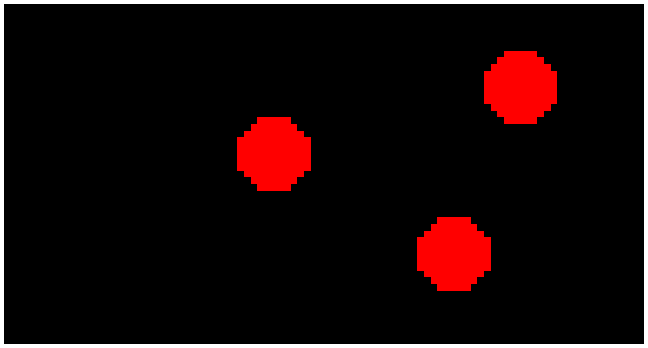
Physics of Nuclear Weapons



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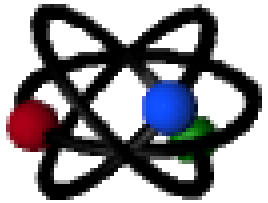
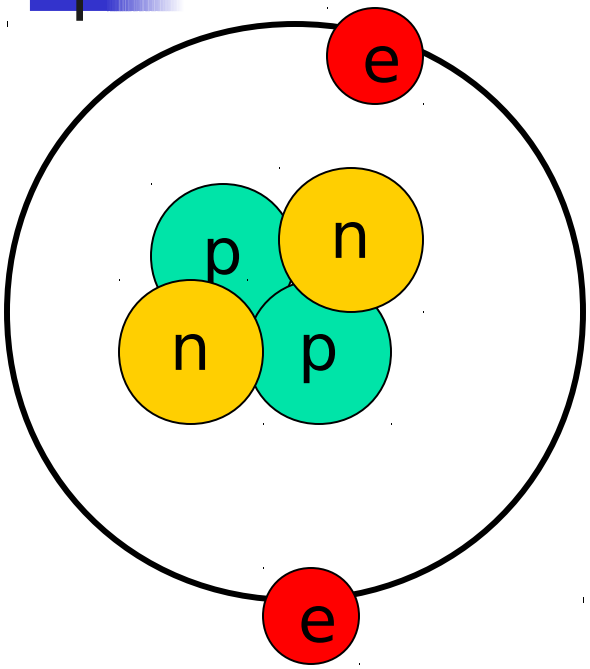
Talk Outline



- Nuclear Weapons
  - Background
  - Nuclear materials Processing
  - Fission Weapons
  - Fusion Weapons
  - Effects
- Proliferation

The Helium Atom



^{4}He

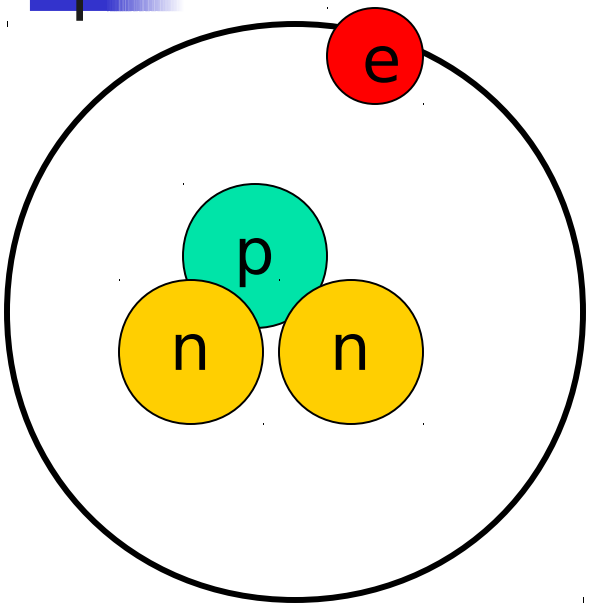
- Two electrons orbiting a nucleus with:

2 protons = Z = atomic number

2 neutrons = N

- Total mass = A = Z+N
- Singly ionized Helium is missing one electron = $^{4}He^{+}$
- Doubly ionized Helium is missing both electrons = α particle = $^{4}He^{++}$

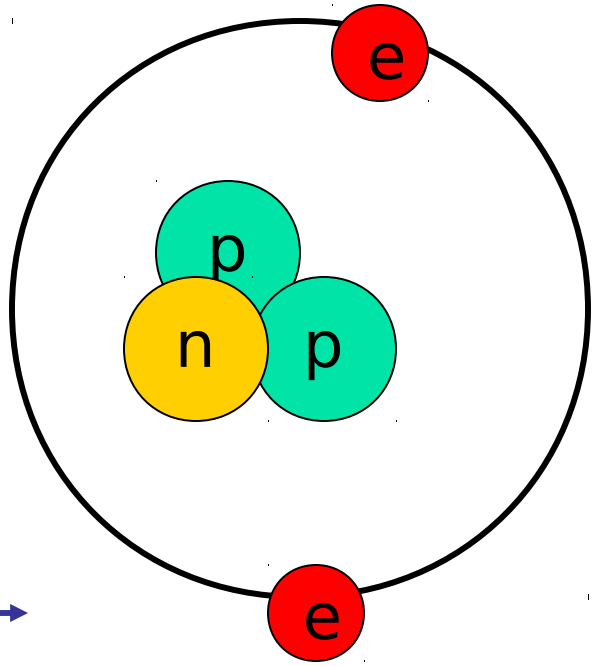
Isotopes and Elements



- If Helium loses an electron & proton, it becomes a different element

^{3}H

$=T$



- If Helium loses one of its neutrons, it becomes an isotope

^{3}He

Materials

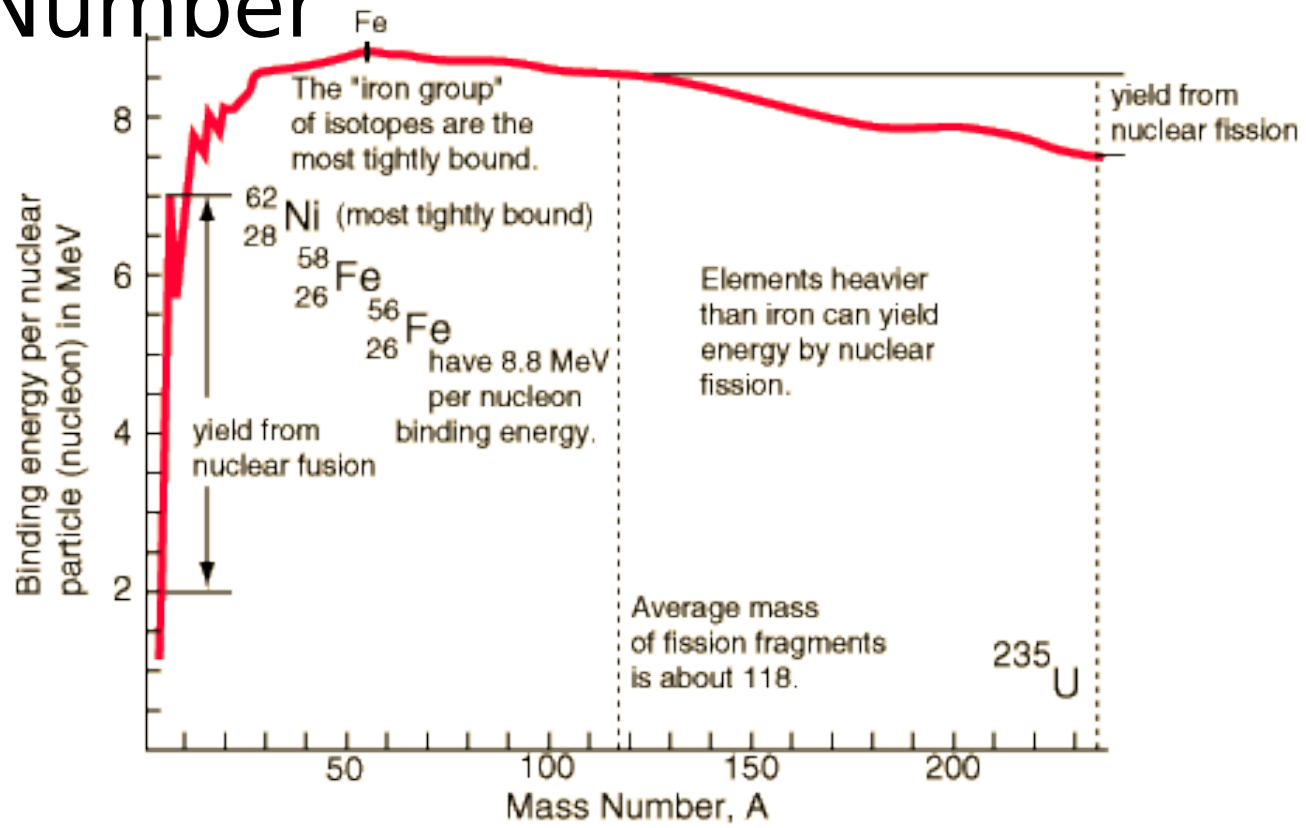
- Tritium = ^{3}H = very heavy Hydrogen (1p + 2n), used in fusion weapons
- Deuterium = ^{2}H = heavy Hydrogen (1p + 1n), used in fusion weapons
- Uranium: ^{238}U is >99% in nature ^{235}U is ~0.7% in nature – major ingredient in fission weapons
- Plutonium: ^{239}Pu is not found in

Radioactivity

- Primordial –
  - formed before Earth's creation
  - long half lives – ^{238}U is 4.5×10^9 y
- Cosmogenic – formed as a result of cosmic ray interactions
  - Examples: ^{14}C (5730 y) and ^{3}H (12.3 y)
- Man-made – typically in power plants or accelerators
  - Examples: ^{239}Pu (2.4×10^4 y) and ^{131}I (8 d) and also ^{3}H (12.3 y)

Fission or Fusion?

- Nuclear binding energy vs. Mass Number



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Uranium processing

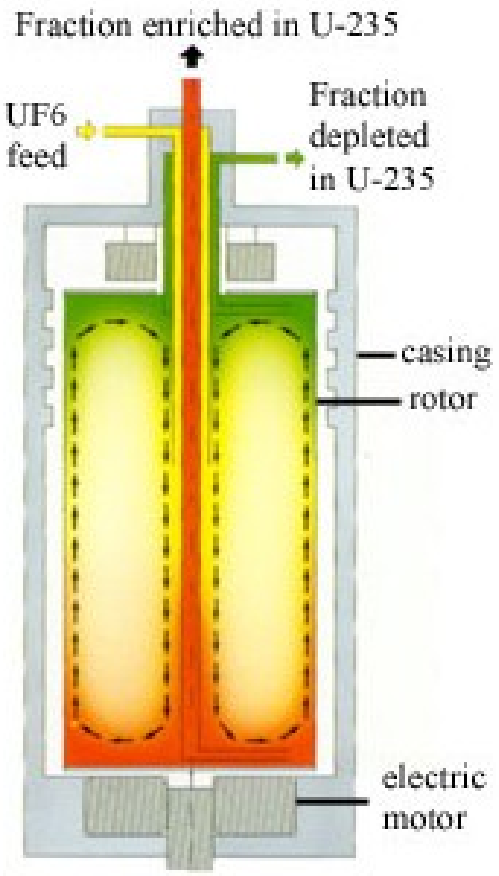
- Uranium is mined as ore from open pits or deep shaft mines, often with the help of extracting solutions
- At nearby mills, ore is crushed and U is extracted, leaving behind radioactive tailings
- Extracted U is then leached (with sulfuric acid) forming a concentrate known as “yellowcake” (aka Uranium oxide)
- Yellowcake is then turned into UF_6 gas, which can be cooled to a solid for easier

Enriching Uranium

- Naturally occurring Uranium must be enriched to >90% ^{235}U in order to make fission weapons (or to ~5% for nuclear power plants)
- Enrichment methods
  - Gas centrifuge (now under construction in Iran and formerly found in Iraq)
  - Gaseous diffusion (used in USA)
  - Electromagnetic isotope separation – uses strong magnetic field to deflect ions of lighter isotope farther than

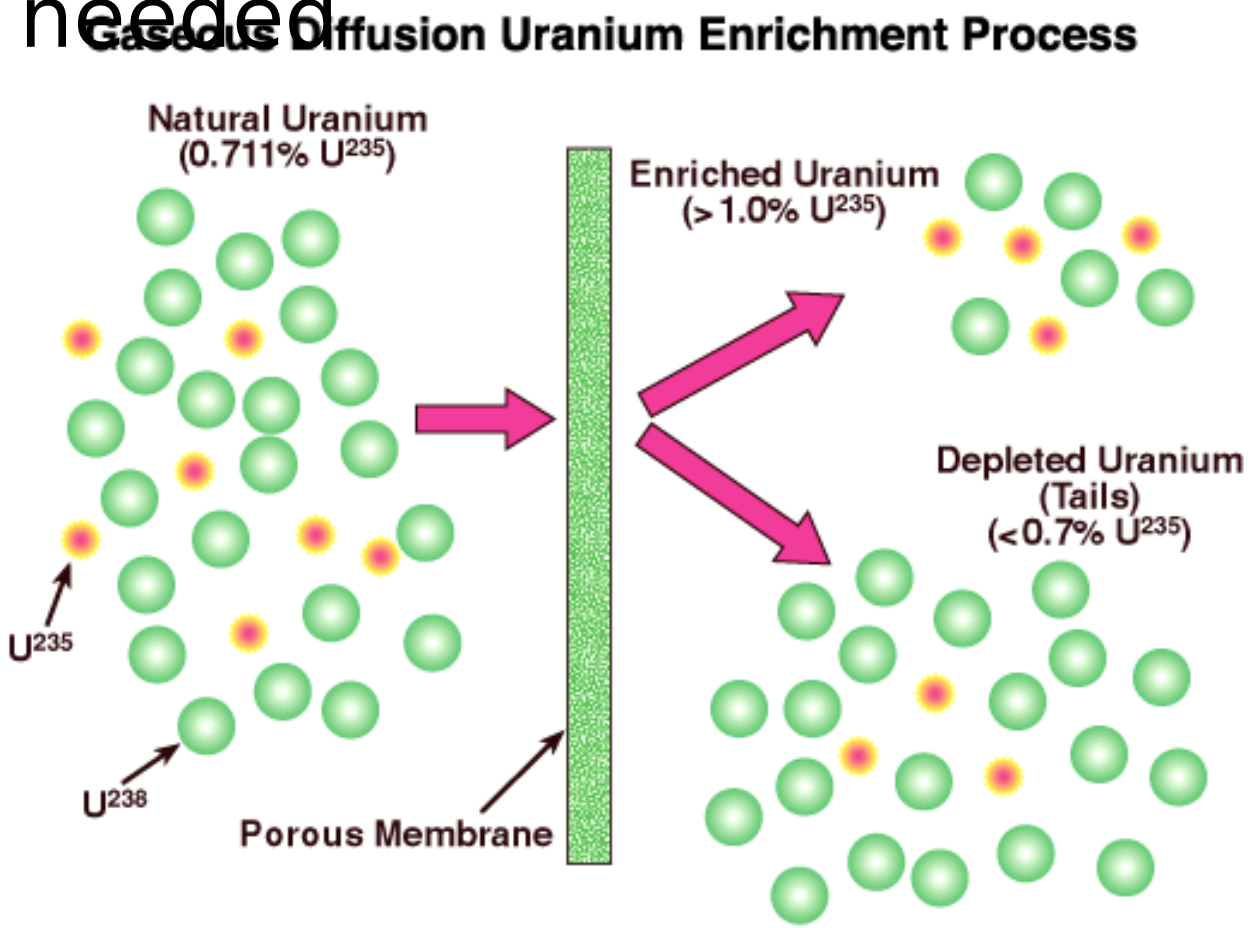
Gas centrifuge

- Uses successive stages to isolate isotopes by weight – lighter mixture is sent on to the next stage, heavier mixture is sent back to the previous stage
- Requires thousands of successive stages to create weapons grade ^{235}U



Gaseous diffusion

- Thousands of diffusion filters needed



Electromagnetic isotope separation

- Iraq's extensive EMIS program was unknown until its discovery after the Gulf War by UN inspectors
- Several unreported and disguised facilities were found, capable of creating quantities of weapons grade U
- Huge power requirements for EMIS have precluded use in USA – and were thought to preclude use by others

Depleted Uranium

- After isotope separation, the remaining ^{238}U is said to be “depleted” as it is missing ^{235}U – however, ^{238}U is still naturally radioactive
- Uranium is a very dense metal (1.7 x Pb), making it ideal for use in armor and shell casings
- Uranium is pyrophoric – friction causes it to burn
- The USA used depleted Uranium weapons in the Persian Gulf War (1991), in Bosnia (1995) and Kosovo (1999)
- Various health problems have been associated with the inhalation of vaporized

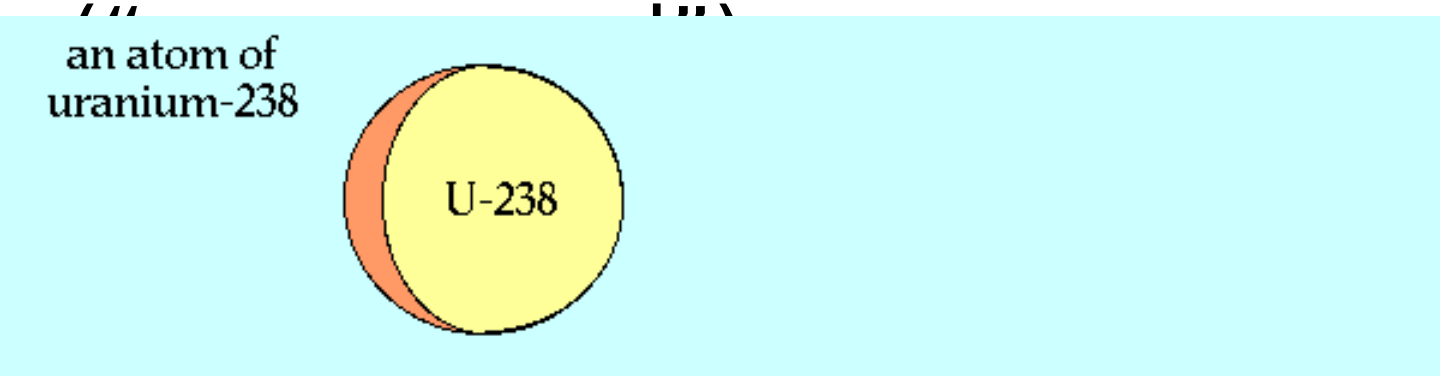
Depleted Uranium

- Depleted Uranium can be put into fuel cells in a nuclear reactor and used to produce weapons grade ^{239}Pu
- This is why Israel bombed the French-built OSIRAK nuclear reactor in Iraq in 1981

Targets made of depleted U which will be bombarded by neutrons to make Pu

Reprocessing Plutonium

- ^{239}Pu is a waste product in nuclear power reactors, that is intermixed with other spent reactor fuels
- In order to become weapons grade, it must be separated out

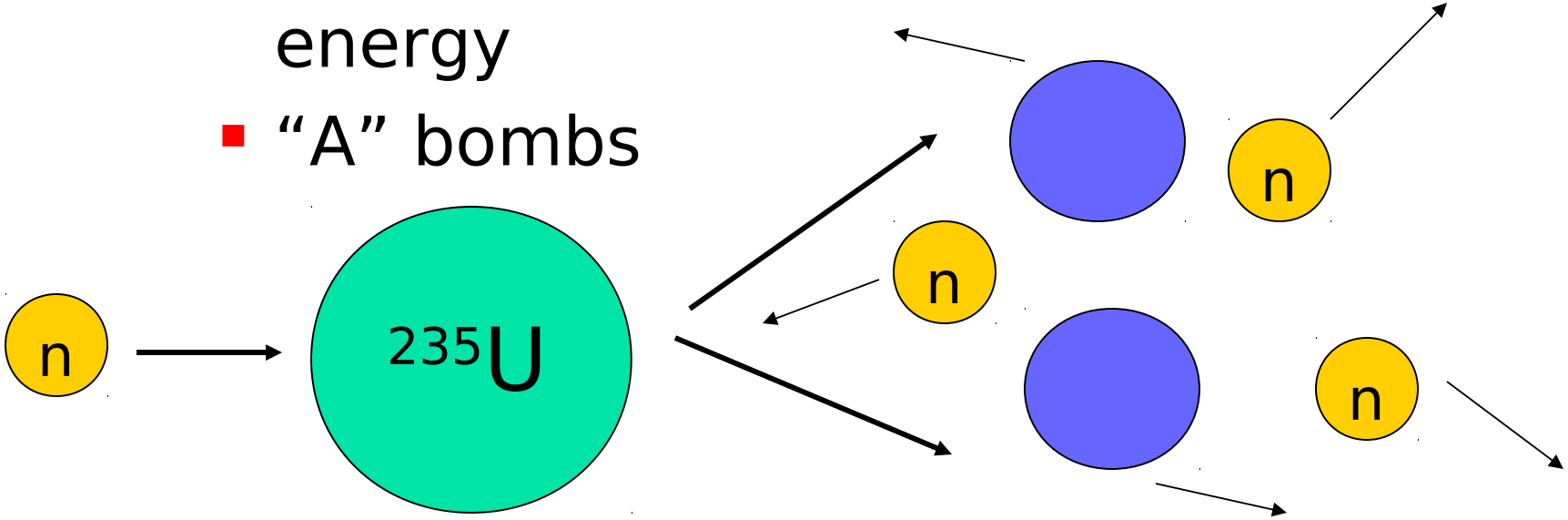


Reprocessing Plutonium

- Spent reactor fuel is chopped up, by remote control, behind heavy lead shielding.
- Chopped-up pieces are then dissolved in boiling nitric acid, releasing radioactive gases in the process.
- Pu is chemically separated from the acid solution, leaving large quantities of high-level radioactive liquid waste and sludge behind.
- After it has cooled down for several years, the liquid waste is solidified for ultimate disposal, while the separated

Fission Weapons

- Fission
  - releases energy in elements heavier than Iron
  - Bombard ^{235}U or ^{239}Pu with neutrons, they split into fragments, releasing energy
  - “A” bombs



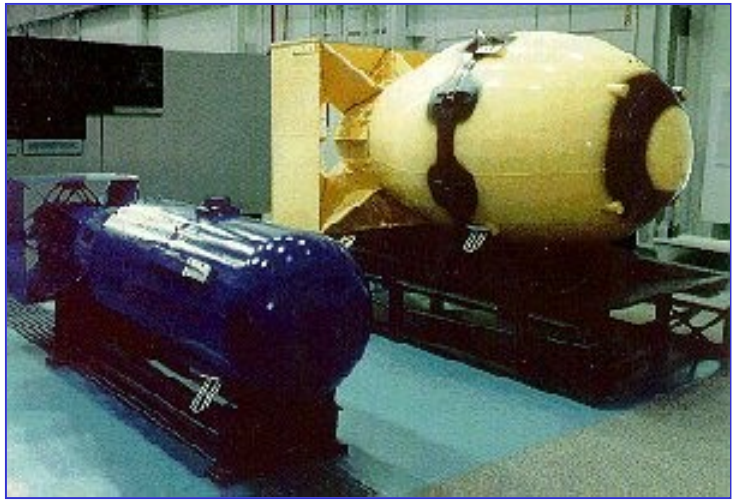
Critical mass → chain reactions

- When a large enough mass of either ^{235}U or ^{239}Pu is assembled, a self-sustaining chain reaction results after the first fission is produced.
- The minimum (“critical”) mass of fissile material that can sustain a nuclear chain reaction depends on the density, shape, and type of fissile material, as well as the effectiveness of any surrounding material (called a reflector or tamper) at reflecting neutrons back into the fissioning mass.
- Depleted U is often used in the tamper

The first “A” bombs

- Trinity – Gadget (7/16/45)
  - Alamagordo test range in New Mexico
  - 20 kTon yield
- Little Boy (8/6/45)
  - Hiroshima
  - 15 kTon yield
- Fat Man (8/9/45)
  - Nagasaki
  - 20 kTon yield

Museum display in NM



How to make an A-bomb

- Use highly enriched ^{235}U (>80%)
- Use initial explosive device to trigger
- Combine two sub-critical masses
- Reflect neutrons back into ^{235}U

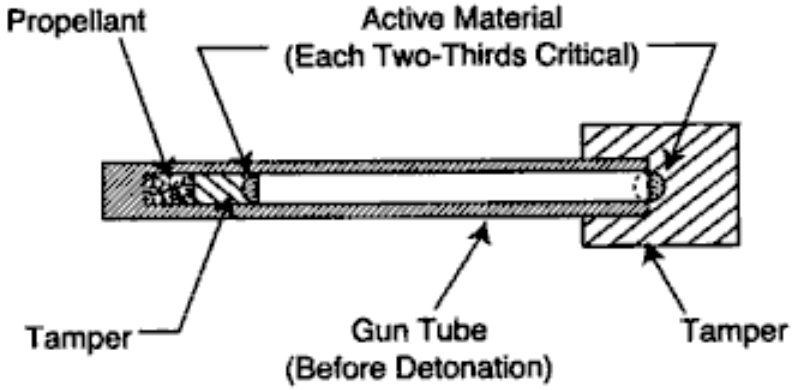
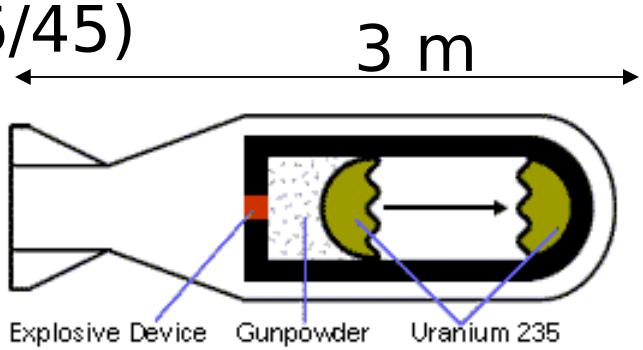


Figure 2-VII. Gun Assembly Principle

Little Boy (Hiroshima 8/6/45)



“Fat Man” style of A-bomb

- High explosives are arranged to form an imploding shock wave which compresses the fissile material to supercriticality

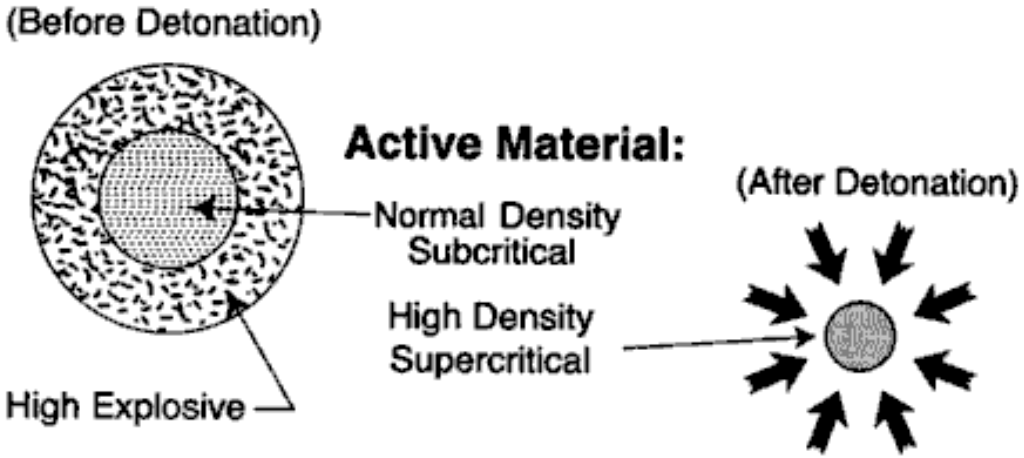
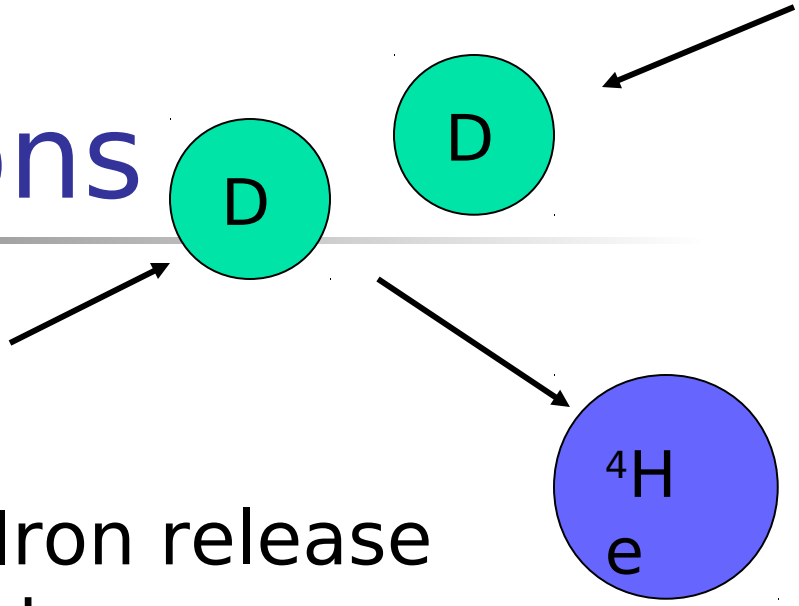


Figure 2-VIII. Implosion Assembly Principle

- Burst of neutrons from generator is timed for moment of maximum compression

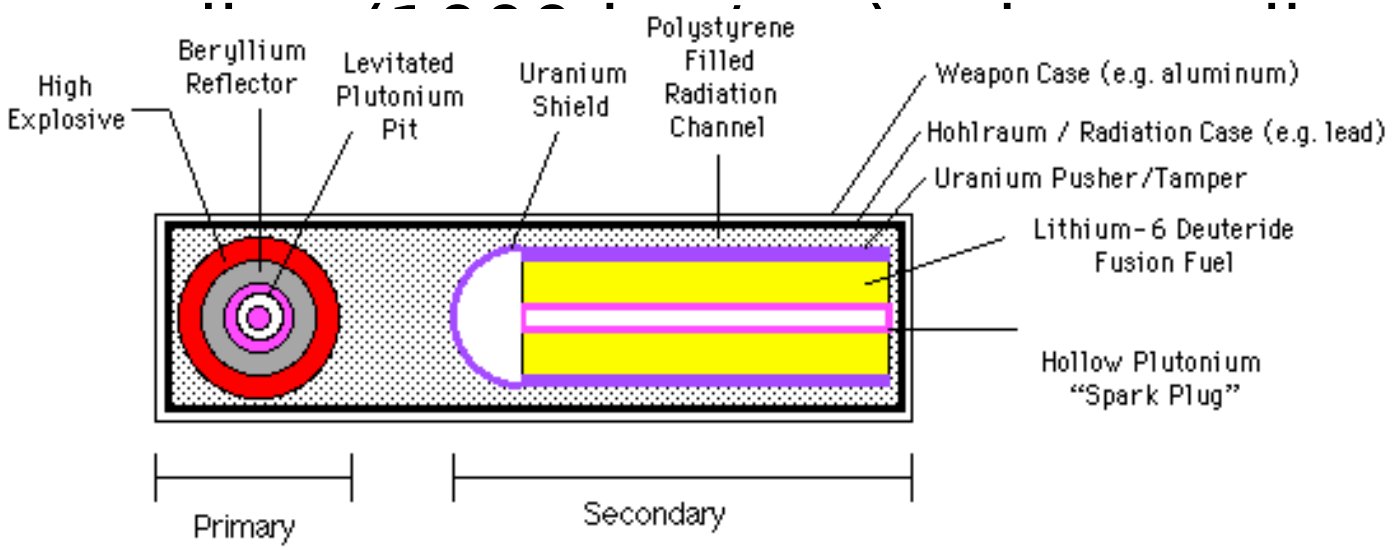
Fusion Weapons



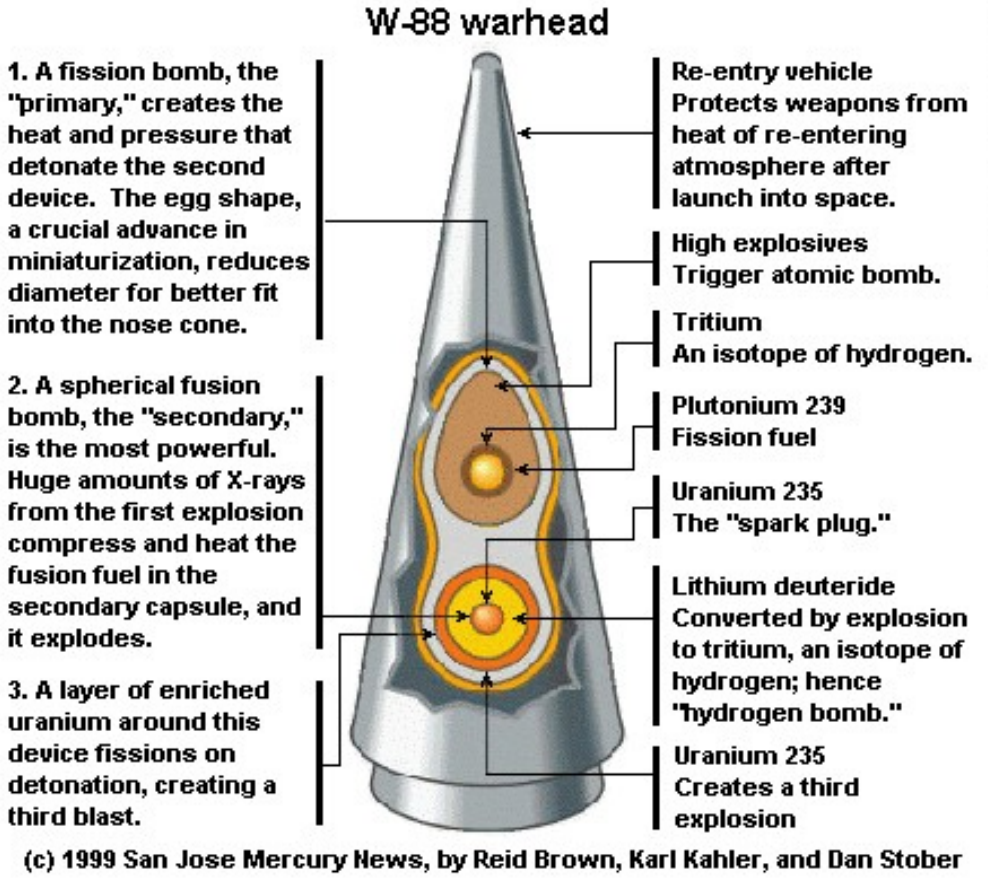
- Fusion
  - Elements lighter than Iron release energy when combined
  - Deuterium, Tritium, Lithium Deuteride
  - Reactions that occur inside Sun
  - “H” bombs
- Thermonuclear Reactions
  - Heat from reaction increases reaction rate, so less fuel is needed → “efficient” bomb

The "secret" of the H-bomb

- At the high temperatures of a fission bomb 80% or more of the energy exists as soft X-rays
- The X-rays heat a polystyrene channel, causing plasma which can compress and ignite the second (fusion) stage before the e[illegible]upts it



Fusion weapons design



Published due to Wen Ho Lee case

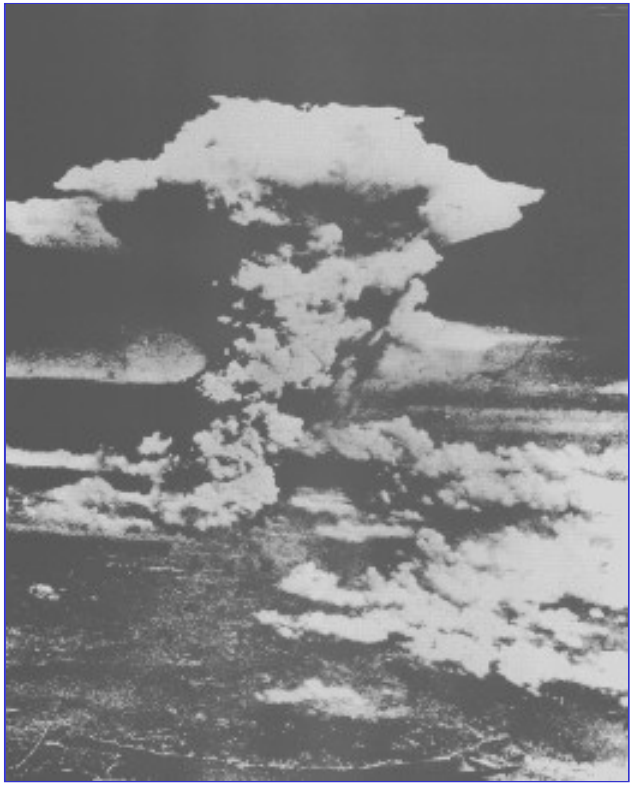
http://www.fas.org/sgp/eprint/morland.html

Weapons design considerations

- Fission bombs produce 90% of their output as KE of fission fragments → fast heat production
- Fusion bombs produce 80% of their output as fast neutrons with <KE> = 14 MeV
- Fast neutrons can produce a fission event of KE=180 MeV, boosting the bomb's "efficiency"
- Most modern weapons therefore consist of at least two stages
  - Primary – fission bomb, often boosted by fusion core produced neutrons
  - Secondary – fusion bomb, with fission "sparkplug" to produce heat that triggers

Why is an atomic bomb so much worse than a TNT bomb?

- Amount of heat and light energy released is ~10^3 times greater
- Explosion is accompanied by invisible, penetrating and harmful radiation
- After explosion, radioactive fallout remains and continues to damage living things for days → weeks → years



Ground level view of Hiroshima cloud

Physical Effects of Nuclear Weapons

- Thermal
  - Fireball → Firestorms
  - Mushroom Cloud
- Initial (prompt) Radiation
  - Alpha particles ($^{4}He^{++}$)
  - Beta particles (e^{+} and e^{-})
  - Gamma-rays (γ)
  - Neutrons (n)

http://nuketesting.enviroweb.org/

Trinit

Bridge in Hiroshima

Physical Effects of Nuclear Weapons

- Pressure Blast Wave
  - Buildings collapse
- Fallout
  - Radioactive fragments which stick to air particles or dirt that is sucked up mushroom stem
  - 80% falls back down in first day
  - 90% falls back down in first week
  - 10% lasts weeks → years

Hiroshima ground

Nagasaki victim

Nagasaki videos

- Nagasaki fireball and early mushroom cloud as seen from an observation plane

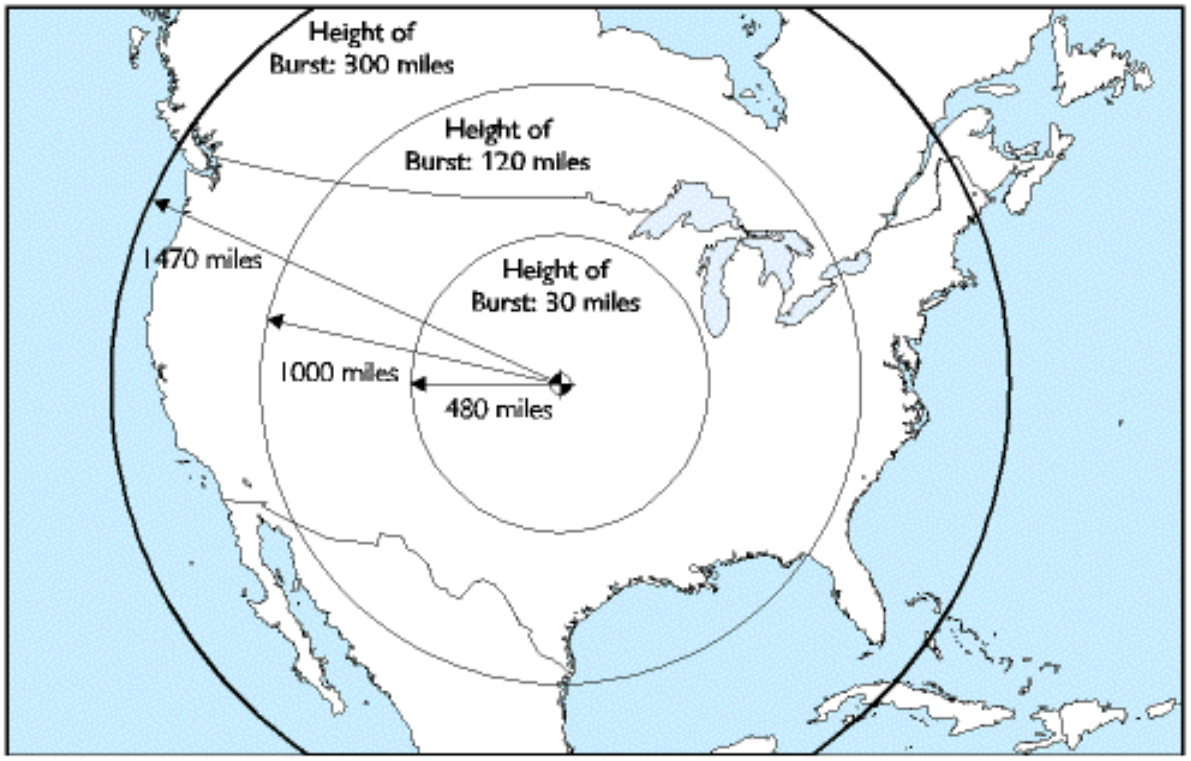
- Later mushroom cloud as seen from an observation plane

- Clips are from *The Atom Strikes*, a movie by the U.S. Army Signal Corps

Physical Effects of Nuclear Weapons

- Electromagnetic Pulse
  - Strongest for very high bursts
  - γ–rays ionize air → electrons
  - Electrons create large currents in air
  - Currents are picked up by power lines
  - Power surges shut down grid, destroy attached electrical devices
- 1.4 Mton airburst in 1962 knocked out lights in Hawaii over 1000 miles away

Electromagnetic Pulse Effects



Area Effected by an Electromagnetic Pulse, by Height of Burst

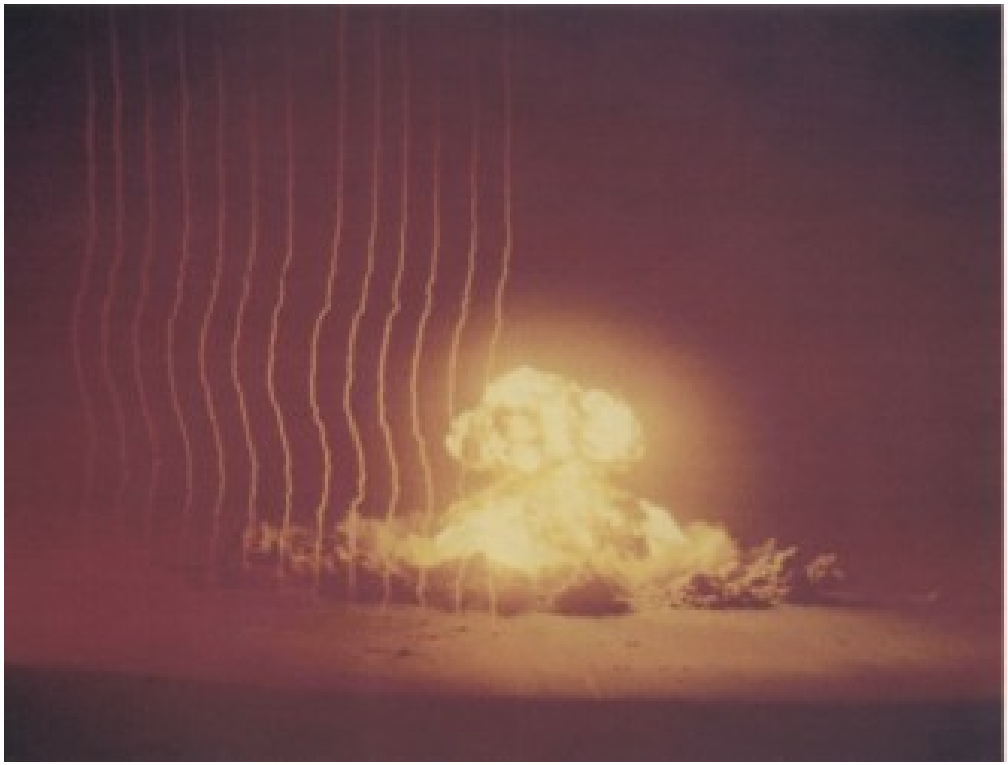
Source: Gary Smith, "Electromagnetic Pulse Threats," testimony before the House National Security Committee, July 16, 1997.

http://www.heritage.org/library/backgrounder/bg1372.html

Smoke trails

- Smoke trails from rockets are used to record the location of the shock front as a function of space and time

- The passage of the shock front through the grid of smoke trails is used to calculate the shock velocity and



http://gawain.membrane.com/hew/Usa/Tests/SmokeTrails.html

Other bomb designs

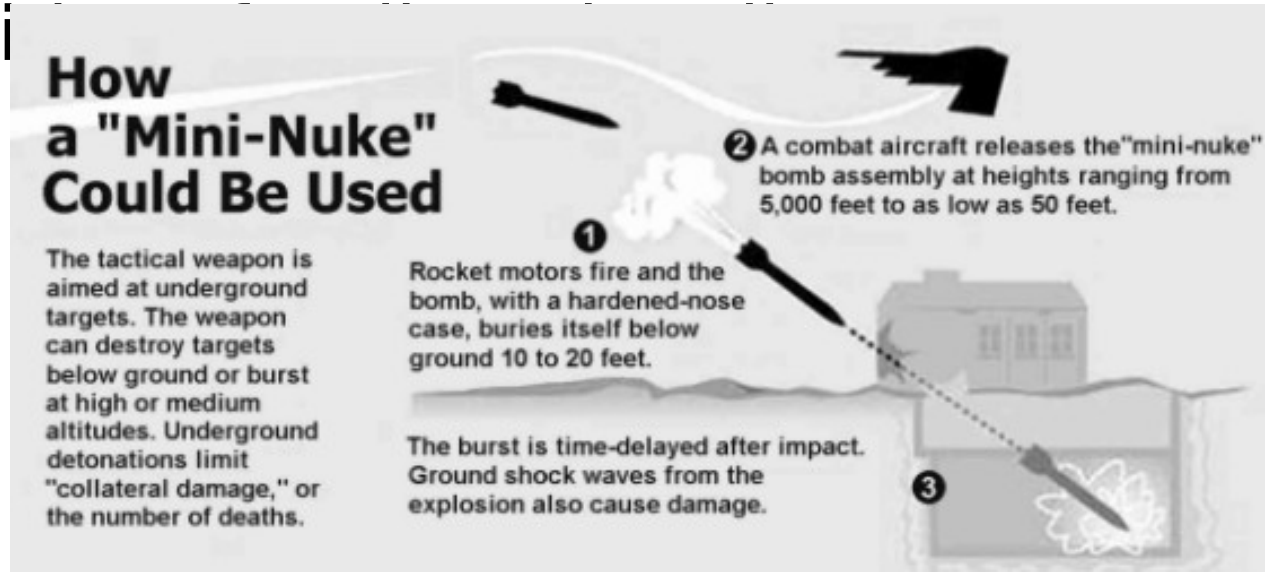
- Neutron bombs
  - Also known as “enhanced radiation” weapons
  - Designed to lower blast wave, thus sparing buildings, but killing people
  - However buildings do become radioactive
- “Clean” bombs
  - Designed with more fusion, and less fission, → more neutrons and less fallout
  - Needed three stages for sufficient

How big are the weapons?

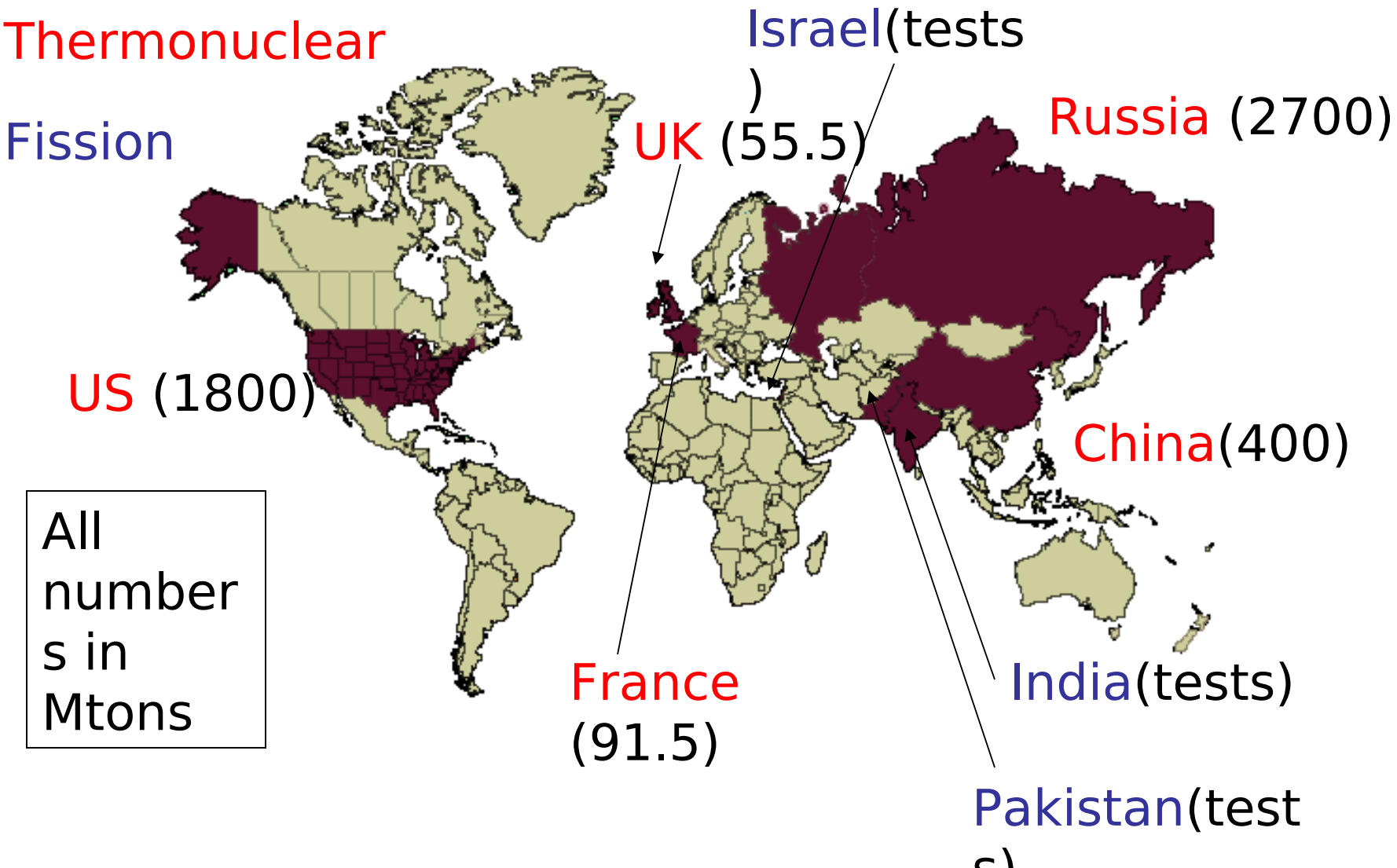
- 1 kTon = 1000 tons = 2,000,000 pounds of TNT equivalent
- 1 kTon = 4.2×10^{12} J
- ~2 pounds of ^{235}U → 20 kTons
- MX missiles have 10 x 300 Kton W87 warheads (ICBM)
- W88 has 475 kTon yield (SLBM)
- Largest underground burst: 4.5Mtons
- Largest airburst: 58 Mtons
- Over 1700 known tests since 1945

Low Yield Nuclear Weapons

- Designed to “threaten hard and deeply buried targets."
- Despite claims to produce less fallout due to underground explosion, a 5 kTon weapon would produce considerable quanti

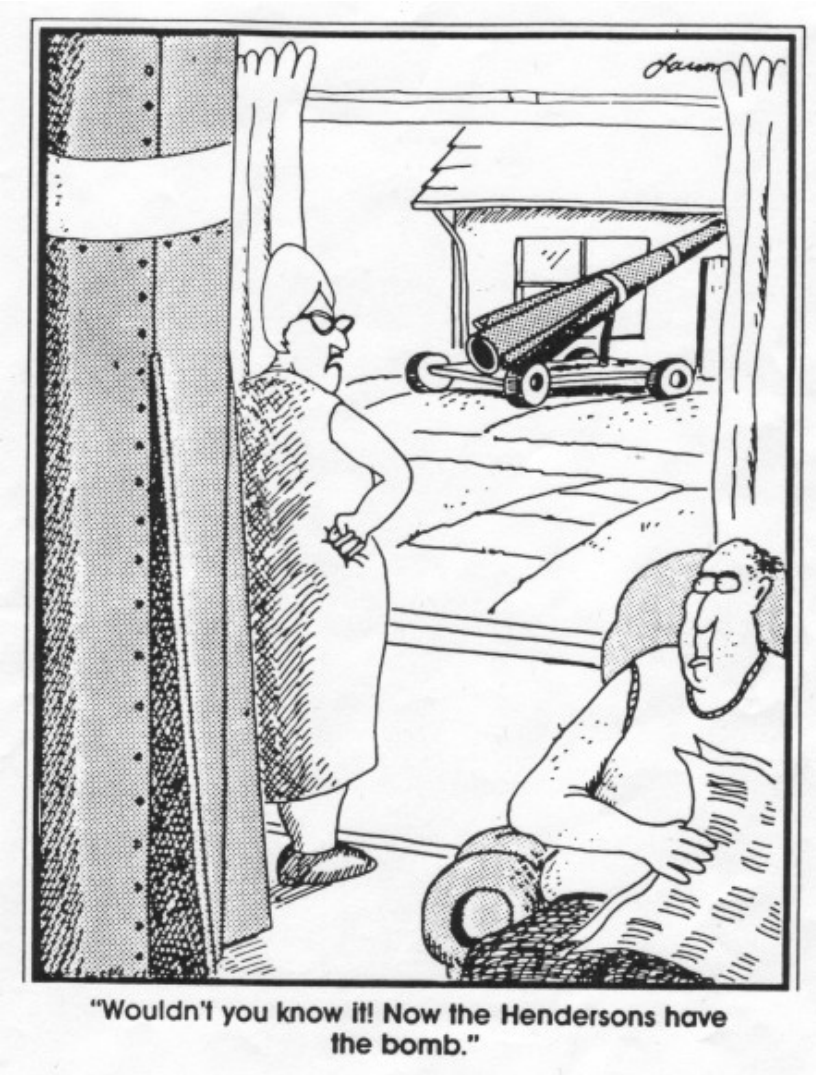


Who has nuclear weapons?



Who still wants nuclear weapons?

- North Korea (may have ~2 untested)
- Iraq
- Iran
- Libya
- Algeria
- Syria
- All subject to severe constraints



No longer on the “watch” list

- S. Africa
  - Eliminated 6 weapons in 1991
  - Formal renunciation of use
- Have backed away or renounced use:
  - Argentina
  - Brazil
  - Romania
  - Taiwan
  - Belarus
  - Ukraine
  - Kazakhstan

Nuclear Non-Proliferation Treaty

- Vertical – development of new weapons by the “Big 5”
- Horizontal – spread of weapons to other countries
- “Haves” agree not to spread weapons, materials or technology to “have-nots” – also, to stop vertical proliferation
- “Have-nots” agree not to try to acquire weapons from the “haves,” and will accept inspection and regulation of “peaceful” nuclear technology by IAEA- this stops horizontal proliferation

Nuclear Non-Proliferation Treaty

- NPT indefinitely extended since May 1995, confirmed again in 2000
- Now signed by 187 countries
- In 1994, North Korea affirmed its signature, and agreed to allow IAEA inspections
- On 1/10/03, N. Korea withdrew from NPT, blaming US “axis of evil” designation, and US first strike intentions. N. Korea is now moving spent nuclear fuel to its reprocessing plant to begin Pu production
- Cuba, Israel, India and Pakistan still

Comprehensive Test Ban Treaty

- Prohibits all nuclear testing
- Opened for signatures in 1996
- Prevents “Big 5” from developing or testing weapons of new design
- Approved by Russian Duma in 4/00
- Rejected by US Senate in 10/99
- Signed by 155 states, ratified by 55
- Needs ratification by 16

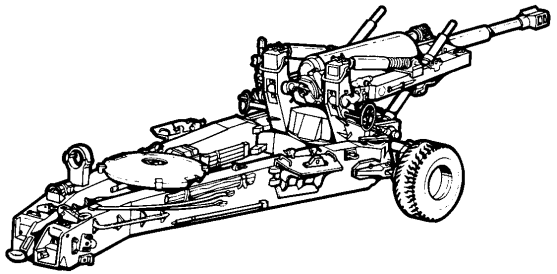
Ballistic Missile Defense

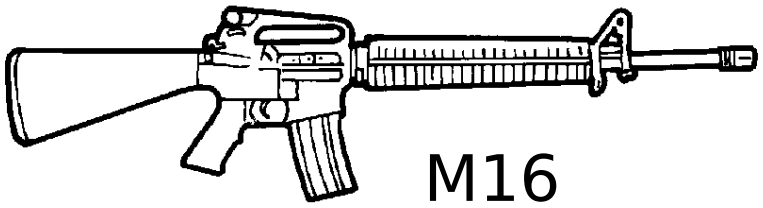
- Idea revived in 1980s as “Strategic Defense Initiative” (SDI) or “Star Wars”
- APS study of the “feasibility of lasers or particle beams as a defense against ballistic missiles” concluded (in 1987) that “at least ten years of research would be required to provide the technical information required to make an informed decision about the effectiveness and survivability of such weapons.”
- BMD research funded by Congress in 1999
- USA unilaterally withdraws from Anti-Ballistic Missile (ABM) treaty in 12/01

Major killers in Wars

- Assault Rifles (64%)
- Handguns (10%)
- Landmines (10%)
- Hand grenades, Artillery, Mortars (16%)
- Since 1900: 34 million soldiers and 80 million civilians killed in wars

Howitzer





M16

killed 200,000

total.

Additional Resources

- Carnegie Endowment for International Peace http://www.ceip.org/
- National Regulatory Council http://www.nrc.gov/
- Institute for Science and International Security http://exportcontrols.org
- Federation of American Scientists http://www.fas.org/index.html
- High Energy Weapons Archive http://gawain.membrane.com/hew/

Additional Resources

- Canadian Coalition for Nuclear Responsibility http://www.ccnr.org/
- Monterey Institute of International Studies – Center for Nonproliferation Studies http://cns.miis.edu/research/korea/outnpt.htm
- Cirincione, Joseph with Jon Wolfsthal and Miriam Rajkumar, Deadly Arsenals: Tracking Weapons of Mass Destruction (Washington DC: Carnegie Endowment for International Peace, 2002)
- Richard Garwin archive http://www.fas.org/rlg/