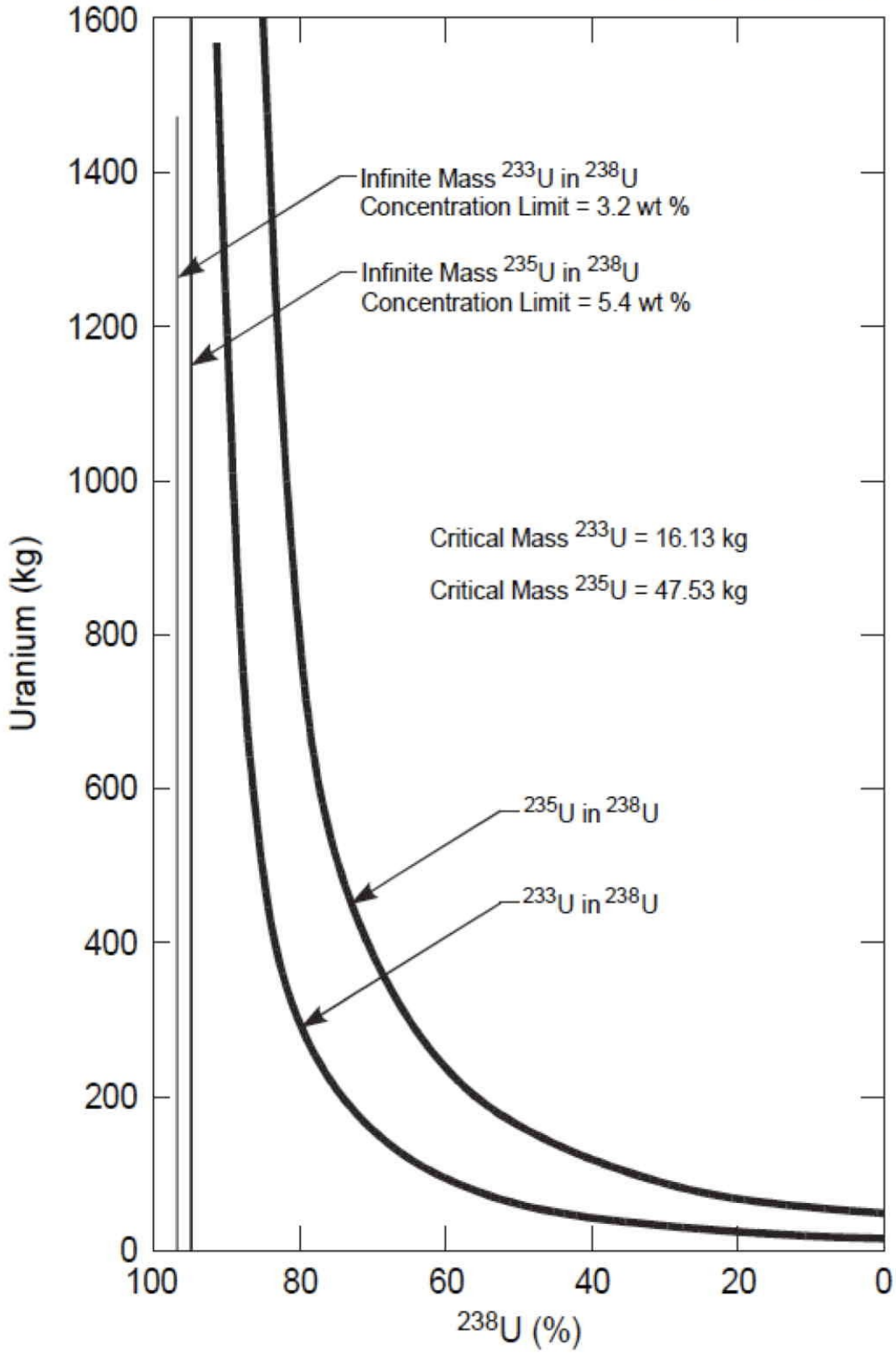
Lecture 8
Nuclear Weapons Physics

Critical Mass

“Tickling the Dragon’s Tail”



Calculated critical masses of homogeneous mixtures of ^{235}U and ^{238}U, and ^{233}U and ^{238}U, for a bare metal sphere.

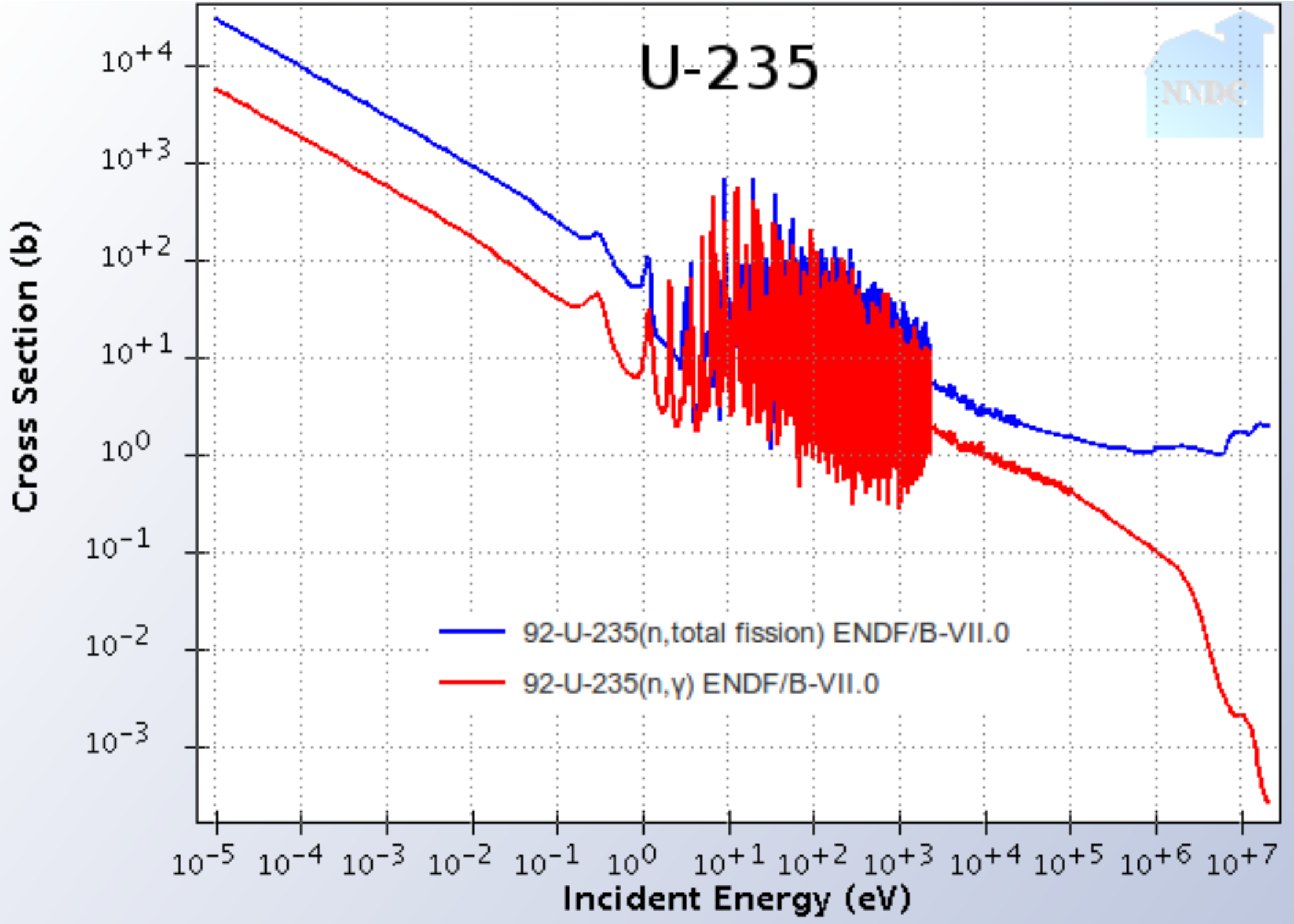
Taken from C.W. Forsberg et al., "Definition of Weapons-Usable Uranium-233", ORNL/TM-13517 (March 1998).

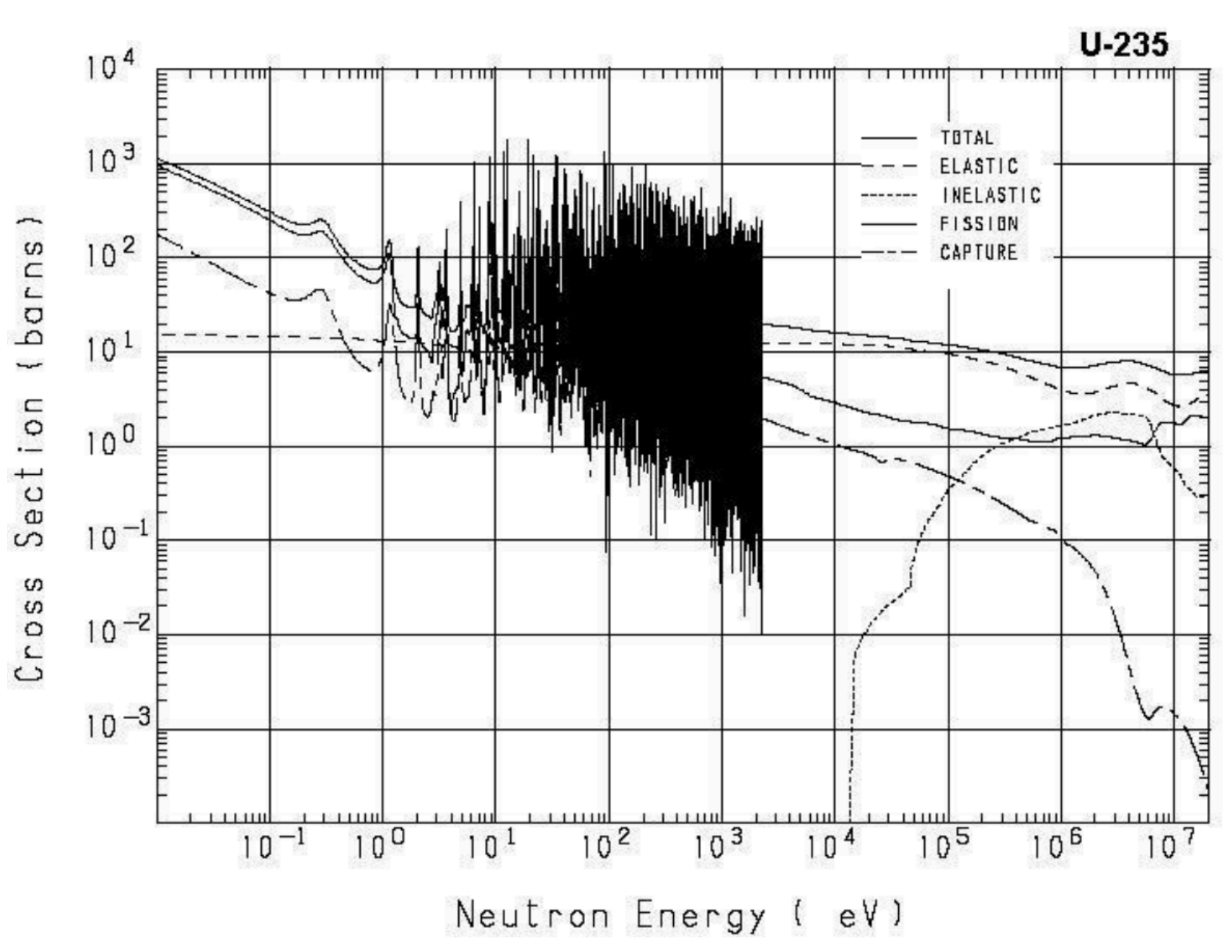
TABLE 2. Calculated Critical Parameters of Mixtures of ^{235}U and ^{238}U Metal Spheres

W% ^{235}U	Density (g/cc)	Radius (cm)	Mass (kg)	Generation Time	Life Time
100	18.7617	8.457	47.53	4.7827-9	5.3427-9
90	18.7855	9.052	58.36	5.4515-9	6.0311-9
80	18.8092	9.656	70.93	6.1311-9	6.8020-9
70	18.8331	10.351	87.48	7.0248-9	7.7641-9
60	18.8570	11.285	113.53	8.3599-9	9.2137-9
50	18.8810	12.000	136.67	9.6334-9	1.0643-8
40	18.9050	14.173	225.47	1.2965-8	1.4281-8
30	18.9291	16.643	365.55	1.7487-8	1.9584-8
25	18.9412	18.528	504.65	2.1000-8	2.3844-8
20	18.9533	21.105	746.30	2.6298-8	3.0437-8
15	18.9654	25.613	1334.82	3.4790-8	4.1901-8
10	18.9775	35.852	3663.15	5.0125-8	6.5314-8
8	18.9820	46.000	7739.47	6.0323-8	8.3586-8
5	18.9896	Not Critical	Not Critical	Not Critical	Not Critical

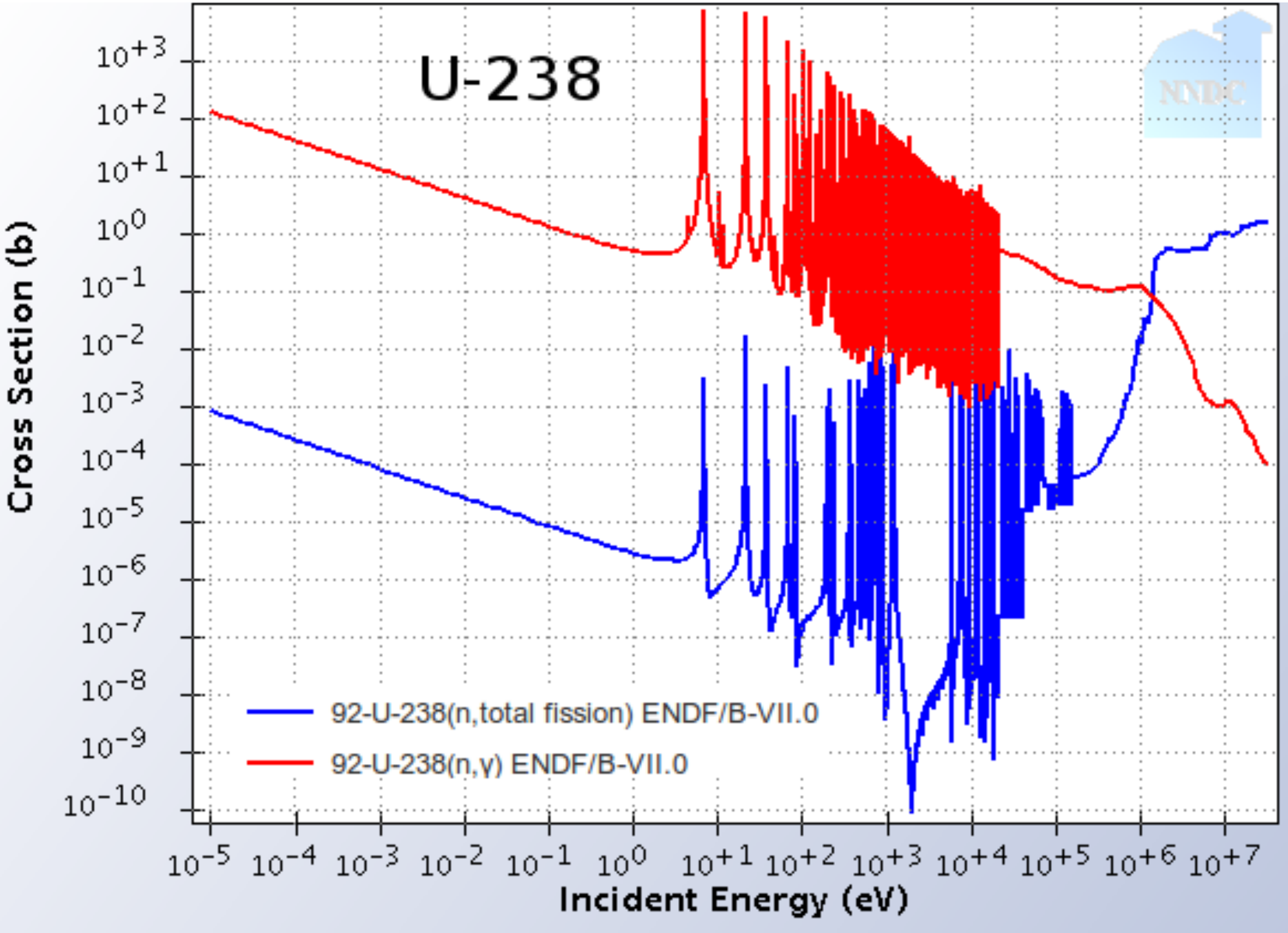
Uranium Enrichment	Reflector thickness			
	Bare	5 cm	10 cm	15 cm
10 wt%	Very large	Very large	1435.0 kg	753.0 kg
15 wt%	1351.0 kg	758.3 kg	426.5 kg	253.8 kg
19.75 wt%	782.2 kg	402.9 kg	220.7 kg	143.8 kg
30 wt%	367.4 kg	171.2 kg	100.3 kg	68.7 kg
45 wt%	184.7 kg	80.5 kg	49.6 kg	35.6 kg
70 wt%	87.2 kg	36.5 kg	23.7 kg	18.2 kg
93 wt%	53.3 kg	22.3 kg	14.9 kg	11.7 kg
Reactor-grade Pu	14.6 kg	6.92 kg	5.29 kg	4.58 kg
Fuel-grade Pu	13.2 kg	6.24 kg	4.76 kg	4.10 kg
Weapon -grade Pu	11.5 kg	5.53 kg	4.26 kg	3.71 kg

What does ^{235}U have going for it as a weapons fuel?

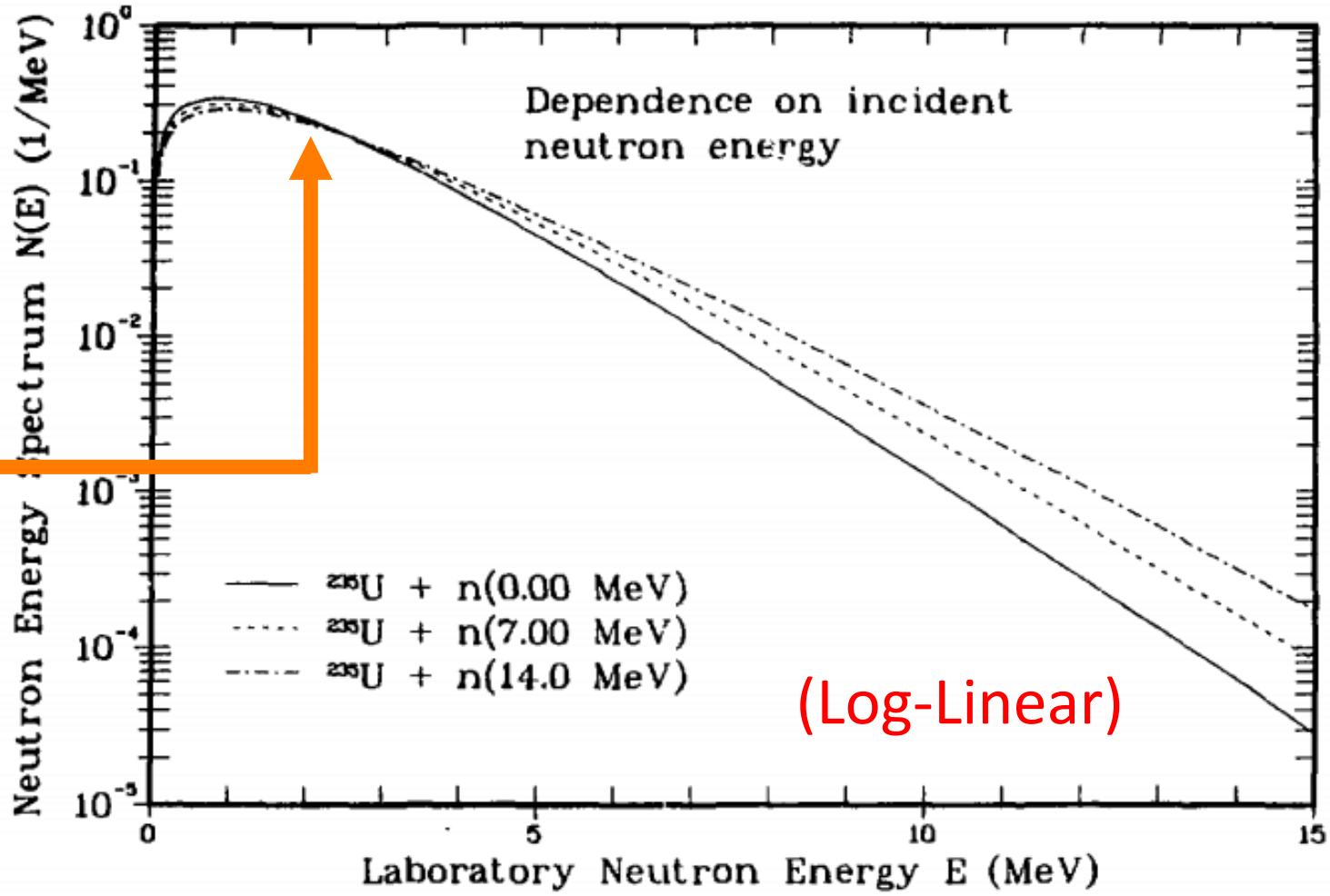



U-235
TOTAL
ELASTIC
INELASTIC
FISSION
CAPTURE
Cross Section (barns)
Neutron Energy (eV)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

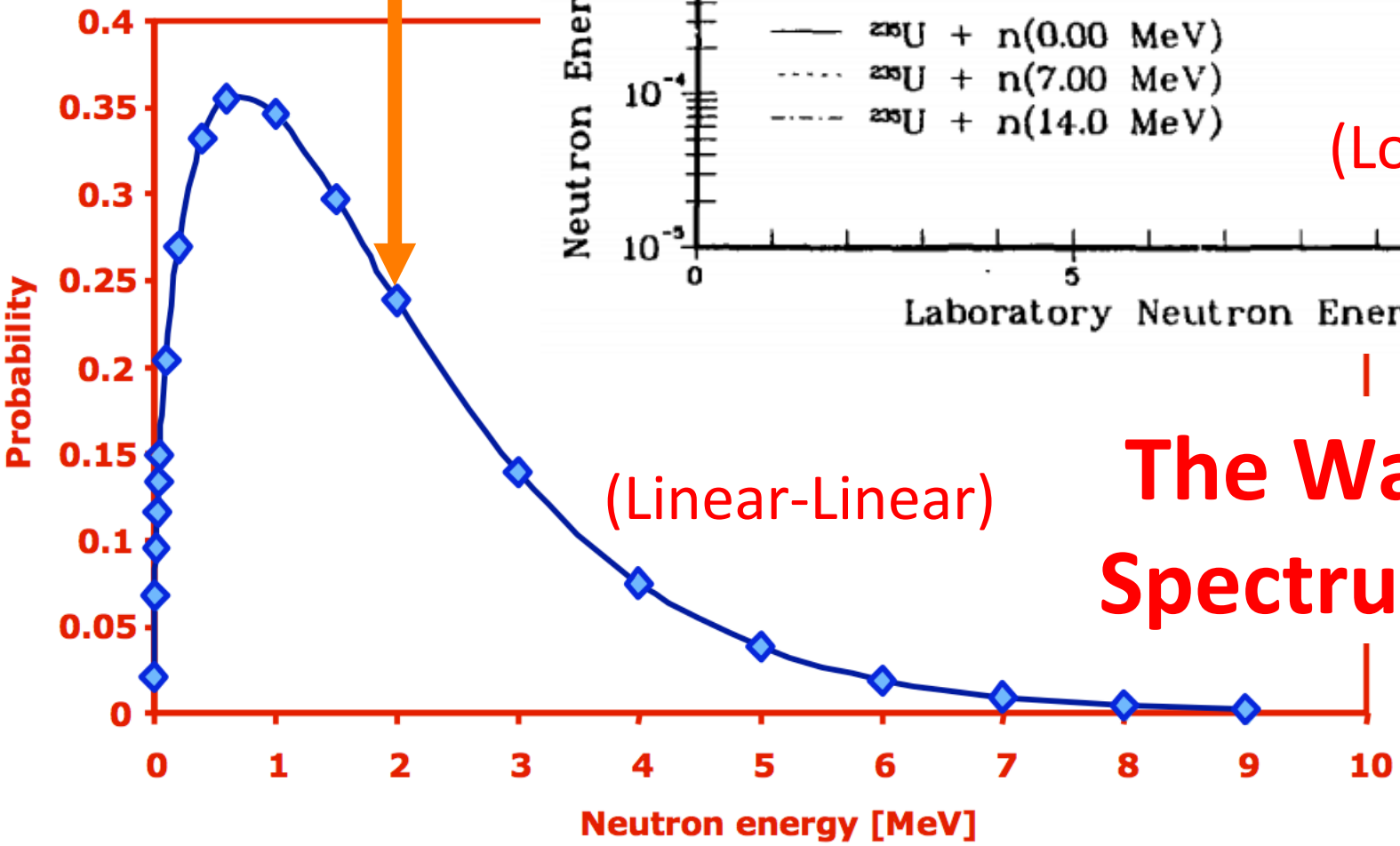
What's the problem with ^{238}U?



Average Neutron Energy ~ 2 MeV



(Log-Linear)



(Linear-Linear)

The Watt Fission Spectrum for ^{235}U

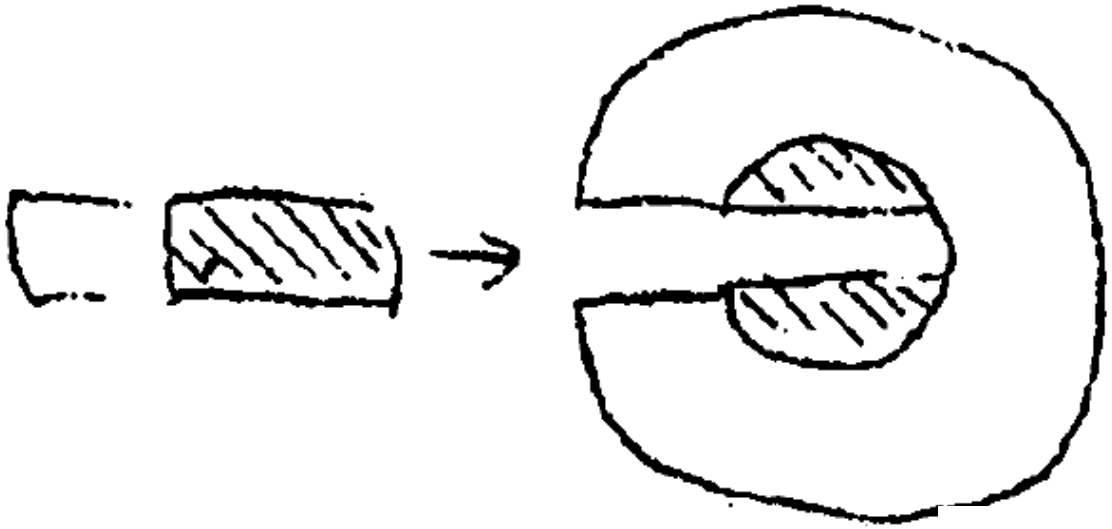
The Physics of Prompt Critical Reactions

à la Serber "The Los Alamos Primer"

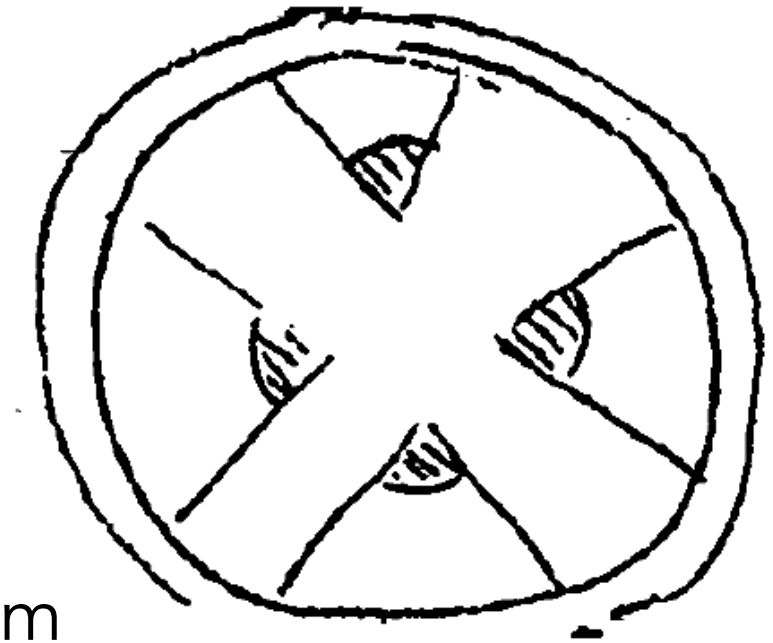
Off to the blackboard !

Basic concept from “Los Alamos Primer”
Little Boy & Fat Man

First concepts for ^{235}U & ^{239}Pu devices
(sketches from Serber's "Los Alamos Primer")

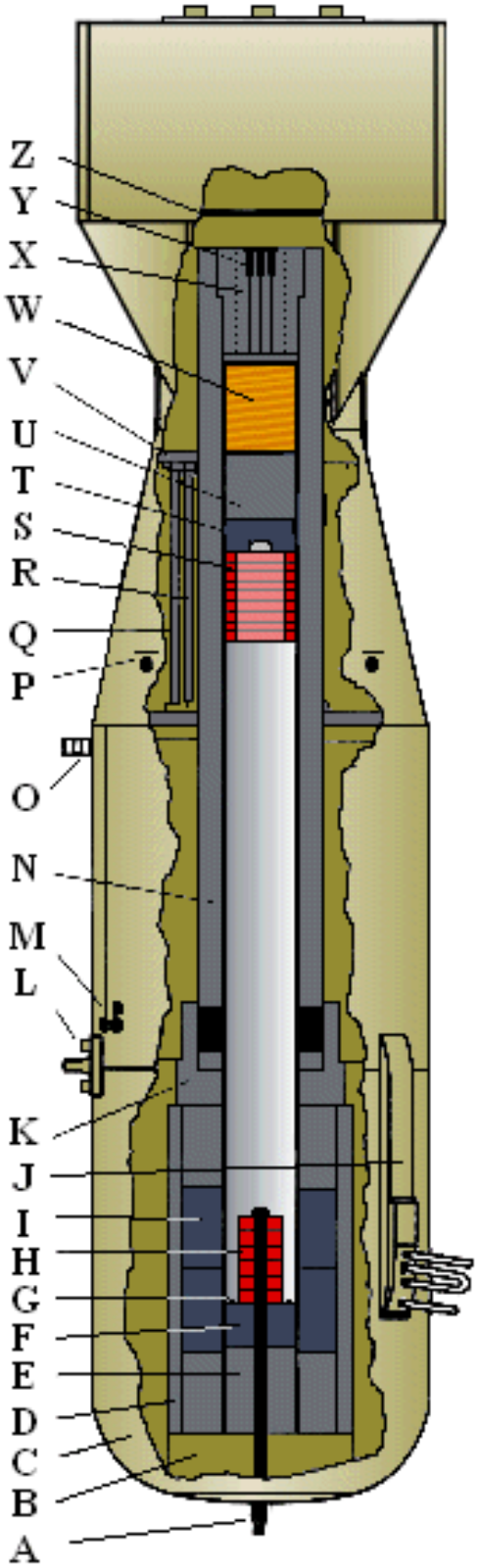


Uranium weapon
"Gun type"



Plutonium weapon
Implosion design

Required to avoid the ^{240}Pu
SF neutrons pre-initiation problem

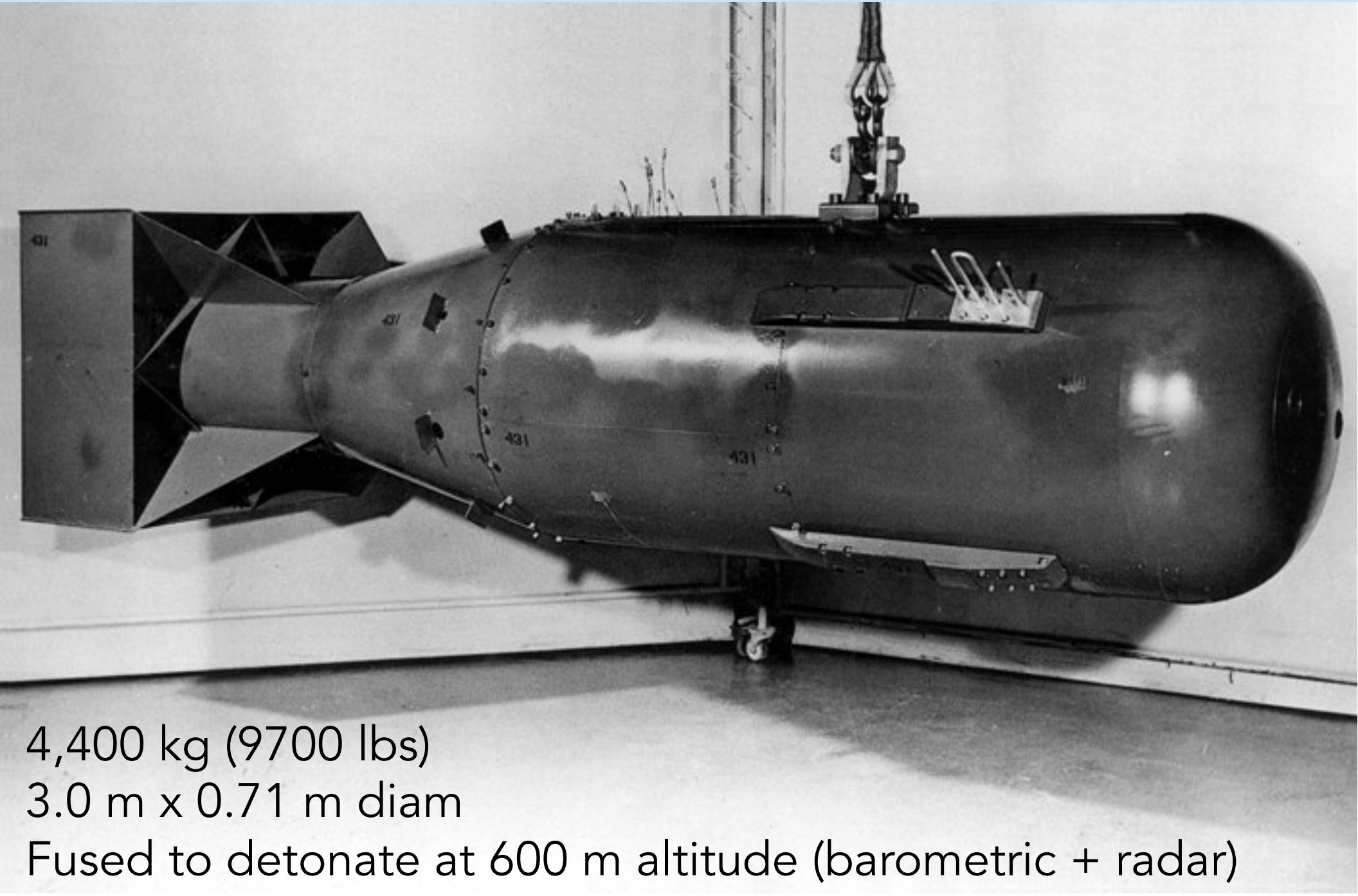


Cross-section drawing of Y-1852 Little Boy showing major mechanical component placement. Drawing is shown to scale. Numbers in ( ) indicate quantity of identical components. Not shown are the APS-13 radar units, clock box with pullout wires, baro switches and tubing, batteries, and electrical wiring.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

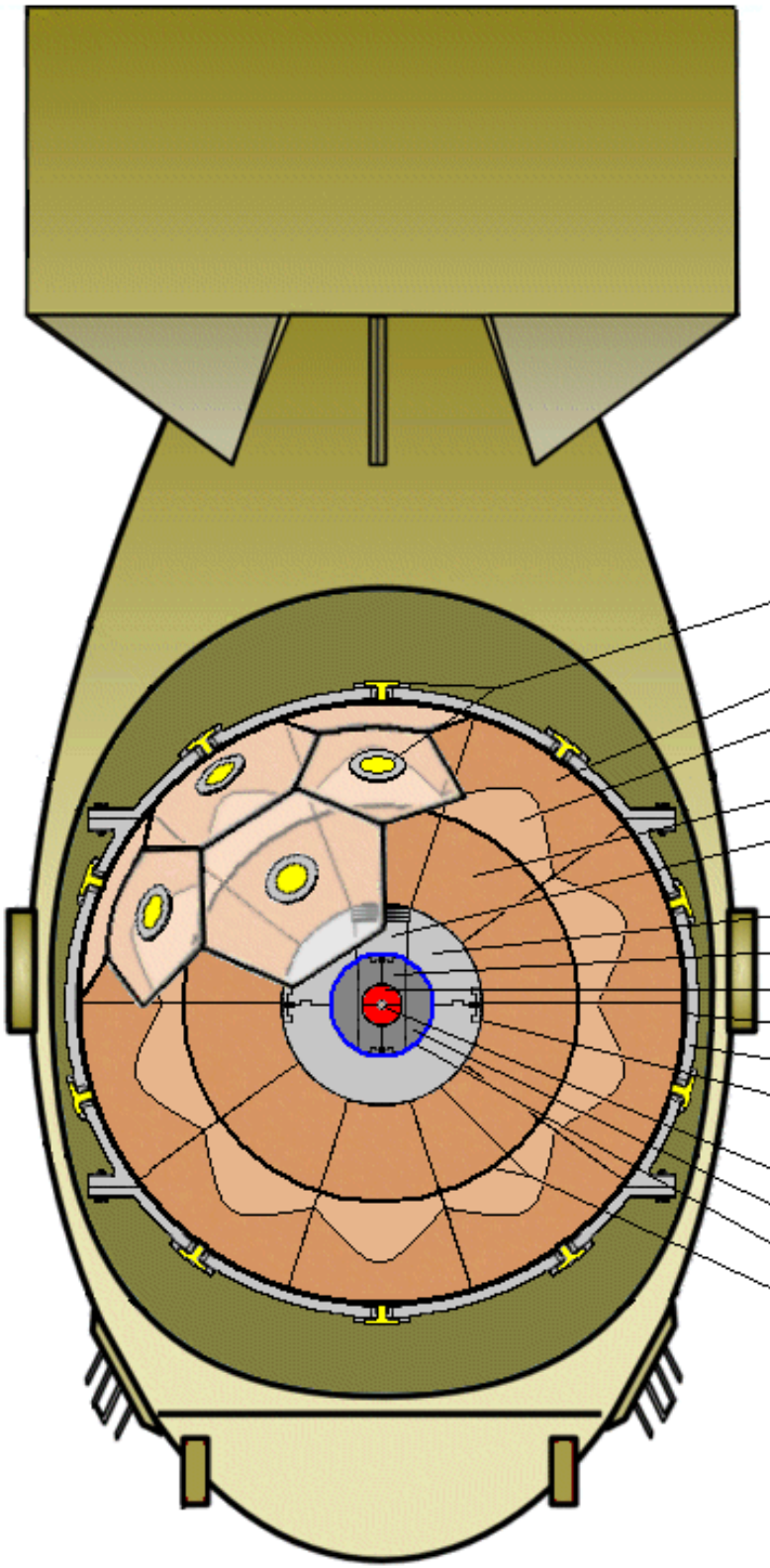
Z) Armor Plate
Y) Mark XV electric gun primers (3)
X) Gun breech with removable inner plug
W) Cordite powder bags (4)
V) Gun tube reinforcing sleeve
U) Projectile steel back
T) Projectile Tungsten-Carbide disk
S) U-235 projectile rings (9)
R) Alignment rod (3)
Q) Armored tube containing primer wiring (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

"Little Boy"
64 kg ^{235}U
15 kT yield
(or what is found on Wikipedia, at least)

Government-released mock-up of Little Boy casing



4,400 kg (9700 lbs)
3.0 m x 0.71 m diam
Fused to detonate at 600 m altitude (barometric + radar)



Cross-section drawing of the Y-1561 implosion sphere showing component placement. Numbers in ( ) indicate quantity of identical components. Drawing is shown to scale. (Author)

A) 1773 EBW detonators inserted into brass chimney sleves (32)
B) Comp B component of outer lens (32)
C) Cone-shaped Baratol component of outer lens (32)
D) Comp B inner charge (32)
E) Removable aluminum pusher trap-door plug screwed into upper pusher hemisphere
F) Aluminum pusher hemispheres (2)
G) Tuballoy (U-238) two-piece tamper plug
H) Pu-239 hemispheres (2)
I) Cork lining
J) 7-piece Duralumin sphere
K) Aluminum cups holding pusher hemispheres together (4)
L) Polonium-Beryllium initiator
M) Tuballoy (U-238) tamper sphere
N) Boron plastic shell
O) Felt padding layer under lenses and inner charges

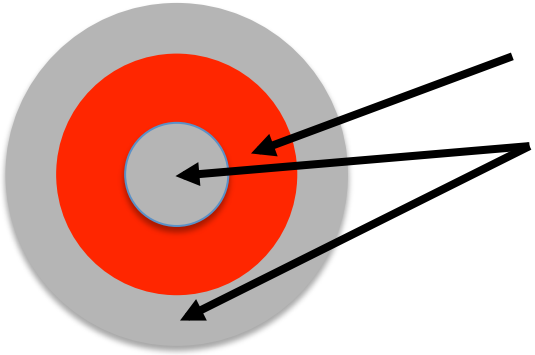
"Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man," 2003, p 140. John Coster-Mullen drawing used with permission.

"Fat Man"
6.2 kg ^{239}Pu
22 kT yield
(or what is found on Wikipedia, at least)

Government-released mock-up of Fat Man casing

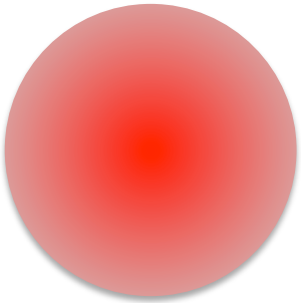
4,700 kg (10,300 lbs)
3.3 m x 1.5 m diam
Fused to detonate at 500 m altitude (barometric + radar)

Early implosion devices used initiators that introduce more neutrons at the right time to speed up multiplication



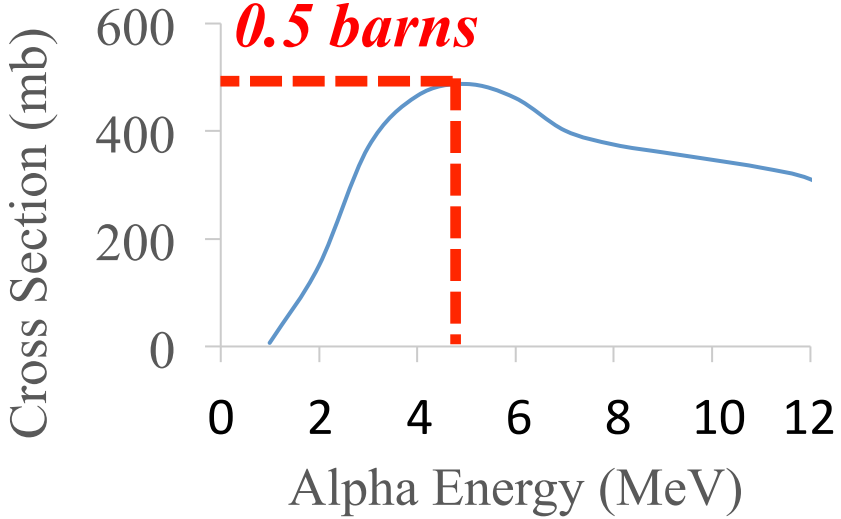
≈11 grams of ^{210}Po (139 day half-life)

Beryllium ball and shell



Shock the system and mix it up

^{9}Be(^{4}He,n)^{12}C Fusion Reaction
(Q= +5.7 MeV)



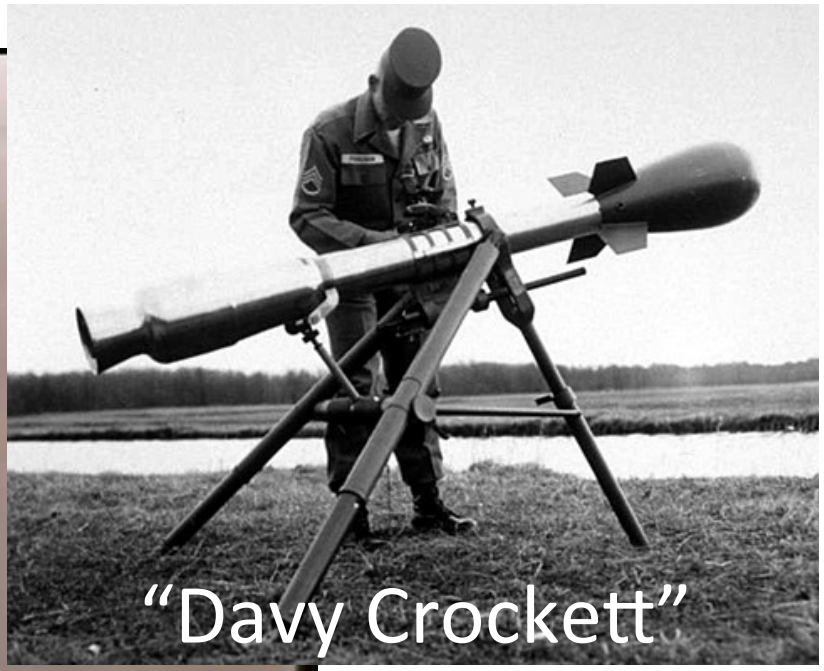
Efficiency ≤0.1% - Why???

α range is only ≈ 10 μm

Initiators only require mixing to work

The imagination of the weapons designers ran wild

(But largely driven by preparations for a Soviet tank invasion on NATO forces through the Fulda Gap)



https://www.youtube.com/watch?v=XT5jo7aZzTw

5-1346503

Las Vegas was a hot place to be until 1962 !

LAX8-INP SOUNDPHOTO, Las Vegas,Nev.,6/24/57- One of the largest mushrooms ever seen from Las Vegas rises 40,000 feet over the Nevada Test Site 65 miles away at 6:30 a.m. Tuesday seconds after detonation of the fifth atomic device in current Series. Device was detonated from a helium balloon 700 feet in the air and was larger than one dropped on Hiroshima. Next test is scheduled for June 27.

Two topics discussed only in scanty detail

- Boosting: The use of DT gas in the pit, which when ignited, will emit a burst of 14 MeV neutrons then further increases the yield of the weapon – thus cutting down the weight of a critical assembly

- Two-stage weapons: The *primary* is a low-yield fission device, whose purpose is to create a flow of x-rays, which will then drive the implosion of the *secondary.* The secondary is usually both a combined fusion and fission device, of much greater yield, typically >100x the primary. All modern weapons today are optimized, compact, high yield/weight ratio.

The two-stage weapon was the invention of Edward Teller & Stanislaus Ulam

~~SECRET~~ ~~/RD~~ UNCLASSIFIED

LOS ALAMOS SCIENTIFIC LABORATORY

of

THE UNIVERSITY OF CALIFORNIA

March 9, 1951 LAMS-1225

This document consists of 20 pages.

No. 20 of 20 copies. Series A

ON HETEROCATALYTIC DETONATIONS I. (U)

Hydrodynamic Lenses and Radiation Mirrors

Work done by:

E. Teller
S. Ulam

Report written by:

E. Teller
S. Ulam

UNCLASSIFIED

WEAPON DATA

~~/RD~~

Although "unclassified", the report after redaction leaves only about 2.25 pages out of the original 20 pages of text ! It doesn't say much.

Nevertheless, I will put it up on the bCourse site. What remains has no significant mathematical or physical content.

Two-Stage Weapons

Exit to Prof. Lee Bernstein's Animations (NE/PP 285 C - Sp18)

Ivy/Mike Shot - 10.6 MT (November 1, 1952)

https://www.youtube.com/watch?v=h7vyKDcSTaE

The world's first thermonuclear explosion

A "wet bomb", i.e. cryogenic DD

Just a scientific test, impossible to weaponize

Castle Bravo – 03/01/1954

https://www.youtube.com/watch?v=fd1IFjBNNVo

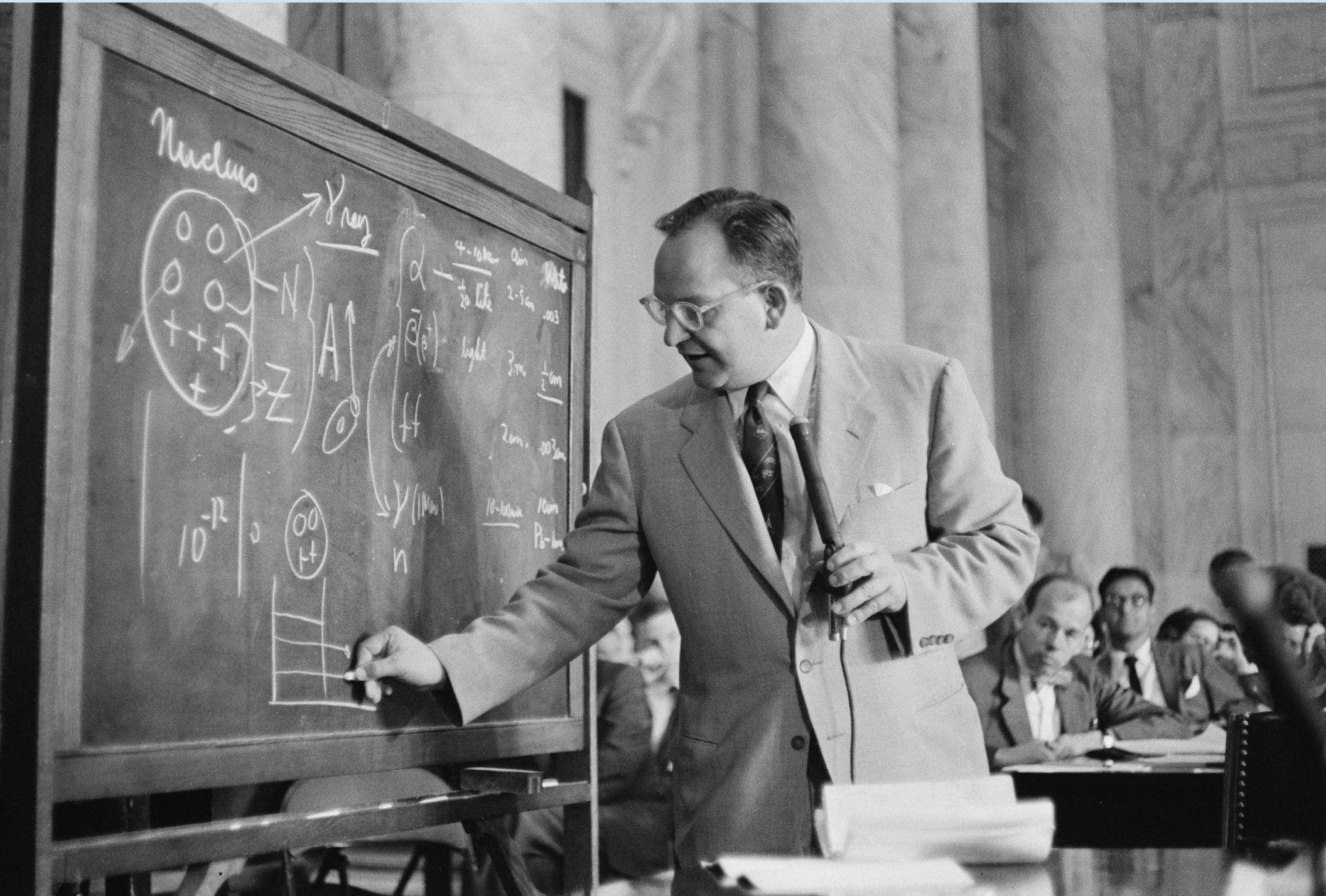
The first US “dry bomb”; to continuously make T on the fly by $^{6}Li(n,\alpha)T$.

Castle Bravo was estimated to yield 6 MT, but it ran away to 15 MT, causing fallout over hundreds of miles, requiring the evacuation of Marshall Island natives, sickening the crew of a Japanese fishing boat (one died), and endangering the scientists themselves.

It had not been understood that fast neutrons also produce tritium from ^{7}Li as well.

But this design was weaponizable for a gravity bomb in the MT range, albeit still very heavy.

Mark Muir Mills (Dec. 1, 1917 – April 7, 1958), founded Berkeley NE.
Died in helicopter crash, Eniwetok Atoll preparing for TN bomb tests.



The US Nuclear Deterrent Triad – today

Sandia National Laboratories

Submarine Launched Ballistic Missiles (SLBMs)

OHIO Submarine
Trident II D5 Missile
- W76-0 (1978)
- W76-1 (2008)
- W88 (1989)

Minuteman III Missile
- W78 (1979)
- W87 (1986)

Intercontinental Ballistic Missiles (ICBMs)

Air Launched Cruise Missile (ALCM)
- W80-0 (1984)
- W80-1 (1982)
- W84 (1983)

Air Delivered Bombs and Cruise Missiles

B-52H, B-2A Bombers
F-15E, F-16 Aircraft
- B61-3,4 (1979)
- B61-7 (1985)
- B61-10 (1990)
- B61-11 (1997)
- B83-0 (1983)
- B83-1 (1983)

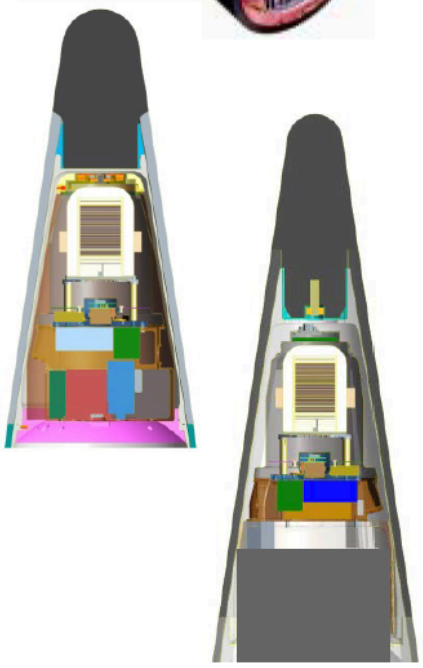
The US Nuclear Deterrent Triad – today

Type [a]	Description	Delivery System	Laboratories	Mission	Military
Warheads—Strategic Ballistic Missile Platforms					
W78	Reentry vehicle warhead	Minuteman III intercontinental ballistic missile	LANL/SNL	Surface to surface	Air Force
W87	Reentry vehicle warhead	Minuteman III intercontinental ballistic missile	LLNL/SNL	Surface to surface	Air Force
W76-0/1	Reentry body warhead	Trident II D5 submarine-launched ballistic missile	LANL/SNL	Underwater to surface	Navy
W88	Reentry body warhead	Trident II D5 submarine-launched ballistic missile	LANL/SNL	Underwater to surface	Navy
Bombs—Aircraft Platforms					
B61-3/4/10	Non-strategic bomb	F-15, F-16, certified NATO aircraft	LANL/SNL	Air to surface	Air Force/Select NATO forces
B61-7	Strategic bomb	B-52 and B-2 bombers	LANL/SNL	Air to surface	Air Force
B61-11	Strategic bomb	B-2 bomber	LANL/SNL	Air to surface	Air Force
B83-1	Strategic bomb	B-52 and B-2 bombers	LLNL/SNL	Air to surface	Air Force
Warheads—Cruise Missile Platforms					
W80-1	Air-launched cruise missile strategic weapons	B-52 bomber	LLNL/SNL	Air to surface	Air Force

LANL = Los Alamos National Laboratory
LLNL = Lawrence Livermore National Laboratory
NATO = North Atlantic Treaty Organization
SNL = Sandia National Laboratories

[a] The suffix associated with each warhead or bomb type (*e.g.*, "-0/1" for the W76) represents the modification associated with the respective weapon.

3+2 The US Nuclear Deterrent Triad – tomorrow



Submarine Launched Ballistic Missiles (SLBMs)

OHIO Replacement
Trident II D5 LE Missile
- W76-1 (2008)
- IW1 (20xx)
- IW2 (20xx)

Long Range Stand-Off (LRSO)
- W80-4 (2025)

Air Delivered Bombs and Cruise Missiles

Ground Based Strategic
Deterrent
- IW1 (20xx)
- IW2 (20xx)

Long Range Strategic Bomber
F35 Joint Strike Fighter
- B61-12 (2020)

Intercontinental Ballistic Missiles (ICBMs)