Nuclear Weapons: A Technical Overview

Steve Fetter
University of Maryland
King's College London

International Centre for Theoretical Physics, Trieste, Italy
23 October 2023

Outline

- Nuclear weapon primer
- Nuclear weapon effects
- Current nuclear arsenals
- Modernization and expansion
- Deterrence and risks

Nuclear Weapons Primer

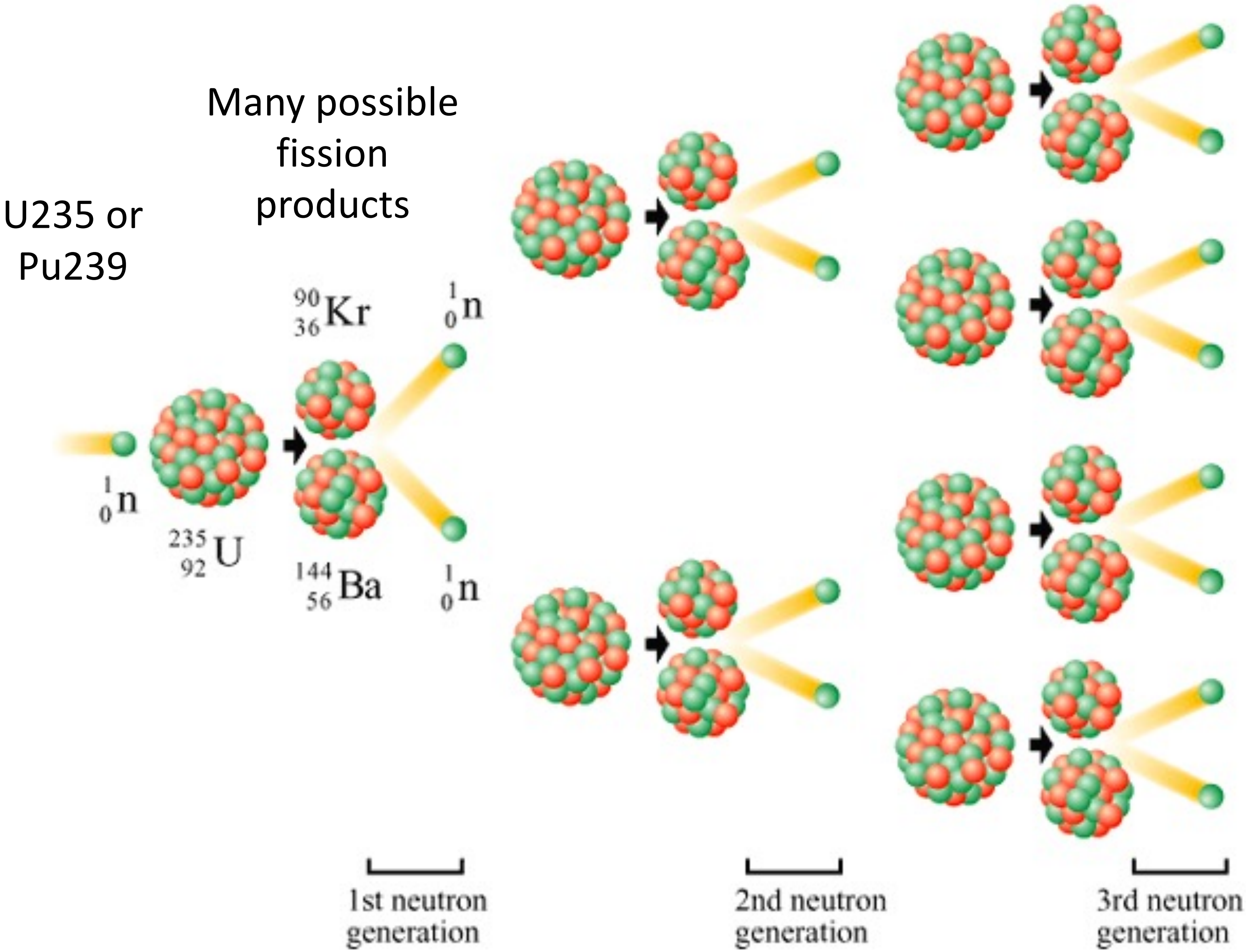
- All nuclear weapons use materials that can sustain a fast-fission chain reaction.
- Highly-enriched uranium (HEU)
  - Natural uranium is 0.7% U235, 99.3% U238
  - Isotope enrichment in needed to increase U235 to ~90%
    - Electromagnetic, gaseous diffusion, gas centrifuge, laser
- Plutonium
  - Pu does not exist in nature; produced in reactors from U238:

$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[23.5\ \mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.3565\ \mathrm{d}]{\beta^-} {}^{239}_{94}\mathrm{Pu} $$

    1 gram per MW-d (25 MW reactor produces 8 kg per year)

  - Pu is chemically separated from highly radioactive spent nuclear fuel in reprocessing plants
- Limiting the spread of enrichment and reprocessing technology is key to limiting the spread of nuclear weapons

Fast Fission Chain Reaction



Energy Release from Fission of 1 kg U235 (or Pu239)

200 MeV per fission:

KE of fission fragments	165 MeV	≈180 MeV Immediately Available (KE of fission fragments, KE of neutrons, Gamma-rays)
KE of neutrons	5 MeV	
Gamma-rays	7 MeV	
Decay of fission products	13 MeV	
Neutrinos	10 MeV	

$$\left[\frac{1000\ g}{kg}\right]\left[\frac{mol}{235\ g}\right]\left[\frac{6\times10^{23}\ nuclei}{mol}\right]\left[\frac{180\ MeV}{fission}\right]\left[\frac{1.6\times10^{-13}J}{MeV}\right]\left[\frac{ton\ TNT}{4.2\times10^{9}J}\right]$$

$$= 17{,}500\ \frac{ton\ TNT}{kg} = 17.5\ \frac{kt}{kg}$$

Hiroshima: 15 kilotons (kt)

Nagasaki: 20 kt

Neutron Velocity, Mean Free Path, Generation Time

200 MeV per fission:

KE of fission fragments	165 MeV
KE of neutrons	**5 MeV**
Gamma-rays	7 MeV
Decay of fission products	13 MeV
Neutrinos	10 MeV

= (2.5 neutrons/fission) x (2 MeV/neutron)

Average cross section for fast fission:

U235: 1.2 barn = 10^{-24} cm^2

Pu239: 1.8 barn

$$v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2(2\ MeV)\left(1.6\times10^{-6}\ \frac{erg}{MeV}\right)}{1.67\times10^{-24} g}} = \mathbf{2\times10^{9}\,\frac{cm}{s}}$$

$$\lambda = \frac{A}{\rho N_A \sigma} = \left[\frac{235\ g}{mol}\right]\left[\frac{cm^3}{19\ g}\right]\left[\frac{mol}{6\times10^{23}}\right]\left[\frac{1}{1.2\times10^{-24}\ cm^2}\right] = \mathbf{17\ cm}$$

Pu239: 11 cm

$$\tau = \frac{\lambda}{v} = \frac{17\ cm}{2x10^9\ \frac{cm}{s}} \approx 10^{-8}\ s = \mathbf{10\ ns} = \text{“}shake\text{”}$$

Time to Fission of 1 kg U235

Number of nuclei in 1 kg of U235:

$$\left[\frac{1000\ g}{kg}\right]\left[\frac{mol}{235\ g}\right]\left[\frac{6\times10^{23}\ nuclei}{mol}\right] = 2.5\times10^{24}\ \frac{nuclei}{kg}$$

If the number of fissions doubles each generation, then after *n* generations the total number of fissions is:

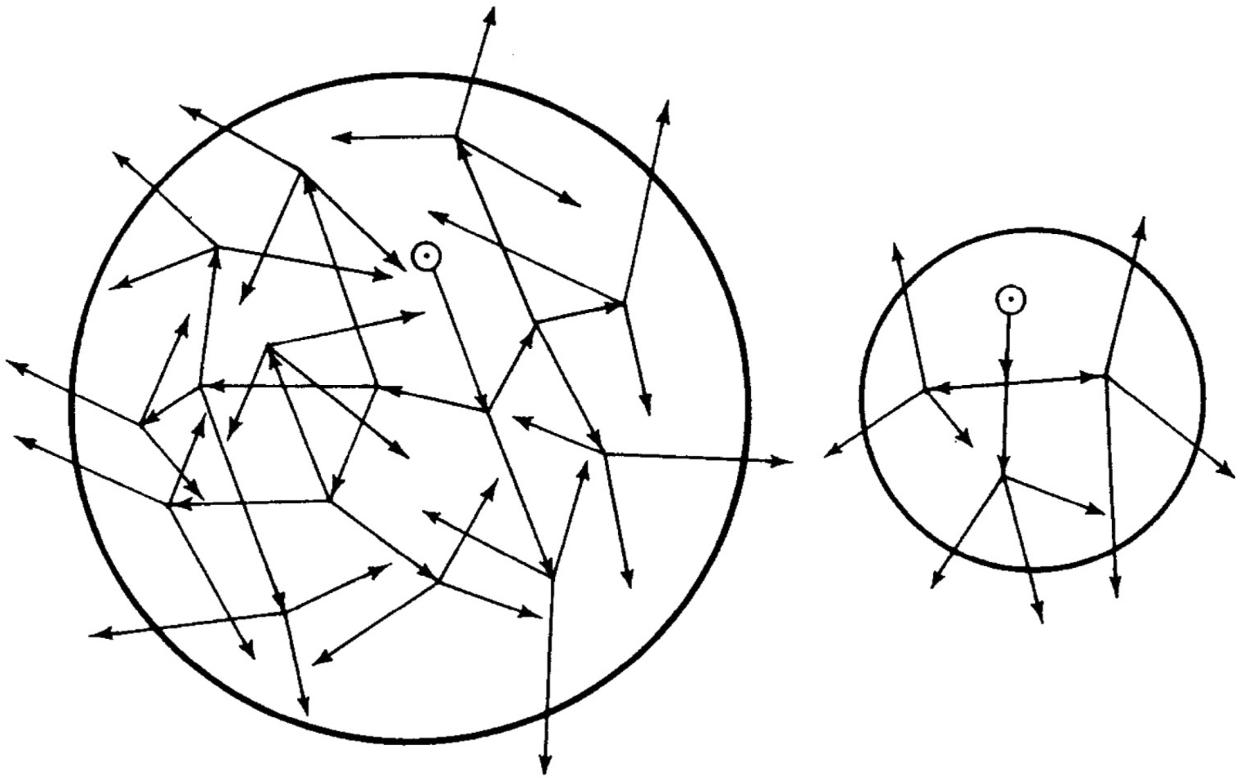
$$2^{n+1} = 2^{81} = 2.4\times10^{24}$$

So about 80 generations to fission 1 kg—less than 1 μs.
99.9% of the energy is released in the last 10 generations, 0.1 μs.

Critical Mass

An assembly of fissile material is "critical" fission rate and neutron population is constant (i.e., each fission causes one new fission)

super-critical: exponential increase

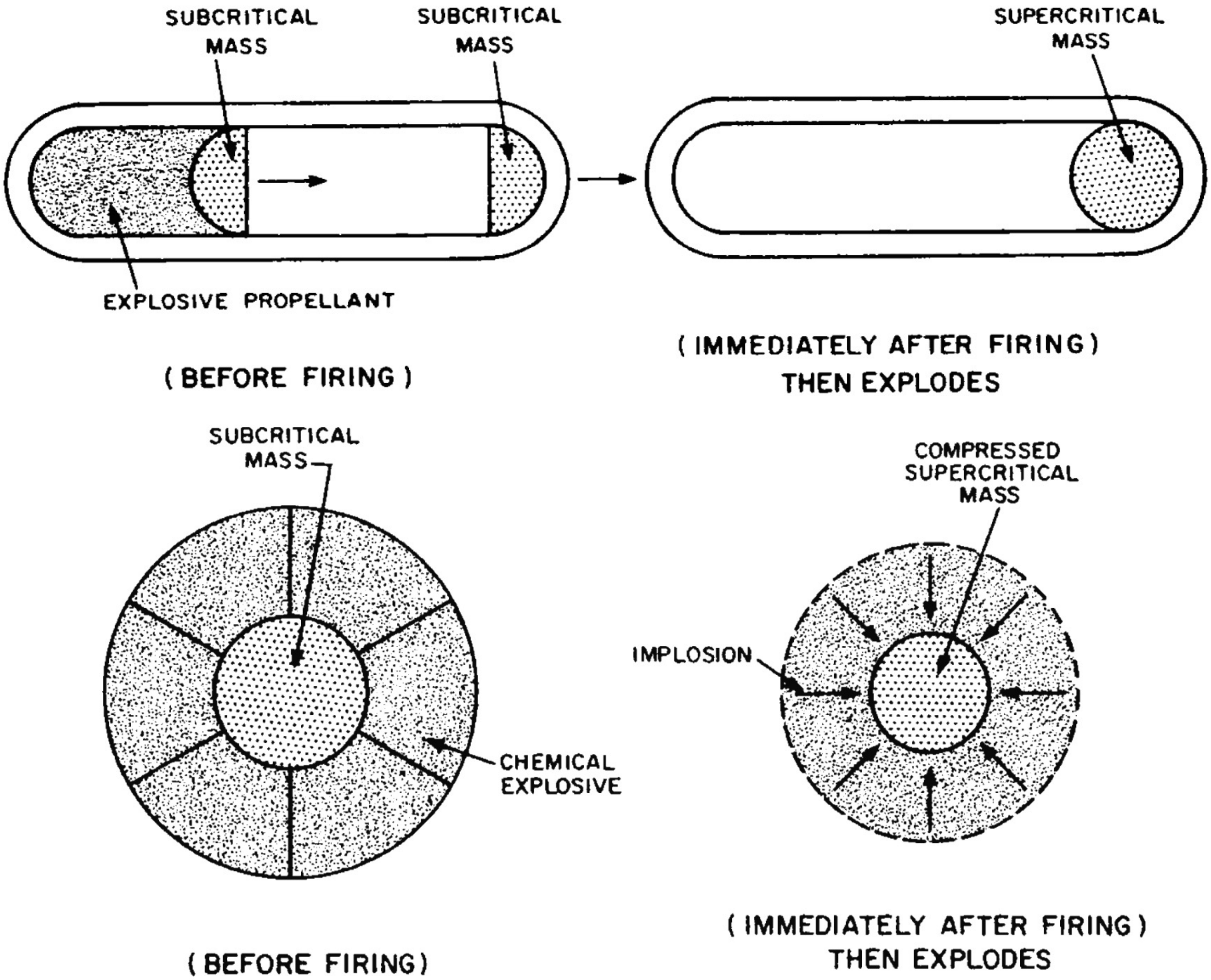


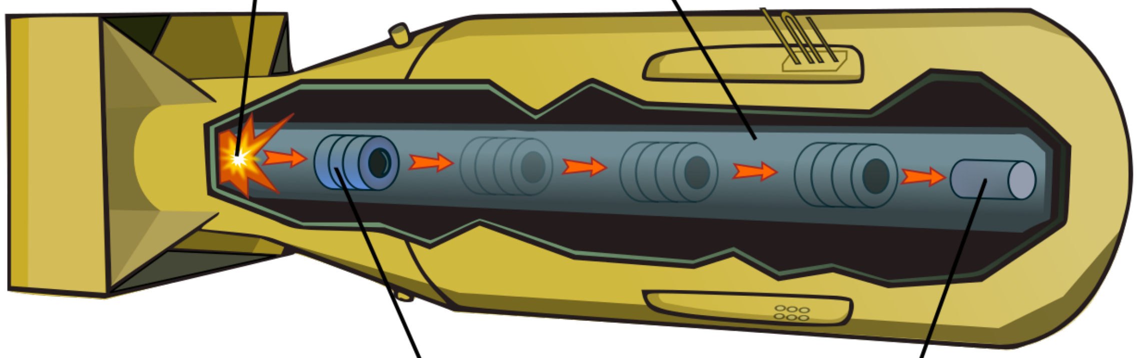
subcritical: exponential decrease

Bare critical mass
U235: 52 kg (17 cm sphere)
Pu: 10 kg (10 cm sphere)

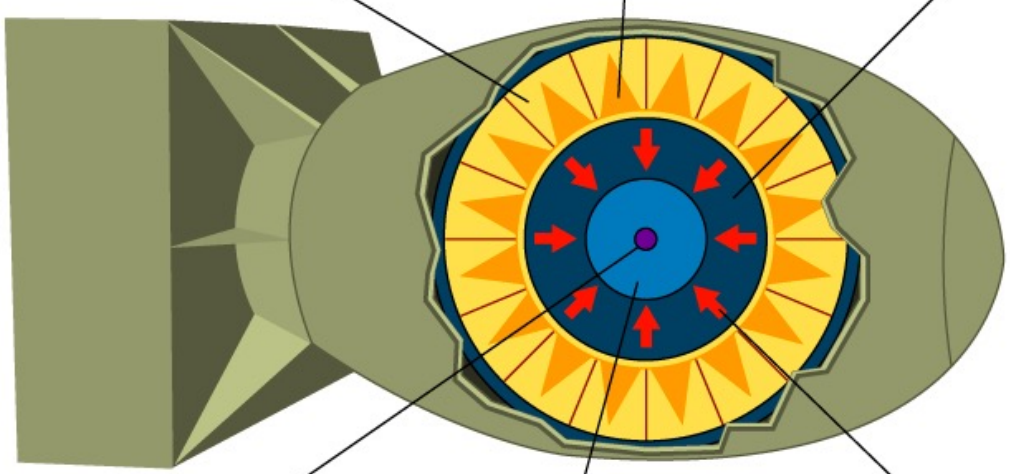
Critical mass can be decreased by:
Using a reflector
Increasing density

Assembly of Super-Critical Mass: Gun v. Implosion



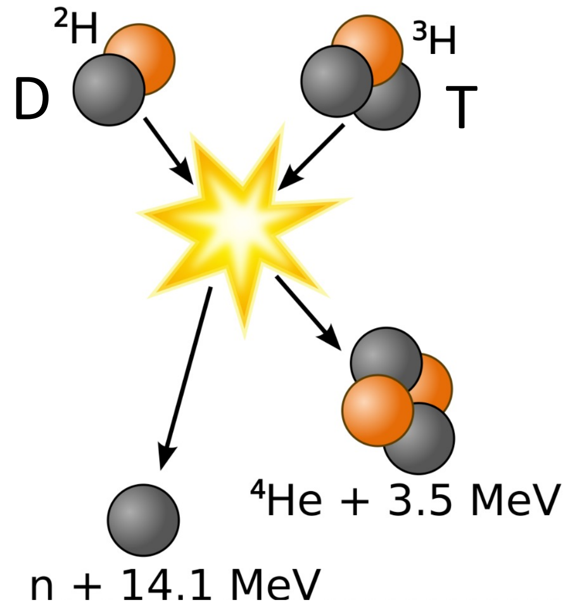


“Little Boy” (Hiroshima)
Gun-type device
64 kg of HEU (51 kg U235)
15 kilotons
Efficiency = 1.7%



“Fat Man” (Nagasaki)
Implosion device
6.2 kg of Pu
20 kilotons
Efficiency = 18%

Fusion Reactions



D + T → He4 + n + 17.6 MeV

D + D → He3 + n + 3.2 MeV

D + D → T + H + 4.0 MeV

T + T → He4 + 2n + 11.3 MeV

D-Li6: 65 kt per kg (3.6x the 17.5 kt/kg for fission)

Li6 + n → He4 + T + 4.8 MeV

↓

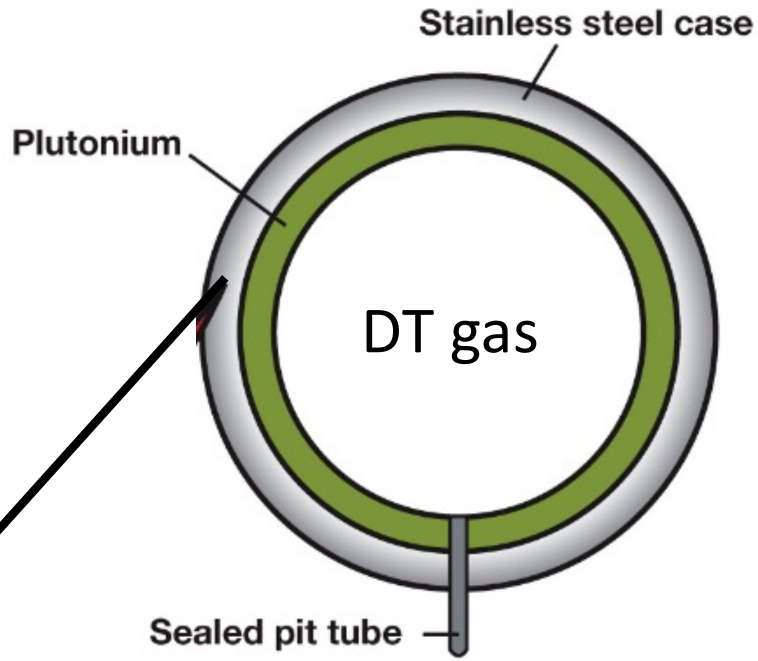
D + T → He4 + n + 17.6 MeV

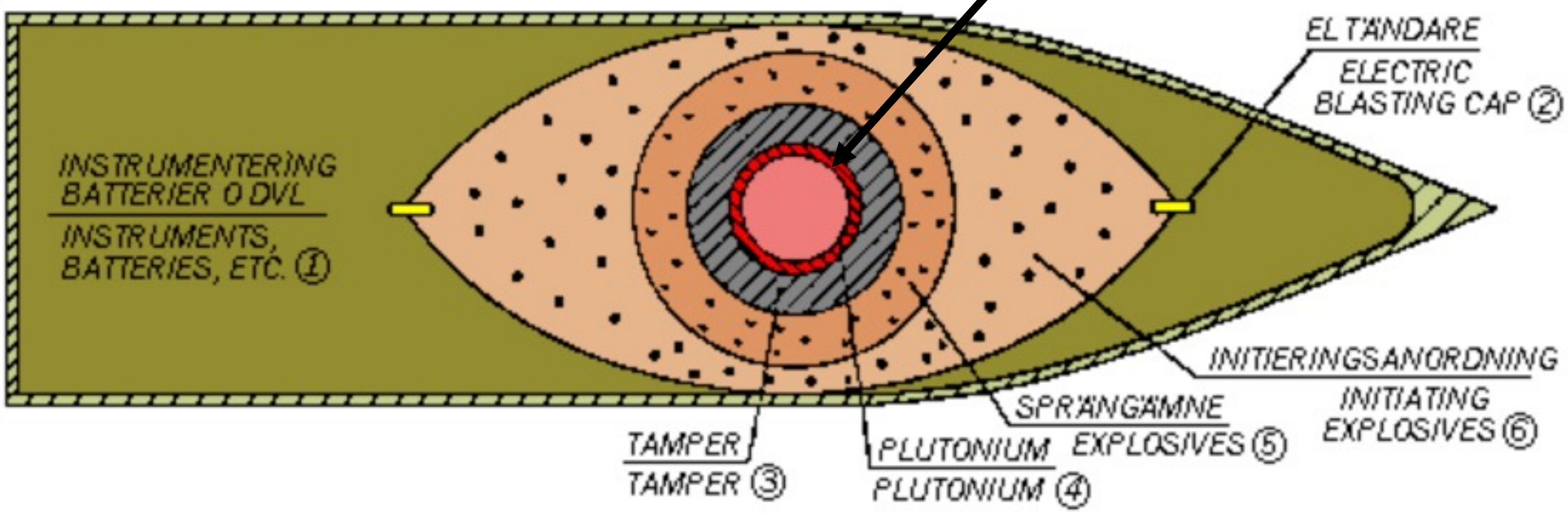
Use fission to cause fusion: boosted and two-stage weapons

Boosted Fission Weapon

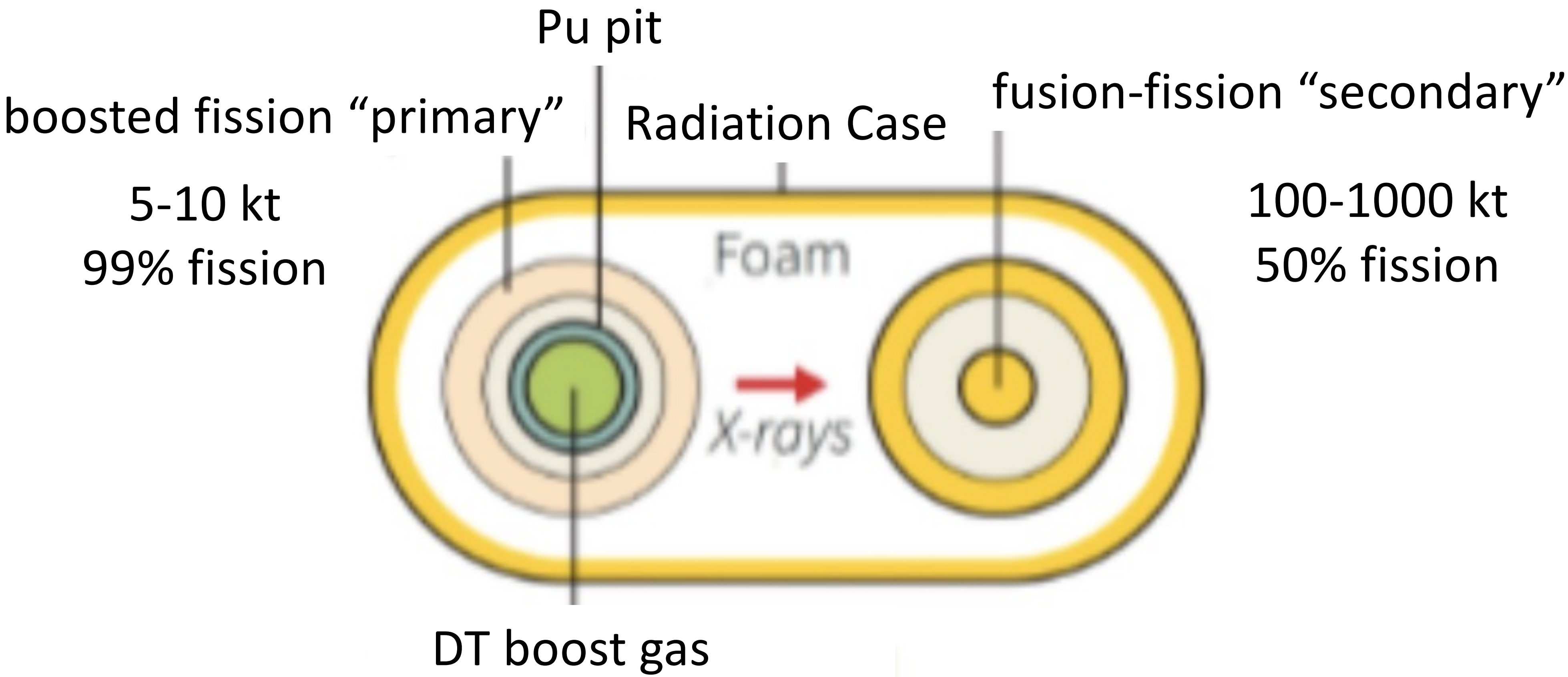
- The neutrons from DT fusion increase fission by ≈10x, making possible compact fission devices
- Fusion does contribute significantly to the yield

Hollow Pu Pit

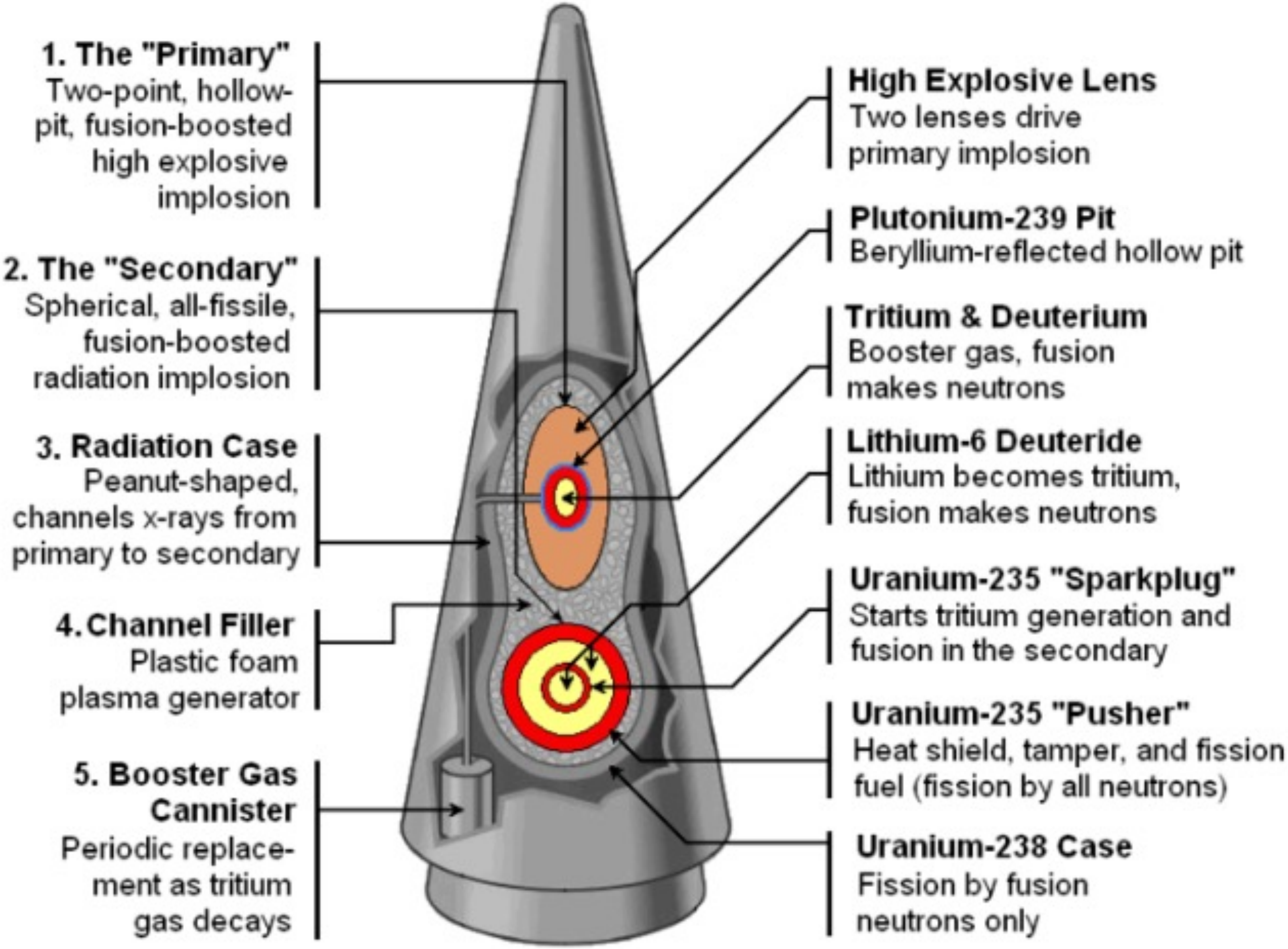




Two-Stage Fission-Fusion Weapon



Two-stage Thermonuclear (fission-fusion) Weapons



Effects of Nuclear Weapons

- Blast and Shock (≈50% of energy)
  - Air blast
  - Ground shock, cratering
- Thermal Radiation (35-45%)
  - Fires and firestorms
  - Burns, blindness
- Initial Nuclear Radiation (5%)
  - γ, n released during fission
- Fallout (5-10%)
  - γ, β released during decay of fp
  - Local (if fireball touches ground)
  - Global fallout
- EMP and Radar Effects

The Effects of Nuclear Weapons

Compiled and edited by
Samuel Glasstone *and* Philip J. Dolan

Third Edition

Prepared and published by the
UNITED STATES DEPARTMENT OF DEFENSE
and the
UNITED STATES DEPARTMENT OF ENERGY

1977

Effects of Nuclear Weapons

Distribution of energy, effects depends on

- Environment
  - Air burst (maximizes blast, thermal)
  - Ground burst (shock, local fallout)
  - Underground, underwater (shock)
  - High altitude, space (EMP, radio)
- Weapon yield
  - Low yield: blast and initial radiation are dominant effects
  - High yield: thermal radiation

Effects calculator:
https://nuclearsecrecy.com/nukemap/

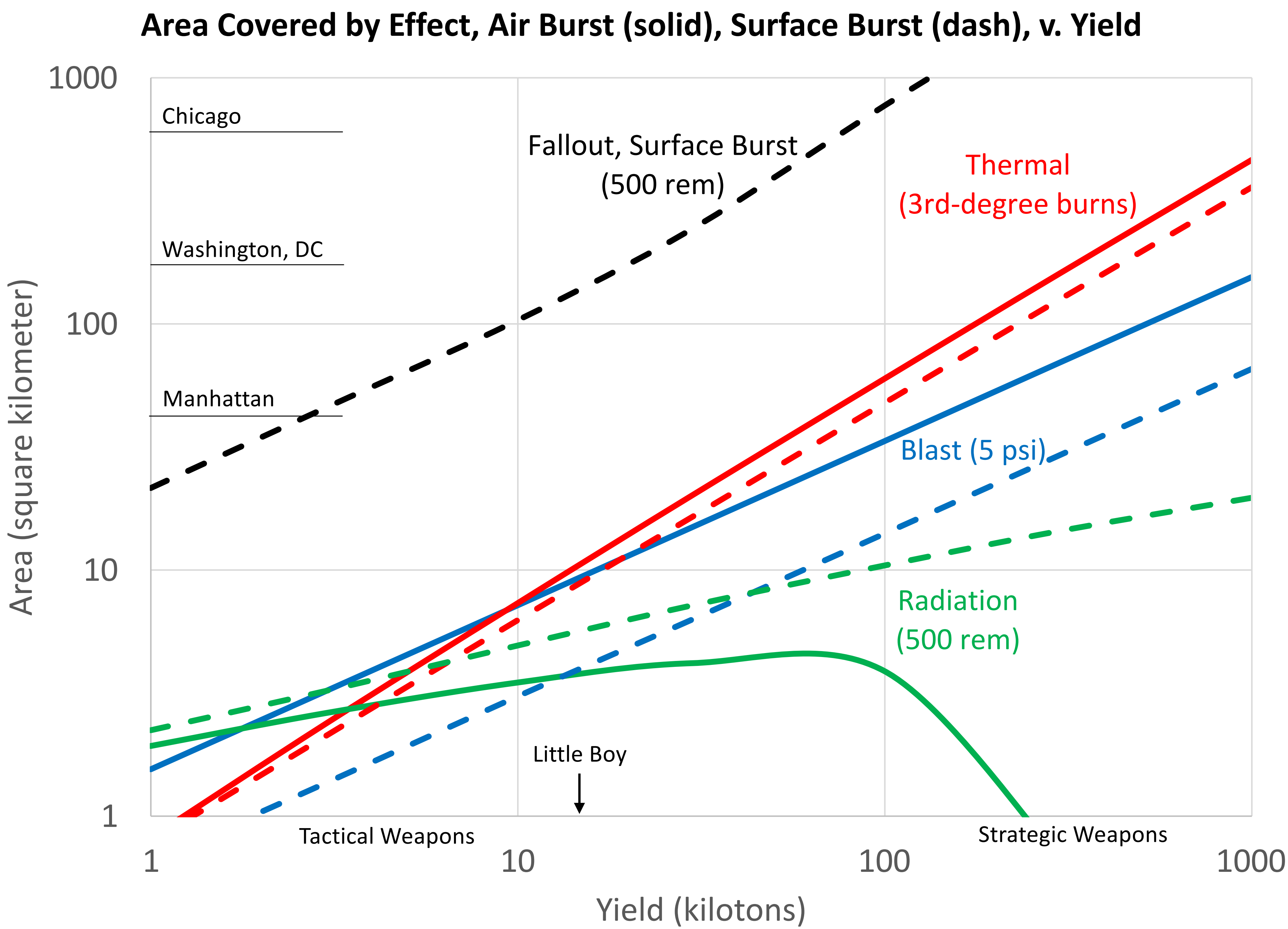
The Effects of Nuclear Weapons

Compiled and edited by
Samuel Glasstone *and* Philip J. Dolan

Third Edition

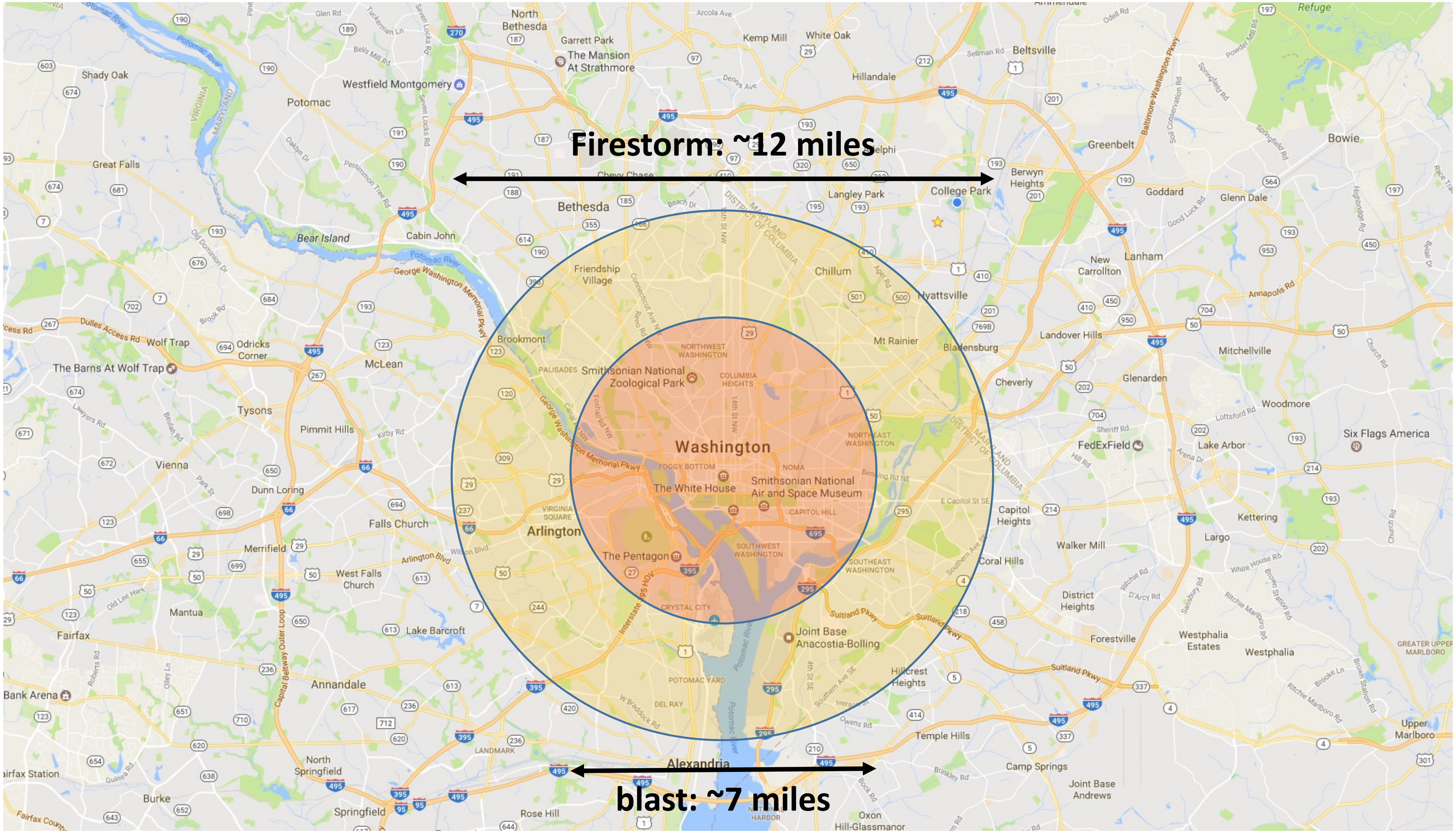
Prepared and published by the
United States Department of Defense
and the
United States Department of Energy

1977


Area Covered by Effect, Air Burst (solid), Surface Burst (dash), v. Yield
Chicago
Washington, DC
Manhattan
Fallout, Surface Burst
(500 rem)
Thermal
(3rd-degree burns)
Blast (5 psi)
Radiation
(500 rem)
Little Boy
Tactical Weapons
Strategic Weapons
1000
100
10
1
1
10
100
1000
Area (square kilometer)
Yield (kilotons)

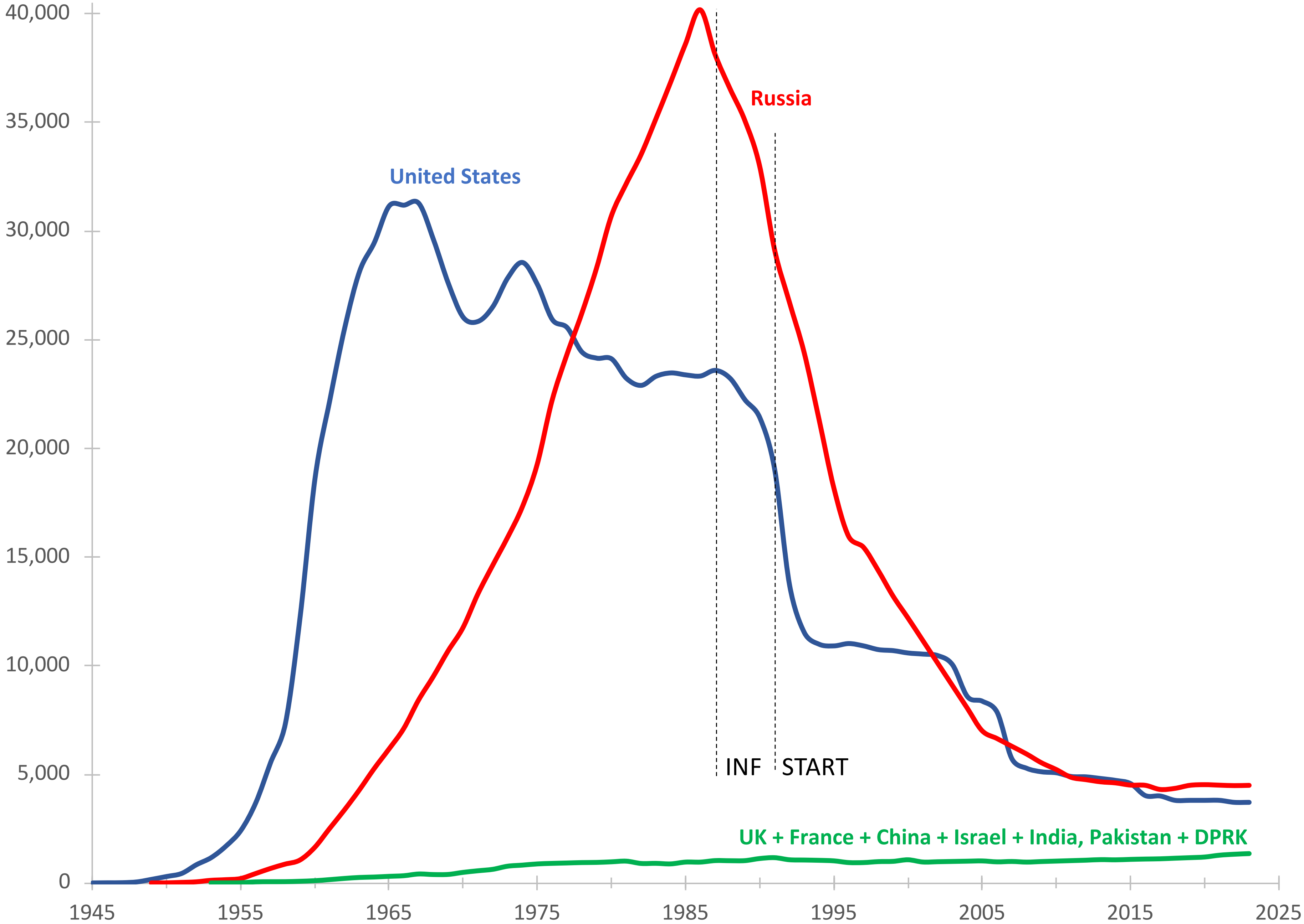
Hiroshima: 125,000 deaths from burns, firestorm, debris, radiation, and radiation-induced cancer

Area of Complete Destruction
350-kt warhead centered on White House



About 1 million deaths from blast and fire

Global Nuclear Arsenals, 1945-2023



Global Nuclear Arsenals: 2023

P5	Russia	4,500
	United States	3,700
	China	400
	France	300
	United Kingdom	220
non-NPT	Pakistan	170
	India	160
	Israel	90
	North Korea	20-30
	Total	9,600

Russia + United States: ≈ 90%

U.S. Nuclear Stockpile, 2022

	Delivery Vehicles	Warheads
ICBMs	400 Minuteman-III x 1 warhead	400
SLBMs	12 Trident SSBN x 20 D-5 x 4-5 warheads	920
Bombers	45 B-52 x 4 ALCMs x 1 warhead	180
	20 B-2 x 5 bombs	100
Deployed strategic warheads		1,600
on alert; can be launched within minutes		900
Deployed nonstrategic warheads		150
Reserve strategic and nonstrategic warheads		2,050
Total active stockpile		3,800
Retired and awaiting dismantling		2,000





All to be replaced starting 2030
at a total cost of $1.3 trillion


Nuclear Forces Costs, 2017-2046

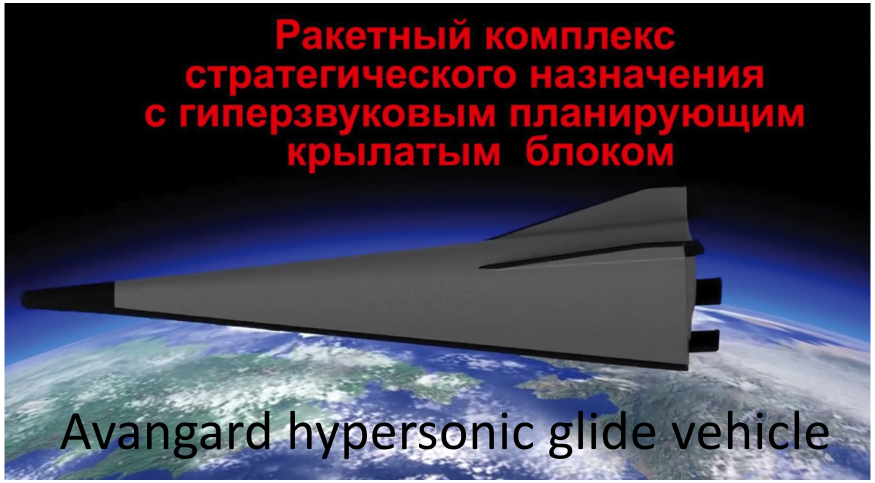
Modernization	Cost (billion)	Deployment
400 new ICBMs (GBSD)	$84	2030-2080
12 new Columbia-class SSBNs	$182	2031-2080s
100 new B-21 bombers	$134	2030-2080s
Long-range standoff ALCM (LRSO)	$20	2030-2060s
	$420	

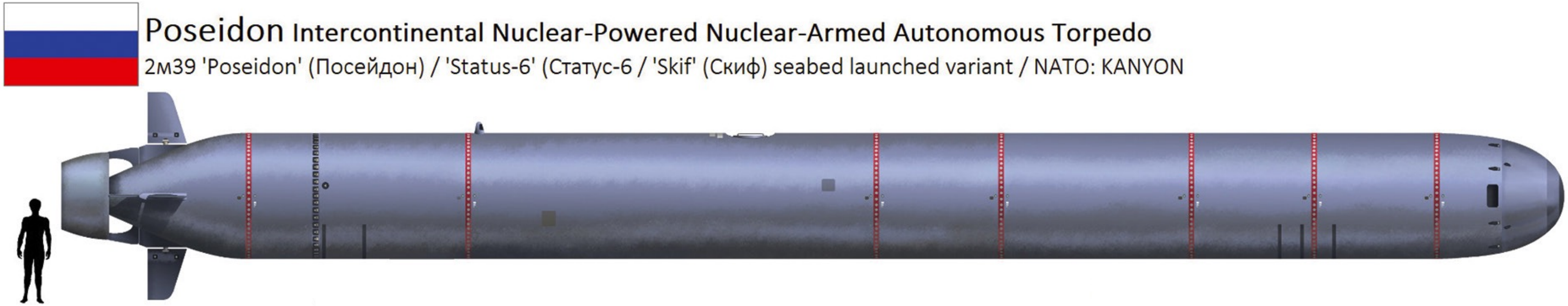
Operation/sustainment		
Strategic and tactical nuclear forces	$405	
Nuclear command and control	$202	
Warhead production complex	$298	
	$905	

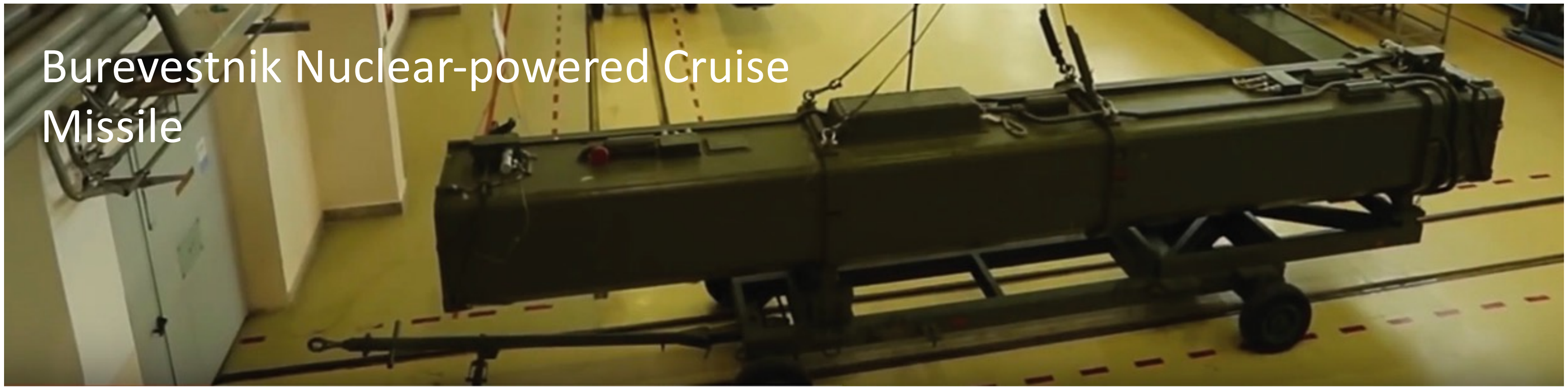
Russian Nuclear Stockpile, 2022

	Delivery Vehicles	Warheads
ICBMs	306 ICBMs x 1-10 warheads	812
SLBMs	10 SSBN x 16 SLBMs x 4-6 warheads	576
Bombers	68 bombers x 6-16 ALCMs x 1 warhead	200
Deployed strategic warheads		1,588
on alert and can be launched within minutes		1,000
Reserve strategic warheads		1,000
Nonstrategic warheads		1,900
Total active stockpile		4,500
Retired and awaiting dismantling		1,500

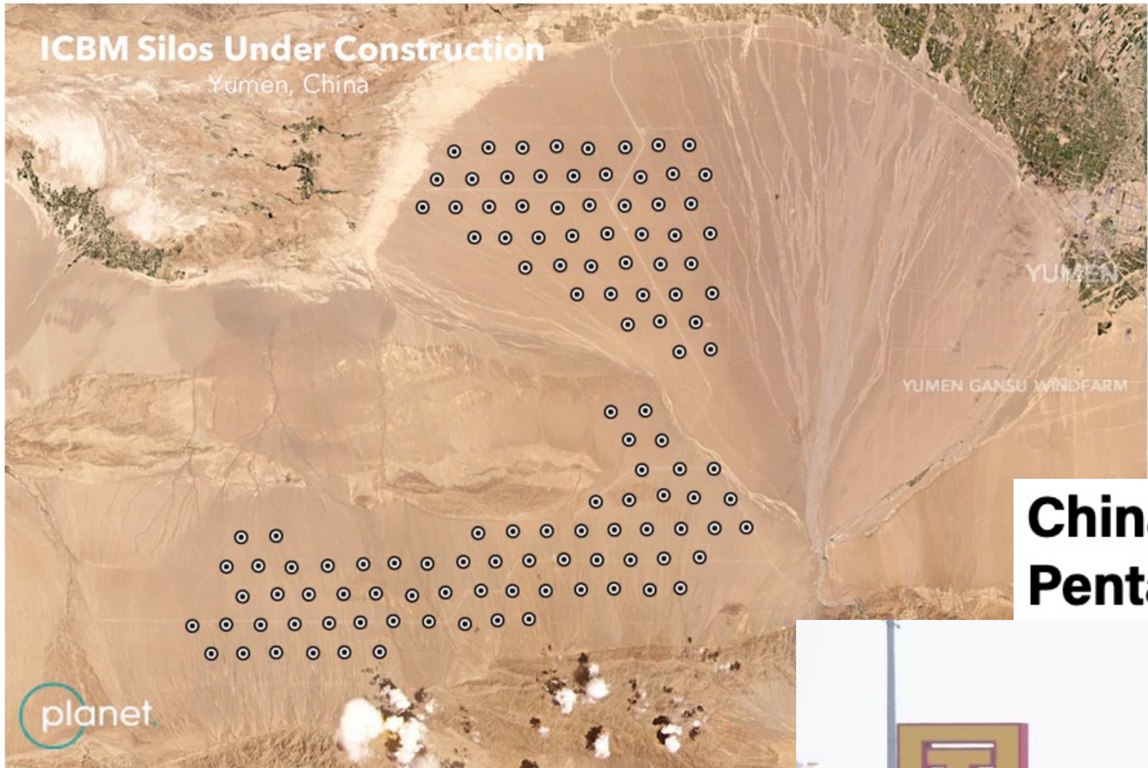
Russia’s New Nuclear Weapons







China is building more than 100 new missile silos in its western desert, analysts say



China plans to double nuclear arsenal, Pentagon says

Deterrence through Assured Destruction

Because nuclear weapons are so destructive, effective defense against nuclear attack is impossible

- A large country can be destroyed by fewer than 100 nuclear detonations
- Weapons are deployed on submarines, mobile missiles, and aircraft designed to survive an attack and penetrate missile and air defenses
- Because countries cannot prevent a devastating nuclear attack, they deter such an attack by maintaining a capability to deliver devastating nuclear retaliation
- When adversaries both have assured retaliatory capability, a state of “mutual assured destruction” exists and both should be deterred from using nuclear weapons

Nuclear Weapon Risks

Deterrence can fail through miscalculation and mistakes

- A conflict that escalates to use of nuclear weapons
  - Russian aggression against a NATO country
  - Chinese aggression against Taiwan or Japan
  - North Korean attacks against South Korea or Japan
  - War between India and Pakistan
  - Wars involving Israel
- Accidental, inadvertent, mistaken, or unauthorized use
  - Accidental detonation; false warning; rogue officer
- Nuclear terrorism using stolen weapons or materials
  - 21 known intercepts of 20 kg of stolen HEU and Pu
- Spread to additional states (Iran, Saudi Arabia, South Korea)
- Nuclear arms races that result in unnecessary expenditures