

Power from Nuclear Transmutation (Fission and Fusion)

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ESTS 4-3-Nucl_Fission

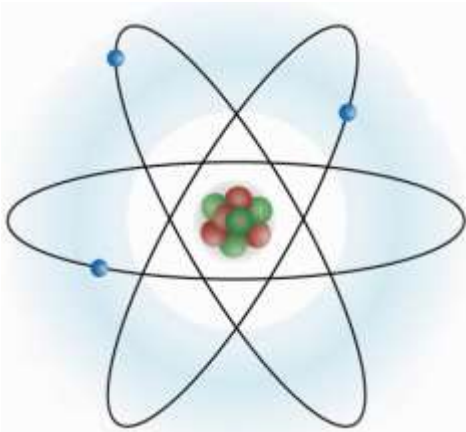


The Diablo Canyon NPPT produced CO₂-free electricity at 2¢/kwh, half the state's (CA) average cost.

Agenda

- Nuclear stability & particle radiation
Potential biological hazards
- Energy Generation from Nuclear Fission
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)
- U.S./World trends,
Nuclear fuel resources (U.S.),
- Strategic Issues for Nuclear Power
Sustainability, reliability, scalability, safety, eco-footprint, cost
- Energy from nuclear fusion reactions
Fusion energetics, critical
Principles of magnetic and inertial confinement

Basic Nuclear Properties



Classical Model of Atom

Isotope Terminology

A_{number}	14	C
Z_{number}	6	
N_{number}	$= A - Z$	

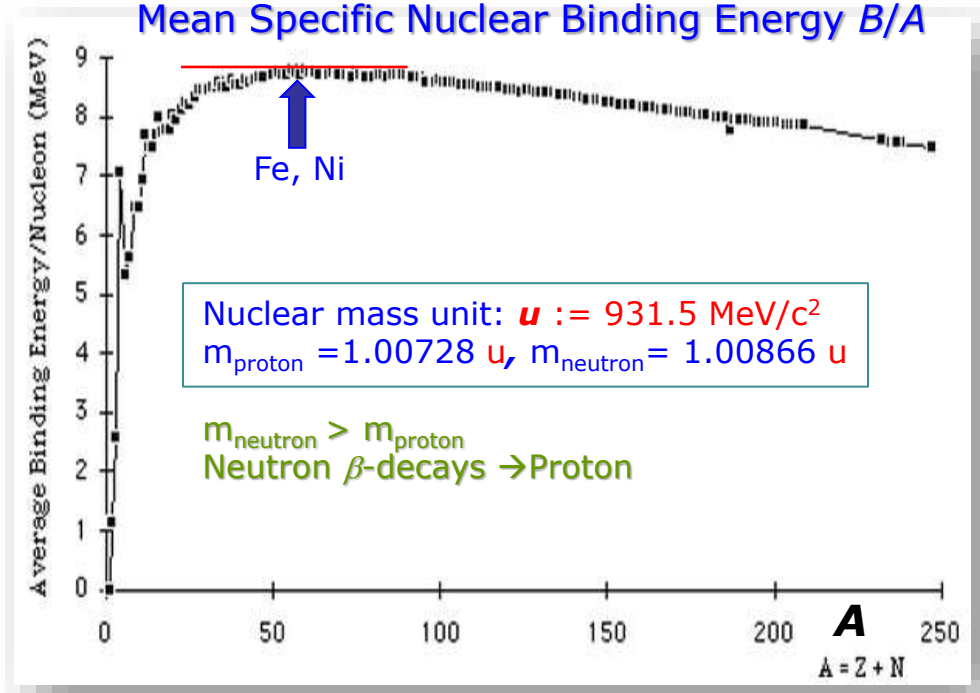
^{12}C = **stable isotope**
 \rightarrow ^{14}C or C-14 \leftarrow
 = **radioactive isotope**

Atom of element Z: Z negatively charged electrons orbit around a Z-times positively charged, small nucleus in center. Nucleus = (Z protons, N neutrons), mass number $A = N + Z$. Nuclear radii range $R_{\text{Nucleus}} \approx (1-10) \cdot 10^{-15}\text{m}$. (1 fm = 10^{-15}m)

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

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

Mean Specific Nuclear Binding Energy B/A

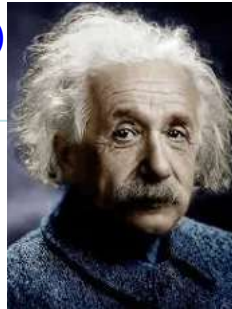


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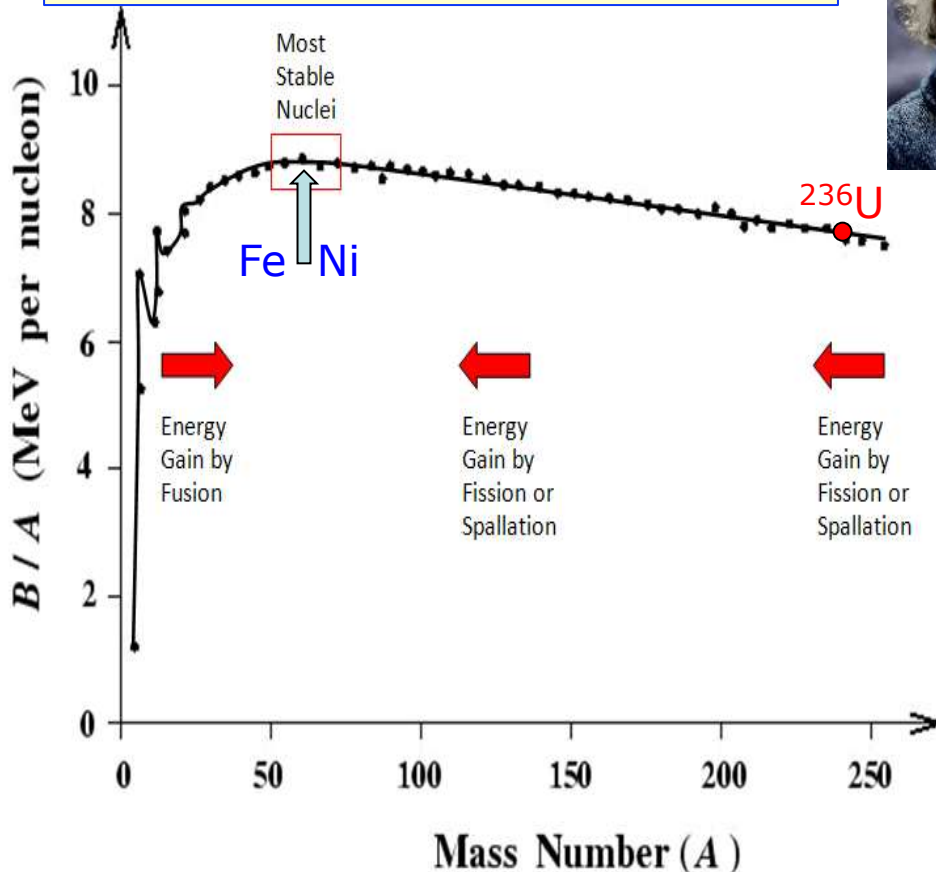
Basic Energetics: Nuclear Rearrangement Energies

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

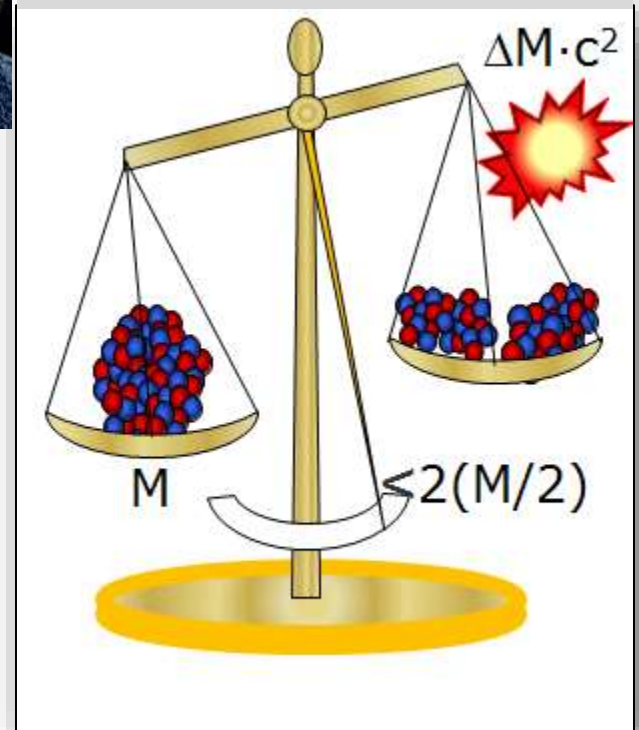
Einstein: equivalence
mass = energy $E = M \cdot c^2$



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



Energy release in fission $A \rightarrow 2A/2$



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

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

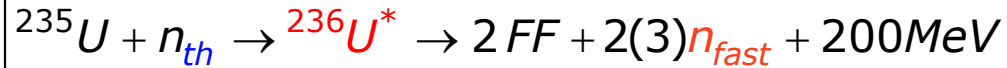
Fission of $^{235,238}\text{U}$ from g.s. is not spontaneous \rightarrow Activation energy = Fission Barrier
Pass via n-capture $^{235}\text{U} + n \rightarrow ^{236}\text{U}^*$



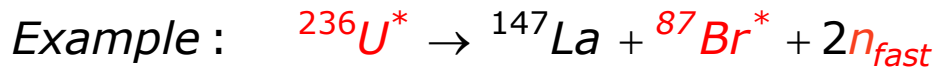
ESTS_4-3-Nucl_Fission

Energy Release in n_{th} -Induced Fission

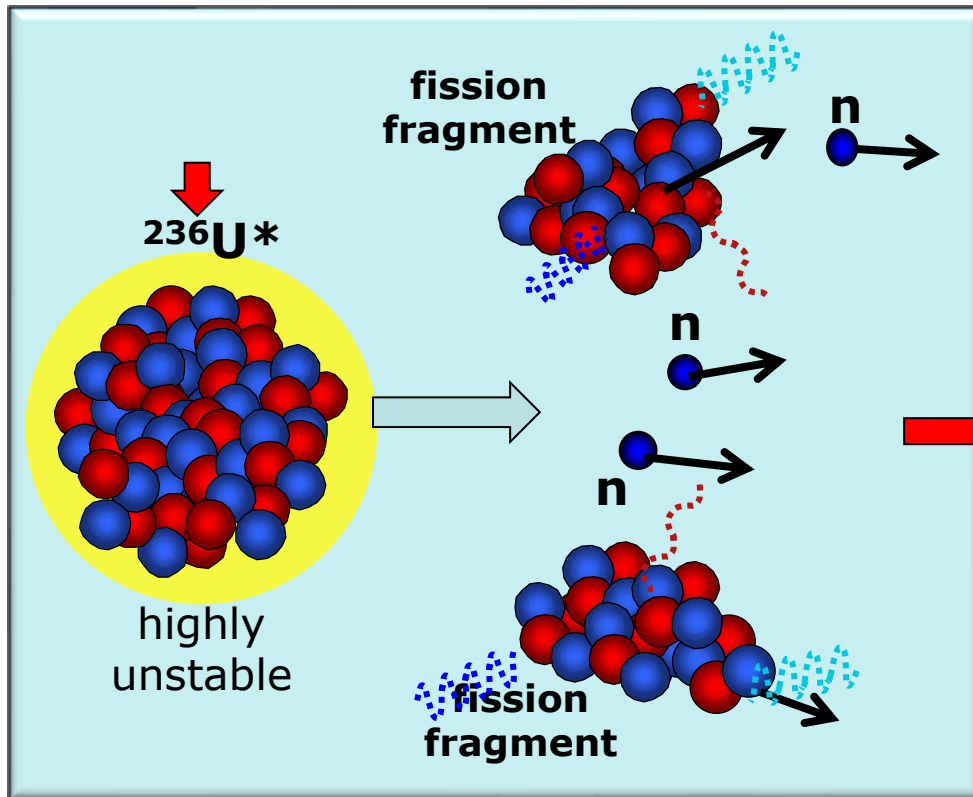
↓ thermal → $E = (3/2)k_B T$, $k_B T = 25 \text{ meV}$



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



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



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

→ Thermal energy/heat

$$1 \text{ g } {}^{236}\text{U}/\text{day} = 1 \text{ MW}$$

$> 10^8$ x chemical energies

$$E_{ff} = 168 \text{ MeV}$$

$$E_{n \text{ tot}} = 5 \text{ MeV}$$

$$E_{\gamma} = 7 \text{ MeV}$$

$$\text{FF } \beta\text{-decay} = 27 \text{ MeV}$$

$$Q_{\text{total}} = 207 \text{ MeV}$$

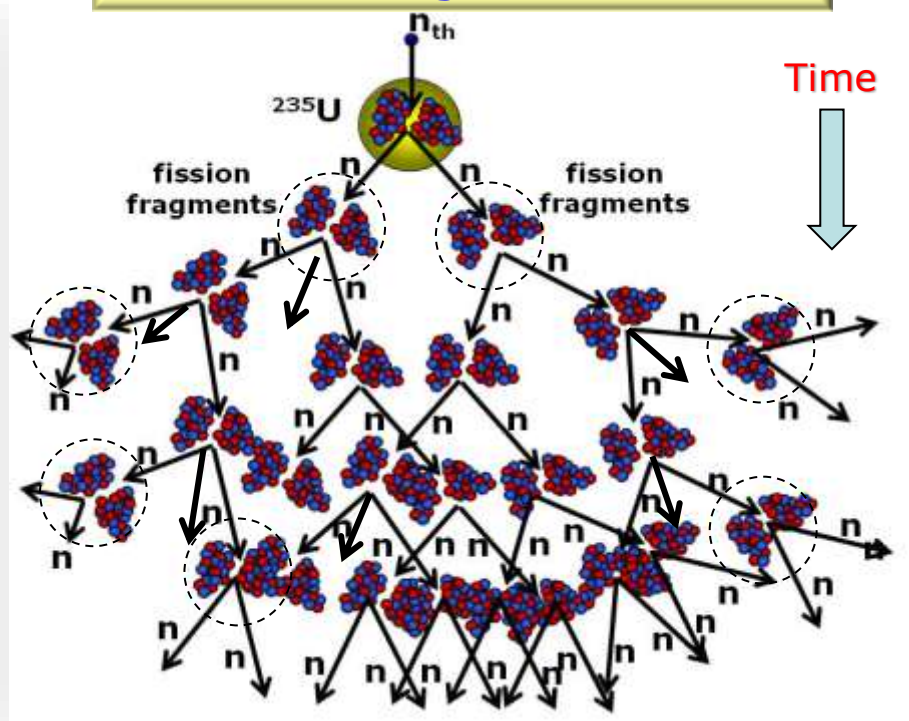
Self-Sustaining Fission Chain Reaction



Leo Szilard
1938

Neutron multiplication through fission: $k=2.4$, minus losses (capture, leaking, escape,..) \rightarrow effective $k < 1$.
One n used in each fission \rightarrow 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
 ($\tau \sim 40\mu\text{s}$ in critical reactors
 $\tau \sim \text{ns}$ in explosive devices)

$k_{\text{eff}} = k_{\text{prompt}} + k_{\text{delayed}}$
 Reactor Control: delayed n 's

Characteristic time period

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

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



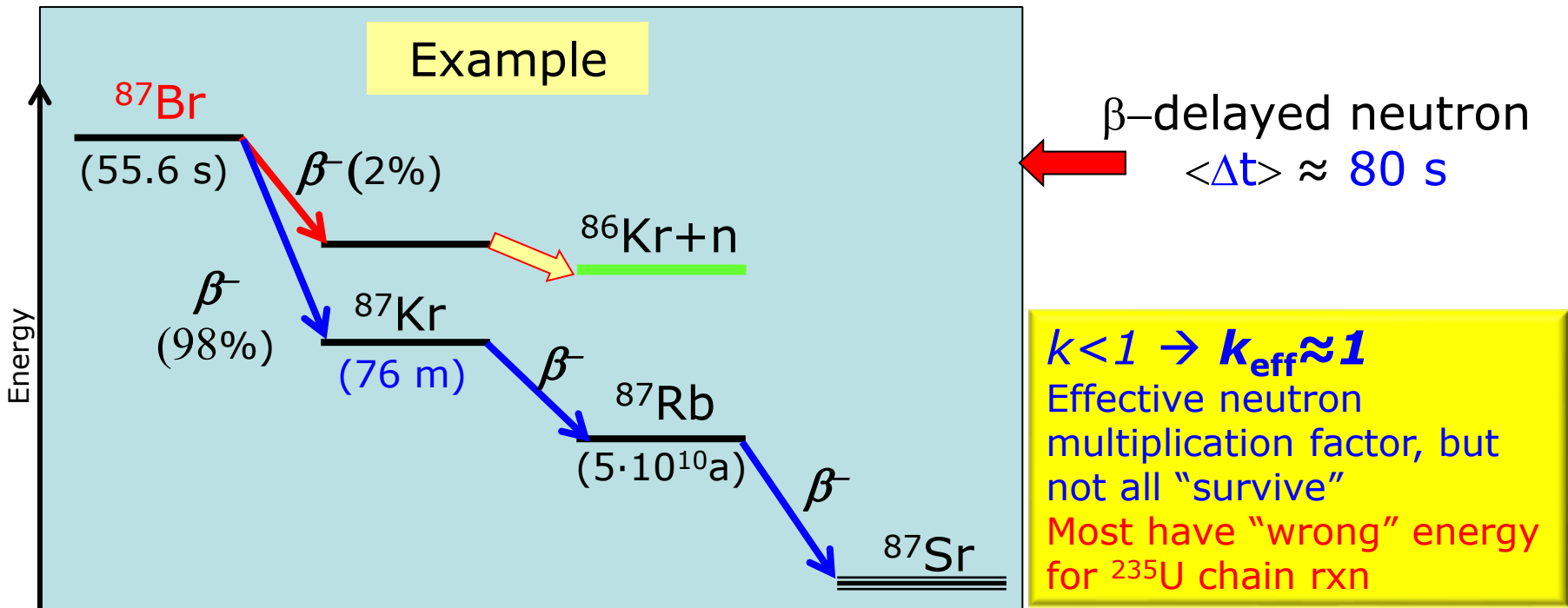
Most fission neutrons are lost or not useful for further fission.
 Fission fragments = "reactor poison" $\rightarrow k_{\text{eff}} < 1$ stops chain reaction!

β -Delayed Neutrons

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

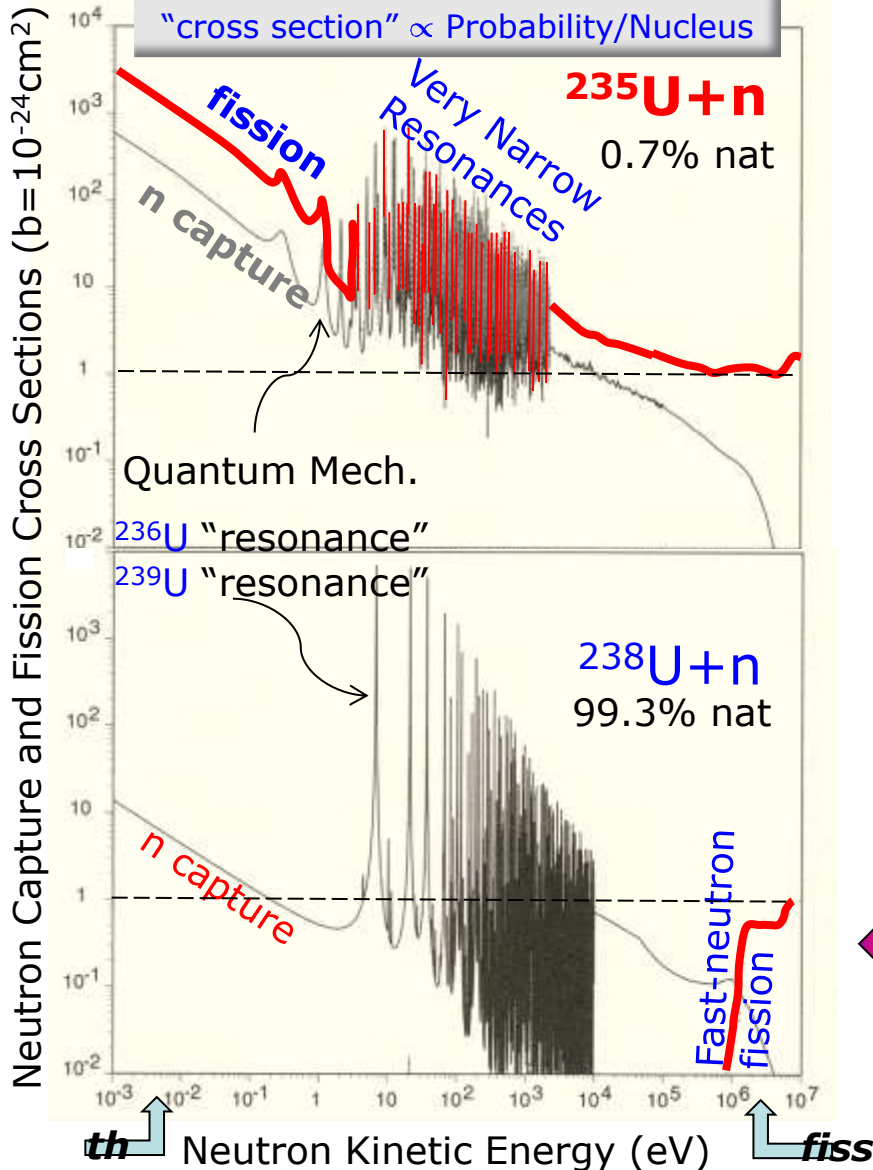
0.65% of neutrons from ^{236}U fission are delayed (occur after fission) \rightarrow
 = *Essential for sustaining chain rxn + control function*

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"Ignition" possible? \rightarrow self-sustaining chain reaction

Fission and n-Capture Probabilities ("Cross Sections")



Central Challenge:

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

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

Fission cross sections → typically small,

^{238}U : $\sigma_f \sim 1 \text{ b}$ for $E_n > 1 \text{ MeV}$
 $\approx 0 \text{ b}$ for $E_n < 1 \text{ eV}$ $1 \text{ b} = 10^{-24} \text{ cm}^2$

dominating: scattering ($\sim 8 \text{ b}$) + capture

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

dominating: (n, f) fission

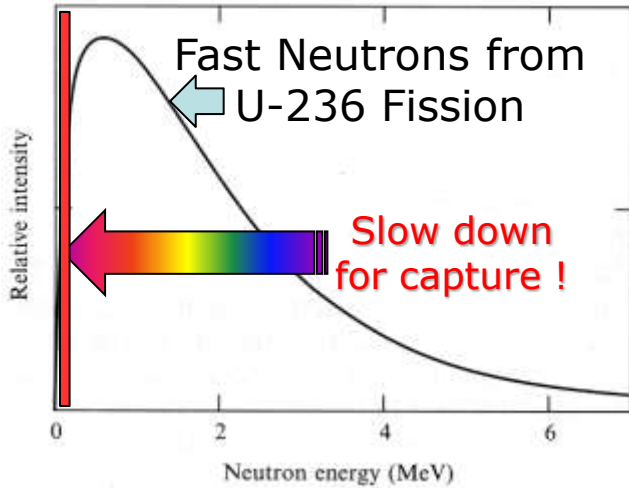
Observed natU fission is due to (0.7%) ^{235}U

→ isotopically enrich ^{235}U , > 4% -20% for higher efficiency (\propto 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



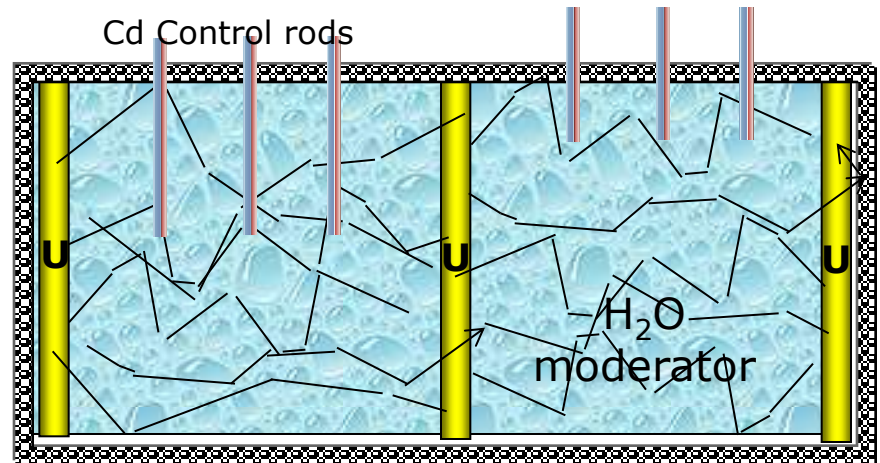
Fission neutrons too energetic, \rightarrow
 "thermalize" to maximize $\sigma_{n,fiss}$ for ^{235}U !
 \rightarrow multiple elastic scattering ("moderation")
 moderator: small σ_{capt} !

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

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

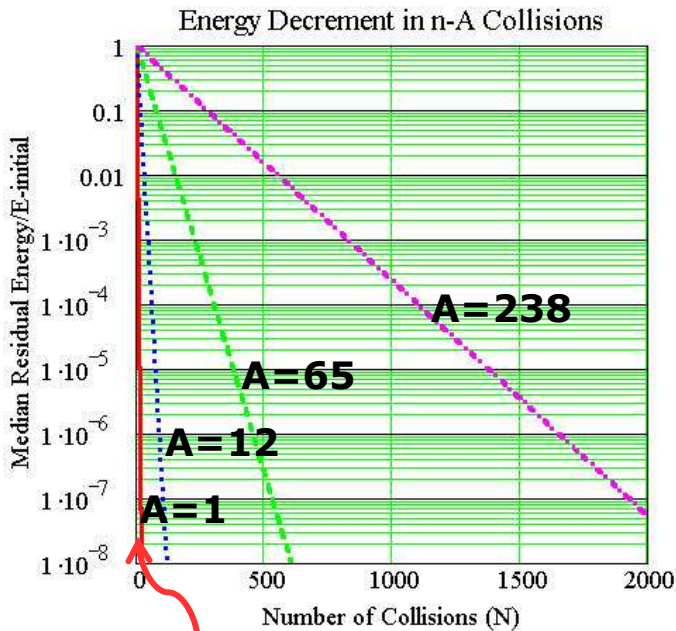
Needed: moderator and fuel coolant

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



H can capture neutrons ($k < 1$!):

$H+n_{th} \rightarrow D+2.2\text{ MeV}$



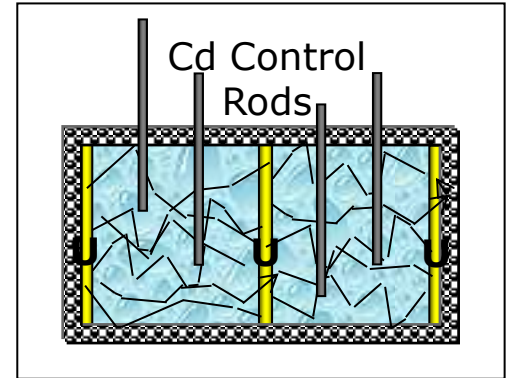
H, D are best moderators

Reactor Control and Safety

“Reactivity $d\rho/dT$ ”; $\rho = (k_{\text{eff}} - 1)/k_{\text{eff}}$

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

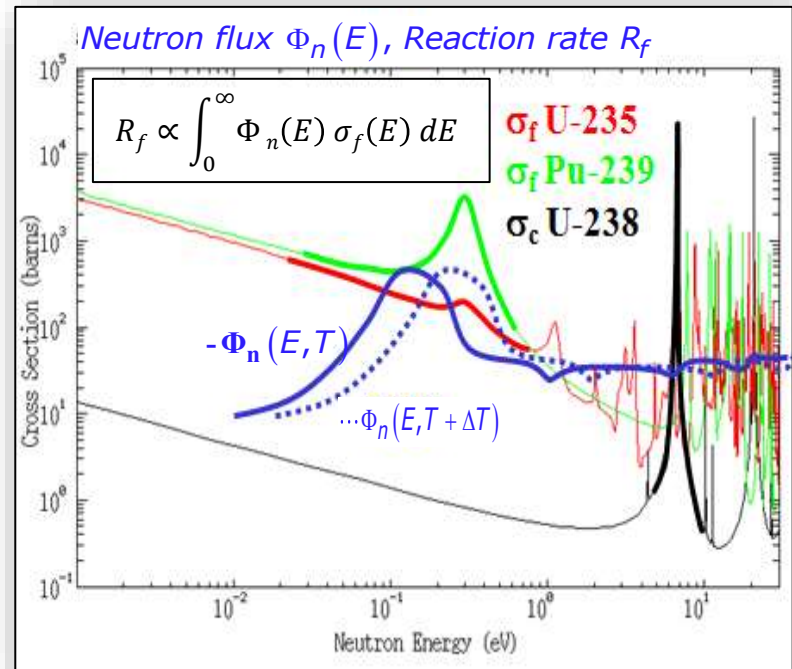
Doppler Effect: broadening of resonance and n spectrum leads to increased n-capture by ^{238}U $\rightarrow d\rho/dT < 0$

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

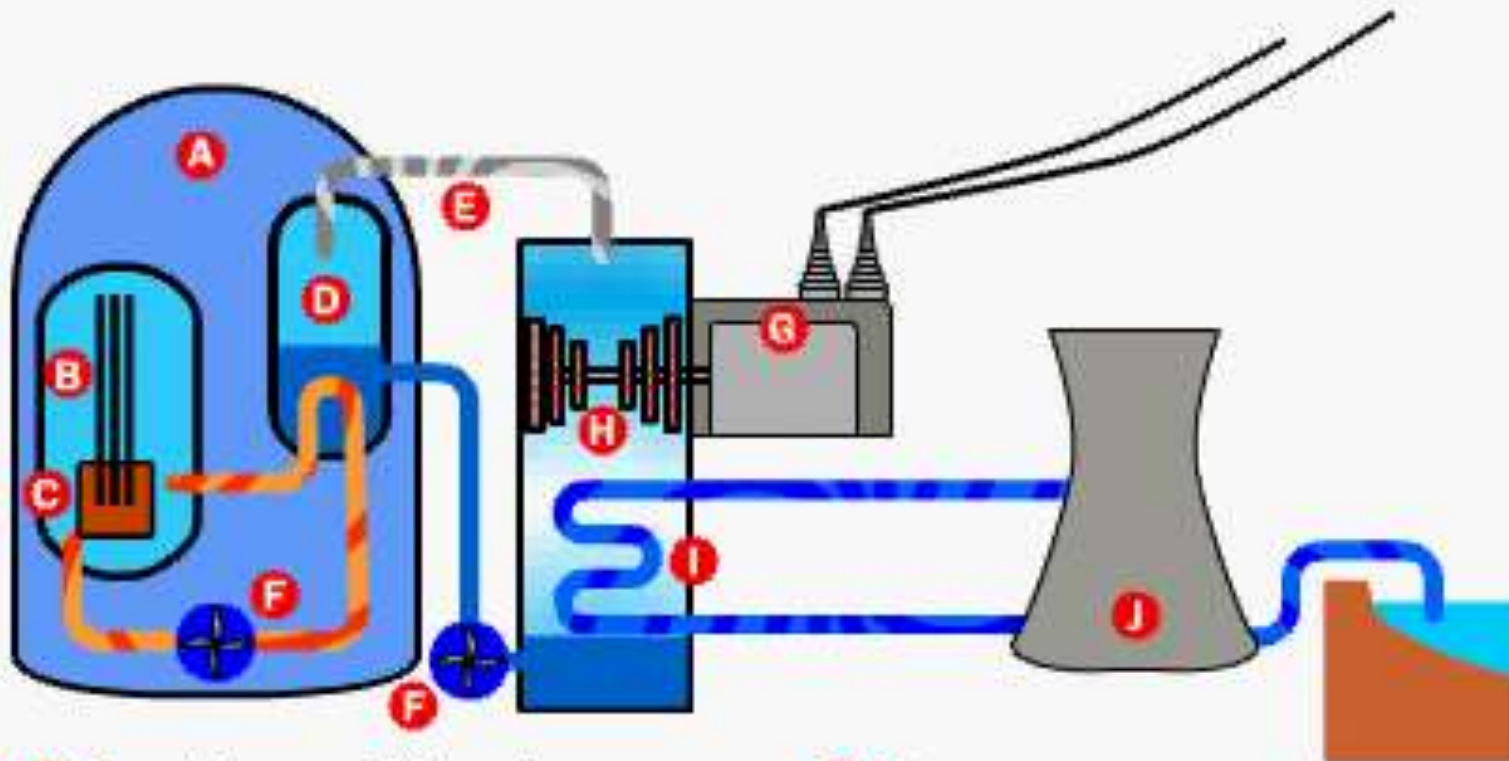
Dilatation Effect: hot moderator delays slowing down $\rightarrow d\rho/dT < 0$

$d\rho/dT = -(0.5-1) \times 10^{-4} / ^\circ\text{C}$ PWR

$d\rho/dT = -1 \times 10^{-3} / ^\circ\text{C}$ Breeder, EA



Principle Boiling Water Reactor



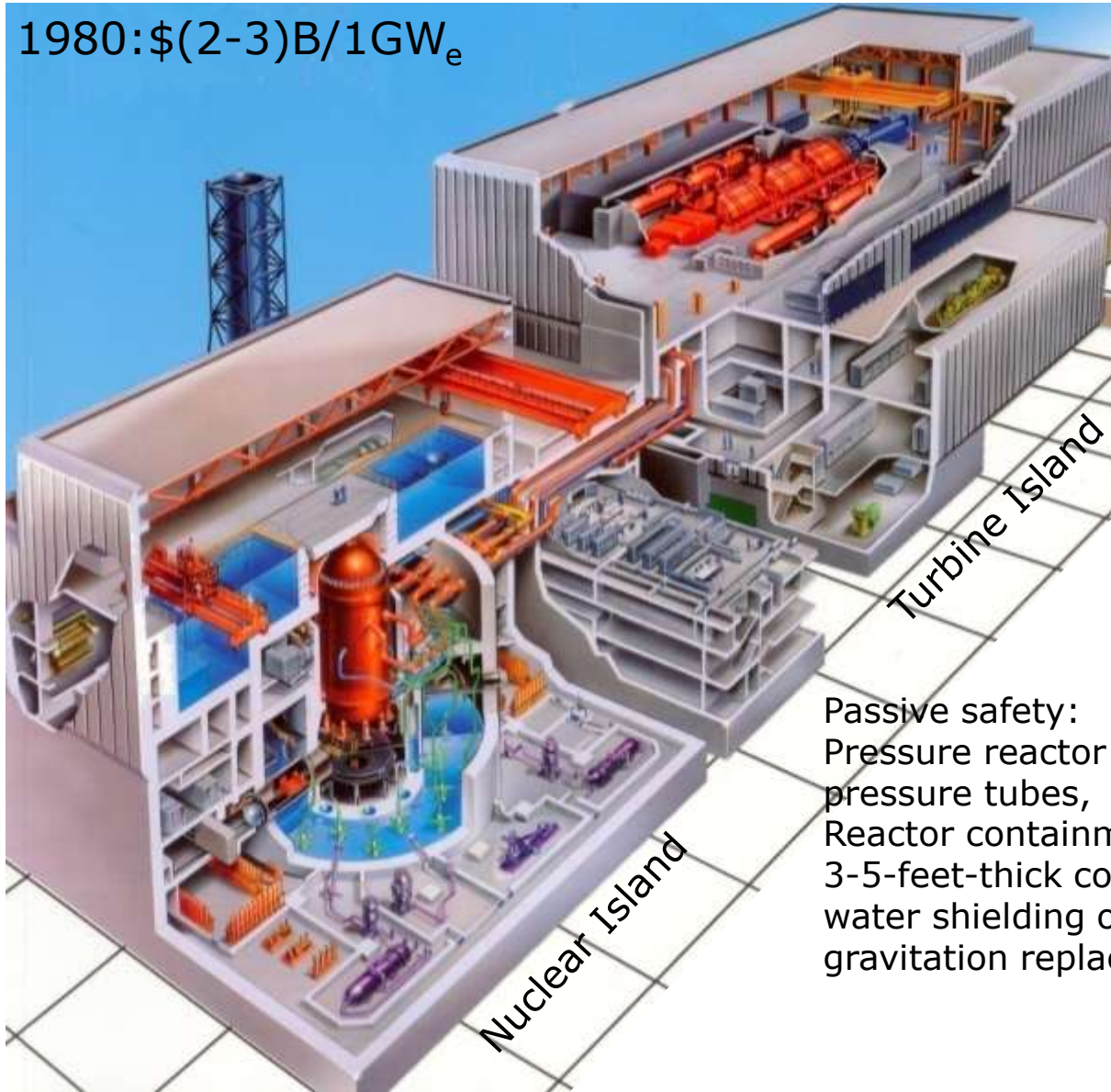
- A** Containment Structure
- B** Control Rods
- C** Reactor
- D** Steam Generator
- E** Steam Line

- F** Pump
- G** Generator
- H** Turbine
- I** Cooling Water Condensor
- J** Cooling Tower

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

1980: \$(2-3)B/1GW_e



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:

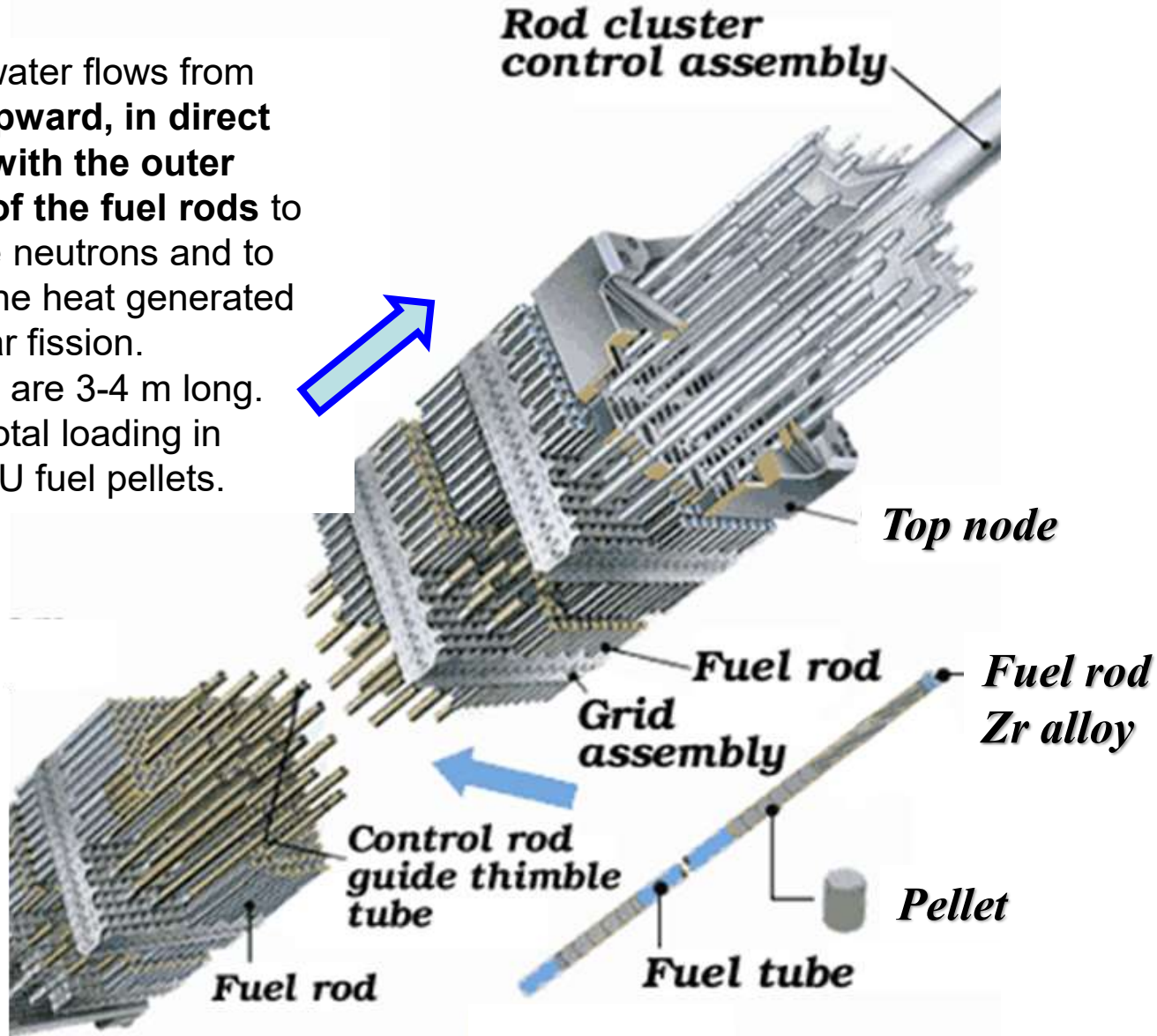
Pressure reactor vessel $\sim 1'$ thick steel, pressure tubes, Reactor containment building with several 3-5-foot-thick concrete walls, concrete + water shielding on top of reactor vessel, gravitation replaces mechanical pumps.

Fuel Elements



Reactor Fuel Assembly

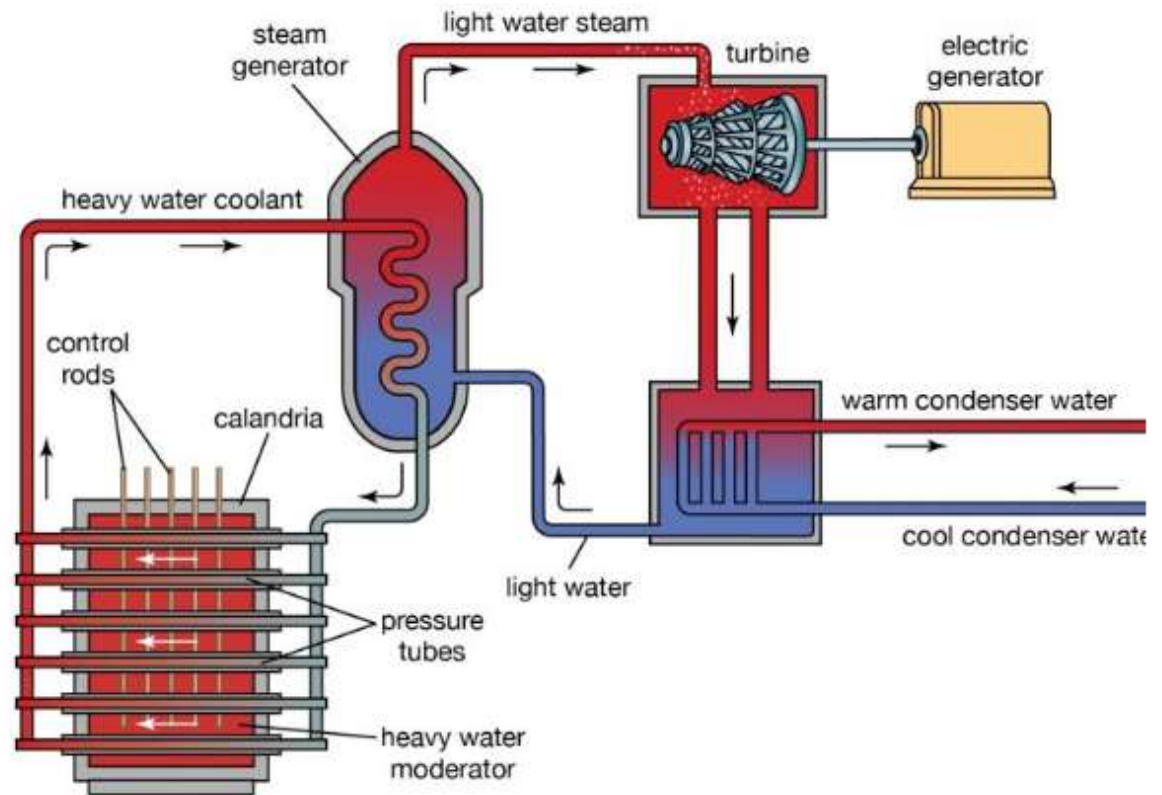
Cooling water flows from bottom **upward**, in **direct contact with the outer surface of the fuel rods** to moderate neutrons and to remove the heat generated by nuclear fission. Fuel rods are 3-4 m long. 10-20kt total loading in enriched U fuel pellets.



CANDU Pressurized Water Reactor

CANDU (CANadian Deuterium Uranium) reactor uses "heavy water" ($^2\text{H}_2\text{O}$) as moderator/coolant. Heavy water is an excellent moderator and neutron loss is lower because of less capture in heavy water. → Natural uranium and any other fuel can be used in the reactor.

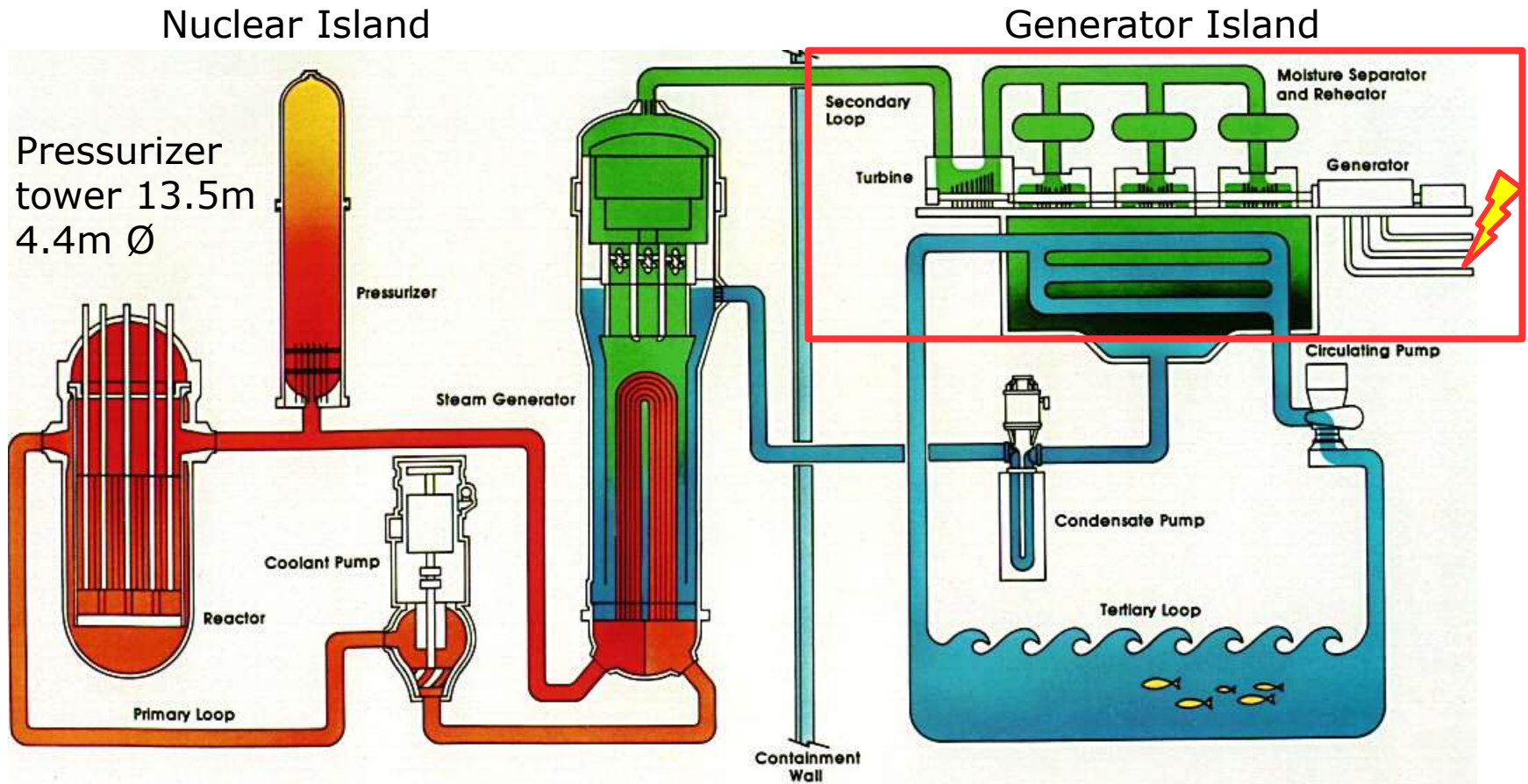
Fuel can be loaded with reactor in operation.



PWR Primary and Secondary Cooling Systems

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Nuclear Steam Supply System

MB 3618A

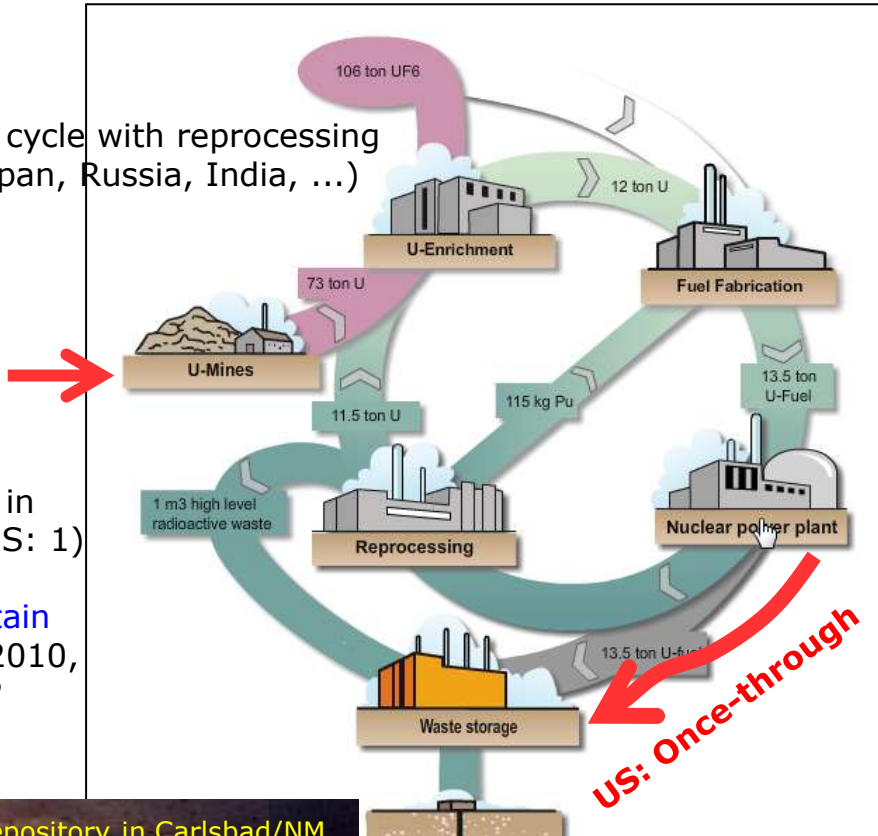
Nuclear Fuel Storage & Transport



Uranium and Thorium Fuel Cycles

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

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

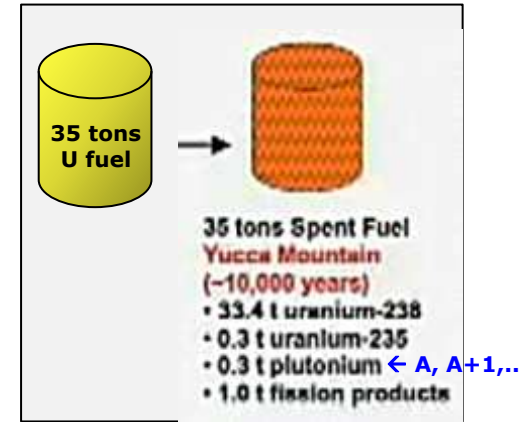


Worldwide: 5 geological depositories in operation (US: 1)

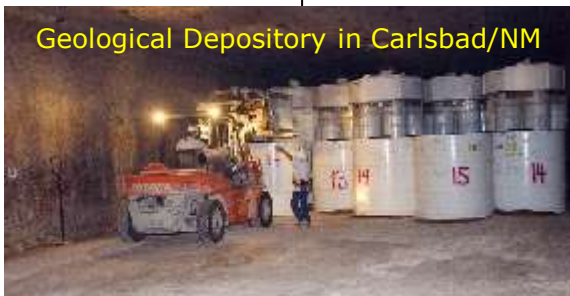
Yucca Mountain Stopped in 2010, temporarily?

Permanent storage of high-level waste already paid for by consumers $\phi 0.1/\text{kWh}$.

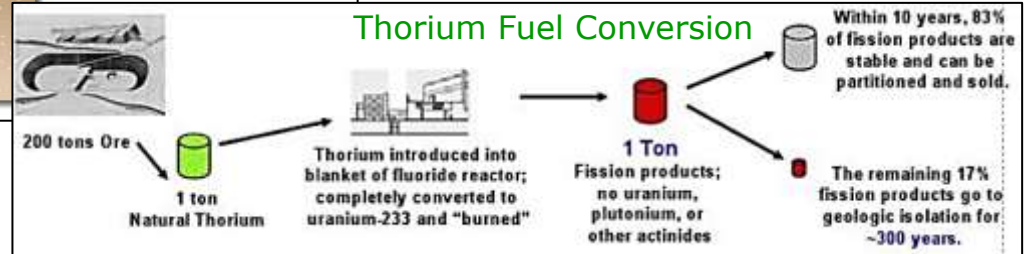
Uranium Fuel Conversion



Geological Depository in Carlsbad/NM



Thorium Fuel Conversion



Fuel Cycle: Fuel Enrichment

OHD 87-520

Paducah/KY Separation Plant



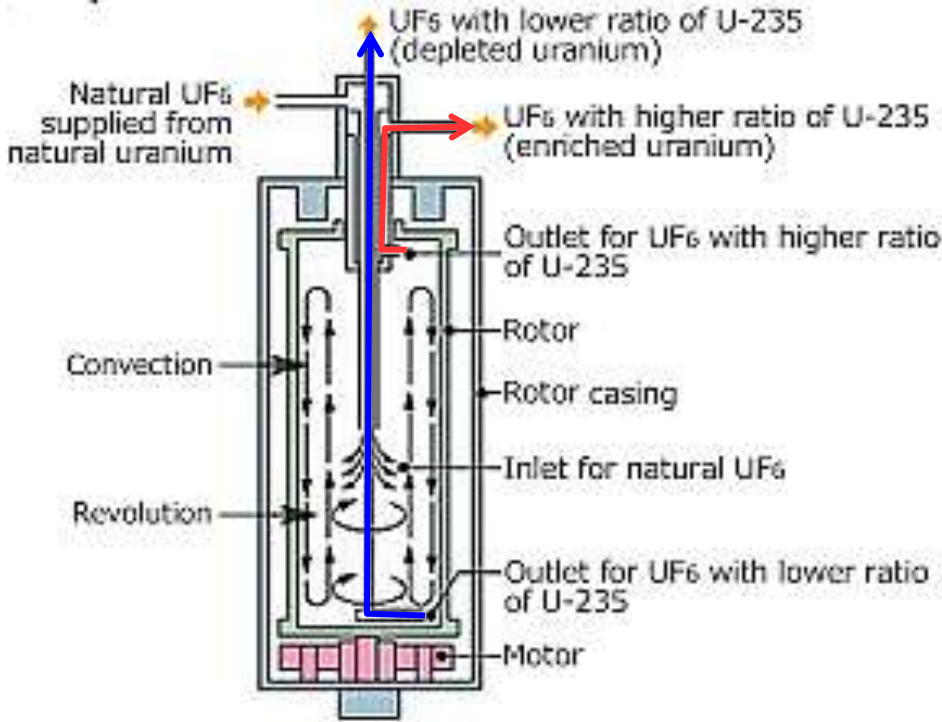
plant control room



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



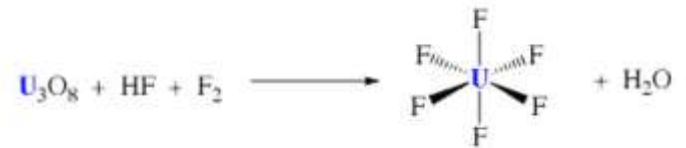
Gas Diffusion Isotope Enrichment



NPP (7TWh/a output) needs
 ≈ 6 GWh/a for $0.7 \rightarrow 6\%$ ^{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
 $\sim 20\%$ needed for research & radio-pharma reactors

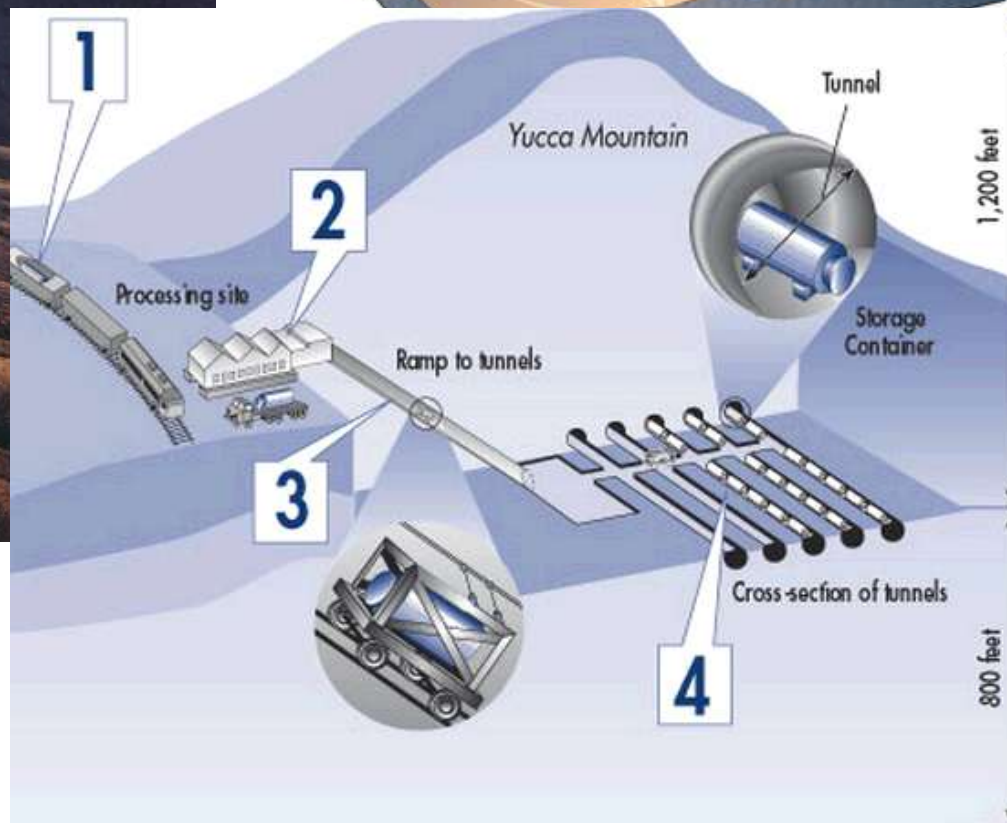
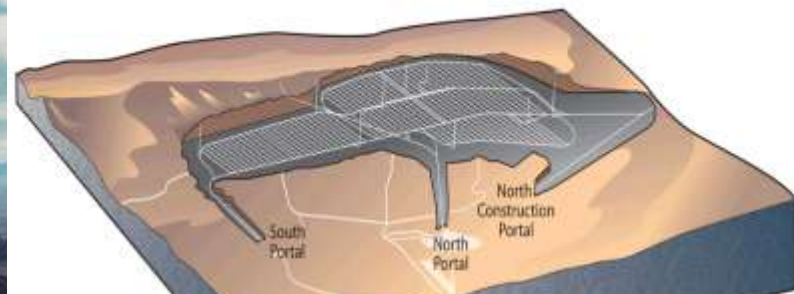
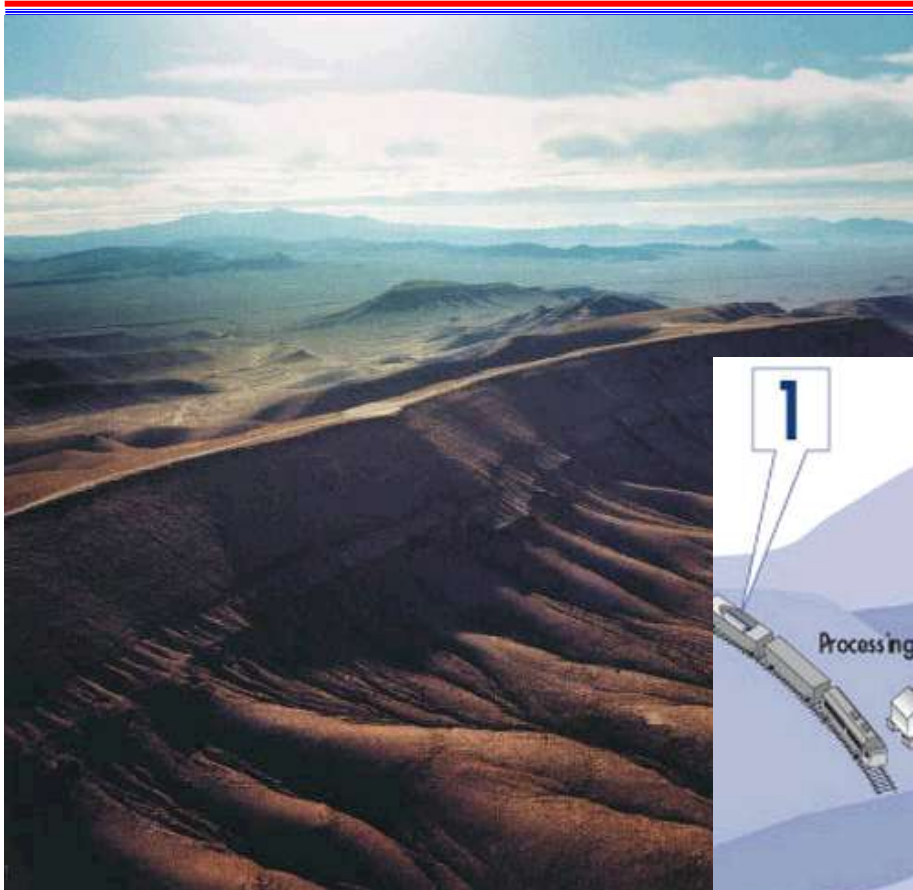


Preferred technology: Gaseous diffusion of UF_6 (^{19}F mono-isotopic)

Laser ionization possible, economics

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

Yucca Mountain (NV) Depository

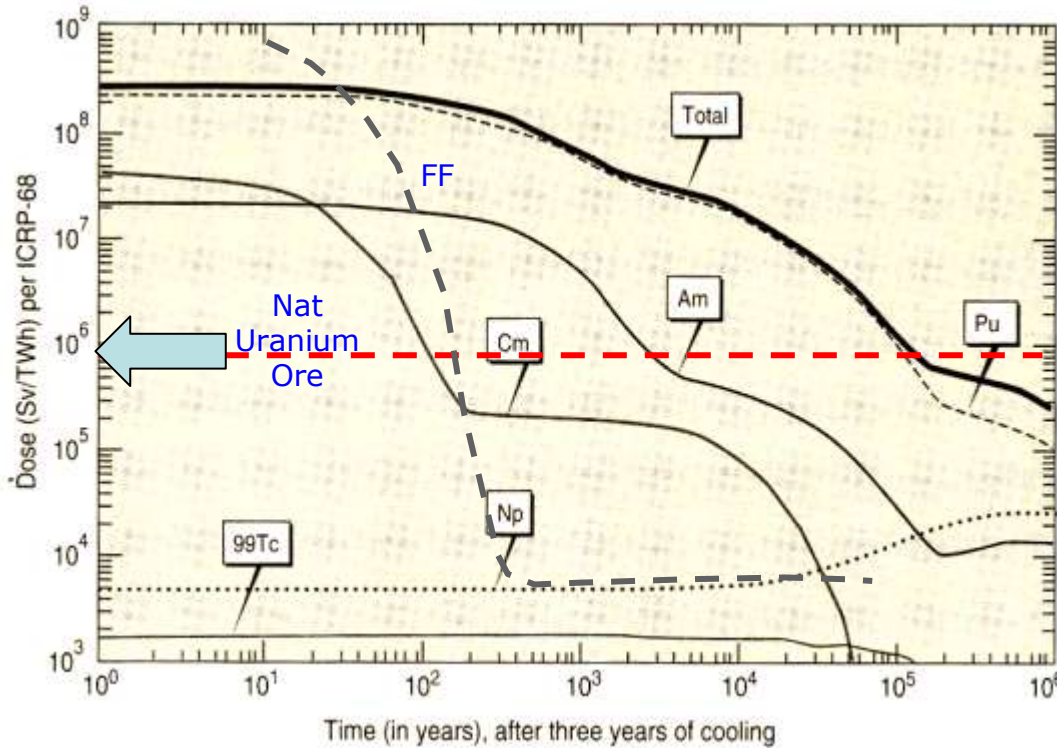


Spent-fuel canisters, sealed in special casks, are shipped to the site by truck or train.
Shipping casks are removed, inner tube with fuel elements is placed in a steel, multilayered storage container.
Automated system sends and manages storage containers in underground tunnels.
Containers stored on their side along the tunnels.
Retrievable for later use (or not)

16 countries have geological depositories

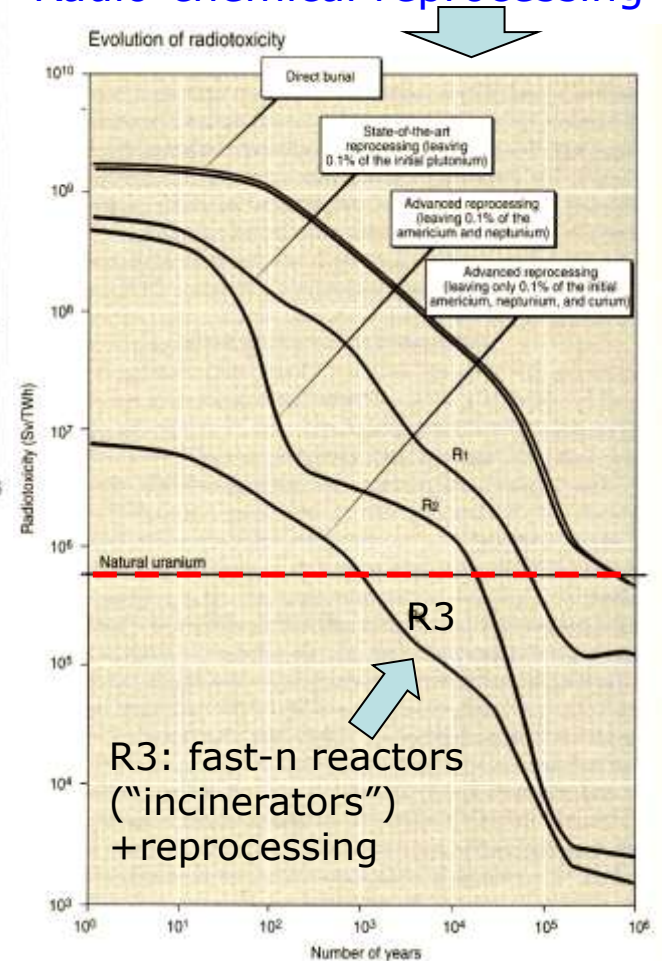
Radioactive Waste: Power Reactors/Weapons Stewardship

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

Radio-chemical reprocessing



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

➡ Better: reprocessing, transmutation/incineration of ⁹⁹Tc, ¹²⁹I, Np

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

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

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