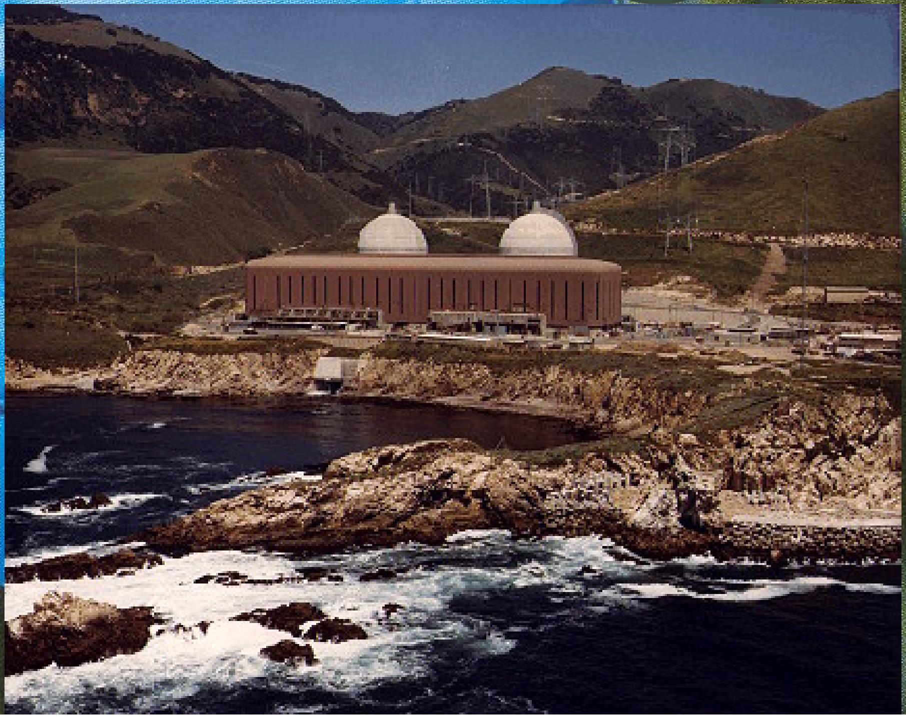
NuclEnergy

Nuclear Energy



Prevalence of Nuclear Fission Energy

Einstein: equivalence mass = energy **E = Mc²**

$$M\left({}^{235}U\right) = 47\,mg \xrightarrow[fission]{\Delta M = M \times 10^{-3}} \Delta E = 47\,\mu g \cdot c^2 \approx 4 \cdot 10^9\,J$$

$$M\left(TNT\right) = 1\,t \xrightarrow[combustion]{\Delta M = M} \Delta E \approx 4 \cdot 10^9\,J$$

1 GWe → 800,000 inhabitants

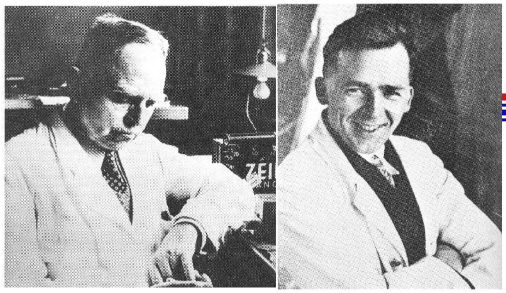
US: 18% of electric power generated by (103) nuclear plants

Average world wide: 17%

France: 80 %

Highly politically founded nuclear power preferences

- Coal/oil producing countries (USA, UK, Germany, ..) anti-nuclear
- Countries without coal/oil resources (France, Japan, India,..) pro-nuclear



n-Induced Nuclear Fission

1938: Otto Hahn
Fritz Straβmann
Lise Meitner, Otto Frisch

$$\boxed{{}^{235}U + n_{th} \rightarrow {}^{236}U^{*} \rightarrow 2\,FF + 2(3)n + 200\,MeV}$$

$$Ex:\ {}^{235}U + n_{th} \rightarrow {}^{236}U^{*} \rightarrow {}^{147}La + {}^{87}Br + 2n$$

$\langle E_n \rangle_{th} = 0.025$eV

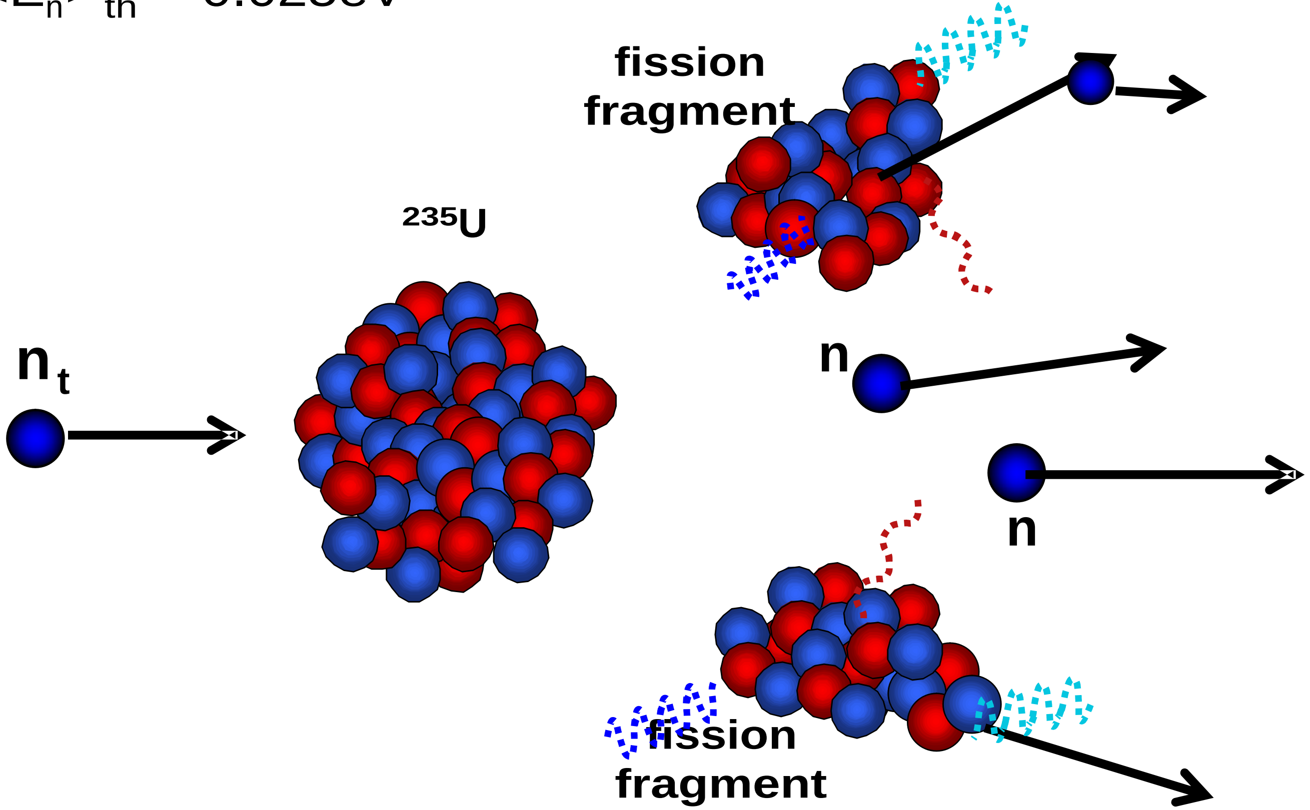
converts 0.1% of the mass into energy

1g ^{235}U/day = 1MW

10^8 x chemical energies

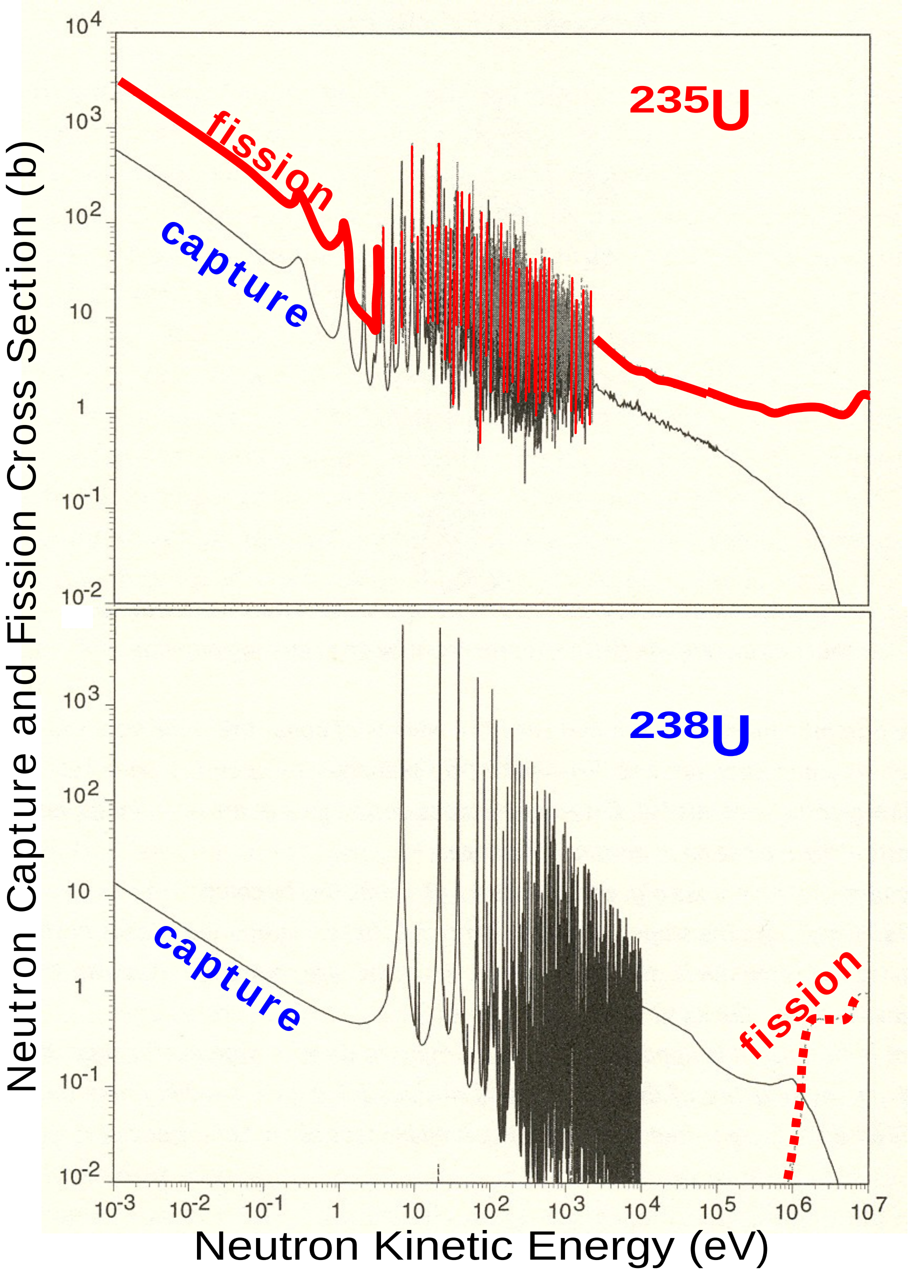
E_{ff} = 168 MeV
$E_{n\ tot}$ = 5 MeV
E_{γ} = 7 MeV
FF β-decay = 27 MeV

Q_{total} = 207 MeV



Neutrons:
$\langle m_n \rangle = 2.5 \pm 0.1$
neutron energies
$\langle E_n \rangle \approx 2$MeV

n-Capture and Fission Cross Sections



^{nat}U: 99.3% ^{238}U, 0.7% ^{235}U

Fission cross sections

^{238}U: $\sigma_f \sim$ b for $E_n > 1$ MeV

$\approx$ 0b for $E_n < 1$ eV

dominating: scattering (~8b) + capture

^{235}U: $\sigma_f \sim$ b for $E_n > 1$ MeV

$\sim 10^3$ b for $E_n < 1$ eV

dominating: (n,f) fission

Observed fission due to ^{235}U

→isotopically enrich ^{235}U (4% for reactors)

How to induce a self-sustaining fission reaction?

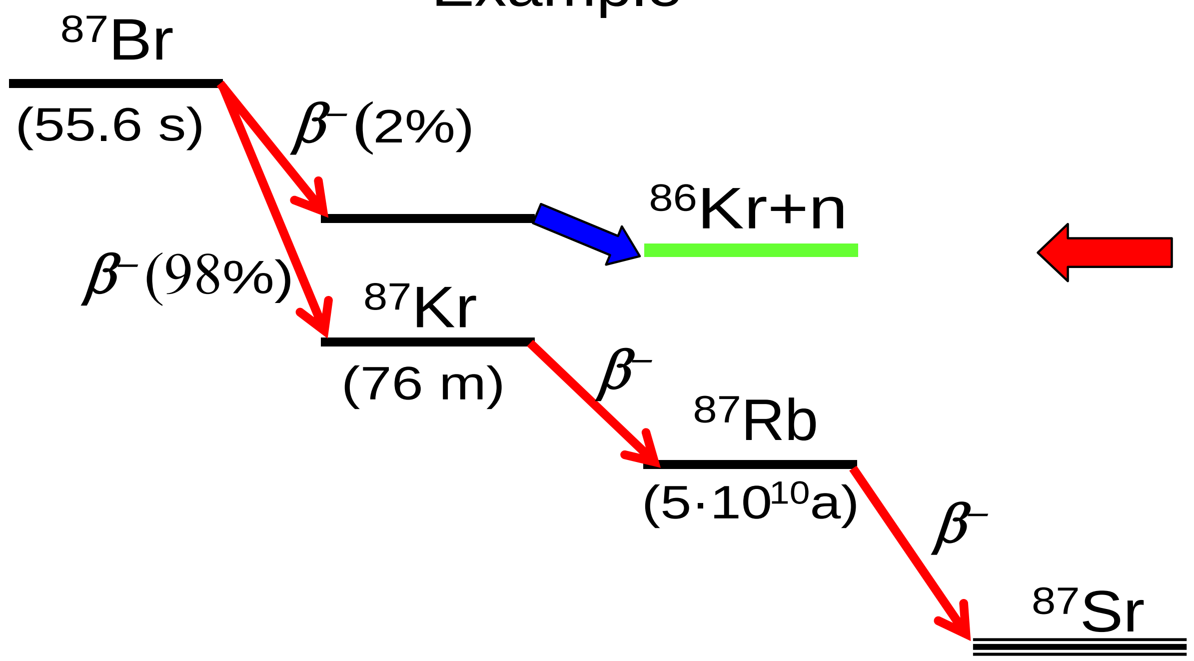
Recycle fission neutrons!

β–Delayed Neutrons

87% of fission energy (200MeV) promptly in fission $\leq 10^{-14}$s
13% emitted in β-decays of fission fragments, range of life times → delayed emission of β^+, β^-, ν_e, γ, n

0.65% of neutrons from ^{236}U fission are delayed → control function

Example



β–delayed neutron
$\langle\Delta\tau\rangle \approx 80$ s

Natural Uranium Fission Probability

$$^{nat}U: \quad ^{235}U \big/ ^{238}U = 1/141$$

$$^{235}U: \ \sigma_f = 583\, b$$

$$^{235}U: \ \sigma_C = 98\, b \ \times \ abundance \quad (=1) = \ 98\, b$$

$$^{238}U: \ \sigma_C = 2.7\, b \ \times \ abundance \underline{(=141) = 381\, b}$$

$$\underline{\underline{\sigma_C = 381 b + 98 b = 479\, b}}$$

$$Probability \ \ for \ \ fission\, in \ ^{nat}U:$$

$$P_f = \frac{\sigma_f}{\sigma_f + \sigma_C} = \frac{583\, b}{583\, b + 479\, b} = 0.55$$

$$\rightarrow 45\% \ \ of \ \ (M_n = 2.4) \ fission \ neutrons \ lost \ to \ capture$$

$$\rightarrow M_{n,eff} \le 2.4 \times 0.55 = 1.32 \ neutrons \ available\, for\, fission$$

$$additional\, losses\, in\, reactors\, due \ to \ leakage, \ moderation$$

Canadian ^{nat}U reactor CANDU, 40 t ^{nat}U, moderator D_2O (heavy water).

^{239}Pu/ ^{233}U Breeding

$$^{238}U + n \rightarrow {}^{239}_{92}U \xrightarrow[t_{1/2}=23\,\mathrm{min}]{\beta^-} {}^{239}_{93}Np \xrightarrow[2.4d]{\beta^-} {}^{239}_{94}Pu\left(2.4\cdot 10^4\,a\right)$$

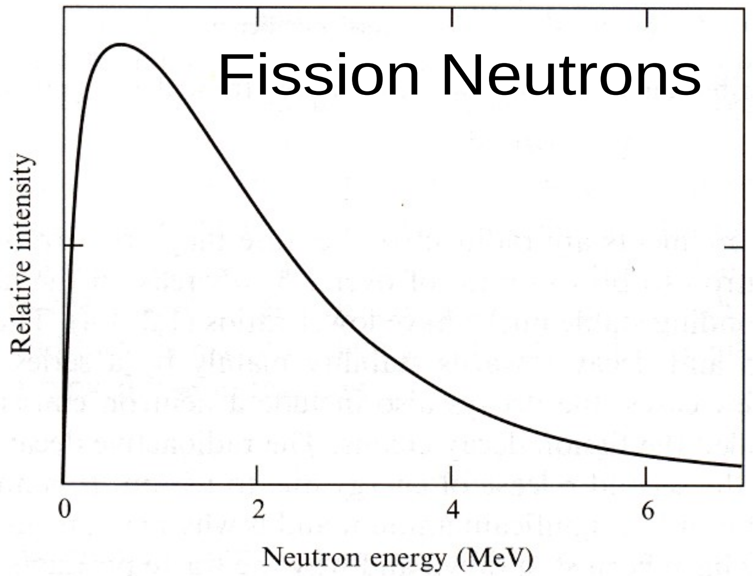
Occurs over broad energy range
thermal motion broadens capture resonances (Doppler Effect)
→ increased capture

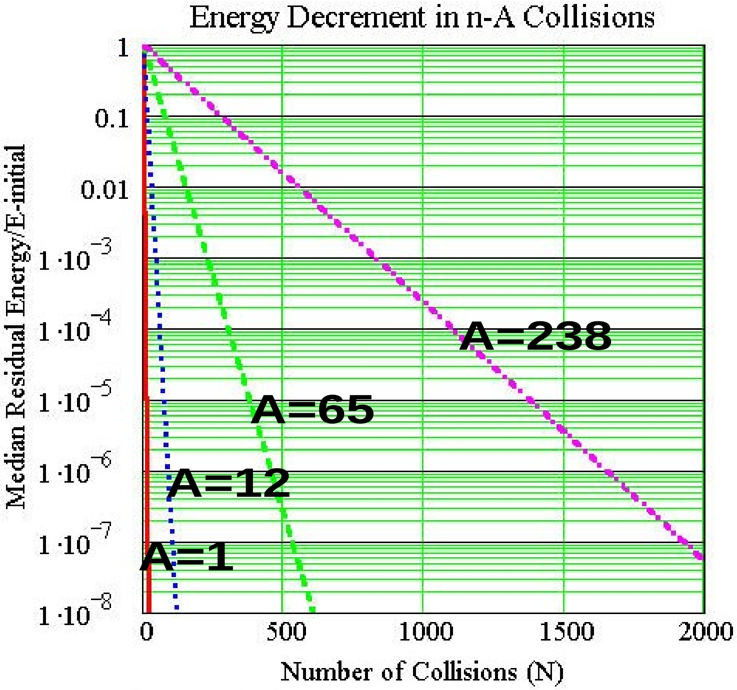
^{nat}U reactor: 1MW fission energy → 1g ^{239}Pu/day
6 kg needed for bomb

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow[t_{1/2}=22\,\mathrm{min}]{\beta^-} {}^{233}_{91}Np \xrightarrow[27d]{\beta^-} {}^{233}_{92}U\left(1.6\cdot 10^5\,a\right)$$

^{233}U also fissionable
Both ^{233}U, ^{239}Pu contribute to fission in a reactor

Neutron Moderation





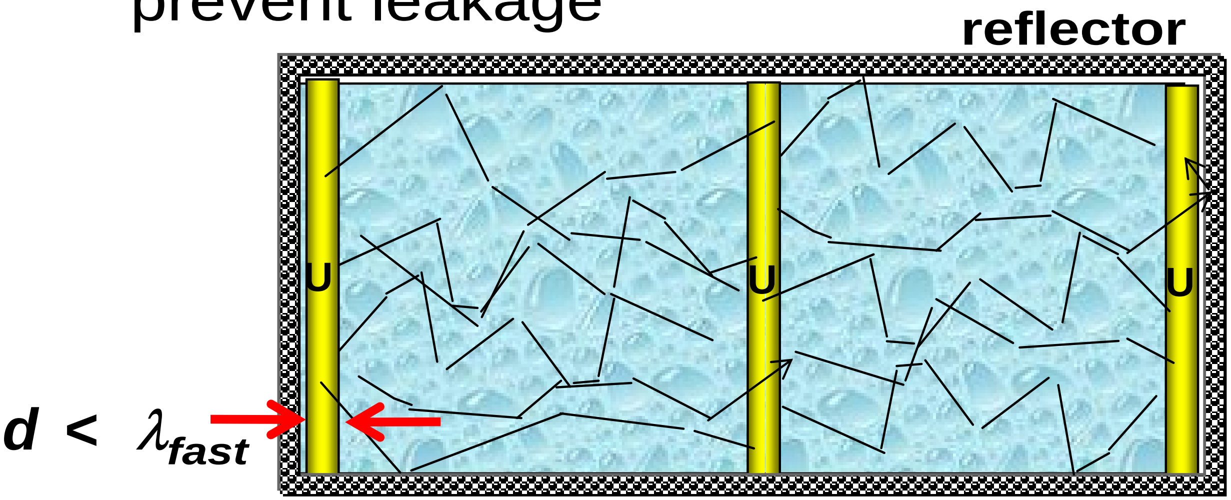
Fission neutrons too energetic, "thermalize" to maximize σ_f

→ multiple elastic scattering ("moderation")
moderator: small σ_{capt} !

Need: **$0.025eV / 2MeV = 10^{-8}$**

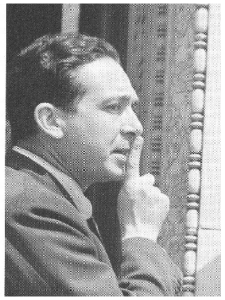
If possible, bypass ^{238}U capture domain ($2eV < E_n < 10keV$)

D_2O, Be, C(graphite), prevent leakage



W. Udo Schröder, 2004

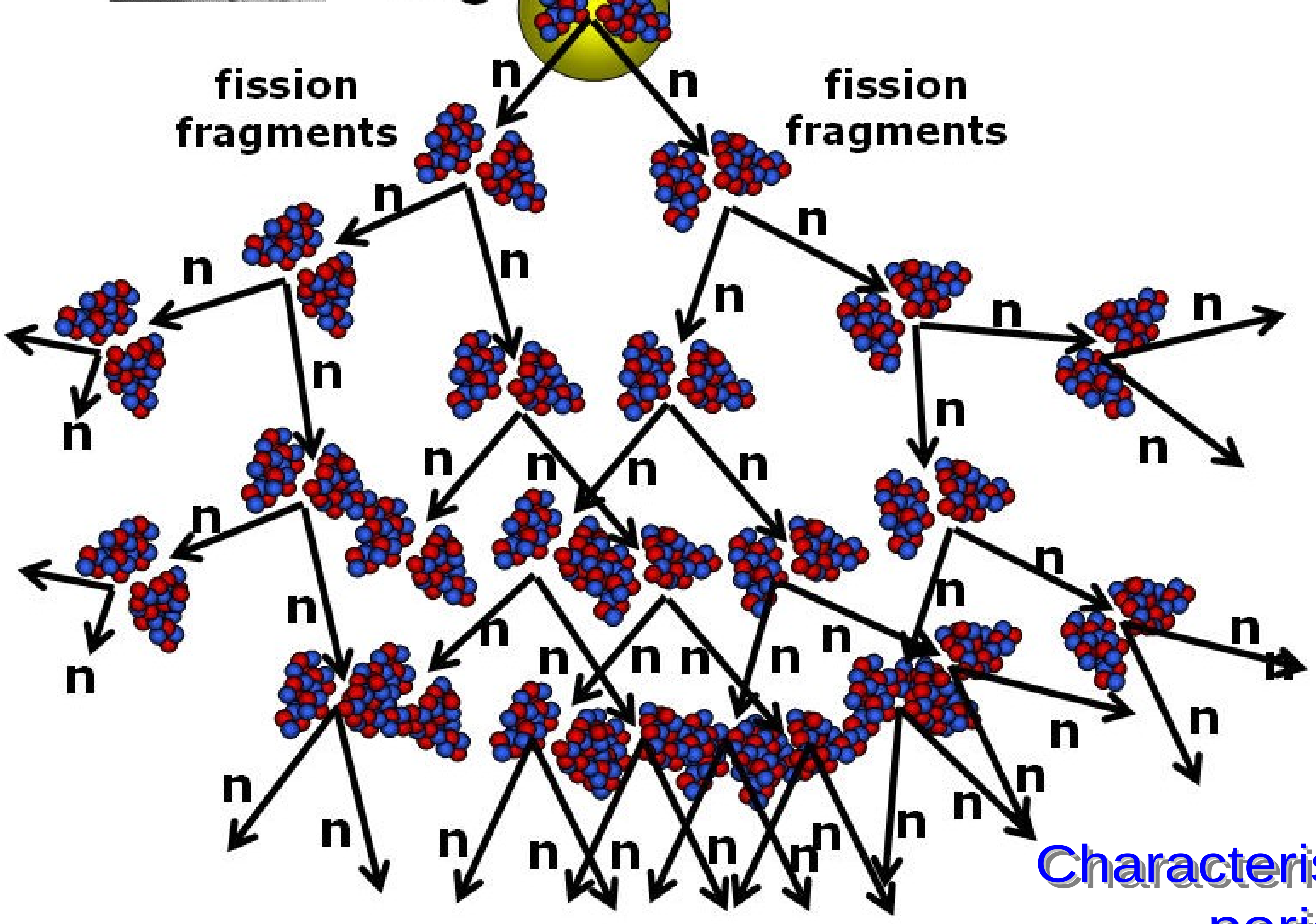
The Chain Reaction



Leo Szilard
1938

Neutron multiplication through fission *k=2.4*, minus losses (capture, leaking,..), → effective *k < 2.4.*

One n used in fission
→ effective multiplication ***k-1***:



$$\frac{dN_n}{dt} = \frac{1}{\tau}(k-1)N_n \rightarrow$$

$$\boxed{N_n(t) = N_n(0)\cdot e^{(k-1)t/\tau}}$$

k >1: exponential avalanche of f-neutrons
τ = time between gen's
(τ ~ 40μs in reactors
τ ~ ns in explosives)

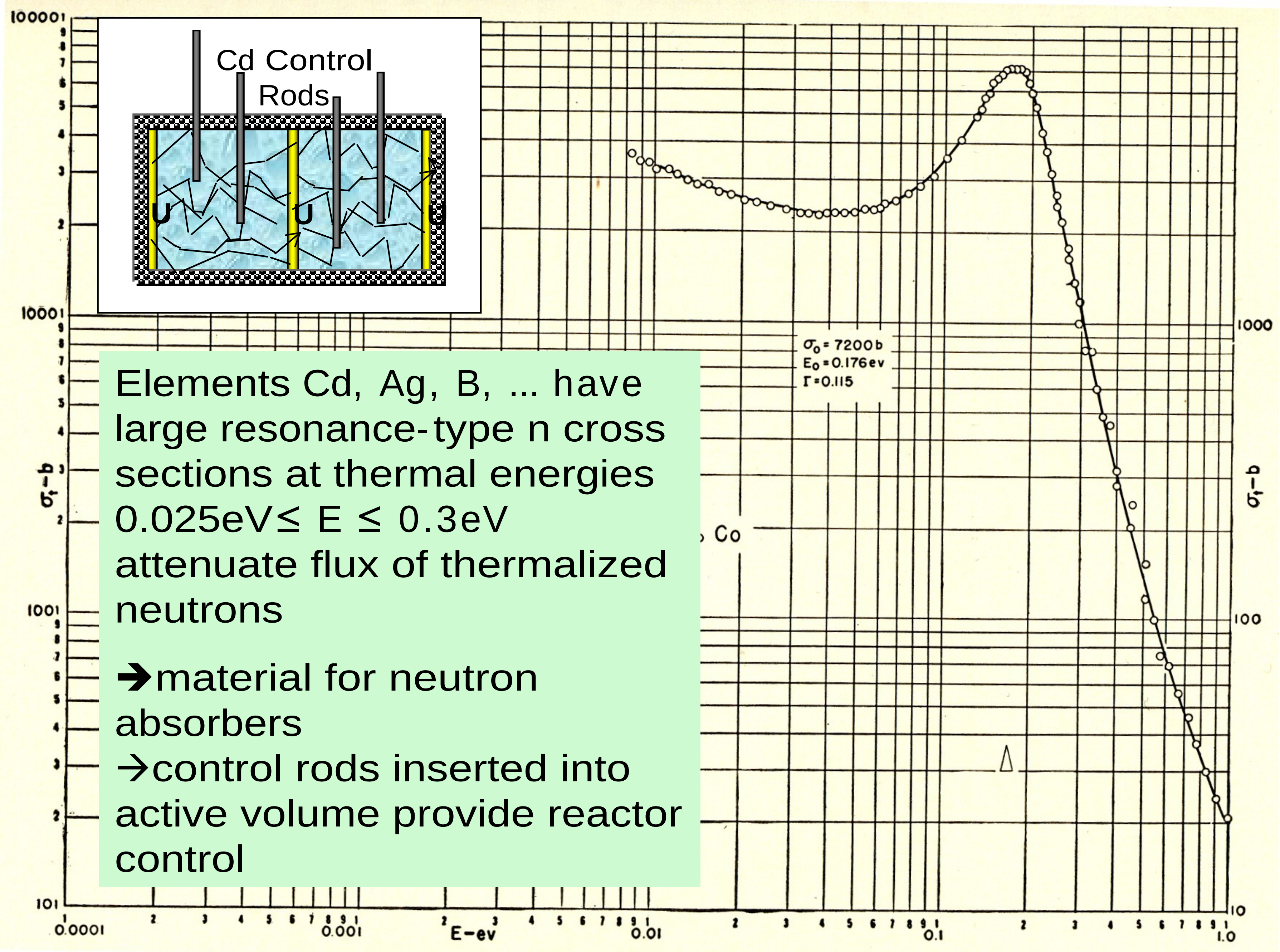
$$k_{eff} = k_{prompt} + k_{delayed}$$

Reactor Control

Characteristic period: $\boxed{T = \frac{\tau}{(k_{eff}-1)}}$

$k_{eff} \approx 1$
e.g., $k_{eff}=1.03$

Cd n-Capture Cross Section



Elements Cd, Ag, B, ... have large resonance-type n cross sections at thermal energies 0.025eV≤ E ≤ 0.3eV attenuate flux of thermalized neutrons

➔material for neutron absorbers
→control rods inserted into active volume provide reactor control

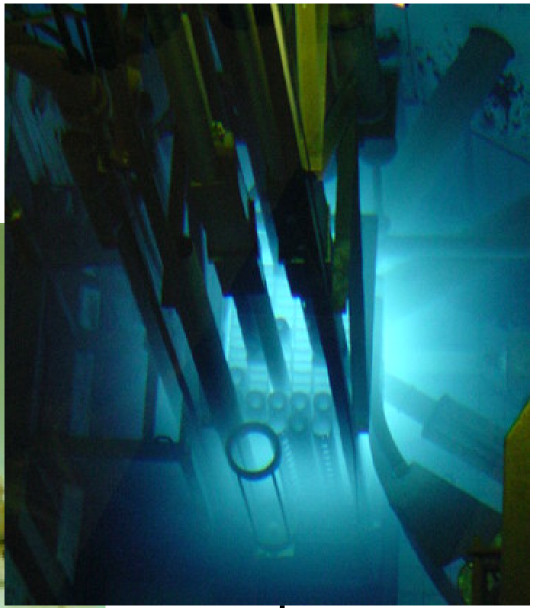
"Swimming-Pool" Research Reactors

side view of core

MM-Reactor: 2 MW nominal
low-enriched U,
light H_2O as moderator & coolant
n-flux= 1.10^{14} n/(s·cm$^{2)}$

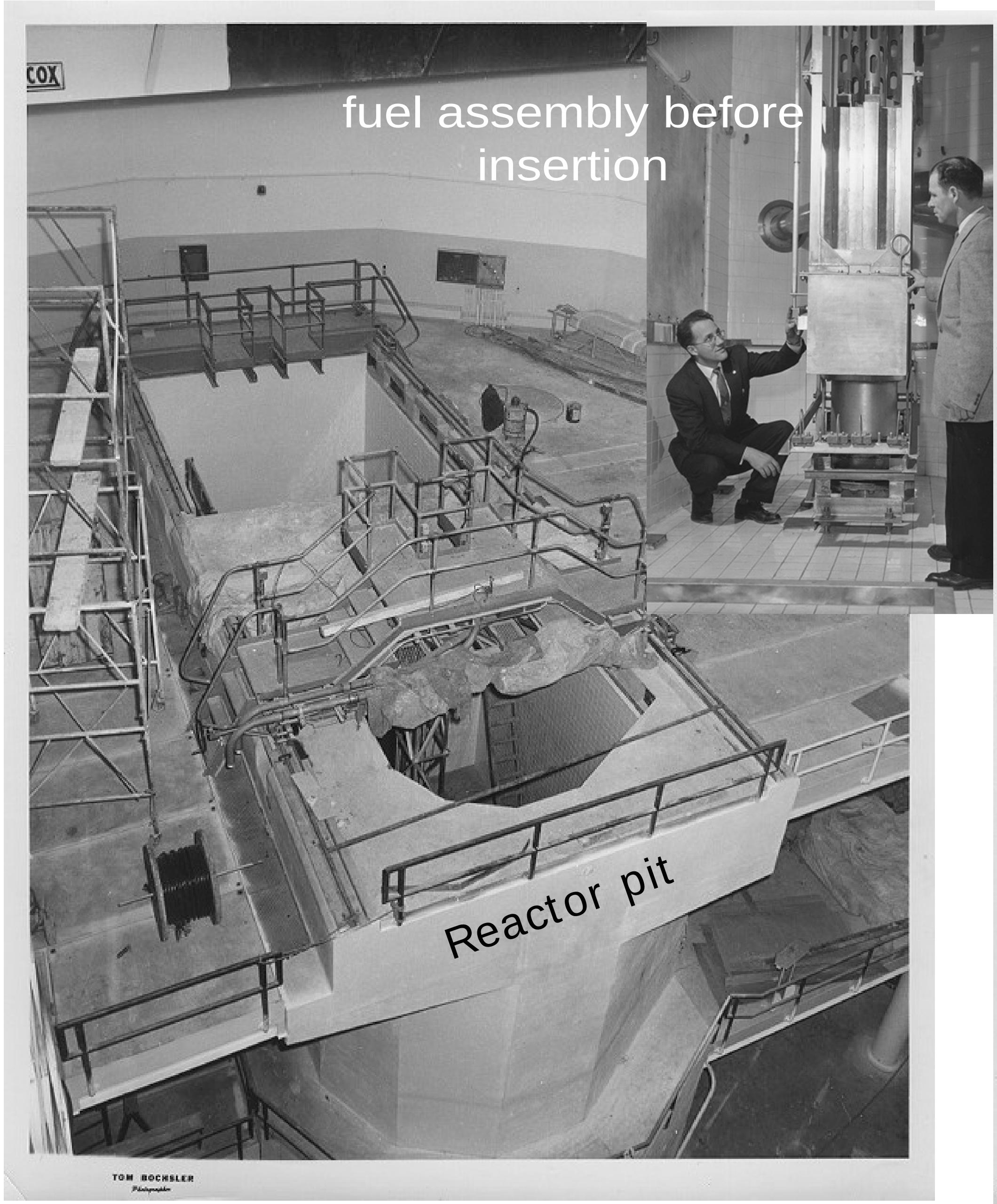
McMaster University Nuclear Reactor (1959-)

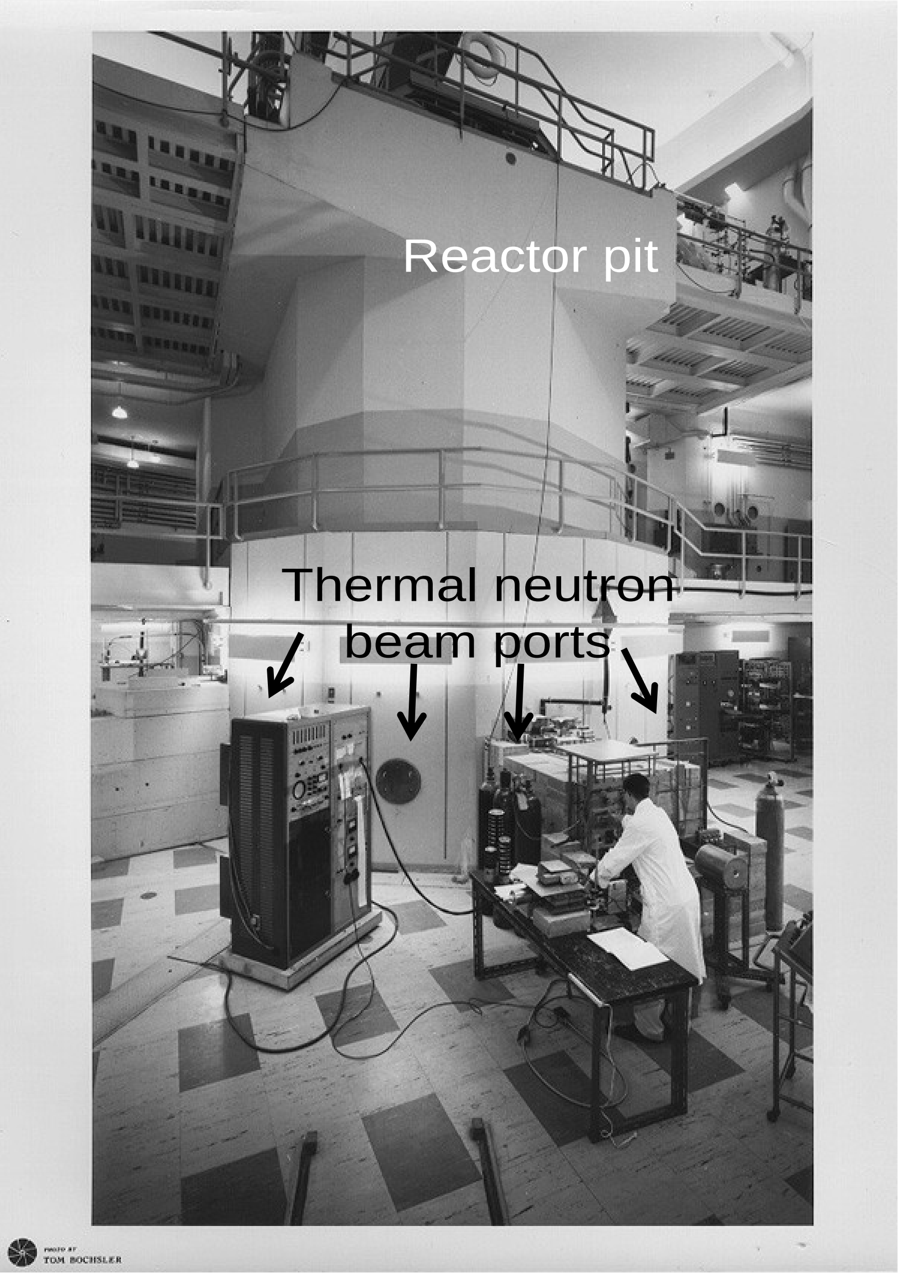
Reactor containment and fuel storage pool



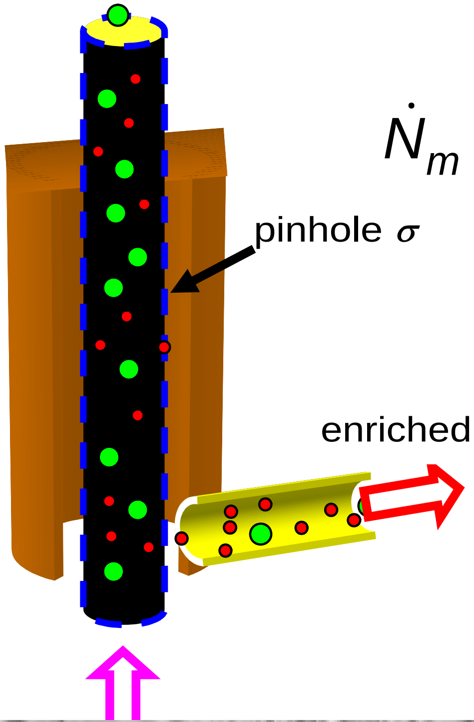
core in operation, Čerenkov light from β-decay electrons stopped in water

McMaster-Research Reactor Facility





Gas Diffusion Isotope Enrichment



$$\dot{N}_m \propto \langle |v_x| \rangle = \sqrt{\frac{k_B T}{2\pi m}}$$

$$\frac{\dot{N}_M}{\dot{N}_m} = \sqrt{\frac{m}{M}}$$

1.5% mass difference

Manhattan Project: Electromagnetic separation too expensive → Gaseous diffusion of UF_6 (^{19}F mono-isotopic)

Still used as main separation technique (also in France)

Laser ionization possible, uncertain economics

US: NPP (7TWh/a output) needs 250 GWh/a for enrichment

ORNL K-25 Gas diffusion plant (1/2 mi long) Manhattan Project

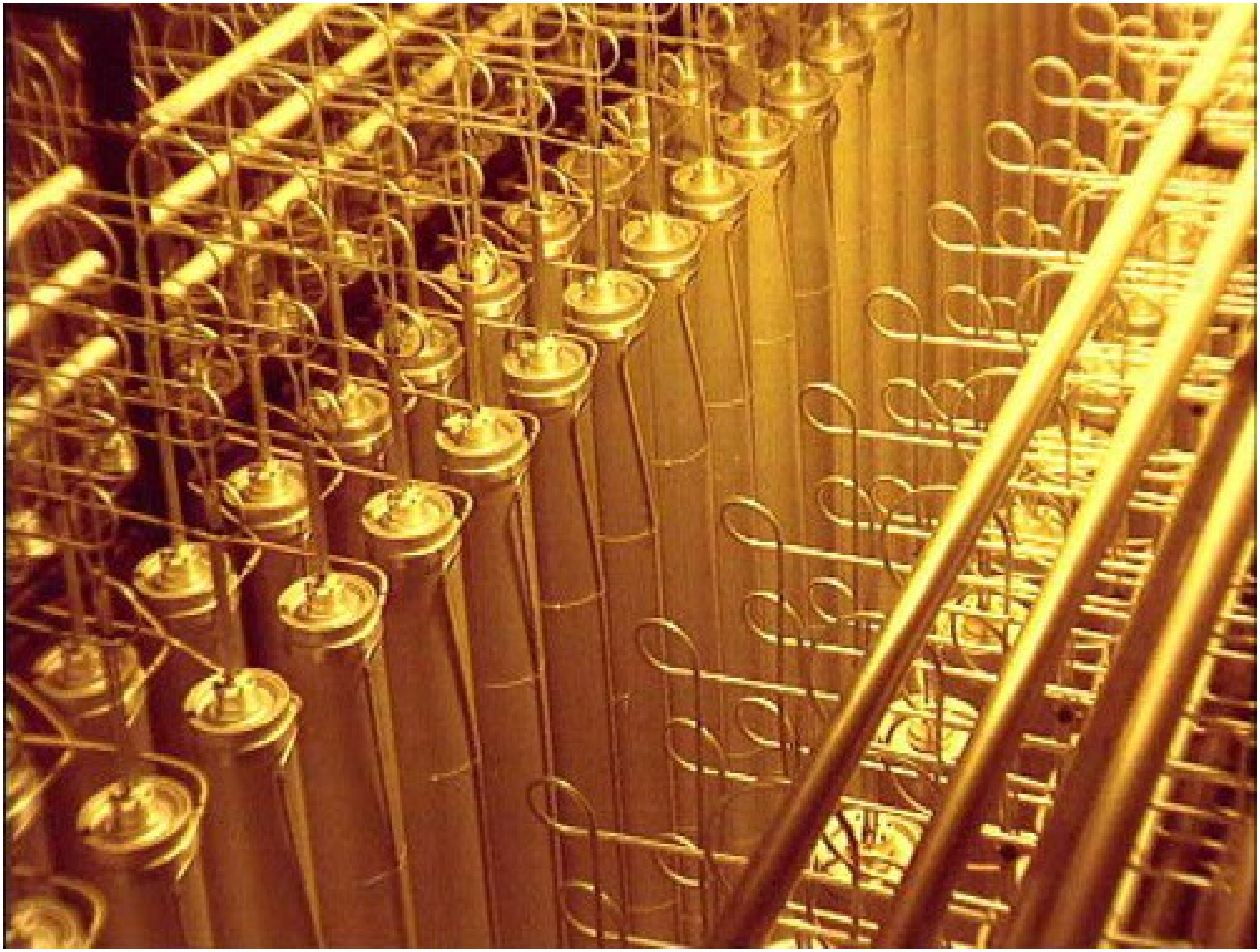
Paducah/KY Separation Plant

plant control room

cooling towers

Sedimentation-Gas Centrifuges

Modern separation methods used mostly in Europe, Asia, US test plant



Cylinders spin at 1.5km/s surface velocity → centrifugal forces produce different sedimentation rates

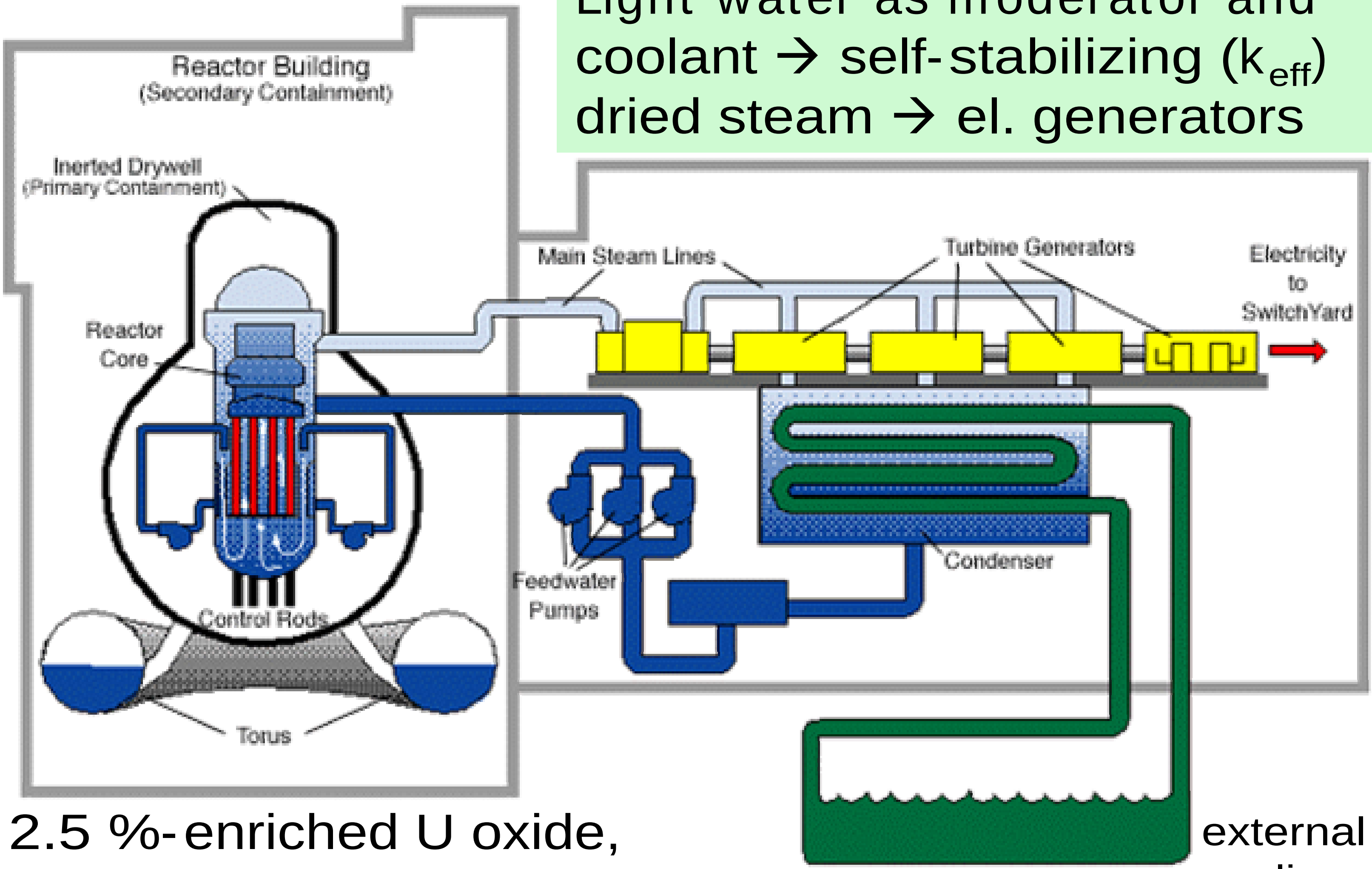
NPP (7TWh/a output) needs ≈ 6 GWh/a for enrichment

Layout of Nuclear Power Plant

EPR- Areva/Siemens

Boiling-Water Thermal Power Reactor

Light water as moderator and coolant → self-stabilizing (k_{eff})
dried steam → el. generators



1.7-2.5 %-enriched U oxide,
4 m x 5 m Ø: 140 t fuel
p=70 at(1000psi), 290^0C

external
cooling water
supply (river)

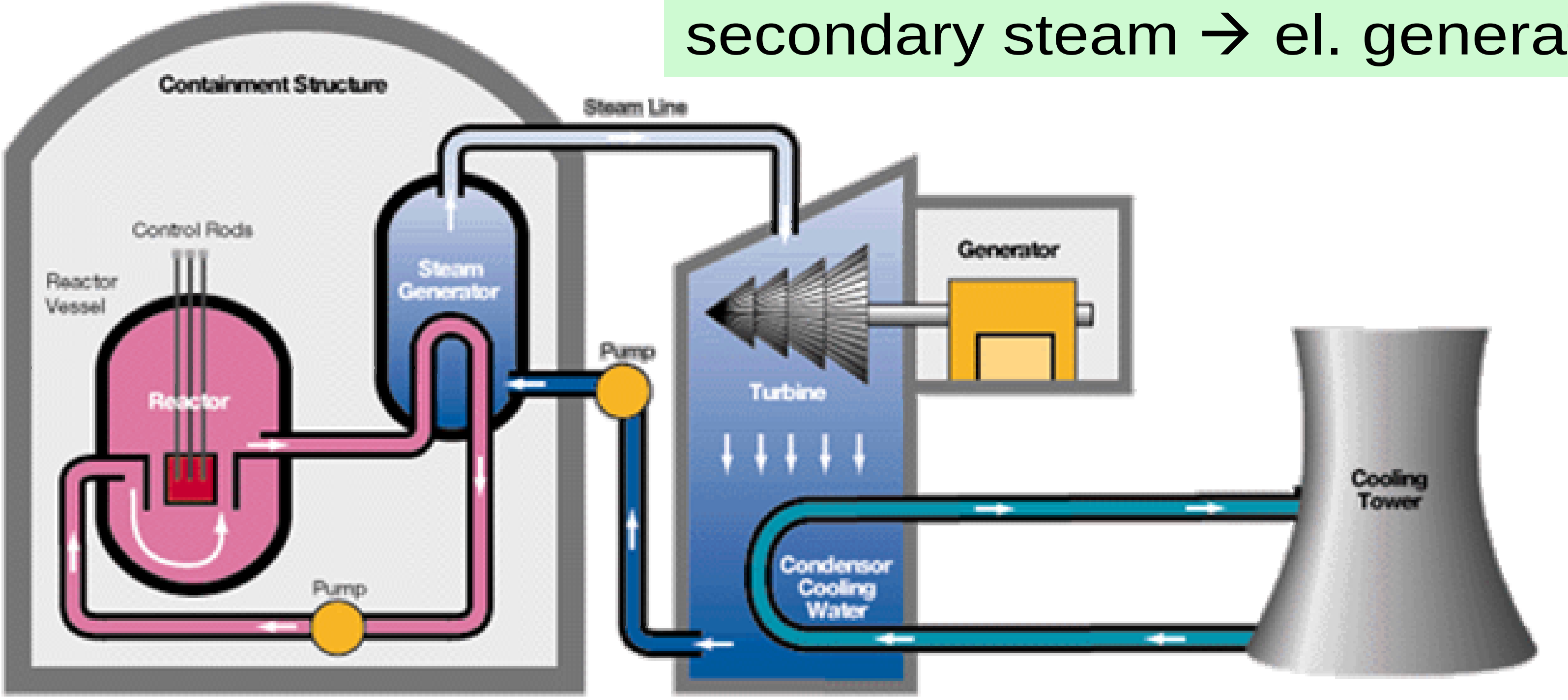
water caused corrosion
overall efficiency: 35%

Pressurized-Water Thermal Power Reactor

naval applications

Light water as moderator and primary coolant p ~ 160 bar (at)

secondary steam → el. generators



cooling towers

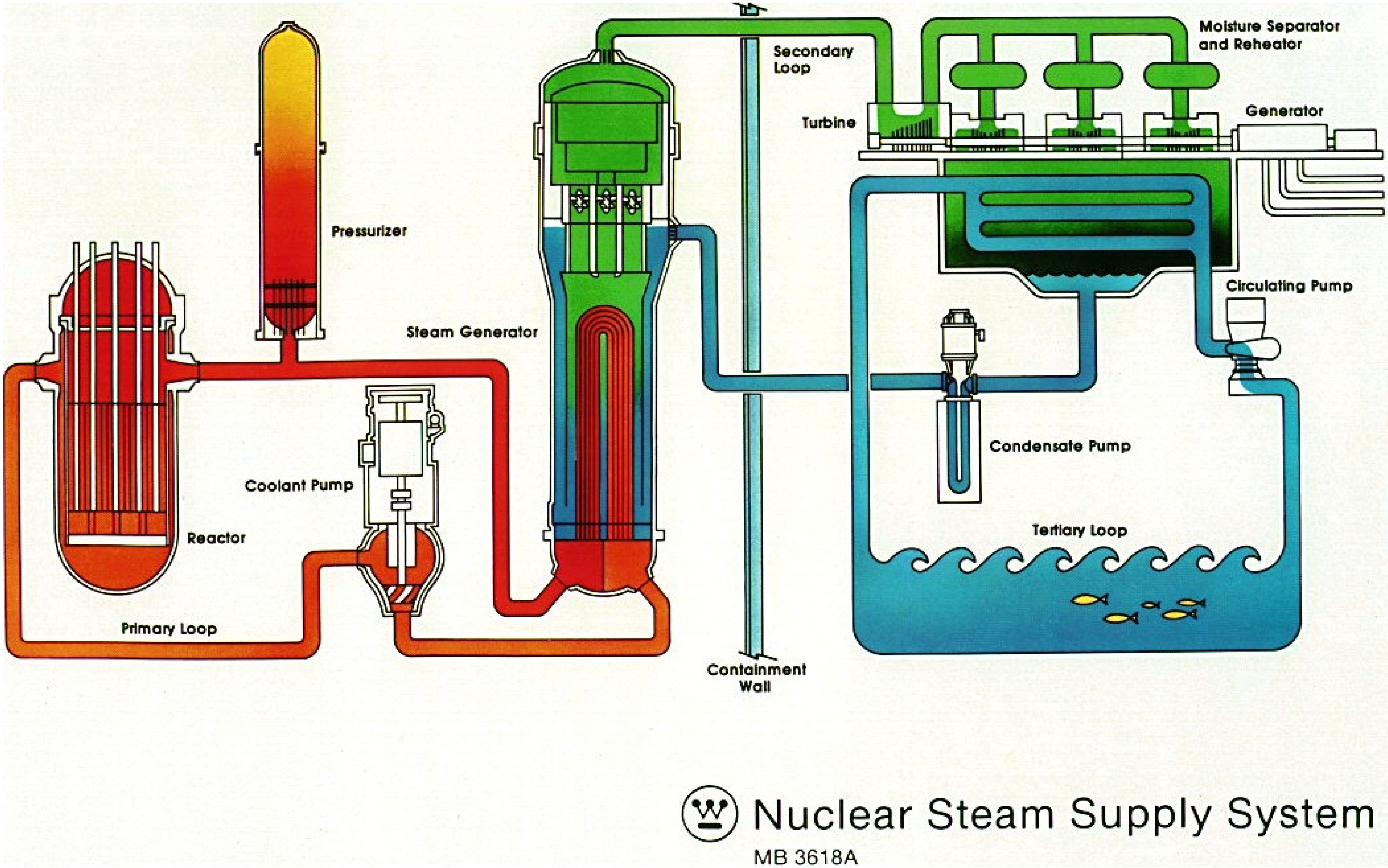
4.5 %-enriched UO_2 pellets.
core 3.5 m x 3.5 m Ø: 140 t fuel
p=160 bar (2300psi), 540^0C

efficiency 30-40%

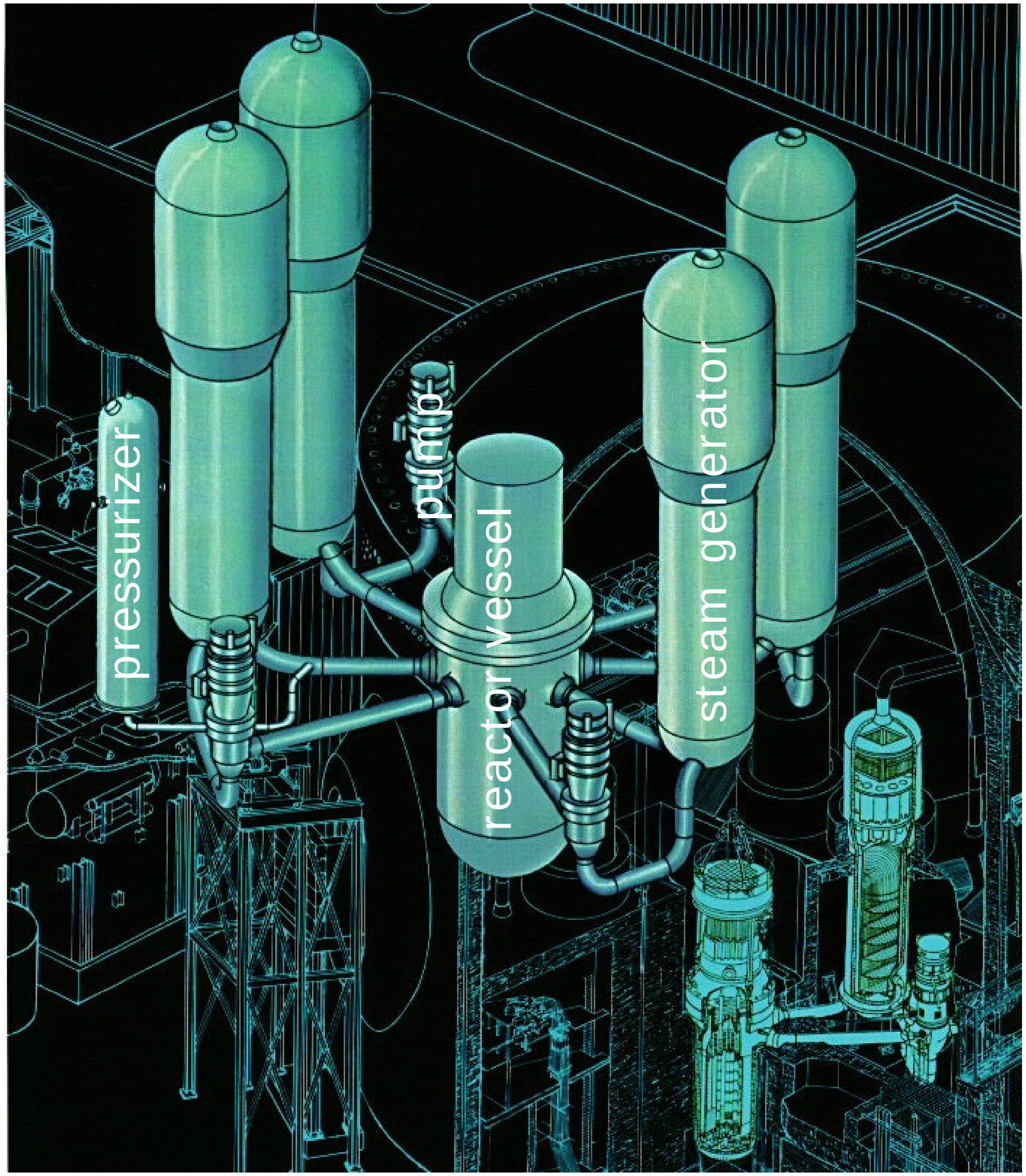
pressurizer tower 13.5m
4.4m Ø

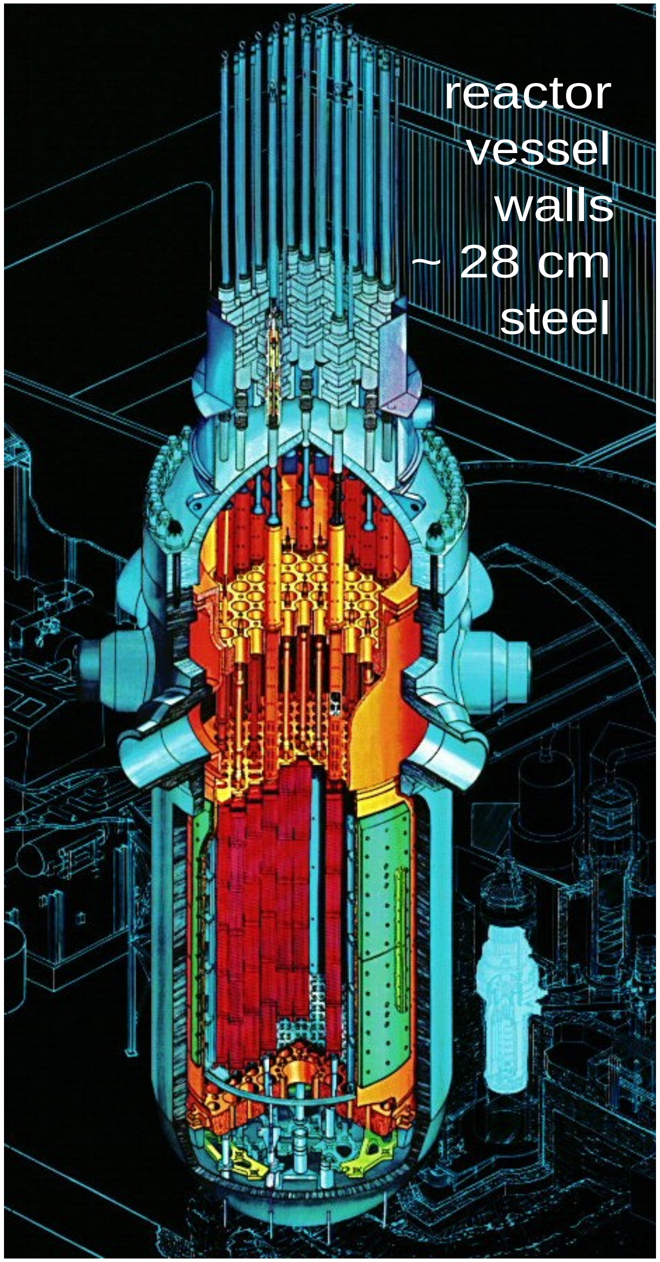
PWR Primary and Secondary Cooling Systems

pressurizer tower 13.5m
4.4m Ø



Westinghouse PWR Core and Service



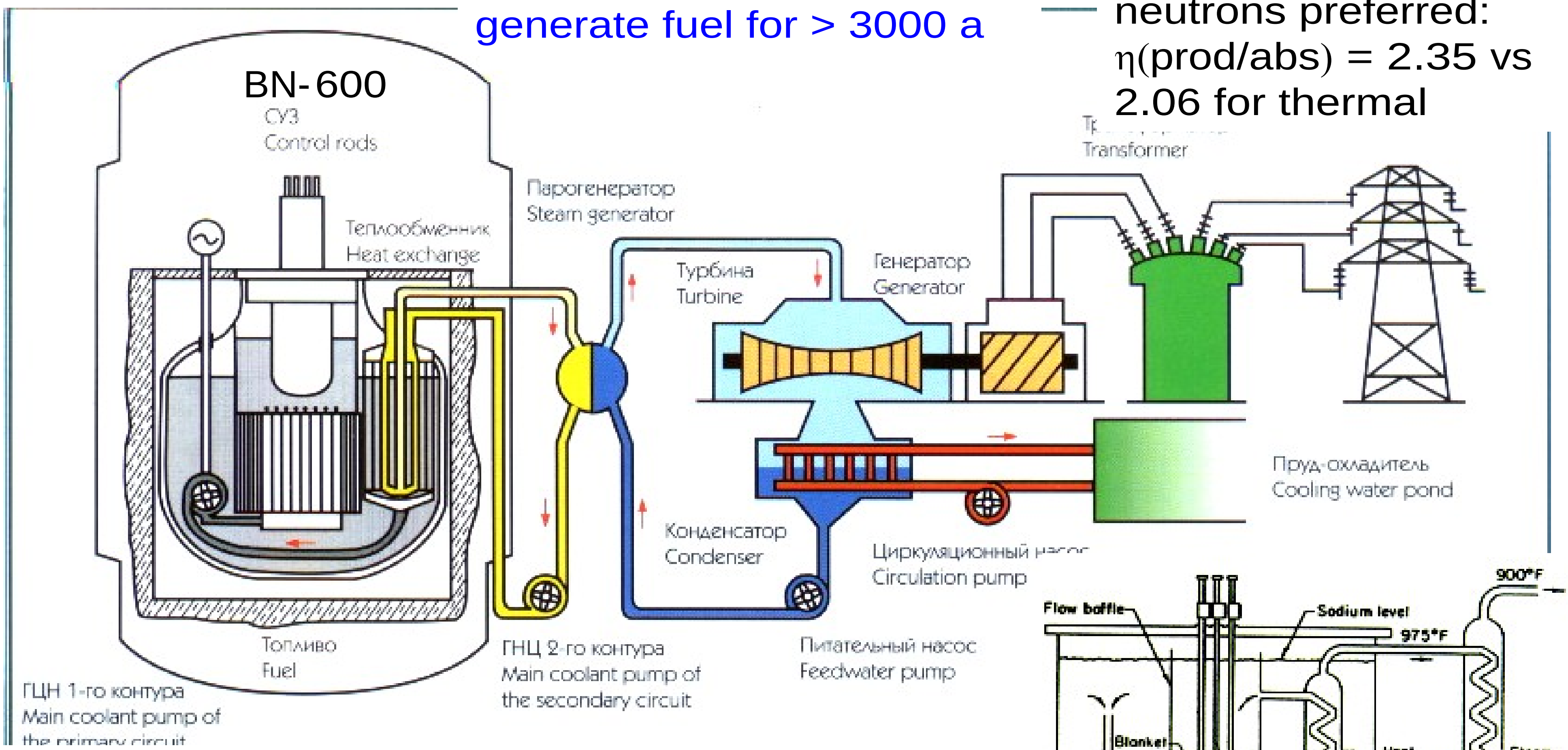


Metal-Cooled Breeder Reactor

$$^{238}U + n \to {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu$$

generate fuel for > 3000 a

Fast (>0.5 MeV) neutrons preferred: η(prod/abs) = 2.35 vs 2.06 for thermal

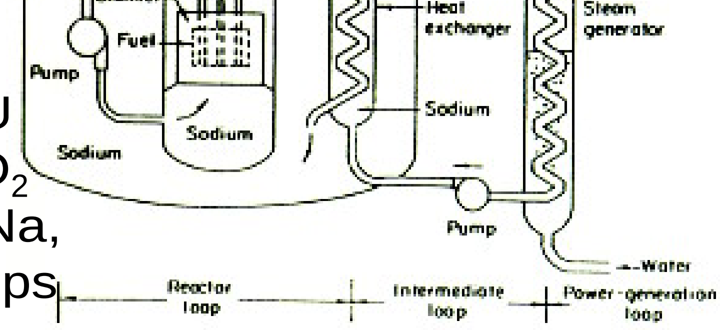


$$B \approx 1.2,\ \sigma_{abs} \sim 1.2b, \Phi_n = \frac{3 \cdot 10^{15}}{s \cdot cm^2}$$

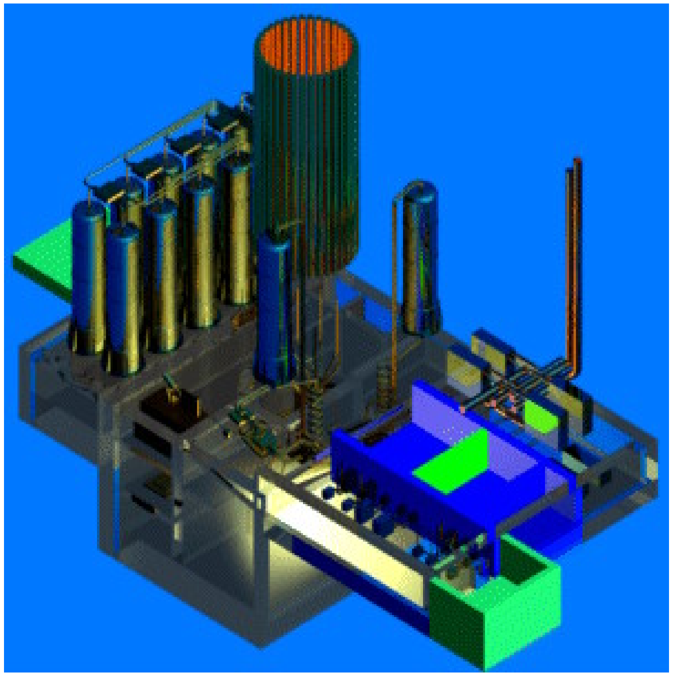
$$T_{doubling} = \left[(B-1)\sigma_{abs}\Phi_n\right]^{-1} \approx 44a$$

long doubling time!

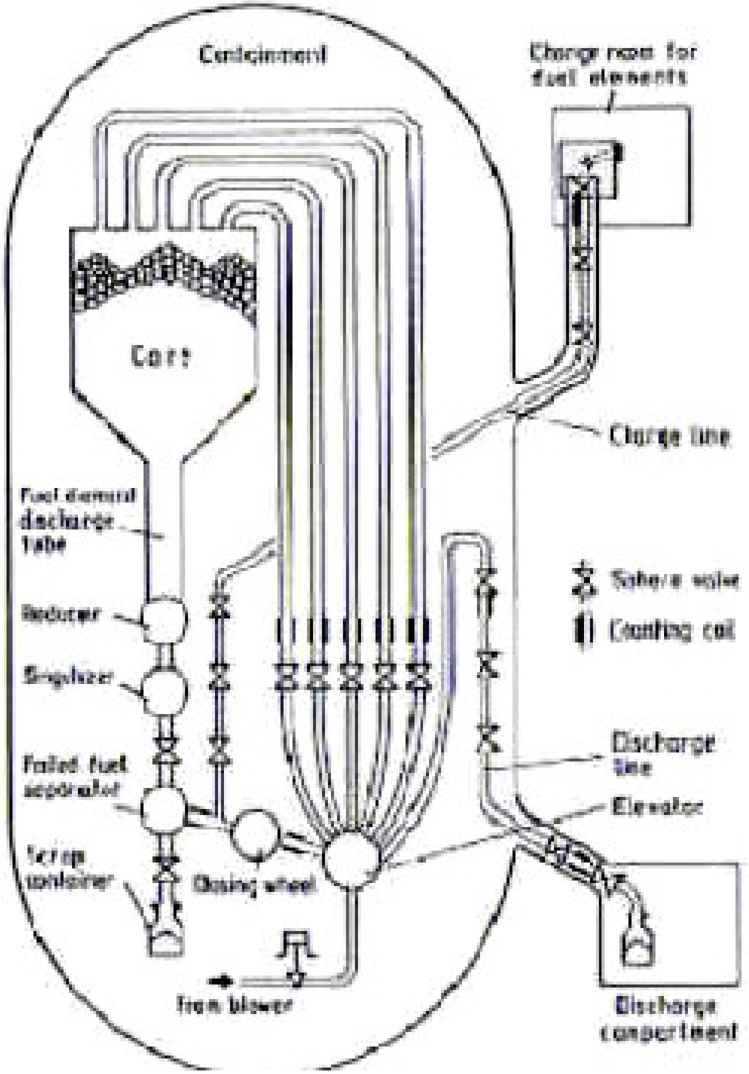
core:45.5% ^{235}U
blanket: 20 t UO_2
cooling molten Na,
K magnetic pumps



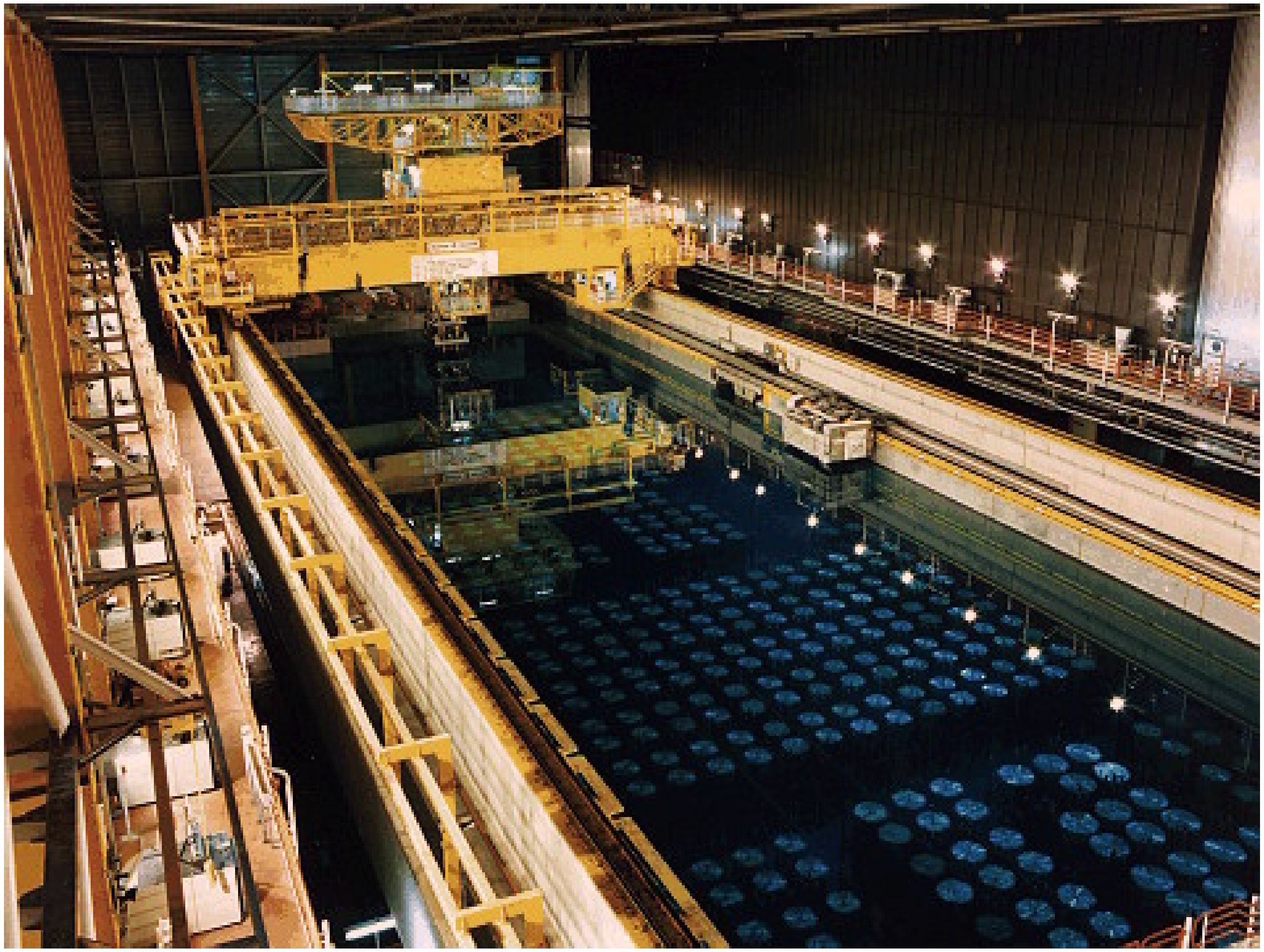
Pebble-Bed AGC Reactor



(FZ-Jülich)/Germany: Continuous supply of fuel pellets, He cooled



Storage and Reprocessing of Fuel Elements

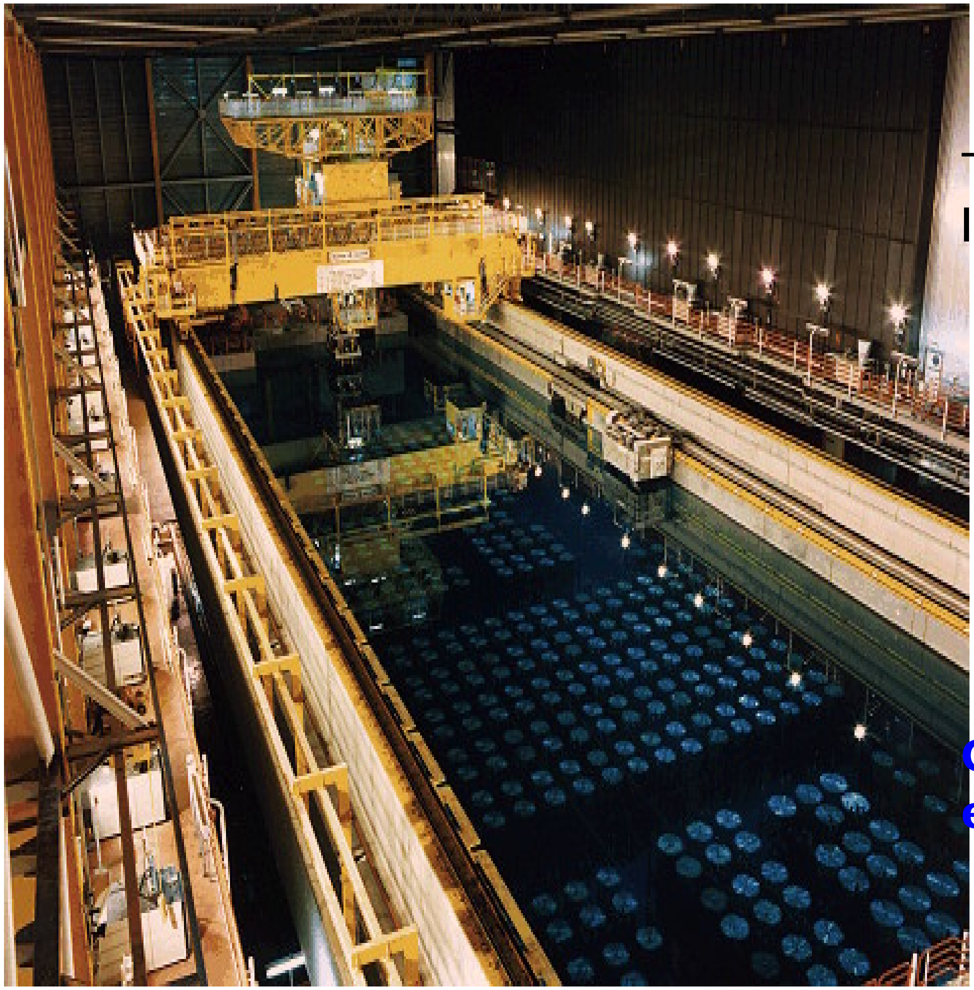


Typically 3-6 y on site in pools →

PWR 37 t/a low-enr. U

Reprocessing extracts
Pu: 330 kg/a
Am+Cm: 5 kg/a
reactor "n-poisons"
lanthanides
fission products: 1 t/a

Reprocessed fuel:
1% ^{235}U



Typical 1-GWe PWR unit operating at 75 % load factor:

(43 GWd/t) 6.6TWh (6.6 billion kWh)

→ 21 t(ons) spent fuel

(42 elements, $V_{tot} = 11\ m^3$)

$$\left.\begin{array}{l}\text{20 t of enriched U}\\ \text{230 kg of Pu}\\ \text{23 kg of minor actinides}\end{array}\right\} \longrightarrow \text{recycle}$$

750 kg of fission products

Conventional equivalent for same energy output:

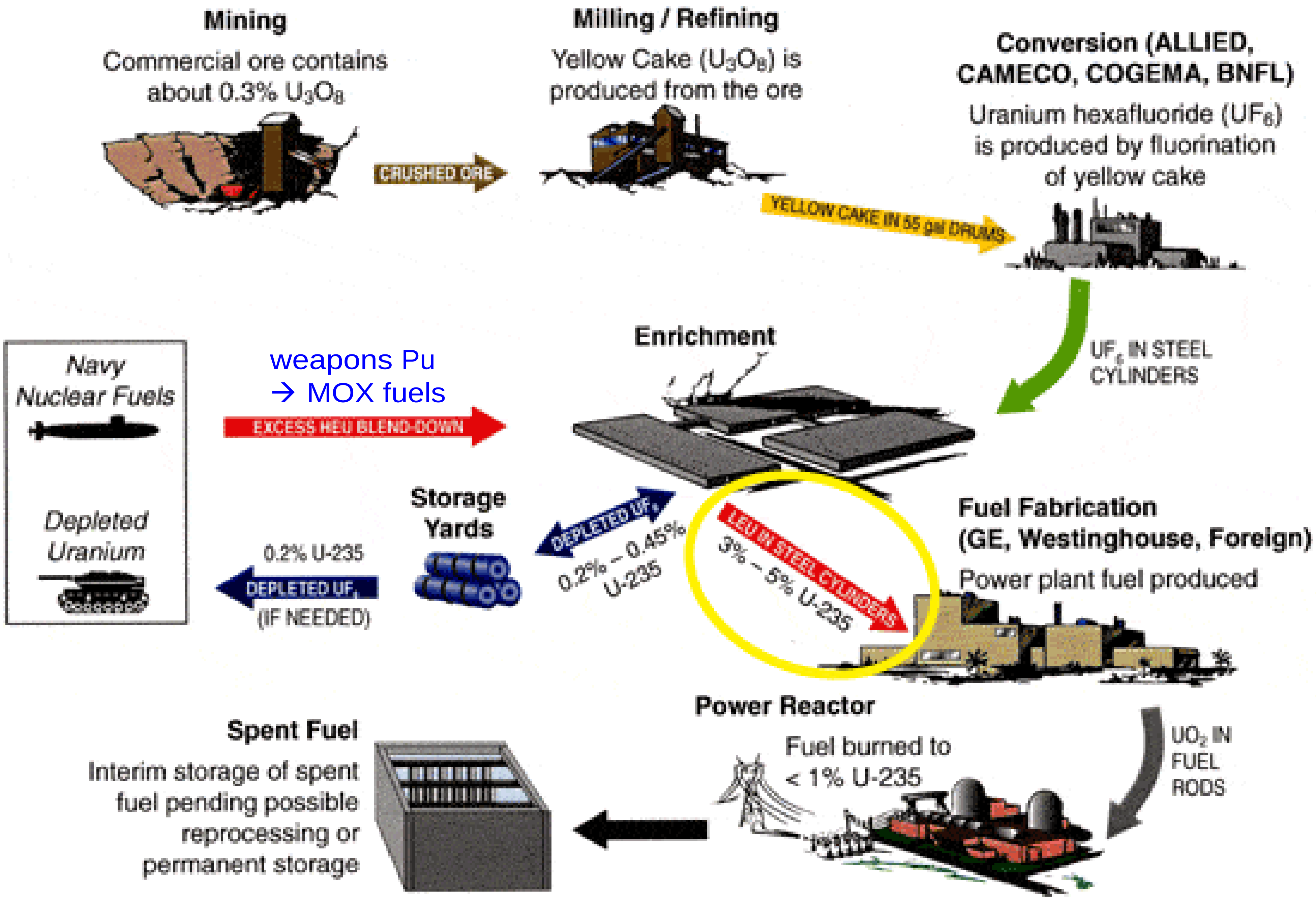
2 million tons of coal

120, 000 t of ashes

5.4 million tons of CO_2

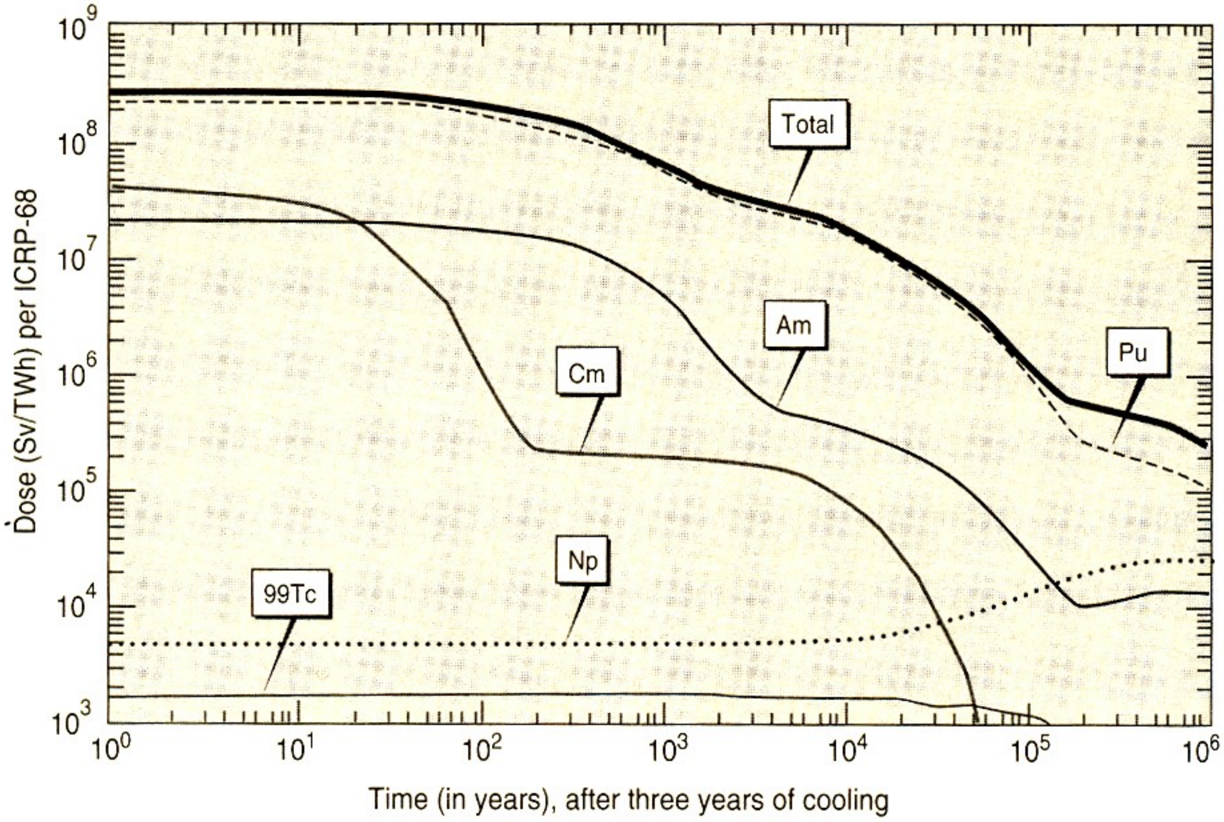
50, 000 t of SO_2.

Open Fuel Cycle



weapons Pu
→ MOX fuels

Radioactive Waste: Power Reactors/Weapons Stewardship



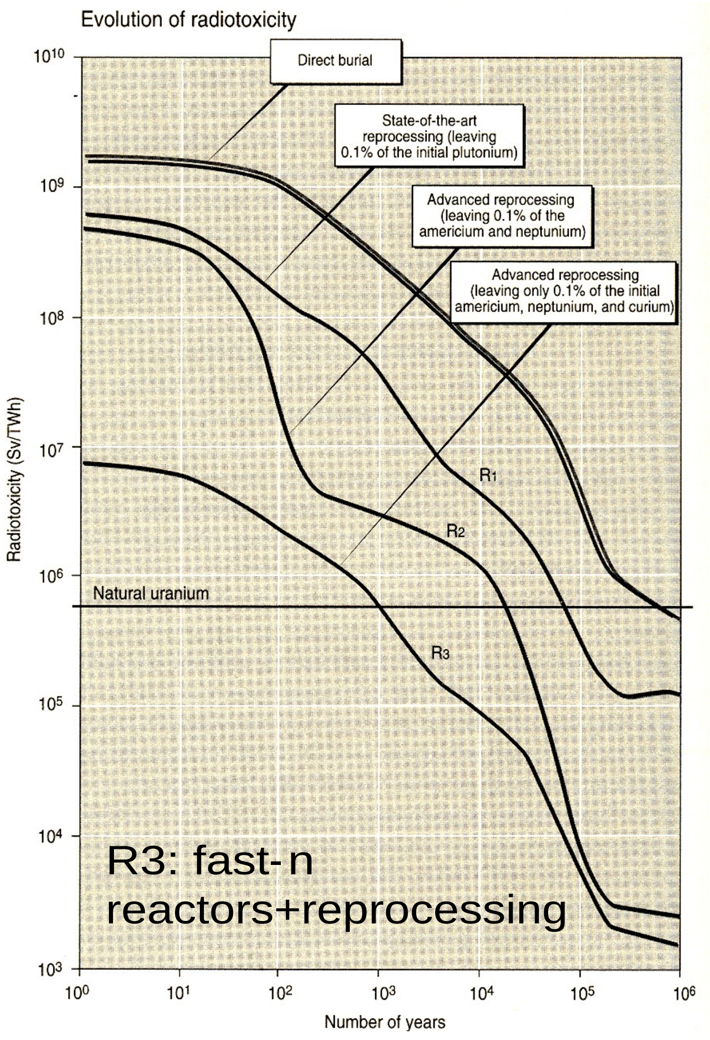
High-level waste depository for geological times → Yucca Mtns/NV

^{99}Tc, ^{129}I very long-lived and dissolve readily in groundwater, move easily throughout the ecosystem

→ disposal strategies for isolation

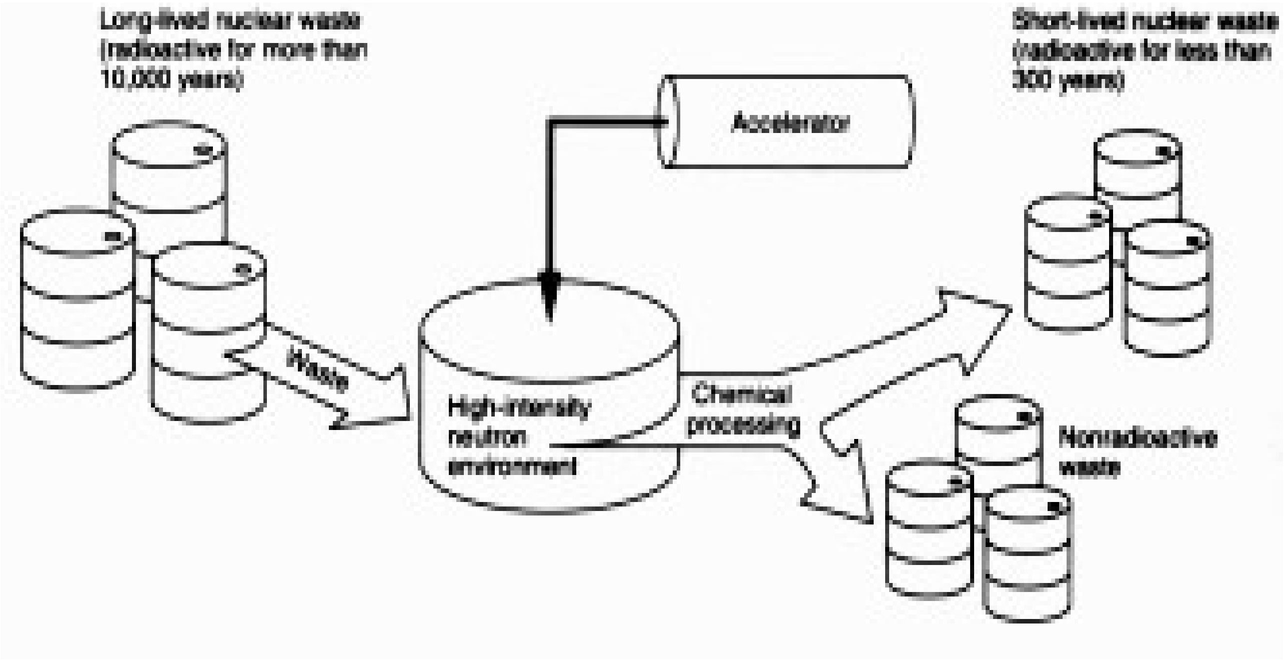
1 Sv (Sievert) = 100 rem, biolog. equivalent to 1J/kg X-rays

Radiotoxicity: R(Sv)=(Dose in Sv/decay).Activity/kg



R3: fast-n reactors+reprocessing

Nuclear Transmutation



$$\left.\begin{array}{l} {}^{99}Tc + n \rightarrow {}^{100}Tc \xrightarrow[15.8s]{\beta^-} {}^{100}Ru \\ {}^{129}I + n \rightarrow {}^{130}I \xrightarrow[12.4h]{\beta^-} {}^{130}Xe \end{array}\right\} \text{stable isotopes}$$

Transmutation of fission products carried out by specific nuclear reactions induced by neutrons, protons, photons, light nuclei, e.g., resonant n-capture.
Need high n flux
$\Phi_n \sim 10^{16}/s\cdot cm^2$

C.D. Bowman et a., NIM A320, 336 (1992)
H. Nifenecker et al., *Accelerator Driven Subcritical Reactors*, IOP Bristol, 2003

Transmutation of actinides:
n-induced fission of Pu, Np, Am, Cm
→ radioactive and nonradioactive fission products (most with half-lives < 30 a).

Neutron Multipliers

Neutron induced n emission, e.g., (n,f), (n,xn), in reactor core
Secondary n emission per incident neutron: $\boldsymbol{k_{eff}}$

Total # neutrons: $G = 1 + k_{eff} + k_{eff}^2 + k_{eff}^3 + ... = \dfrac{1}{1 - k_{eff}} \quad (k_{eff} < 1)$

Total/initial n: $M_n = k_{eff} G \quad \left(G := \dfrac{initial + created}{initial} = \dfrac{1}{1 - k_{eff}} = gain \right)$

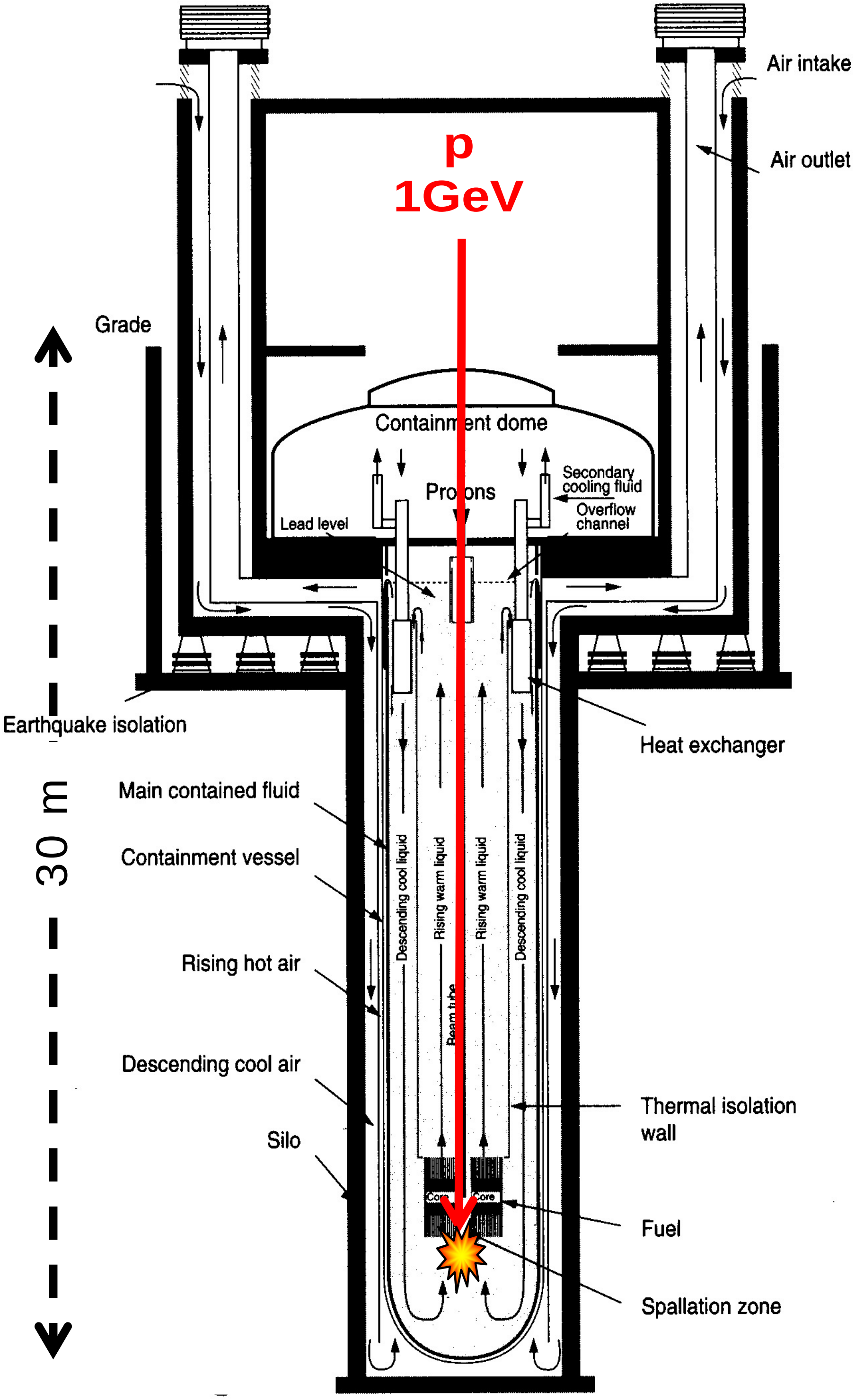
Hold $k_{eff} \lesssim 1$ in reactor, $k_{eff} > 1$ in weapons

Inject N_0 neutrons, e.g., by a p-induced spallation process →

$$N = N_0 \cdot G = \frac{N_0}{1 - k_{eff}} \gg N_0$$

Obtain high enough *fast-neutron* flux for MA incineration/transmutation

ERN-Subcritical Energy Amplifier



Bowman 1992, Rubbia 1993 **Th-U**

Needs high-intensity (10mA) 1-GeV p accelerator, beyond existing technology

Energy gain $G_E = 120$

Avoid slowing of n: molten Pb/Bi (tested in Russian submarines)

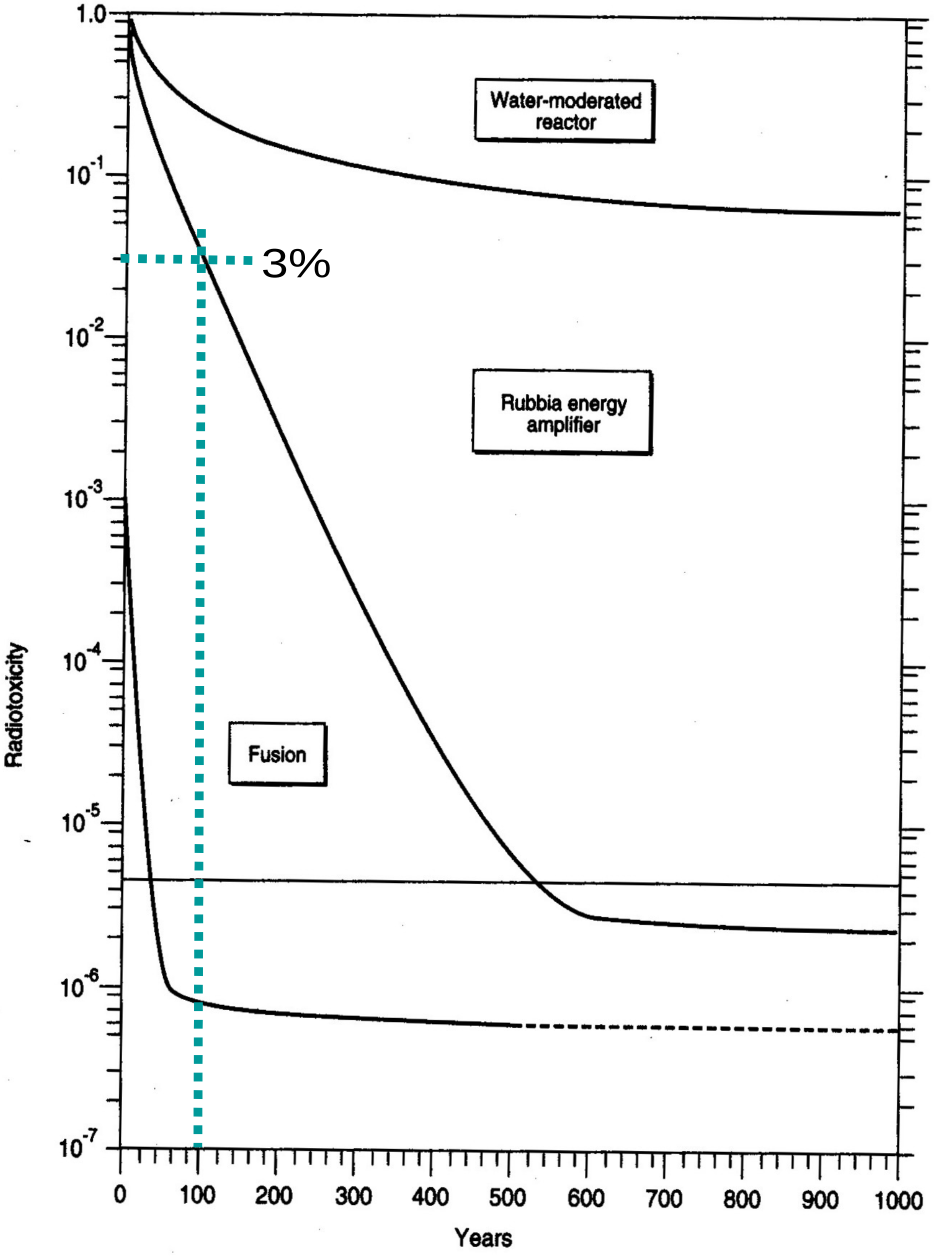
cooling by convection

Many passive safety features, e.g., core shielded by 20 m Pb layer

overheated Pb overflows into beam tube, stops spallation

Burns Th, incinerates minor actinides, Pu, Am, Cm transmutes fission products

Waste Reduction in CERN Th-U EA



Fast-n hybrid reactor (EA) like breeder with external accelerator

Reactor Accident Scenario