Hands on: Nuclear weapons

nuclearweaponarchive.org

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Nuclear technologies 4

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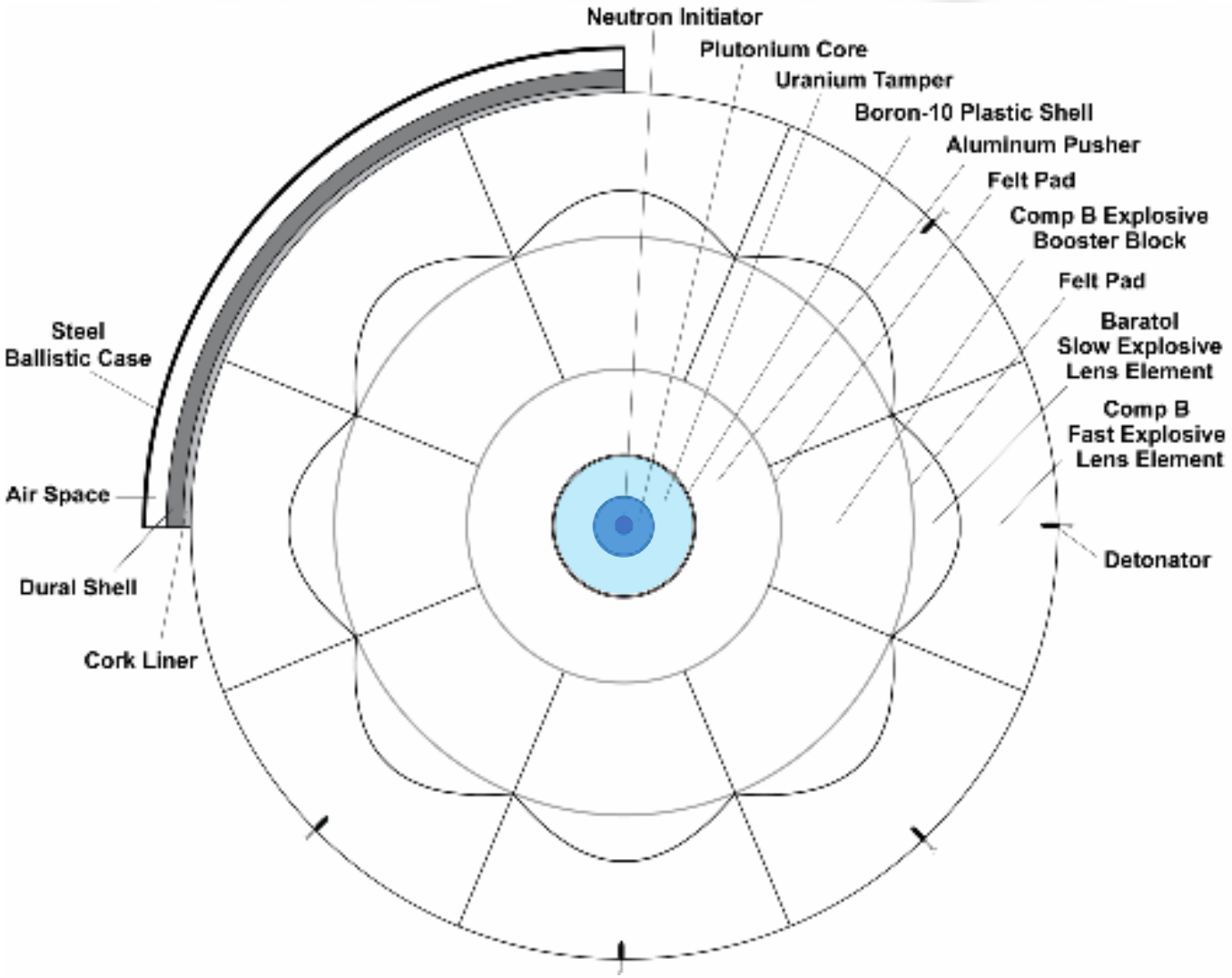

Explosive Sphere Component	Dimensions (Outside Diameters)	Mass
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source: nuclearweaponarchive.org

Nuclear technologies

Discovery of the **neutron** by James Chadwick in February 1932.

On May 10, 1934, Fermi's research group published a report on experiments with neutron bombardment of uranium. Appearance of the "**Uranium Problem**".

Fermi discovered the extremely important principle of neutron behavior called "**moderation**" on October 22, 1934.

December 1935, Chadwick won the Nobel Prize for discovery of the neutron.

In November-December 1938, the Otto Hahn and Lise Meitner correctly unravel the Uranium Problem, i.e. **evidence of fission**.

January 13, 1939 - Otto Frisch observed fission directly by detecting **fission fragments in an ionization chamber**. With the assistance of William Arnold, he coins the term "fission".

January 26, 1939 - Niels Bohr publicly announces the discovery of fission at an annual theoretical physics conference at George Washington University in Washington, DC. This announcement was the principal revelation of fission in the United States.

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Nuclear technologies

January 29, 1939 - Robert Oppenheimer hears about the discovery of fission, within a few minutes he realized that excess neutrons must be emitted, and that it might be **possible to build a bomb**.

February 5, 1939 - Niels Bohr gained a crucial insight into the principles of fission - that U-235 and U-238 must have different fission properties, that U-238 could be fissioned by fast neutrons but not slow ones, and that U-235 accounted for observed slow fission in uranium. Key uncertainties were:

- The number of neutrons emitted per fission
- The cross sections for fission and absorption at different energies for the uranium isotopes.

For a chain reaction there would need to be both a sufficient excess of neutrons produced, and the ratio between fission to absorption averaged over the neutron energies present would need to be sufficiently large. The different properties of U-235 and U-238 were essential to understand in determining the feasibility of an atomic bomb, or of any atomic power at all. The only uranium available for study was the isotope mixture of natural uranium, in which U-235 comprised only 0.72%.

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Nuclear technologies

March, 1939 - Fermi and Herbert Anderson determine that **there are about two neutrons produced for every one consumed in fission**. This paper is the first experimental evidence of neutron multiplication. See >>.

June, 1939 - Fermi and Szilard submit a paper to Physical Review describing sub-critical neutron multiplication in a lattice of uranium oxide in water, but it is clear that **natural uranium and water cannot make a self-sustaining reaction**.

July 3, 1939 - Szilard writes to Fermi describing the idea of using a uranium lattice in carbon (graphite) to create a chain reaction. This is the first proposal of the graphite moderated reactor concept. See >>.

August 31, 1939 - Bohr and John A. Wheeler publish a theoretical analysis of fission. This theory implies U-235 is more fissile than U-238, and that the undiscovered element 94-239 (Plutonium!) is also very fissile. These implications are not immediately recognized.

September 1, 1939 - Germany invades Poland, beginning World War 2.

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3. Introducing neutrons into the critical mass when it is at the optimum configuration (i.e. at maximum supercriticality);
4. Keeping the mass together until a substantial portion of the material has fissioned.

Solving issues 1, 2 and 3 together is greatly complicated by the unavoidable presence of naturally occurring neutrons. Neutrons can be generated by cosmic rays (at a low rate), and by spontaneous fission.

The process of assembling the supercritical mass must occur in significantly less time than the average interval between spontaneous fissions to have a reasonable chance of succeeding. This problem is difficult to accomplish due to the very large change in reactivity required in going from a subcritical state to a supercritical one. The time required to raise the value of **k from 1 to the maximum value of 2** or so is called the reactivity insertion time, or simply **insertion time**.

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Critical mass of an untampered gadget

Diffusion equation:

$$\frac{\partial F}{\partial t} = \frac{1}{3}\lambda_t v\,\nabla^2 F + \frac{\nu_f - 1}{t_f} F$$

1. Persistent time-dependent solution:

$$F(t) \sim e^{\nu' t/t_f}$$

2. Space-dependence for a spherical assembly:

$$F(r) \sim \frac{\sin Kr}{r}, \text{ with } K^2 = \frac{3(\nu_f - \nu' - 1)}{\lambda_t v\, t_0}$$

Vanishing at the boundary provides $KR = \pi$, hence

$$R = \frac{\pi}{\sqrt{3}} \sqrt{\frac{\lambda_t v\, t_f}{\nu_f - \nu' - 1}}$$

REPORT OF THE THIRD MEETING HELD ON APRIL 17, 1943.

(3) The physical constants determining the critical mass and efficiency of an untamped gadget.
--- Bethe.

1. The diffusion theory critical mass and multiplication time: The rate of growth of the neutron density, F, is given by,

$$\frac{\partial F}{\partial t} = \frac{1}{3}\lambda v \Delta F + \frac{\nu - 1}{t} F$$

where l is the transport mean free path, v is an appropriate average of the neutron velocities, ν is the number of neutrons emitted per fission, and t is the mean time between fission collisions. Aside from transient solutions, there is the persistent solution varying exponentially in time as

$$F \sim e^{\nu' t/t}$$

The space dependence of the solution appropriate for a spherical mass is $F \sim \frac{\sin Kr}{r}$

where $K^2 = \frac{3(\nu - \nu' - 1)}{\lambda v t}$

The transport mean free path is, $l = 1/N\sigma_t$, where σ_t is the (1- cosθ) average of the elastic scattering cross section plus all the reaction cross sections.

According to elementary diffusion theory the density F should vanish at the boundary, which gives $kR = \pi$, hence

$$R = \frac{\pi}{\sqrt{3}} \sqrt{\frac{\lambda v t}{\nu - \nu' - 1}}$$

The elementary diffusion theory is accurate only in the limit of dimensions large compared to the mean free path and for small absorption. An approach to the correct solution is obtained by making the density vanish a distance outside the actual boundary. The critical radius, i.e. that for a static solution, is given by setting $\nu' = 0$. The more accurate integral theory divides the above derived critical radius by $(1 + .9(\nu - 1)\sigma_t/\sigma_s)$.

Fig. 9. Bethe's summary of critical mass calculations from the first Los Alamos conference, April 1943, LA-2 (Ref. 34).

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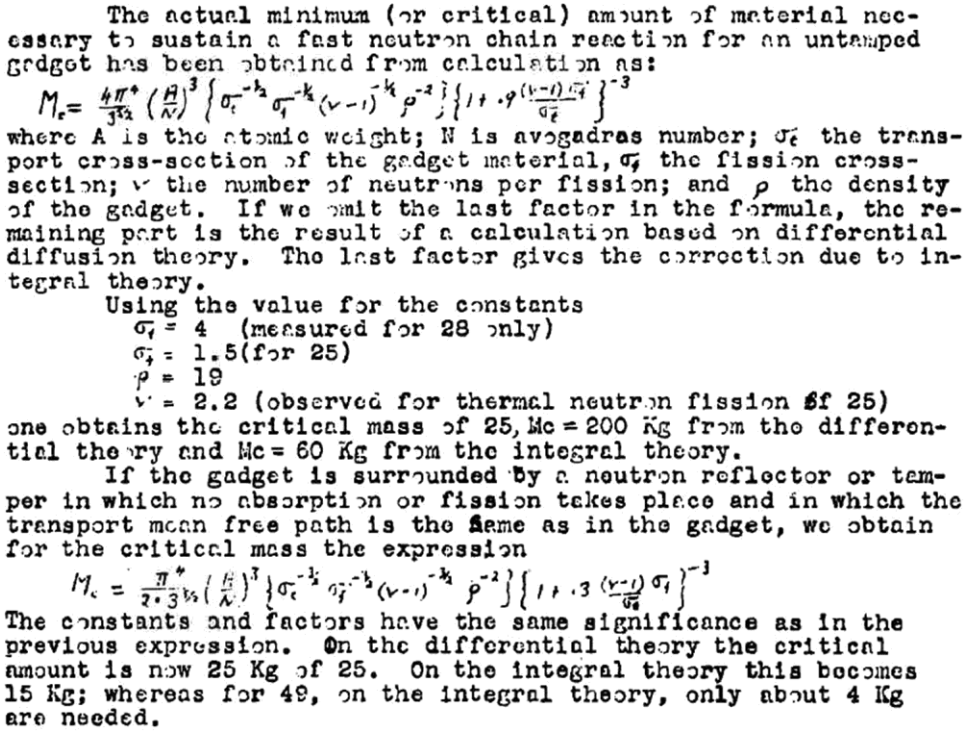
Mark B. Chadwick (2021) Nuclear Science for the Manhattan Project and Comparison to Today's ENDF Data, Nuclear Technology, 207:sup1, S24-S61, DOI: 10.1080/00295450.2021.1901002

Critical mass of an untampered gadget

The critical radius is obtained by making $\nu' = 0$ (static solution), hence

$$R_c = \frac{\pi}{\sqrt{3}} \sqrt{\frac{\lambda_t v\, t_f}{\nu_f - 1}}$$

$$M_C = \frac{4\pi^4}{3^{5/2}} \left(\frac{A}{N_A}\right)^3 \left[\sigma_t^{-1/2}\, \sigma_f^{-1/2}\, (\nu_f - 1)^{-1/2}\right]^3 \left(\frac{1}{\rho}\right)^2 \times \left(1 + 0.9\,(\nu_f - 1)\sigma_f/\sigma_t\right)^{-3}$$



The actual minimum (or critical) amount of material necessary to sustain a fast neutron chain reaction for an untamped gadget has been obtained from calculation as:

$$M_c = \frac{4\pi^4}{3^{5/2}} \left(\frac{A}{N}\right)^3 \left\{\sigma_t^{-1/2}\, \sigma_f^{-1/2}\, (\nu-1)^{-1/2}\, \rho^{-2}\right\} \left\{1 + .9\,\frac{(\nu-1)\sigma_t}{\sigma_f}\right\}^{-3}$$

where A is the atomic weight; N is avogadros number; σ_t the transport cross-section of the gadget material, σ_f the fission cross-section; ν the number of neutrons per fission; and ρ the density of the gadget. If we omit the last factor in the formula, the remaining part is the result of a calculation based on differential diffusion theory. The last factor gives the correction due to integral theory.

Using the value for the constants

σ_t = 4 (measured for 28 only)
σ_f = 1.5(for 25)
ρ = 19
ν = 2.2 (observed for thermal neutron fission of 25)

one obtains the critical mass of 25, Mc = 200 Kg from the differential theory and Mc = 60 Kg from the integral theory.

If the gadget is surrounded by a neutron reflector or tamper in which no absorption or fission takes place and in which the transport mean free path is the same as in the gadget, we obtain for the critical mass the expression

$$M_c = \frac{\pi^4}{2 \cdot 3^{5/2}} \left(\frac{A}{N}\right)^3 \left\{\sigma_t^{-1/2}\, \sigma_f^{-1/2}\, (\nu-1)^{-1/2}\, \rho^{-2}\right\} \left\{1 + .3\,\frac{(\nu-1)\sigma_t}{\sigma_f}\right\}^{-3}$$

The constants and factors have the same significance as in the previous expression. On the differential theory the critical amount is now 25 Kg of 25. On the integral theory this becomes 15 Kg; whereas for 49, on the integral theory, only about 4 Kg are needed.

Fig. 8. Oppenheimer's summary of critical mass calculations from the first Los Alamos conference, April 1943, LA-2. Because the image is of poor quality, the first equation appears to have typos, with the parameters $\sigma_t, \sigma_f, (\bar{\nu} - 1)$ raised to the power $-1/2$. A careful study though shows that they are correctly raised to the power $-3/2$, as in Eq. (1).

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Mark B. Chadwick (2021) Nuclear Science for the Manhattan Project and Comparison to Today's ENDF Data, Nuclear Technology, 207:sup1, S24-S61, DOI: 10.1080/00295450.2021.1901002

Critical mass of an untampered gadget

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4. Keeping the mass together until a substantial portion of the material has fissioned.

The problem is further complicated by the **subcritical neutron multiplication:**

k	neutron generations before chain stops
0.90	10
0.99	100

This persistence of neutrons in subcritical masses further reduces the time window for assembly and requires that the reactivity of the mass be increased from a value of <0.9 to a value of 2 or so within that window.

Simply splitting a supercritical mass into two identical parts, and bringing the parts together rapidly is unlikely to succeed since neither part will have a sufficiently low k value, nor will the insertion time be rapid enough with achievable assembly speeds.

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Nuclear weapons: Units

1 kt = 4.18×10^{12} Joule
= 26.1×10^{24} MeV

1 Joule = 6.24×10^{12} MeV
= 2.39×10^{-13} kt (kilotons)

15 kt (Hiroshima) = $3.92/200 \times 10^{26}$ = 2.0×10^{24} fissions

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Nuclear weapons: Units

$$N(t) = N_0\, e^{(k-1)t/t_0}$$

n : number density [1/cm^3]
σ_f : fission cross section [cm^2]
The macroscopic cross section is defined by
$\Sigma_f \equiv n\,\sigma_f$ $[\Sigma_f]$ = 1/cm

$$t_0 = \frac{\lambda_f}{v_n} = \frac{1}{\Sigma_f}\,\frac{1}{v_n}$$

The mean-free path is
$\lambda_f = 1/\Sigma_f$ $[\lambda_f]$ = cm

$\lambda_f = 18.7$ cm, $\sigma_f = 1.1$ b at $E_n \approx 2$ MeV, $t_0 = 9.6$ ns ≈ 10 ns (1 “shake”)

$N = 2 \times 10^{24} = e^{(k-1)t/t_0}$

$\log(2\times10^{24}) = (k-1)\,t/t_0$ and, if $k = 2$, $t = 56\,t_0$ or $t = 560$ ns (56 “shakes”)

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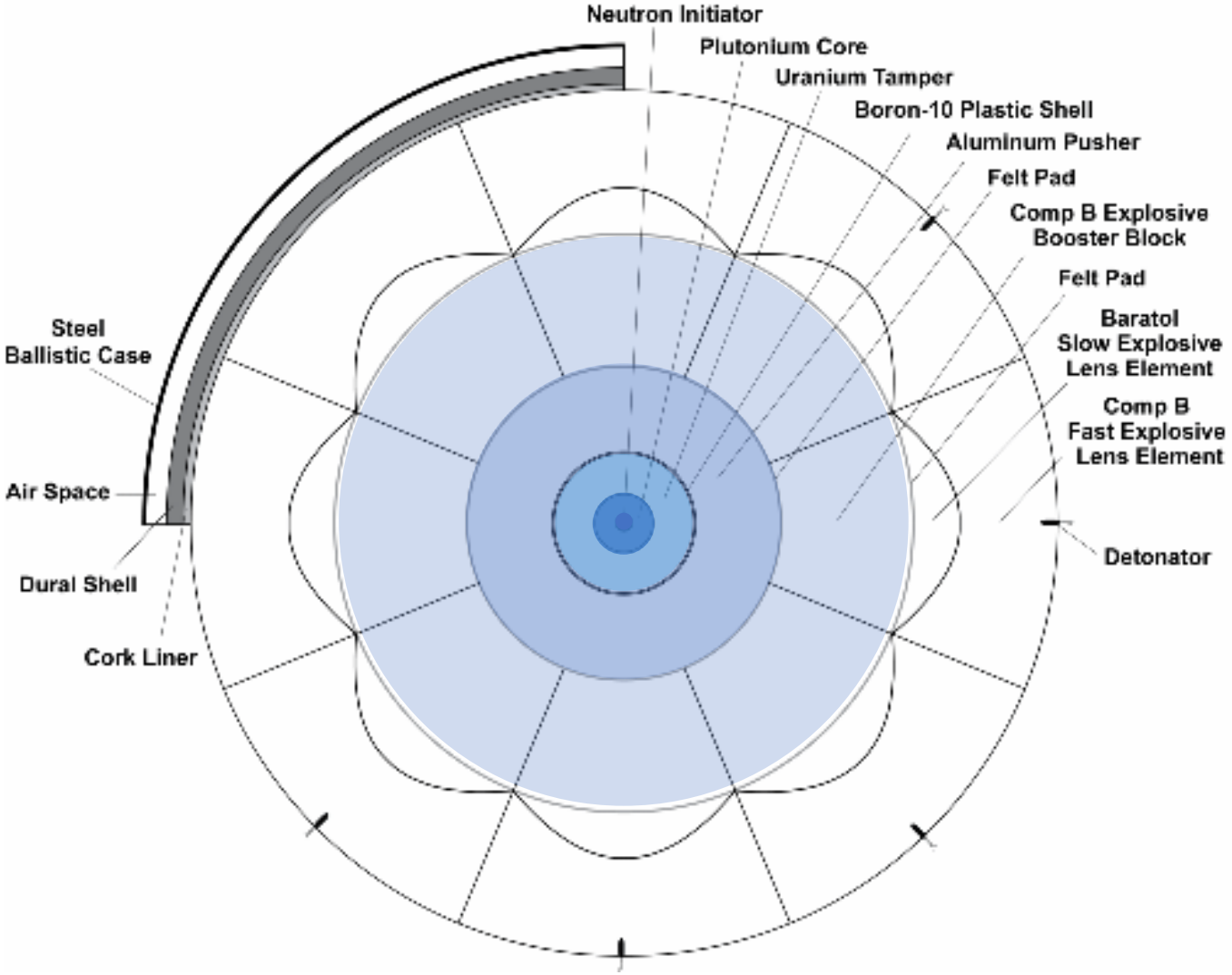
Nuclear weapons: Implosion assembly



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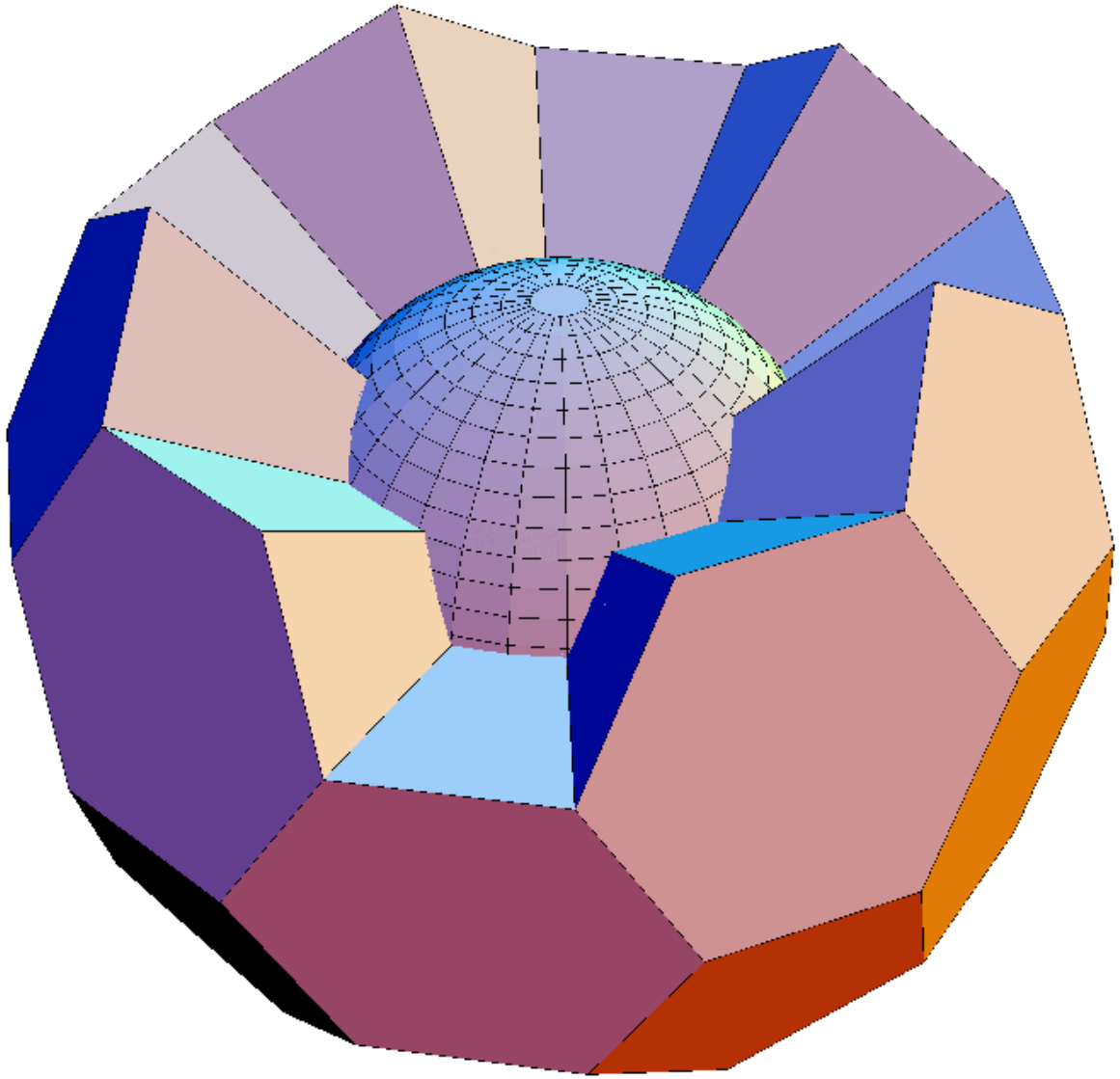

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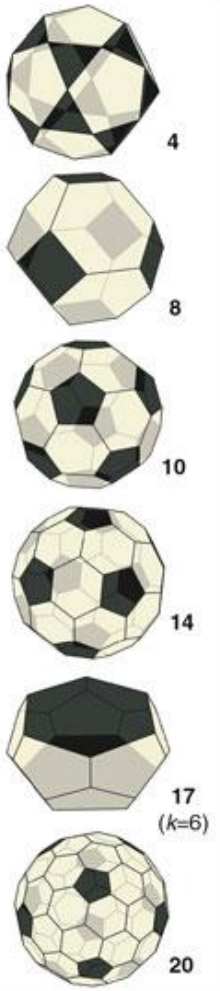
Nuclear weapons: Implosion assembly

type	k	m	n	minimal realization	b	w
1	3	3	1	octahedron	4	4
2	3	4	1	cuboctahedron	8	6
3	4	3	1	cuboctahedron	6	8
4	3	5	1	icosidodecahedron	20	12
5	5	3	1	icosidodecahedron	12	20
6	3	3	2	truncated tetrahedron	4	4
7	3	4	2	truncated cube	8	6
8	4	3	2	truncated octahedron	6	8
9	3	5	2	truncated dodecahedron	20	12
10	5	3	2	truncated icosahedron = **standard soccer ball**	12	20
11	≥ 3	2	2	truncated beach ball	2	*k*
12	3	2	3	variation on the tetrahedron	4	6
13	4	2	3	variation on the cube	6	12
14	5	2	3	variation on the dodecahedron	12	30
15	≥ 3	1	3	partially truncated beach ball	1	*k*
16	≥ 3	1	4	double tin can	2	2*k*
17	≥ 3	1	5	zigzag tin can	2	2*k*
18	3	1	6	subdivision of the tetrahedron	4	12
19	4	1	6	subdivision of the cube	6	24
20	5	1	6	subdivision of the dodecahedron	12	60



32 explosive blocks (20 hexagonal and 12 pentagonal blocks) which fit together in the same pattern as a soccer ball.

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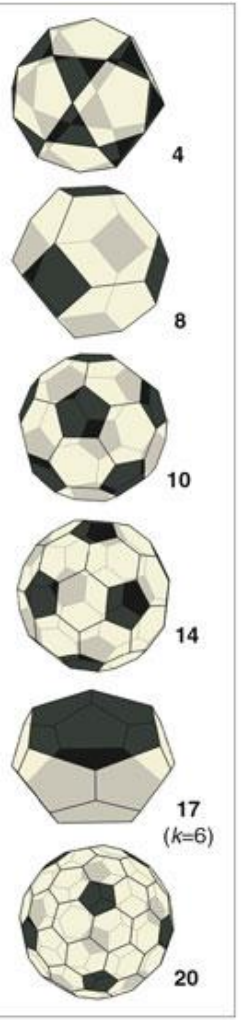

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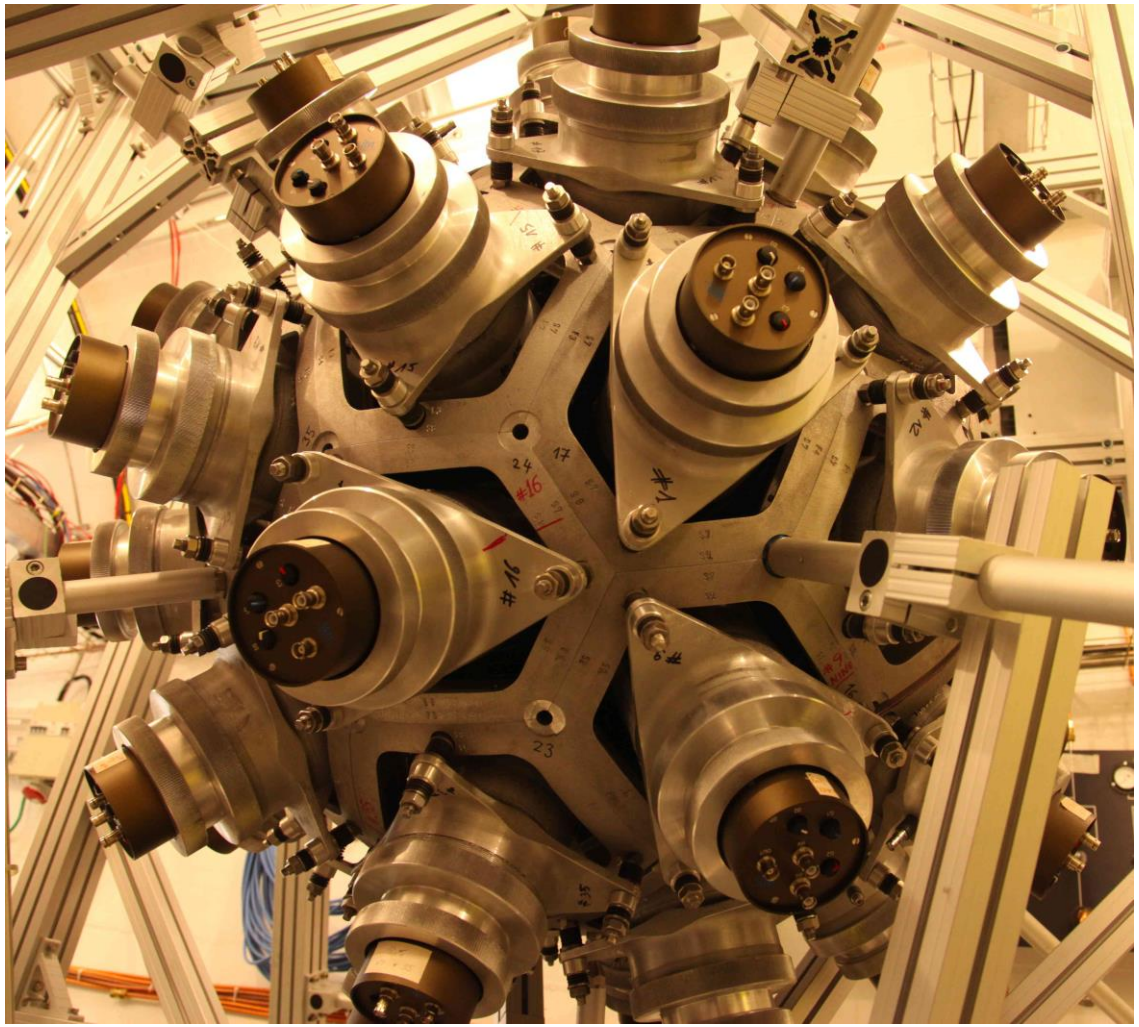

40 BaF_2 crystals for γ-ray detection: a 4π Total Absorption Calorimeter (TAC) at CERN n_TOF

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Nuclear weapons: Implosion assembly

A high performance explosive can generate shock wave pressures of **400 kilobars** (four hundred thousand atmospheres), implosion convergence and other concentration techniques can boost this to **several megabars**.

The convergent shock wave of an implosion can compress solid uranium or plutonium by **a factor of 2 to 3**. The compression occurs very rapidly, typically providing insertion times in the range to **1 to 4 microseconds**. The period of maximum compression lasts less than a microsecond.

A two-fold compression will boost a slightly sub-critical solid mass to nearly **four critical masses**.

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Nuclear weapons

In addition to its major objective of achieving supercriticality, compression has another important effect: The increased density **reduces the neutron mean free path**, which is inversely proportional to density. This reduces the time period for each generation and allows a faster reaction that can progress farther before disassembly occurs. Implosion thus considerably increases a bomb's efficiency.

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Initiating fission

There are three different ways to generate the neutrons that starts the chain reaction (10^7 – 10^9 n/s needed)

1. $^{9}Be + \alpha \rightarrow {}^{8}Be + \alpha + n$ with the α provided by a ^{210}Po source of 3-30 Ci

The major problem with the beryllium/alpha emitter generators is that the strong emitters used have very short half-life (138.4 days for ^{210}Po). Maintaining an inventory of weapons thus requires continual manufacture and replacement of generators.

2. Use the implosion to initiate a neutron generating fusion D+T reactions (placed at the center of the imploding device).

This type of implosion initiator is even more difficult to engineer than the Be/^{210}Po type since the very high precision implosion is required to achieve the required symmetry. The major advantage is that the short half-life ^{210}Po is not needed.

3. Use an electronically controlled particle accelerator (a pulse neutron tube). Can produce 10^8 – 10^9 n/s (pulsed or continuous)

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Initiating fission

SODERN

NEUTRON TUBE — SODITRON

- 2.10^8 n/s at 14 MeV
- continuous or pulsed mode
- small diameter: 25 mm (1")
- minimum shielding required

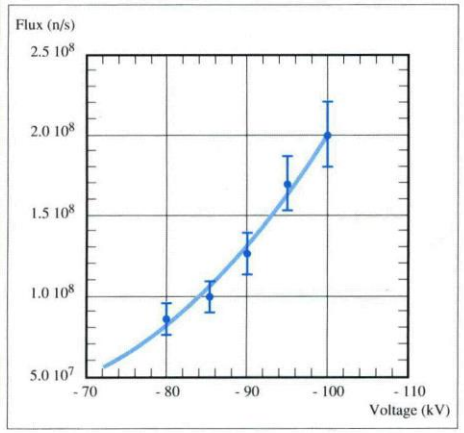
The SODITRON is a small diameter sealed neutron tube; it is well suited for laboratory or industrial portable neutron generators, and can be installed in geophysical probes (oil industry excepted).

The equimolecular loading of deuterium-tritium gas provides a self replenishing of the target, thus increasing the tube lifetime.

The SODITRON operates either in continuous mode or in pulsed mode and emits up to 2 x 10^8 neutrons at 14 MeV per second.

It offers obvious advantages in comparison with isotopic sources, such as no radiation hazard when the tube is not in operation.

TECHNICAL DATA



(Variation of neutron production rate with applied VHV)

Physical

- Neutron energy: 14 MeV
- Neutron emission:
  - adjustable up to 2 x 10^8 neutron per second / 4 π sr
  - peak in pulsed mode: up to 10^5 n/s depending on pulse width and pressure
  - pulse flux: up to 10^7 neutrons /p. at 10 Hz
- Pulse rate: up to 20 kHz
- Pulse width: from 5 µs to continuous mode
- Rise and fall time: from 1 to 5 µs depending on the pressure
- Tritium: < 10^{11} Bq (2.6 Ci)

Electrical

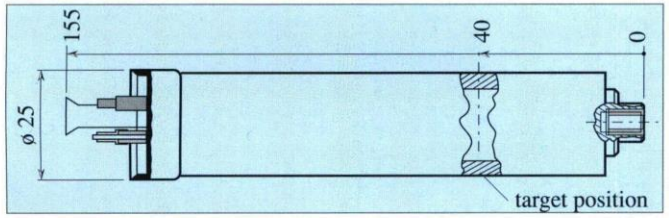
– Accelerating voltage	:	up to - 100 kV (typical value - 90 kV)
– Target current	:	up to 100 µA
– Target dissipation	:	< 10 Watts
– Ion source voltage	:	2 kV ± 10%
– Ion source current	:	750 µA typ
– Replenisher voltage	:	1 V typ., 3 V max
– Replenisher current	:	1 A typ., 2 A max

Mechanical

– Presentation	:	ceramic wall tube
– Diameter	:	25 mm (1")
– Length	:	155 mm (6.1")
– Weight	:	200 g

Environment

- Operating temperature range : + 5 to + 125° C
- Insulation by mean of: oil, Fluorinert of SF 6 under 4 atm. with optional radiator



(Dimensions mm)

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Nuclear weapons: Gun assembly

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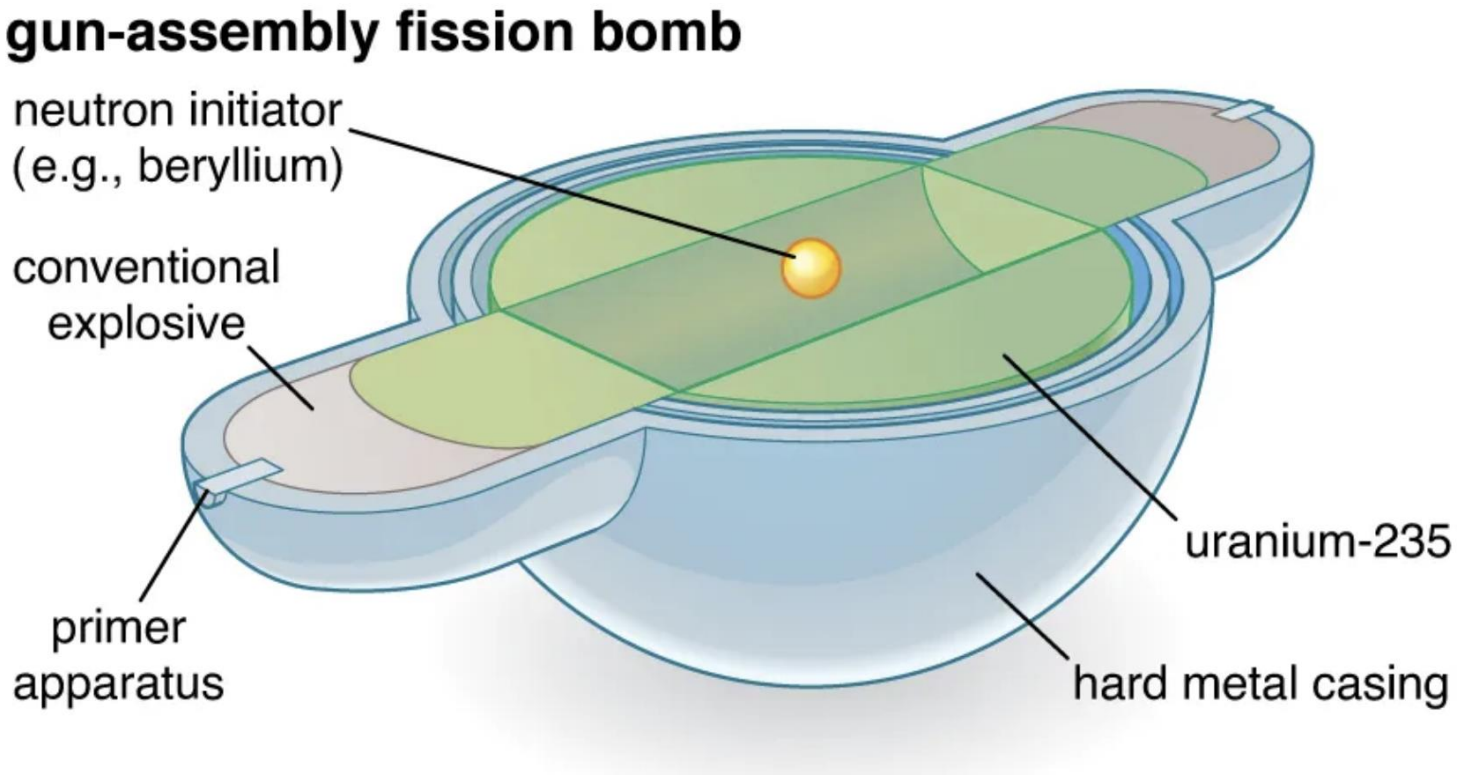
Gun-assembly

Take two subcritical masses and obtain the equivalent of three critical masses by bringing them together.

Imagine a spherical pit made up of about three critical masses of fissionable material. Now remove a core from the pit with a mass slightly less than critical. Since the center of the pit is now hollow, its effective density has been reduced to 2/3 of the original density. Since we now have two critical masses remaining in the pit, and the reduction in density leads to a further reduction of (2/3)^2 = 4/9, the pit now contains only 2*(4/9) = 8/9 of a critical mass.



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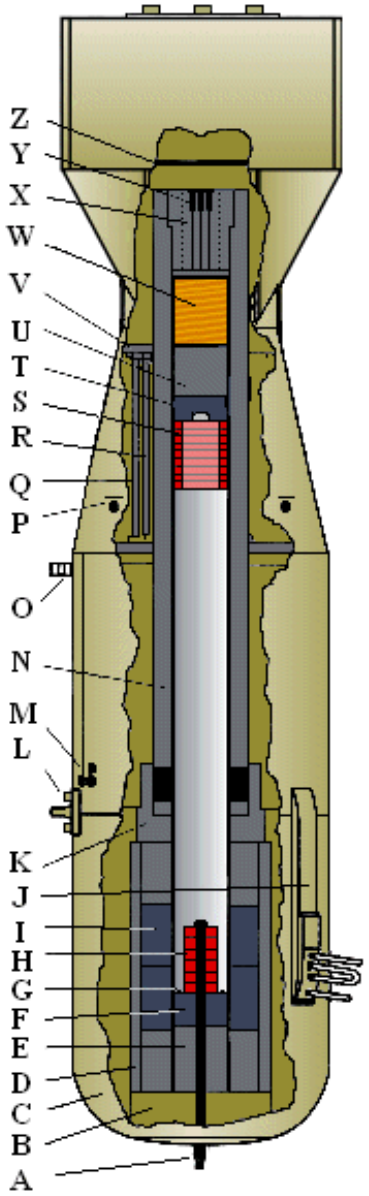

Cross-section drawing of Y-1852 Little Boy showing major mechanical component placement. Drawing is shown to scale. Numbers in ( ) indicate quantity of identical components. Not shown are the APS-13 radar units, clock box with pullout wires, baro switches and tubing, batteries, and electrical wiring. (John Coster-Mullen)

Z) Armor Plate
Y) Mark XV electric gun primers (3)
X) Gun breech with removable inner plug
W) Cordite powder bags (4)
V) Gun tube reinforcing sleeve
U) Projectile steel back
T) Projectile Tungsten-Carbide disk
S) U-235 projectile rings (9)
R) Alignment rod (3)
Q) Armored tube containing primer wiring (3)
P) Baro ports (8)
O) Electrical plugs (3)
N) 6.5" bore gun tube
M) Safing/arming plugs (3)
L) Lift lug
K) Target case gun tube adapter
J) Yagi antenna assembly (4)
I) Four-section 13" diameter Tungsten-Carbide tamper cylinder sleeve
H) U-235 target rings (6)
G) Polonium-Beryllium initiators (4)
F) Tungsten-Carbide tamper plug
E) Impact absorbing anvil
D) K-46 steel target liner sleeve
C) Target case forging
B) 15" diameter steel nose plug forging
A) Front nose locknut attached to 1" diameter main steel rod holding target components

"Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man," 2003, p 112.
John Coster-Mullen drawing used with permission

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Nuclear weapons: Efficiency

By the time a significant percentage of the atoms have fissioned, their thermal kinetic energy is so high that the pit will expand enough to shut down the reaction in only a few of shakes.

This severely limits the efficiency of fission weapons (percentage of material fissioned). The practical efficiency limit of a typical pure fission bomb is about 25% and could be much less.

Little Boy (Hiroshima, gun-type) had an efficiency of only **1.4%**. The **Fat Man** implosion bomb (Nagasaki) was **17% efficient** (counting only the energy produced by the fissile core, the natural uranium tamper contributed another 4% through fast fission). Very large pure fission bombs can achieve efficiencies approaching 50% but have been supplanted by thermonuclear weapon technology. Anything that will increase the confinement time of the fissionable core or decrease the generation time, even slightly, can cause a significant increase in bomb yield.

all details in: Elements of Fission Weapon Design

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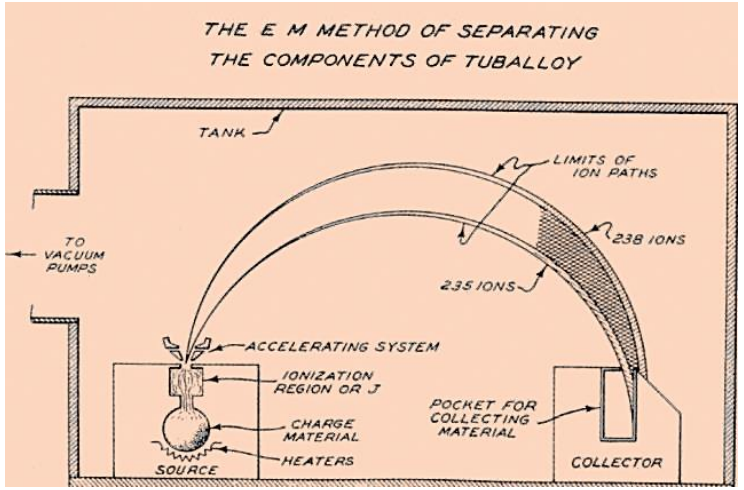
source: nuclearweaponarchive.org

Nuclear weapons: ^{239}Pu & ^{235}U production

The three reactors (B and D which went started up for production in December 1944, and F which started up February 1945) at Hanford had a combined design thermal output of 750 MW and were theoretically capable of producing **19.4 kg of plutonium a month** (6.5 kg/reactor), enough for over 3 Fat Man bombs. Monthly or annual production figures are unavailable for 1945 and 1946, but by the end of FY 1947 (30 June 1947) 493 kg of plutonium had been produced. Neglecting the startup month of each reactor, this indicates **an average plutonium production 5.6 kg/reactor/month** even though they were operated at reduced power or even shut down intermittently beginning in 1946.

Enriched uranium production is more difficult to summarize since there were three different enrichment processes in use that had interconnected production. The Y-12 plant calutrons also had reached maximum output early in 1945, but the amount of weapon-grade uranium this translates into varies depending on the enrichment of the feedstock. Initially this was natural uranium giving a production of **weapon-grade uranium of some 6 kg/month**.



remember the critical masses:

U-233	16 kg
U-235	52 kg
Pu-239 (alpha phase)	10 kg

source: nuclearweaponarchive.org

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Fusion weapons

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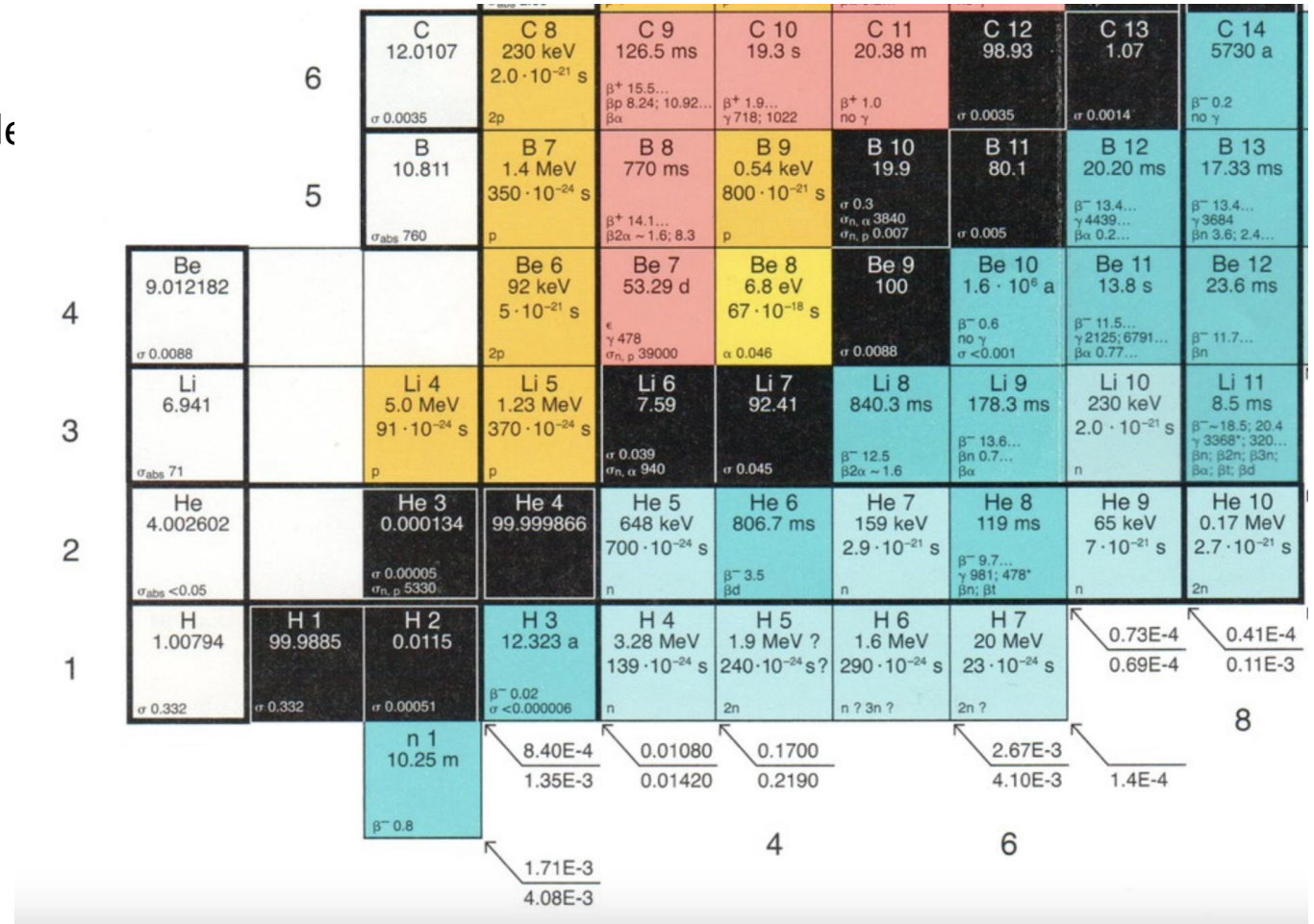
Fusion weapons

The most important fusion reactions for thermonucle

1. D + T → ^{4}He + n + 17.588 MeV
2. D + D → ^{3}He + n + 3.268 MeV
3. D + D → T + p + 4.03 MeV
4. ^{3}He + D → ^{4}He + p + 18.34 MeV
5. ^{6}Li + n → T + ^{4}He + 4.78 MeV
6. ^{7}Li + n → T + ^{4}He + n - 2.47 MeV



At ordinary material densities (e.g. liquid hydrogen, compressed hydrogen gas, or hydrogen-rich solids), the D+T reaction is the only reaction that can occur to a significant extent at the temperature of an atomic bomb of 50-100 million degrees. The temperature at the center of the Sun is only 14 million degrees!

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Fusion weapons

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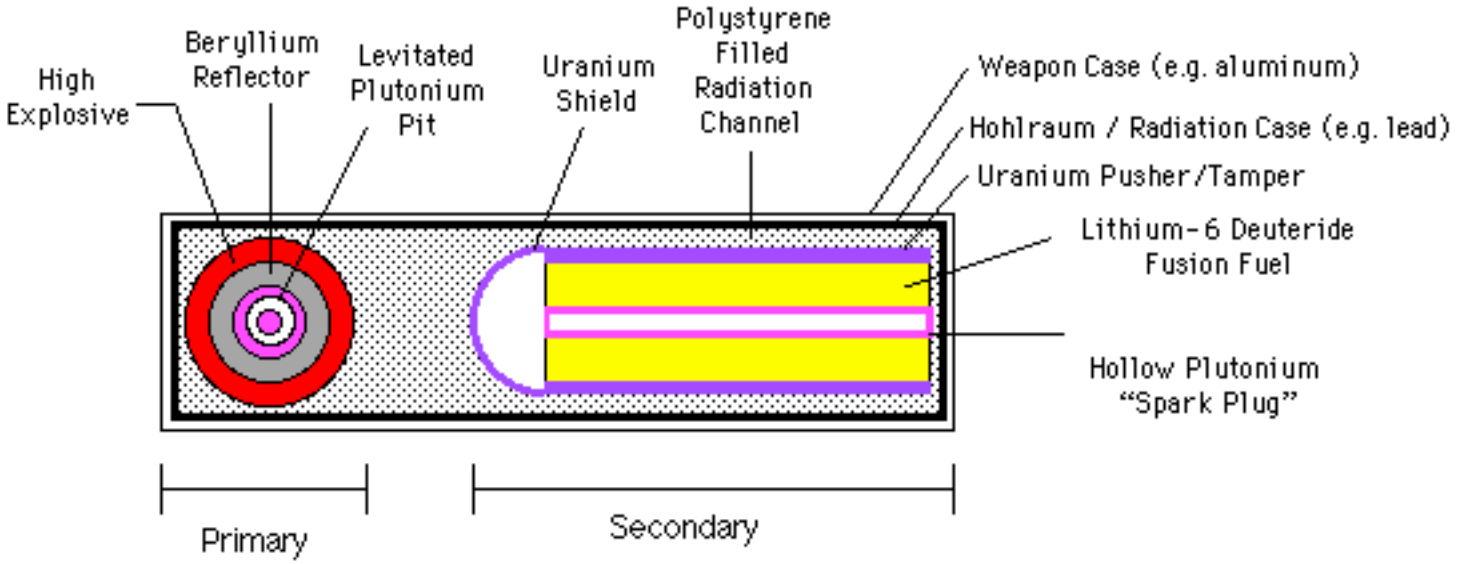

The Teller-Ulam configuration makes use of the fact that at the high temperatures of a fission bomb 80% or more of the energy exists as soft X-rays, not kinetic energy. The transport of energy by radiation from the fission core greatly exceeds the core's expansion rate (a mere 1000 km/sec or so). It is possible then to use this energy to compress, and ignite a physically separate mass of fusion fuel (the second stage) through radiation implosion before the expanding trigger disrupts it.

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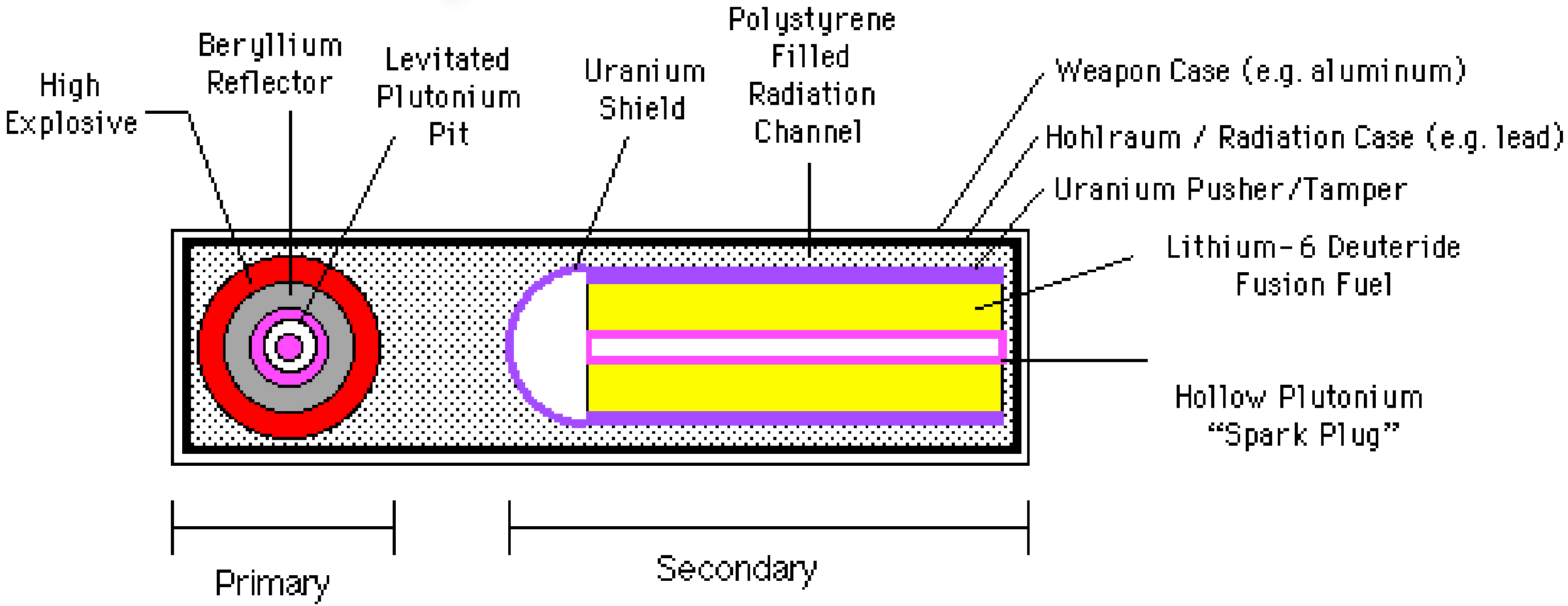
source: nuclearweaponarchive.org

Fusion weapons



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source: nuclearweaponarchive.org

Fusion weapons

At the temperatures achievable in the fission core of the primary (up to 10^8 degrees K) nearly all of the energy is present as a thermal radiation field (up to 95%) with average photon energies **around 10 KeV** (moderately energetic X-rays).

As energy flows down the radiation channel, the energy density drops since the photon gas is now filling a greater volume. This means the temperature of the photon gas, and the average photon energy must drop as well. From an initial average energy of 10 KeV, the X-rays **soften to around 1-2 KeV**. This corresponds to a temperature in the casing of some 10-25 million degrees K.

By applying the blackbody radiation laws we can determine the corresponding radiation intensities and temperatures: **9.8 MK** and 5.3 x 10^16 W/cm^2 for Mike; and **20 MK** and 1.0 x 10^18 W/cm^2 for the W-80. The radiation pressures are 73 and 1400 Mbar respectively.

The pressure exerted by the plasma causes cylindrical (or spherical) implosion of the **fusion capsule**, consisting of the pusher/tamper, fuel, and the axial fissionable rod. The capsule is compressed to perhaps **1/30 of its original diameter** for cylindrical compression (1/10 for spherical compression), and thus reaches or exceeds **1000 times its original density**. It is noteworthy that at this point the explosive force released by the trigger, an amount of energy sufficient to destroy a small city, is being used simply to squeeze several kilograms of fuel!

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source: nuclearweaponarchive.org

Fusion weapons

It is unlikely that **the fissionable rod** reaches such extreme compression. Located at the center, it will experience an extremely violent shock wave that will heat it to high temperatures but compress it only modestly, **increasing its density by a factor of 4 or so**. This is sufficient to **make the rod super-critical**.

Combined with the high temperatures generated by the convergent shock wave, this raises the temperature of the fusion fuel around the rod high enough to **initiate the fusion reaction**. The temperatures generated by fusion burning can considerably exceed that produced by fission (**up to 300 million K**). As the temperature rises, the fusion reactions accelerate.

The 2.45 MeV and 14.1 MeV neutrons that escape from the fusion fuel can also contribute greatly to bomb yield by **inducing fission in the highly compressed fusion tamper**. This extra boost can release most of the explosion energy, and commonly accounts for half of the yield of large fission-fusion-fission bombs and **can reach at least 85%** of the total yield.

A large part of the fusion fuel can be burned before expansion quenches the reaction by reducing the density, which takes some 20-40 nanoseconds. The power output of a fusion capsule is noteworthy. **The largest bomb ever exploded had a yield of 50 Mt**, almost all produced by its final fusion stage. Since 50 Mt is 2.1×10^{17} joules, the power produced during the burn was around 5.3×10^{24} watts. This is **more than one percent of the entire power output of the Sun** (4.3×10^{26} watts)!!

アメ

source: nuclearweaponarchive.org

2023 ESTIMATED GLOBAL NUCLEAR WARHEAD INVENTORIES

The world's nuclear-armed states possess a combined total of over 12,500 nuclear warheads; nearly 90% belong to Russia and the United States. Approximately 9,600 warheads are in military service, with the rest awaiting dismantlement.

Source: Hans M. Kristensen, Matt Korda, Eliana Reynolds, and Kate Kohn, Federation of American Scientists, U.S. Department of State, and the Stockholm International Peace Research Institute. Updated: June 2023

Arms Control Association

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Nuclear weapons

Type	Nuclear bombing
Location	Hiroshima and Nagasaki, Japan
Date	6 and 9 August 1945
Executed by	Manhattan Project 509th Composite Group: 1,770 U.S.
Casualties	Hiroshima: • 70,000–126,000 civilians killed • 7,000–20,000 soldiers killed • 12 Allied prisoners of war Nagasaki: • 60,000–80,000 killed (within 4 months) • 150+ soldiers killed • 8–13 Allied prisoners of war Total killed: • 129,000–226,000

The boy standing by the crematory, Hiroshima (1945)
Joe O'Donnell (photojournalist)

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Thank you!

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The End

アメ

Additional material

アメ

Nuclear Reactors

by uranium, we have to determine what fraction of the total number of neutrons emitted by the photo-neutron source is, in our experiment, absorbed in the thermal region by uranium. The number of photo-neutrons

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アメ

Neutron Production and Absorption in Uranium*

H. L. Anderson, E. Fermi and Leo Szilard
Columbia University, New York, New York

(Received July 3, 1939)

It has been found[1-3] that there is an abundant emission of neutrons from uranium under the action of slow neutrons, and it is of interest to ascertain whether and to what extent the number of neutrons emitted exceeds the number absorbed.

This question can be investigated by placing a photo-neutron source in the center of a large water tank and comparing, with and without uranium in the water, the number of thermal neutrons present in the water. In the previous experiments of this type[1, 3] it was attempted to have as closely as possible a spherically symmetrical distribution of neutrons. The number of thermal neutrons present in the water was determined by measuring along one radius the neutron density ρ as a function of the distance r from the center, and then calculating $\int r^2 \rho dr$. A difference in favor of uranium of about five percent was reported by von Halban, Joliot and Kovarski.[4]

Since one has to measure a small difference, slight deviations from a spherically symmetrical distribution might give misleading results. The present experiments which are based on the same general principle do not require such symmetry. In order to measure the number of thermal neutrons in the water we filled the tank with a ten-percent solution of $MnSO_4$. The activity induced in manganese is proportional to the number of thermal neutrons present. A physical averaging was performed by stirring the solution before measuring the activity of a sample with an ionization chamber. To obtain an effect of sufficient magnitude, about 200 kg of U_3O_8 was used.

The experimental arrangement is shown in Fig. 1. A photo-neutron source, consisting of about 2 g of radium and 250 g of beryllium was placed in the center of the tank. The geometry was such that practically all neutrons emitted by the source and by the uranium oxide were slowed down and absorbed within the tank. Each irradiation extended over several half-life periods of radiomanganese and the observed activity of the solution was about four times the background of the ionization chamber. Alternating measurements were taken with the cans filled with uranium oxide, and with empty cans of the same dimensions. The activity proved to be about ten percent higher with uranium oxide than without it. This result shows that in our arrangement more neutrons are emitted by uranium than are absorbed by uranium.

In order to find the average number of fast neutrons emitted by uranium for each thermal neutron absorbed by uranium, we have to determine what fraction of the total number of neutrons emitted by the photo-neutron source is, in our experiment, absorbed in the thermal region by uranium. The number of photo-neutrons

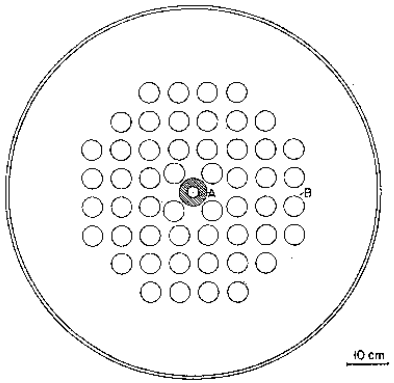

Fig. 1. Horizontal section through center of cylindrical tank which is filled with 540 liters of 10-percent $MnSO_4$ solution. A, Photo-neutron source composed of 2.3 grams of radium and 250 grams of beryllium. B, One of 52 cylindrical cans 5 cm in diameter and 60 cm in height, which are either empty or filled with uranium oxide.

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] v. Halban, Joliot and Kovarski, Nature **143**, 470 (1939).
[2] L. Szilard and W. H. Zinn, Phys. Rev. **55**, 799 (1939).
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Nuclear Reactors

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$$k_\infty = \eta \epsilon p f$$

η : reproduction
ϵ : fast fission
p : resonance escape
f : thermal utilization

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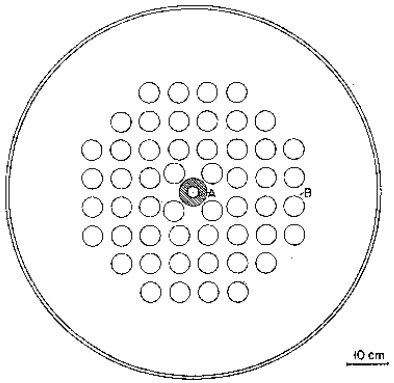

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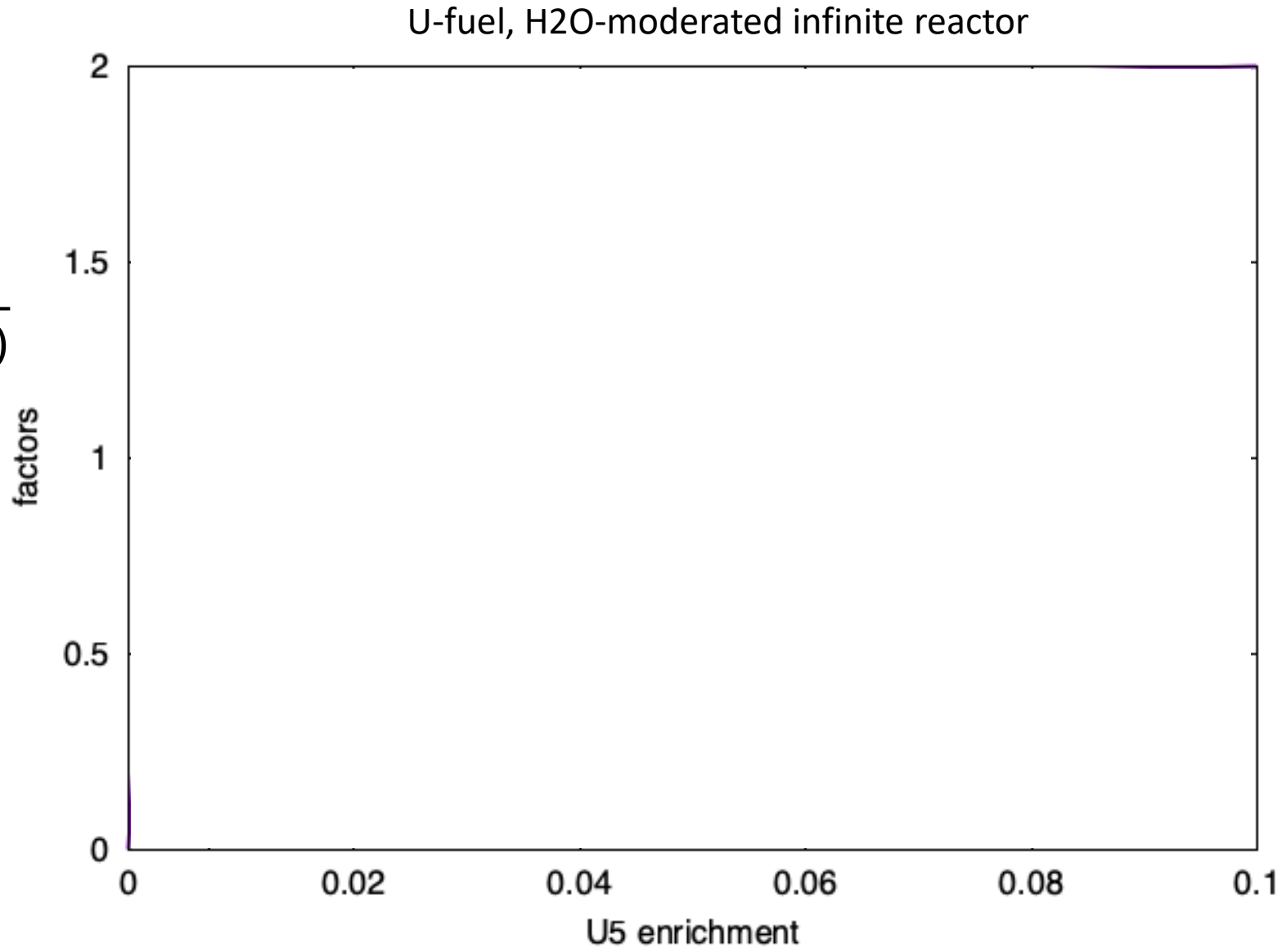
[4] v. Halban, Joliot and Kovarski, Nature **143**, 680 (1939).

Nuclear Reactors

$$\eta(x) = \frac{\nu\sigma_f}{\sigma_a}$$

$$= \frac{2.42\ \sigma_f(\mathrm{U5})\ x}{(x\ \sigma_a(\mathrm{U5}) + (1-x)\ \sigma_a(\mathrm{U8}))}$$

Nucleus	Density g/cm^3	σ_f	σ_c	σ_a	σ_s
^{232}Th	11.7	$< 10^{-6}$	7.34	7.34	13.0
^{233}U	18.7	531	45.3	576	12.2
^{235}U	18.7	585	98.7	684	15.1
^{238}U	18.9	1.68×10^{-5}	2.68	2.68	9.30
U$^*_{\text{natural}}$	18.9	4.21	3.37	7.59	9.34
^{239}Pu	19.8	748	271	1 019	7.99



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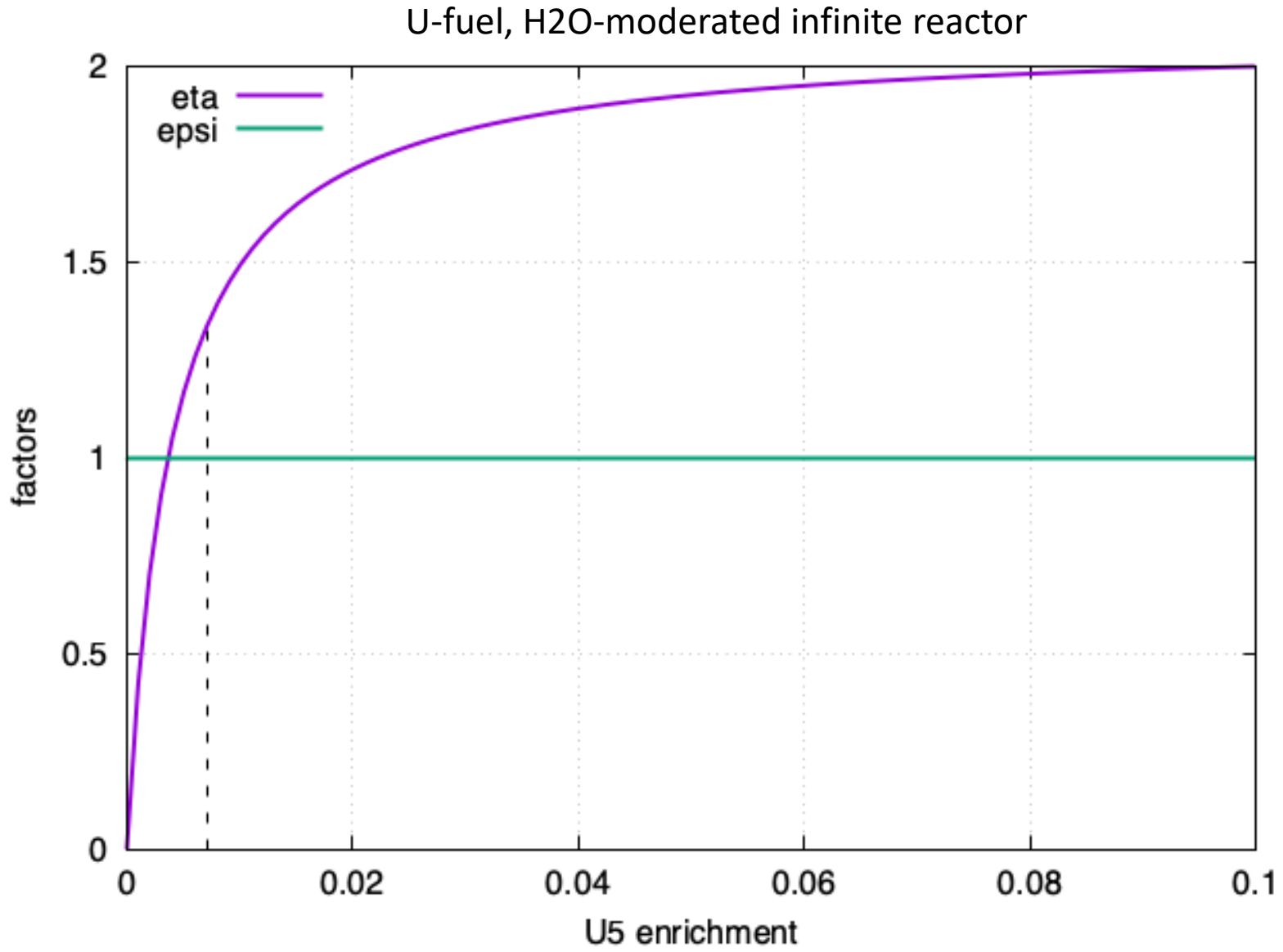
Nuclear Reactors

$\epsilon \approx 1$



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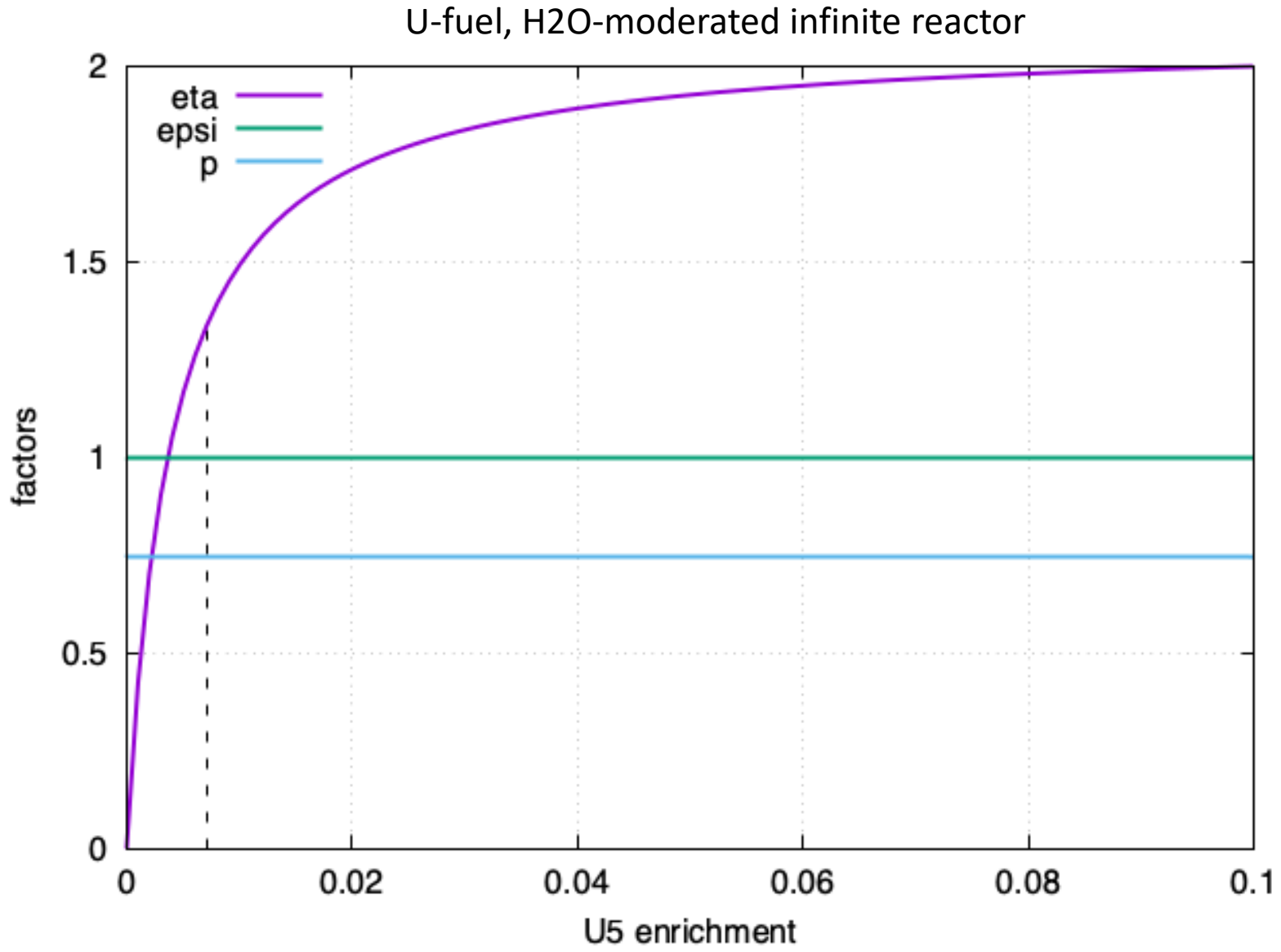
Nuclear Reactors

$p \approx 0.74$



アメ

Nuclear Reactors

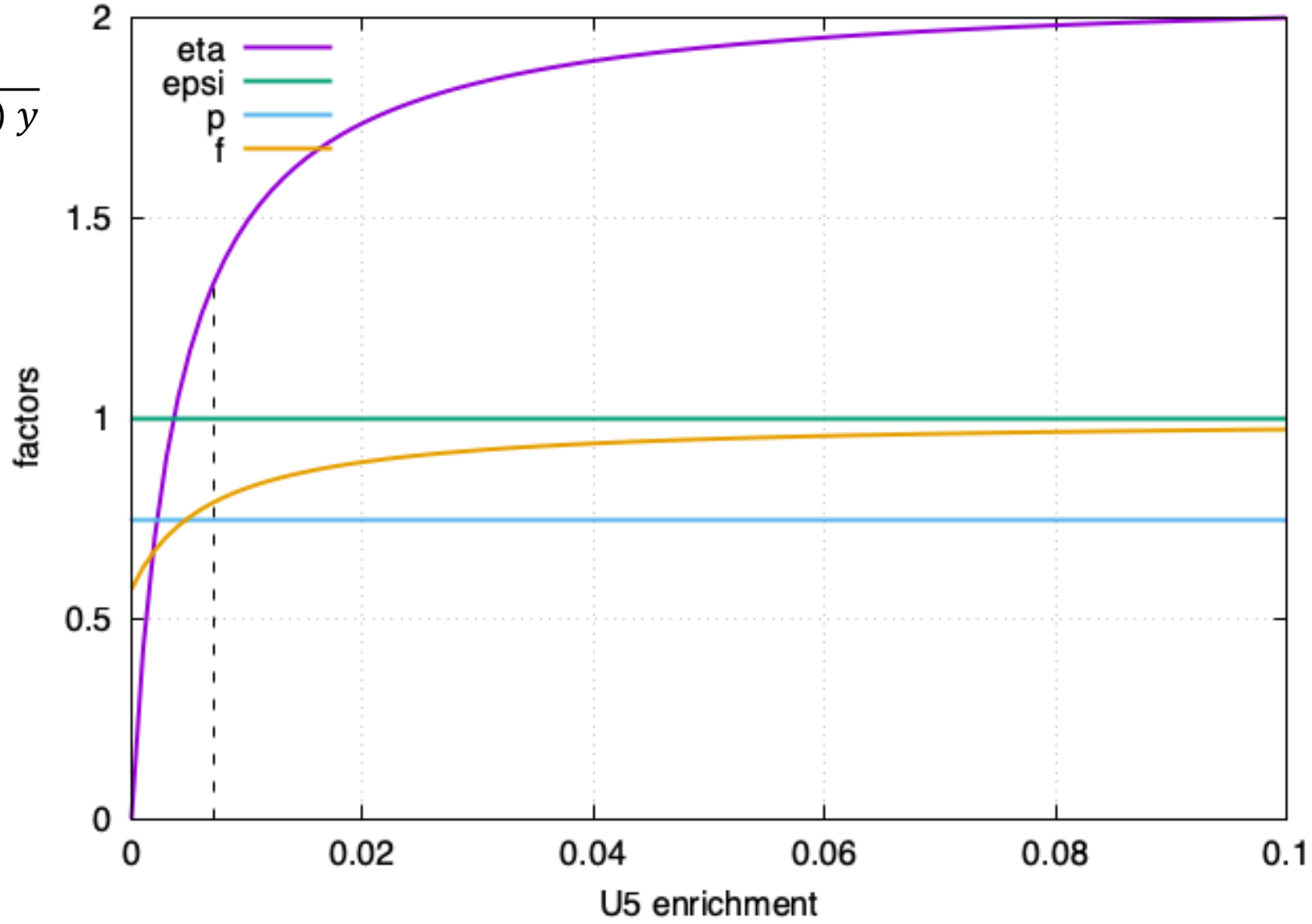
$$f(x) = \frac{x\,\sigma_a(U5) + (1-x)\sigma_a(\mathrm{U8})}{x\,\sigma_a(\mathrm{U5}) + (1-x)\sigma_a(\mathrm{U8}) + \sigma_a(\mathrm{mod})\,y}$$

for $y = 3$

Table 19.2 Properties of moderators relevant for thermal fission reactors, including density (in g/cm^3), atomic mass, cross sections (in barns) for thermal neutrons ($v \cong 2200$ m/s), and logarithmic energy decrement ξ (§18.3.6) [70, 77].

Material	Density	A	σ_a	σ_s	ξ
H_2O	1.0	18	0.664	49.2	0.920
D_2O	1.1	20	1.20×10^{-3}	10.6	0.509
C	1.6	12	3.37×10^{-3}	4.94	0.158

U-fuel, H2O-moderated infinite reactor



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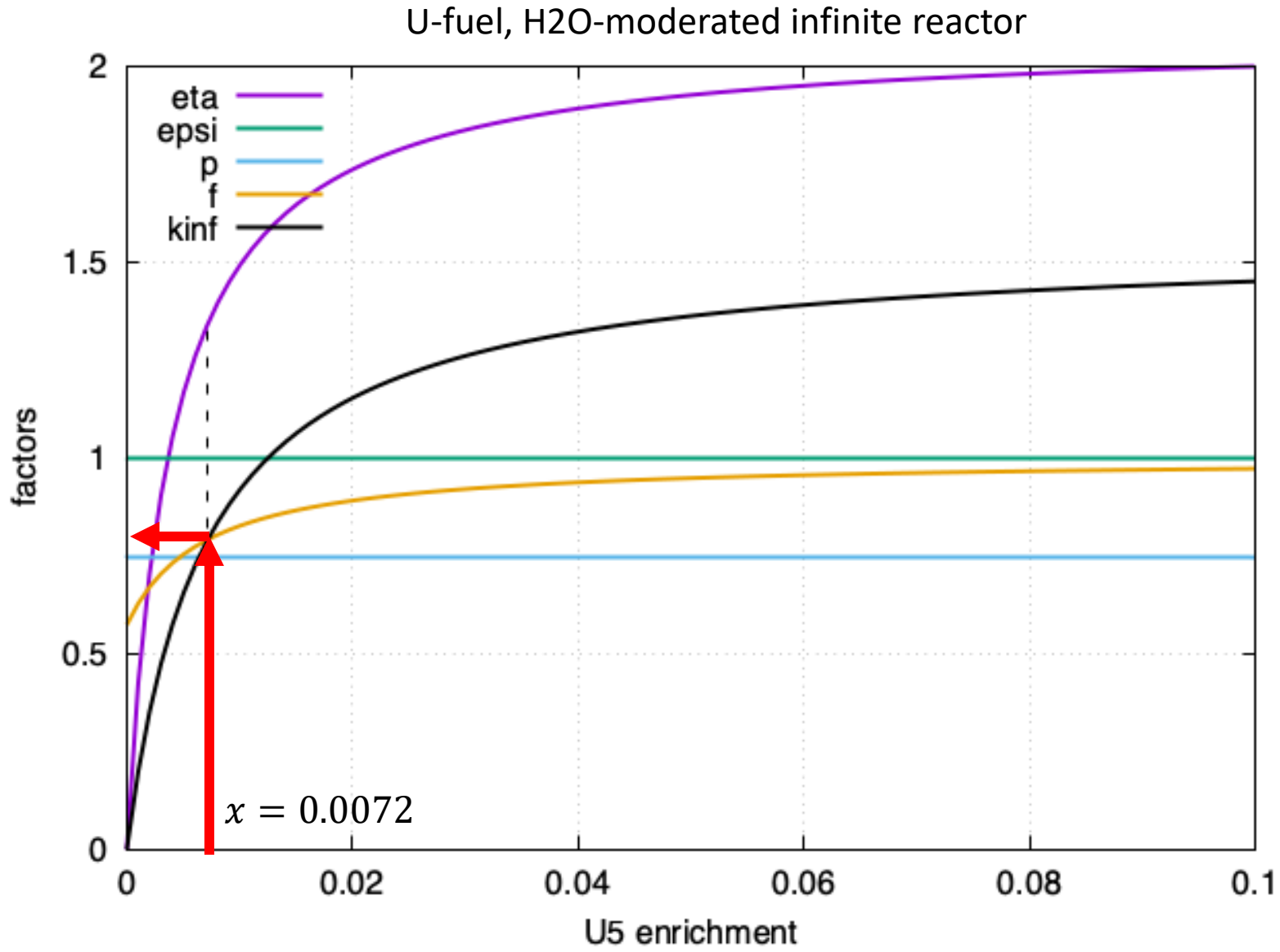
Nuclear Reactors

$$k_\infty = \eta \epsilon p f$$

$k_\infty < 1$ for $x = 0.072$
(U-nat)



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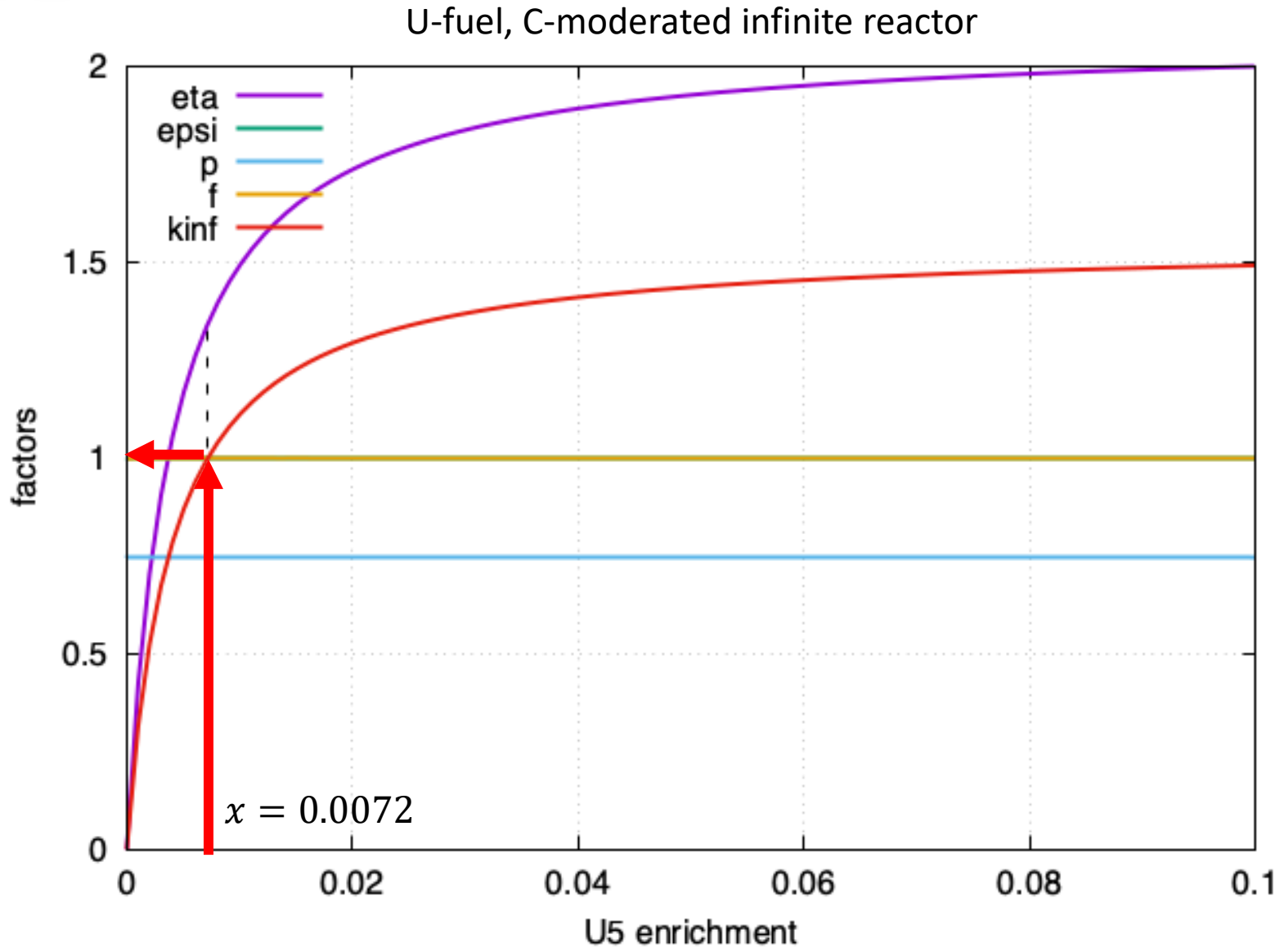
Nuclear Reactors

$$k_\infty = \eta \epsilon p f$$

$k_\infty = 1$ for $x = 0.072$
(U-nat)



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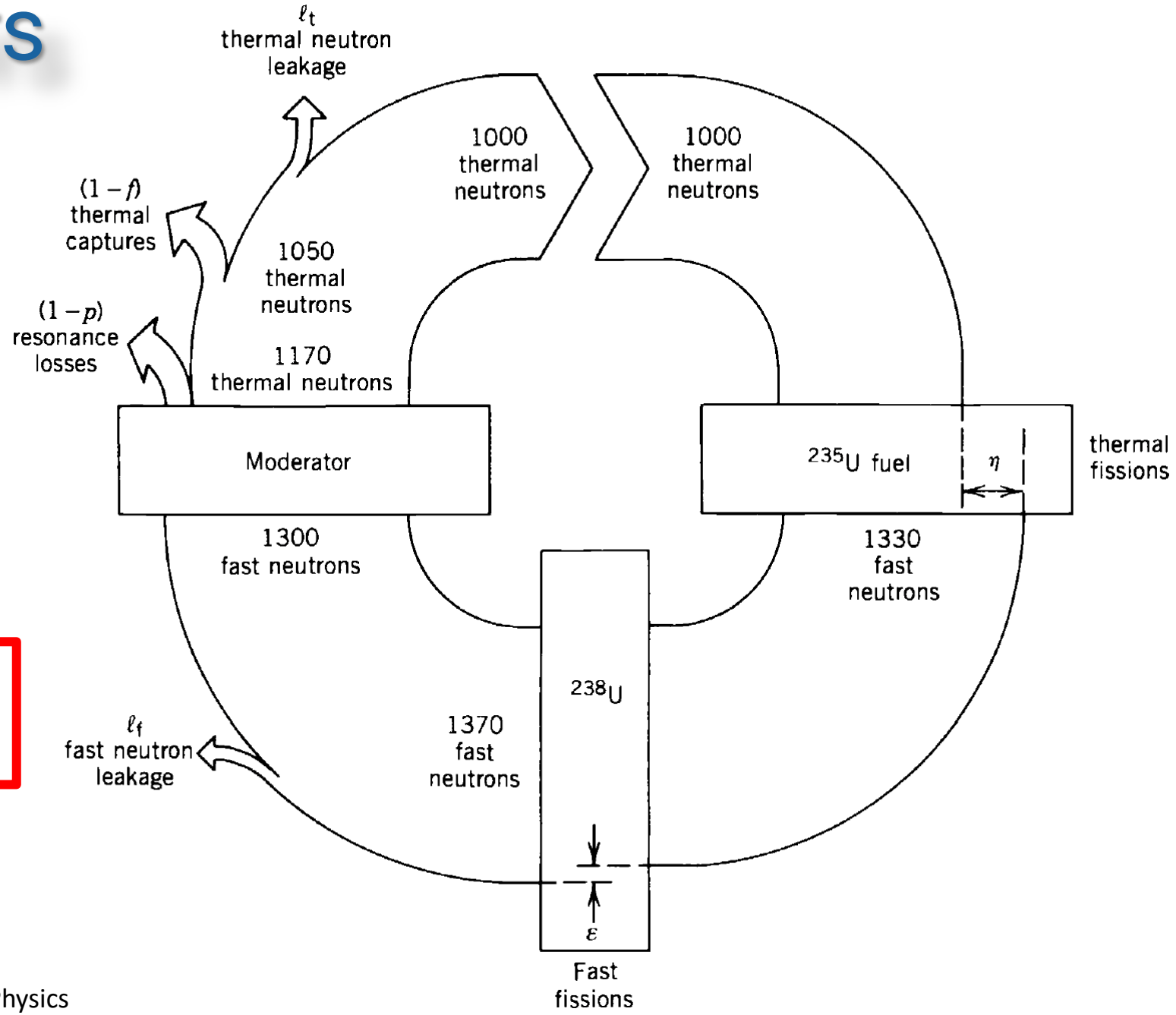
Nuclear Reactors

$$k_\infty = \eta \epsilon p f$$

η : reproduction
ϵ : fast fission
p : resonance escape
f : thermal utilization

$$k_{eff} = \eta \epsilon p f \mathcal{L}_f \mathcal{L}_t$$

$\mathcal{L}_f$: fast neutron leakage
$\mathcal{L}_t$: thermal neutron leakage



source: Kenneth S Krane, Introductory Nuclear Physics

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Nuclear Reactors

$$k_\infty = \eta \, \epsilon \, p \, f$$

Symbol	Name	Meaning	Formula	Typical thermal reactor value
η	Reproduction factor (eta)	neutrons produced from fission / absorption in fuel isotope	$\eta = \frac{\nu \sigma_f^F}{\sigma_a^F}$	1.65
f	Thermal utilization factor	neutrons absorbed by the fuel isotope / neutrons absorbed anywhere	$f = \frac{\Sigma_a^F}{\Sigma_a}$	0.71
p	Resonance escape probability	fission neutrons slowed to thermal energies without absorption / total fission neutrons	$p \approx \exp\left(-\frac{\sum_{i=1}^{N} N_i I_{r,A,i}}{\left(\bar{\xi}\Sigma_p\right)_{mod}}\right)$	0.87
ϵ	Fast fission factor	total number of fission neutrons / number of fission neutrons from just thermal fissions	$\varepsilon \approx 1 + \frac{1-p}{p} \frac{u_f \nu_f P_{FAF}}{f \nu_t P_{TAF} P_{TNL}}$	1.02

source: wikipedia

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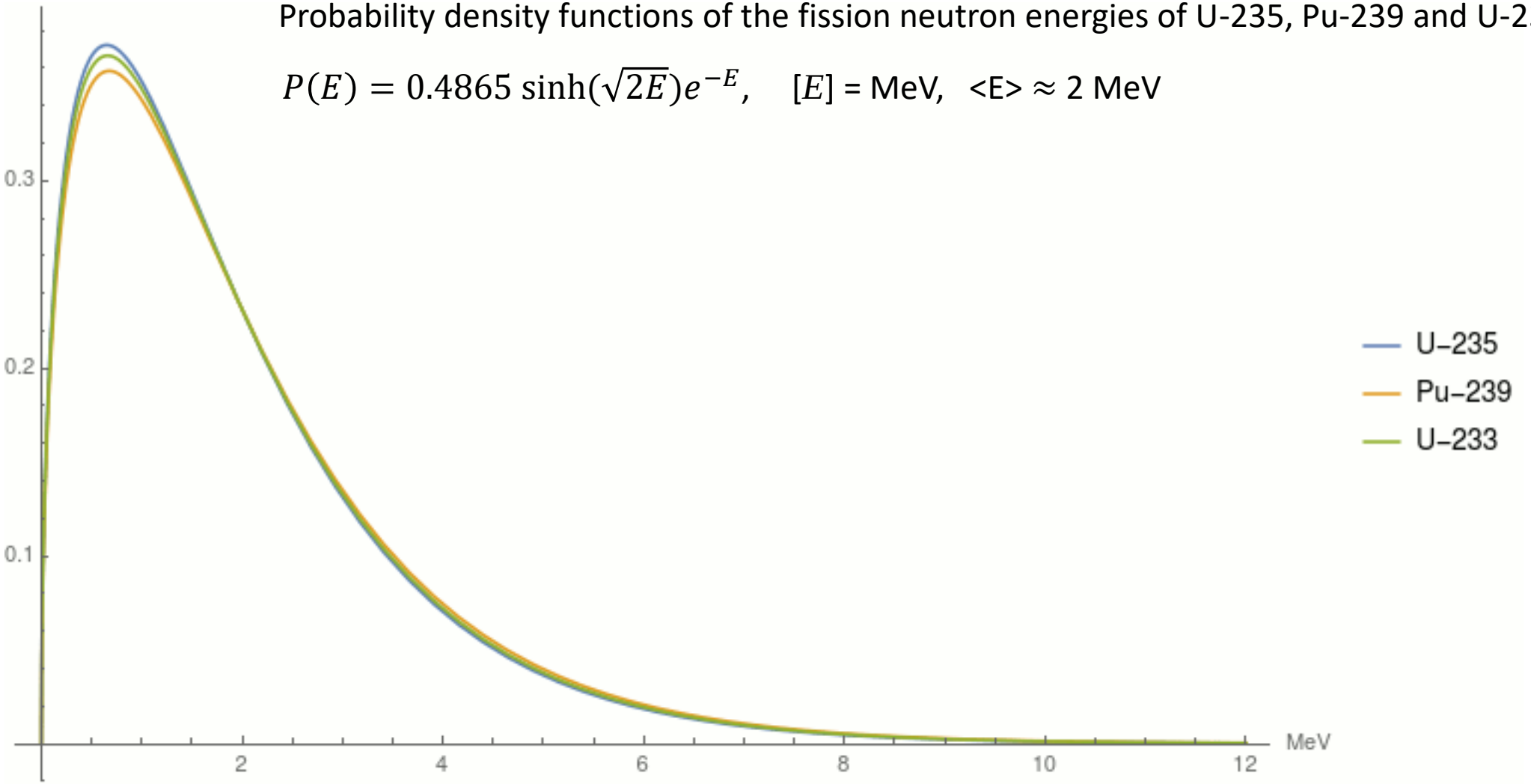
Nuclear Reactors: neutronics

Probability density functions of the fission neutron energies of U-235, Pu-239 and U-233

$P(E) = 0.4865 \sinh(\sqrt{2E})e^{-E}$, [$E$] = MeV, <E> ≈ 2 MeV



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The 100 ton test

The first nuclear explosion in history took place in New Mexico, at the Alamogordo Test Range, on the **Jornada del Muerto** (Journey of Death) desert, in the test named Trinity.

Before Trinity: May 7, 1945

To help in preparing the instrumentation for the Trinity shot the "100 Ton Test" was fired on 7 May 1945. This test detonated 108 tons of TNT stacked on a wooden platform 800 yards from Trinity ground zero. The pile of high explosive was threaded with tubes containing 1000 curies of reactor fission products. This is the largest instrumented explosion conducted up to this date. The test allowed the calibration of instruments to measure the blast wave, and gave some indication of how fission products might be distributed by the explosion.

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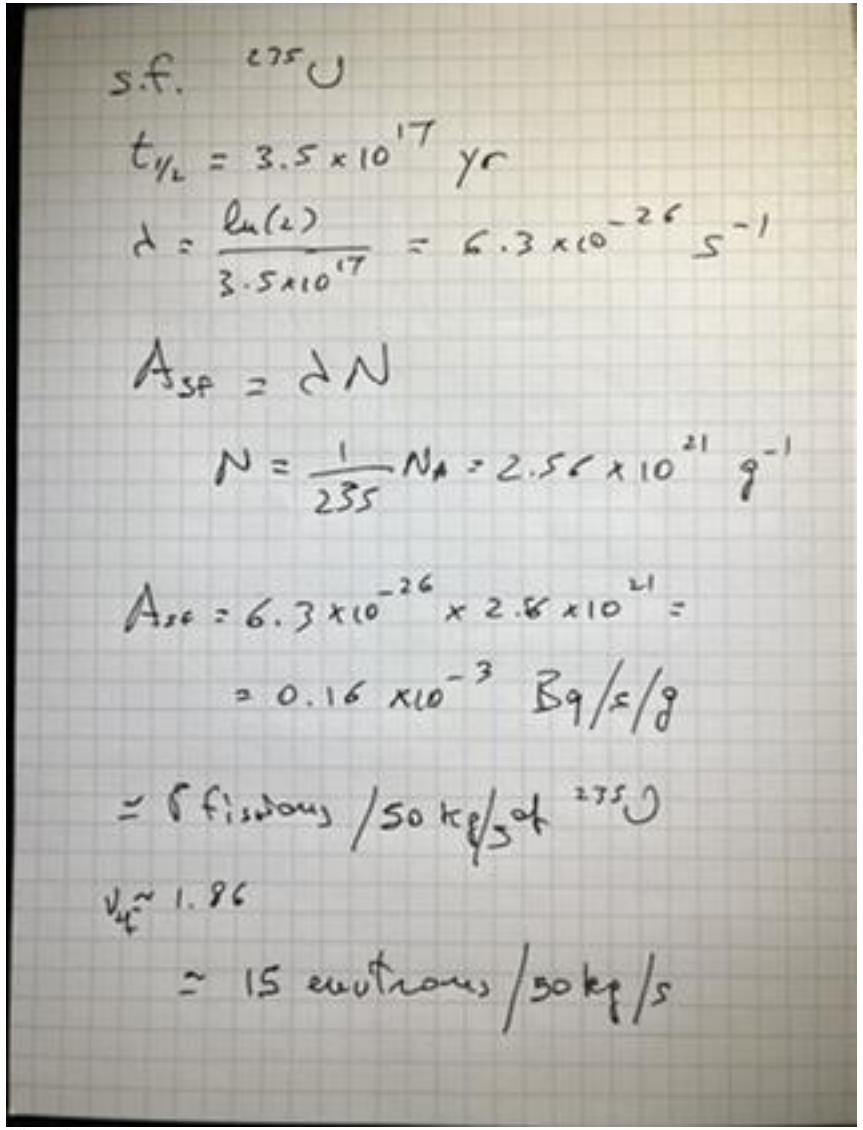
Spontaneous fission



Spontaneous fission rates[12]

Nuclide	Half-life (yrs)	Fission rate (% of decays)	Neutrons per		Spontaneous half-life (yrs)	$\frac{Z^2}{A}$
			Fission	Gram-sec		
^{235}U	$7.04 \cdot 10^{8}$	$2.0 \cdot 10^{-7}$	1.86	0.0003	$3.5 \cdot 10^{17}$	36.0
^{238}U	$4.47 \cdot 10^{9}$	$5.4 \cdot 10^{-5}$	2.07	0.0136	$8.4 \cdot 10^{15}$	35.6
^{239}Pu	24100	$4.4 \cdot 10^{-10}$	2.16	0.022	$5.5 \cdot 10^{15}$	37.0
^{240}Pu	6569	$5.0 \cdot 10^{-6}$	2.21	920	$1.16 \cdot 10^{11}$	36.8
^{250}Cm	8300[13]	≃74	3.31	$1.6 \cdot 10^{10}$	$1.12 \cdot 10^{4}$	36.9
^{252}Cf	2.6468[14]	3.09	3.73	$2.3 \cdot 10^{12}$	85.7	38.1

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Nuclear Reactors

Number of fissions:

$$N(t) = N_0 e^{(k-1)t/t_0}$$

t_0 is the time needed to go from one generation of neutrons to the next

reactivity: $\rho = \dfrac{k-1}{k}$

Most neutrons from are emitted within 10^{-13} s (prompt)
The slowing-down process takes, typically 10^{-4} s

The multiplication factor k represents the number of neutrons of (*n*+1)st generation, produced by each neutron of the *n*-th generation

In an infinite reactor

$$k_\infty = \eta \epsilon p f$$

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Nucleosynthesis: TRU (1000 Mw_e LWR)

^{244}Cm
1.5 Kg/yr

^{241}Am:11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

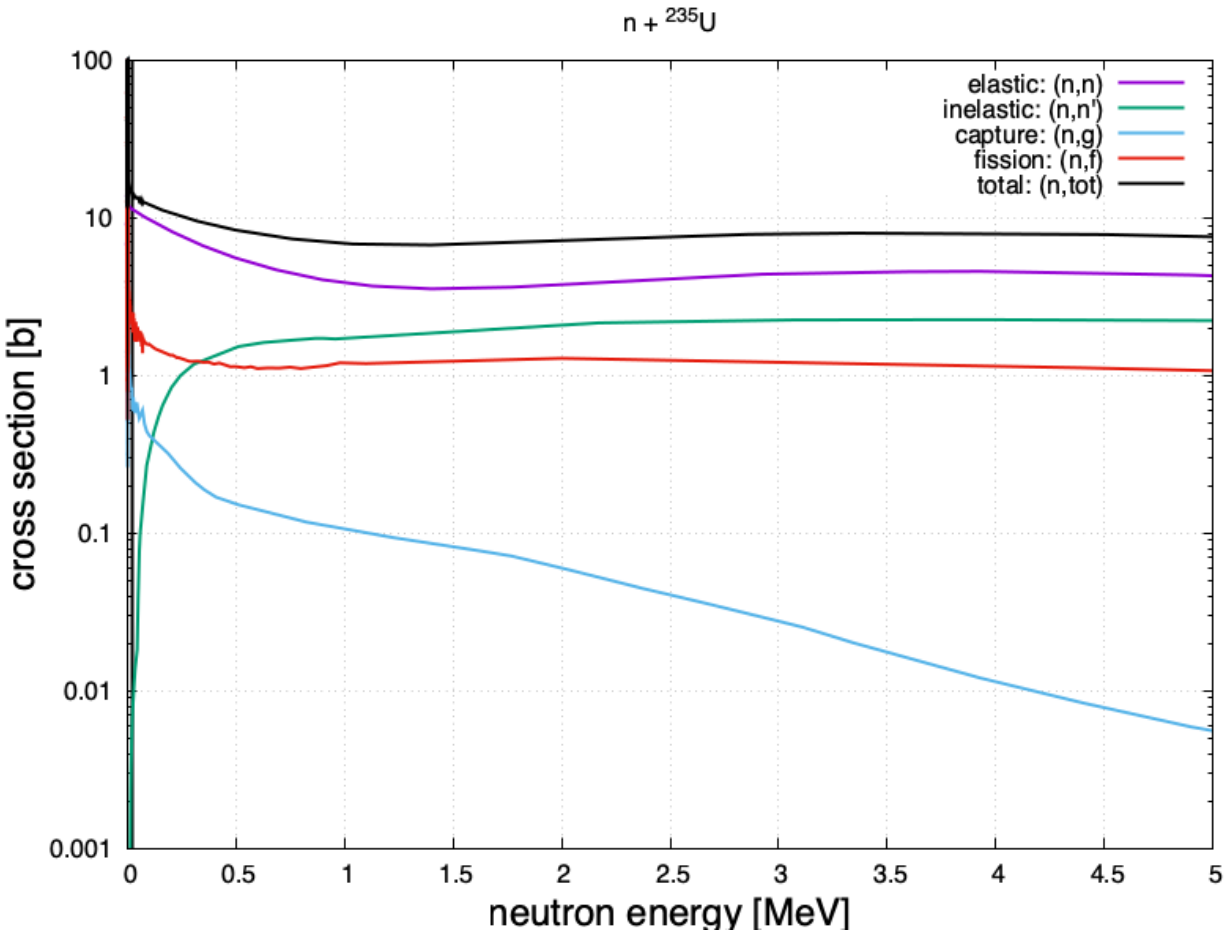
source: Actinide and Fission Product Partitioning and Transmutation – NEA (1999)

Criticality

A neutron entering a pure chunk of one of the slow-fissionable isotopes would have a high probability of causing fission compared with the chance of unproductive neutron capture. If the chunk is large and compact enough, then the rate of neutron escape from its surface will be so low that it becomes a "critical mass", a mass in which a self-sustaining chain reaction occurs. Non-fissionable materials mixed with these isotopes tend to absorb some of the neutrons uselessly and increase the required size of the critical mass or may even make it impossible to achieve altogether.

Typical figures for critical masses for bare (unreflected) spheres of fissionable materials are:

U-233	16 kg
U-235	52 kg
Pu-239 (alpha phase)	10 kg



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Criticality: HEU

The macroscopic cross section is defined by

$$\Sigma_f \equiv n\,\sigma_f \qquad [\Sigma_f] = 1/\text{cm}$$

The mean-free path is

$$\lambda_f = 1/\Sigma_f \qquad [\lambda_f] = \text{cm}$$

Considering that $\sigma_t = \sigma_f + \sigma_{el}$ the criticality radius is given by

$$R_C = k\sqrt{\lambda_f \lambda_t}$$

With the constant k related to the effective number of neutrons emitted/fission, given by

$$k = \frac{1.82}{\sqrt{\log(\nu)}}$$

Table I. U-235 bare critical radii and masses.

Quantity	Unit	Compton case (a)[a]	Compton case (b)[b]	Present-day value
ρ	gr/cm^3	18.6	18.6	18.95
σ_f	bn	3	0.5	1.235[c]
σ_{el}	bn	6	6	4.566[c]
ν		3	3	2.637[d]
n	10^{22} cm^{-3}	4.8	4.8	4.855
λ_f	cm	7	42	16.68
λ_t	cm	2.3	3.5	3.55
R_o	cm	7[e] (3.46[f])	21[e]	8.261[f]
M_o	kg	26[e] (3.2[f])	720[e]	44.8[f]

[a]Actual high fission threshold for U-238.
[b]No definite high fission threshold for U-238.
[c]I have adopted fission-spectrum averaged cross sections listed in the Table of Nuclides site maintained by the Korean Atomic Energy Research Institute, ⟨www.atom.kaeri.re.kr⟩.
[d]Secondary-neutron number adopted from the Evaluated Nuclear Data Files maintained by the National Nuclear data Center at Brookhaven National Laboratory, ⟨www.nndc.bnl.gov⟩.
[e]From $R_o = 1.73\sqrt{\lambda_f \lambda_t}$.
[f]From diffusion theory for the cross sections and ν values listed.

B Cameron Reed, Am. J. Phys., Vol. 75, No. 12, December 2007

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The radius of a critical assembly is

$$R_C = \lambda_f \sqrt{s}$$

where s is the number of steps in a random walk. Then, considering that $n = \frac{\rho}{A} N_A$

$$1 = \frac{f\,\sigma_f}{A\,\sqrt{s}} \rho^{2/3}\, M_C^{1/3}$$

f is a "fudge" factor incorporating constants and geometrical factors. It follows that:

$$M_C \propto 1/\rho^2$$

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