.1	3.6	0.2	0.05	**2.0**
Pu-238	2.4	27.7	12	1.1	0.58	0.53	**22.6**
Pu-239	102	58.7	0.58	1.86	0.56	0.3	**1.9**
Pu-240	0.53	210.2	396.6	0.36	0.57	1.6	**247.9**
Pu-241	102.2	40.9	0.4	2.49	0.47	0.19	**2.1**
Pu-242	0.44	28.8	65.5	0.24	0.44	1.8	**36.4**
Am-241	1.1	110	100	0.27	2	7.4	**13.5**
Am-242	159	301	1.9	3.2	0.6	0.19	**10.0**
Am-242m	595	137	0.23	3.3	0.6	0.18	**1.3**
Am-243	0.44	49	111	0.21	1.8	8.6	**12.9**
Cm-242	1.14	4.5	3.9	0.58	1	1.7	**2.3**
Cm-243	88	14	0.16	7.2	1	0.14	**1.1**
Cm-244	1	16	16	0.42	0.6	1.4	**11.4**
Cm-245	116	17	0.15	5.1	0.9	0.18	**0.8**
U-235	38.8	8.7	0.22	1.98	0.57	0.29	**0.8**
U-238	0.103	0.86	8.3	0.04	0.3	7.5	**1.1**

- Ratio σ_c/σ_f = efficiency of conversion (neutron capture) vs. fission
- Lower σ_c/σ_f means better elimination of long-live actinides

➢ Fast spectrum of neutrons better converts actinides into fission products

➢ Reduce decay period in final waste depository

A fast rector can do both

(exception: Thorium…)

Difference lies in fuel and fuel cycle

Breeders

- Load fast reactors with fissile and fertile material
- Reprocessing separates fissile material
- Close fuel cycle for fissile material

Low acceptance

Full actinide recycling

- Load fast reactor with fresh fissile + fertile material and minor actinides
- Reprocessing separates all actinides from fission products
- Close fuel cycle for all actinides

"Breed & Burn cycles"

Highest sustainability

Actinide burners

- Load fast reactor only with plutonium and minor actinides (use inert matrix fuel)
- Reprocessing separates actinides from fission products (reactor poisons)
- Close fuel cycle for plutonium and minor actinides

Highest political acceptance (D)

Reduce moderation by

- Liquid metal cooling (**Na**, NaK, Hg, **Pb**, PbBi =LBE)
  - ❖ high mass number → low energy decrement of the elastic scattering reaction
- Low density coolant (He, H_2O vapor)
  - ❖ Reduce nuclear density of coolant → low macroscopic elastic scattering cross-section → low moderation
- No coolant at all (Molten Salt Reactors without solid moderator)

Adverse effect of missing moderator:

- No benefit from dominance of fission cross-section of fissile nuclides in thermal region → fuel with high concentrations of fissile material needed

Liquid metals at ambient pressure

	T_{melt}	T_{boil}	ρ	c_p	$\rho \cdot c_p$	λ	Pr	$\nu \cdot 10^6$
	°C	°C	kg/m^3	kJ/(kg·K)	kJ/(m^3·K)	W/(m·K)	-	m^2/s
Bi	271	1477	9846	0.1507	1483	10.70	0.01226	0.13155
Pb	327	1737	10445	0.1581	1651	10.86	0.02170	0.02086
PbBi	125	1670	10119	0.1465	1483	13.67	0.01502	0.13853
Na	97.8	883	847	1.2743	1079	68.34	0.00462	0.29372
NaK	-11.1	784	809	1.0502	849	27.68	0.00800	0.26371

Solid at room temperature

high boiling point at low pressure

lower specific heat capacity

higher thermal conductivity

lower Prantl numbers

equally low viscosity

	T_{melt}	T_{boil}	ρ	c_p	$\rho \cdot c_p$	λ	Pr	$\nu \cdot 10^6$
	°C	°C	kg/m^3	kJ/(kg·K)	kJ/(m^3·K)	W/(m·K)	-	m^2/s
H_20	0	324	725	5.4760	3970	0.56	0.86160	0.12170

Water at 15 MPa

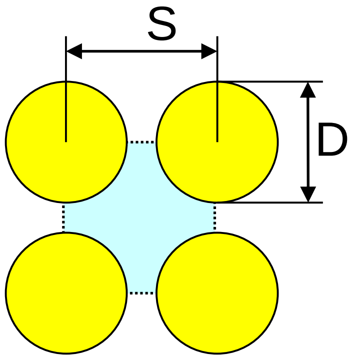
	Na	Lead/LBE	H_2O
Vapor pressure	Low	Low	High
Heat transfer	Excellent	Very good	Fair
Activation by neutrons	High (not long-live)	High	Lower
Corrosivity	Low	High	Medium
Chemical reactivity	High with H_2O / air	Low	Low
Optical properties	Opaque	Opaque	Transparent
Melting point	Solid at room temperature	Solid at room temperature	Liquid at room temperature
Lattice void feedback	Positive (without measures)	Positive, but hard to void	Negative (if undermoderated)

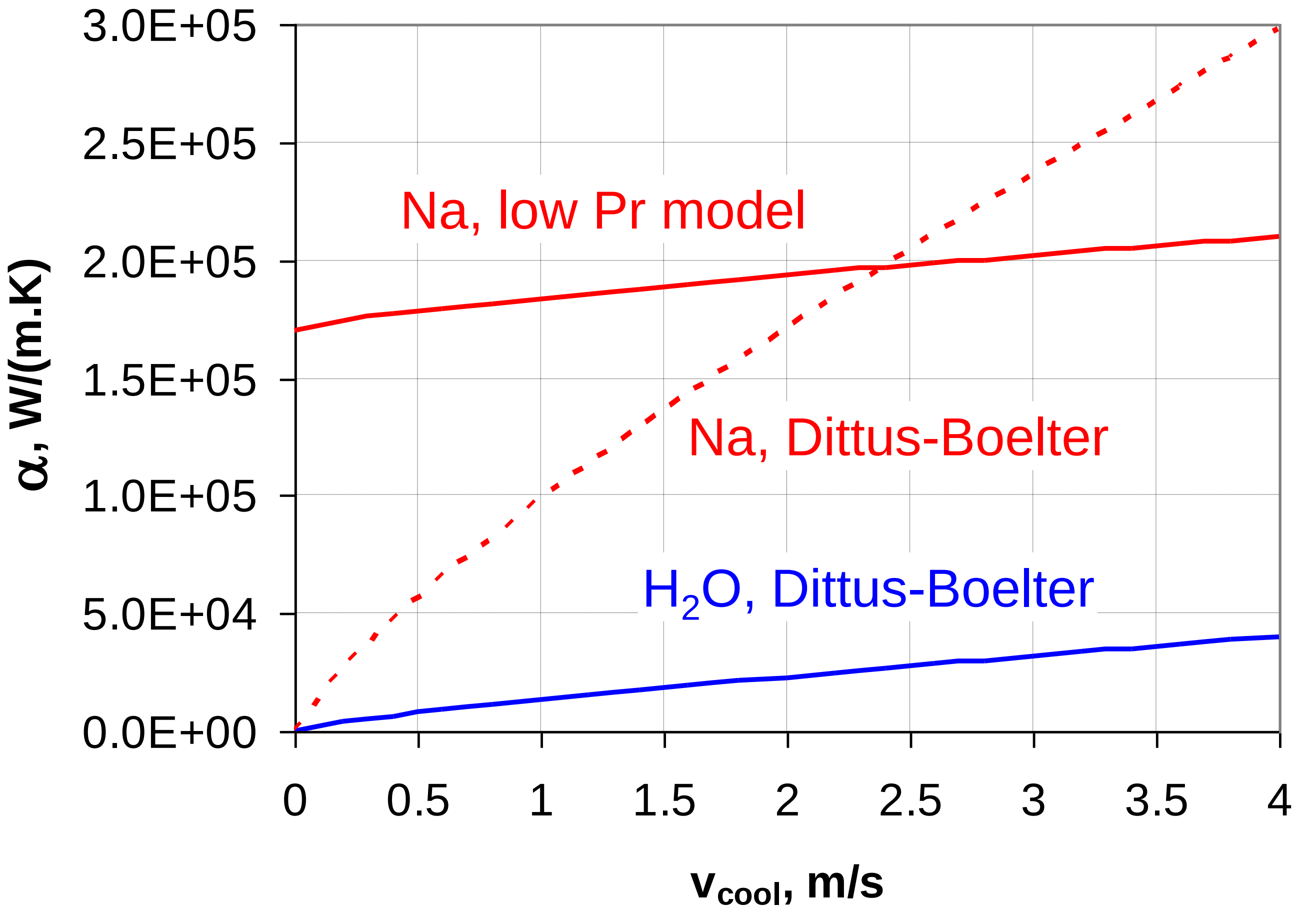
Sodium-water reaction: $2Na + 2H_20 \rightarrow 2Na^+ + 2OH^- + H_2 \quad \left(\Delta h_R = -368 \frac{kJ}{mol}\right)$

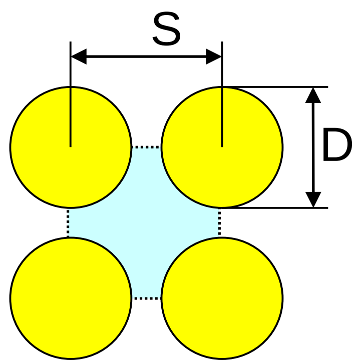
Sodium-air reaction: $4Na + O_2 \rightarrow 2Na_2O \quad \left(\Delta h_R = -836 \frac{kJ}{mol}\right)$

Example: D = 6 mm Water at 300 °C

S = 7 mm Sodium at 450 °C

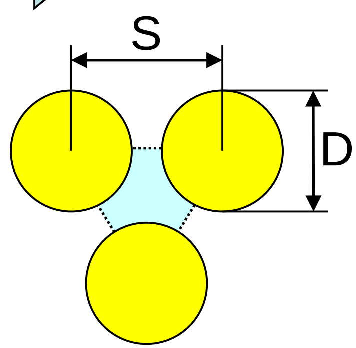






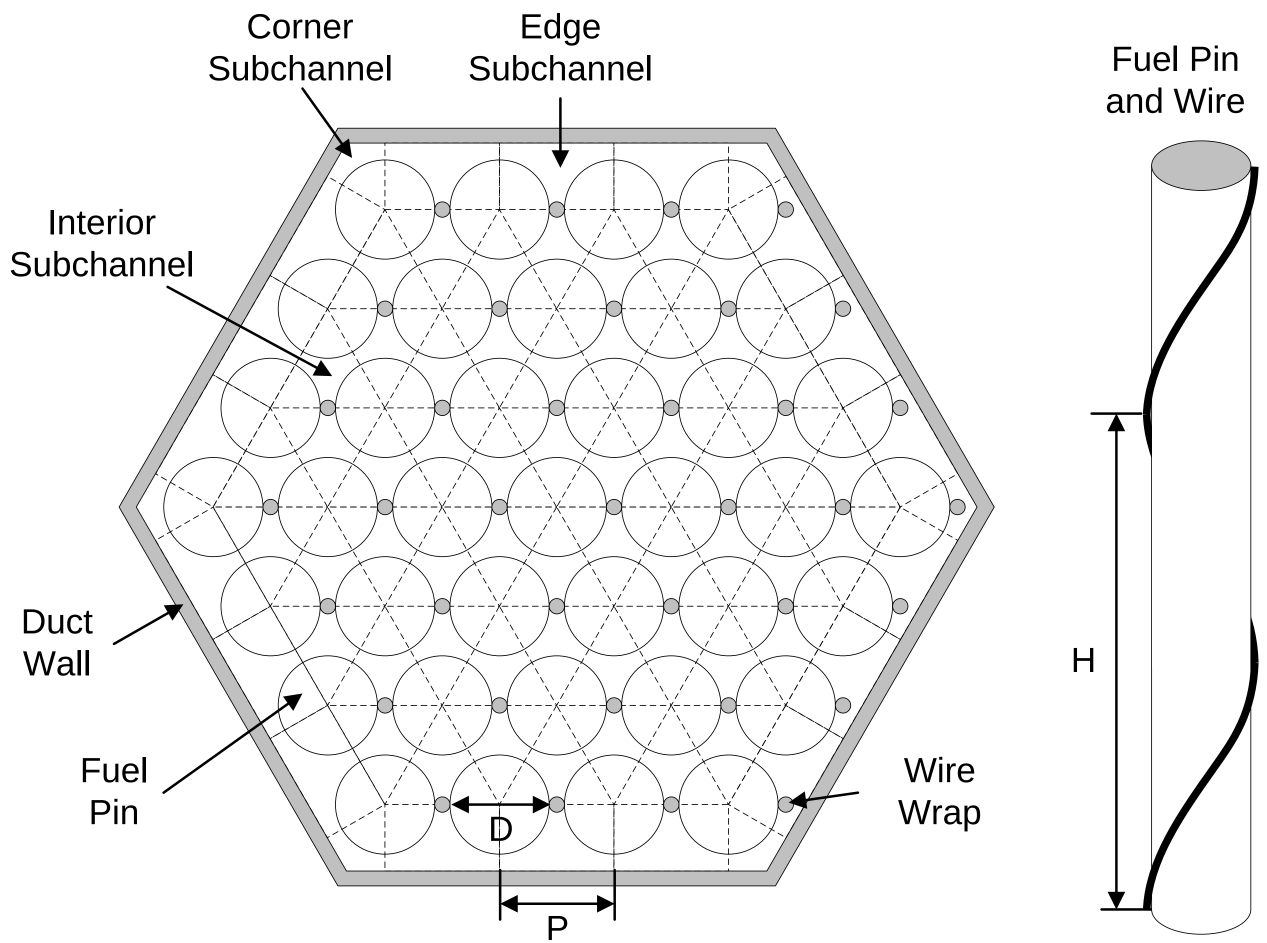
$$\frac{A_{cool}}{A_{fuel}} = \frac{4}{\pi} \cdot \frac{S^2}{D^2} - 1 \quad \cong \boxed{1.237} \cdot \frac{S^2}{D^2} - 1$$

Dense lattice / Triangular lattice



$$\frac{A_{cool}}{A_{fuel}} = \frac{2\sqrt{3}}{\pi} \cdot \frac{S^2}{D^2} - 1 \cong \boxed{1.103} \cdot \frac{S^2}{D^2} - 1$$

- Higher heat source density $\rightarrow$ possible due to excellent heat removal capabilities of the liquid metal coolant

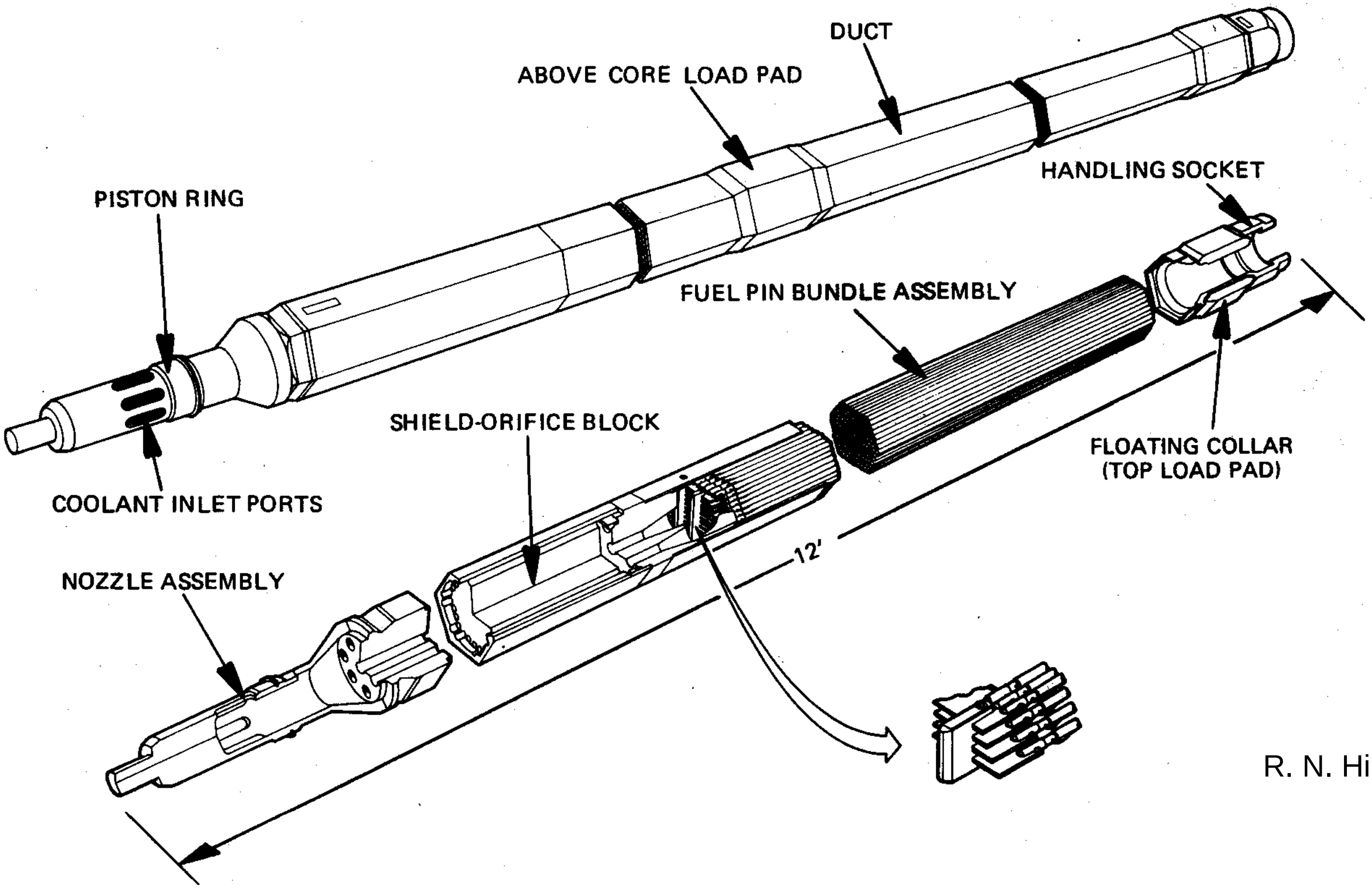


R. N. Hill, 2012

Wire-wrapped fuel rods:

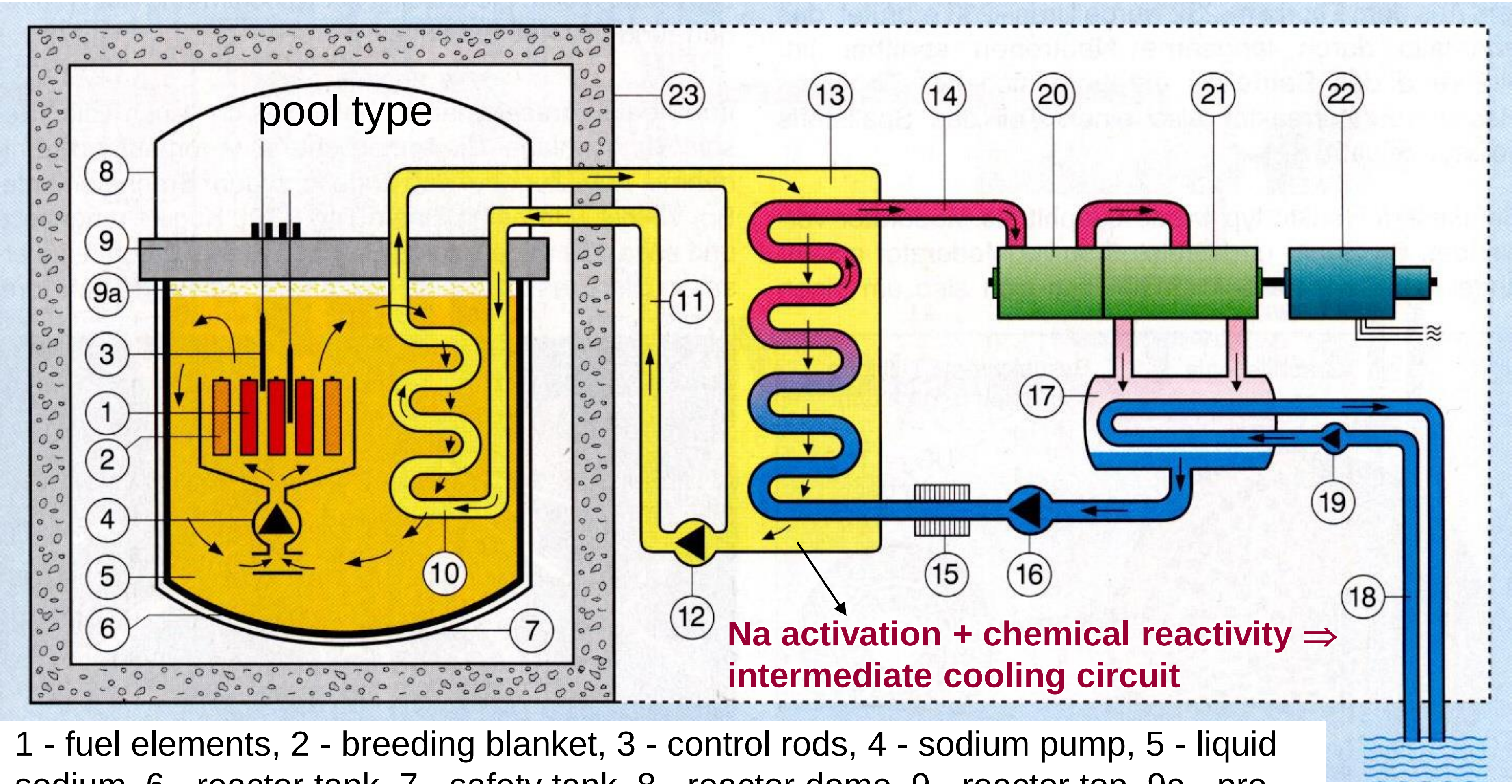
- dense fuel rod bundle
- good mechanical fixing of fuel rods
- comparatively low pressure drop
- heat transfer enhancement

TYPICAL SFR FUEL ELEMENT

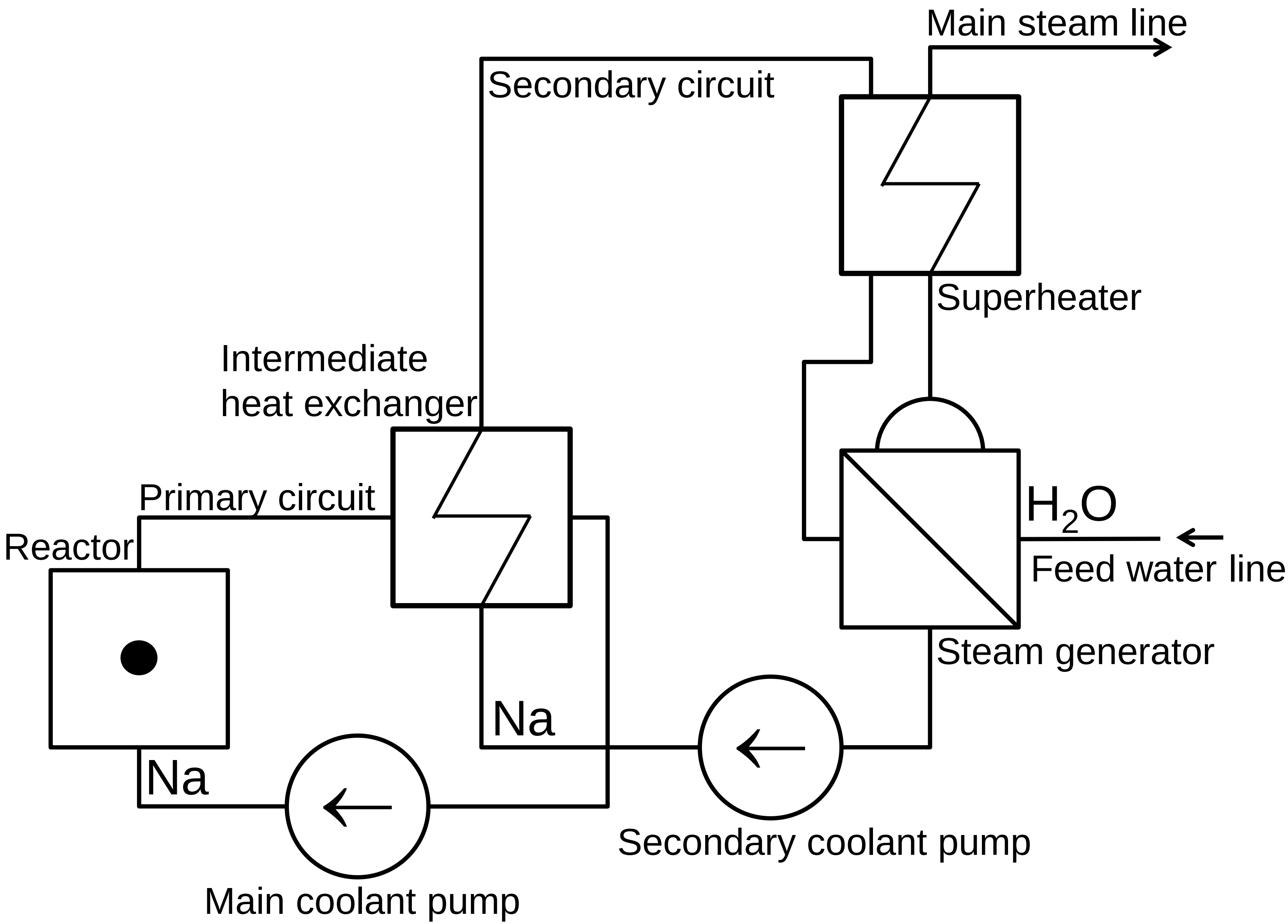


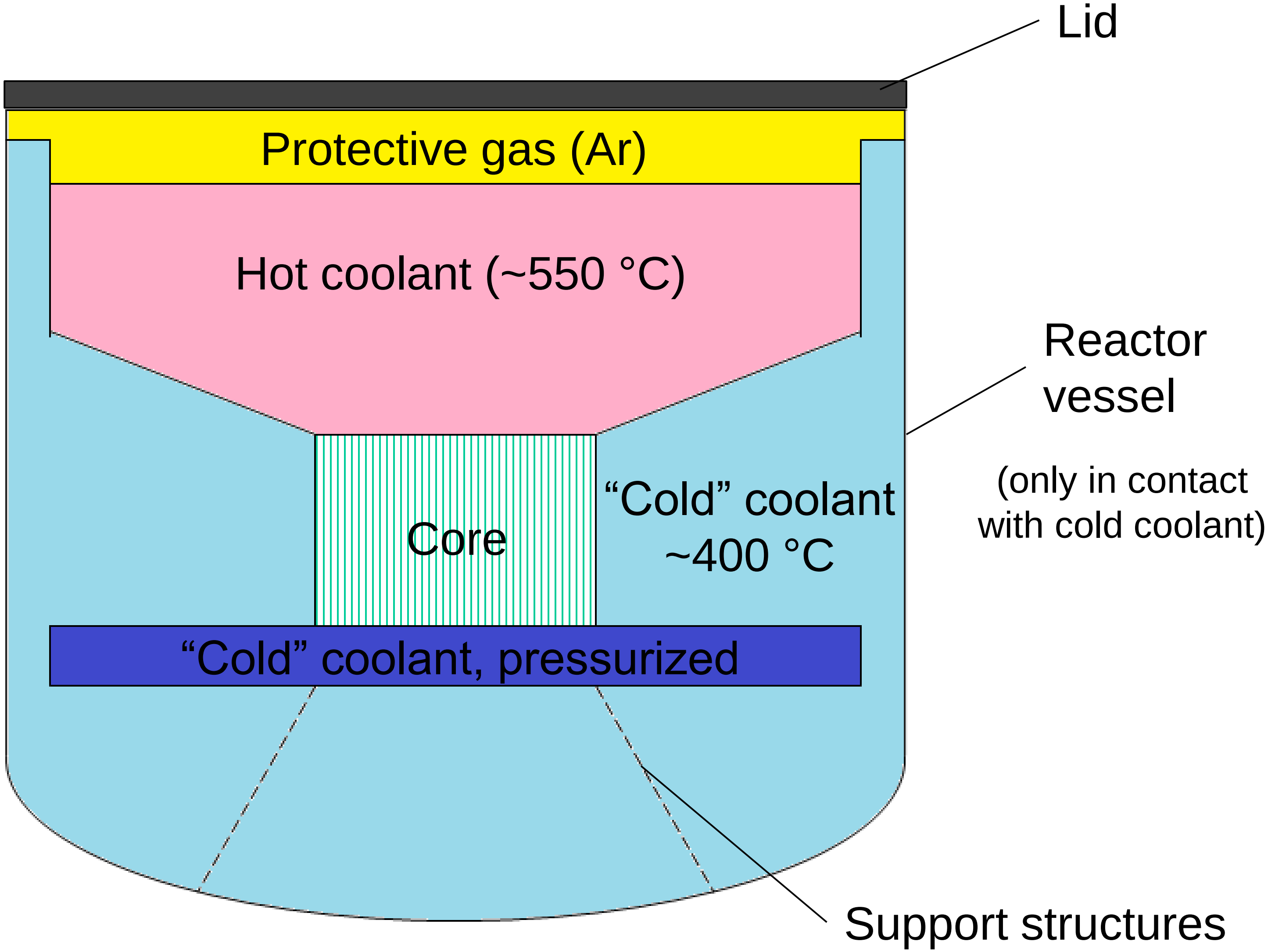
R. N. Hill, 2012

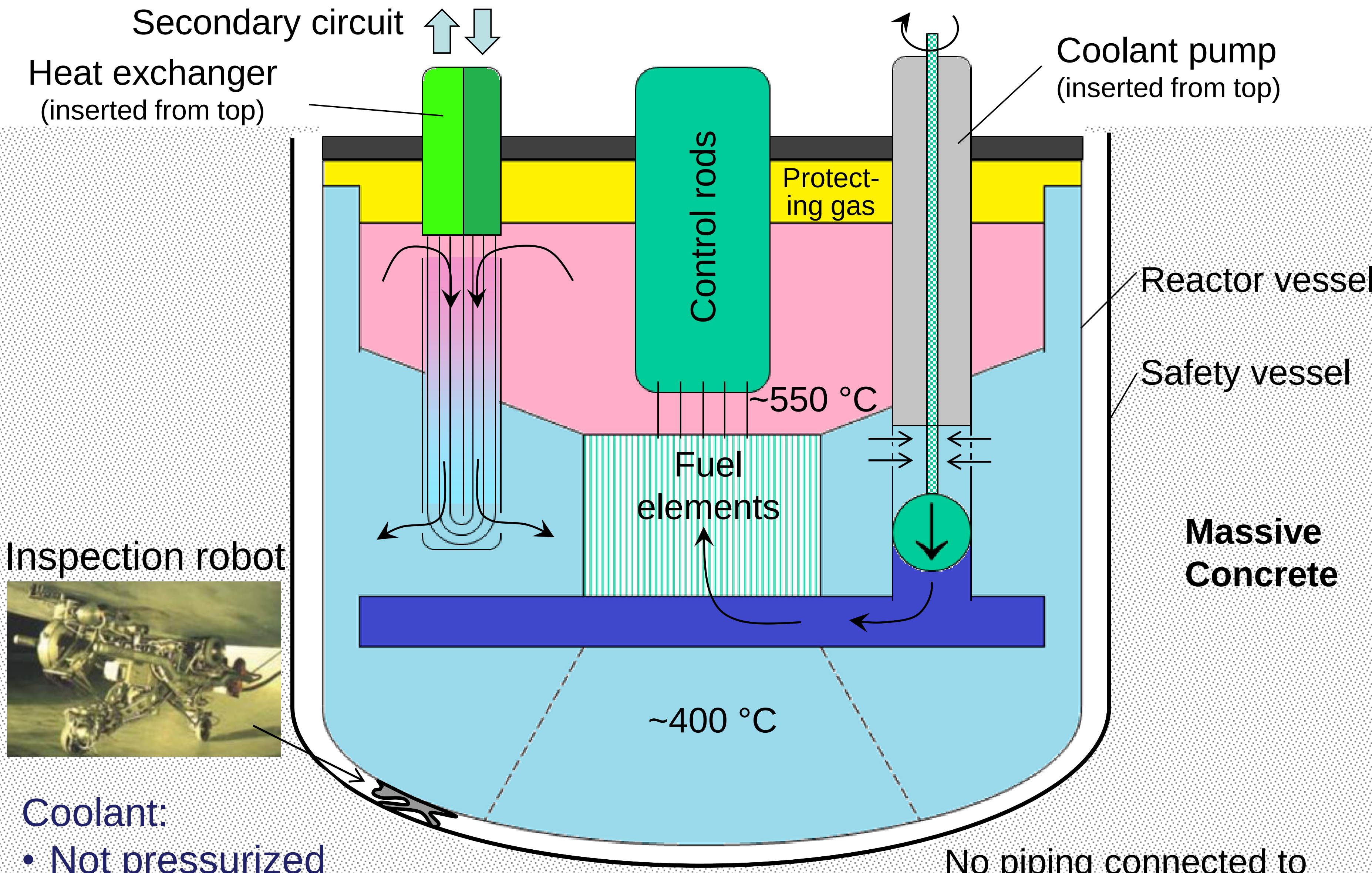
SCHEME OF AN NPP WITH SODIUM-COOLED FAST BREEDER REACTOR (SFR)



1 - fuel elements, 2 - breeding blanket, 3 - control rods, 4 - sodium pump, 5 - liquid sodium, 6 - reactor tank, 7 - safety tank, 8 - reactor dome, 9 - reactor top, 9a - protective gas (Argon), 10 - intermediate heat exchanger, 11 - secondary circuit (non-activated sodium), 12 - secondary pumps, 13 - steam generators, 14 - main steam, 15 - regenerative pre-heaters, 16 - feed water pump, 17 - condenser, 18 - cooling water, 19 - cooling water pump, 20 - high-pressure turbine, 21 - low-pressure turbine


Main steam line
Secondary circuit
Superheater
Intermediate heat exchanger
Primary circuit
Reactor
H2O
Feed water line
Steam generator
Na
Na
Secondary coolant pump
Main coolant pump

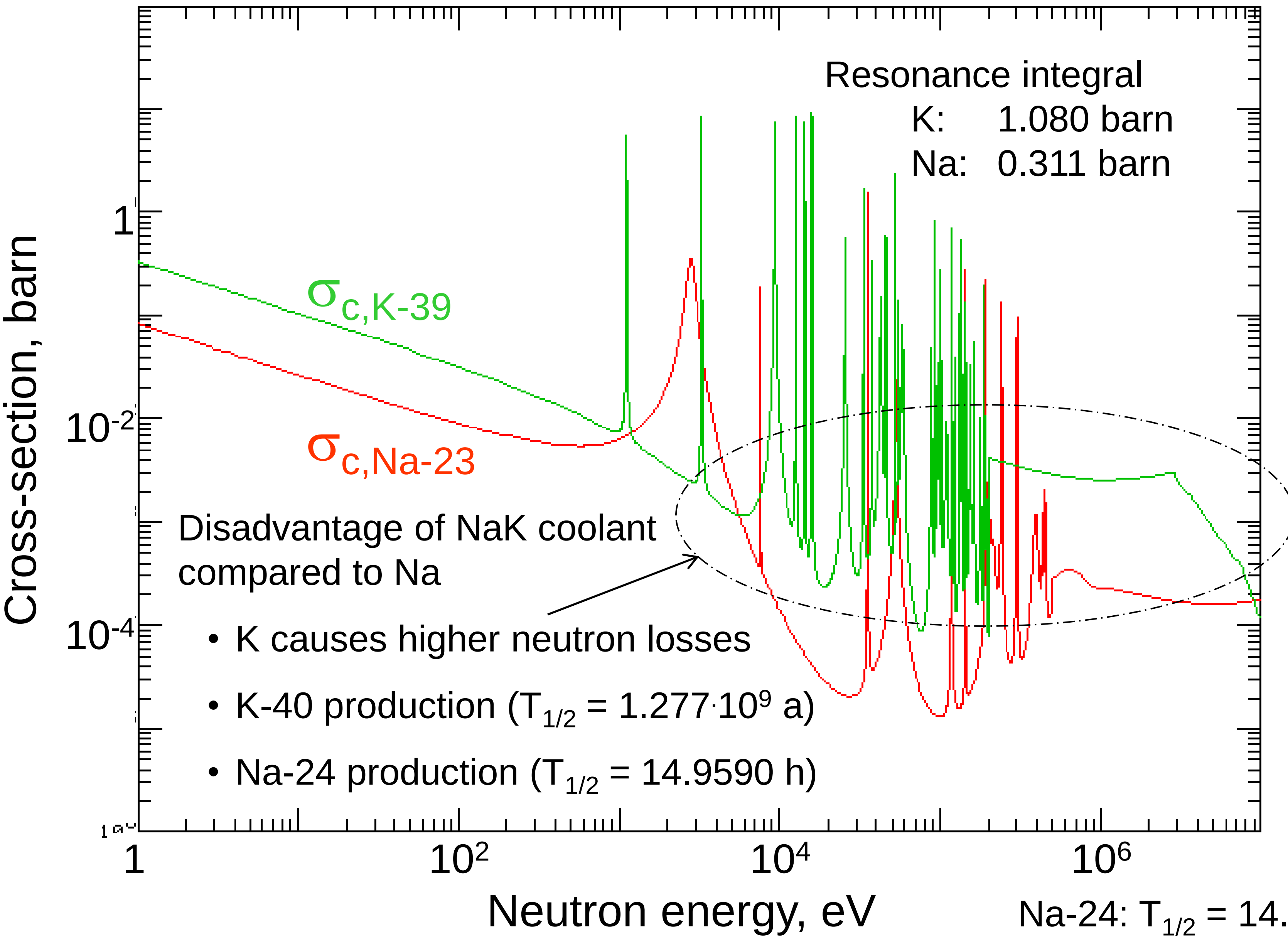

Lid
Protective gas (Ar)
Hot coolant (~550 °C)
Reactor vessel
(only in contact with cold coolant)
Core
"Cold" coolant ~400 °C
"Cold" coolant, pressurized
Support structures



Coolant:
- Not pressurized
- Leak deterministically excluded

No piping connected to reactor vessel

EPFL



Na-24: $T_{1/2}$ = 14.9590 h

- **Activation of sodium by neutrons**
  - intermediate cooling circuit

Reaction	σ, mbarn (fission neutrons)	$T_{1/2}$	Decay	$E\gamma$, MeV
Na-23 (n,γ) Na-24	225.8	15 h	β^- to Mg, γ	1.37 & 2.75
Na-23 (n,p) Ne-23	1.524	23 s	β^- to Na, γ	0.440
Na-23 (n,α) F-20	601.7	11 s	β^- to Ne, γ	1.634
Na-23 (n,2n) Na-22	2.563	2 a	β^+ to Ne, γ	1.275

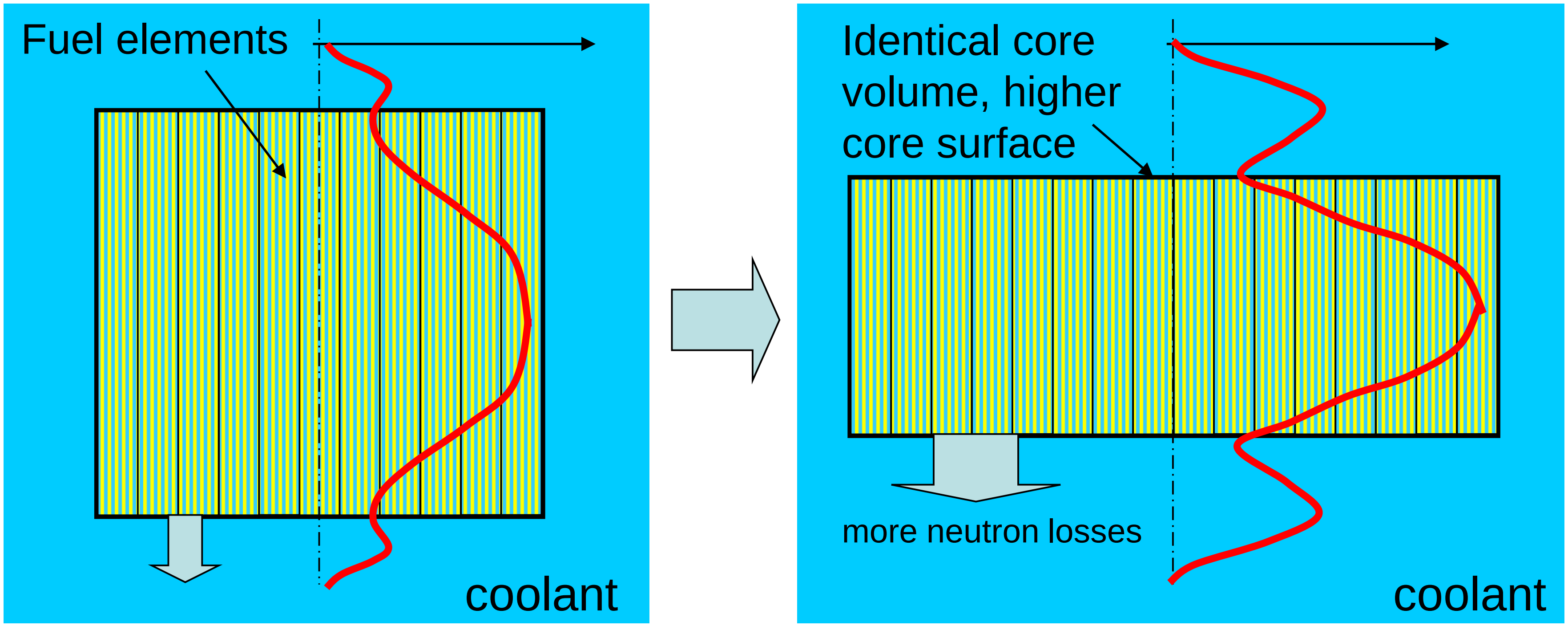
- **Positive feedback (!) effect** from coolant density to reactivity
  - Coolant heat-up
  - Density decrease
  - Less absorption
  - Positive reactivity contribution
- Danger of reactivity induced accidents in case of sodium boiling

DESIGN OF A VOID EFFECT BY "PANCAKE CORES"

Two competing effects of a decrease of sodium density in the fuel lattice

Neutron capture by Na: Less neutron absorption → $k_\infty \uparrow$

Neutron scattering by Na: Larger free traveling length → larger neutron losses



"Normal" core: minimized neutron losses

Sodium voiding: neutron capture reduction dominates → void effect positive

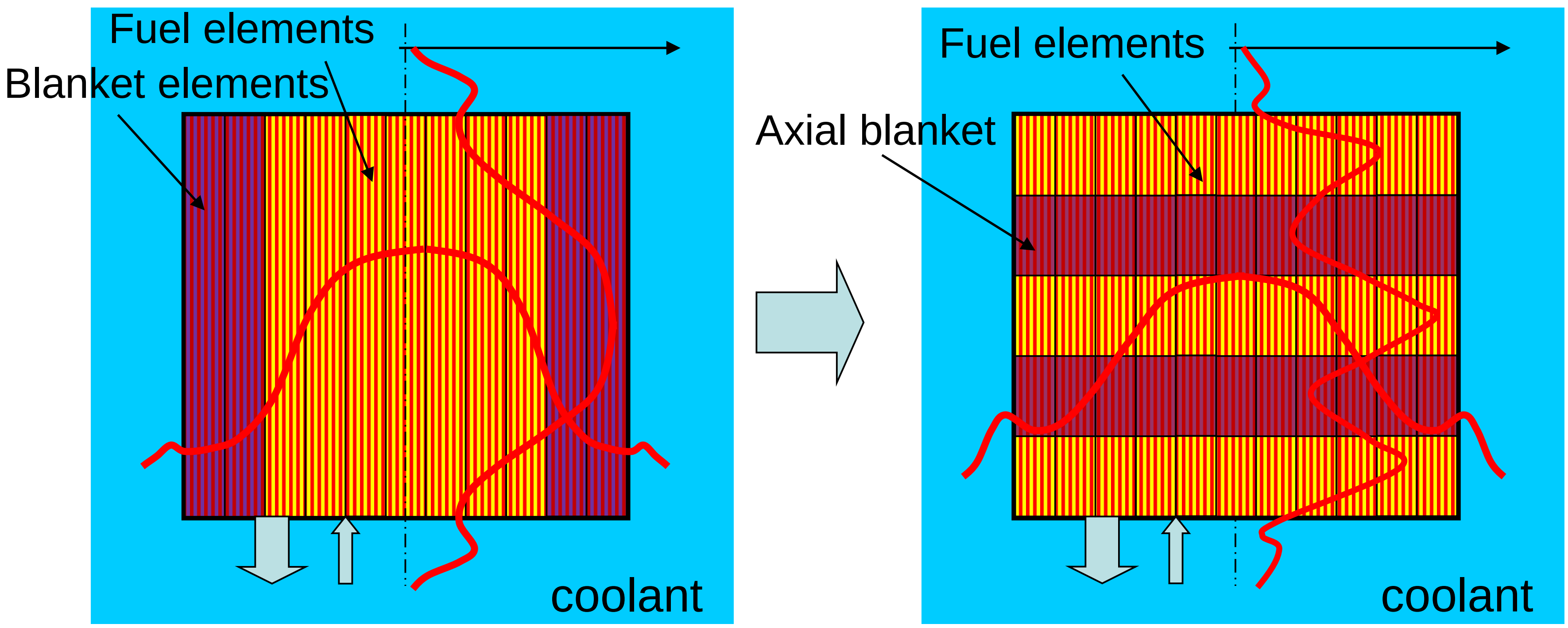
$\rho_{Na}(\Downarrow) \rightarrow k_\infty(\Uparrow)$ x [1 - losses] $(\downarrow) = k_{eff}(\uparrow)$

"Pancake" core: enhanced neutron losses

Sodium voiding: increase of neutron traveling length effect dominates → void effect negative

$\rho_{Na}(\Downarrow) \rightarrow k_\infty(\Uparrow)$ x [1 - losses] $(\Downarrow\Downarrow) = k_{eff}(\downarrow)$

ADVANCED ALTERNATIVE: "PARFAIT CORE"



- Radial blanket: optimal breeding efficiency
- Easy removal of weapon grade Pu-239
- Criticized for low proliferation resistance

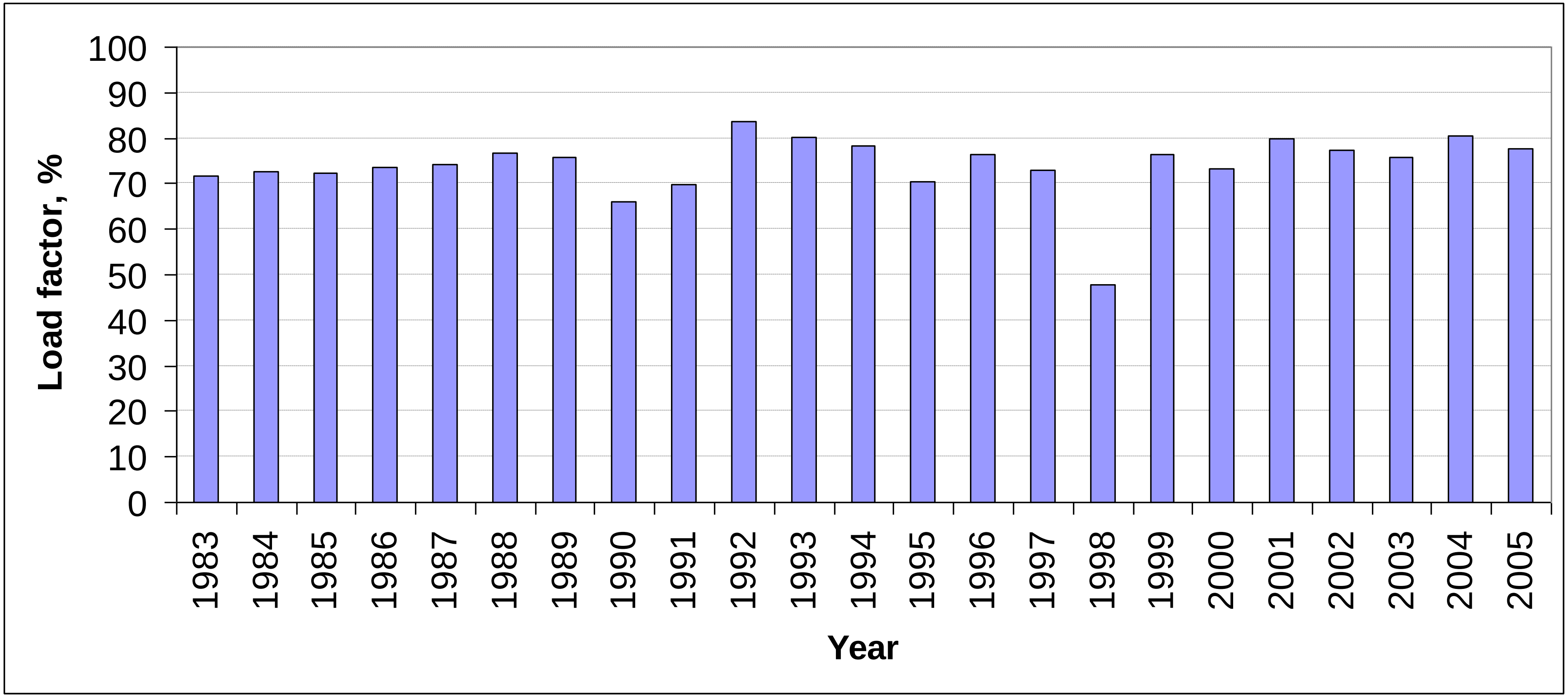
- "Parfait" core with axial breeding blanket zones inside the fuel rods
- Fissile fuel with fission products and blanket material cannot be easily separated
- Improved proliferation resistance

- Neutronics: "Parfait" core combines positive dynamic properties (negative void effect) with good breeding efficiency (leakage neutrons are absorbed by blanket material)

- Low temperature research reactors not included

Research plants			Start Con.	Criticality	Power	Full power	Decomm.	Th. power	El. power	Breeding f.
								MW	MW	
1	EBR-I	USA	1951	1951	1951				0,2	0.27
2	Rapsodie	France	1962	1967		1967	1983	40	0	
3	KNK-II	Germany		1972	1978	1978	1991	58	20	
4	FBTR	India	1972	1985	1994	1996		40	13	
5	JOYO	Japan	1970	2003		2003		140	0	0,03
6	DFR	Great Britain	1954	1959	1962	1963	1977	60	15	
7	BOR-60	Russia	1964	1968	1969	1970		55	12	
8	EBR-II	USA	1958		1964	1965	1998	62.5	20	
9	Fermi	USA	1956	1963	1966	1970	1975	200	61	0,16
10	FFTF	USA	1970	1980		1980	1996	400	0	
11	BR-10	Russia	1956	1958		1959	2003	8	0	
12	CEFR	China			1997			65	23,4	
Prototypes and power plants										
13	**Phénix**	**France**	**1968**	**1973**	**1973**	**1974**	2010	**563**	**255**	**0.16**
14	**MONJU**	**Japan**	**1985**	**1994**	**1995**	**-**	2018	**714**	**280**	**0.2**
15	PFR	Great Britain	1966	1974	1975	1977	1994	650	250	-0.05
16	BN-350	Kasachstan	1964	1972	1973	1973	1999	750	130	0
17	**BN-600**	**Russia**	**1967**	**1980**	**1980**	**1981**		**1470**	**600**	**-0.15**
18	Super-Phénix 1	France	1976	1985	1986	1986	1998	2990	1242	0.18
19	BN-800	Russia	1984	2014	2016	2016		2100	885	
20	PFBR	India	2004	2019				1250	500	

Availability of the BN-600 in Bjeloyarsk (in operation)

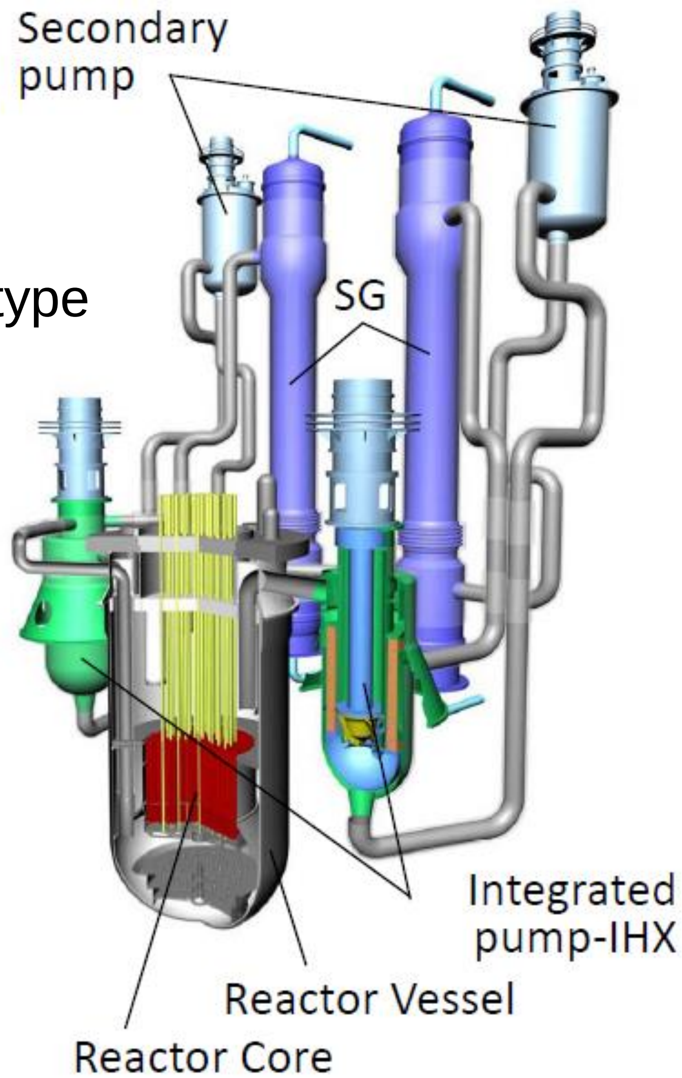


Specific electricity output: LWR: 50 MWh/kg U-nat
Breeder: ~3500 MWh/kg U-nat

- Existing depleted Uranium (mostly U-238) sufficient for thousands of years
- Less long-live nuclear waste / more fission products with moderate half-life periods
- But: Reprocessing needed and more expensive

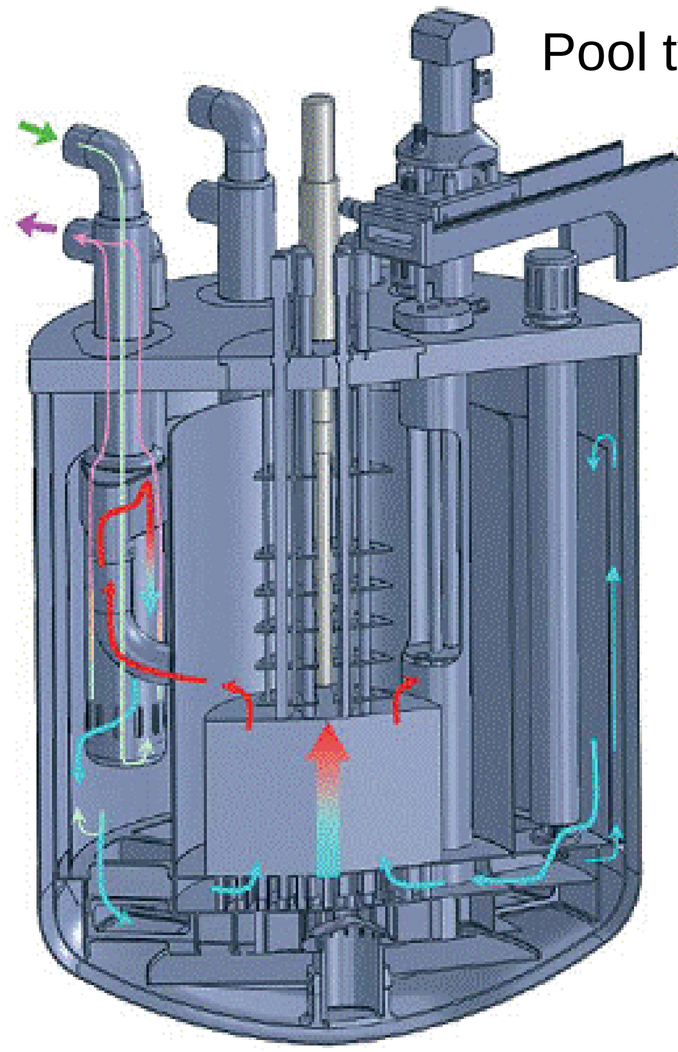
- **Decrease of costs**
  - Simplify reactor and primary circuit (Two-loop reactors, back to loop type...)
- **Enhance safety**
  - Eliminate positive void effect ("pancake core")
  - Change to chemically less reactive coolants (Pb-Bi, He)
  - Development of safety systems / severe accident management
- **Increase of proliferation safety**
  - Abandon breeding blanket concept (homogeneous breeder)
  - ➢ High fission product activity makes it difficult to extract weapon grade plutonium
  - ➢ Short-term irradiation to produce weapon grade plutonium is more difficult (contradicts decent burn-up of fissile material)

Loop type



JSFR = Japanese Sodium Fast Reactor
(Project: 1500 MW_{el})

Pool type



ASTRID = Advanced Sodium Technological Reactor for Industrial Demonstration
(Project of CEA: 600 MW_{el} in 2020)

Engineering basis of SVBR-type reactors

SVBR-type reactors were designed within the framework of the conversion of unique Russian technology for lead-bismuth coolant marine reactors.

SVBR – **L**ead **B**ismuth **F**ast **R**eactor

EPFL

Lead / LBE does not react with water or air

- Safety issue of pressure peaks in case of direct water contact with melt
- Intermediate loop not needed
- Steam generator units can be installed inside the Reactor Vessel

High boiling point (1745 °C) and very low vapor pressure

- Reduced core voiding risk

Higher density than the oxide fuel

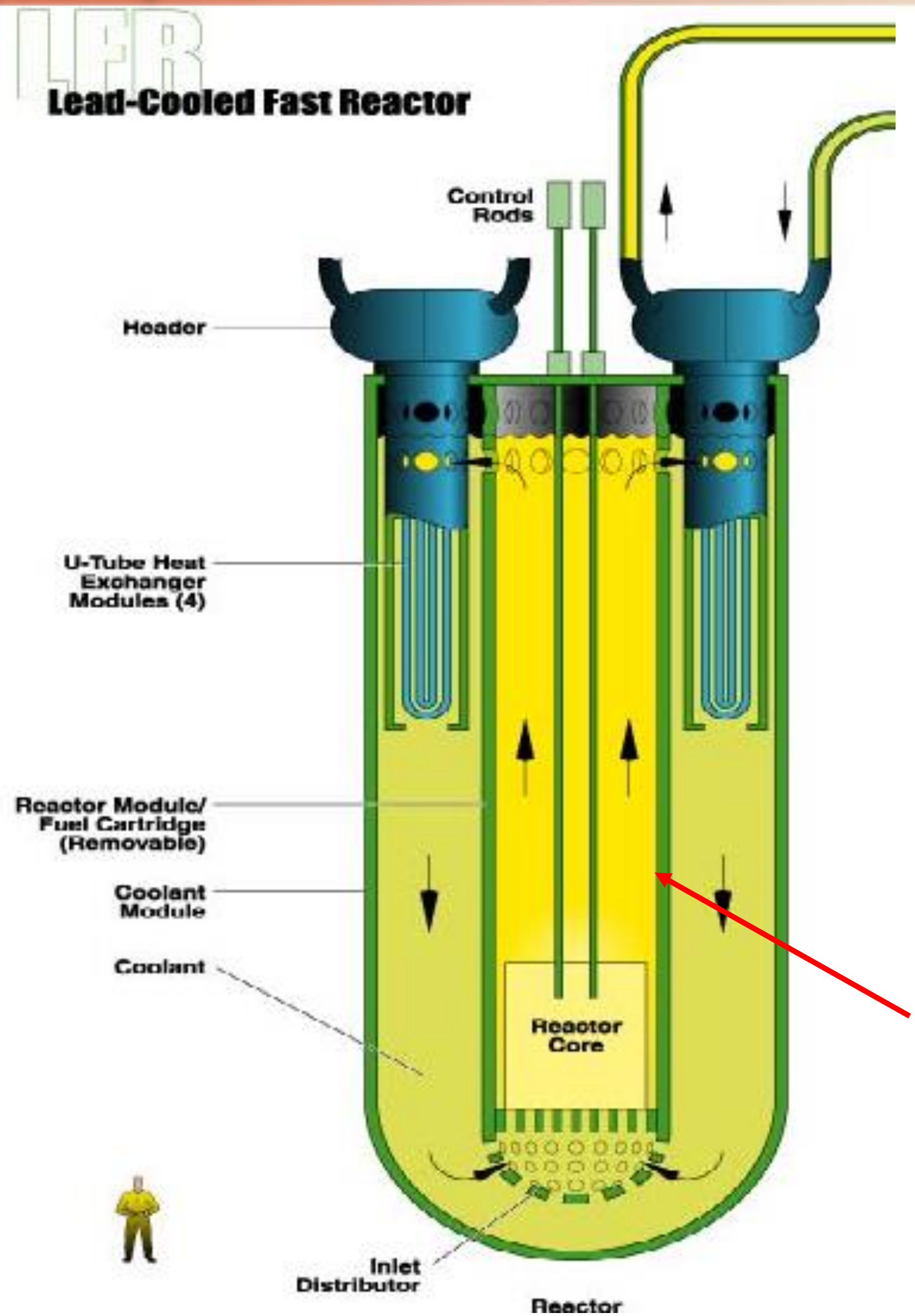
- Fuel elements buoyant (special constructive solutions needed)

Low moderation, **low absorption of neutrons**

- No tight fuel rod lattice needed
- No heat transfer enhancement needed
- Low hydraulic resistance of the core → better natural circulation capability

High gamma attenuation

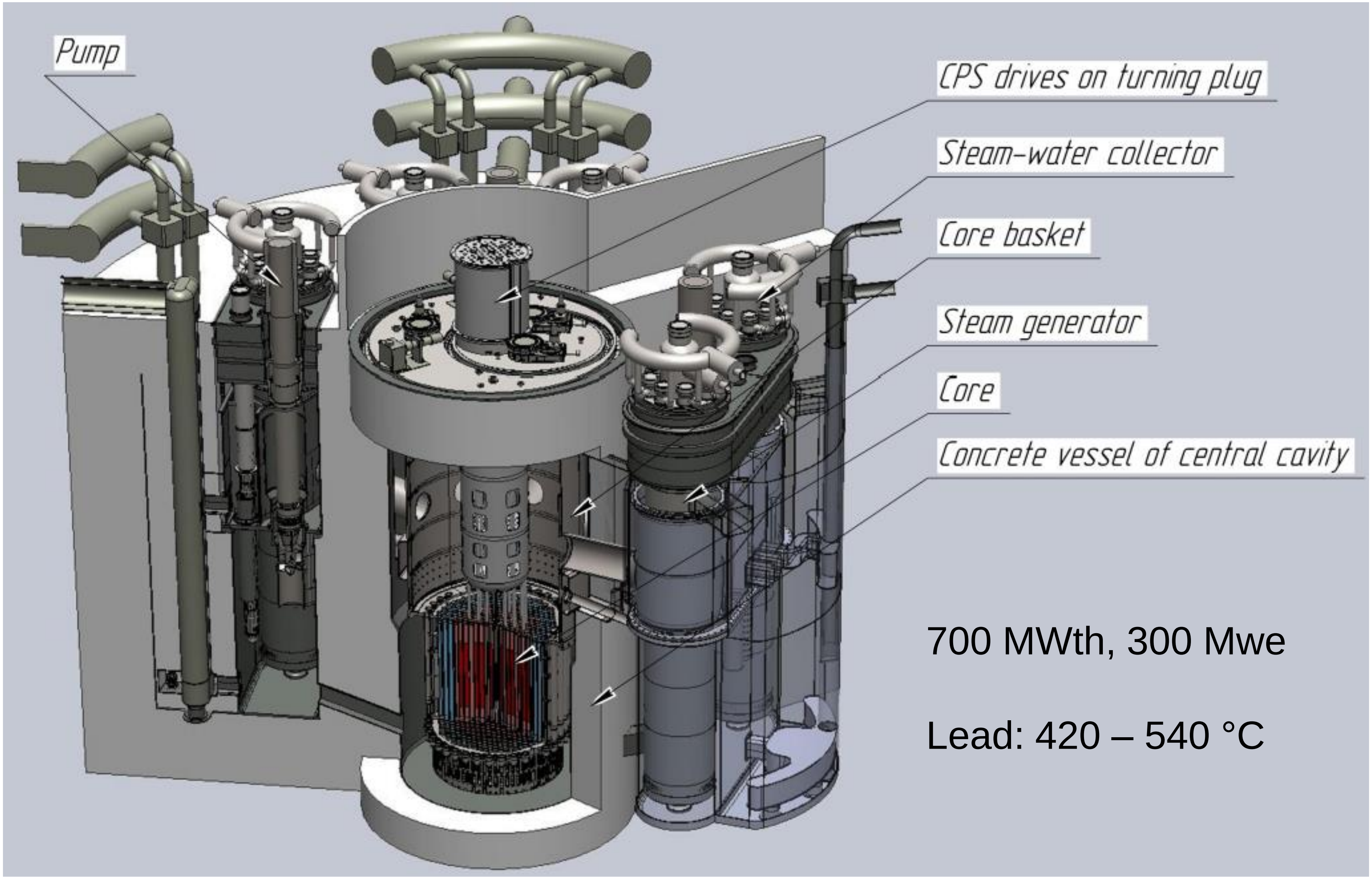
Corrosive with steel



Coolant:	Pb or PbBi (=LBE)
Power:	50-150 MW / Cycle 15-20 a (!) 300-400 MW module type or 1200 MW
Spectrum:	Fast neutrons
Purpose:	Transmutation of actinides breeding of fissile material electricity, process heat
NPP:	Superheated steam cycle or combined cycle

T_{out} = 550 °C
(with new materials: 800 °C)

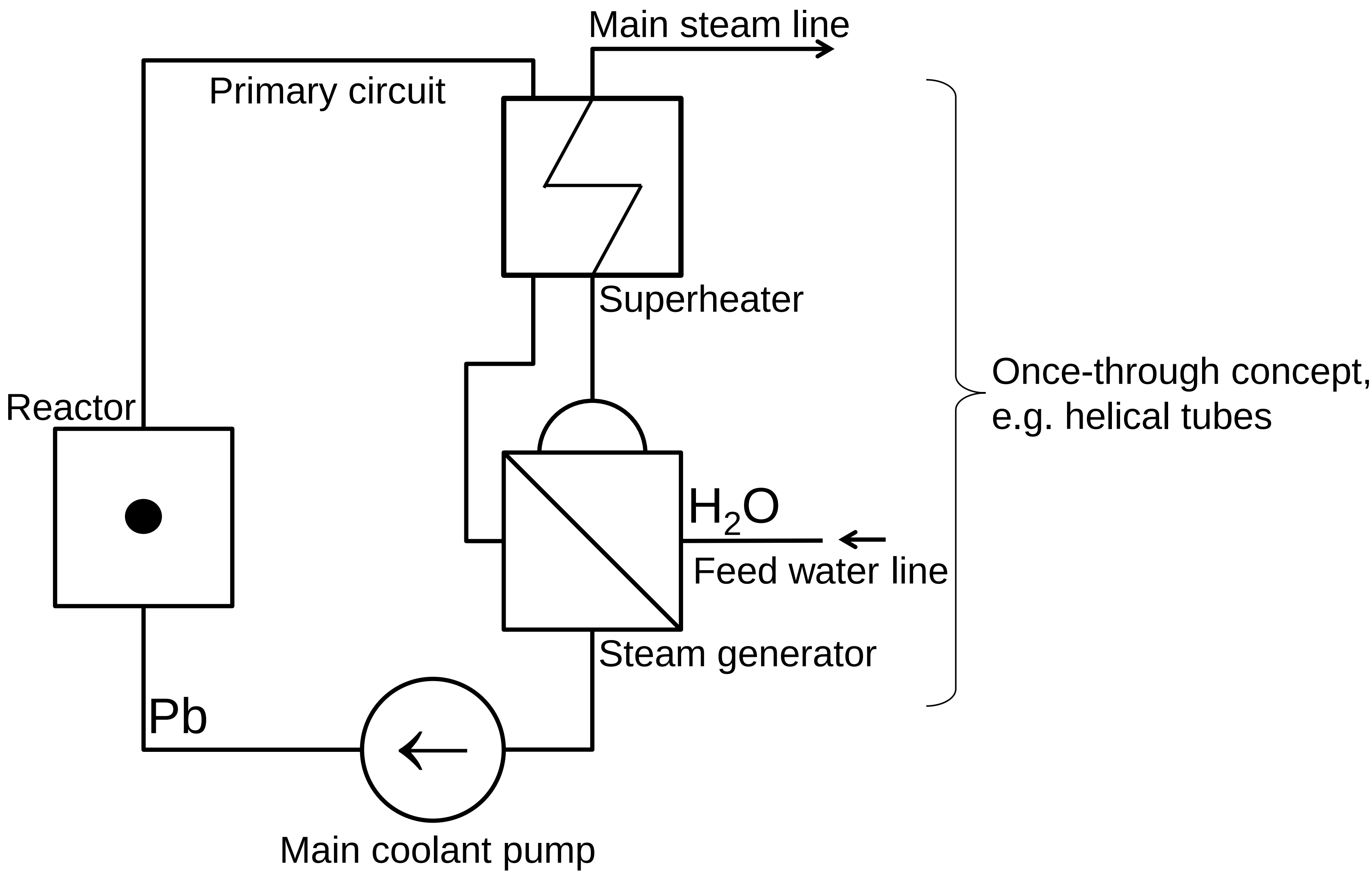
http://www.gen-4.org/



700 MWth, 300 Mwe

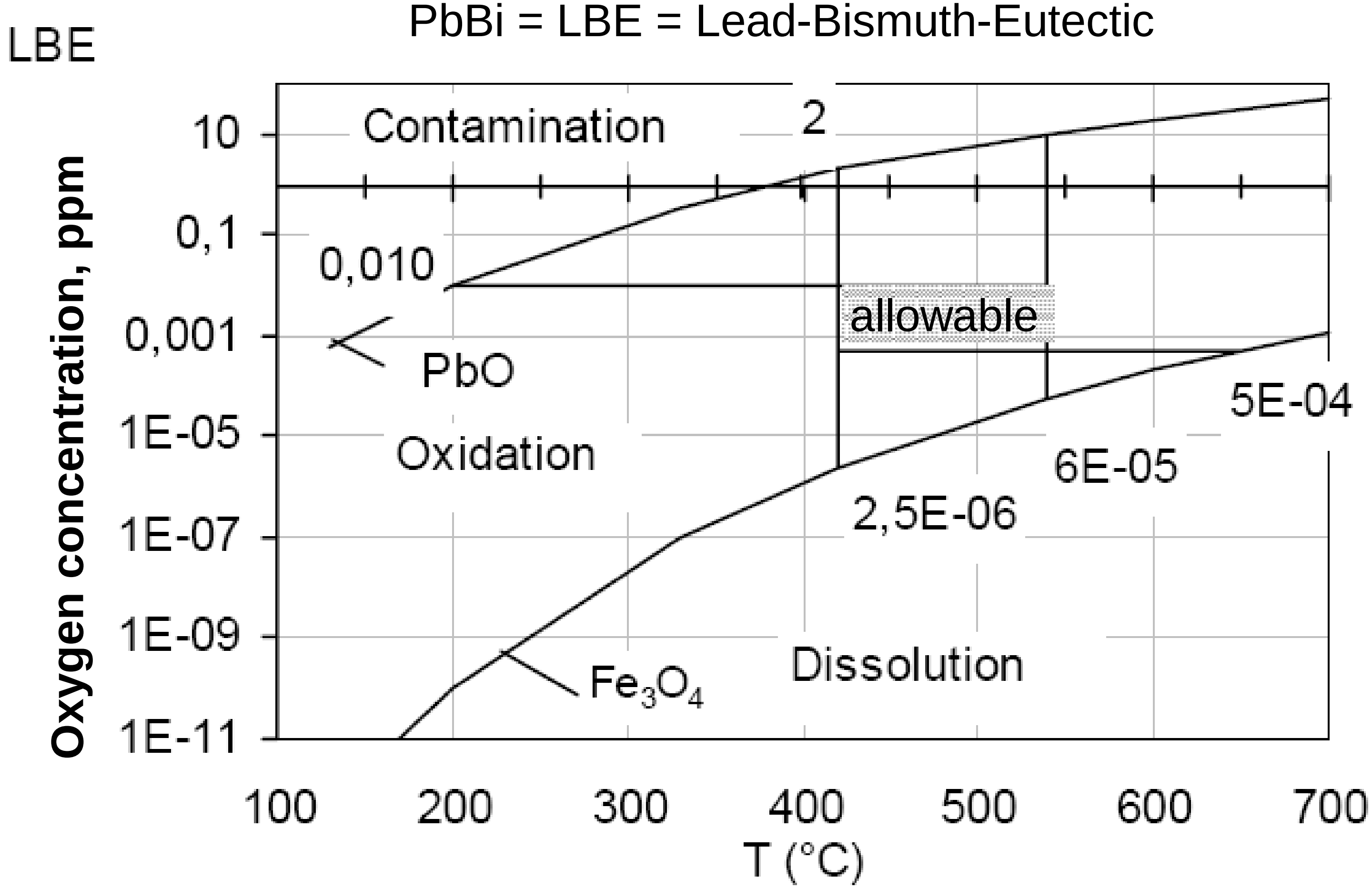
Lead: 420 – 540 °C

NIKIET


Main steam line
Primary circuit
Superheater
Reactor
Once-through concept,
e.g. helical tubes
H_2O
Feed water line
Steam generator
Pb
Main coolant pump

- Excess of PbO (high melting point) may result in cooling channel plugging.
- Presence of oxygen creates protective oxide layer on steel structures

PbBi = LBE = Lead-Bismuth-Eutectic



Keep oxygen concentration between PbO contamination and Fe_3O_4 dissolution limits

Gas phase control:

$$Pb_{(liquid)} + O_{2\,(gas)} \rightarrow PbO_{(dissolved)} \qquad \rightarrow \text{Oxygen conc.} \uparrow$$

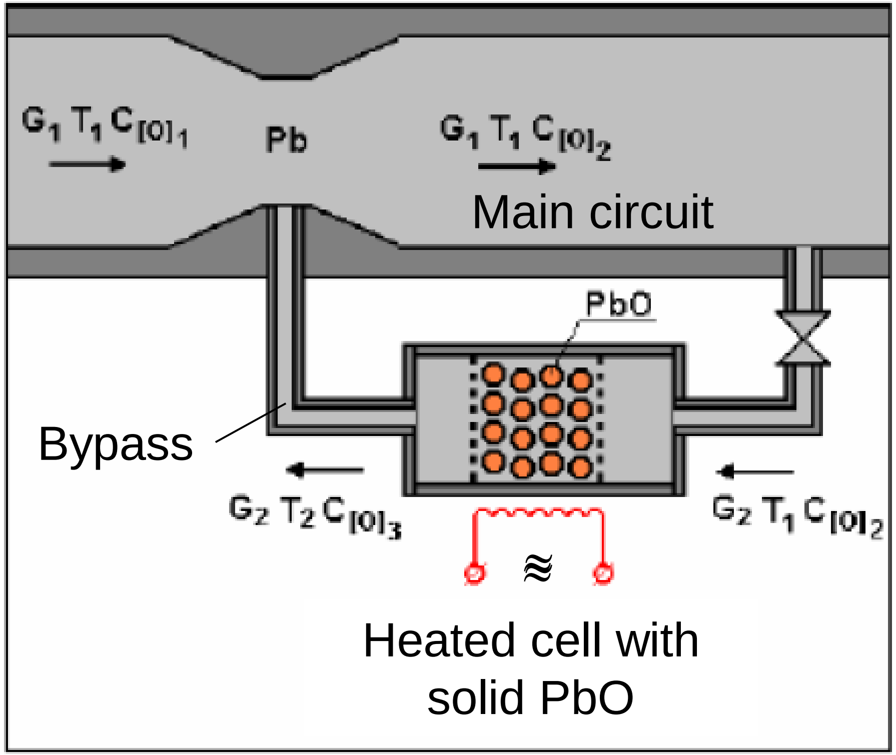
$$PbO_{(dissolved)} + H_{2\,(gas)} \rightarrow H_2O_{(vapor)} + Pb_{(liquid)} \qquad \rightarrow \text{Oxygen conc.} \downarrow$$

Gases (H_2, O_2) directly bubbled through the liquid metal

Solid phase control:

Heating on $\Rightarrow$ Temperature $\uparrow$
$\Rightarrow$ more PbO dissolves
$\Rightarrow$ oxygen concentration $\uparrow$

Heating off $\Rightarrow$ Temperature $\downarrow$
$\Rightarrow$ less PbO dissolves $\Rightarrow$
oxygen concentration $\downarrow$



Lead monoxide pellets device for oxygen supply to the coolant using the solid phase method [Martynov, 2003], [Askhadulline, 2005]

Option A: Transmutation in fast reactors

- Most minor actinides have low shares of delayed neutrons →
- More to reactivity induced accidents (in combination with positive coolant feedback)

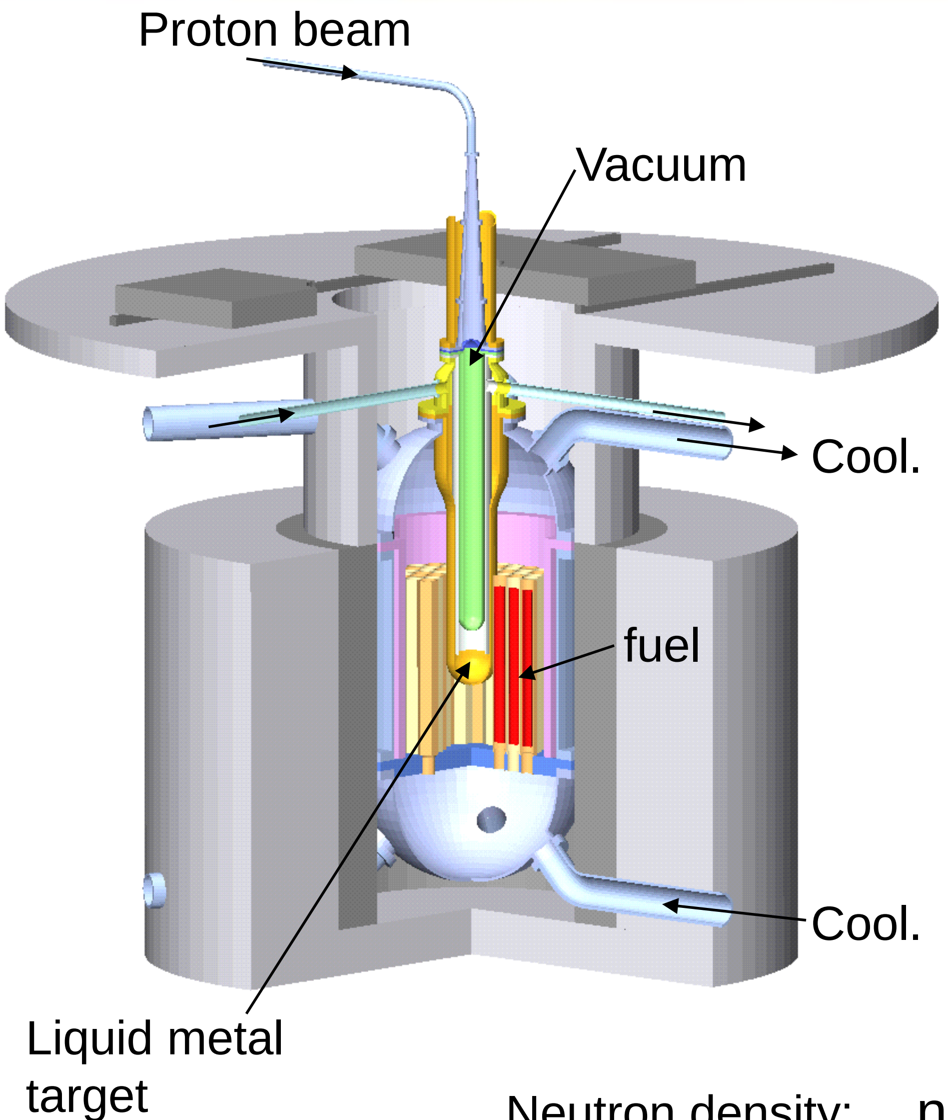
Nuclide	β
^{238}U	0.0172
^{237}Np	0.0388
^{238}Pu	0.0014
^{239}Pu	0.0021
^{240}Pu	0.0030
^{241}Pu	0.0054
^{242}Pu	0.0066
^{241}Am	0.0013
^{243}Am	0.0023
^{242}Cm	0.0004
^{235}U	**0.0064**

Option B: Transmutation in subcritical reactors

- Fast neutrons are generated by spallation
- High-energy protons are shot on a heavy metal target (20 neutrons per proton)
- Neutrons are multiplied in a subcritical reactor

$$n = \frac{\dot{S}_{n,spallation}}{(1-k_{eff})} \cdot l \qquad \dot{S}_{n,spallation} \approx 20 \cdot \dot{n}_p$$

- No criticality - no reactivity induced accidents
- Attention: Decay heat as safety issue unchanged



Coolant: Lead-Bismuth eutectic

Target: Lead-Bismuth eutectic

Spectrum: Fast neutrons

Neutron source:

Spallation of heavy nuclei by energetic protons (yield ~20 neutrons / proton)

Purpose: Transmutation of actinides in a sub-critical fuel assembly

(Actinides have low yields of delayed neutrons → sub-criticality is a safety advantage, problem of decay heat remains unchanged)

Disadvantage: High costs of neutrons

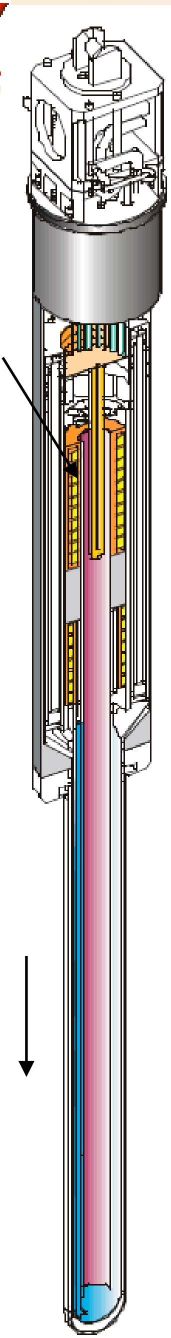
Neutron density: $n = \frac{\dot{S}_{n,spallation}}{(1-k_{eff})} \cdot l$ $\quad \dot{S}_{n,spallation} \approx 20 \cdot \dot{n}_p$

An "only actinide burning" regime requires the smallest number of reactors

1 MW Pilot Experiment for a Liquid Metal Spallation Target

Paul Scherrer Institut (!)
CEA Cadarache
Forschungszentrum Karlsruhe

Protons come from below in the PSI MEGAPIE experiment



Production of highly radiotoxic Po-210 ($T_{1/2}$ = 138 d)

protons + Bi generate Po isotopes up to Po-209

Po-209 + n $\rightarrow$ Po-210

in ADS

Bi-209 + n $\rightarrow$ Bi-210

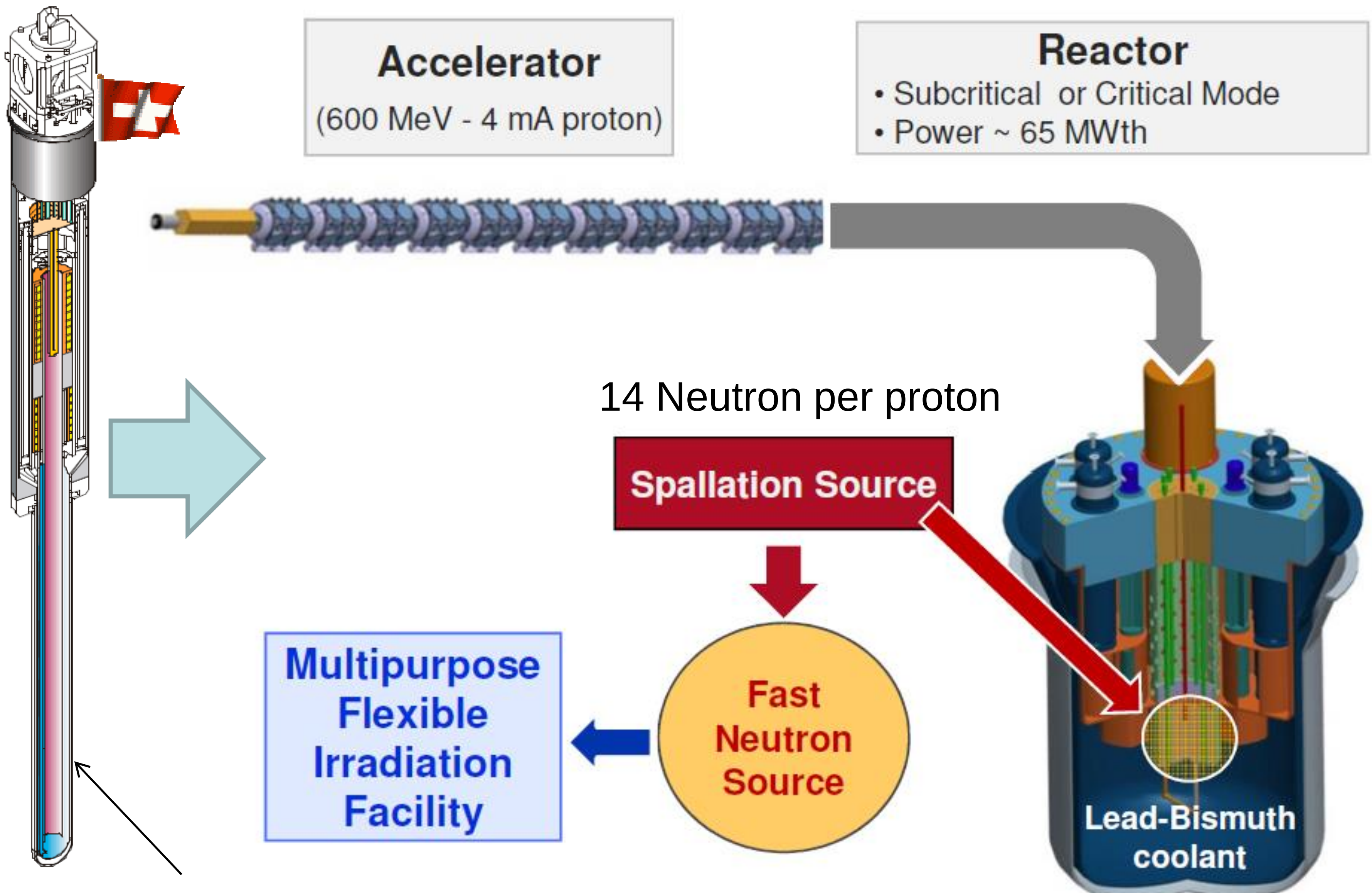
Bi-210 $\rightarrow$ Po-210 + β^-

in all fast LBE systems

$\rightarrow$ pure Pb systems are interesting

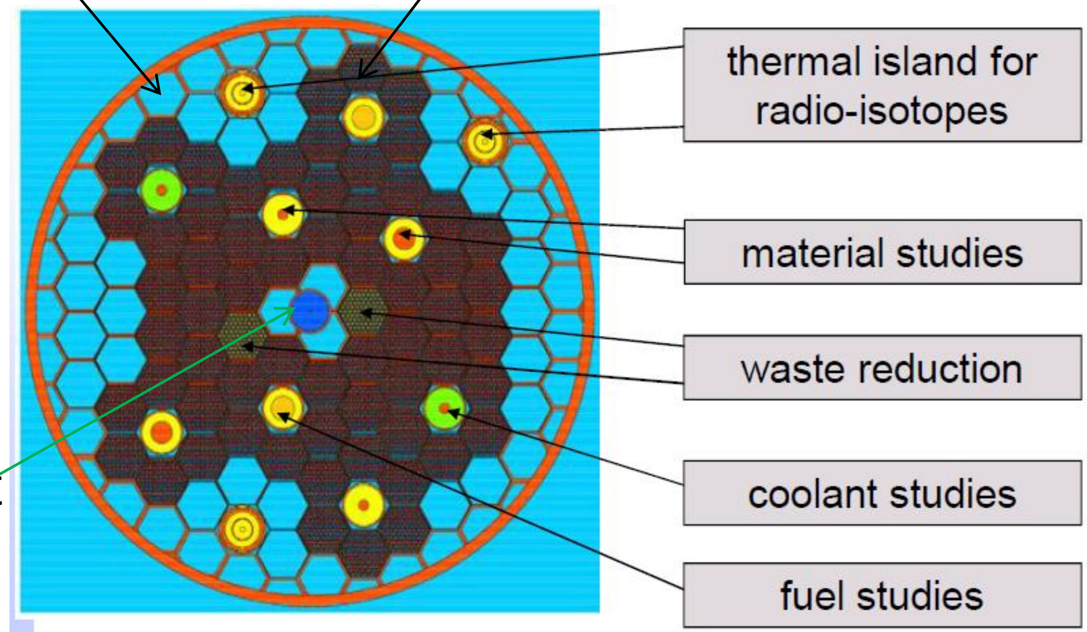
technology more difficult: higher melting point

Multi-purpose hybrid research reactor for high-tech applications



MEGAPIE, PSI, 2009

$k_{eff} = 0.955$



- Fresh core of MYRRHA –lattice of 183 hexagonal channels loaded with 68 fuel assemblies (MOX)
- 3 hexagons kept free for the spallation source

- Breeding, partitioning and transmutation to handle front- and back- end issues associated with the fuel cycle
- Fast reactors using liquid metal coolants
- Technological aspects related to
  - Sodium Fast Reactors
  - Lead Fast Reactors
  - Accelerator Driven Systems