Science for Nuclear Arms Control

Lecture I: Nuclear Weapons

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CERN Academic Training, 5 February 2024

About the Nuclear Verification and Disarmament Group

Research topics

- Nuclear verification technologies and concepts
- Fuel cycle simulations and reactor calculations
- Radiation detection
- Nonproliferation and disarmament policy

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Nuclear Verification
and Disarmament

RWTH AACHEN
UNIVERSITY

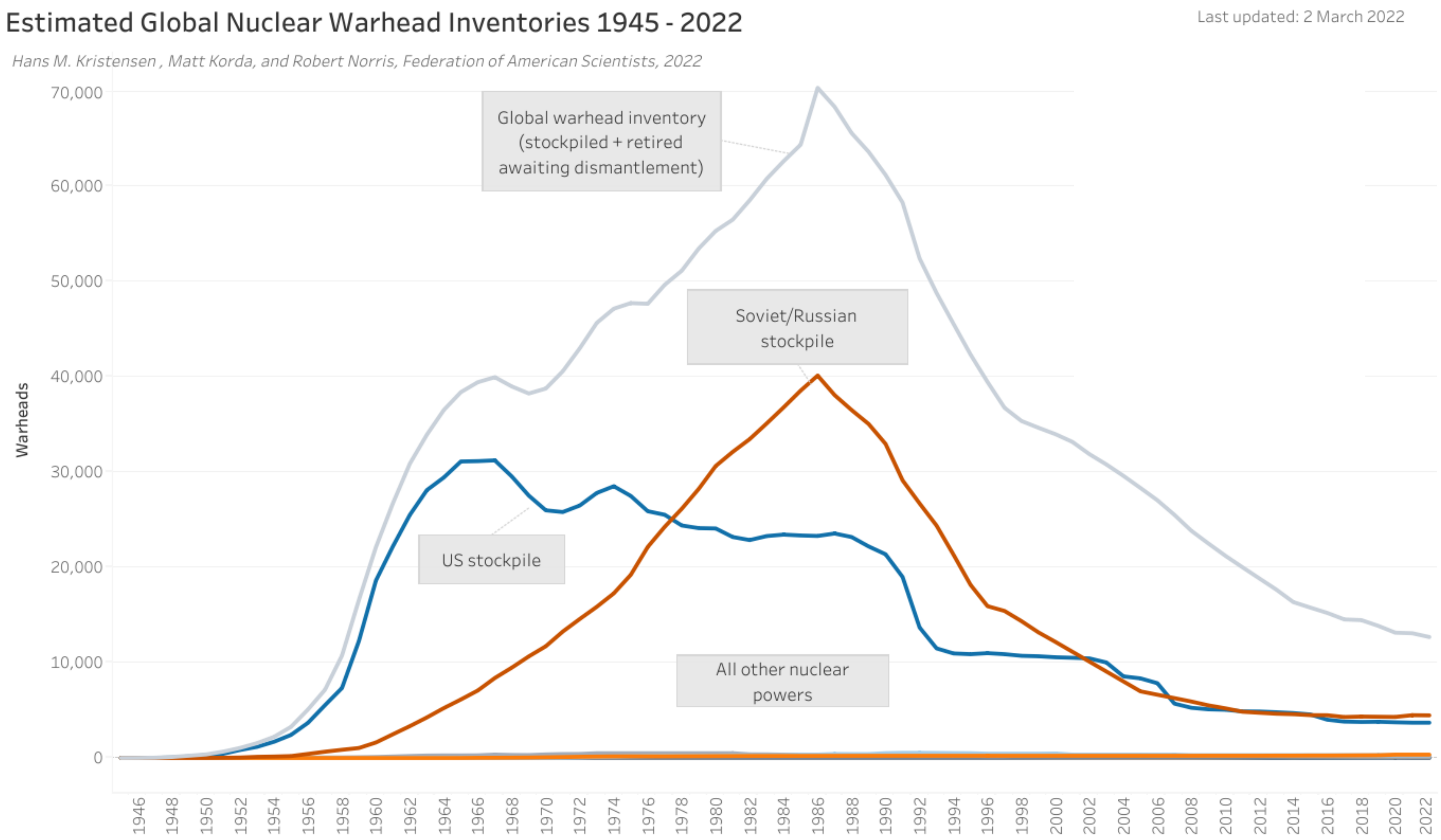
Lecture outline

The first talk will introduce what makes a nuclear weapon program, focusing on technical aspects and past proliferation cases. It will also look at the effects of nuclear weapon explosions.

The second talk will address how the world deals with these weapons: What are the related politics, the role of states and the United Nations. What can civil society – including the academic community – do?

The third talk will highlight another important contribution by physicists: International agreements on nuclear nonproliferation and disarmament require internationally developed verification measures to monitor compliance – or: science for peace. Current verification research will be presented, including particle detection.

Warhead stocks



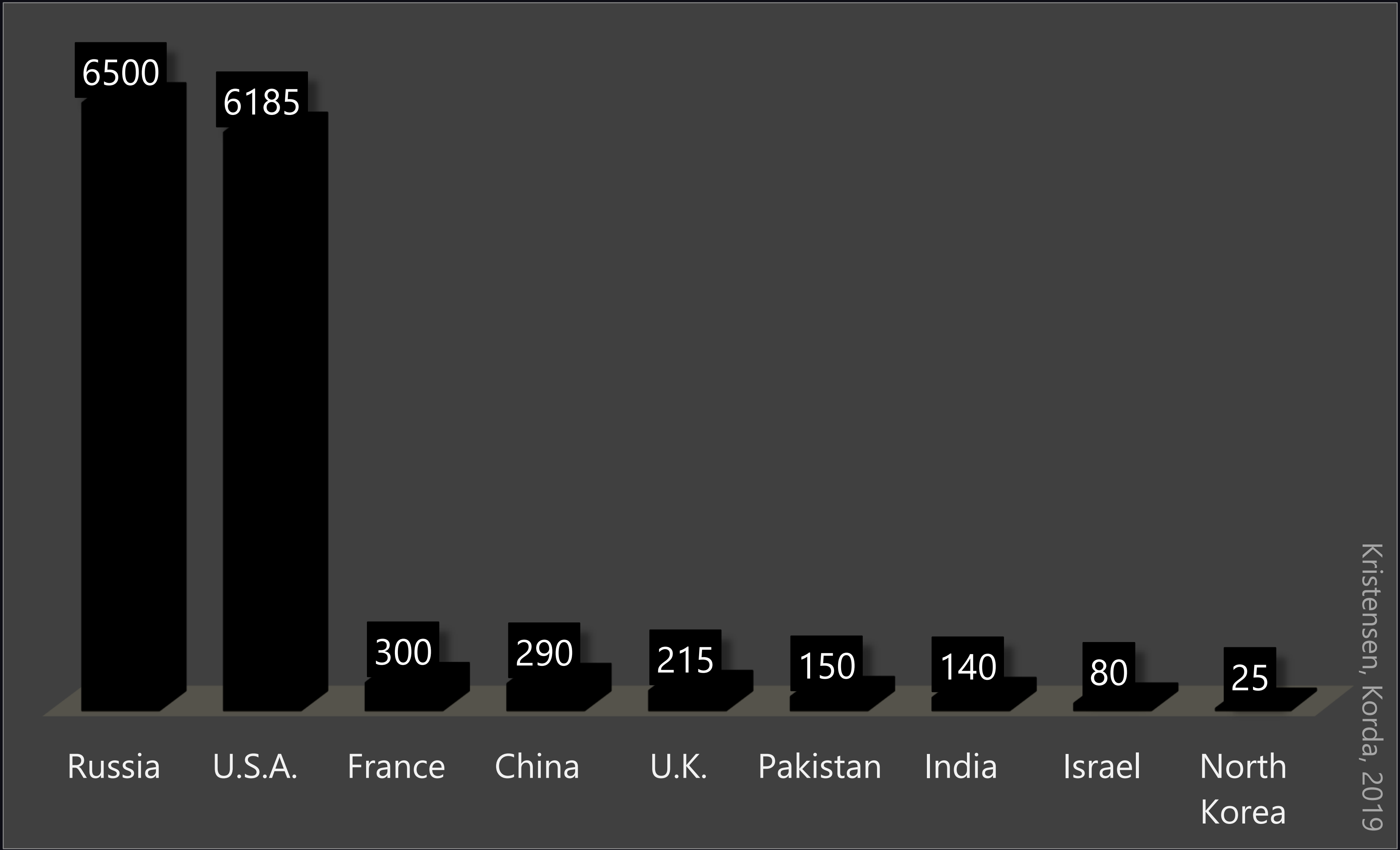
Estimated Global Nuclear Warhead Inventories 1945 - 2022

Hans M. Kristensen , Matt Korda, and Robert Norris, Federation of American Scientists, 2022

Last updated: 2 March 2022

H.M. Kristensen and M. Korda. “Status of World Nuclear Forces”. https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/

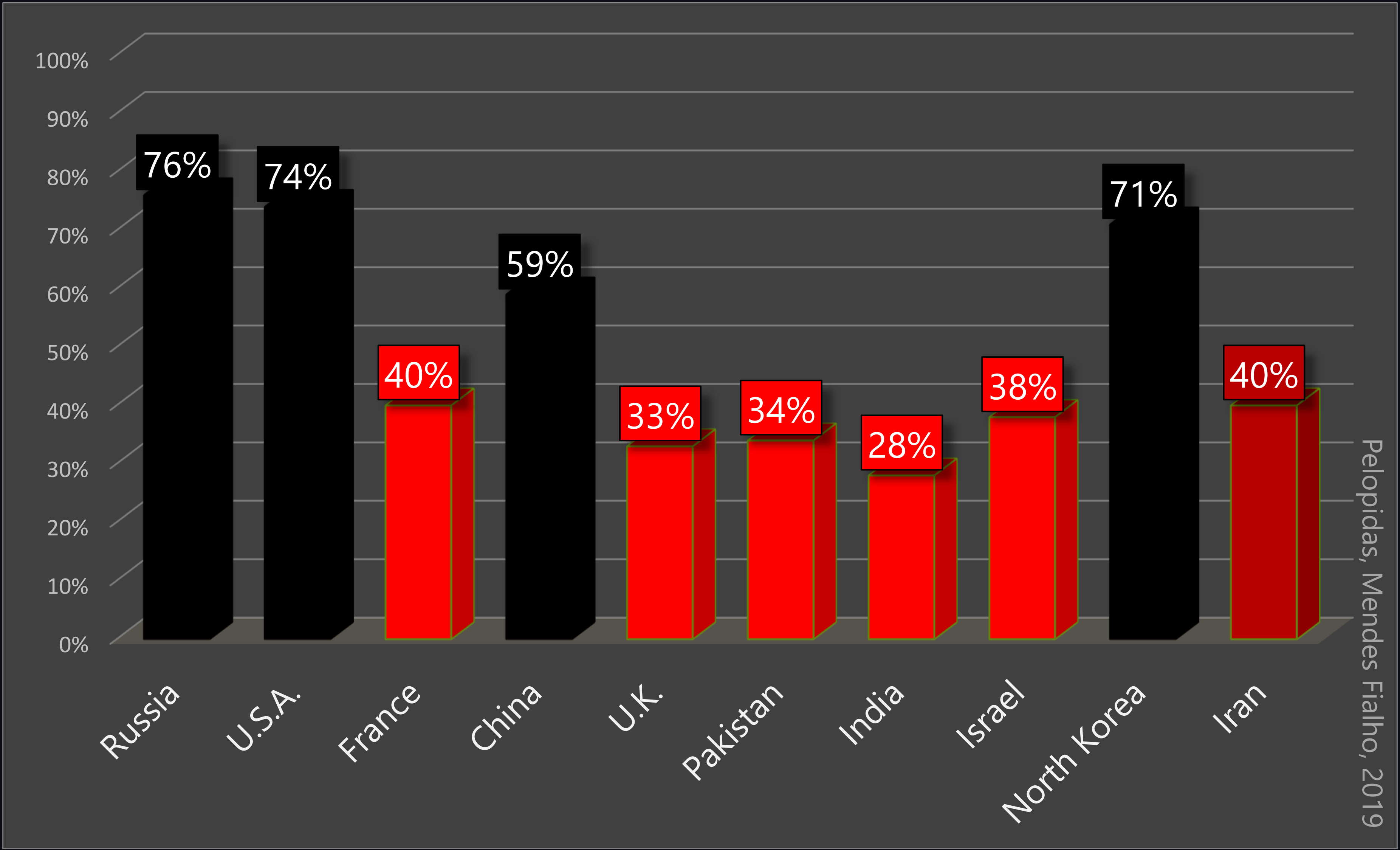
Nuclear weapons today



Kristensen, Korda, 2019

Who possesses nuclear weapons?

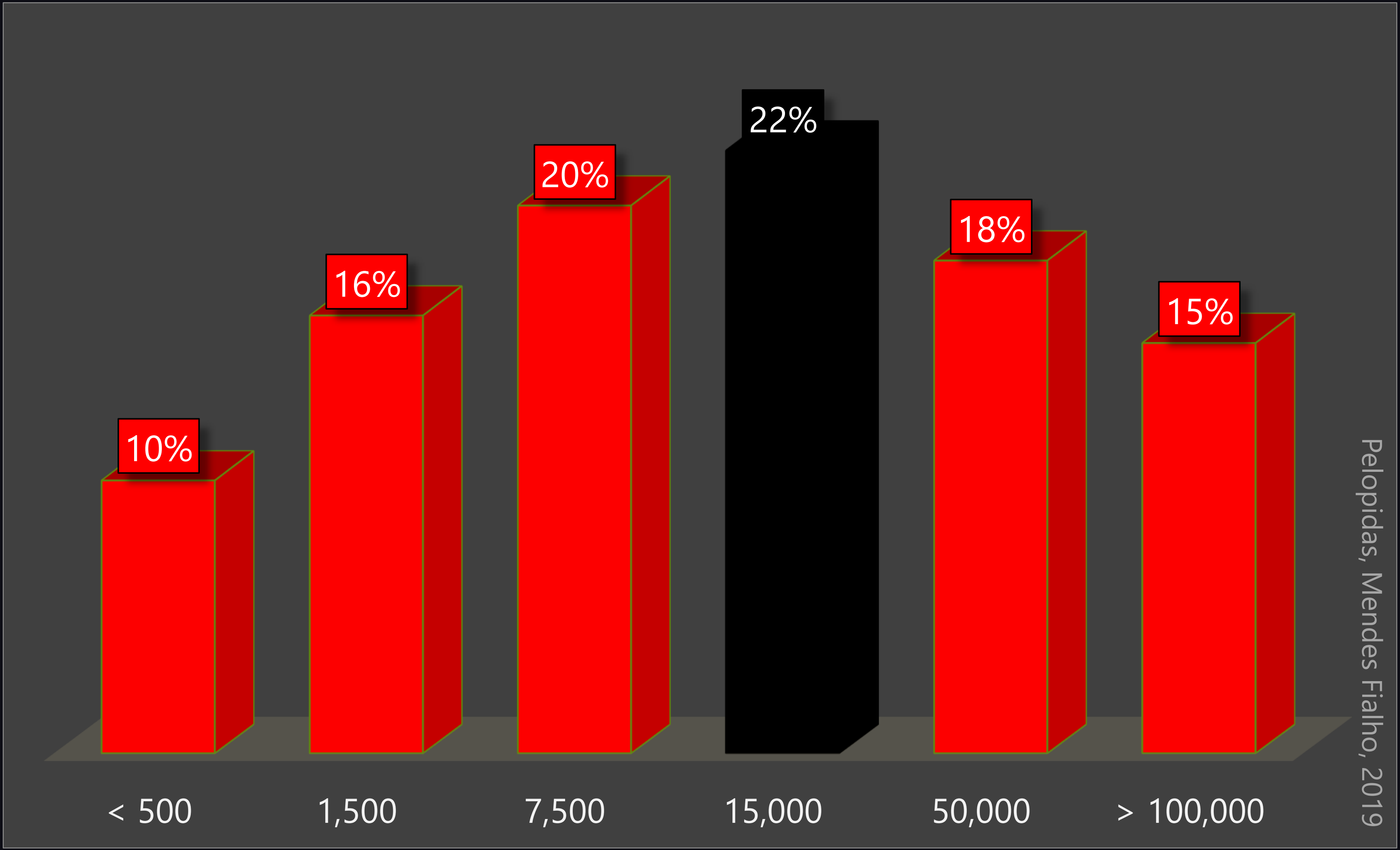
Representative survey in Germany



Pelopidas, Mendes Fialho, 2019

How many nuclear weapons are in the world?

Representative survey in Germany

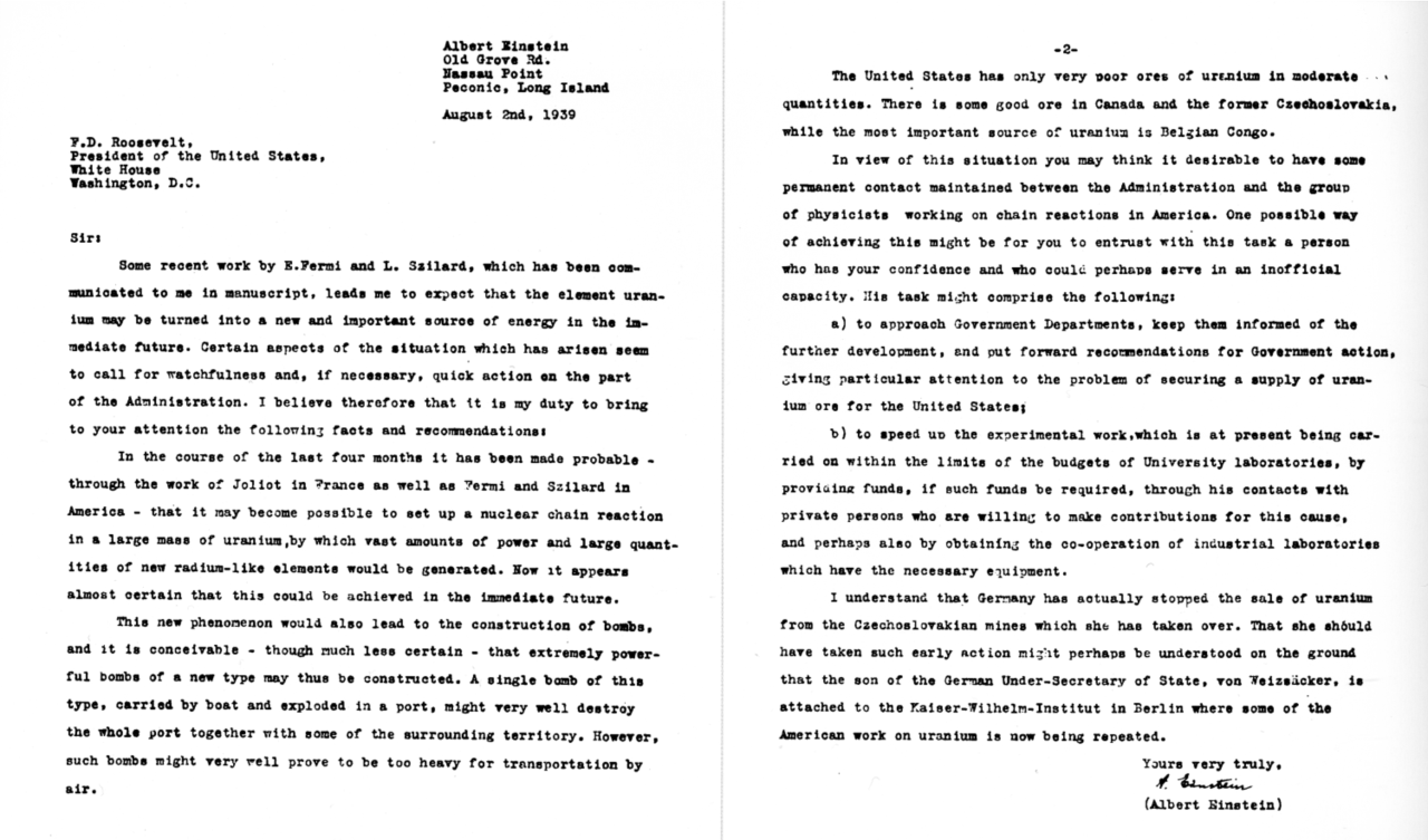


Pelopidas, Mendes Fialho, 2019

How did it start?

- 1938: Discovery of fission in Nazi Germany (Otto Hahn, Fritz Straßmann, Lise Meitner, Otto Frisch)
- Nuclear research by e.g. Carl Friedrich von Weizsäcker and Werner Heisenberg
  → Goal to build a reactor
  → Haigerloch reactor does not reach criticality in 1945 (By 1942, Chicago Pile 1 by Enrico Fermi has reached criticality, but it was unknown by Germany at the time)

How did it start?



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,
A. Einstein
(Albert Einstein)

How did it start?

Manhattan Project

Some involved scientists: Robert Oppenheimer, Leo Szilard, Otto Frisch, Niels Bohr, James Franck, Enrico Fermi, Edward Teller

How did it start?

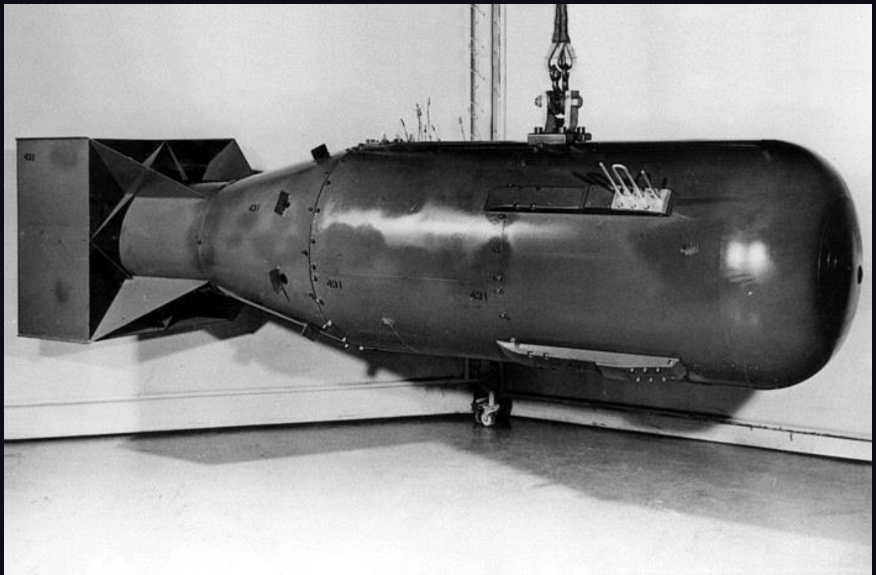
Manhattan Project

The Gadget (15 July 1945)

Trinity Test (16 July 1945)
Fireball (0.016 s after detonation)

Weapons dropped on Japan

U.S. Atomic Energy Commission,



Little Boy, dropped on Hiroshima
6 August 1945
Highly enriched uranium

Fat Man, dropped on Nagasaki
9 August 1945
Plutonium instead of uranium!

U.S. Department of Defense

Hiroshima


City of Hiroshima
Genbaku Dome
October 1945
Hiroshima Peace Memorial
Today

Criticality

$$0 = \frac{\partial n}{\partial t} = \nu \Sigma_F \Phi - \underbrace{\Sigma_A}_{\Sigma_A = \Sigma_F + \Sigma_C} \Phi + \underbrace{\frac{\partial n}{\partial t}_{\text{leak}}}_{\begin{array}{c}\text{Neutrons leaking the volume}\\ \text{(if leaking outward, term is}\\ \text{negative)}\end{array}}$$

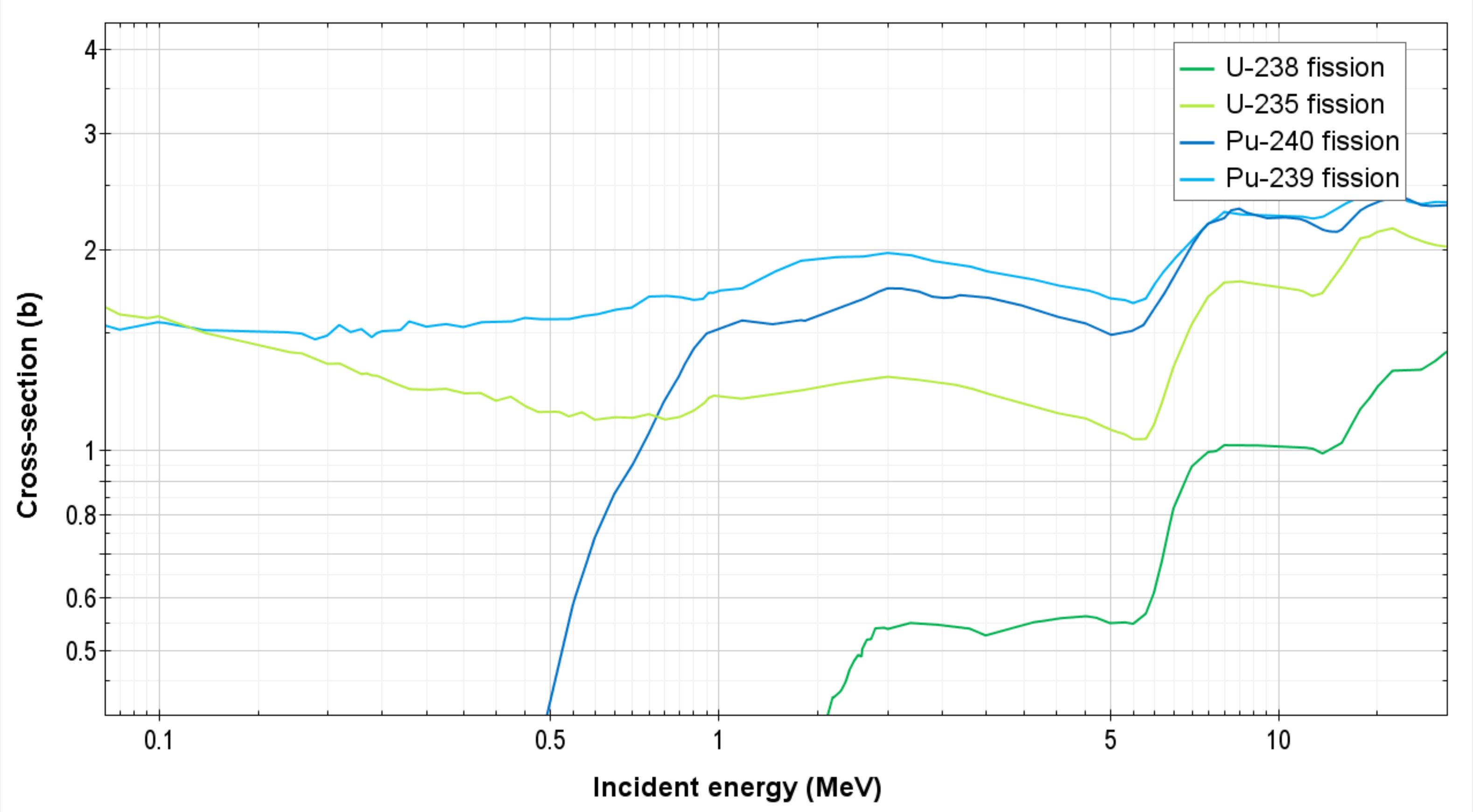
Absorption = fission + capture

Definition of criticality:

$$k_{eff} = \frac{Rate\ of\ neutron\ production}{Rate\ of\ neutron\ absorption\ and\ leakage}$$

Ingredients for nuclear weapons

Highly enriched uranium or plutonium



Criticality of a nuclear weapon

Evolution of neutron densities over m generations

$$n_i = n_{i-1} k_{eff}; n_m = n_0 k_{eff}^m$$

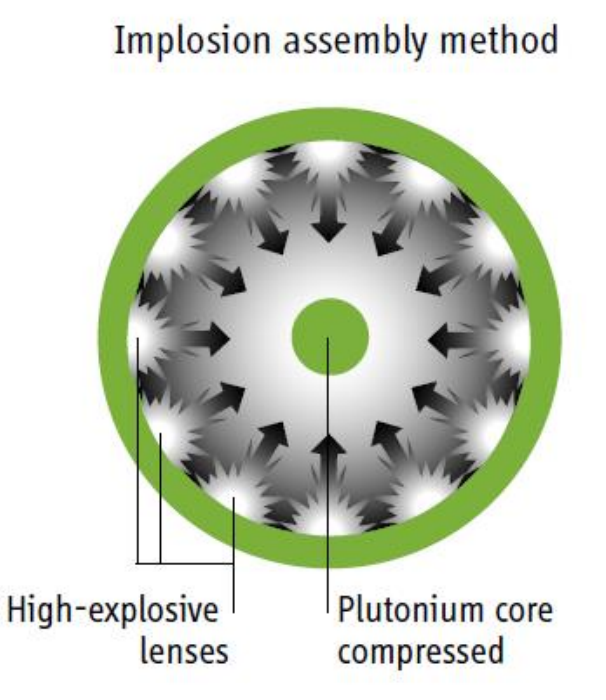
n proportional to flux, proportional to reaction (fission) rate
Per fission: around 200 MeV energy release

$$t = m \cdot \bar{l}$$

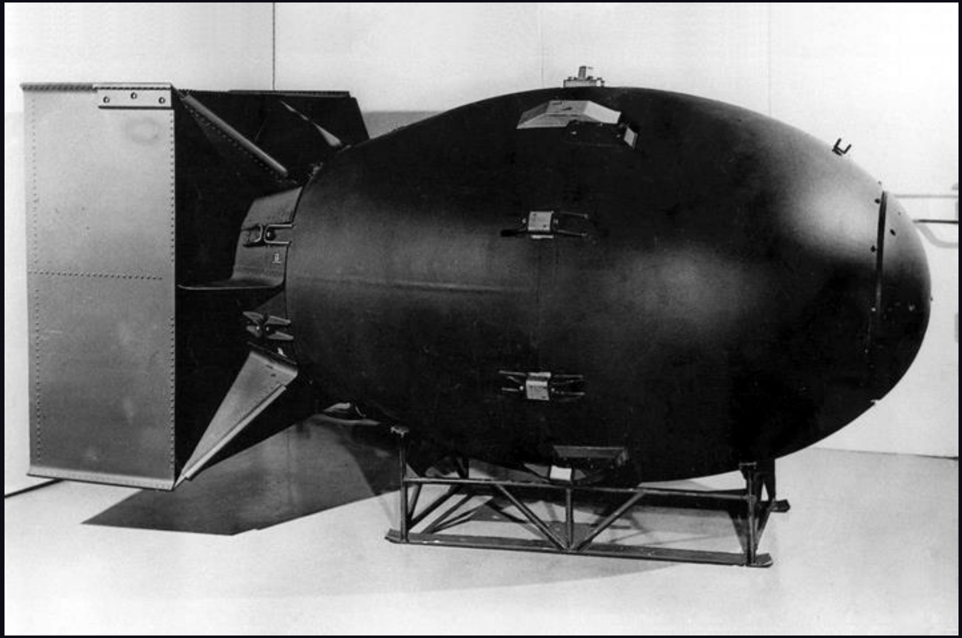
$\bar{l}$: Duration of one generation

$$n(t) = n_0 k_{eff}^{t/\bar{l}} = n_0 \exp(\frac{\ln k_{eff}}{\bar{l}} t)$$

Criticality of a nuclear weapon



International Panel on Fissile Materials, 2006



U.S. Department of Defense

Fat Man, dropped on Nagasaki, 9 August 1945
Plutonium instead of uranium!

Criticality of a nuclear weapon

$$n(t) = n_0 k^{t/\bar{l}} = n_0 \exp(\frac{\ln k}{\bar{l}} t)$$

How to achieve n_0?

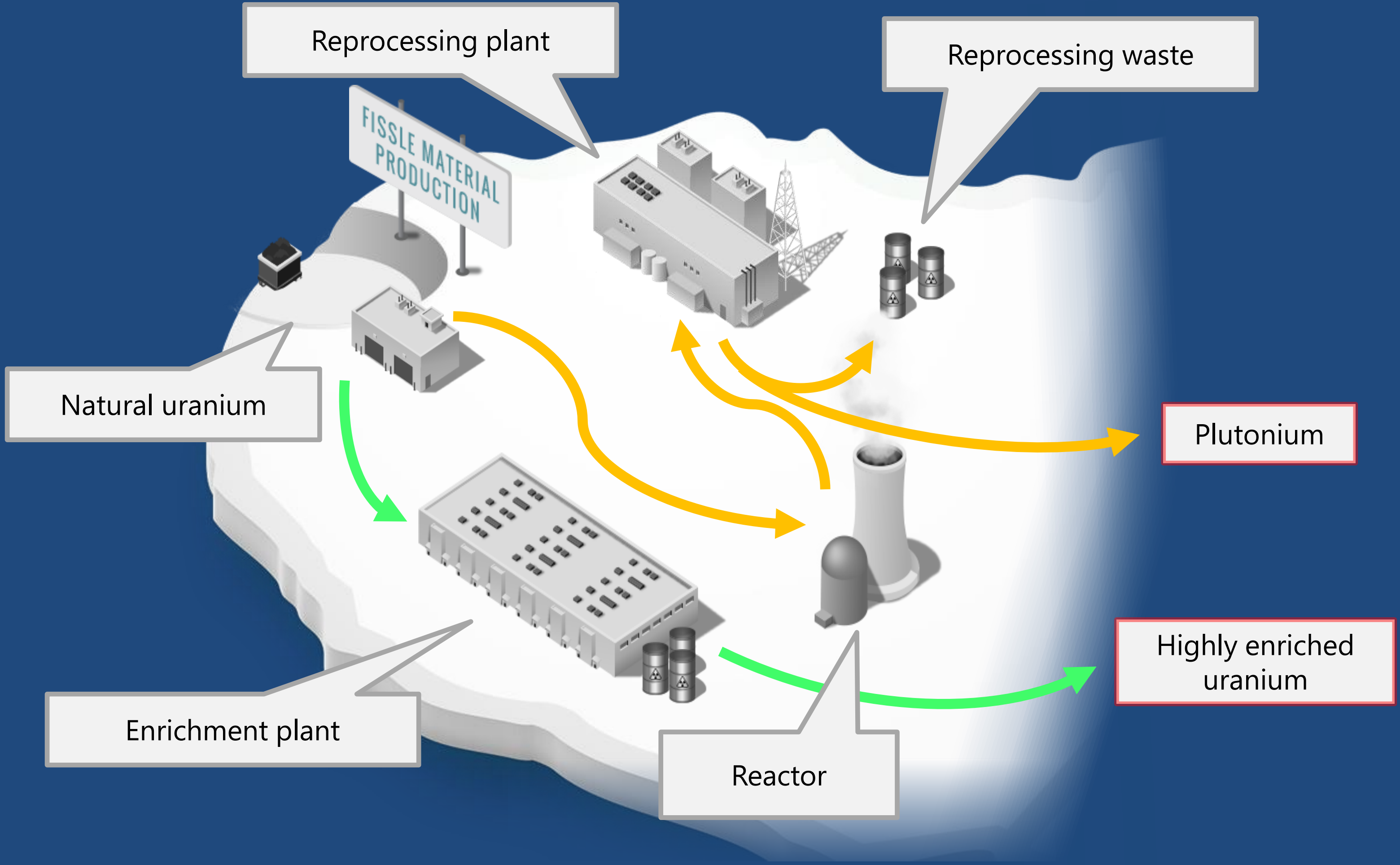
- Initiation with deuterium and tritium fusion in accelerator

$$^{2}D + \ ^{3}T \ \rightarrow \ ^{4}He + n + 17.6\ MeV$$

$$^{210}Po \rightarrow \alpha + {}^{206}Pb\ ; \quad Be(\alpha, n)C$$

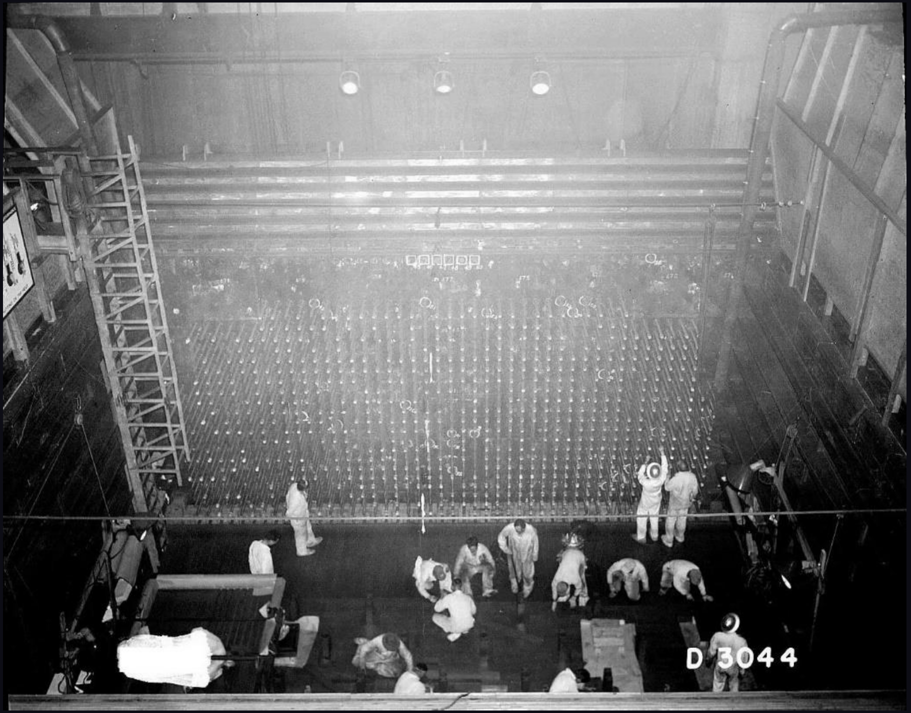
- Additional neutrons during fission: Boosting

$$^{2}D + \ ^{3}T \ \rightarrow \ ^{4}He + n + 17.6\ MeV$$



FISSLE MATERIAL PRODUCTION
Reprocessing plant
Reprocessing waste
Natural uranium
Plutonium
Enrichment plant
Reactor
Highly enriched uranium

Fissile material production

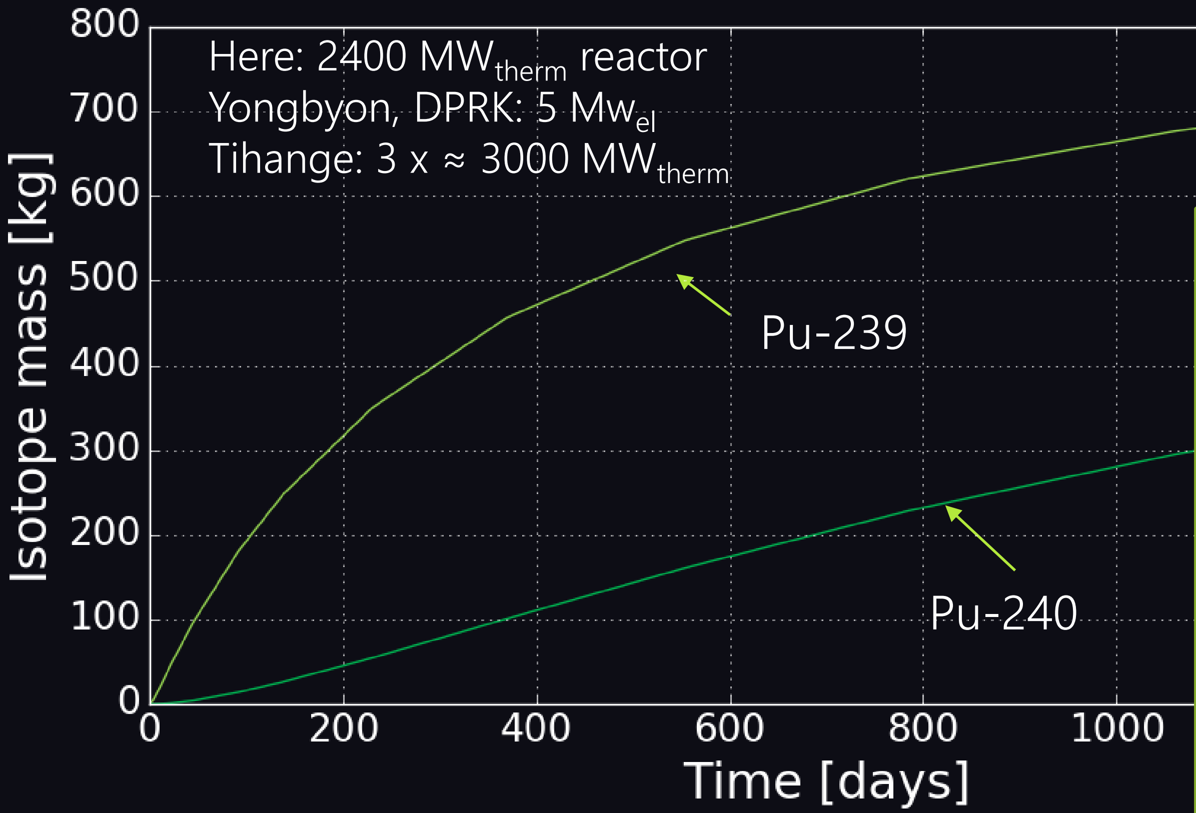


U.S. Hanford reactor

U.S. Oak Ridge enrichment plant

Plutonium production

$$^{238}U \xrightarrow{(n,\gamma)} {}^{239}U \xrightarrow{\beta^-} {}^{239}Np \xrightarrow{\beta^-} {}^{239}Pu \xrightarrow{(n,\gamma)} {}^{240}Pu$$

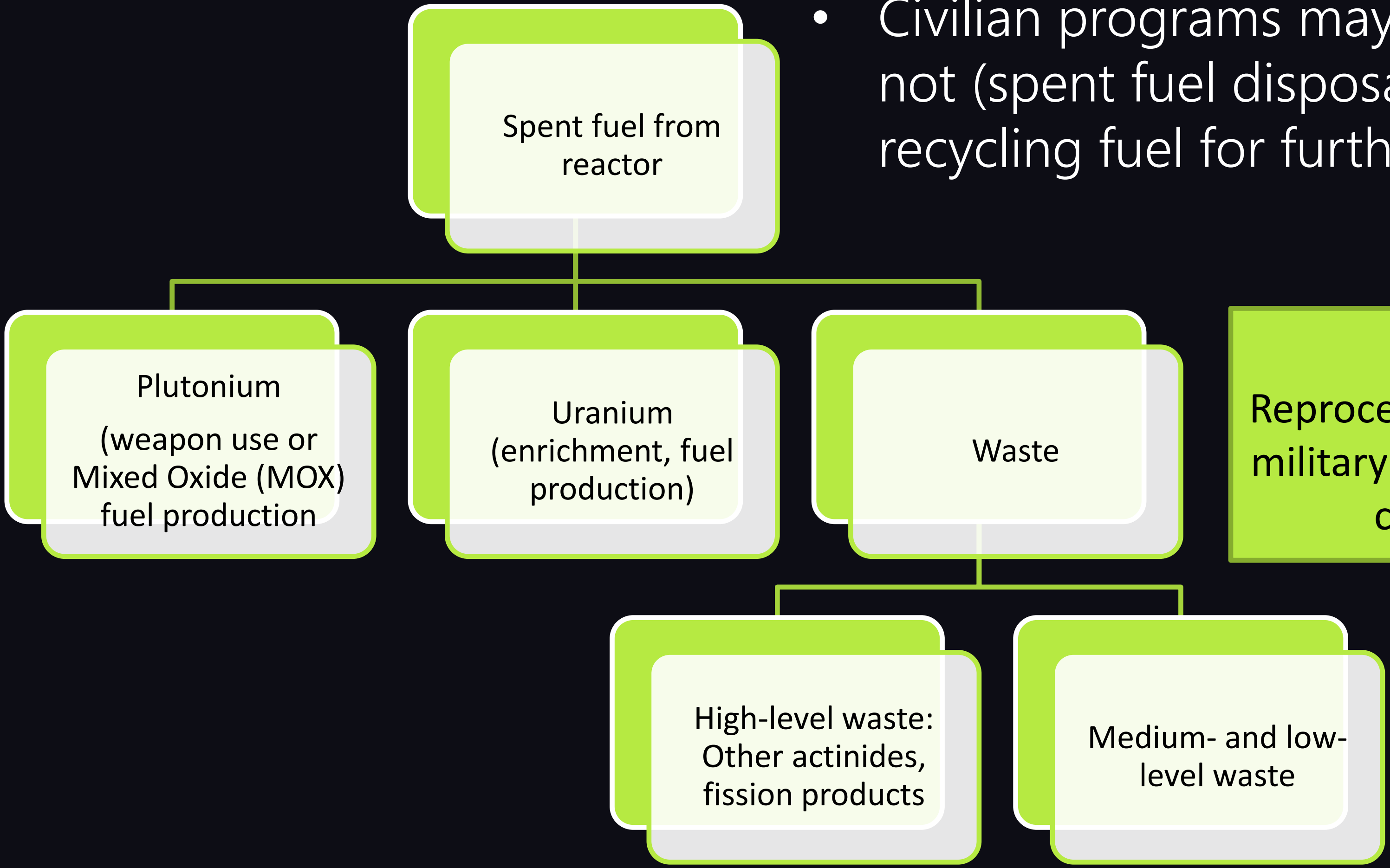


Here: 2400 MW_{therm} reactor
Yongbyon, DPRK: 5 Mw_{el}
Tihange: 3 x ≈ 3000 MW_{therm}

Dual use:
Civilian uses: Nuclear energy, research, medical isotope production
Military plutonium production
→ Reactor design and operation may give indication, but any design/operation is feasible for military purposes

Reprocessing

- Separation by nuclear chemistry
- Civilian programs may reprocess or not (spent fuel disposal or recycling fuel for further use)



Spent fuel from reactor

Plutonium

(weapon use or Mixed Oxide (MOX) fuel production

Uranium (enrichment, fuel production)

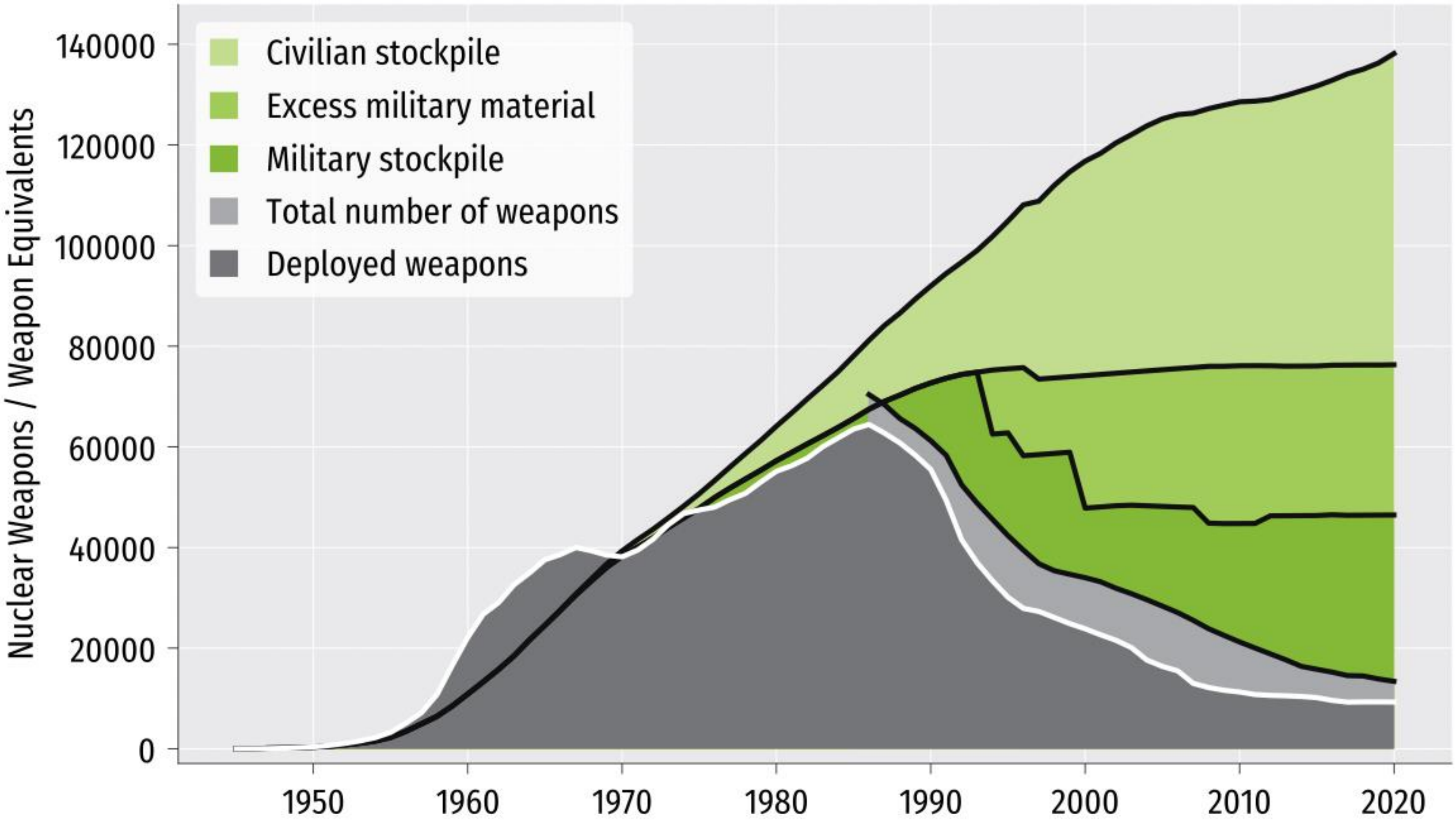
Waste

High-level waste: Other actinides, fission products

Medium- and low-level waste

Dual use:
Reprocessing needed for military use, optional for civilian use

Weapons and plutonium stocks



International Panel on Fissile Materials, Global Fissile Material Report, 2022

Uranium enrichment

AP/Iranian President's Office

Natanz, 2008

Uranium use

- Natural uranium (0.7% U-235)
  - E.g. civilian or military heavy water reactors
- Low enriched uranium, LEU (<20% U-235)
  - E.g. light water reactors (3-5%)
  - Naval fuel (e.g. France)
- Highly enriched uranium, HEU (>20% U-235)
  Weapon-grade uranium (>90% U-235)
  - Research and isotope production reactors
  - Naval fuel (e.g. United States)
  - Nuclear weapons

Dual use:
Different degrees of enrichment used both for civilian and military applications
→ Non-trivial to assess military nature of an enrichment program

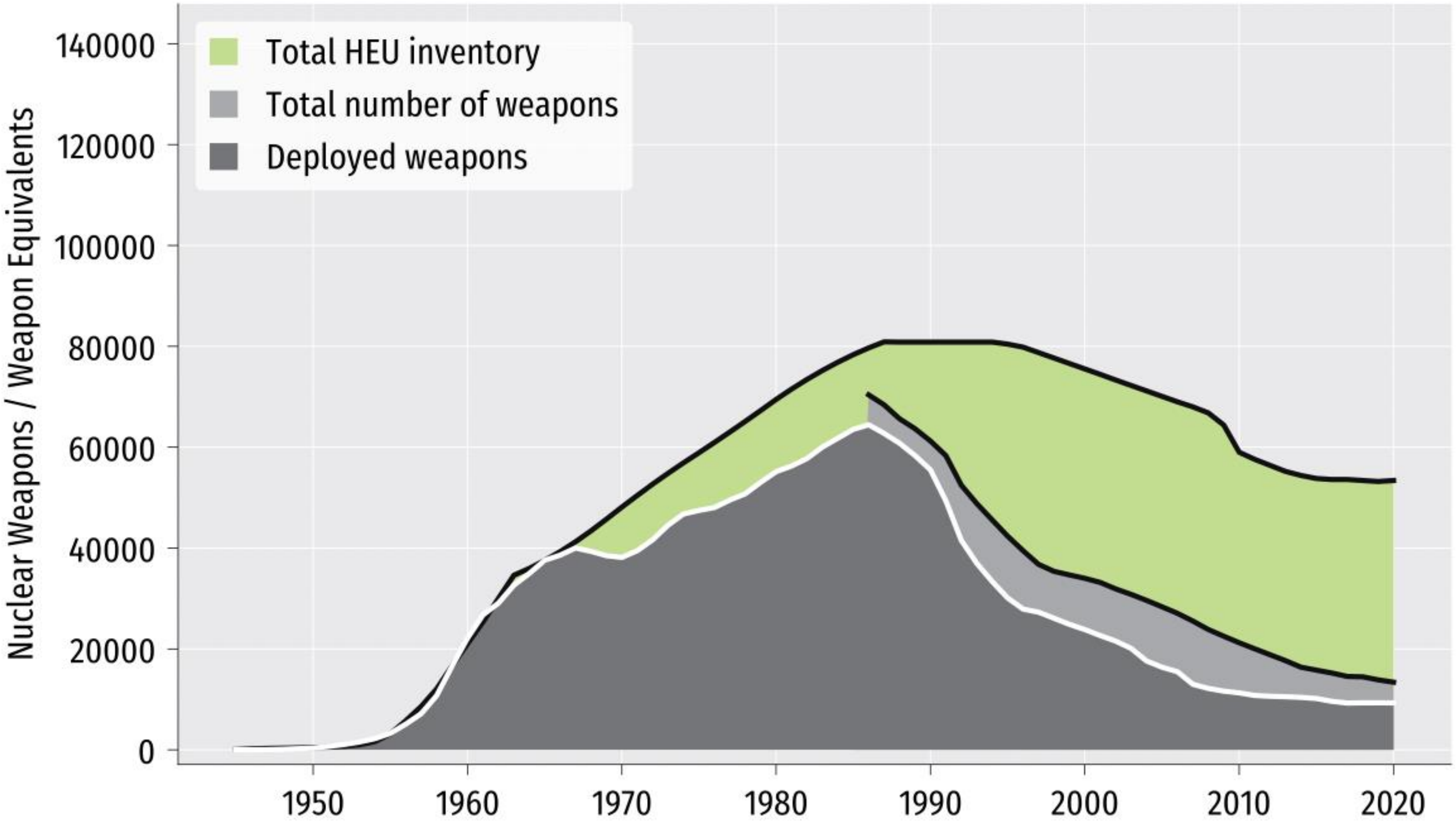
Enriching for one bomb

From natural uranium (0.72% U-235) to 25kg of 93% U-235:

Feed: 4460 kg

Enrichment step	Percent of total kg SWU required	Feed mass required
072% → 3.5%	64%	4460 kg
3.5% → 20%	27%	702 kg
20% → 93%	9%	117 kg

Weapons and HEU stocks



International Panel on Fissile Materials, Global Fissile Material Report, 2022

Emissions from nuclear weapons

Thermal radiation (around 35% for atmospheric explosion)

- Due to the massive energy release, the weapon parts heat up as gas to several tens of million degrees (sun‘s surface: 5000 K, comparable to sun‘s inner temperature)
- Weapon residues radiate x-rays within less than a millionth of a second, absorbed within a few meters
- This leads to the formation of an extremely hot spherical mass of air and gaseous weapon residues („fireball“)
- Fireball grows to over one kilometer in 10 seconds

→ Thermal radiation emitted from it causes skin burns and fires

The Greenhouse George test early fireball, Wikipedia

Emissions from nuclear weapons

Shock wave (around 50% for atmospheric explosion)

- From the rapid weapon explosion: Sudden increase in pressure at the front, gradual decrease behind it (extraordinarily strong winds)

→ Destroying structures, can also be directly lethal

Frame house in 1953 nuclear test, 5 psi overpressure, Wikipedia

Emissions from nuclear weapons

Initial nuclear radiation (around 5% for atmospheric explosion)

- Especially gamma rays, neutrons

Residual nuclear radiation (around 10% for atmospheric explosion)

- Especially beta particles

Emissions from nuclear weapons

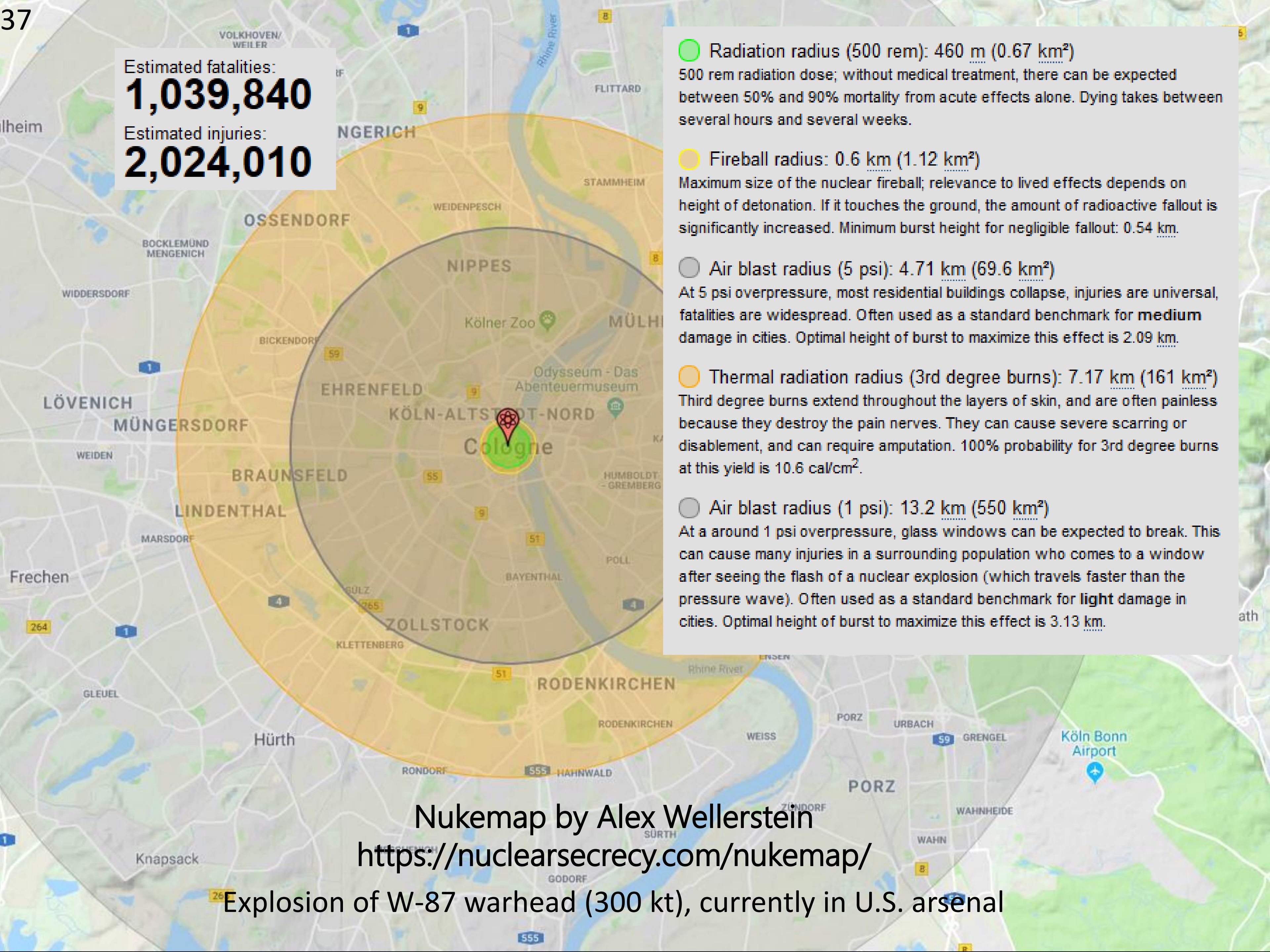
The radioactive „mushroom“ clound

- Fission products, uranium and plutonium, weapon casing and other materials heat up and vaporize
- Upward drag of hot weapon debris, as well as dirt and debris from the earth‘s surface

Emissions from nuclear weapons

Fallout

- When sufficient cooling has occured, the fission products and other radioactive residues become incorporated with the earth particles as a result of the condensation of vaporized fission products into fused particles
- Due to gravity, the contaminated particles gradually descend to earth („fallout“) and contaminates the soil (residual radiation)



Estimated fatalities:
1,039,840
Estimated injuries:
2,024,010

🟢 Radiation radius (500 rem): 460 m (0.67 km²)
500 rem radiation dose; without medical treatment, there can be expected between 50% and 90% mortality from acute effects alone. Dying takes between several hours and several weeks.

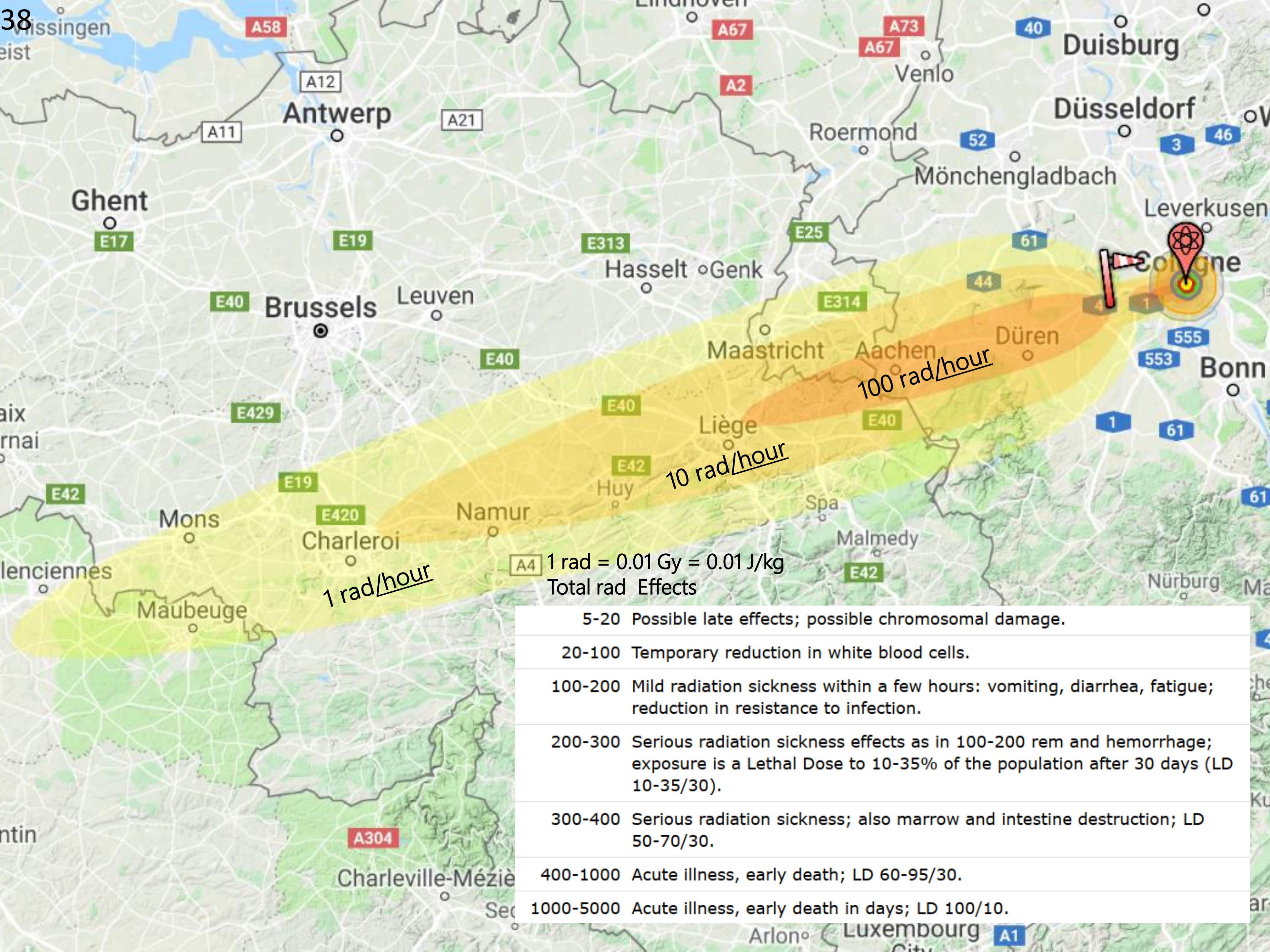
🟡 Fireball radius: 0.6 km (1.12 km²)
Maximum size of the nuclear fireball; relevance to lived effects depends on height of detonation. If it touches the ground, the amount of radioactive fallout is significantly increased. Minimum burst height for negligible fallout: 0.54 km.

⚪ Air blast radius (5 psi): 4.71 km (69.6 km²)
At 5 psi overpressure, most residential buildings collapse, injuries are universal, fatalities are widespread. Often used as a standard benchmark for **medium** damage in cities. Optimal height of burst to maximize this effect is 2.09 km.

🟠 Thermal radiation radius (3rd degree burns): 7.17 km (161 km²)
Third degree burns extend throughout the layers of skin, and are often painless because they destroy the pain nerves. They can cause severe scarring or disablement, and can require amputation. 100% probability for 3rd degree burns at this yield is 10.6 cal/cm^2.

⚪ Air blast radius (1 psi): 13.2 km (550 km²)
At a around 1 psi overpressure, glass windows can be expected to break. This can cause many injuries in a surrounding population who comes to a window after seeing the flash of a nuclear explosion (which travels faster than the pressure wave). Often used as a standard benchmark for **light** damage in cities. Optimal height of burst to maximize this effect is 3.13 km.

Nukemap by Alex Wellerstein
https://nuclearsecrecy.com/nukemap/
Explosion of W-87 warhead (300 kt), currently in U.S. arsenal



100 rad/hour

10 rad/hour

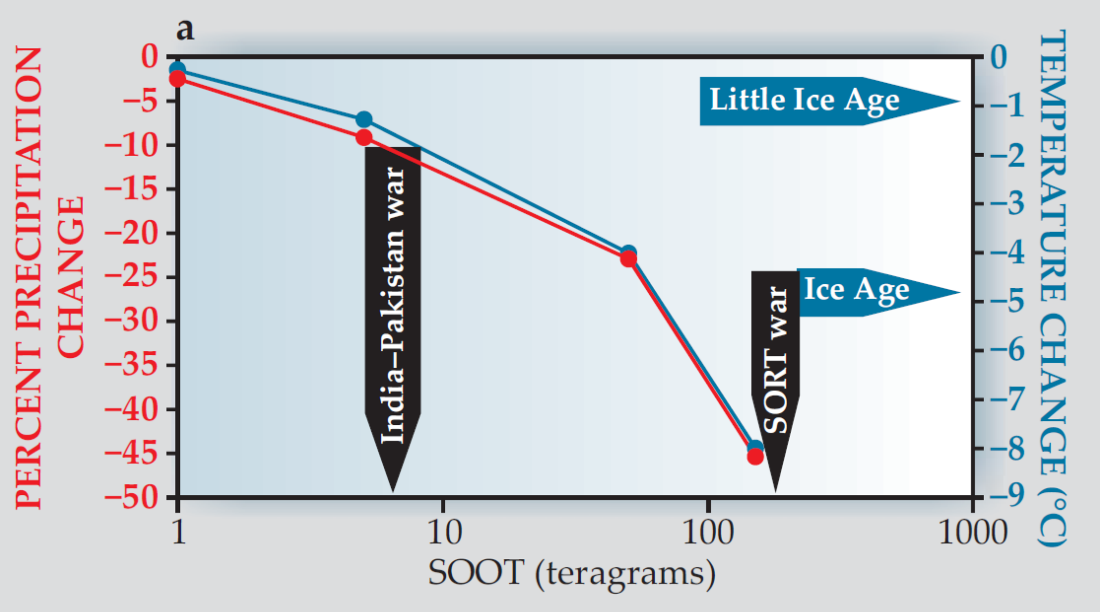
1 rad/hour

1 rad = 0.01 Gy = 0.01 J/kg

Total rad	Effects
5-20	Possible late effects; possible chromosomal damage.
20-100	Temporary reduction in white blood cells.
100-200	Mild radiation sickness within a few hours: vomiting, diarrhea, fatigue; reduction in resistance to infection.
200-300	Serious radiation sickness effects as in 100-200 rem and hemorrhage; exposure is a Lethal Dose to 10-35% of the population after 30 days (LD 10-35/30).
300-400	Serious radiation sickness; also marrow and intestine destruction; LD 50-70/30.
400-1000	Acute illness, early death; LD 60-95/30.
1000-5000	Acute illness, early death in days; LD 100/10.

Nuclear winter

- Soot (German: “Ruß”) from large-area fire is injected into the atmosphere and reaches the stratosphere
- The concentration would be reduced by 1/e in only 5 years → effects for a decade
- Climate models predict
  - Decrease of temperature (SORT scenario: Last ice age) for a decade
  - Decrease of precipitation for a decade
  - Dramatic depletion of ozone layer, loss of protection against ultraviolet radiation
- Profound impact on agriculture (10-100% reduced growing season → food availability
- Such indirect effects of nuclear war would have a global impact, largely outweighing the direct explosion effects.



I-P-Scenario: 1.5 Mt TNT total yield
SORT: 440 Mt TNT total yield

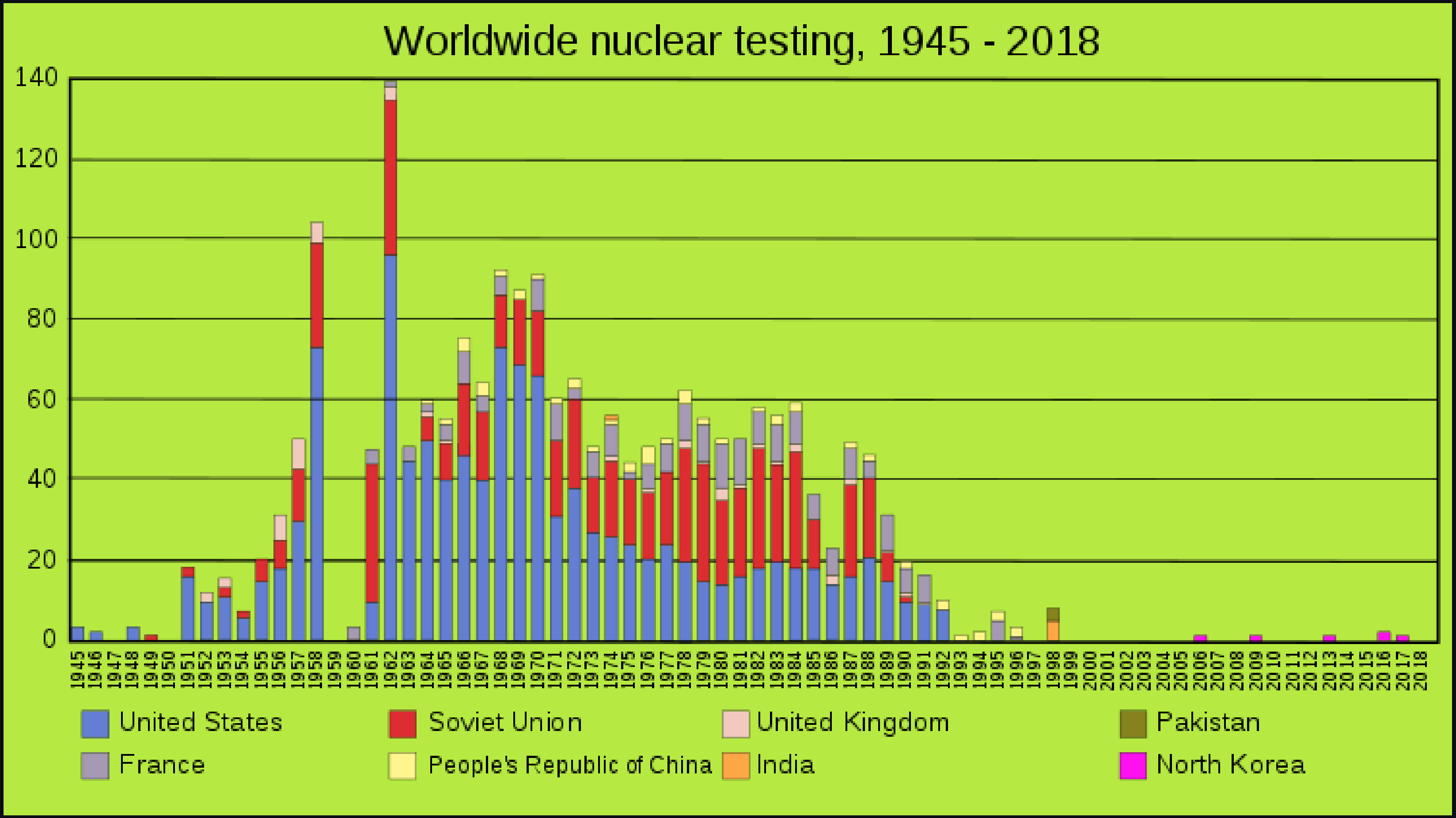
Toon, Robock, Turco, Physics Today, 2008

Weapon tests

Country	Number of tests
United States	1054
Soviet Union	715
United Kingdom	45
France	210
China	45
India	6
Pakistan	6
North Korea	6
Israel	1?

Effective moratorium on nuclear testing (except North Korea)

Weapon tests



Weapon tests

Atmospheric tests, underground tests, underwater tests

Atmospheric test: Operation Greenhouse, Eniwetok-Atoll, 1951

Weapon tests

Atmospheric tests, underground tests, underwater tests

Underground test: Sedan test, Nevada Test Site, 1962

Weapon tests

Atmospheric tests, underground tests, underwater tests

Underwater test: Crossroads Baker, Bikini Atoll, 1946

Local population was evacuated, cannot return until today
due to radioactive contamination