Reducing the Risks of Nuclear Weapons

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A FILM BY CHRISTOPHER NOLAN
OPPENHEIMER


I KIND OF FORGOT THESE THINGS NEVER WENT AWAY.
HORSEY
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The Seattle Times

Steve Fetter is a professor of public policy at the University of Maryland in College Park. **Richard Garwin** has served as a high-level national security adviser since the Eisenhower administration. (Photo by Marianne Weiss, CC BY 2.0.) **Frank N. von Hippel** is a senior research physicist with the program on science and global security at Princeton University in New Jersey.

NUCLEAR WEAPONS dangers & policy options

With the end of the Cold War, most physicists turned their attention away from the nuclear threat. It is now time for us to reengage in the debate over how to reduce the dangers from nuclear weapons.

Steve Fetter, Richard L. Garwin, and Frank von Hippel

THE KOREAN CENTRAL NEWS AGENCY

Three months after nuclear weapons leveled Hiroshima, J. Robert Oppenheimer gave voice to a dark vision. In a 16 November 1945 speech to the American Philosophical Society, he said, "If they are ever used again, it may well be by the thousands, or perhaps by the tens of thousands." The number of US and Soviet nuclear warheads rose to extremely high levels during the Cold War, giving substance to that vision. With the end of the Cold War, however, the size of the US nuclear stockpile declined dramatically, and the number of Russian nuclear warheads is believed to have dropped in parallel. START (Strategic Arms Reduction Treaty), which came into force on 5 December 1994, and New START, which came into force on 5 February of this year, formalized limits on the strategic arsenals of the US and Russia.

Although the global nuclear stockpile is at its lowest level since 1958 (see figure 1), its destructive power remains enormous. The explosive power of each of the 4000 active US nuclear warheads is equivalent to hundreds of thousands of tons of TNT—an order of magnitude beyond the 15- to 20-kiloton yields of the warheads that destroyed Hiroshima and Nagasaki. It is therefore unfortunate that the downward impulse created by the end of the Cold War appears to be spent. In June 2013 President Barack Obama proposed to reduce the number of deployed US and Russian strategic weapons by one-third and to seek reductions in the number of nondeployed and nonstrategic weapons, but no negotiations were launched.

Nuclear weapons policy has prompted a spectrum of views. At one end is a strong movement to eliminate nuclear arsenals and the danger they pose to civilization. At the other are governments that see as essential the deterrence of major war that nuclear weapons can provide. Those governments include the Trump administration, whose views have just been laid out in the 2018 *Nuclear Posture*

PHYSICISTS COALITION FOR NUCLEAR THREAT REDUCTION

News & Events

Featured in July/August 2020 APS News: The Increasing Peril of Nuclear Weapons: And how physicists can help reduce the threat

Stay tuned for upcoming site visits, advocacy actions, and more!

Sign up to be notified about upcoming events and learn how you can get involved.

Nuclear Testing and New START: Nuclear Threat Reduction in 2020 and Beyond
View Video
September 9, 2020
List of participants: Prof. Steve Fetter (University of Maryland), Prof. Frank Von Hippel (Princeton University), Dr. Laura Grego (Union of Concerned Scientists), Prof. Stewart Prager (Princeton University), Dr. Sébastien Philippe (Princeton University), & Charlotte Selton (APS)

Sign up to receive more information and learn how you can help.

Join the Coalition

Outline

- Nuclear weapon primer
- Nuclear weapon effects
- Current nuclear arsenals
- Modernization and expansion
- Deterrence and possible failures
- Increasing risks in the post-post-Cold War era

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:

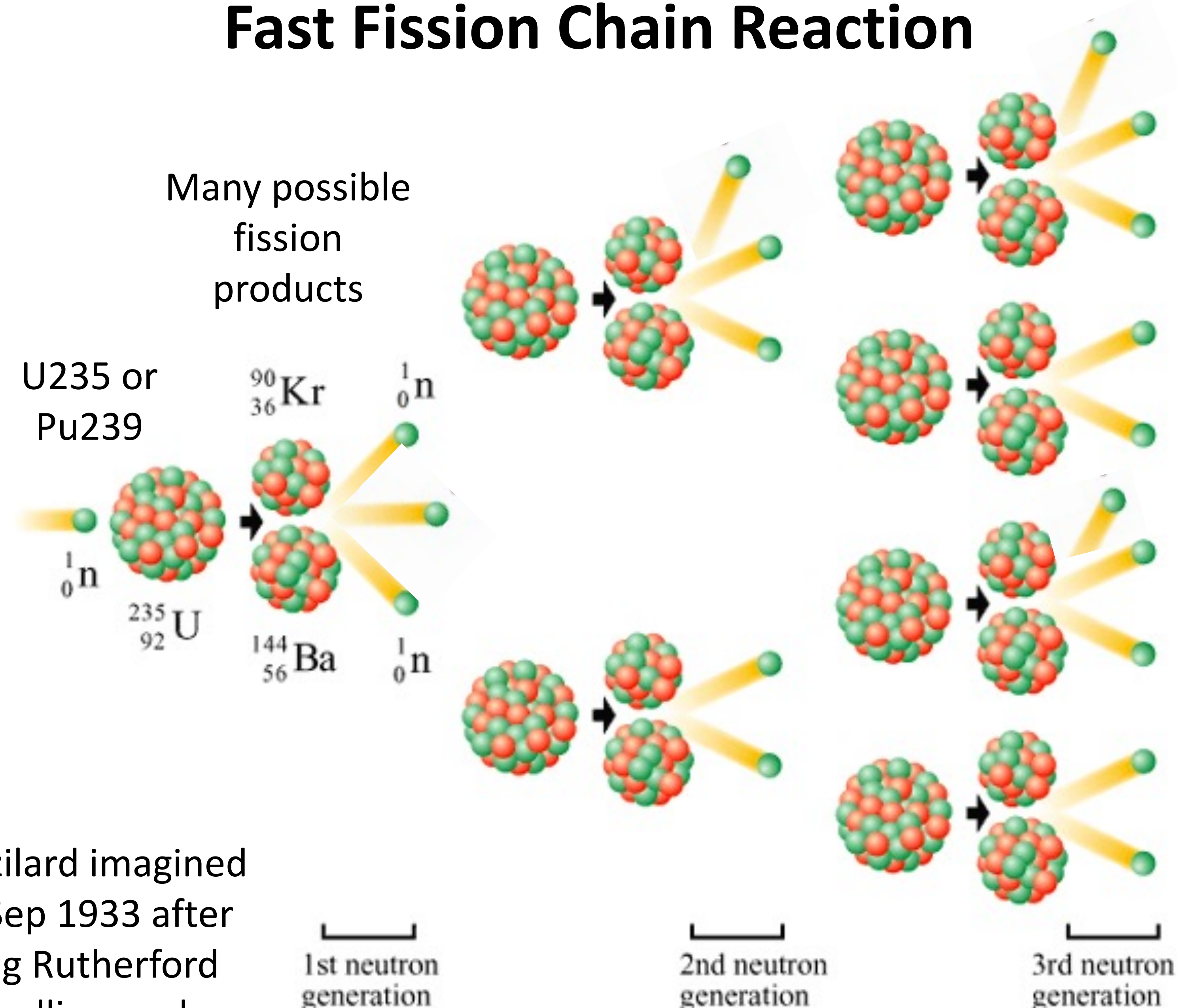
$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{239}_{92}\mathrm{U} \xrightarrow[23.5\ \mathrm{min}]{\beta^-} ^{239}_{93}\mathrm{Np} \xrightarrow[2.3565\ \mathrm{d}]{\beta^-} ^{239}_{94}\mathrm{Pu}$$

    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

Many possible fission products

U235 or Pu239



What Szilard imagined on 12 Sep 1933 after reading Rutherford speech calling nuclear energy “moonshine”

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 = (2.5 neutrons/fission) x (2 MeV/neutron)**
Gamma-rays	7 MeV
Decay of fission products	13 MeV
Neutrinos	10 MeV

Cross section for fast fission:
U235: 1.2 barn
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:

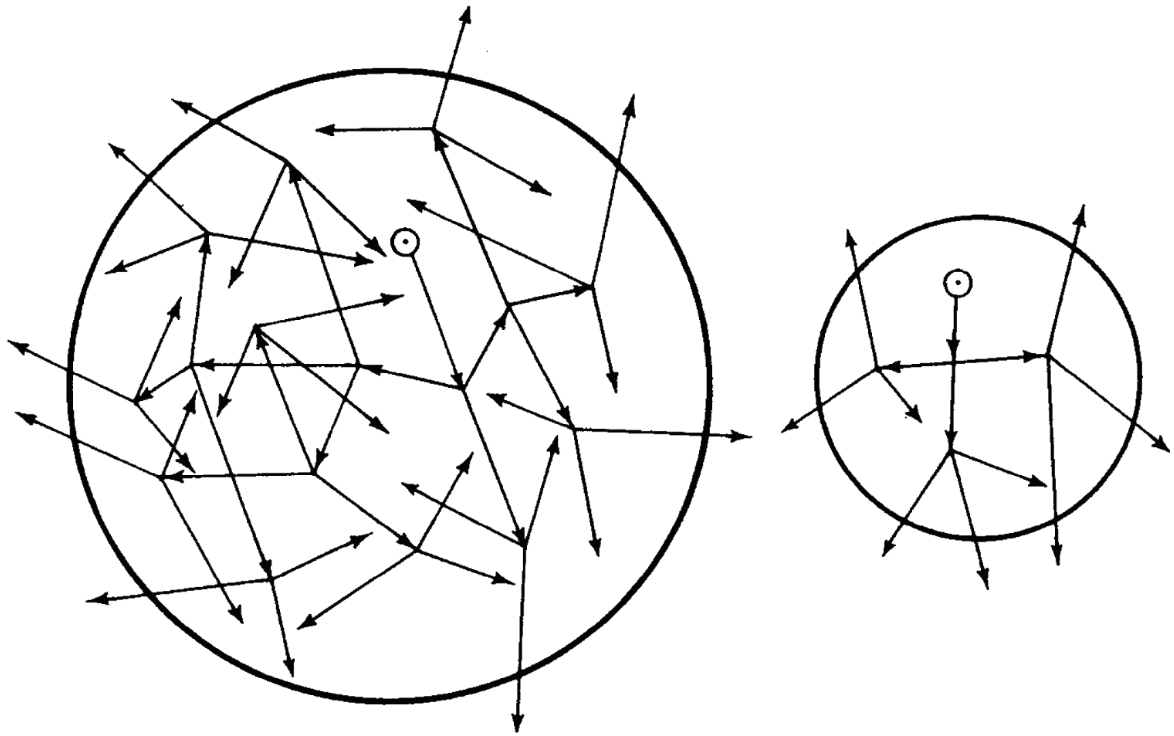
$$2^{n+1} = 2^{81} = 2.4\times10^{24}$$

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

Assembly of fissile material is “critical” if fission rate and neutron population is constant (i.e., each fission causes one new fission)

super-critical: exponential increase

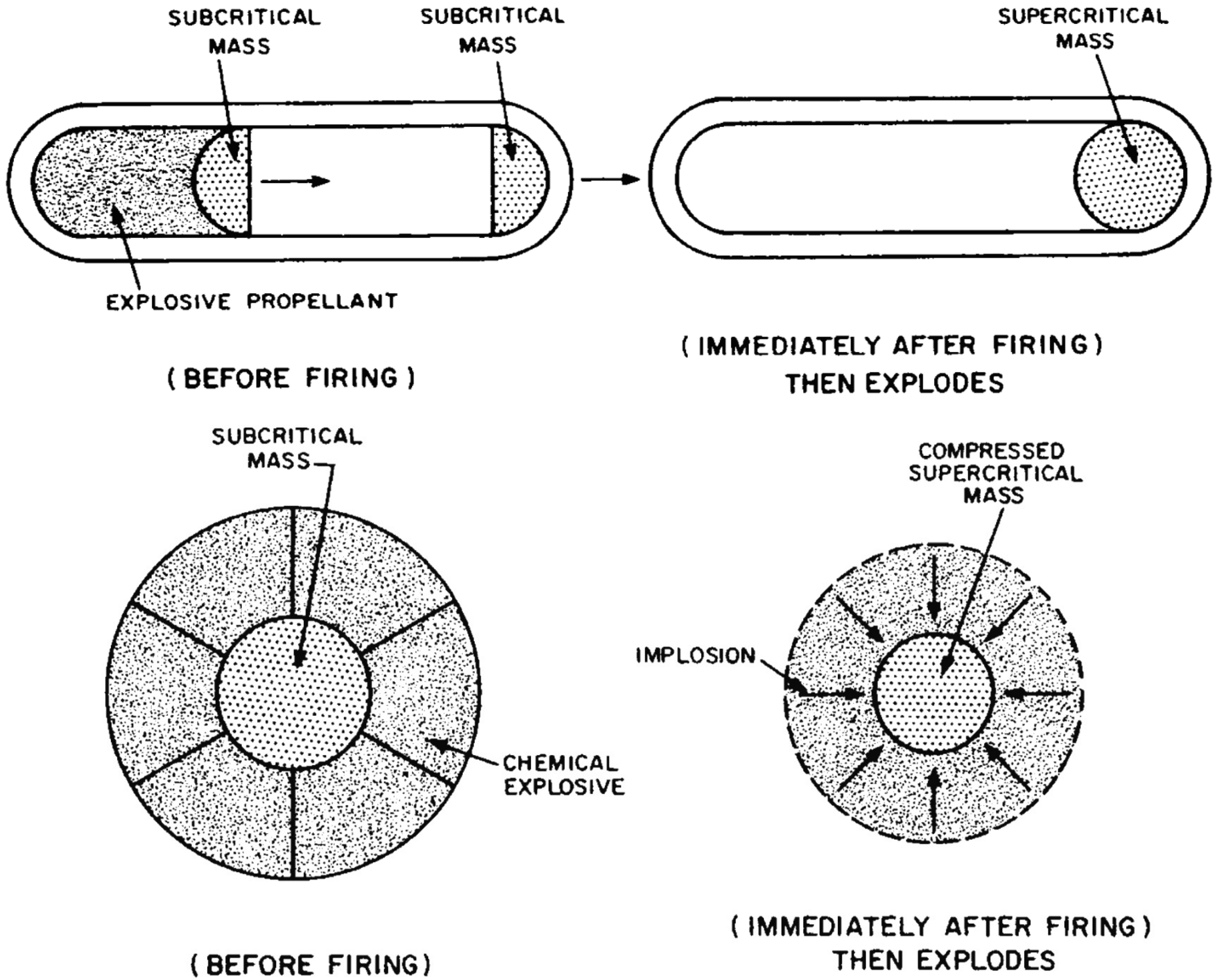


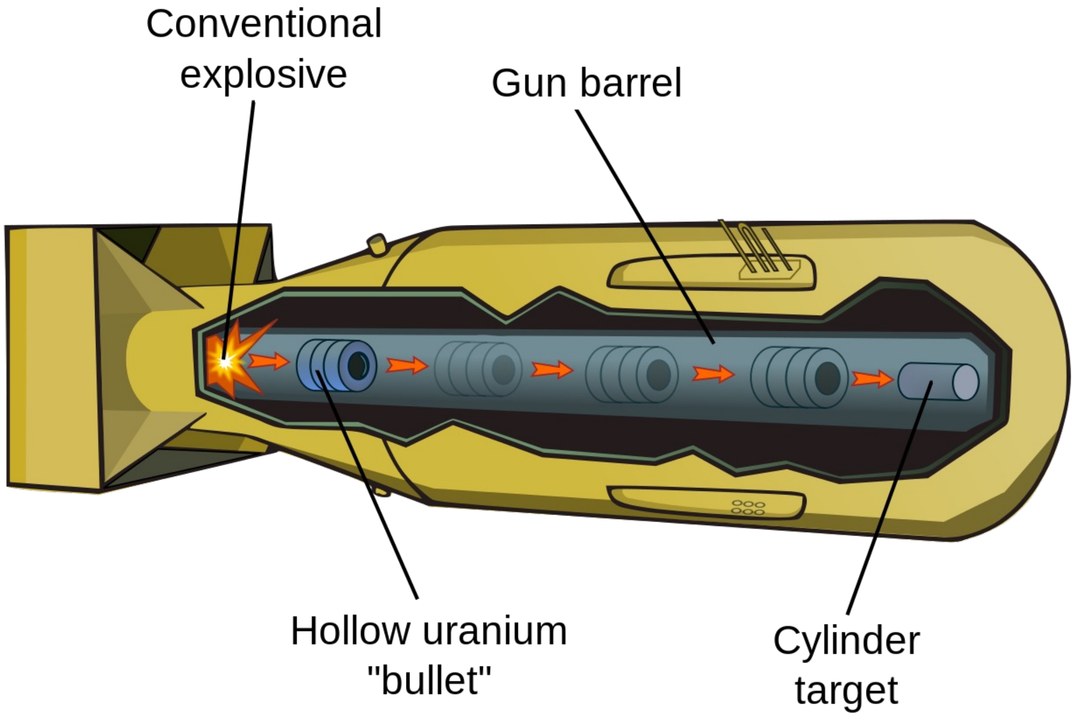
subcritical: exponential decrease

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

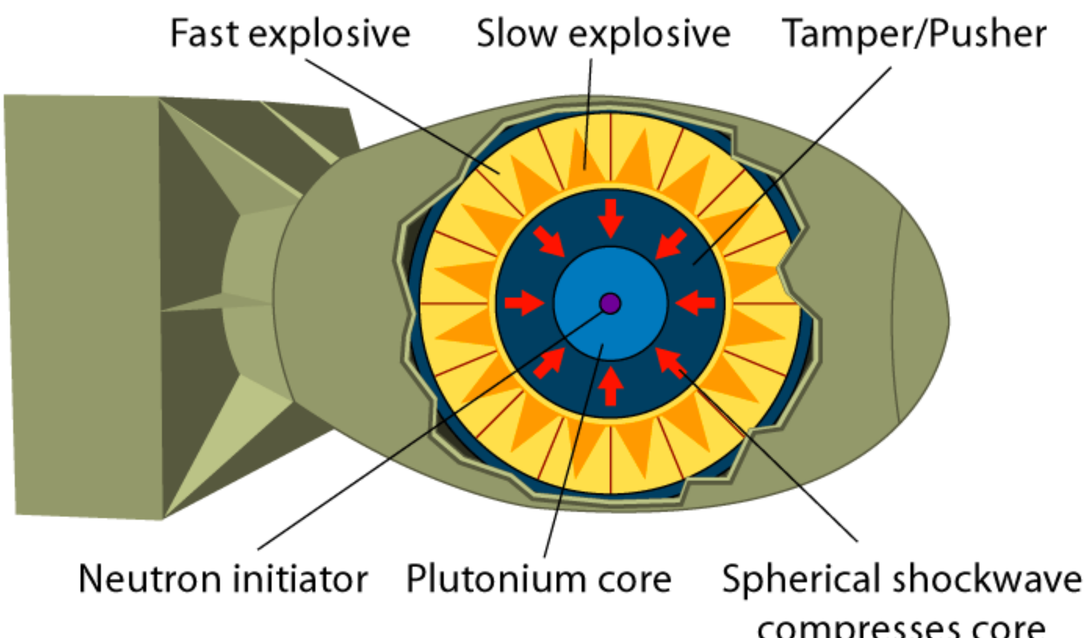
Critical mass can be decreased by:
- Using a reflector
- Increasing density

Assembly of Super-Critical Mass: Gun v. Implosion



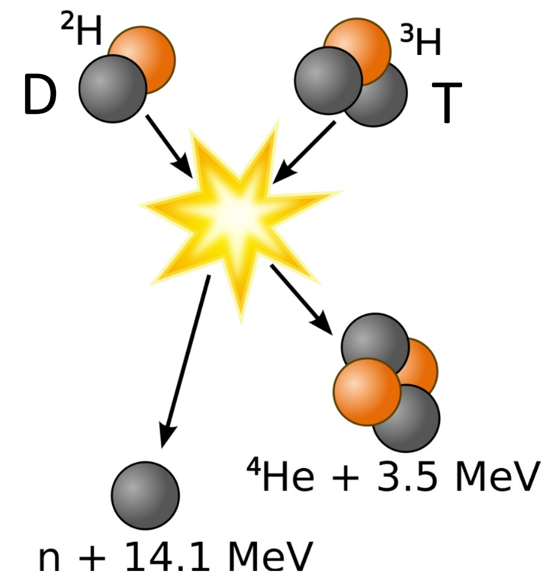


"Little Boy" (Hiroshima)
Gun-type device
64 kg of HEU (51 kg U235)
15 kilotons
Efficiency = 1.7%



"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

↓

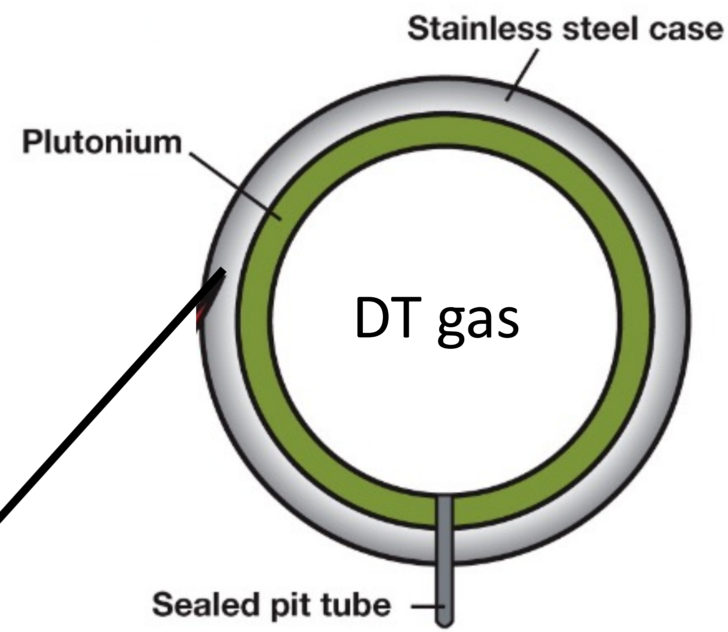
D + T → He4 + n + 17.6 MeV

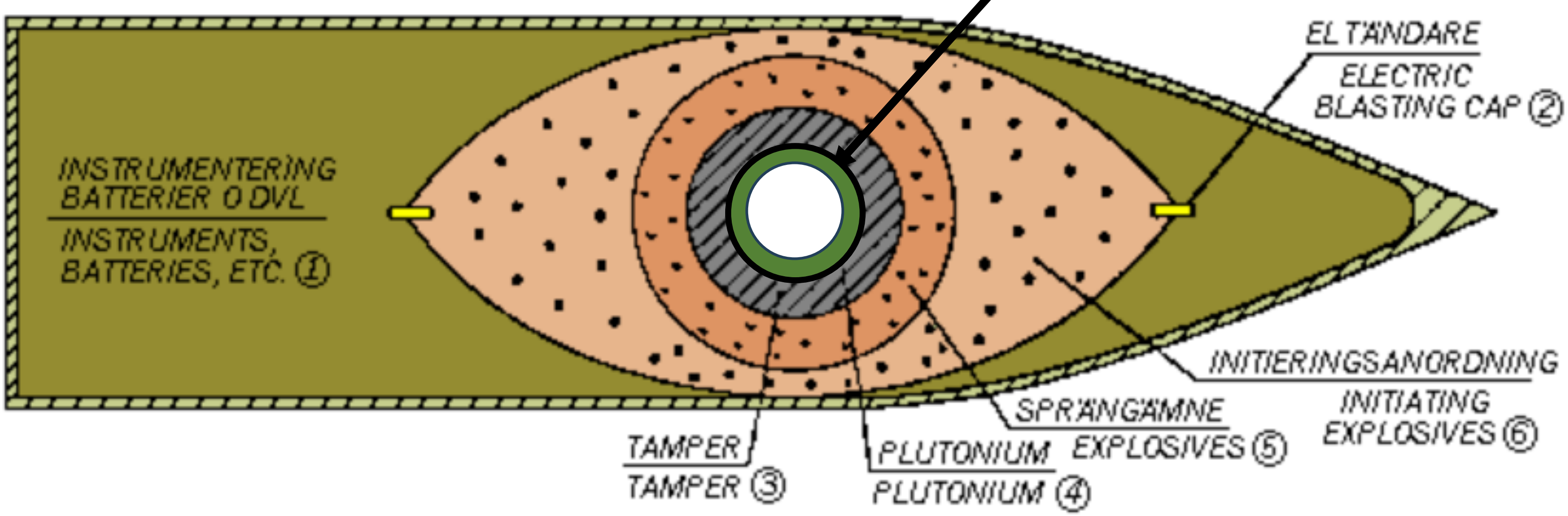
Use fission to cause fusion: boosted and two-stage weapons

Boosted Fission Weapon

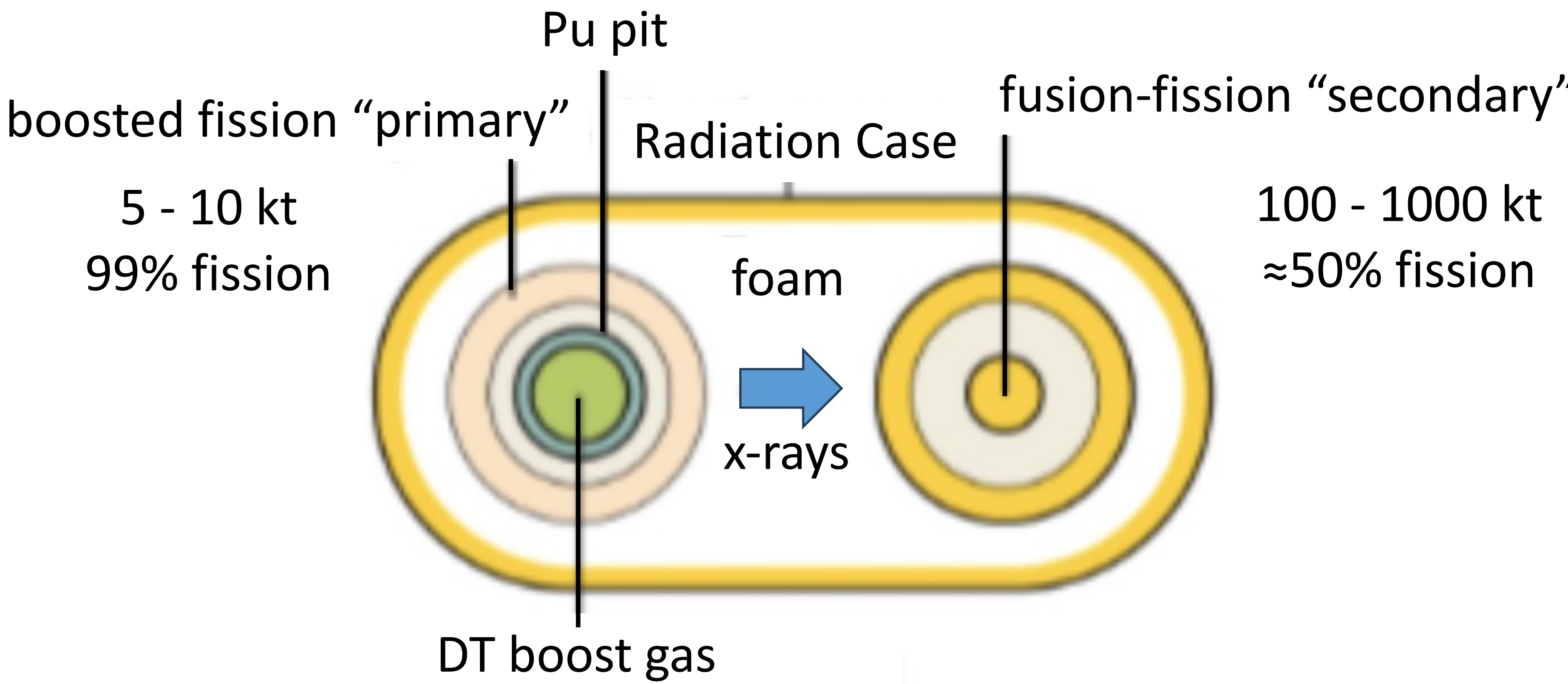
- The neutrons from DT fusion increase fission by ≈10x, making possible compact fission devices
- Fusion does contribute significantly to the yield

Hollow Pu Pit



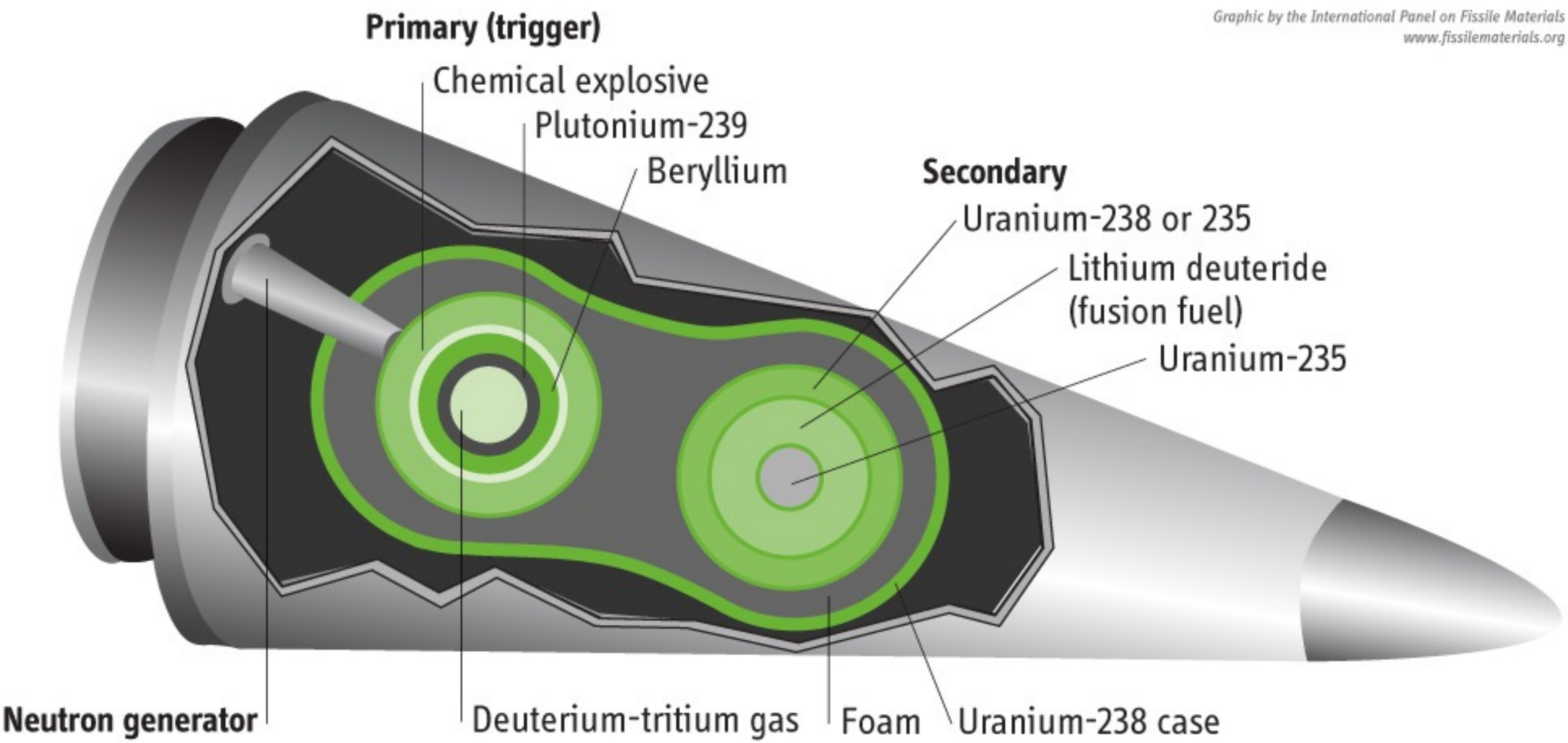


Two-stage Thermonuclear (fission-fusion) Weapon



"radiation implosion" similar to indirect-drive ICF, in which laser pulse on hohlaum produces x-rays to compress fusion capsule

Two-stage Thermonuclear (fission-fusion) Weapons



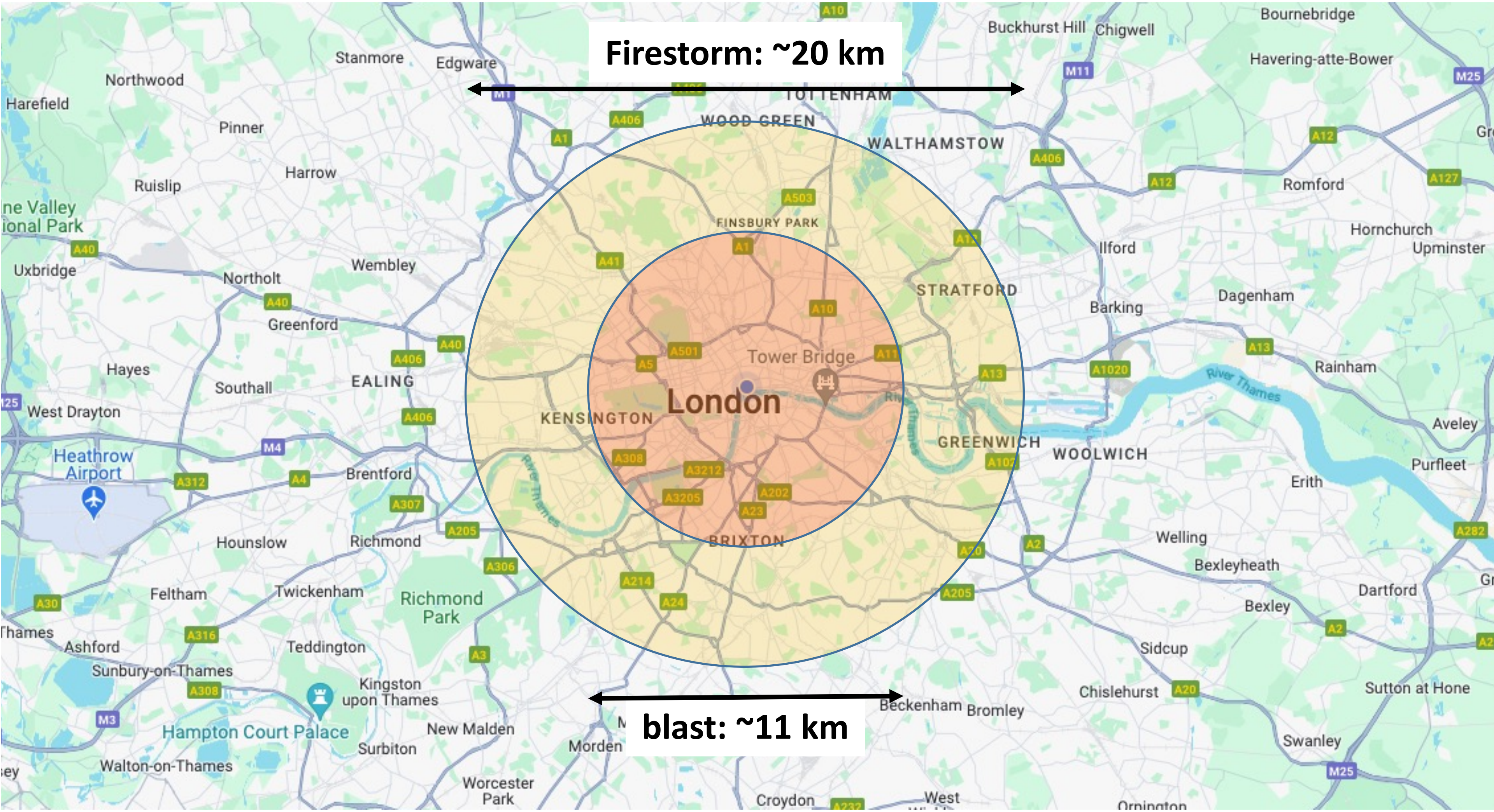
Using these design principles, the U.S. deployed weapons with yields up to 25,000 kt.
The Soviet Union produced a 100,000 kt device ("Tsar Bomba"), which it tested at 57,000 kt.
The nuclear weapons deployed today have an average yield of about 350 kt.

Effects of Nuclear Weapons

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

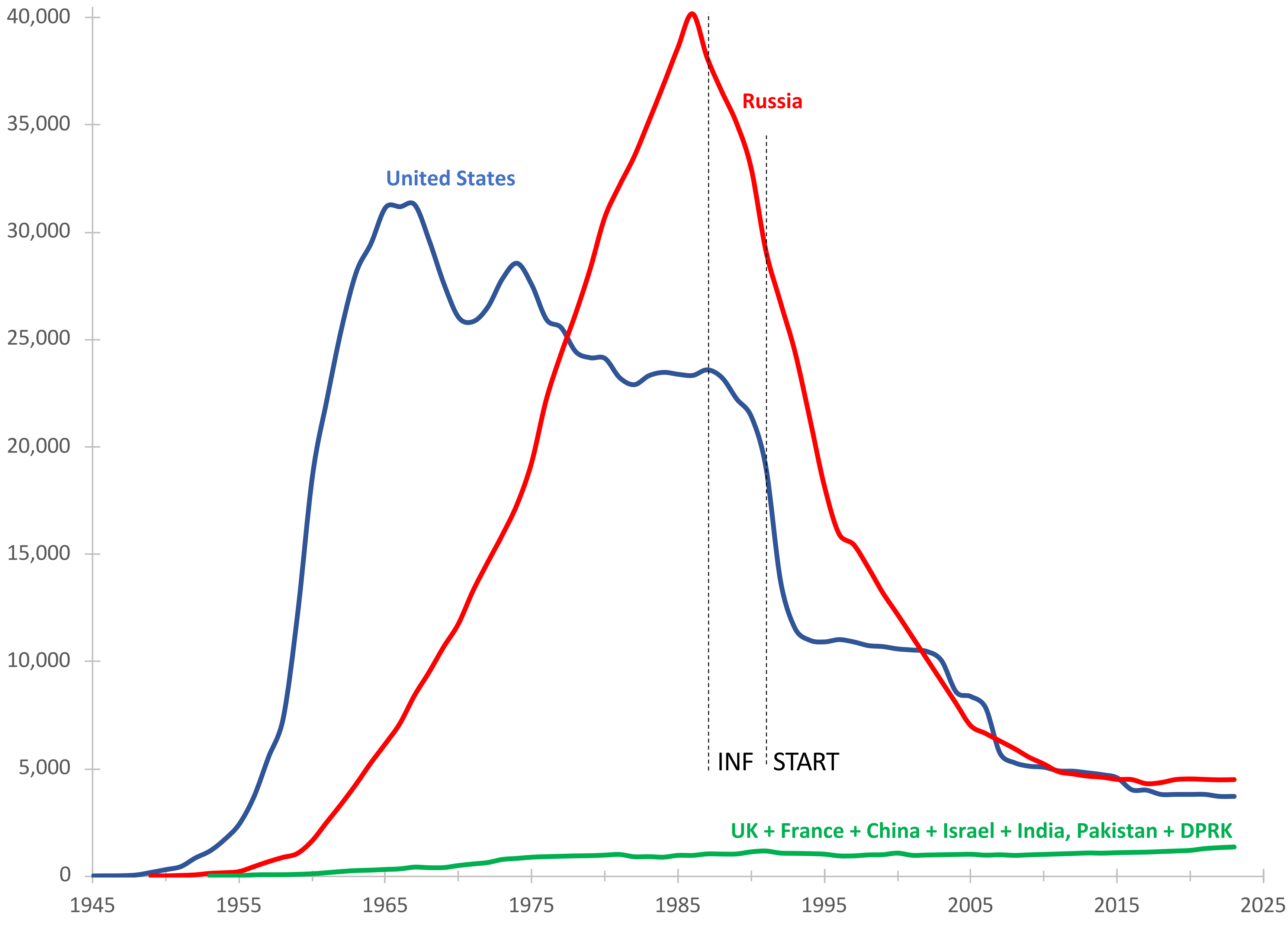
Hiroshima: 125,000 deaths from burns and firestorm; building collapse and flying debris; radiation and radiation-induced cancer

Area of Destruction
350-kt warhead centered on White Hall

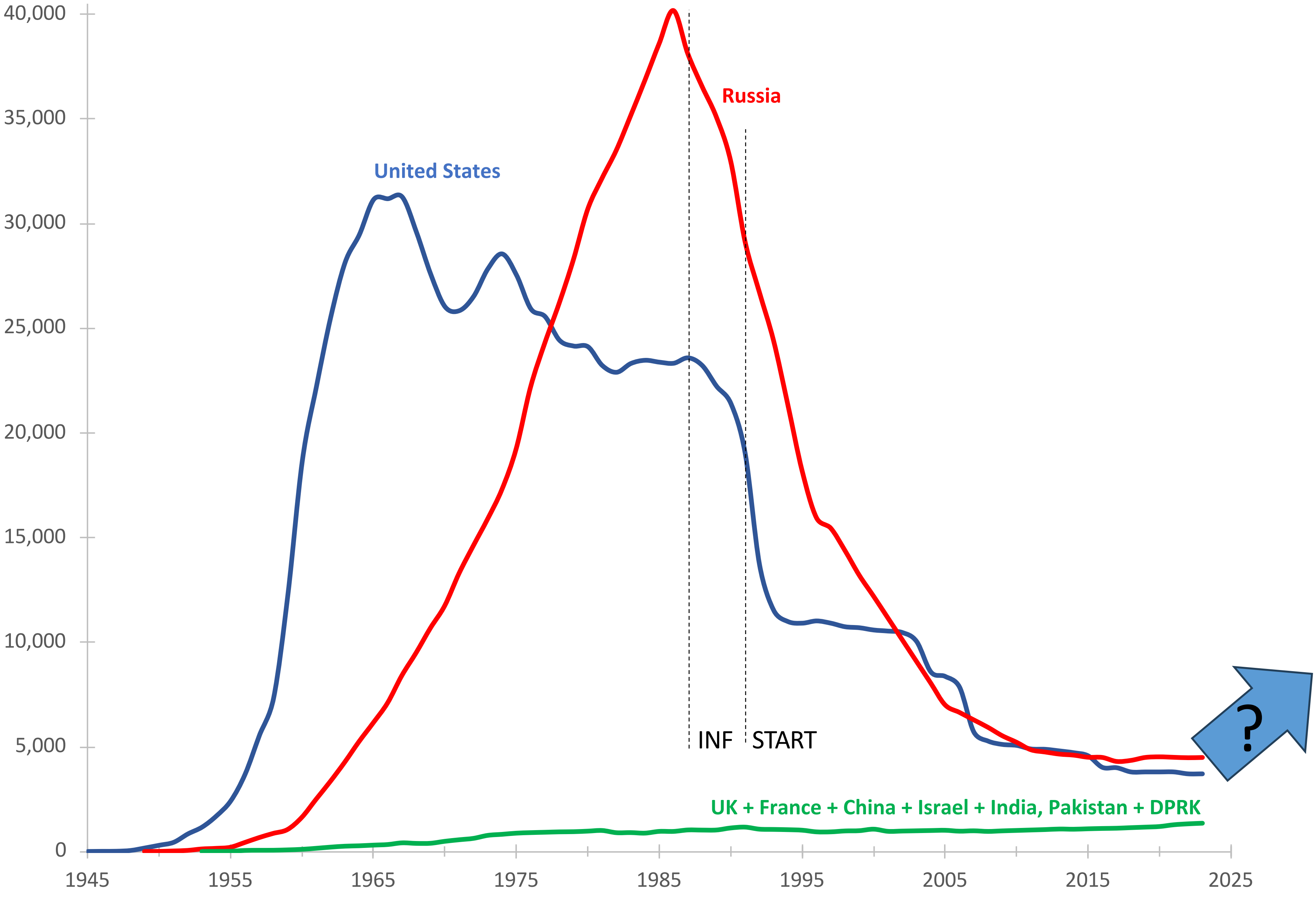


About 1 million deaths from blast and fire

Global Nuclear Arsenals, 1945-2023



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, 2023

	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

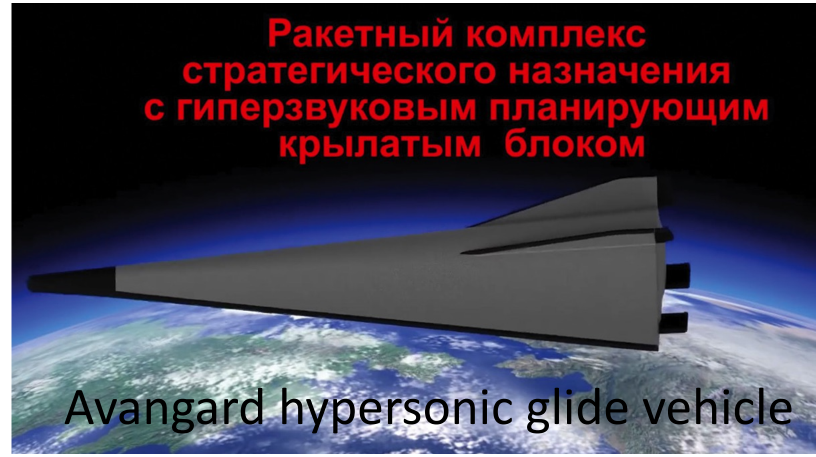



All to be replaced starting 2030
at a total cost of $1.3 trillion

Russian Nuclear Stockpile, 2023

	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

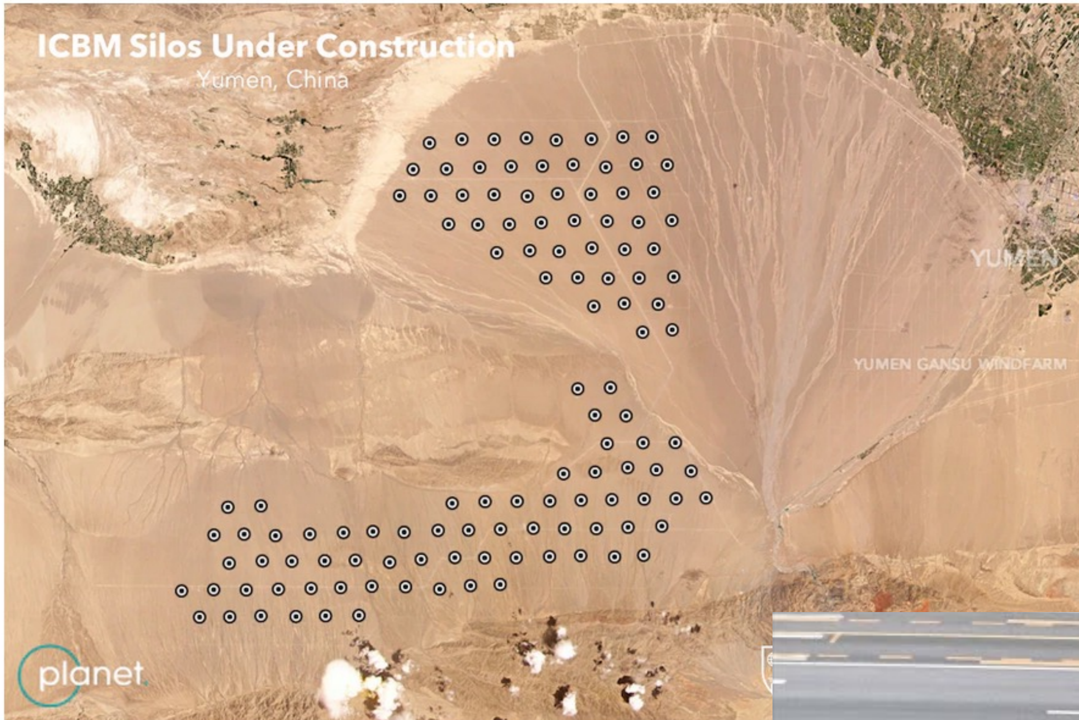
Russia’s New Nuclear Weapons



Poseidon Intercontinental Nuclear-Powered Nuclear-Armed Autonomous Torpedo

2м39 'Poseidon' (Посейдон) / 'Status-6' (Статус-6 / 'Skif' (Скиф) seabed launched variant / NATO: KANYON

China is building more than 1~~0~~0 new missile silos in its western desert, analysts say 300



Deterrence through Assured Destruction

Because nuclear weapons are so destructive, effective defense is impossible

- US, Russia, and China 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 attack by maintaining a capability to deliver devastating nuclear retaliation
- When adversaries both have assured retaliatory capability, a state of “mutual assured destruction” exists
- Because no political or military goal is worth destruction, avoid conflicts that could lead to nuclear war

Deterrence Failure and Other Risks

- Conflicts that escalates to nuclear use
  - Russia v. NATO; China v. Taiwan or Japan; North Korea v. South Korea or Japan; India v. Pakistan; Israel
  - Use of nuclear weapons to forestall conventional defeat
- Accidental, inadvertent, mistaken, or unauthorized use
  - Accidental detonation; false warning; rogue officer
- Nuclear terrorism using stolen weapons or materials
- Spread of nuclear weapons to additional states (Iran, Saudi Arabia, South Korea, Japan)
- Nuclear arms races that result in unnecessary expenditures

Challenges to the Global Nuclear Order

Stability that characterized post-Cold War period is ending

- Russia
  - Invasion of Ukraine and nuclear threats
  - Suspension of New START, refusal to discuss follow-on
  - De-ratification of CTBT
  - End of INF and Open Skies
  - Development and deployment of new nuclear systems
- China
  - large expansion of nuclear arsenal
  - potential for conflict over Taiwan and South China Sea
- North Korea: continued development and testing of ICBMs
- Iran: continued production of HEU; failure to restore JCPOA
- Emerging technologies: hypersonic and autonomous weapons, space-based radar, AI/ML, quantum sensors

Congressional Commission on Strategic Posture

"The following should be pursued with urgency:

- Upload hedge warheads
- Deploy new ICBM in MIRVed or road-mobile configuration
- Increase number of new SSBNs and Trident missiles
- Increase number of new cruise missiles on bombers
- Increase number of new bombers
- Plan for new bombers to be on continuous alert
- Develop and deploy additional theater nuclear weapon systems
- Increase production capacity for nuclear weapons and delivery systems
- Develop and deploy homeland missile and air defenses "that can deter and defeat coercive attacks by Russia and China."

FOREIGN AFFAIRS

The U.S. Nuclear Arsenal Can Deter Both China and Russia

Why America Doesn't Need More Missiles

By Charles L. Glaser, James M. Acton, and Steve Fetter October 5, 2023

Posing with nuclear missiles in Beijing, October 2022

What can physicists do?

PHYSICISTS COALITION FOR NUCLEAR THREAT REDUCTION

https://phycisistscolation.org

Home | About the Coalition | Events | Policy and Advocacy | Next-Generation Fellowship | Press Room | Resources | JOIN

What We Offer

Colloquia

To build a national network of physicist-advocates on this issue, we are sending experts in nuclear arms control issues to physics institutions across the country to deliver colloquia, recruit physicists to the coalition, and foster local and national advocacy.

Policy and Advocacy

There are numerous practical steps to reduce the nuclear threat. We can advocate for the importance of international nuclear weapons treaties, beginning with extending New START for another five years. We can teach how the Launch-On-Warning option risks accidental nuclear war. We can defend the expert consensus that the US should not and need not resume explosive nuclear testing. Finally, we can urge our country to commit to a No-First-Use policy, and more.

Next Generation Fellowship

This fellowship aims to strengthen the participation of graduate students, postdocs, and early-career physicists and engineers in advancing nuclear weapons threat reduction.