



MSc Energy (2019/20)

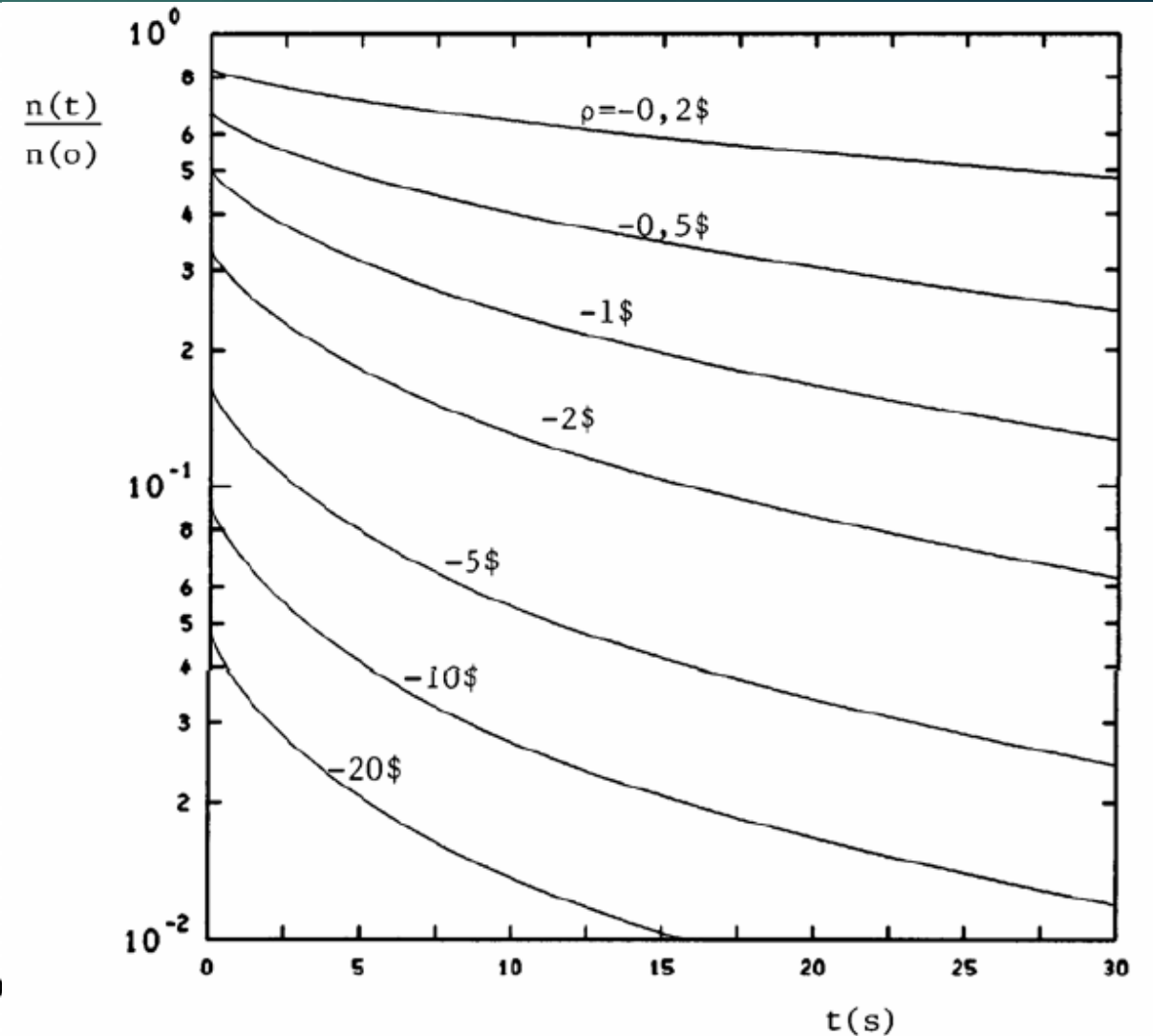
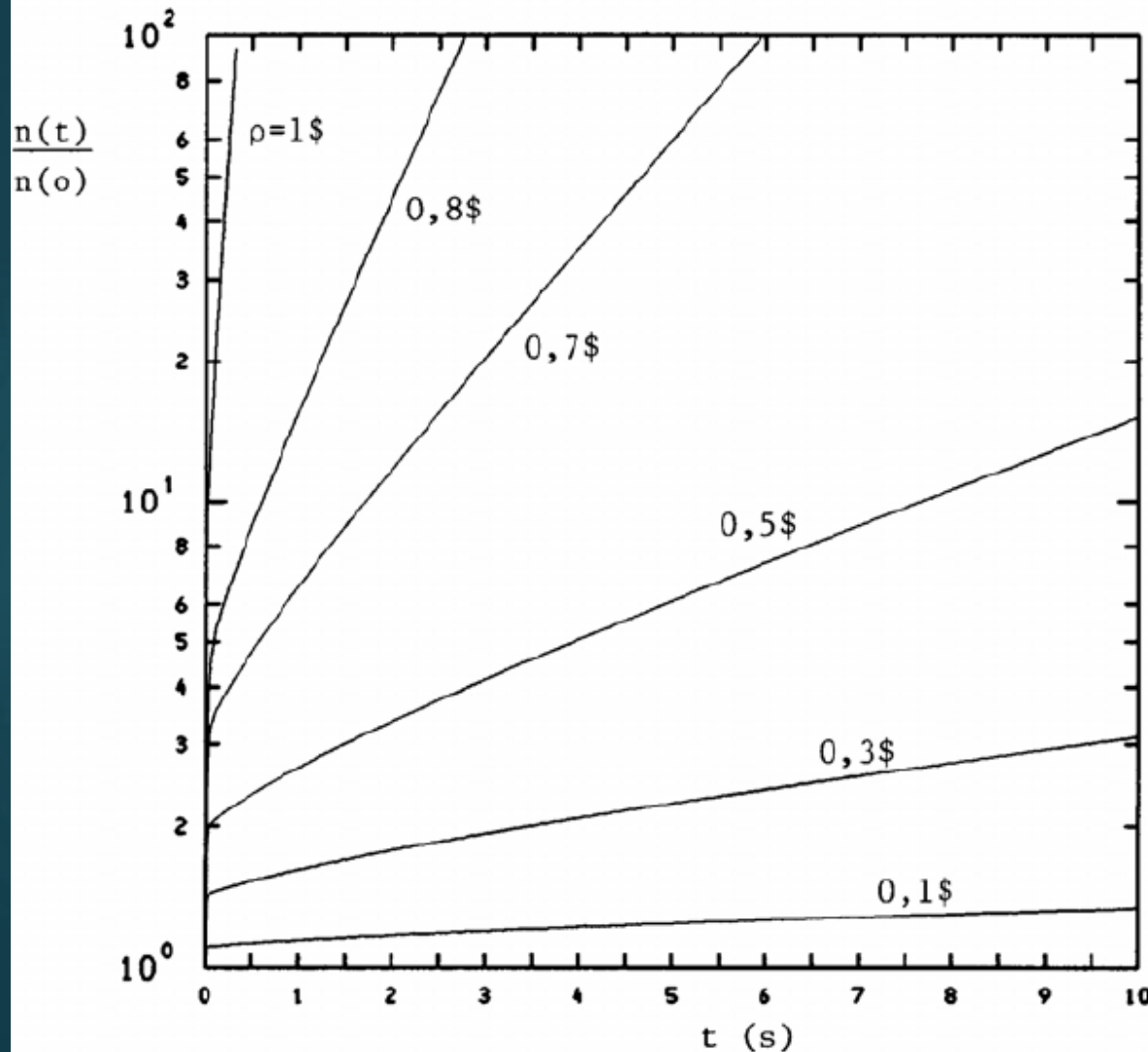
NUCLEAR REACTOR TECHNOLOGY (LECTURE 5)

P. STAMENOV

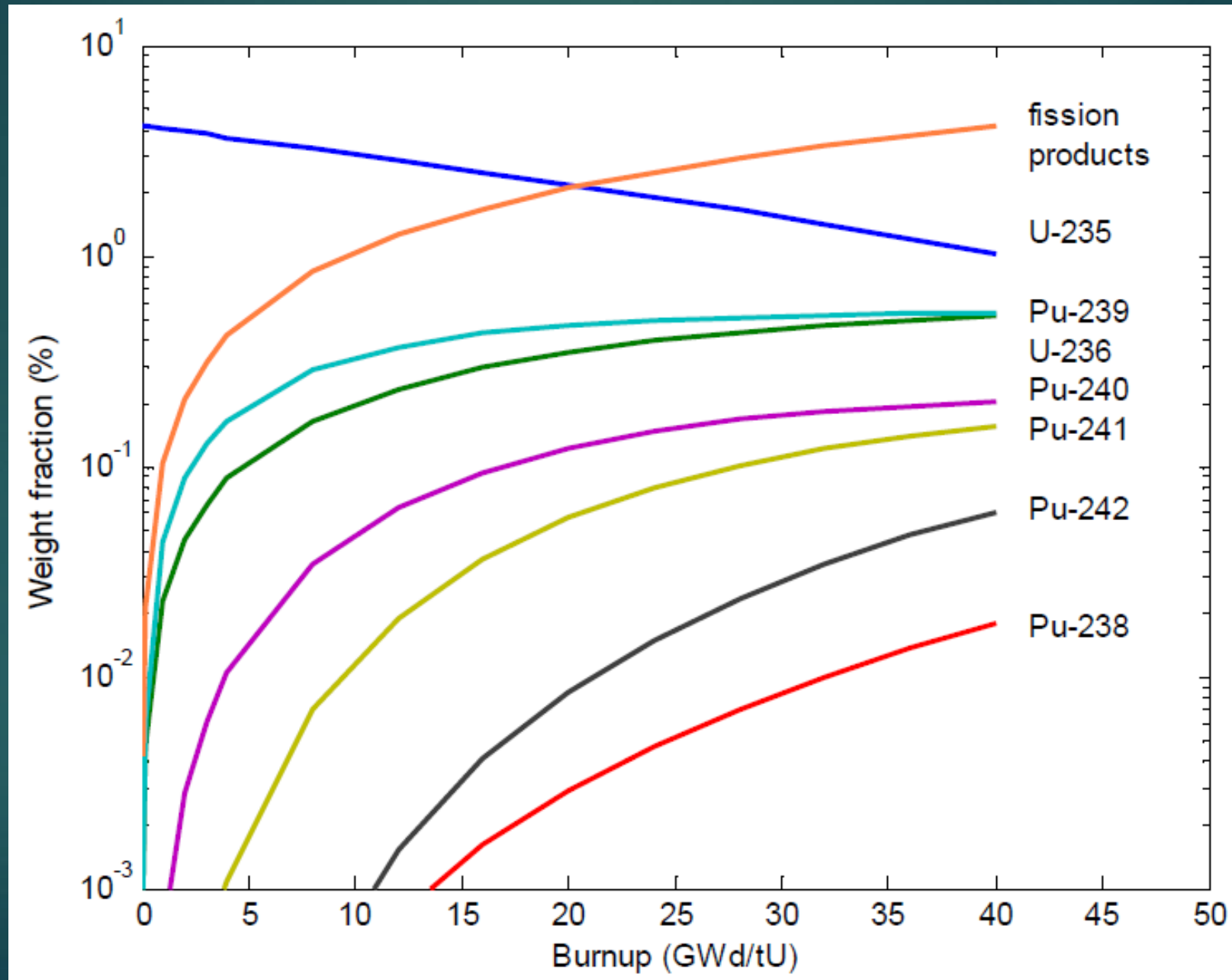
Reactivity Behaviour (delayed fraction)

► Reactivity is sometimes expressed in dollars: \$

$$\rho(\$) = q / d$$



Burnup and Build-up



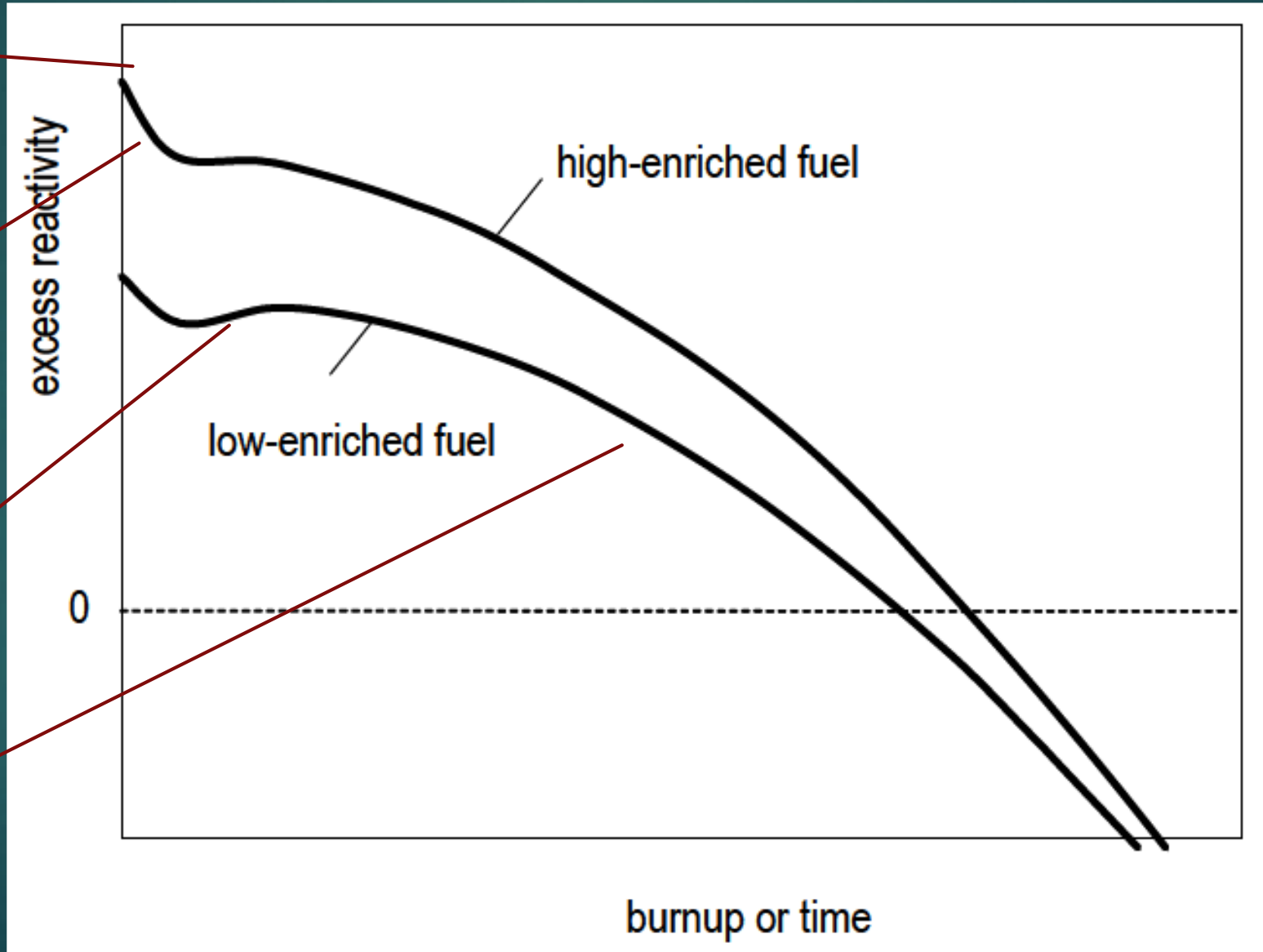
Excess Reactivity During Burnup

Heating
(Doppler
Effect)

Xe, Kr etc.
Poisoning

^{239}Pu
Accumulation

Self-Shielding



burnup or time

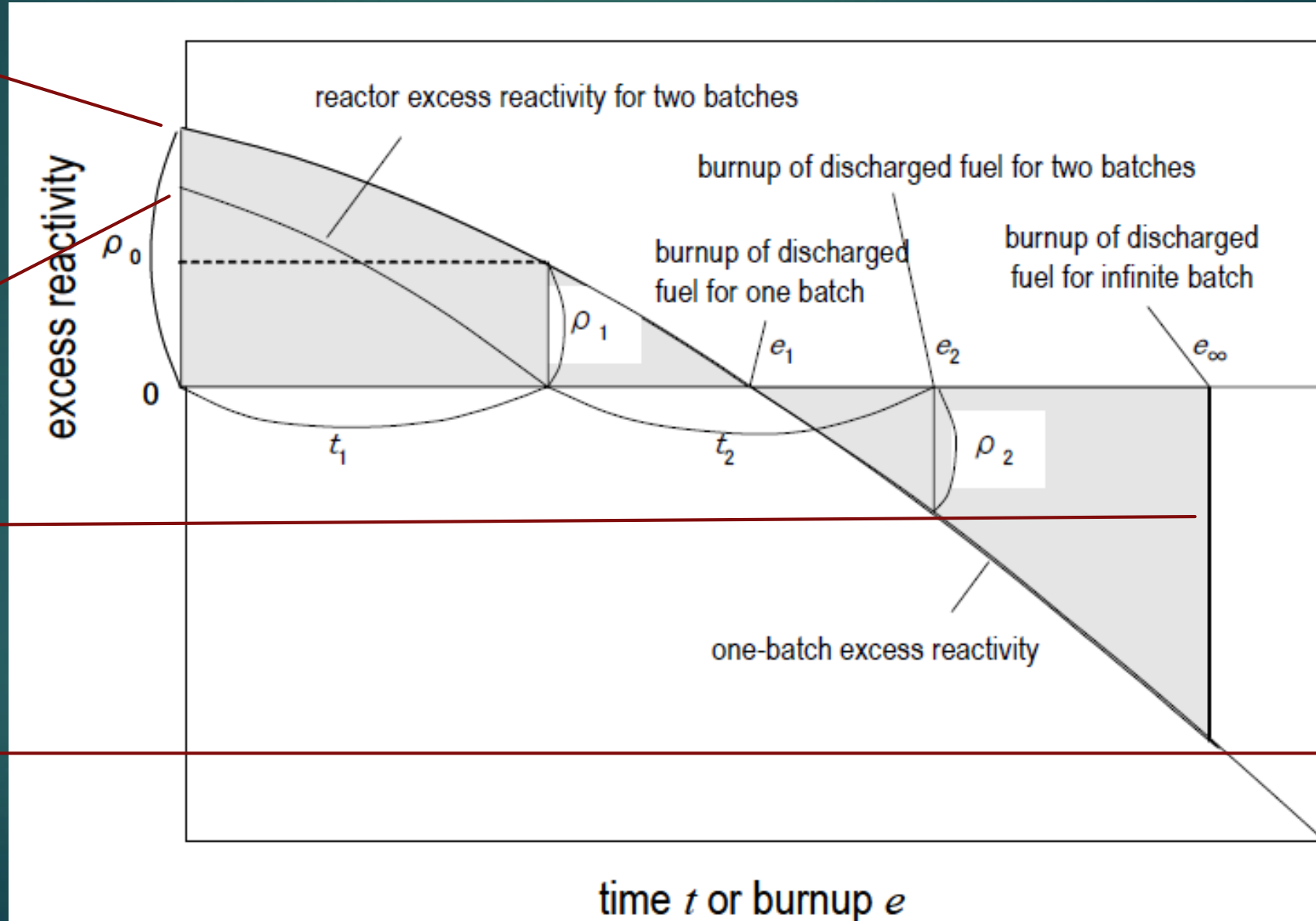
More than one batch?

Excess reactivity for one batch

Excess reactivity for two batches

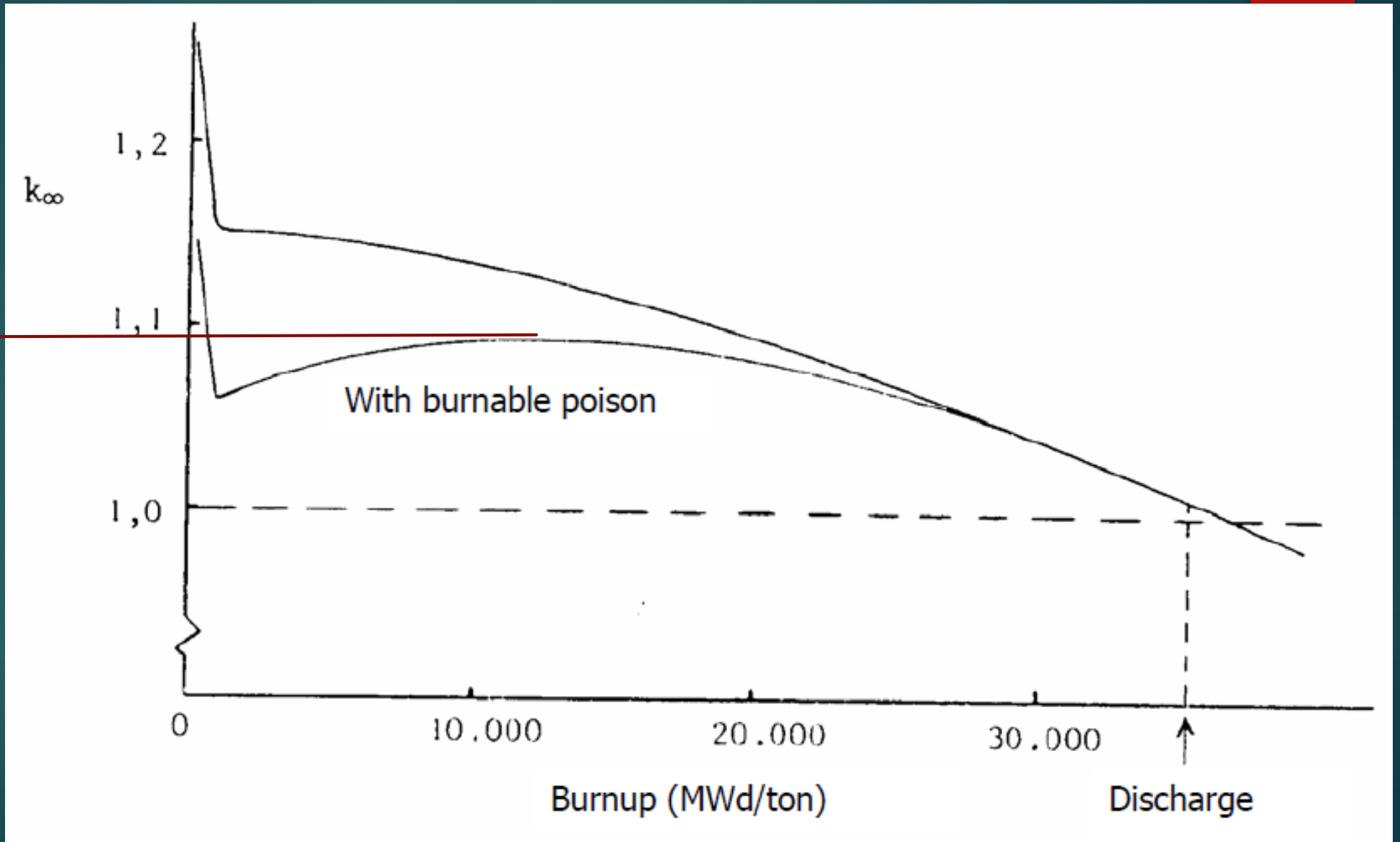
If only one could refuel on the fly...

Maximal level of control system action



Actual Light-water Reactor Burnup

Mixing-in
Poison
Moderates
Reactivity



Control System Components and Strategies

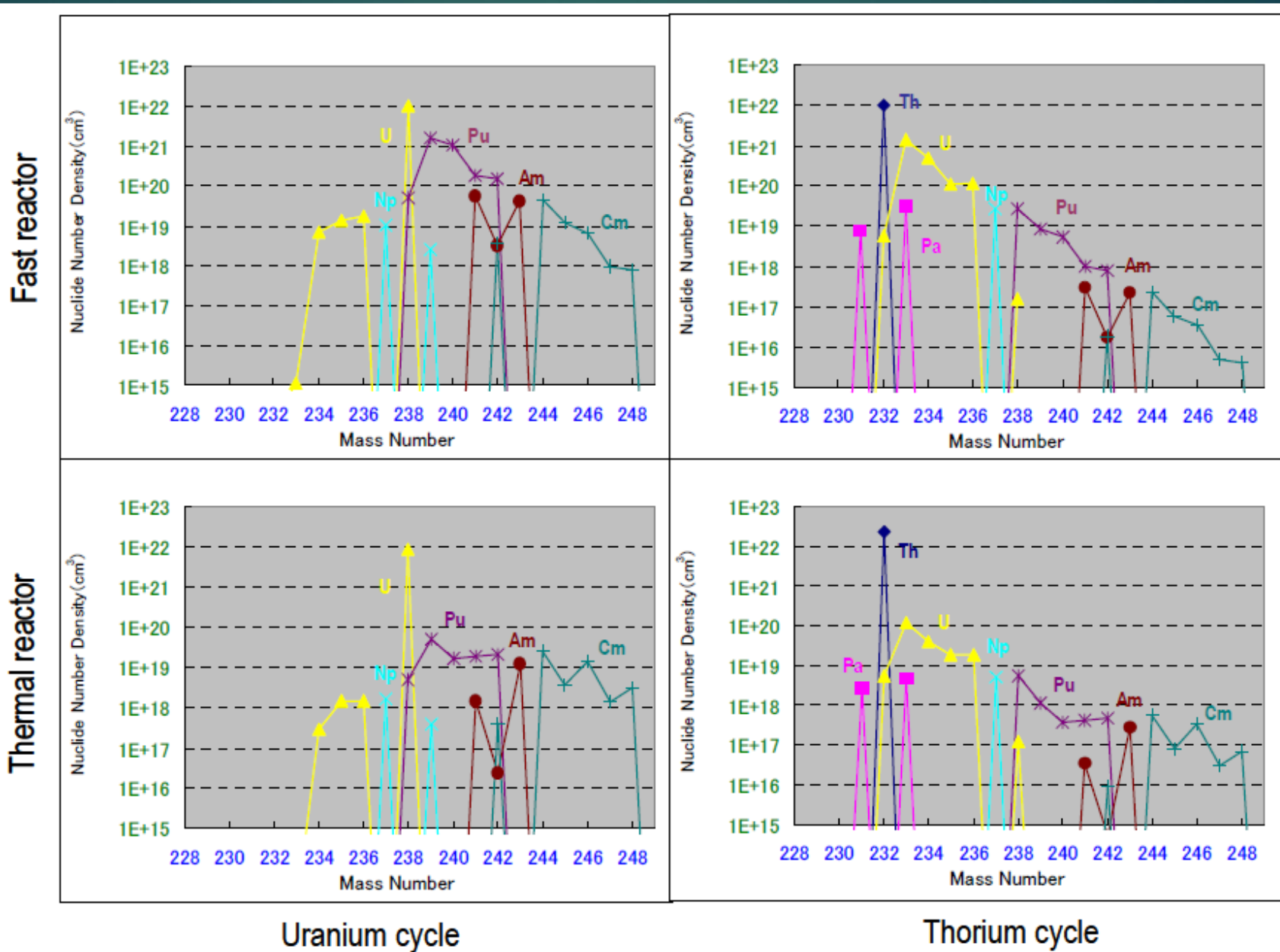
- ▶ Doppler Effect (temperature expansion, spectral shift, resonance absorption)
- ▶ Moderator rods (we have been there before)
- ▶ Reflector rods (cladded Be)
- ▶ Absorber rods (^{10}B , Hf, Cd) – B in stainless steel or as B_4C , Cd is alloyed with Ag or In, Hf is often alloyed
- ▶ Boric Acid – $\text{B}(\text{OH})_3$ – added into the moderator fluid in a rather controlled manner, for homogenous neutron absorption control
- ▶ Moving fuel – likely the most risky possibility – possible with liquid fuel reactors
- ▶ Burnable poisons – B, Cd, etc. mixed with the fuel

- ▶ Haling principle – create and maintain a constant power distribution during the burn cycle (including start-up, refuelling and fuel redistribution)

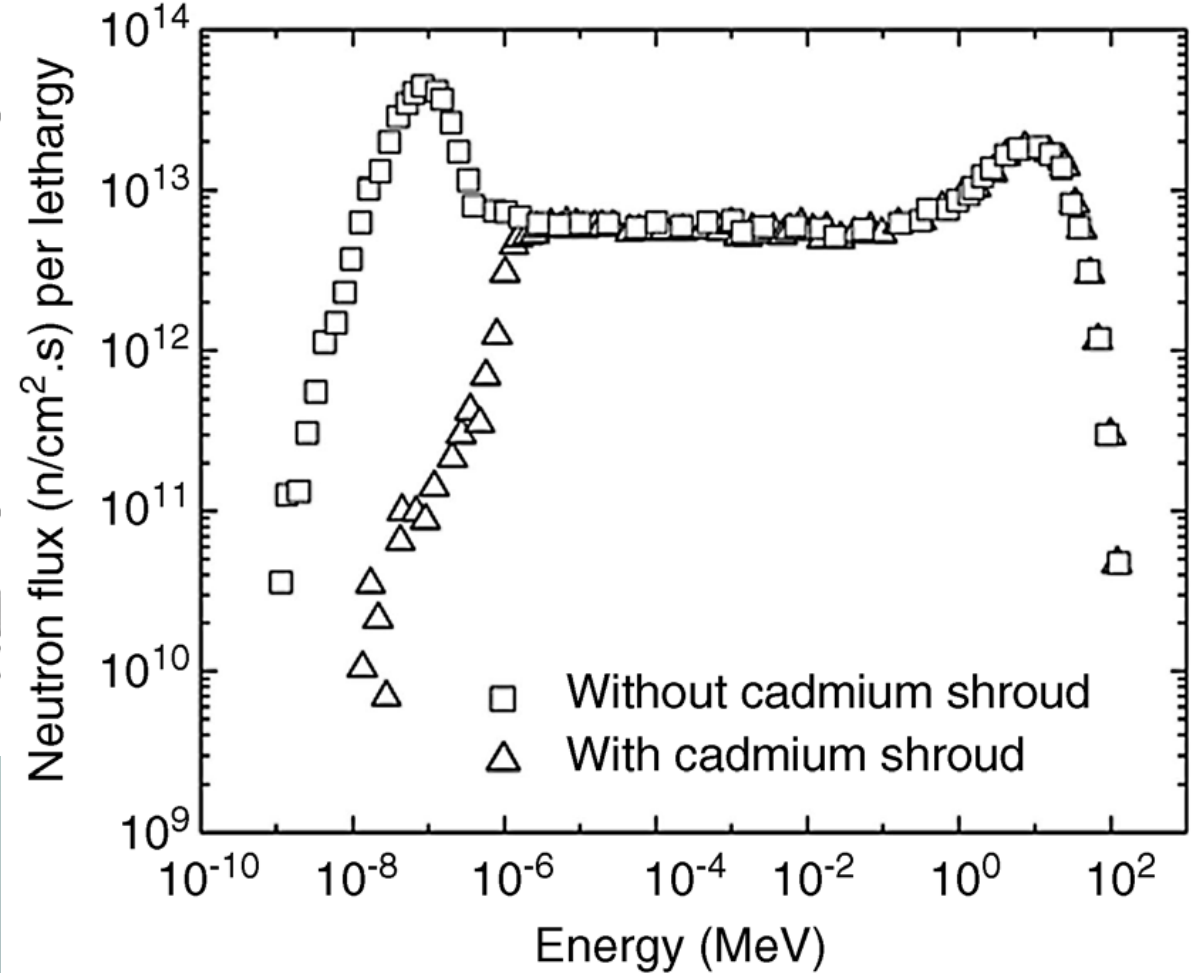
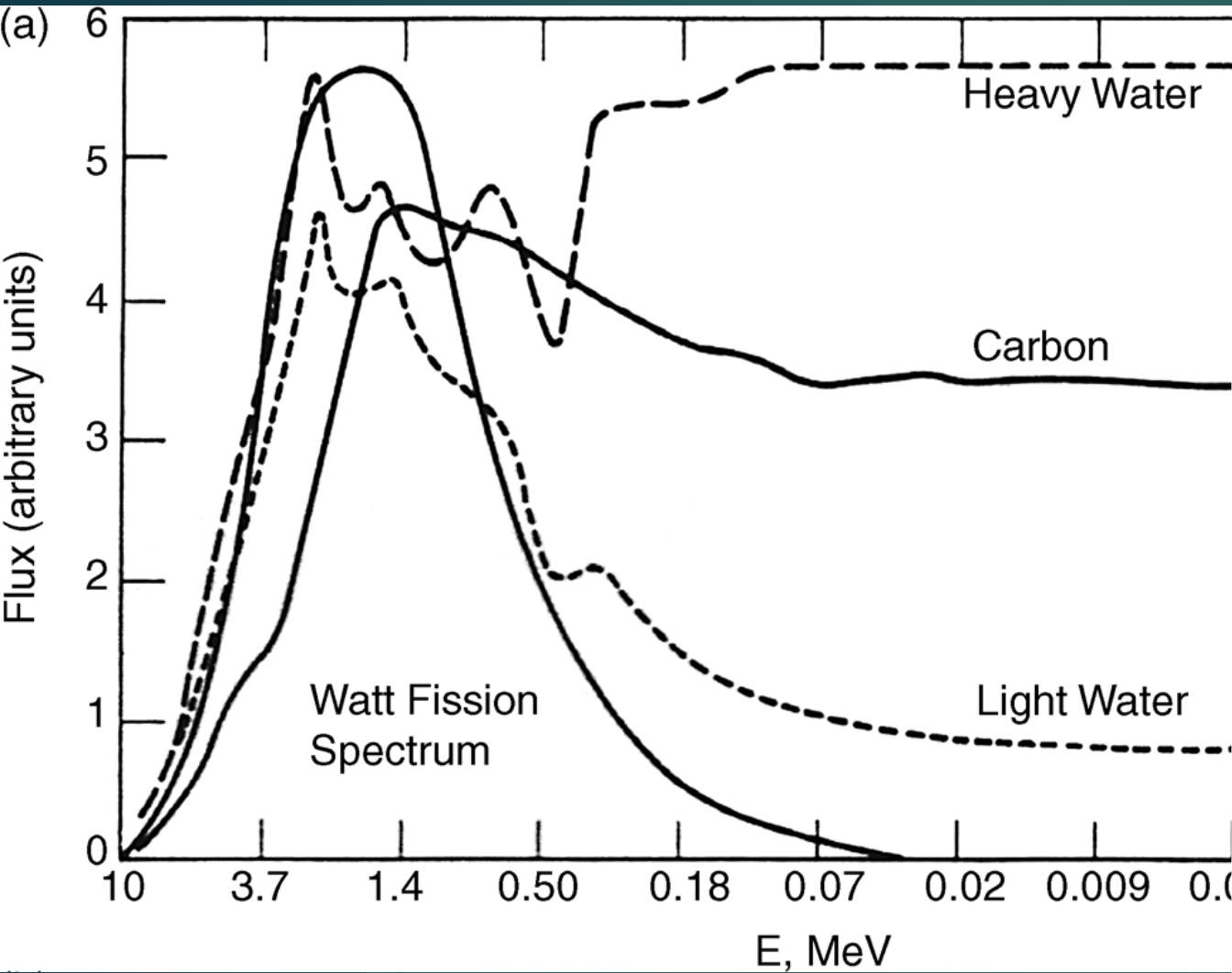
Two Examples of Reactivity Choices

Reactor type	PWR Borssele	BWR Gundremmingen
Average nuclear fuel enrichment in new core (% ^{235}U)	2.8	2.22
k_{eff} of new core	1.28	1.26
Reactivity effects during operation (Δk in %)		
poisoning (Xe + Sm)	4	4.0
temperature effect	7	1.4
bubble formation	-	1.6
burn-up	16	18.0
Reactivity value of neutron absorbers for control (Δk in %)		
control rods	9	20
absorber plates	-	10
boric acid	23	-
boron salt injection for emergencies	-	18

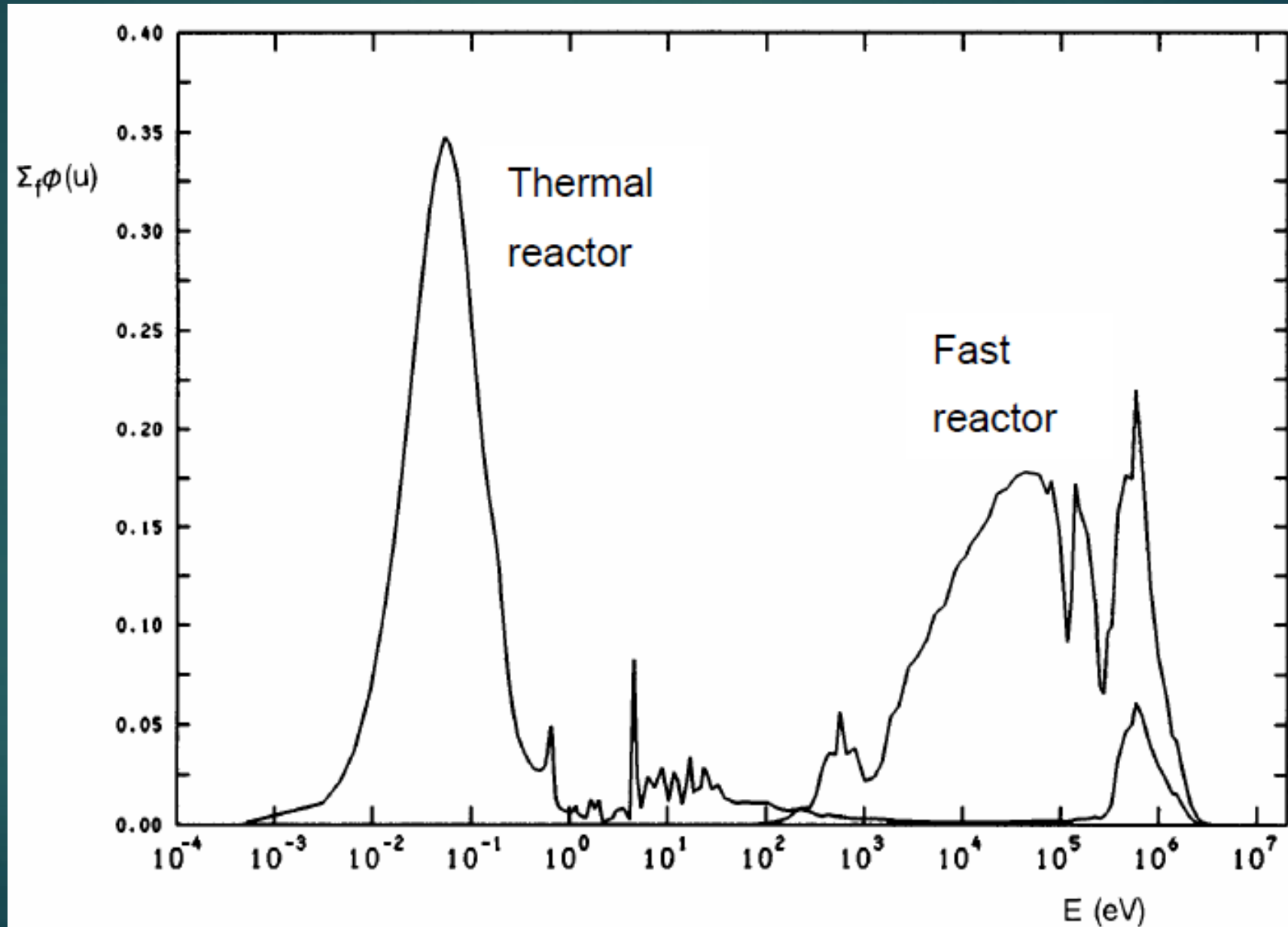
Equilibrium State Composition - Signatures



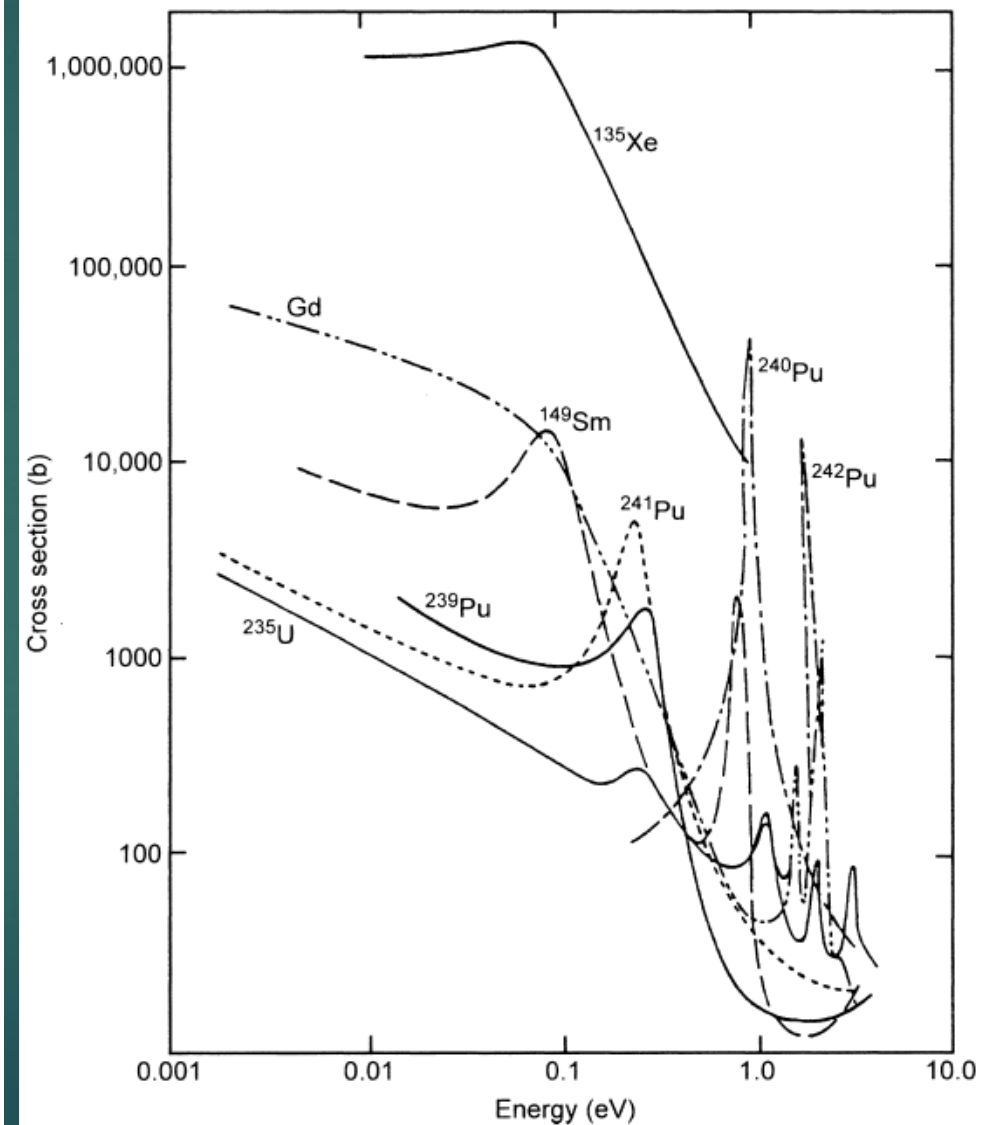
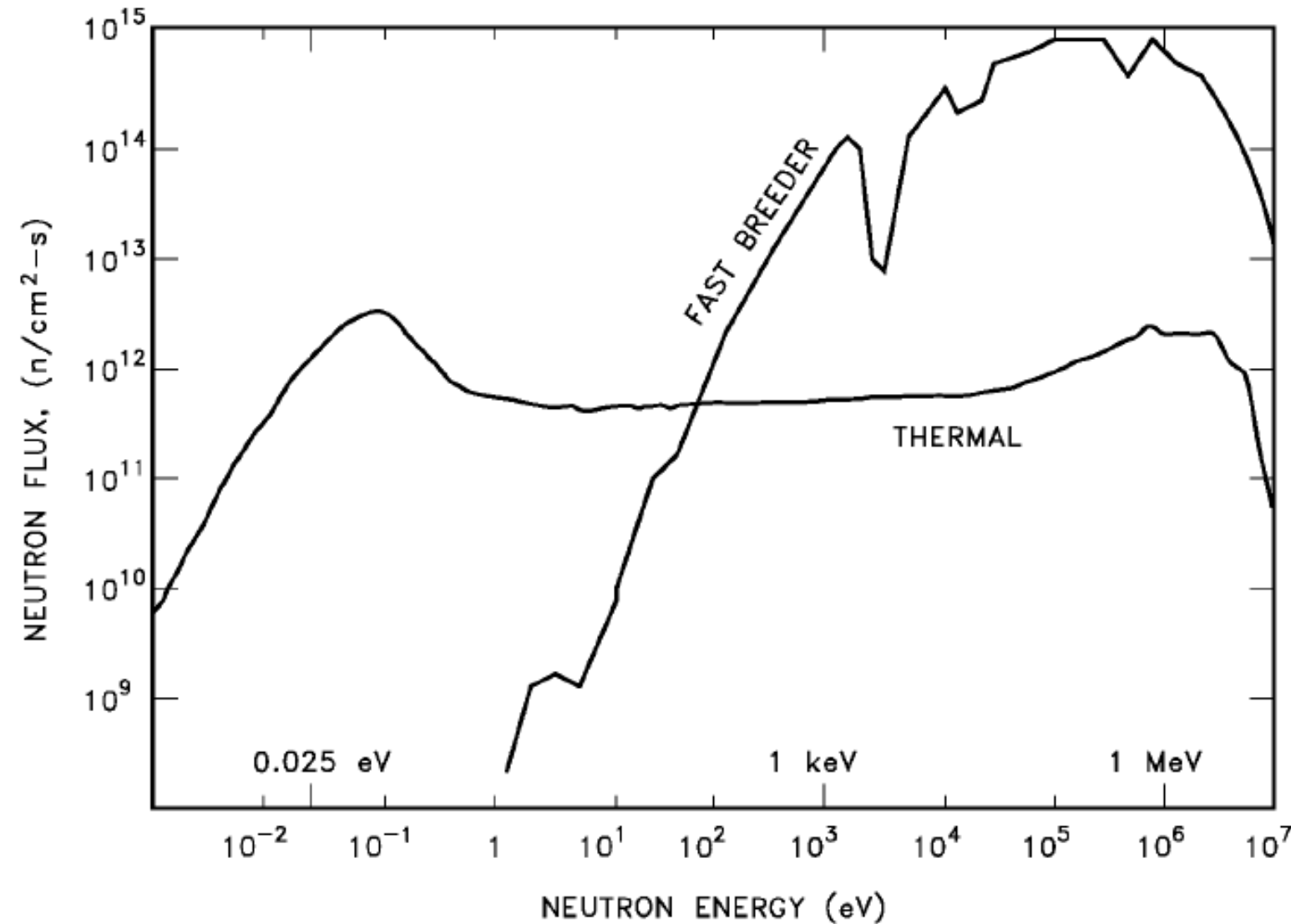
Idealized Neutron Flux and Shrouding



Fission Density



Neutron Spectrum of Actual Reactors



Nuclear Power Plant Evolution

The Evolution of Nuclear Power

Generation I

Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- WER/RBMK

Generation III

Advanced LWRs



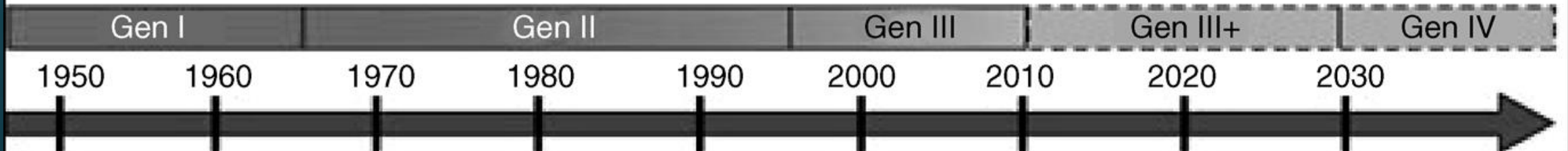
- ABWR, System 80+, AP600, EPR

Generation III+

Generation III Evolutionary Designs Offering Improved Economics

Generation IV

- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant



Modern BWR

Plant	
Core thermal power	3579 MWt
Electric output (gross/net)	1269/1233 MWe
Plant efficiency	33.5%
Core	
Active core height	3.76 m
Core diameter	4.65 m
Fuel inventory	138-t UO ₂
Number of fuel assemblies	748
Assembly pitch	15.2 cm
Rod pitch	1.63 cm
Average power density	56 kW/liter
Fuel	
Fuel material	UO ₂
Enrichment	Average 2.8% ²³⁵ U (initial core 1.77-2.1%)
Pellet dimensions (diam x height)	1.06 x 1.0 cm
Assembly array	8 x 8 with fuel channel around fuel rods
Total number of fuel rods	46,376
Cladding material	Zircaloy-2
Cladding outer diameter	1.25 cm
Cladding thickness	0.86 mm
Control	
Number of control rods	177
Material	Boron carbide (B ₄ C)
Control rod type	"Cruciform" blades inserted hydraulically from below between sets of four assemblies
Other control systems	Use of burnable poison
Vessel	
Material	SA533 (or 533B) manganese molybdenum nickel steel with an inner layer of cladding 3 mm of austenitic stainless steel
Wall thickness	16.4 cm
Vessel height	21.6 m
Vessel inner diameter	6 m
Vessel weight (including head)	885 t approximately

Coolant	
Material	Ordinary water (H ₂ O)-two phase
Pressure	7 MPa
Number of recirculation loops	2
Core coolant flow	13.2 Mg/hr
Core coolant outlet temperature	288°C
Core coolant inlet temperature	277°C
Feedwater flow rate	1.94 Mg/sec
Feedwater temperature	216°C
Average coolant exit quality	14.7% steam by weight
Fueling	
Type	Off-load, radial shuffling
Refueling sequence	1/3 of core every 18 months or 1/4 core every 12 months
Shutdown for refueling	60 days
Annual spent fuel discharge	32 t/yr
Design fuel burnup	28,400 MWd/t at equilibrium

Modern PWR

<i>Plant</i>		
Thermal power		3425 MWt
Electric output (gross/net)		1150/1100 MWe
Efficiency		33%
<i>Core</i>		
Active core (or fuel rod) height		3.7 m
Core diameter (equivalent)		3.4 m
Fuel inventory		101-t UO ₂
Number of fuel assemblies		193
Assembly pitch		30.4 cm
Rod pitch		1.26 cm
Average core power density		104.5 kW/liter
<i>Fuel</i>		
Fuel material		UO ₂
Enrichment		Three regions with 2.1, 2.6, 3.1%
Pellet dimensions (diam and length)		0.82 x 1.35 cm
Assembly array		17 x 17 (open type)
Total number of fuel rods		50,952
Cladding material		Zircaloy-4

Cladding outer diameter		0.95 cm
Cladding thickness		0.6 mm
<i>Control</i>		
Number of control clusters		53
Number of control rods per cluster		20
Absorber material		Ag – In – Cd
Absorber rod cladding		304 stainless steel
Control rod type		Cylindrical rods assembled into clusters inserted from above
Other control systems (first core)		Burnable poison rods, borosilicate glass
<i>Vessel</i>		
Material		SA533, Mg – Mo – Ni steel inner cladding
Wall thickness		21.9 cm
Vessel dimension (diam and height)		4.4 x 12.6 m
<i>Coolant</i>		
Material		Ordinary water (H ₂ O)-liquid phase
System pressure		15.5 MPa
Number of loops/steam generators		4
Mass flow		15.9 Mg/sec
Core inlet temperature		298°C
Core outlet temperature		326°C
<i>Fueling</i>		
Type		Off-load, radial shuffling
Refueling sequence		1/3 of core every 12 months
Shutdown period		30 days
Annual spent fuel discharge		30.4 t
Design fuel burnup		33,000 MWd/t