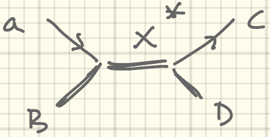
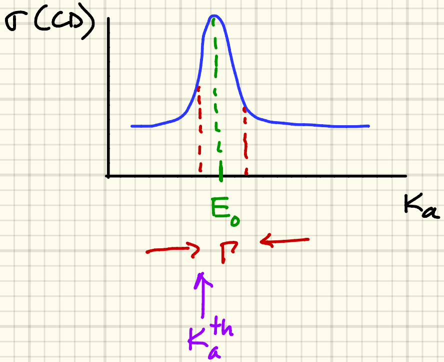
# Intermediate states

often:



short-lived, excited state



"lifetime" from uncertainty.

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

$$\Gamma \tau \geq \frac{\hbar}{2}$$

"Resonance"

think of resonant energy as:

$$m_x c^2$$

and

$X \to C + D$ quickly

in nuclear physics X is often an excited state of C ... $C^*$

in particle physics X is actually an excited state of quarks

# Neutrons are special.

Often: "neutron capture" $\;{}^{1}_{0}n + {}^{A}_{Z}X \longrightarrow {}^{A+1}_{Z}X^{*} \longrightarrow {}^{A+1}_{Z}X + \gamma$

$\hookrightarrow {}^{A+1}_{Z+1}Y + \beta + \nu$

# How often?

depends on nucleus .. neutrons are hard to stop

some substances have high neutron capture cross sections .. Cd, for example

Often: $\quad n + p \to \underset{\substack{\uparrow \\ \text{slower}}}{n} + p$

"moderation" light elements like p are good moderators

water, H, paraffin

principle behind neutron bomb

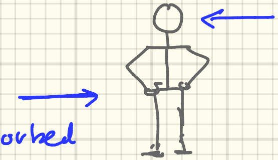
humans — mostly water, neutrons moderate, accelerating protons which ionize DNA, cells, etc

# Primer on radiation units

Activity: remember

Bq SI

Ci



absorbed dose: rad, Gy.

biologically effective absorbed dose rem, Sv

Intensity: Roentgen 1R = 0.000258 C/kg air ionization

Absorbed dose:

1 rad = 0.01 J/kg of tissue

1 Gray = 1 Gy = 1.0 J/kg of tissue = 100 rad. SI

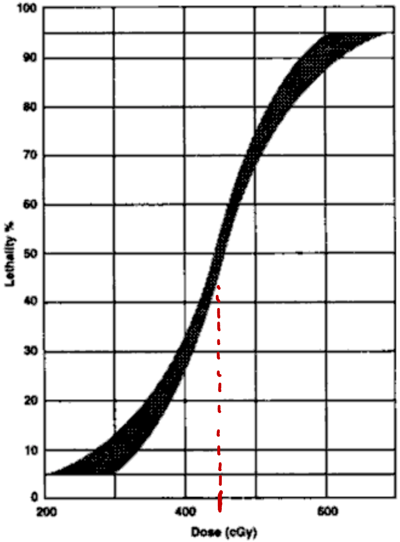
Bio-effective dose:

1 rem = 1 rad × Q

1 Sievert = 1 Sv = 100 rem SI

$Q \simeq$ 10-20 neutrons, E-dependent

| | |
|---|---|
| 20 | $\alpha$ |
| 1 | $\gamma$ |
| 1 | $\beta$ |



4.5 Gy

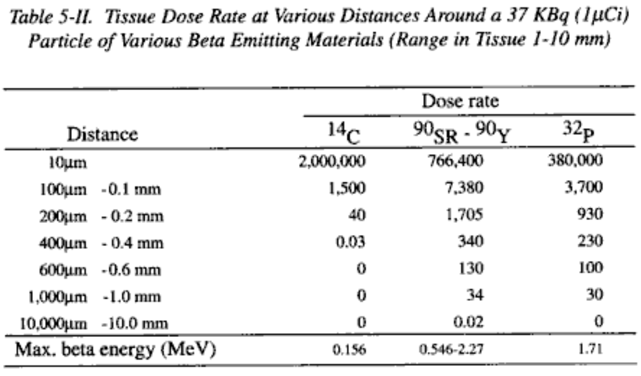


*Table 5-II. Tissue Dose Rate at Various Distances Around a 37 KBq (1μCi) Particle of Various Beta Emitting Materials (Range in Tissue 1-10 mm)*

| Distance | Dose rate | | |
|---|---|---|---|
| | $^{14}C$ | $^{90}SR$ - $^{90}Y$ | $^{32}P$ |
| 10μm | 2,000,000 | 766,400 | 380,000 |
| 100μm -0.1 mm | 1,500 | 7,380 | 3,700 |
| 200μm - 0.2 mm | 40 | 1,705 | 930 |
| 400μm - 0.4 mm | 0.03 | 340 | 230 |
| 600μm -0.6 mm | 0 | 130 | 100 |
| 1,000μm -1.0 mm | 0 | 34 | 30 |
| 10,000μm -10.0 mm | 0 | 0.02 | 0 |
| Max. beta energy (MeV) | 0.156 | 0.546-2.27 | 1.71 |

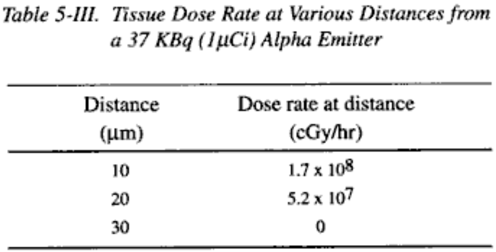
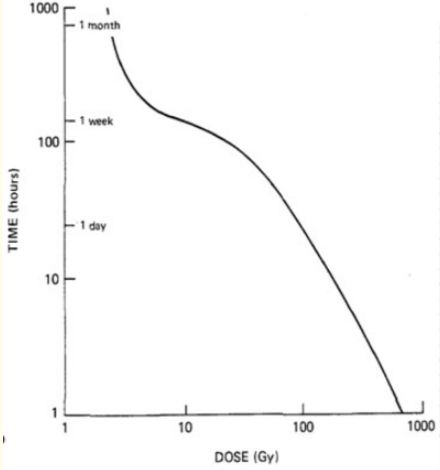


*Table 5-III. Tissue Dose Rate at Various Distances from a 37 KBq (1μCi) Alpha Emitter*

| Distance (μm) | Dose rate at distance (cGy/hr) |
|---|---|
| 10 | $1.7 \times 10^8$ |
| 20 | $5.2 \times 10^7$ |
| 30 | 0 |

https://fas.org/nuke/guide/usa/doctrine/dod/fm8-9/1ch5.htm



Time of occurrence of death from acute radiation effects.

Upper GI X-ray ~ 6mSv = 6mGy.

Life ~ 6mSv/y

Coast-Coast rt airplane = 0.03 Sv = 30mGy.

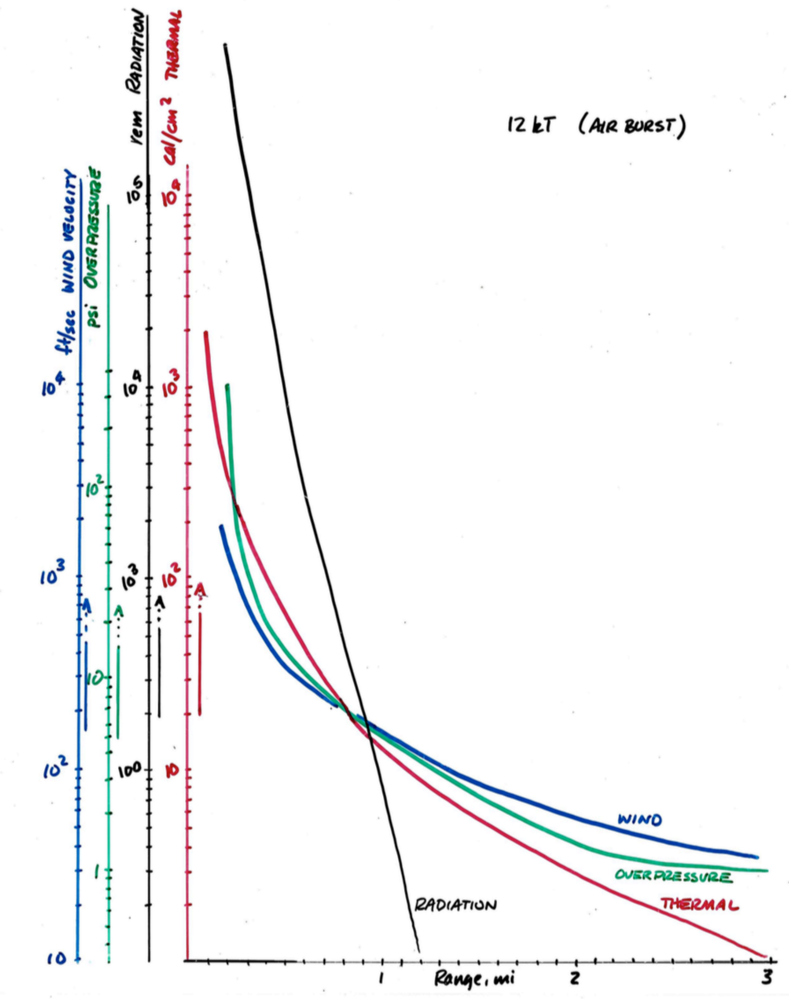
ISS 6mo ~ 160mSv

moon mission ~ 1.2 Sv

Mars mission ~ 0.4 Sv

Mars surface ~ $30 \times 10^{-6}$ Sv/h ~ 0.3 Sv/y.

} occ limits ~1 Sv/y.


12 kT (AIR BURST)
ft/sec WIND VELOCITY
psi OVERPRESSURE
rem RADIATION
cal/cm² THERMAL
10⁴
10³
10²
10
10²
10
1
10⁵
10⁴
10³
100
10⁴
10³
10²
10
A
A
A
A
WIND
OVERPRESSURE
THERMAL
RADIATION
1
Range, mi
2
3

# Fission

- splitting of a heavy nucleus into fragments — Coulomb repulsion.

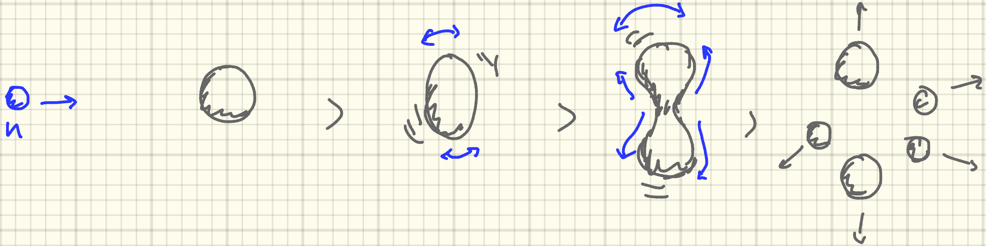
  natural
  induced

- discovered in 1939 by Otto Hahn & Fritz Strassman

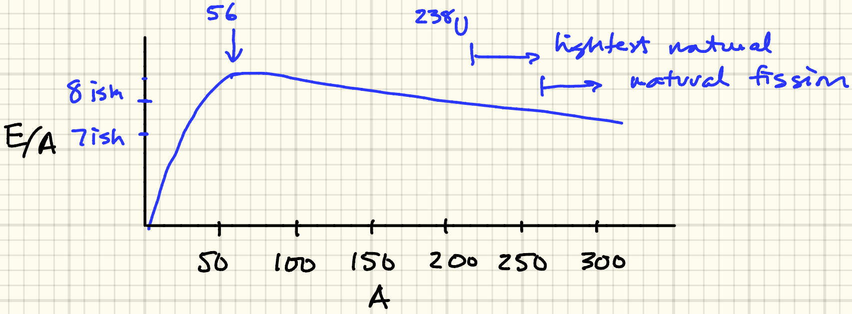
  explained by Lisa Meitner & Otto Frisch .. another Nobel embarrassment

Remember Bohr's model

protons at surface - less bound

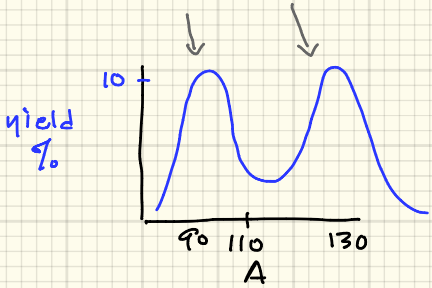


Remember:



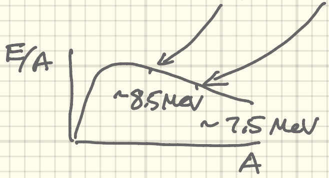
Typical fission...

$${}^{>200}X \longrightarrow {}^{<100}Y + {}^{>100}Z + \text{neutrons}$$



$${}^{>200}X \longrightarrow {}^{<100}Y + {}^{>100}Z + \text{neutrons}$$

energy released to K's



$$Q \simeq (240 \text{ nucleons})\left(8.5 \text{ MeV/nucleon} - 7.6/\text{nucleon}\right) \sim 220 \text{ MeV.}$$

↑ lots into K's

~30-40 MeV into K(neutrons)

Typical ${}^{235}U$:

$$
\begin{aligned}
{}^{1}_{0}n + {}^{235}_{92}U \longrightarrow\ & {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n \\
& {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n \\
& {}^{132}_{40}Sn + {}^{101}_{42}Mo + 3\,{}^{1}_{0}n \\
& \underbrace{{}^{99}_{40}Zr + {}^{134}_{82}Te}_{} + 3\,{}^{1}_{0}n
\end{aligned}
$$

also unstable
β & α

↑ lots of neutrons... prompt & delayed

IF YOUR GOAL IS TO INDUCE FISSION → Use the kinetic energy of fission products to...

...HEAT WATER!?

then there are many technical challenges

**Neutron Economy**

- Capture rate for neutrons
- Keeping # neutrons under control.

Neutron fates:

- elastically scatter from light nuclei ... lose energy. ✓
- be absorbed by relatively heavy nuclei ✓
- absorbed by very heavy nuclei and induce fission ✓

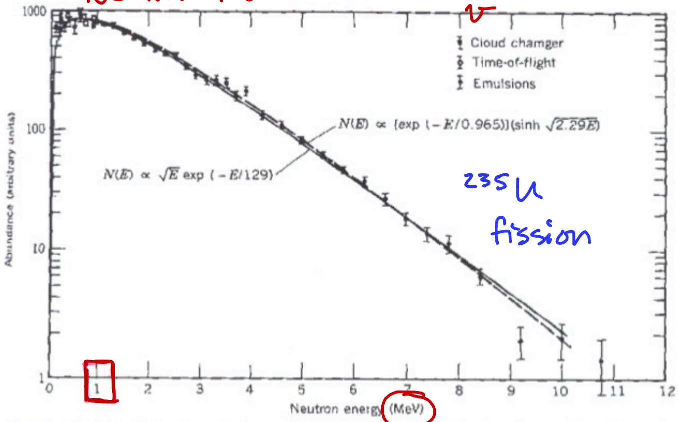
IF YOUR GOAL IS TO INDUCE FISSION

then there are many technical challenges

Neutron Economy

- Capture rate for neutrons
- Keeping # neutrons under control.

Neutron Production ~ $\frac{1}{v}$



$^{235}$U fission

**Figure 13.13** Energy spectrum of neutrons emitted in the thermal-neutron fission of $^{235}$U. From R. B. Leachman, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Vol. 2 (New York: United Nations, 1956), p. 193.

BUT →

IF YOUR GOAL IS TO INDUCE FISSION

then there are many technical challenges

Neutron Economy

- Capture rate fn neutrons
- Keeping # neutrons under control.

aim for "thermal neutrons"

absorption σ grows at low $E_n$

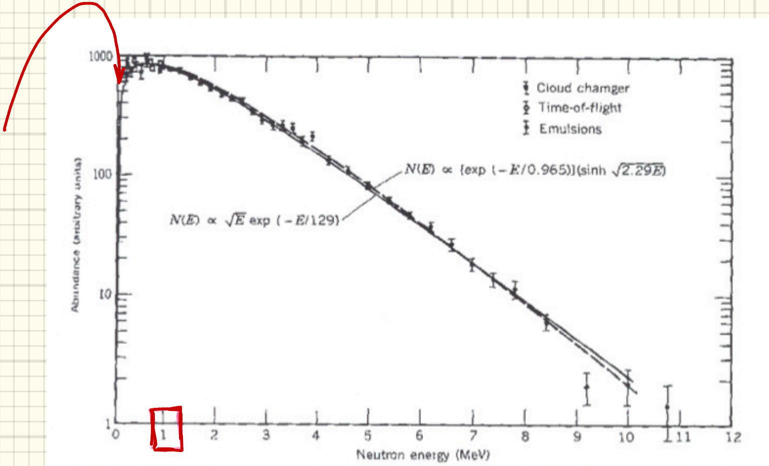
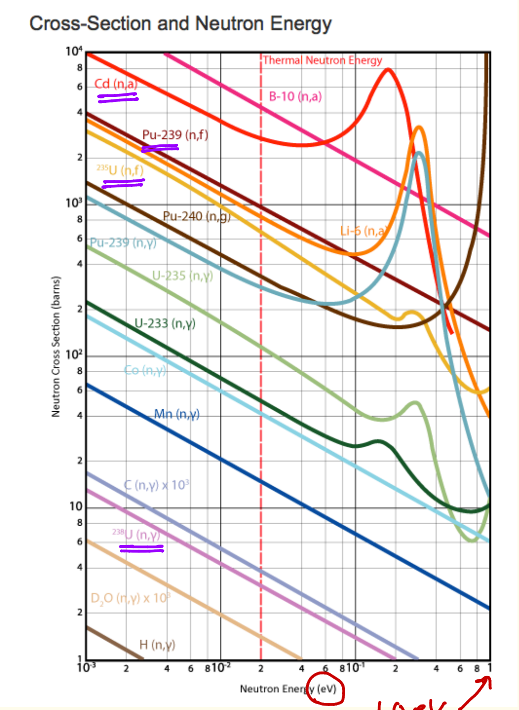


**Figure 13.13** Energy spectrum of neutrons emitted in the thermal-neutron fission of $^{235}$U. From R. B. Leachman, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Vol. 2 (New York: United Nations, 1956), p. 193.



1.0 eV

# Chain Reactions

prompt neutrons

$$\begin{tikzcd}
n + U \arrow[r] & X \arrow[dd] & + Y \arrow[d] & + n's & \\
 & & B, n \arrow[r] & \beta\gamma \arrow[r] & \beta\gamma \\
 & A, n \arrow[r] & \beta\gamma \arrow[r] & \beta\gamma &
\end{tikzcd}$$

delayed neutrons ✓

need to produce $>1$ neutrons per fission... <u>at least</u>

$^{235}U$ & $^{238}U$ both absorb neutrons... but fission is not equal

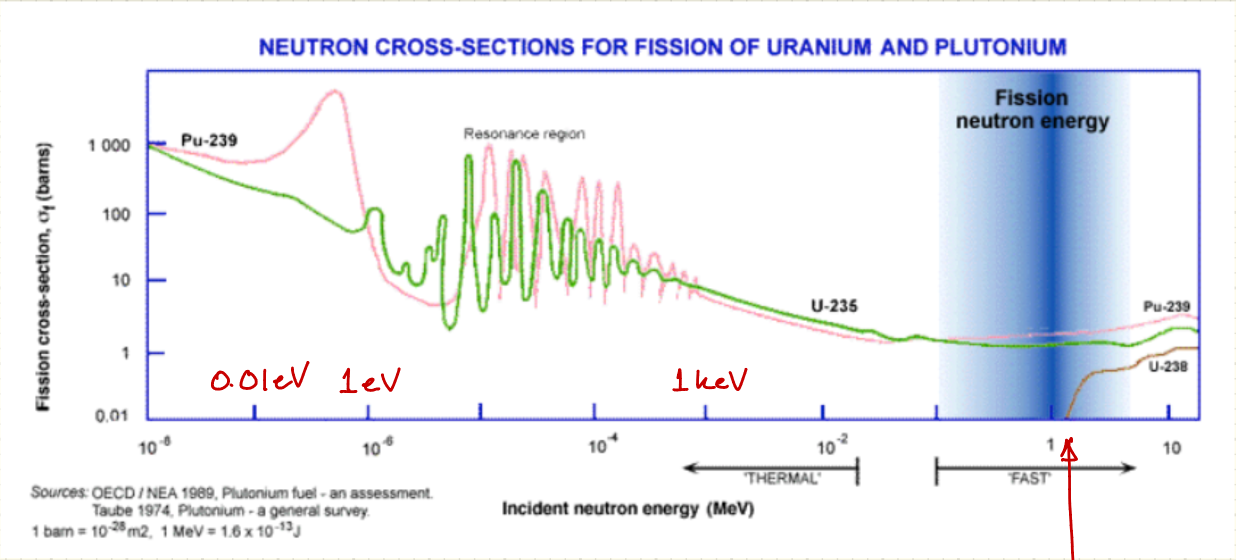
$^{238}U \rightarrow$ 99.3% of natural Uranium

induce fission: $n + {}^{238}U \rightarrow {}^{145}Ba + {}^{94}Kr$

discovery reaction

& generally:

$n + {}^{238}U \rightarrow$ fragments + 2, 3 neutrons



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = $10^{-28}$ m2, 1 MeV = $1.6 \times 10^{-13}$ J

minimum required
1.2 MeV

BUT!

$n + {}^{238}U \rightarrow$ fragments + $\underbrace{2, 3 \text{ neutrons}}$

↳ quickly slow down and there aren't enough to → threshold

SO: ${}^{238}U$ is said to be un-fissionable

## More $^{238}U$ ...

there is a chain – look back at $^{239}Pu$ --- fissions at all $K(n)$

$$n + {}^{238}_{92}U_{146} \longrightarrow {}^{239}_{92}U_{147} \longrightarrow {}^{239}_{93}Np_{146} + e^- + \nu$$

$$\hookrightarrow {}^{239}_{94}Pu_{145} + e^- + \nu$$

- a mechanism to produce Plutonium
- the "breeder cycle" for power → only in Europe

# Criticality. $K$ (reproduction constant)

$$K = \frac{\#\text{ neutrons from one generation}}{\#\text{ neutrons from previous generation}}$$

$K = 1 \Rightarrow$ critical $\longrightarrow$ self-sustaining.

$K < 1 \Rightarrow$ subcritical

$K > 1 \Rightarrow$ supercritical
$\longrightarrow$ can lead to explosive fission

critical mass – mass of fissile material necessary to maintain $k = 1$
$\Rightarrow$ neutrons don't leave

$^{235}U$  17 cm diameter
53 kg

$^{239}Pu$  9 cm diameter
18 kg

$\langle k \rangle$ $U \sim 2.5$

Consider 1 kg $^{235}U$ & 100% efficiently fission it all.

$N = 3 \times 10^{24}$ nuclei assume $k = 2$

$$(k)^G = \#\text{ fissions} = 3 \times 10^{24}$$

$$\ln k^G = \ln 3 \times 10^{24}$$

$$G \ln k = \ln 3 \times 10^{24}$$

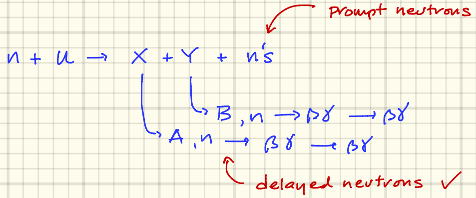
$$G = \frac{\ln 3 \times 10^{24}}{\ln 2} = \frac{56}{0.69} = 81 \text{ generations.}$$

## $^{235}U$ fission for power.

- need neutrons to be slow → "thermal" $K = \frac{3}{2}kT \sim$ eV's

→ moderate them by allowing elastic scattering in "moderator"
water (US reactors), Heavy water (Canadian reactors),
Carbon (original chain by Fermi) ...

→ don't make too many!



prompt neutrons very fast
99%

delayed neutrons... slower.

$$n + {}^{235}U \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$$

${}^{141}Cs \xrightarrow{25\,s} {}^{141}Ba$ & $n$ 0.03%

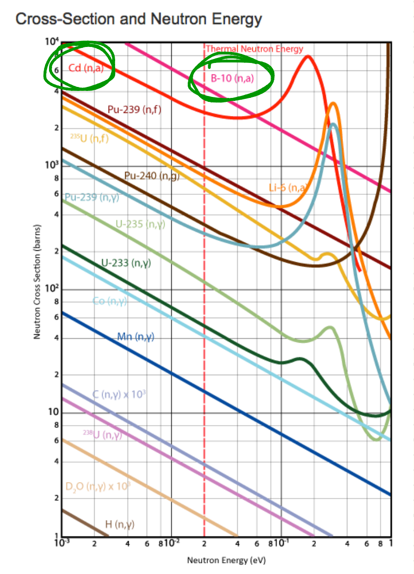
${}^{93}Rb \xrightarrow{6\,s} {}^{93}Sr$ & $n$ 1.4%

Delayed neutrons make power reactors possible

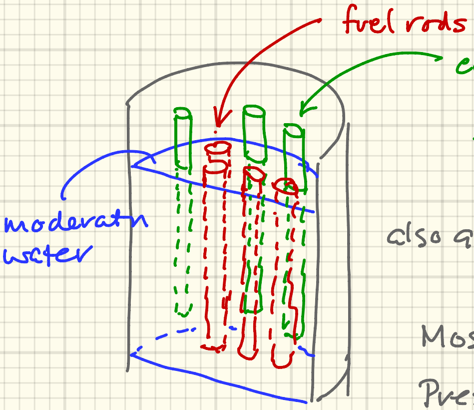
design for some # prompt neutrons

control # delayed neutrons

how? take them out with a "knob" → control rods of high-cross section material



← Cd & B



— moved up and down

→ fully in to stop chain reaction

also graphite probably.

Most U.S. reactors —

Pressurized Water Reactor

PLWR

example –

that 1 kg of $^{235}U$ ? – if $Q = 208$ MeV ... what energy results ?

$$\# \text{ nuclei} = N = \frac{6.02 \times 10^{23} \text{ molecules/mole}}{235 \text{ g/mol}} (10^3 \text{ g})$$

$$= 2.56 \times 10^{24} \text{ nuclei}$$

$$E = N Q = 5.32 \times 10^{26} \text{ MeV}$$

$1 \text{ MeV} = 4.45 \times 10^{-20}$ kWh

$$E = 2.4 \times 10^7 \text{ kWh} = 24{,}000 \text{ MWh}$$

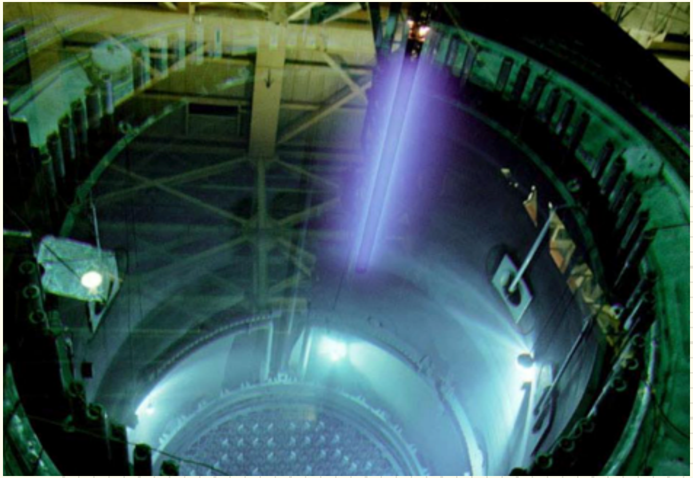
OR

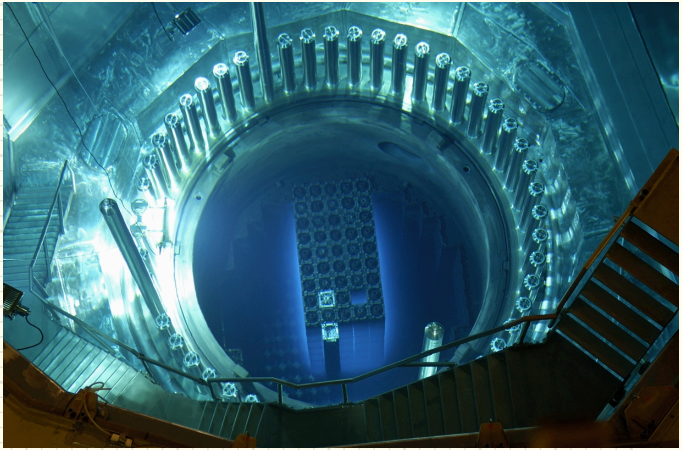
$1 \text{ ton TNT} = 10^9 \text{ cal} = 4.2 \times 10^7$ J

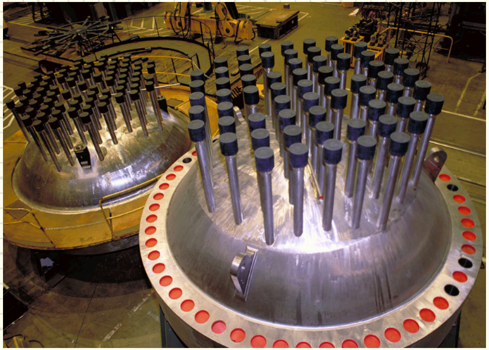
$$E = (5.32 \times 10^{26} \text{ MeV} \times 10^6 \text{ eV/MeV})(1.6 \times 10^{-19} \text{ J/eV})\left(\frac{1 \text{ ton TNT}}{4.2 \times 10^7 \text{ J}}\right)$$

$$E = 20{,}000 \text{ tons TNT}$$

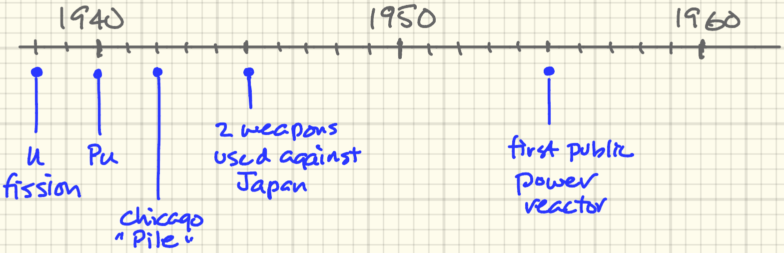
$$E = 20 \text{ kt}$$







## Some history



## German Program

Technical Choices:

1. Did <u>not</u> try to extract $^{235}U$ from $^{238}U$
2. <u>Did</u> tried to convert $^{238}U \rightarrow {}^{239}Pu$
3. Moderator
   - tried Graphite, decided it would not work wrong
   - chose $D_2O$, heavy water

clue to Allies when Germany occuppied Norw & its ammonia production facility

→ $D_2O$ by product

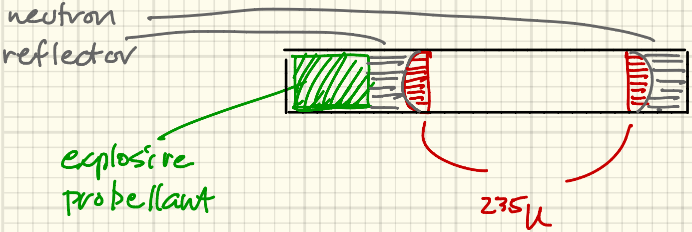
allies, including Norway, destroyed plants repeatedly

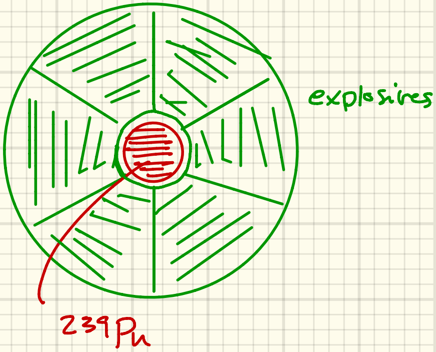
## U.S. program

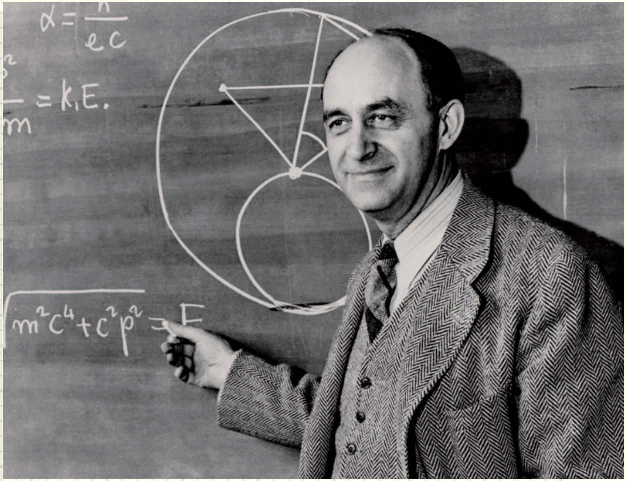
technical choices

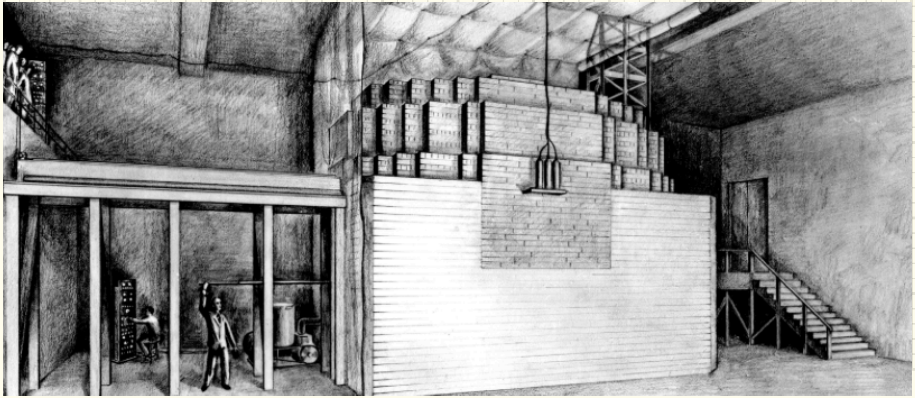
1. chose to try both
   - extract $^{235}U$ from $^{238}U$
   - convert $^{238}U \longrightarrow {}^{239}Pu$
2. moderator
   - Fermi guessed Germans contaminated their graphite
   - he purified graphite and $^{238}U$ fuel achieved criticality

Manhattan Project @ Los Alamos Nat. Lab


neutron
reflector
explosive
probellant
235U


explosives
239Pu



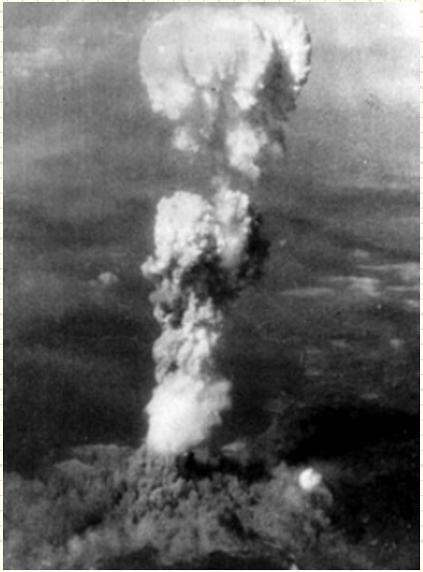


5/8/45 Germany surrendered

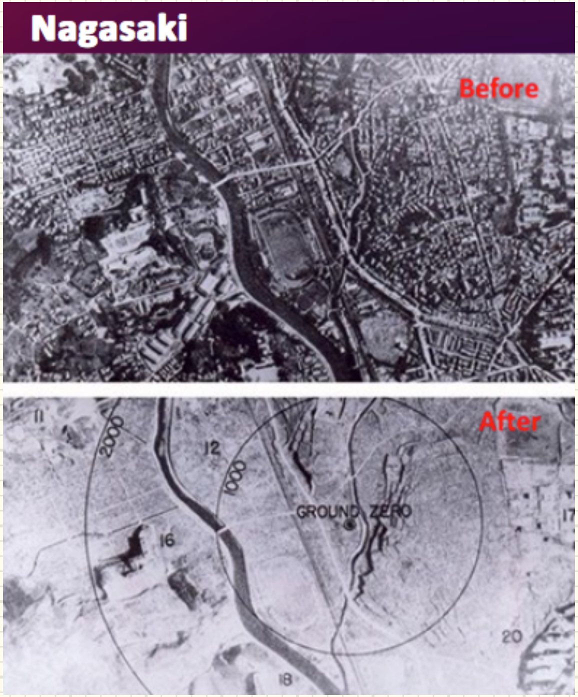
7/16/45 "Trinity Test"
Alamogordo, NM

8/6/45
8/9/45 2 weapons
used against
Japan

$^{235}U$ 12.5 kt Hiroshima 8/6/45



$^{239}Pu$ 20 kt Nagasaki 8/9/45

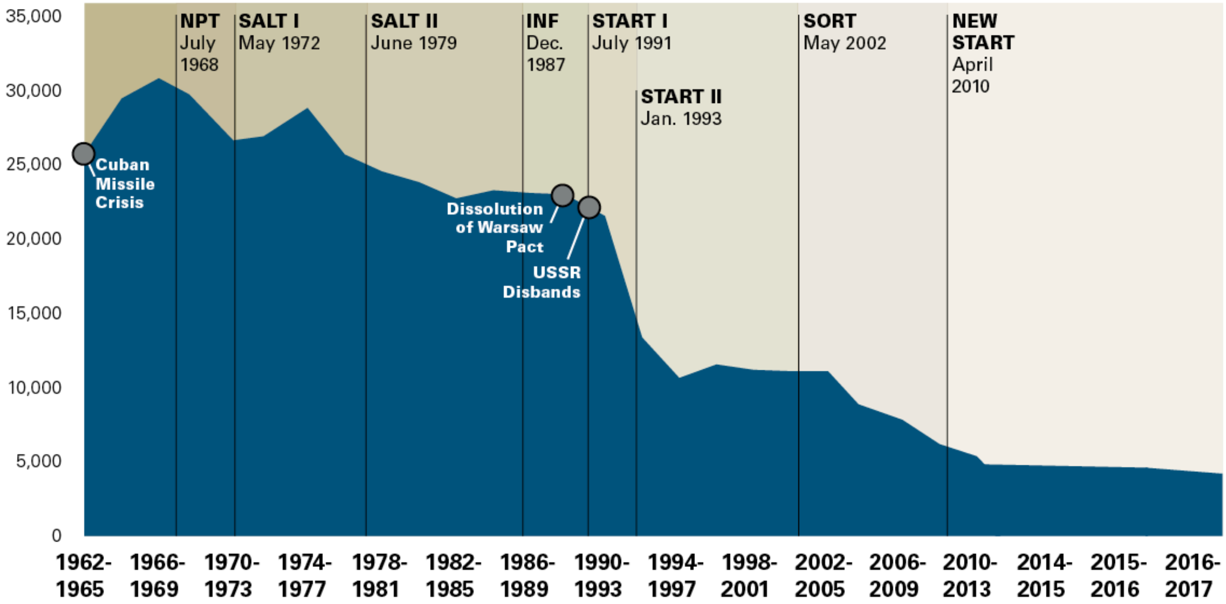


80,000 civilians killed immediately
10,000's later

40,000 civilians killed immediately

## U.S. Nuclear Weapons Stockpile, 1962-2017

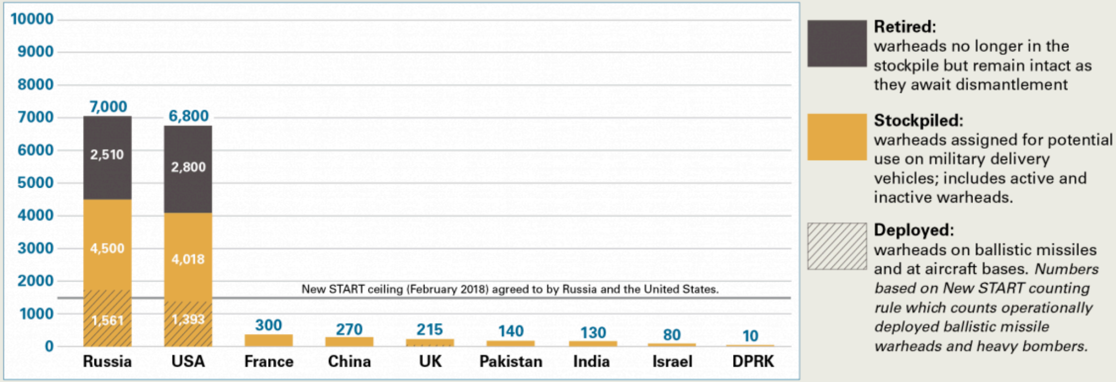
Since the late-1960s, the United States and Russia have signed a series of nuclear arms treaties that have contributed to steep cuts in their active and inactive nuclear warhead stockpiles.



Sources: U.S. Department of State, U.S. Department of Defense, Arms Control Association. Updated: January 19, 2017.

# 2017 Estimated Global Nuclear Warhead Inventories

The world's nuclear-armed states possess a combined total of roughly 15,000 nuclear warheads; more than 90 percent belong to Russia and the United States. Approximately 9,600 warheads are in military service, with the rest awaiting dismantlement.



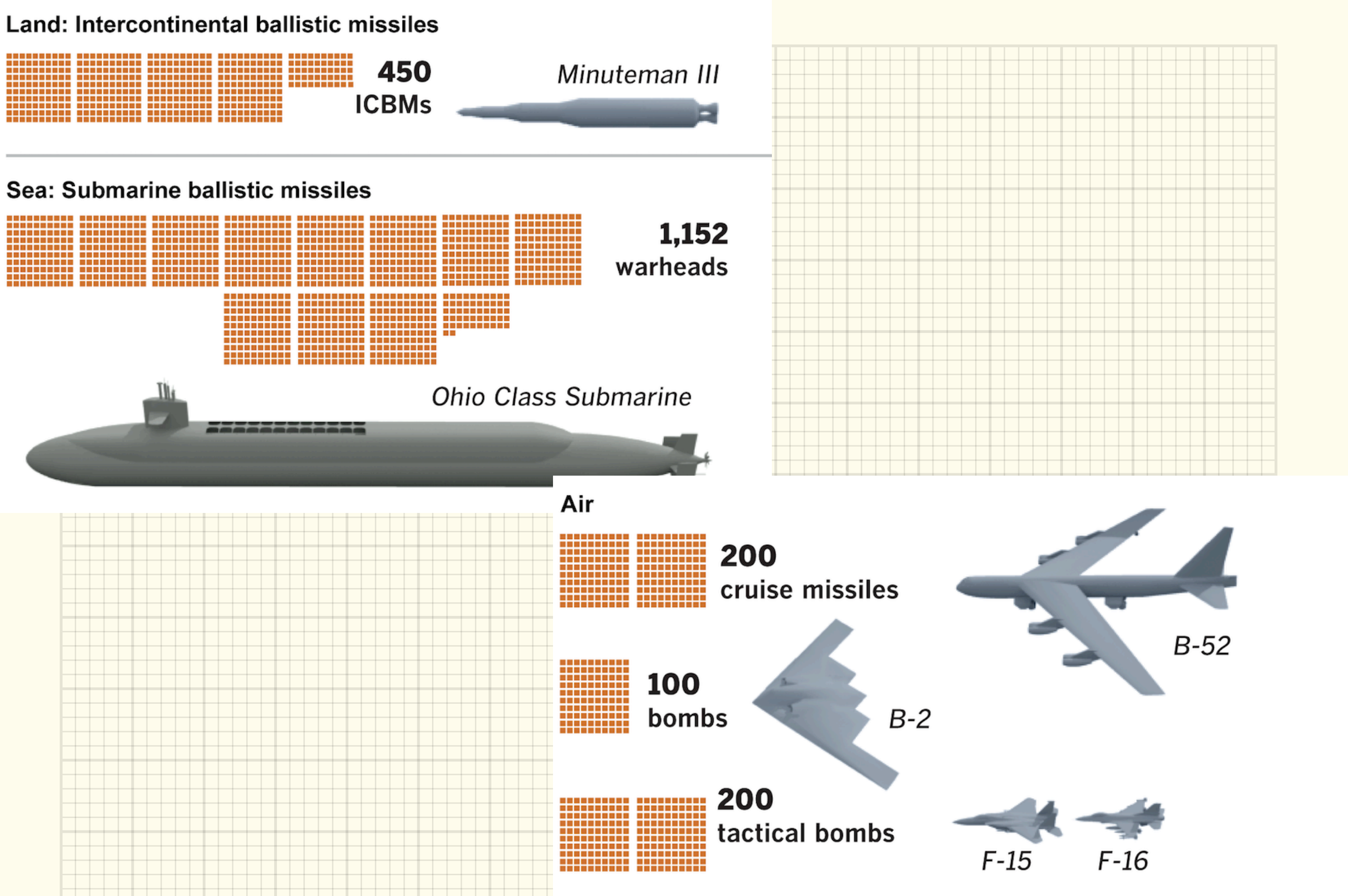
■ **Retired:** warheads no longer in the stockpile but remain intact as they await dismantlement

■ **Stockpiled:** warheads assigned for potential use on military delivery vehicles; includes active and inactive warheads.

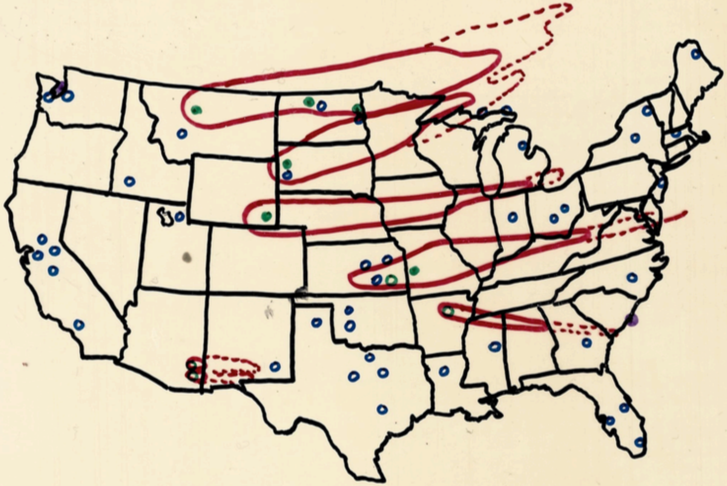
▨ **Deployed:** warheads on ballistic missiles and at aircraft bases. *Numbers based on New START counting rule which counts operationally deployed ballistic missile warheads and heavy bombers.*

Sources: Hans M. Kristensen and Robert S. Norris; U.S. Department of State. Updated October 3, 2017.

Arms Control Association



* The U.S. holds an inactive stockpile of 2,548 to 2,700 tactical warheads



○ ICBM (TITAN) FIELDS

● ICBM (MM) FIELDS

○ SAC BASES

● SSBN SUPPORT BASES

COUNTERFORCE ATTACK ON ICBM FIELDS ONLY

2 1 Mt GROUND BURSTS (50% FISSION) / SILO

⬭ 450-rem indoors (50% DEAD)

⬯ 200-rem indoors (50% HOSPITALIZED)

Raw meterial depends on goal. Natural Uranium 99.3% $^{238}U$
0.7% $^{235}U$

| TYPE | MAIN USES |
|---|---|
| natural $^{238}U$ | some power reactors<br>military Pu production reactors |
| "low enriched" Uranium<br>LEU => 0.7–20% $^{235}U$ | most operating power reactors → 4-5% $^{235}U$<br>some research reactors<br>French naval propulsion reactors |
| "highly enriched" Uranium<br>HEU => > 20% $^{235}U$ | most research reactors<br>US, British, Russian naval propulsion reactors<br>military Pu and T production reactors |
| mixed plutonium-uranium oxide<br>"MOX" | some reseach reactors<br>some Power reactors |
| Pu | reactors |

"weapons-grade" uranium > 90% $^{235}U$

# Enrichment techniques

1. Gaseous diffusion - Manhattan Project @ Oak Ridge Nat. Lab, TN

   diffuses $UF_6$ gas through semi-permiable membranes
   @ high pressure $\propto \frac{1}{M^2}$ so $^{235}U$ wins

2. Electromagnetic isotope separation

   like a high-flux mass spectrometer.

3. Gas centrifuge

   $UF_6$ separated through 100's of stages
   sophisticated metalurgical designs

4. Molecular laser isotope separation

   exploits the molecular energy level differences between
   $^{235}U$ and $^{238}U$ in $UF_6$

## Gaseous Diffusion Enrichment

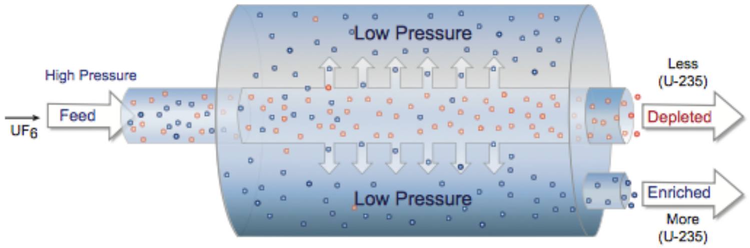
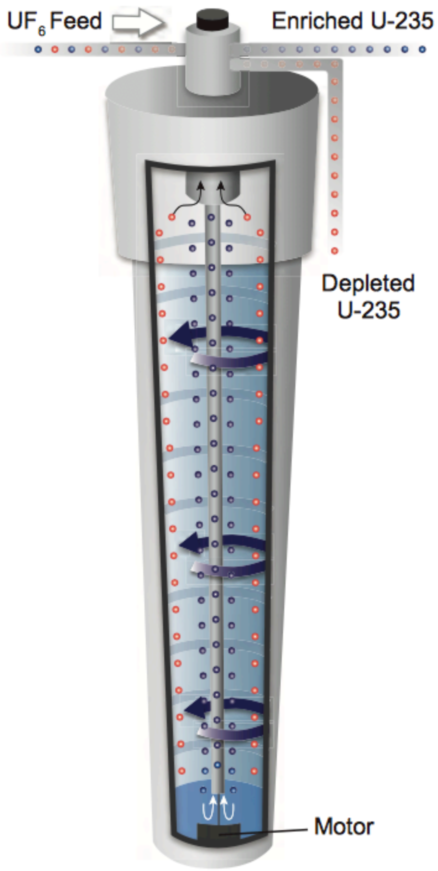
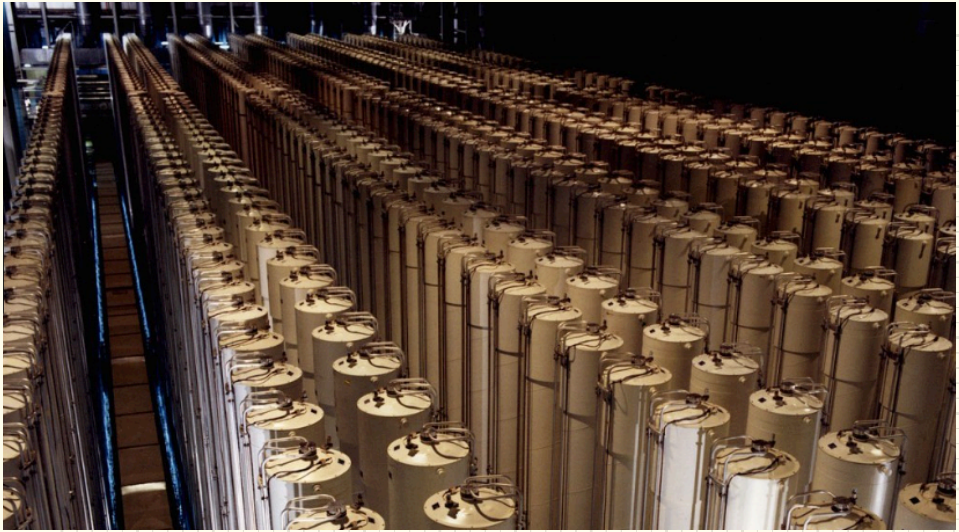
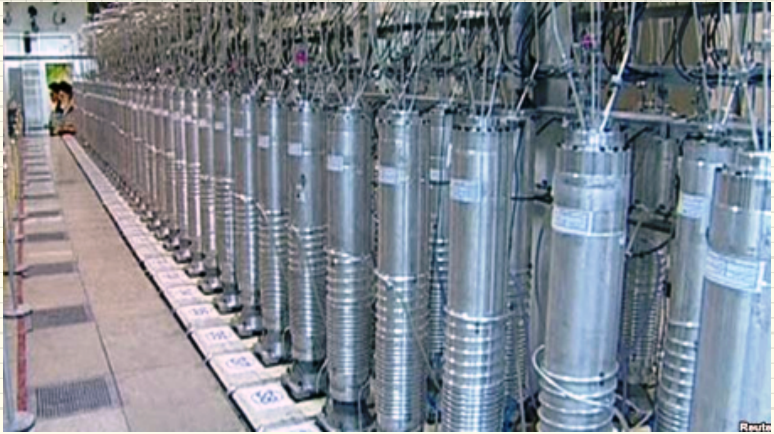


Image Credit: USEC, Inc.

## Centrifuge Enrichment






Reute

# Proliferation concerns

## Technology transfer

Pakistan → Iran, N. Korea, Lybia (1989–1997)

LEU facilities can be → HEU

## Breeder reactors

$$n + {}^{238}U \rightarrow {}^{239}U^{*} \rightarrow {}^{239}U + \gamma$$

$$\hookrightarrow {}^{239}Np + \beta + \nu$$

$$\hookrightarrow {}^{239}Pu + \beta + \nu$$

$$\hookrightarrow \text{fission} + 2.7\, n$$

"breed" Pu fuel

- leave one running for a long time: ${}^{239}Pu + {}^{240}Pu$ ← not fissile
- remove products quickly: ${}^{239}Pu$ + trace ${}^{240}Pu$

  ↑ weapons grade

# IRIANIAN "NUCLEAR DEAL" – you know enough now to understand it

"P5 +1" July 2015

not political except to note: it's the most intrusive, comprensive, inclusive arms control agreement in history.

## My numbering:

1. centrifuge technology. Iran has ~8 generations. Agreement restricts them to only the first 4 generations for a decade. #8 … 1 cascade only, R&D

2. number of centrifuges. Previously, 20,000 … dismantled 15,000

3. uranium enrichment. Restricts them to 3.67% $^{235}$U enrichment. → LWPR
15y

4. stockpile. At agreement signing, they had
10,000 kg LEU <20% in oxide and gaseous form ~8,000 kg?
– ready for further enrichment
Agreement restricts them to 300 kg.

$$\begin{tikzcd} 8{,}000\text{ kg} \arrow[d] & + & 5{,}000 \arrow[d] & \text{centrifuges} \longrightarrow \text{few months to make 8 weapons} \\ 300\text{kg} & & 5{,}000 & \text{centrifuges} \longrightarrow \;>\text{ year} \end{tikzcd}$$