Power from Nuclear Transmutation

(Fission and Fusion)

The Diablo Canyon NPPT produced CO_2-free electricity at 2¢/kwh, half the state's (CA) average cost.

Agenda

- Nuclear stability & particle radiation
  Potential biological hazards

- Energy Generation from Nuclear Fission
  - U.S./World trends,
  - Nuclear fuel resources (U.S.),
  - Fission chain reaction and reactor control,
  - Reactor types,
  - Fuel cycles, radioactive waste & storage.

- New Nukes: Advanced Nuclear Energy Technologies
  - Small modular plants,
  - Advanced (Gen IV) reactors,
  - U & Th breeder reactors, subcritical reactors,
  - Closed fuel cycle,
  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)

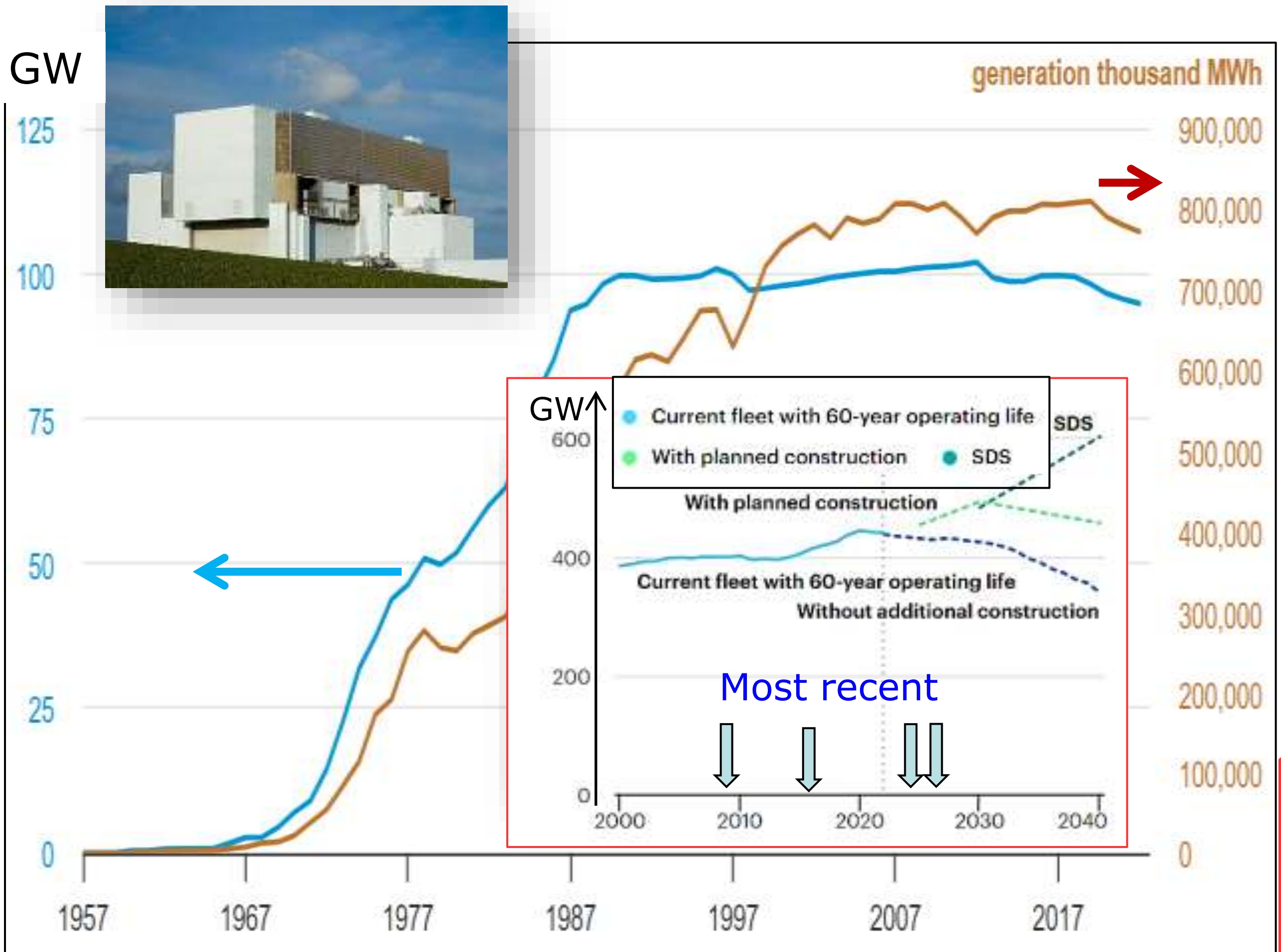
- Energy from nuclear fusion reactions
  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

- Strategic Issues for Nuclear Power
  - Sustainability, reliability, scalability, safety, eco-footprint, cost

U.S./World Trends in Nuclear Energy Production

Steady increase of nuclear power output over 30y. Efficiency ε ↗
Now: ε ≧ 90% → equivalent: 24 quads of oil. NPP lifetime 40a → > 60a

World 2023 (US): 440 (92) reactors; 400 (100) GW, 2.5 PWh → Modernize !



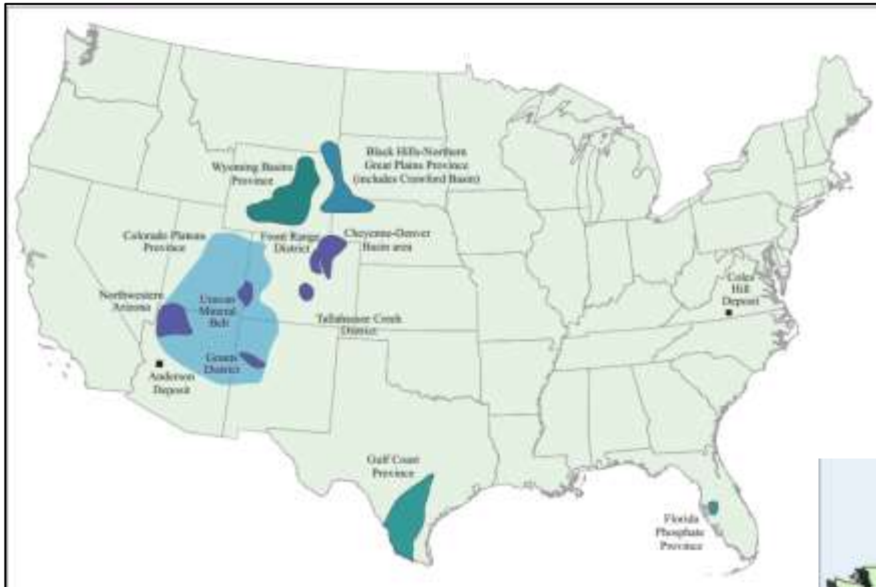
World Trend
>53 new NPPt
→2050: 600GW ?

US(since 2012):
+3 -6
> 20 planned (?)
license app

US potential:
1.Extend plant lifetime,
2.*N* new reactors/a
(@ $(3-4)B/GW_e → (5-10)¢/kWh)

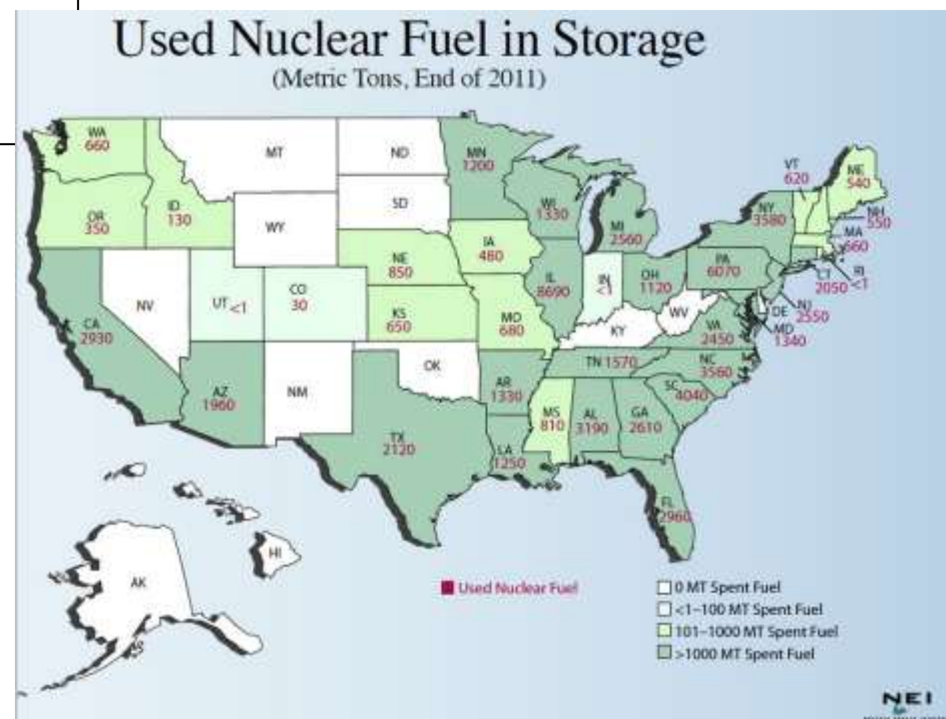
Several new companies →
SMR, Na-cooled
Microreactors
Fusion Demos

U.S. Uranium Resources/Used Fuel Elements



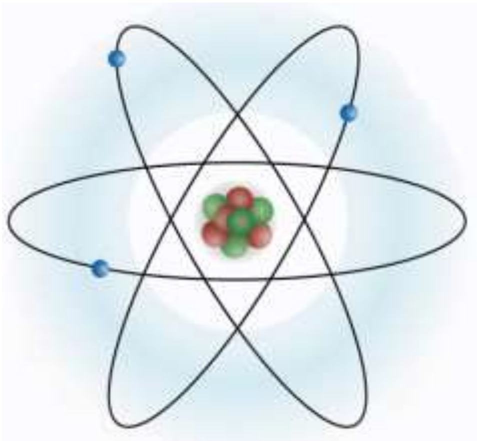
Used fuel elements in NP stations is U enriched in U-235. Used fuel elements: < 3 % U-235, > 95% U-238= fertile fuel for breeding.

Future small modular ppt,
U, Th breeder reactors,
Nuclear Magnetic Confinement fusion demos.



1GWe nuclear reactor requires yearly core load of (17.5-20) t low-enriched uranium U_3O_8 (3.5 - 5)% U-235, > 95% U-238

Basic Nuclear Properties



Classical Model of Atom

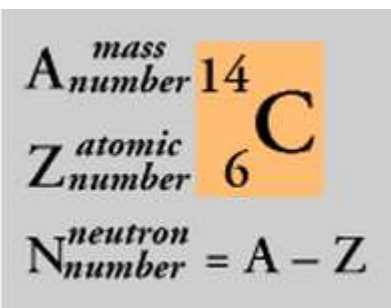
Atom of element Z: Z negatively charged electrons orbit around a Z-times positively charged, small nucleus in center of atom.

Nucleus= (Z protons, N neutrons), mass number A = N+Z
Nuclear radii range from $R_{Nucleus} \approx (1\text{-}10)\cdot 10^{-15}$m. (1 fm= 10^{-15}m)

Nuclear radius $R_{Nucleus} \ll R_{Atom}$ atomic radius (1Å=10^{-10} m)

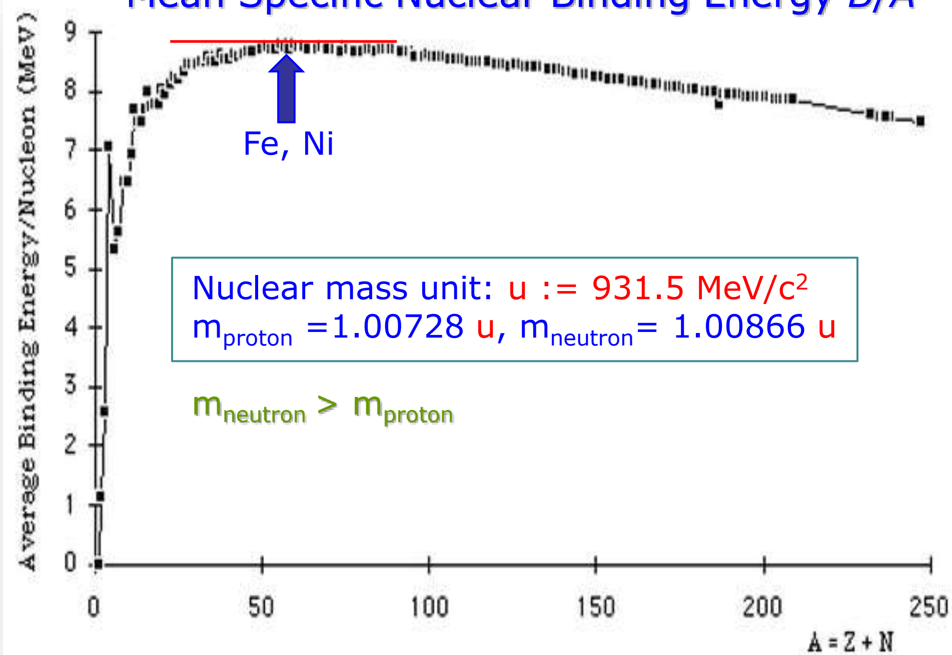
Nuclear mass $\mathbf{m_A} < N\cdot m_{neutron} + Z\cdot m_{proton} \rightarrow$
$\Delta m\cdot c^2$ = binding energy $B > 0$.

Isotope Terminology



^{12}C =stable isotope
>>>^{14}C or C-14<<<
=radioactive isotope

Mean Specific Nuclear Binding Energy *B/A*



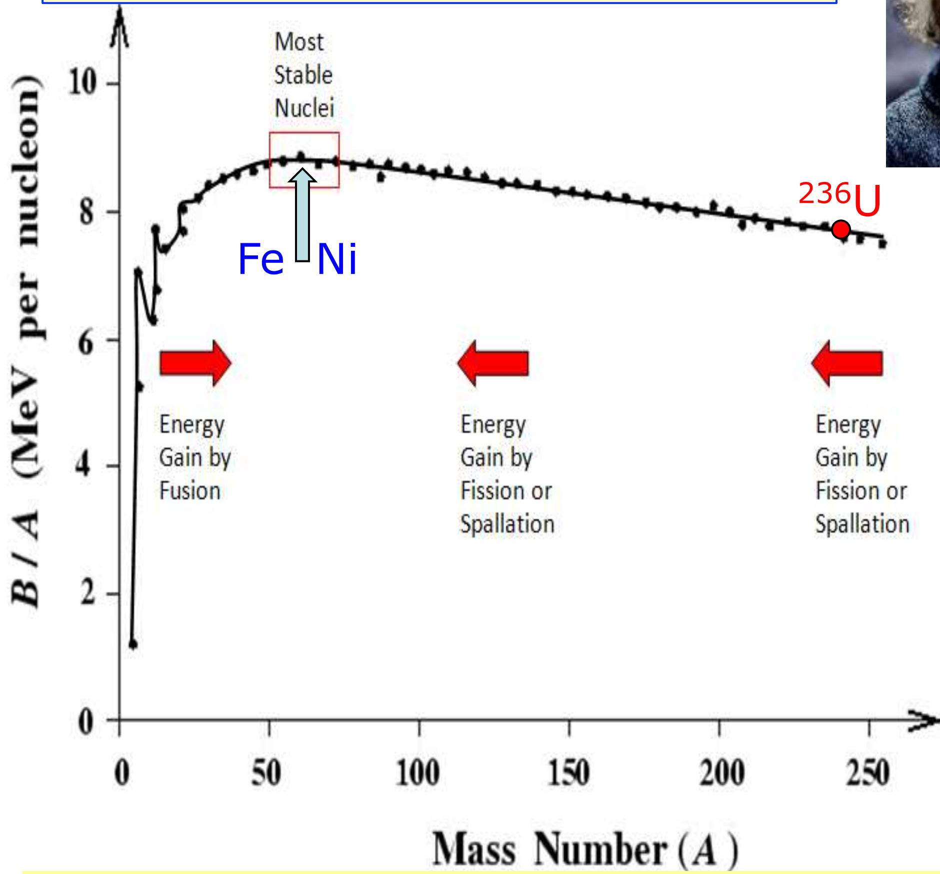
Nuclear mass unit: u := 931.5 MeV/c^2
m_{proton} =1.00728 u, $m_{neutron}$= 1.00866 u

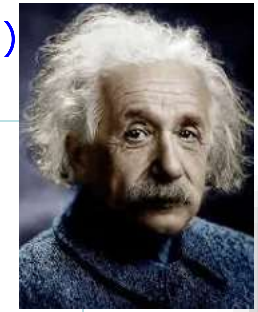
$m_{neutron} > m_{proton}$

Basic Energetics: Nuclear Rearrangement Energies

Mass $M_{(N,Z)} < N \cdot M_n + Z \cdot M_p \rightarrow \Delta M \propto B(A=N+Z)$

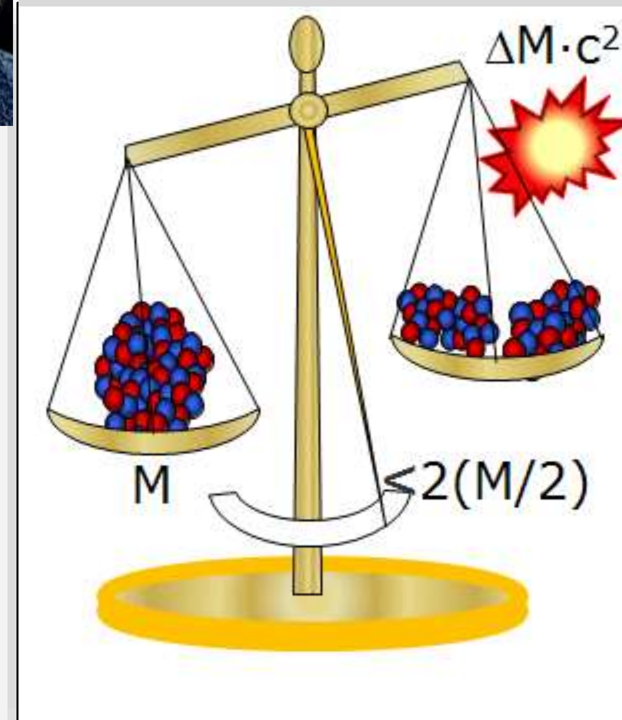
Energy of fusion: $B = \Delta M \cdot c^2$ is released





Einstein: equivalence
mass = energy **$E = M \cdot c^2$**

Energy release in fission A→2A/2



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

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

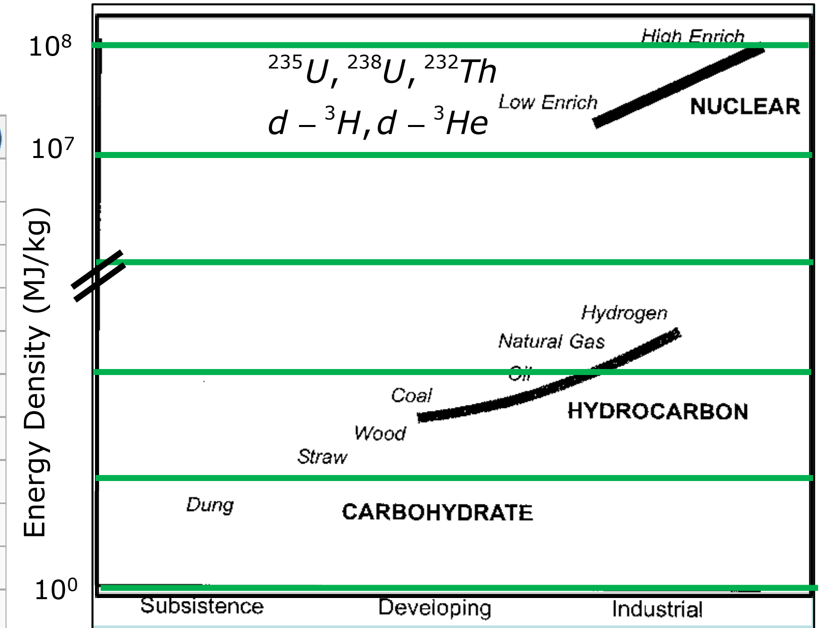
Fission of $^{235,238}U$ from g.s. is not spontaneous → Activation energy = Fission Barrier
Pass via n-capture $^{235}U + n \rightarrow {}^{236}U^*$

Fuel Energy Density

$$P(^{235}U) / P(Coal) = 3 \times 10^{6}$$

Storage material	Energy type	MJ per kilogram	MJ per liter (litre)	
Deuterium–tritium	Nuclear fusion	330 000 000	6 368 000 000	
Uranium-235	Nuclear fission	79 500 000	1 534 000 000	
Hydrogen (compressed at 700 bar)	Chemical	123	5.6	
Gasoline (petrol) / Diesel	Chemical	~46	~36	
Propane (including LPG)	Chemical	46.4	26	
Fat (animal/vegetable)	Chemical	37		
Coal	Chemical	24		
Carbohydrates (including sugars)	Chemical	17		
Protein	Chemical	16.8		
Wood	Chemical	16.2		
TNT	Chemical	4.6		
Gunpowder	Chemical	3		
Lithium battery	Electrochemical	1.8	4.32	
Lithium-ion battery	Electrochemical	0.72	0.9-2.23	Laptop computers, mobile devices, some modern automotive engines
Alkaline battery	Electrochemical	0.59		Portable electronic devices, flashlights
Nickel-metal hydride battery	Electrochemical	0.288	0.504-1.08	Portable electronic devices, flashlights
Lead-acid battery	Electrochemical	0.1		Automotive engine ignition
Electrostatic capacitor	Electrical	0.000036		Electronic circuits

From Wikipedia, Nov. 2012



From P. W. Huber & M. P. Mills, “The Bottomless Well,” Basic Books, New York, 2005

Nuclear fuel has highest known material energy density ($\sim 10^7$)
→ potentially lowest environmental impact (“footprint”)

Fission Reactions

Energy Release in n_{th}-Induced Fission

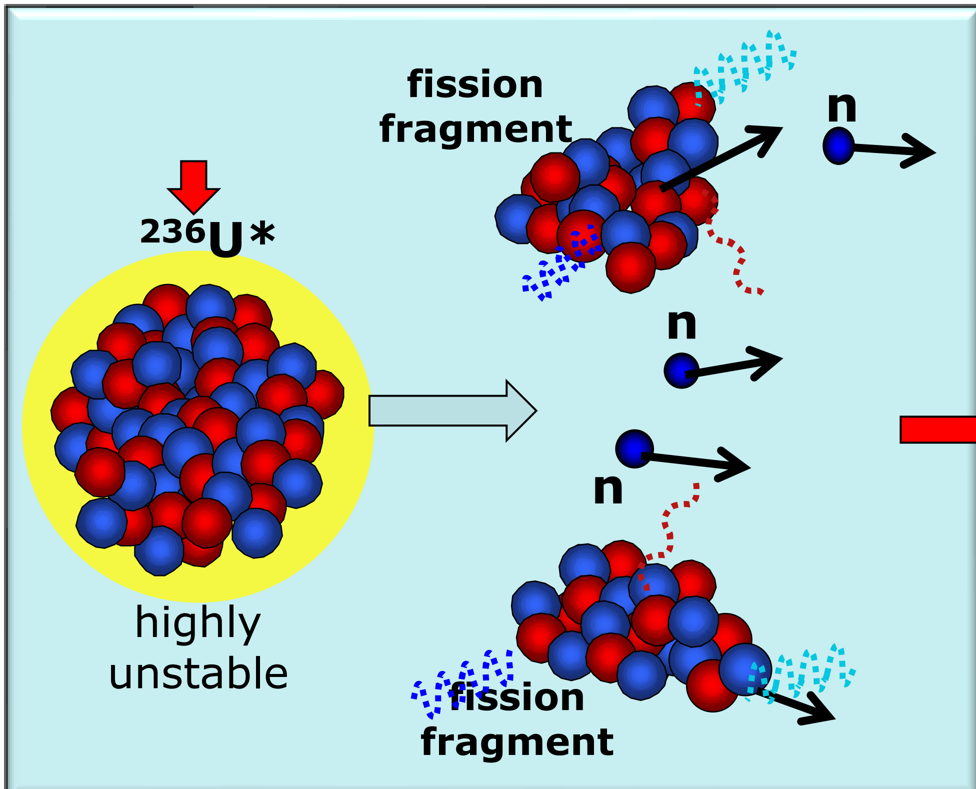
thermal→ E= (3/2)k_BT, k_BT=25meV

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

Fission fragments have a distribution $P_F = P_F\left(Z_F, A_F\right)$

$$Example: \quad {}^{236}U^* \rightarrow {}^{147}La + {}^{87}Br^* + 2n_{fast}$$

Additional fuels: ^{239}Pu
Fertile actinides ^{223}Th, ^{238}U can be made into nuclear fuel by neutron irradiation ("breeding")



Converts 0.1% of the mass
→ energies of fragments+n

→ Thermal energy/**heat**

1g ^{236}U/day = 1MW

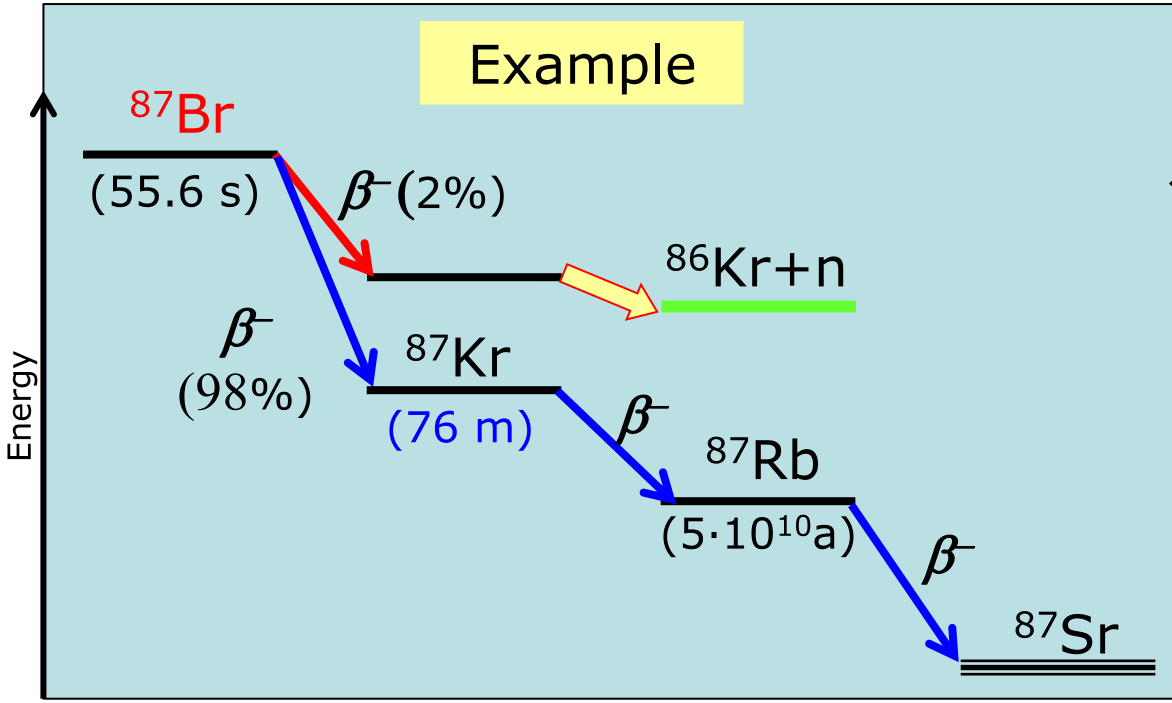
>10^6 x chemical energies

E_{ff}	=	168 MeV
$E_{n\ tot}$	=	5 MeV
E_γ	=	7 MeV
FF β-decay	=	27 MeV
Q_{total}	=	**207 MeV**

β–Delayed Neutrons

87% of fission energy (≈200 MeV) promptly in fission ≤ 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 (occur after fission) → = Essential for sustaining chain rxn + control function

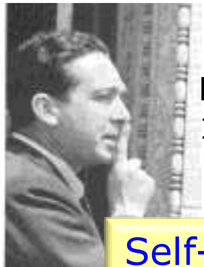


β–delayed neutron
<Δt> ≈ 80 s

k<1 → ***k*****eff**≈**1**
Effective neutron multiplication factor, but not all "survive"
Most have "wrong" energy for ^{235}U chain rxn

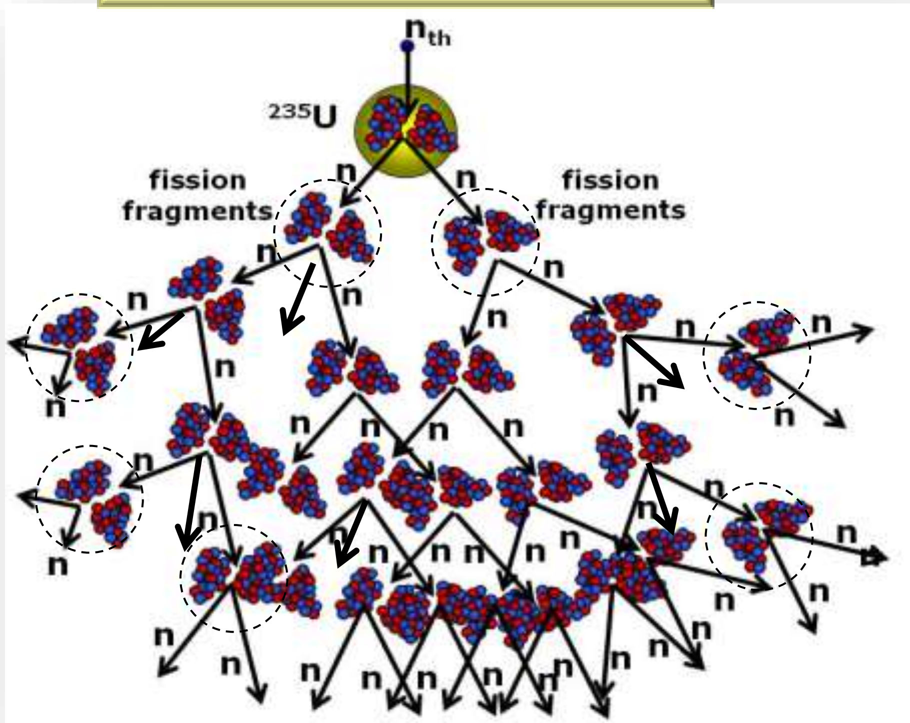
"Ignition" possible? → self-sustaining chain reaction

Self-Sustaining Fission Chain Reaction



Neutron multiplication through fission: *k=2.4*, minus losses (capture, leaking, escape,..) → effective *k < 1*.
One ***n*** used in each fission → effective multiplication ***k-1***

Self-Sustaining Chain Reaction



$$dN_n/dt \approx (k-1)N_n/\tau \rightarrow$$

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

k >1: avalanche of n
τ = time between generations
(τ ~ 40μs in critical reactors
τ ~ ns in explosive devices)

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

Reactor Control: delayed n's

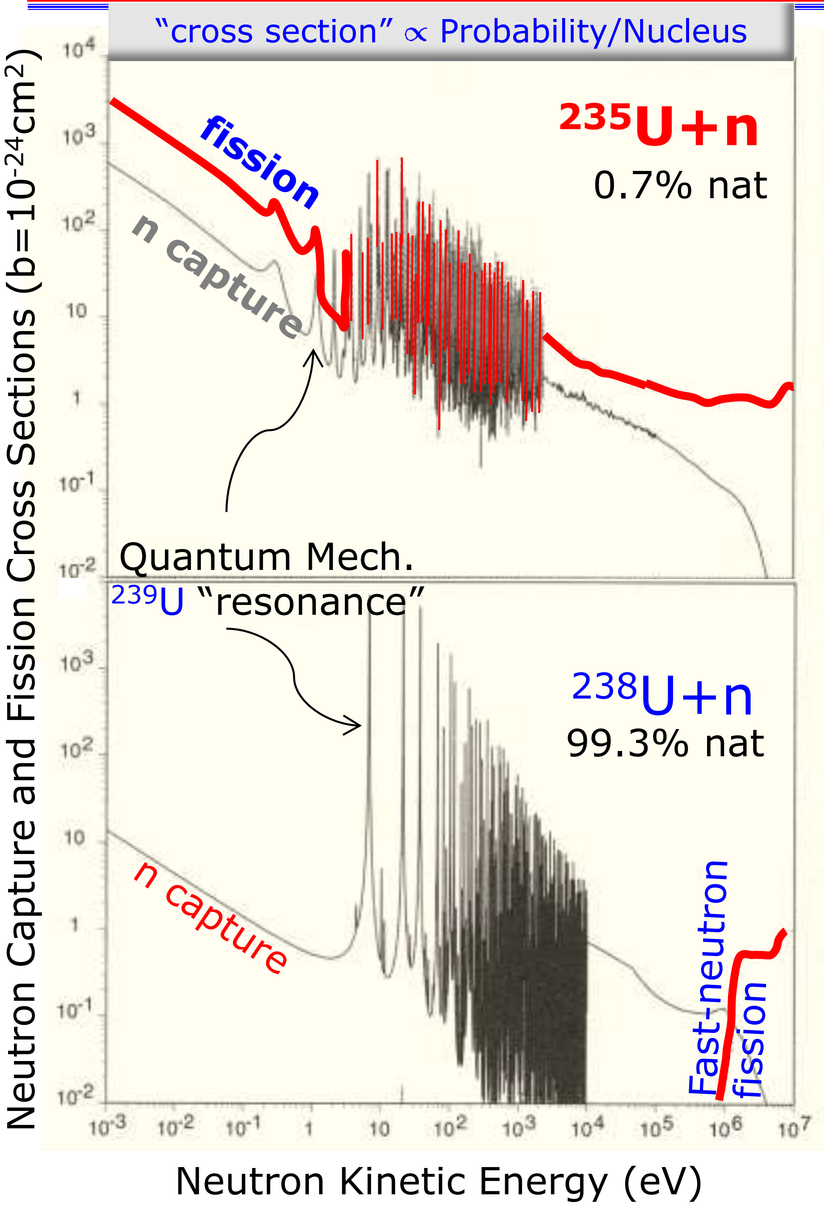
Characteristic time period

$$T = \frac{\tau}{(k_{eff}-1)}$$

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

Most fission neutrons are lost or not useful for further fission.
Fission fragments = "reactor poison" → $k_{eff} < 1$ stops chain reaction!

Fission and n-Capture Probabilities (“Cross Sections”)



Central Problem:
Ignition of a self-sustaining fission reaction.
→ Moderate & recycle fission neutrons!

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

Fission cross sections → typically small,

${}^{238}U$: $\sigma_f \sim$ 1 *b* for E_n > 1 MeV
≈ 0 *b* for E_n < 1 eV

$1b = 10^{-24} cm^2$

dominating: scattering (~8 *b*) + capture

${}^{235}U$: $\sigma_f \sim$ 1-2 *b* for E_n > 1 MeV
~ 10^3 *b* for E_n < 1 eV ***large***!!

dominating: (n, f) fission

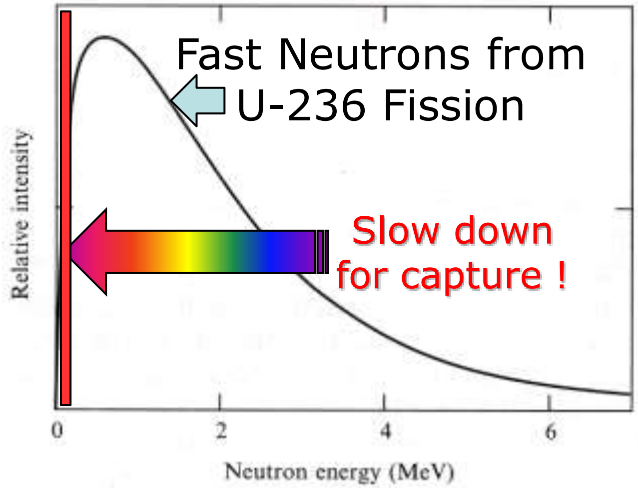
Observed ${}^{nat}U$ fission is due to (0.7%) ${}^{235}U$

→isotopically enrich ${}^{235}U$, > 4% -20% for higher efficiency (∝ output fission energy/input neutron energy)

Slow neutrons → large σ_f!

Slowing-down (moderation) of fission *n*‘s by elastic *n* scattering on light moderator nuclei (H, C,…)

Neutron Energy Moderation



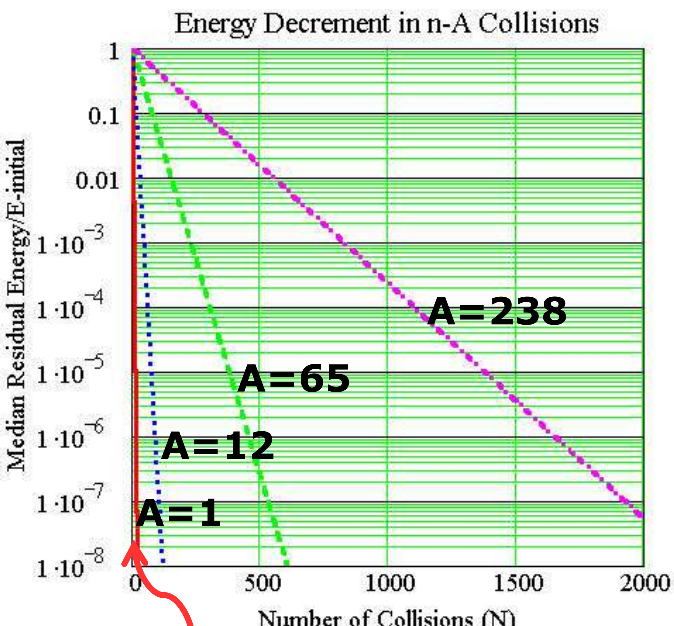
Fission neutrons too energetic, → "thermalize" to maximize $\sigma_{n,fiss}$ for ^{235}U !
→ multiple elastic scattering ("moderation")
moderator: small σ_{capt} !

Need: **2 MeV → 0.025 eV/2MeV (= 10^{-8})**
Must "miss" ^{238}U capture resonances
($2eV < E_n < 10keV$)

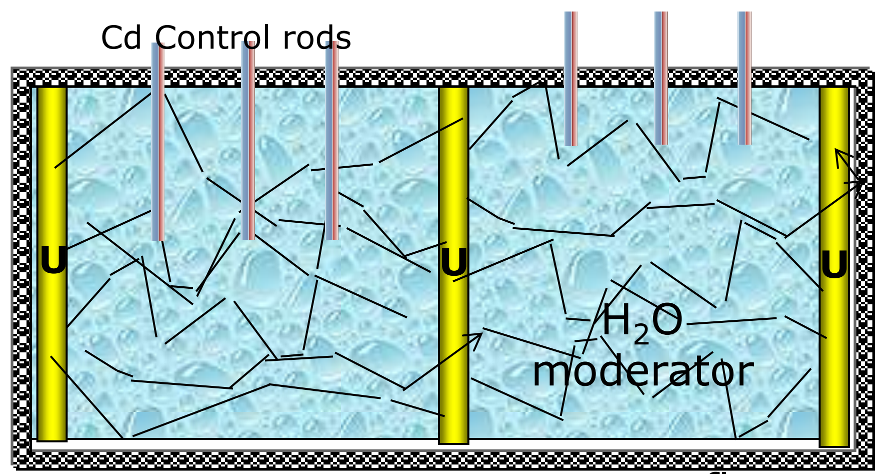
H_2O, D_2O, Be, C(graphite), prevent n leakage

Needed: moderator and fuel coolant

Control rods (Cd,..) capture n's → $k_{eff} \approx 1$



H, D are best moderators



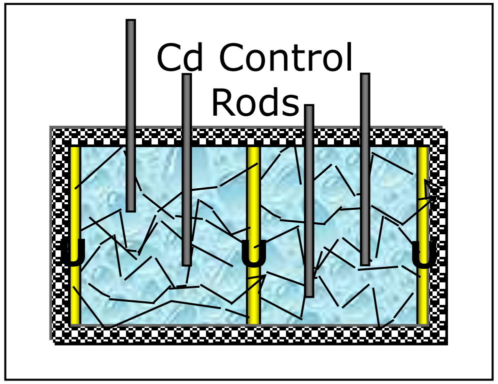
H can capture neutrons (k < 1 !):
$H+n_{th} \rightarrow D+2.2$ MeV

W. Udo Schröder, 2024

Reactor Control and Safety

"**Reactivity** $d\rho/dT$"; $\rho = (k_{eff} - 1)/k_{eff}$

Reduce by n absorbers *Cd*, *B* (control rods, moderator)
Automatic: fission products= "reactor poisons"



Temperature dependent reactivity coefficient $d\rho/dT<0$

→ *Negative reactivity desirable (self-regulating).*

In BWR/PWR

Doppler Effect: broadening of resonance and n spectrum leads to increased n-capture by ^{238}U → $d\rho/dT < 0$

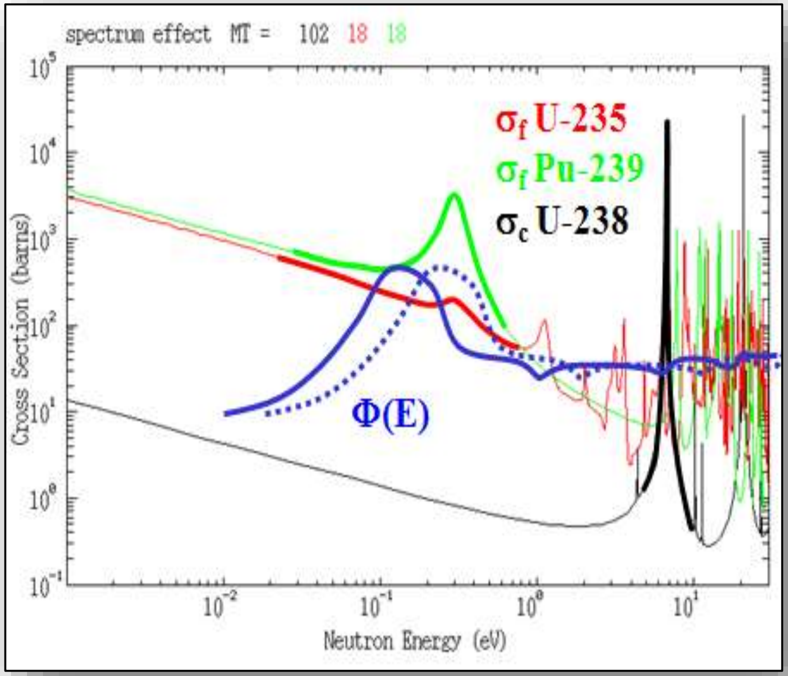
Density Effect: hot moderator expands, lower density → longer mean free path, less moderating efficiency → $d\rho/dT < 0$

Dilatation Effect: hot moderator delays slowing down → $d\rho/dT < 0$

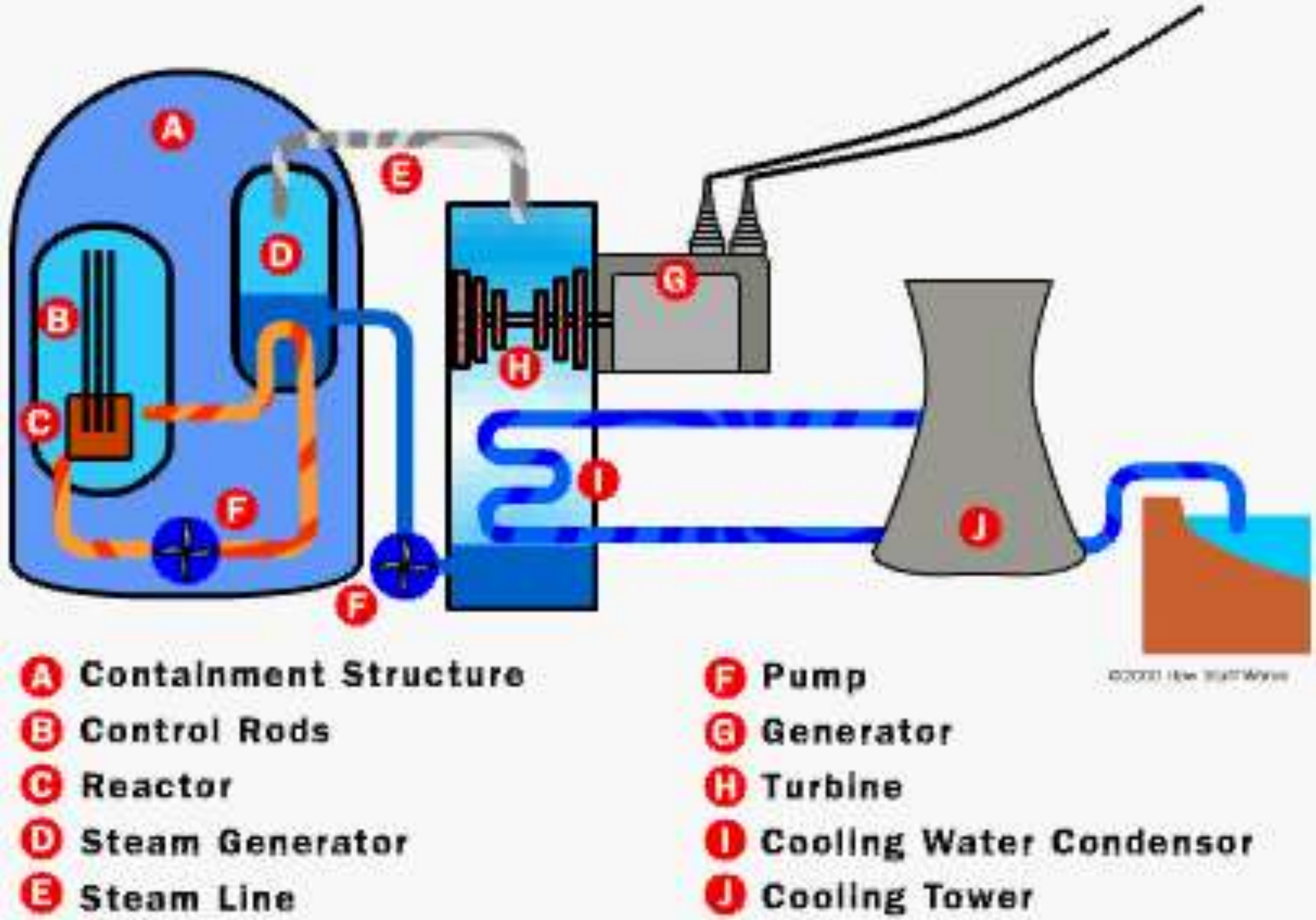
$d\rho/dT = -(0.5\text{-}1)\times10^{-4}/^{0}C$ PWR

⇕

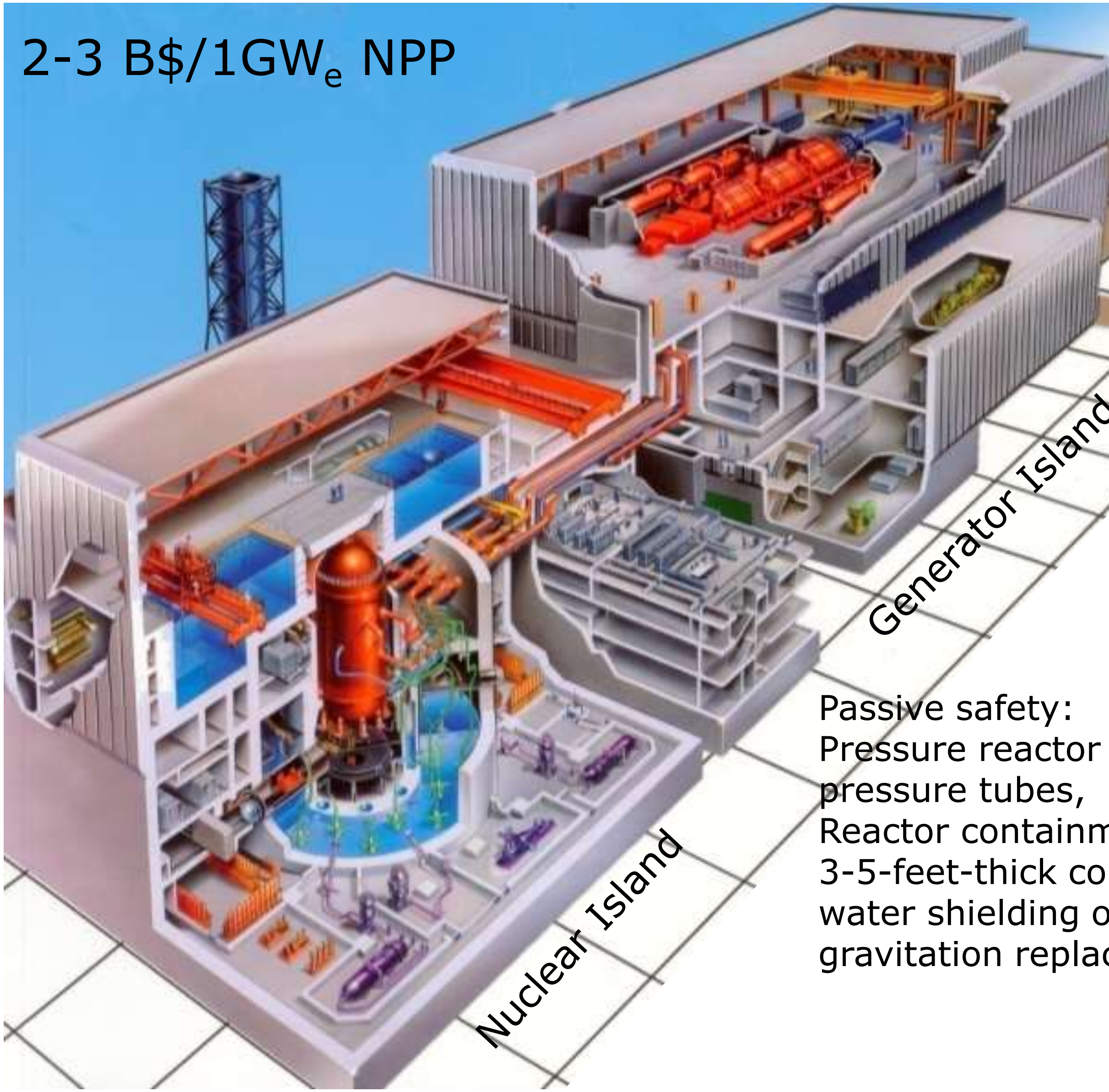
$d\rho/dT = -1\times10^{-3}/^{0}C$ Breeder, EA



Principle Boiling Water Reactor



Conventional Gen-II Nuclear BW Power Plant 1-2GW



Fail-safe operation
Negative Reactivity

Negative feedback loops:
Reaction subsides when

- coolant gets too hot or disappears (less dense, less moderation)
- fuel gets too hot (*n* capture increases)
- control rods are not moved out

Passive safety:
Pressure reactor vessel ~1′ thick steel, pressure tubes,
Reactor containment building with several 3-5-feet-thick concrete walls, concrete + water shielding on top of reactor vessel, gravitation replaces mechanical pumps.

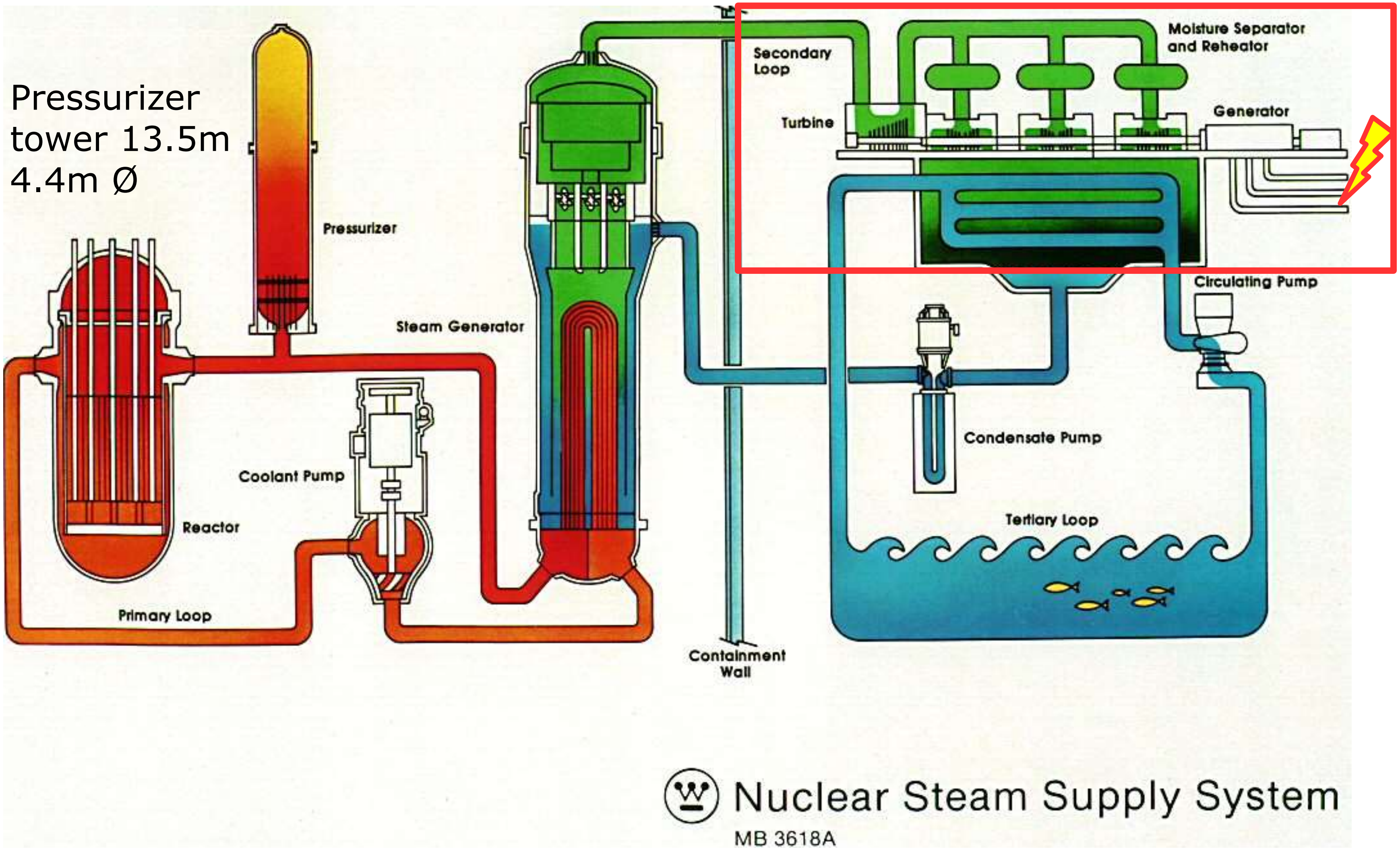
Fuel Elements

PWR Primary and Secondary Cooling Systems

Nuclear Island

Generator Island

Pressurizer
tower 13.5m
4.4m Ø

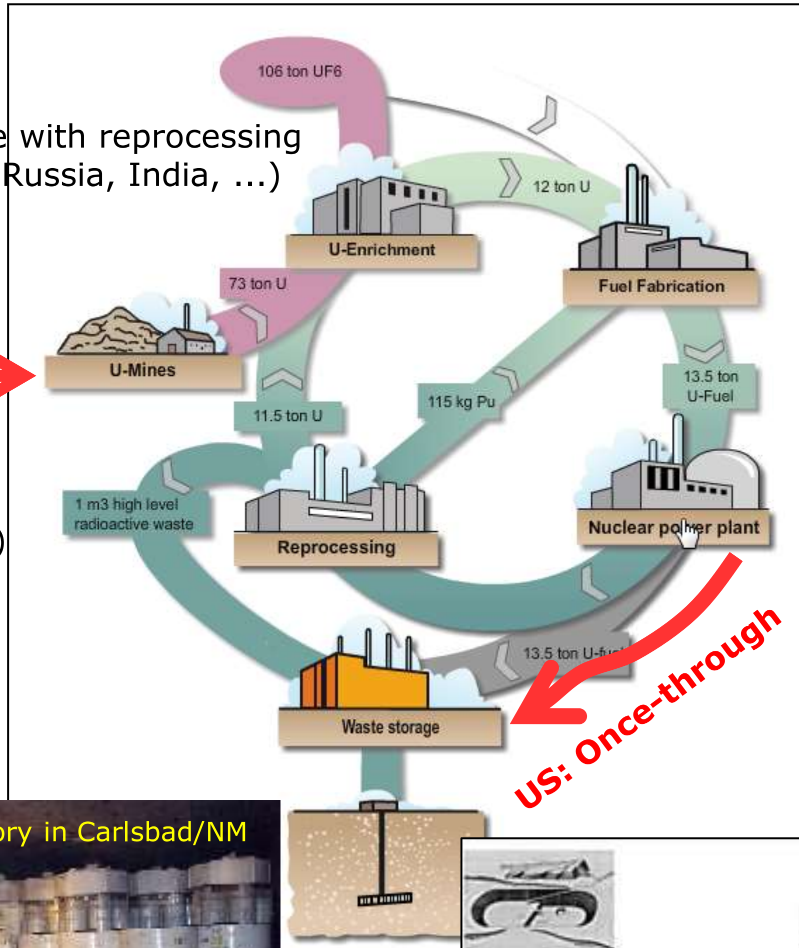


Nuclear Fuel Storage & Transport

Uranium and Thorium Fuel Cycles

"Spent fuel" still contains 97% of nuclear energy ($^{235,238}U$, $^{239,240}Pu$) + FF & MA

Closed fuel cycle with reprocessing (France, Japan, Russia, India, ...)

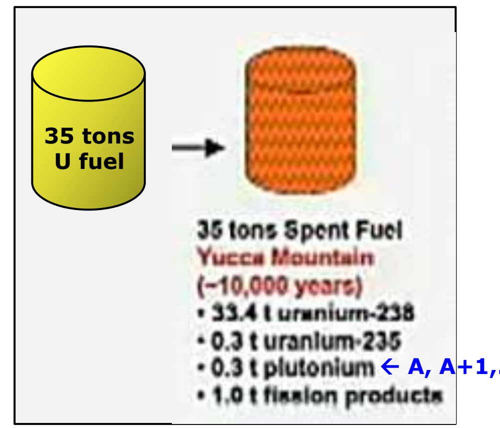


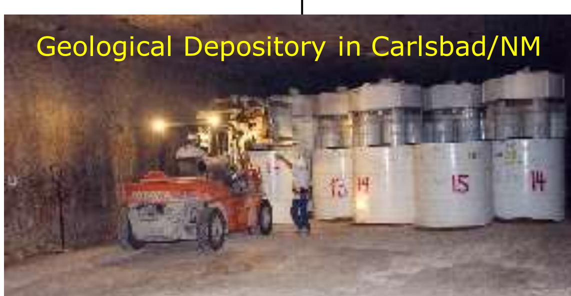
Permanent storage of high-level waste already paid for by consumers ¢0.1/kWh.

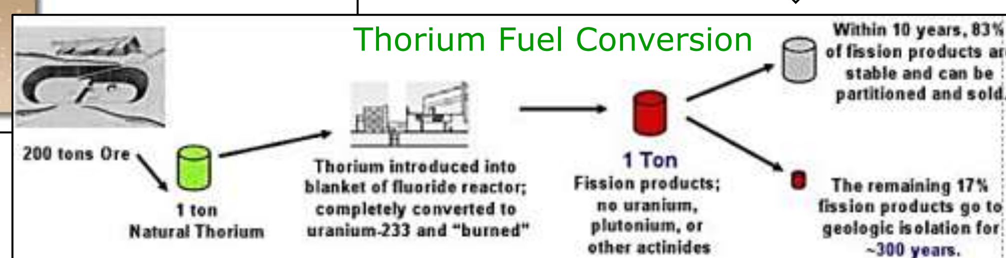
Worldwide:
5 geological depositories in operation (US: 1)

Yucca Mountain
Stopped in 2010, temporarily?

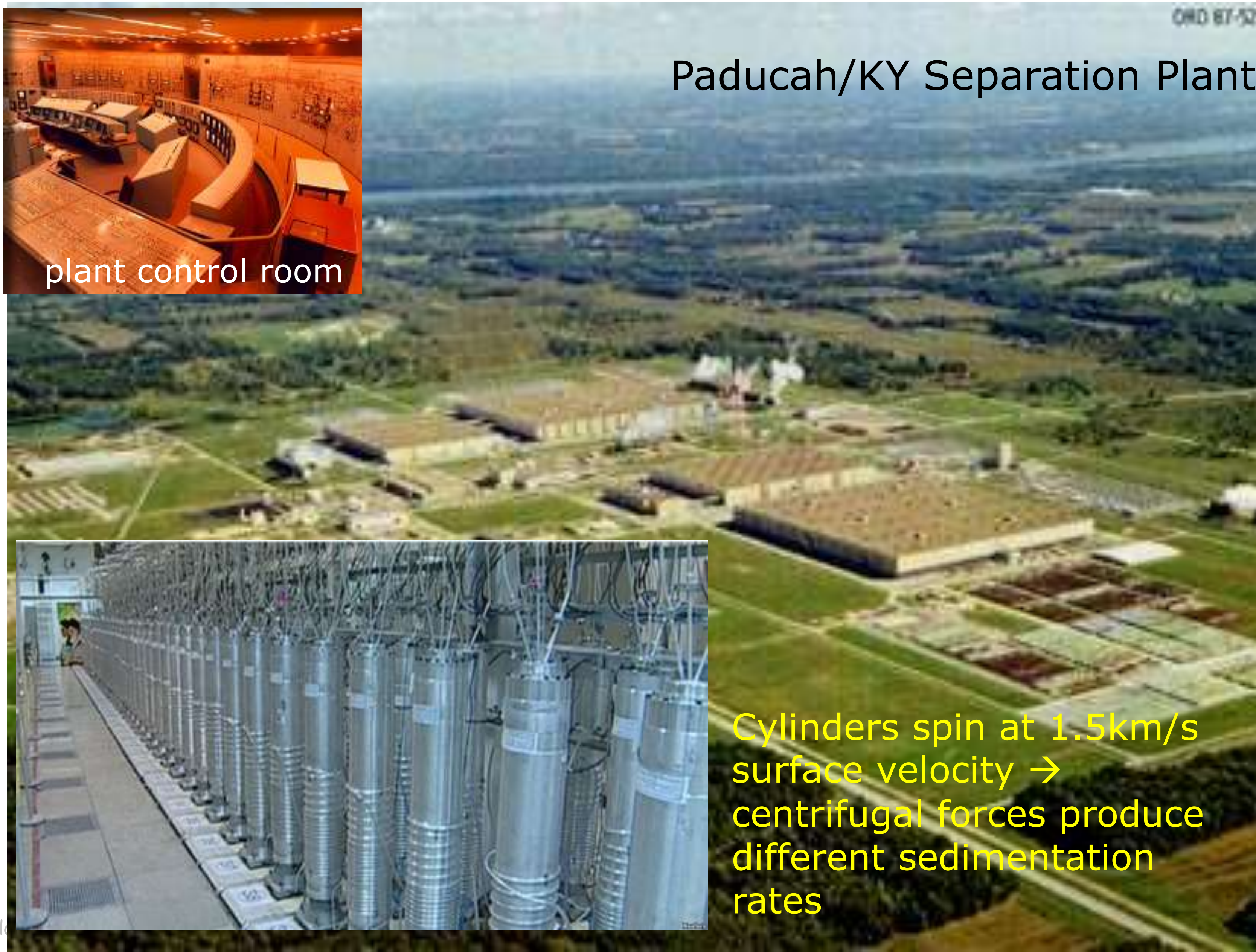
Uranium Fuel Conversion



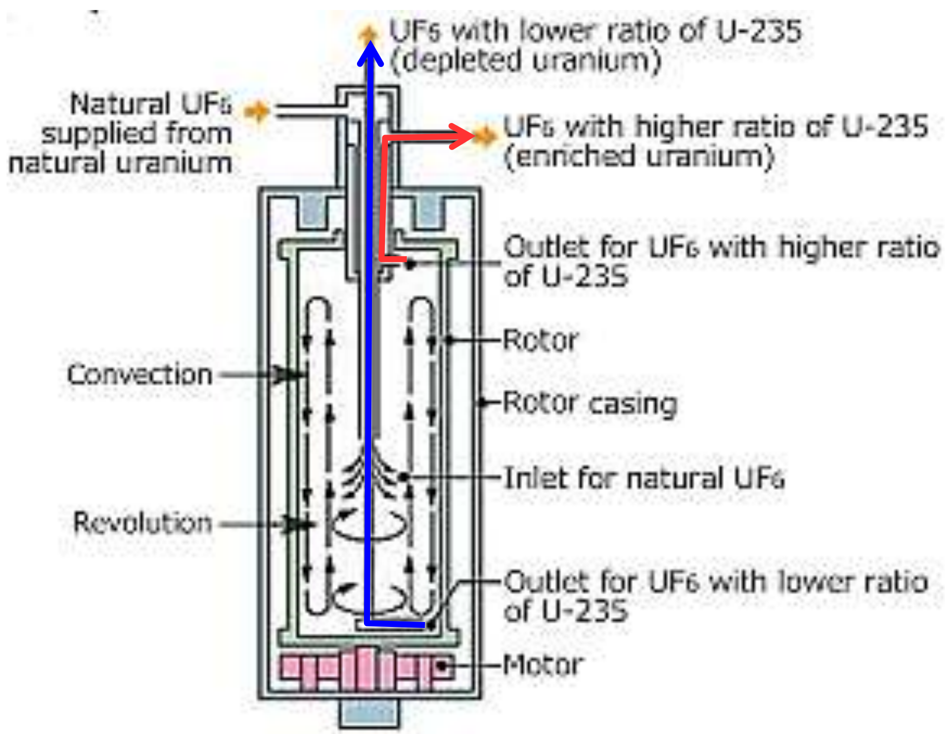




Fuel Cycle: Fuel Enrichment



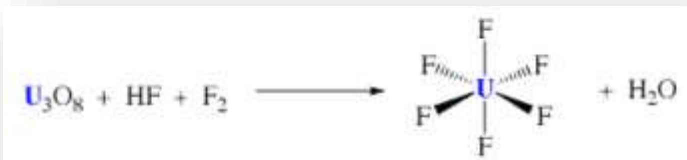
Gas Diffusion Isotope Enrichment



NPP (7TWh/a output) needs ≈ 6 GWh/a for 0.7 → 6% ^{235}U

	Weapons-Grade U (HEU)	Reactor-Grade U (LEU)	Natural U
^{234}U	0.12	0.025	0.0057
^{235}U	94.00	3.500	0.7193
^{238}U	5.88	96.475	99.2750

Intermediate enrichment ~20% needed for research & radio-pharma reactors

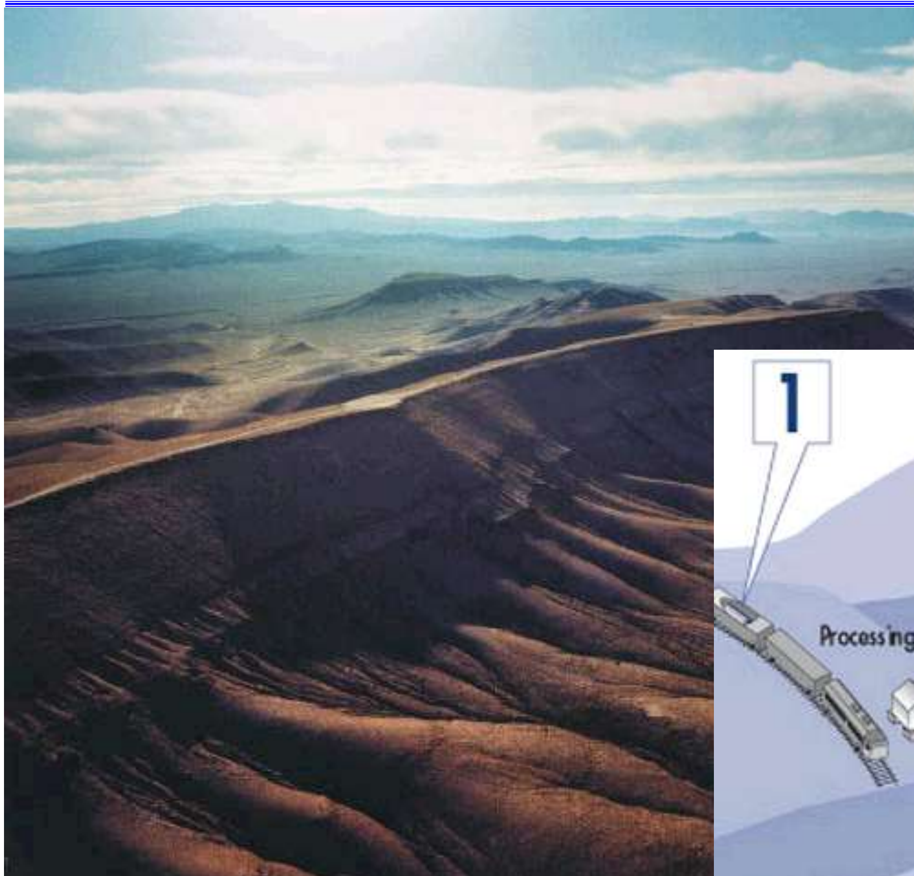


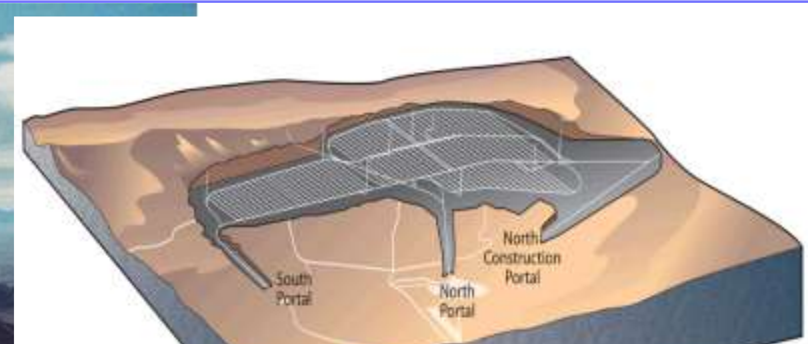
Preferred technology: Gaseous diffusion of UF_6 (^{19}F mono-isotopic)

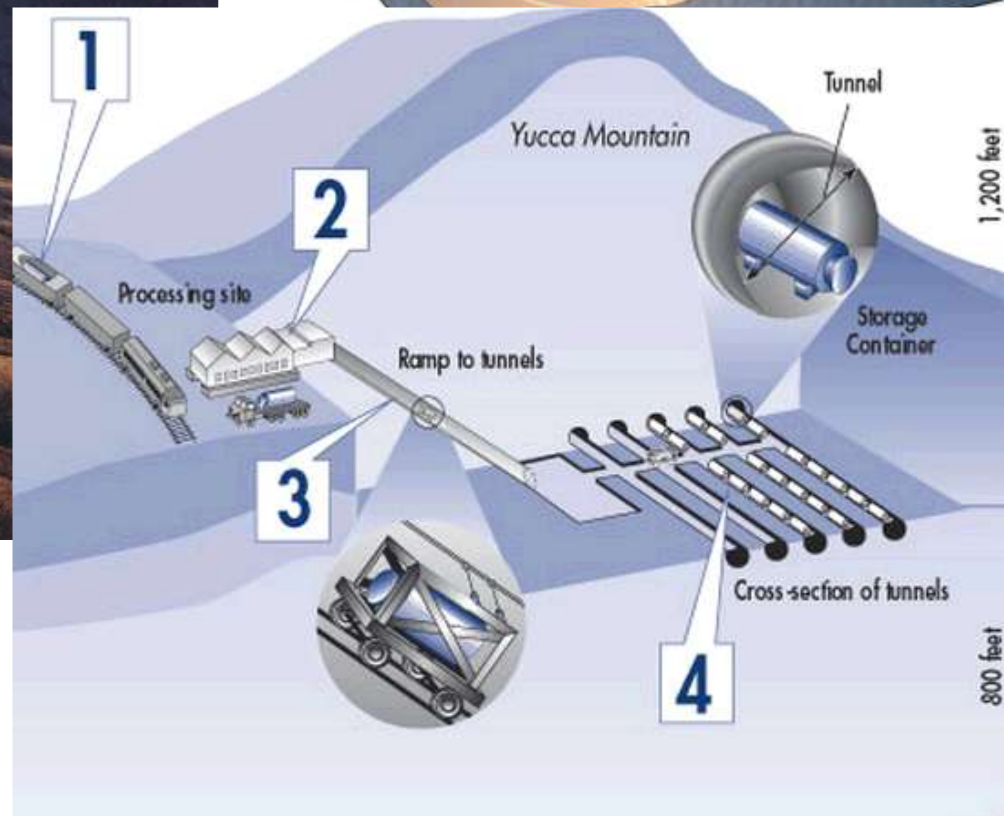
Laser ionization possible, economics

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

Yucca Mountain (NV) Depository







Spent-fuel canisters, sealed in special casks, are shipped to the site by truck or train.

Shipping casks are removed, inner tube with fuel elements is placed in a steel, multilayered storage container.

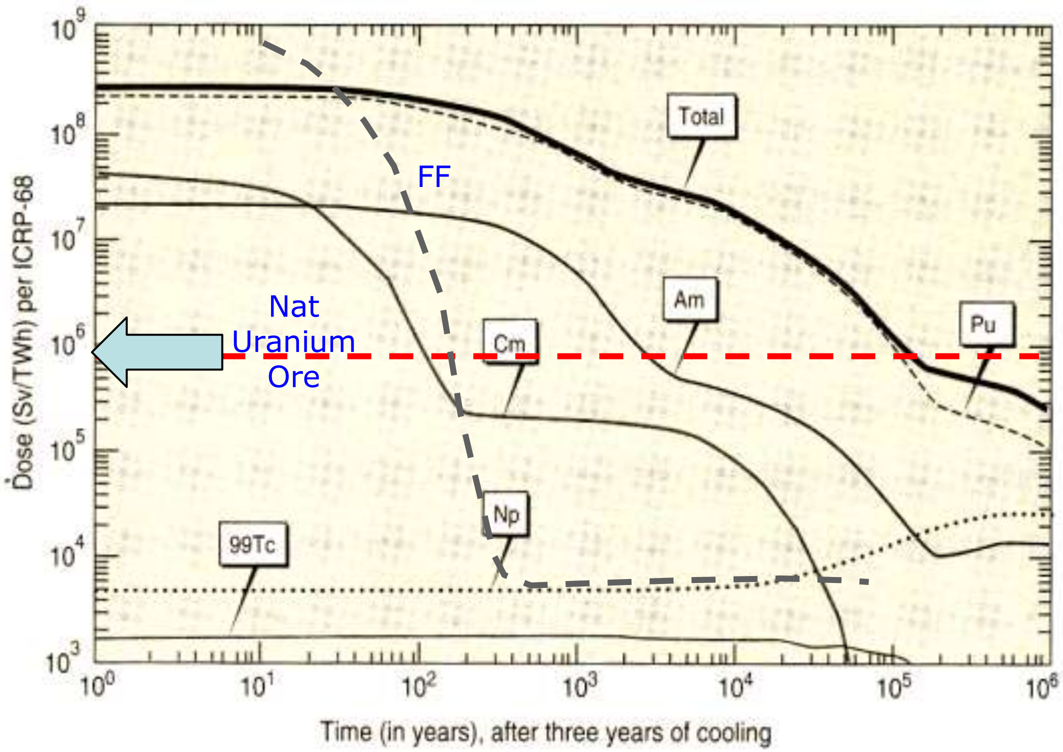
Automated system sends and manages storage containers in underground tunnels.

Containers stored on their side along the tunnels.

Retrievable for later use (or not)

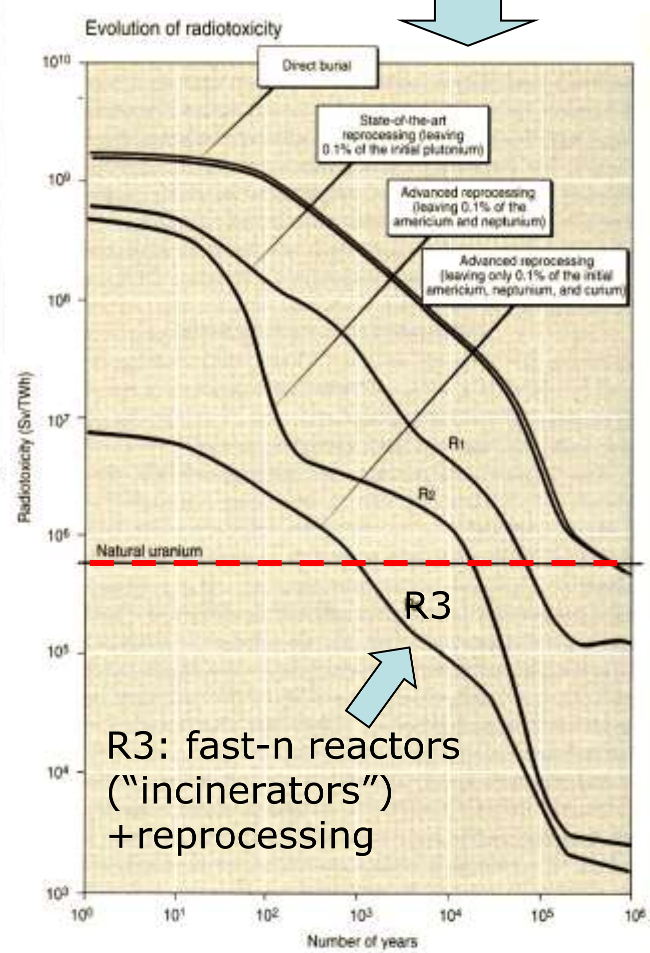
16 countries have geological depositories

Radioactive Waste: Power Reactors/Weapons Stewardship



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

Radio-chemical reprocessing



R3: fast-n reactors ("incinerators") +reprocessing

Very-long-lived ^{99}Tc, ^{129}I >could< dissolve in groundwater and move through ecosystem → disposal strategies for isolation.

→ Better: reprocessing, transmutation/incineration of ^{99}Tc, ^{129}I, Np

1 Sv (Sievert) = 100 rem, biolog. equivalent to 1J/kg X-rays
Radiotoxicity: R(Sv)=(Dose in Sv/decay), Activity/kg

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