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# How Nuclear Bombs Work

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IGA-232: Controlling the World's Most Dangerous Weapons

Harvard Kennedy School

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# The Trinity test: July 1945

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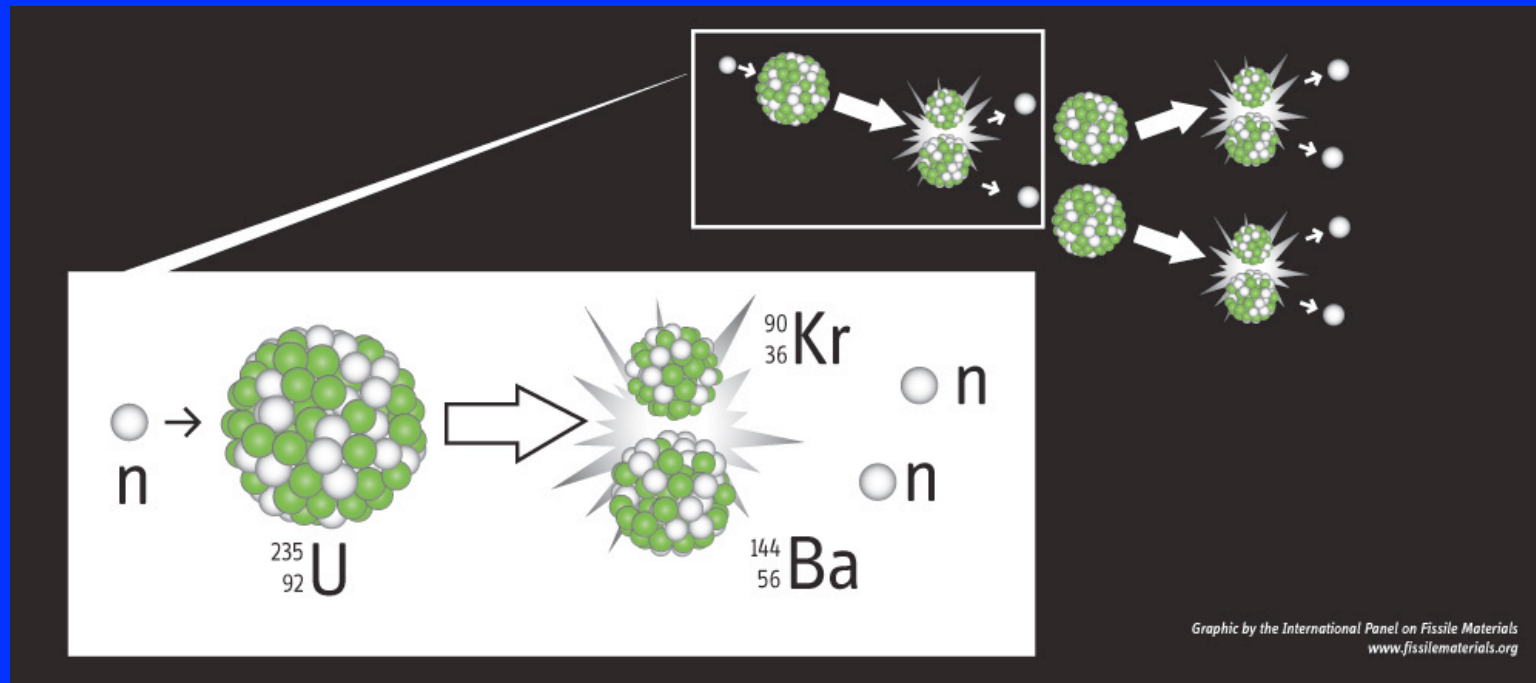
Source: Los Alamos

# Agenda

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- ◆ How nuclear bombs work
  - Fission -- Critical mass – ways to achieve it
  - Gun-type and implosion-type bombs
  - Fusion bombs
- ◆ Nuclear materials
  - Plutonium, HEU
  - Weapon-grade, weapon-usable
- ◆ What are the hard parts
  - Design
  - Casting, machining, assembling, etc.
  - Difference between crude terrorist bomb and state weapon
- ◆ Nuclear weapons effects
  - Fireball, blast, heat, radiation...
  - Dependence on explosive yield

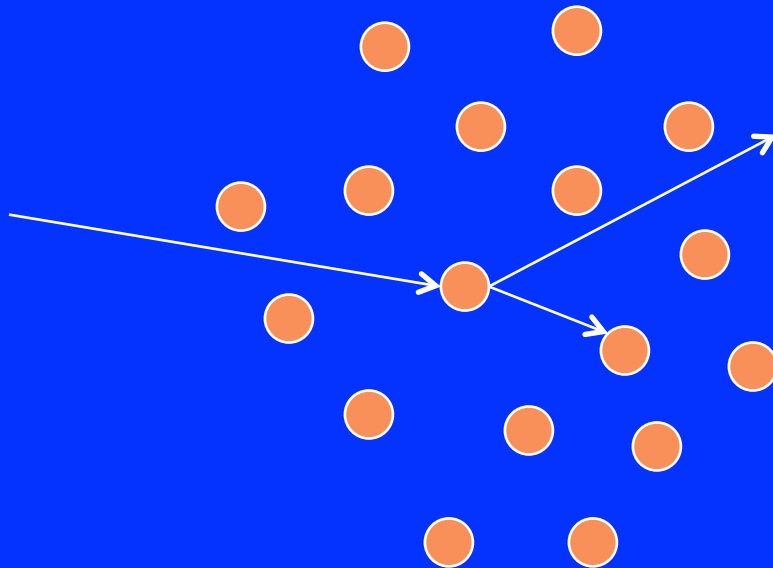
# Nuclear fission: a lot of energy from a little material



- ◆  $\approx 200$  million electron volts (MeV)/fission
  - $\approx$  million times more than chemical reactions
  - Energy for bombs, or for civilian power
- ◆ Can generate huge amounts of energy (and toxicity) in a small space with a modest amount of material
  - Source of safety, security issues for nuclear power

# Fission in a sub-critical mass

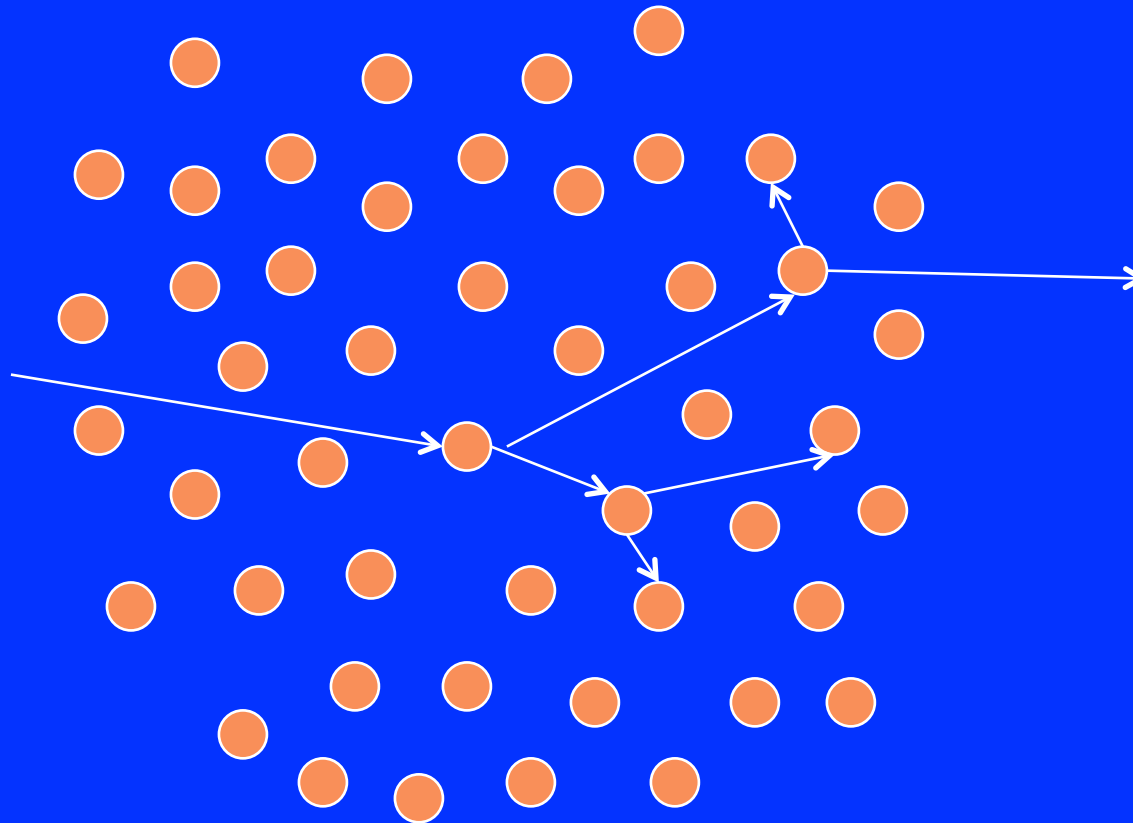
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The neutrons are leaking out and stopping the chain reaction. How would a bomb-maker fix this problem?

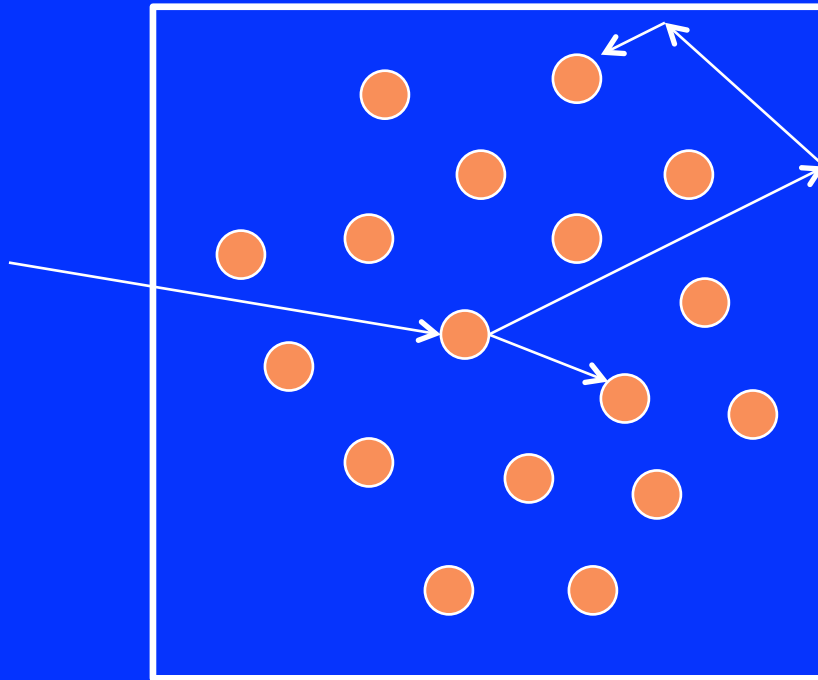
# Solution 1: add more material

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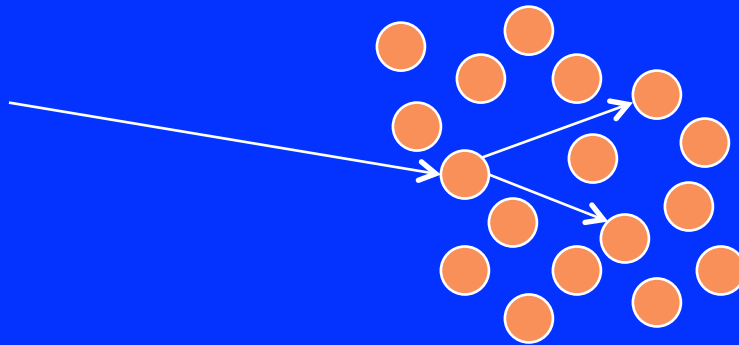
## Solution 2: reflect the neutrons back in

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## Solution three: get the atoms closer together (increase density)

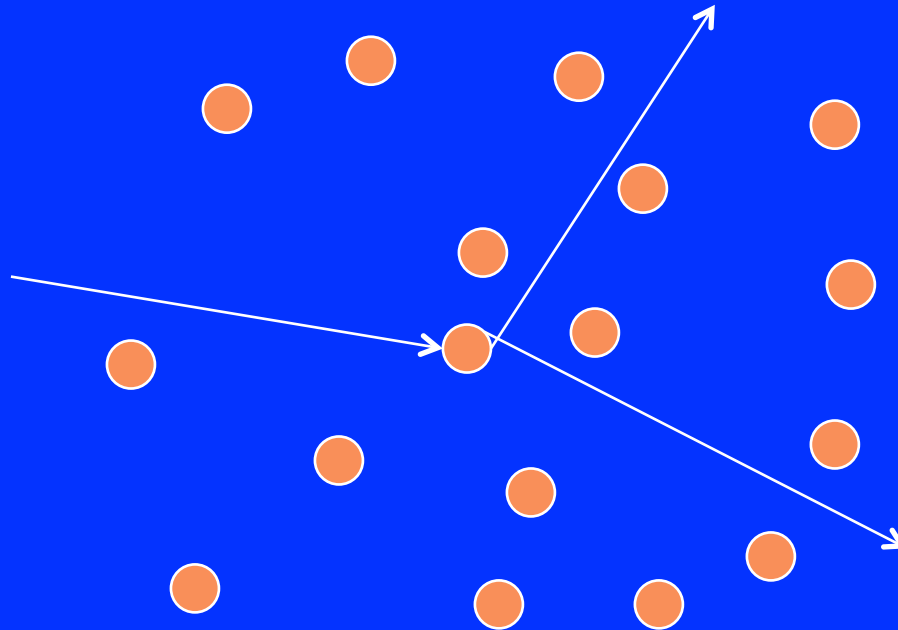
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These solutions can be used together – and usually are.

# How to get the material together before it blows itself apart?

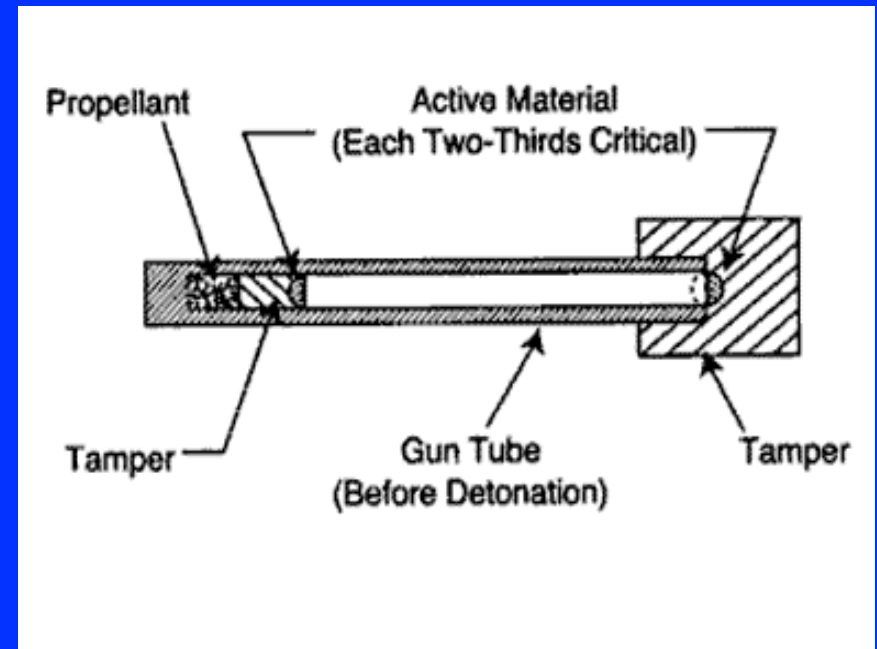
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- ◆ There are *always* neutrons around
- ◆ Once chain reaction starts, material will heat up, expand, stop reaction
- ◆ How to get enough material together fast enough?

# Gun-type bombs

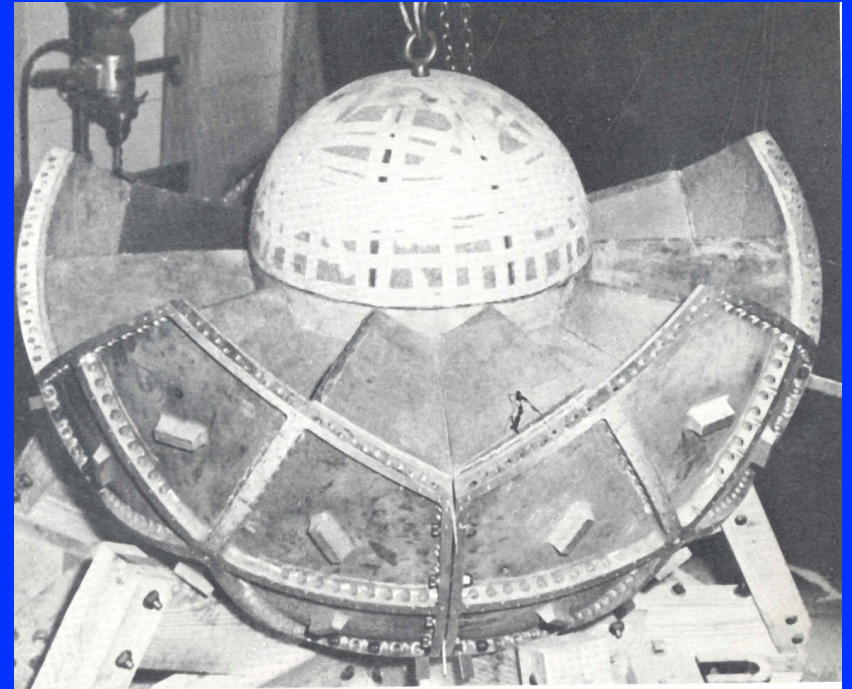
- ◆ Simple, reliable – can be built without testing
- ◆ Highly inefficient – require lots of nuclear material (50-60 kg of 90% enriched HEU)
- ◆ Can only get high yield with HEU, not plutonium
- ◆ Hiroshima bomb: cannon that fired HEU projectile into HEU target



*Source: NATO*

# Implosion-type bombs

- ◆ Much more efficient than gun-type bombs – less nuclear material required
- ◆ Only type that offers substantial yield with plutonium
- ◆ Significantly more complex to design and build
  - More difficult for terrorists, still conceivable (esp. if they got knowledgeable help)
- ◆ Main approaches require explosive lenses, millisecond timing of multiple detonations
- ◆ Some approaches less complex than Nagasaki bomb

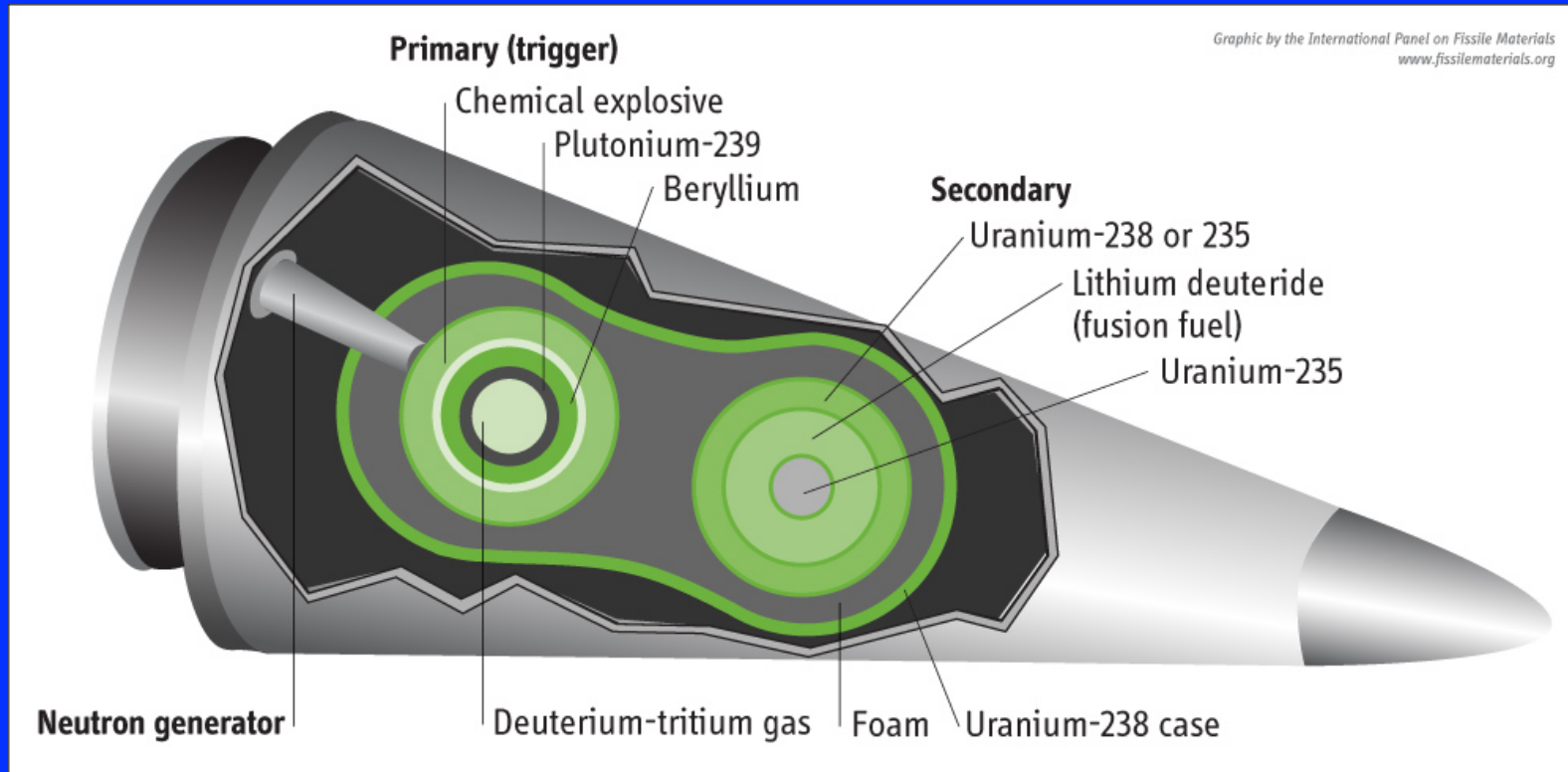


*Source: Rhodes, The Making of the Atomic Bomb (orig. Los Alamos)*

# Evolution of implosion designs

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# Modern thermonuclear weapons



Source: International Panel on Fissile Materials

# Two key potential bomb materials

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- ◆ Highly enriched uranium (HEU)
  - Must separate nearly identical U-235 and U-238 isotopes
  - Nearly all techniques based on their small difference in mass
  - Gaseous diffusion
  - Centrifuges
  - Other: calutrons, laser...
- ◆ Plutonium
  - Cause U-238 to absorb neutrons (typically in a reactor)
  - Chemically separate resulting plutonium from the rest (reprocessing)
- ◆ A few other isotopes could support explosive nuclear chain reactions, have never been used

*None of these materials occur in nature; all are extraordinarily difficult to produce*

# The amounts of material required are small

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- ◆ For simple “gun-type” bomb (with reflector):  $\sim 50\text{-}60$  kg of HEU (Hiroshima bomb was 60 kg of 80% enriched material)
  - Fits in two 2-liter bottles
- ◆ For 1<sup>st</sup>-generation implosion bomb:
  - $\sim 6$  kg plutonium (Nagasaki)
  - $\sim 3\times$  that amount of HEU

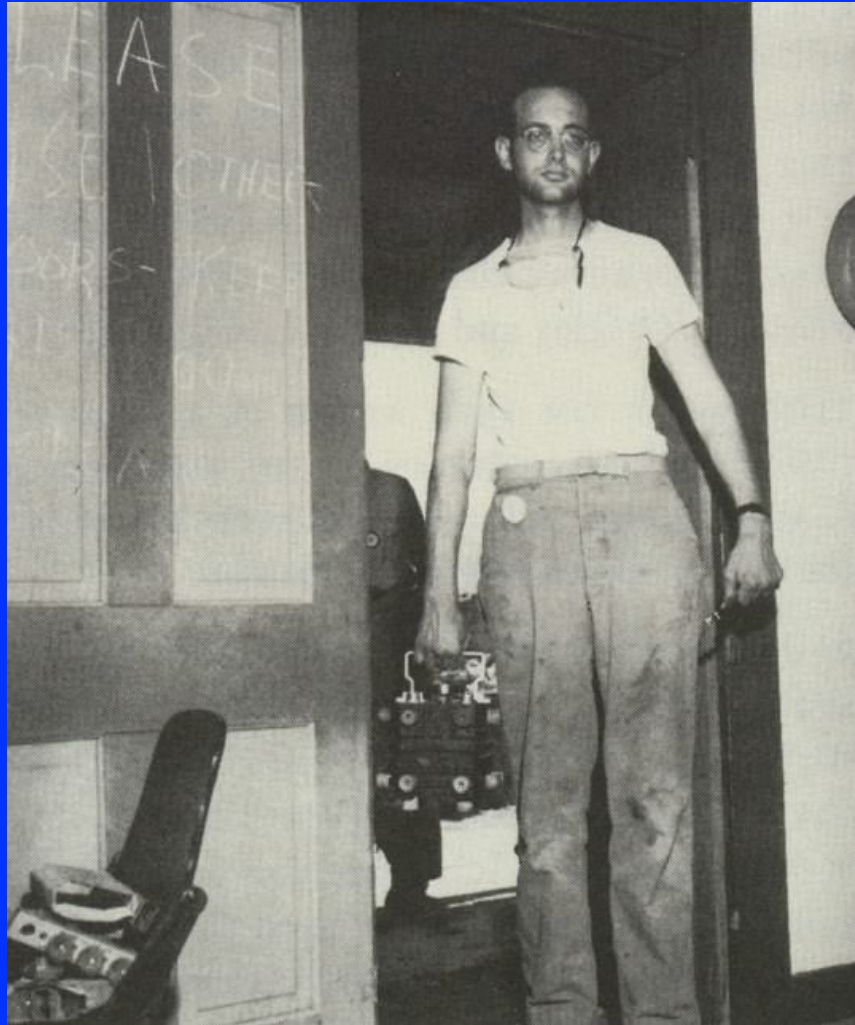


*The size of the plutonium core for the Nagasaki bomb*

Source: Robert del Tredici

# Nuclear material is not hard to smuggle – plutonium box for first-ever bomb

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*Source: Los Alamos*

# Some (sometimes misleading) terms to remember

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- ◆ *Highly enriched uranium (HEU)*
  - Uranium with at least 20% U-235
  - As opposed to *natural uranium* (0.7% U-235), *low-enriched uranium* (LEU, typically 4-5% U-235), or *depleted uranium* (<0.7% U-235)
- ◆ *Weapons-grade uranium*
  - Uranium with ~90% U-235
  - But bombs can be made with material far below weapons-grade
- ◆ *Weapons-grade plutonium*
  - Plutonium with ~ 90% Pu-239
  - As opposed to *reactor-grade* plutonium (much less Pu-239) – contained in spent fuel from typical nuclear power reactors
  - Weapons-makers prefer weapons-grade plutonium, but reliable, effective weapons can also be made with reactor-grade plutonium (once reprocessed from spent fuel)

# Reactor-grade plutonium is weapons-usable

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- ◆ Higher neutron emission rate:
  - For Nagasaki-type design, even if neutron starts reaction at worst possible moment, “fizzle yield” is  $\sim 1\text{kt}$  – roughly 1/3 destruct radius of Hiroshima bomb – more neutrons won’t reduce this
  - Some advanced designs are “pre-initiation proof”
- ◆ Higher heat emission:
  - Various ways to deal with – for example, plutonium component can be inserted into weapon just before use (as in early U.S. designs)
- ◆ Higher radiation:
  - Can be addressed with greater shielding for fabrication facility
  - Last-minute insertion of plutonium component again
- ◆ *Reactor-grade plutonium is not the preferred material for weapons, but any state or group that can make a bomb from weapon-grade plutonium can make one from reactor-grade*

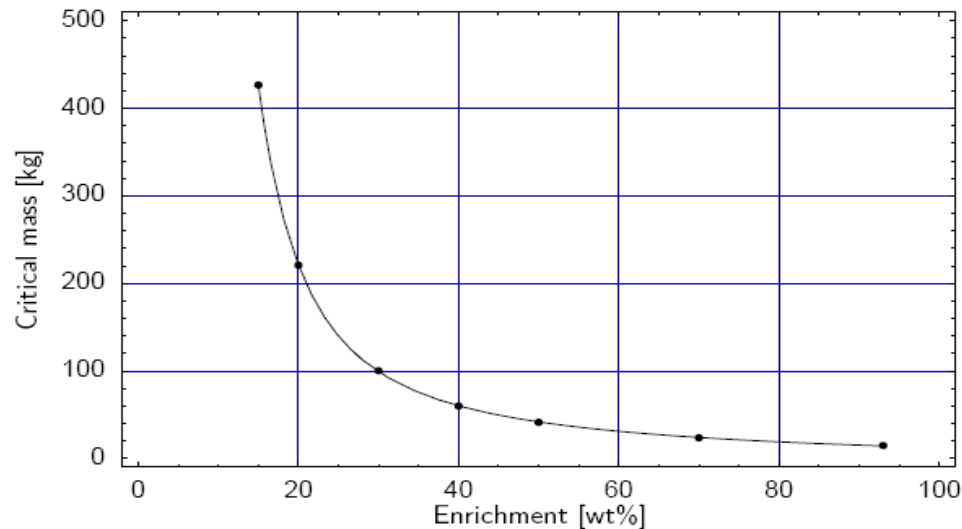
# Reactor-grade plutonium is weapons-usable (II)

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- ◆ “Virtually any combination of plutonium isotopes -- the different forms of an element having different numbers of neutrons in their nuclei -- can be used to make a nuclear weapon... At the lowest level of sophistication, a potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapons-grade plutonium.... Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton-range possible with a simple, first-generation nuclear device.”
  - *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (Washington, DC: DOE, January 1997)

# HEU at far below “weapon-grade” is weapons-usable

**Critical Mass of Reflected Uranium Sphere**



Critical mass of a beryllium-reflected uranium sphere as a function of the uranium-235 enrichment in weight percent (wt%). MCNP 4B simulations at 300 K. Reflector thickness is 10 cm.

*Source: Alexander Glaser, Science & Global Security, 2002*

# Properties of key nuclear explosive isotopes

Isotope	Critical Mass (kg)	Half Life (years)	Decay Heat (watts/kg)	Neutron Generation (neutrons/g-sec)
U-233	15	160,000	0.3	0.0009
U-235	50	700,000,000	0.0001	0.00001
Pu-239	10	24,000	1.9	0.02
Pu-240	40	6,600	6.8	900
Pa-231	162	32,800	1.3	0
Np-237	59	$2.1 \times 10^6$	0.021	0.00014
Am-241	57	430	110	1.2
Am-242m	9-18 kg	141	n.a.	$5.8 \times 10^7$
Am-243	155	7,380	6.4	.9
Cm-245	13	8,500	5.7	147
Cm-246	84	4,700	10	$9 \times 10^6$
Bk-247	10	1,400	36	0
Cf-251	9	898	56	0

Source: "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems" in Technological Opportunities to Increase the Proliferation Resistance of Global Nuclear Power Systems (TOPS) (Washington, D.C.: U.S. Department of Energy, Nuclear Energy Research Advisory Committee, 2000, available at <http://www.nuclear.gov/nerac/FinalTOPSRptAnnex.pdf> as of 9 January 2007), p. 4, with corrections and additions from "Chart of Nuclides" (Upton, N.Y.: Brookhaven National Laboratory), and David Albright and Lauren Barbour, "Troubles Tomorrow? Separated Neptunium-237 and Americium," in David Albright and Kevin O'Neill, eds. *The Challenges of Fissile Material Control*, (Washington, DC: Institute for Science and International Security, 1999)

# What are the hard parts?

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- ◆ #1: Making weapons-usable nuclear material
  - > 90% of the effort of Manhattan Project
  - Both plutonium production and uranium enrichment are difficult
    - plutonium production is easier (but harder to hide)
- ◆ #2: Making nuclear weapons efficient, safe, reliable, predictable, able to be launched on missiles
  - *Far* harder for a state to make an efficient, reliable weapon for launch on a missile than for a terrorist group to make a crude, unsafe weapon of uncertain yield for delivery on a truck
- ◆ #3 Designing and making a hydrogen bomb

*There's no central "secret" – but there are a variety of very real engineering and manufacturing challenges*

# Hard parts for a crude terrorist bomb

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- ◆ #1: Getting weapons-usable nuclear material
  - Once they have that, 80% or more of the way there
- ◆ Others:
  - Processing material into appropriate form
  - Casting and machining (U and Pu difficult materials – esp. Pu)
  - Building explosives, reflector, etc., getting them to work
  - For implosion weapons of the standard type:
    - » Precise shaped explosives with very precise timing
    - » Need to crush material to denser, more critical form, not flatten it into a pancake
    - » Neutron generator to provide shower of neutrons at best moment
  - All this requires an ability to recruit/train skilled personnel, raise money, sustain an organizational effort over a period of time...

*Some scenarios might allow some steps to be bypassed*

# Some technologies to know

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- ◆ “Krytrons”
  - Devices for delivering a powerful electrical signal with precise timing – used for detonating explosives in implosion systems
  - Various alternative approaches possible
- ◆ “Neutron generators”
  - Provide shower of neutrons to start chain reaction – tricky to design and build
  - Not *necessarily* required for gun-type bombs (can rely on stray neutrons always present in material)
- ◆ X-ray flash photography
  - Used to take photos of an imploding system in tests of explosives

*Some technologies in each of these areas export controlled, all also have civilian uses*

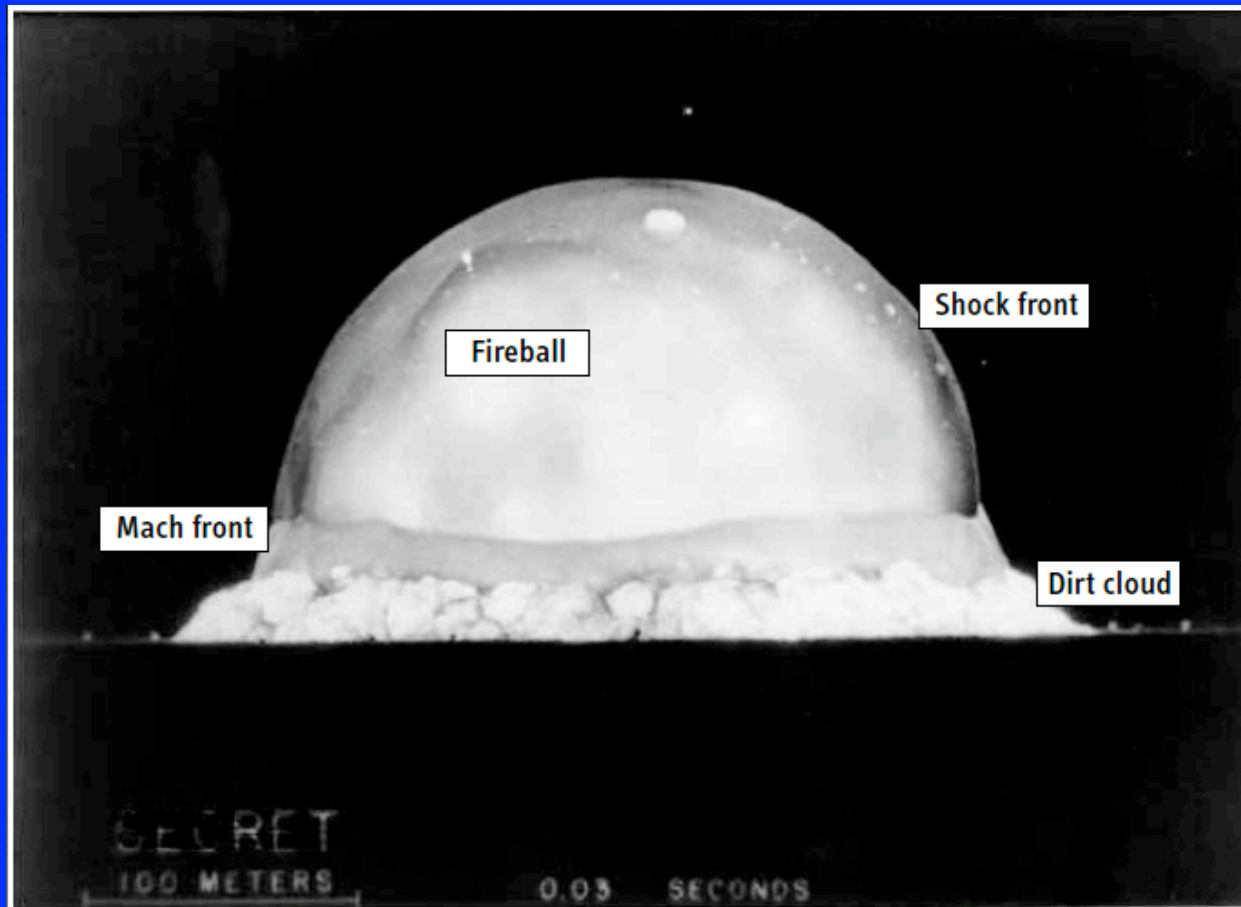
# Effects: Nagasaki, September 1945

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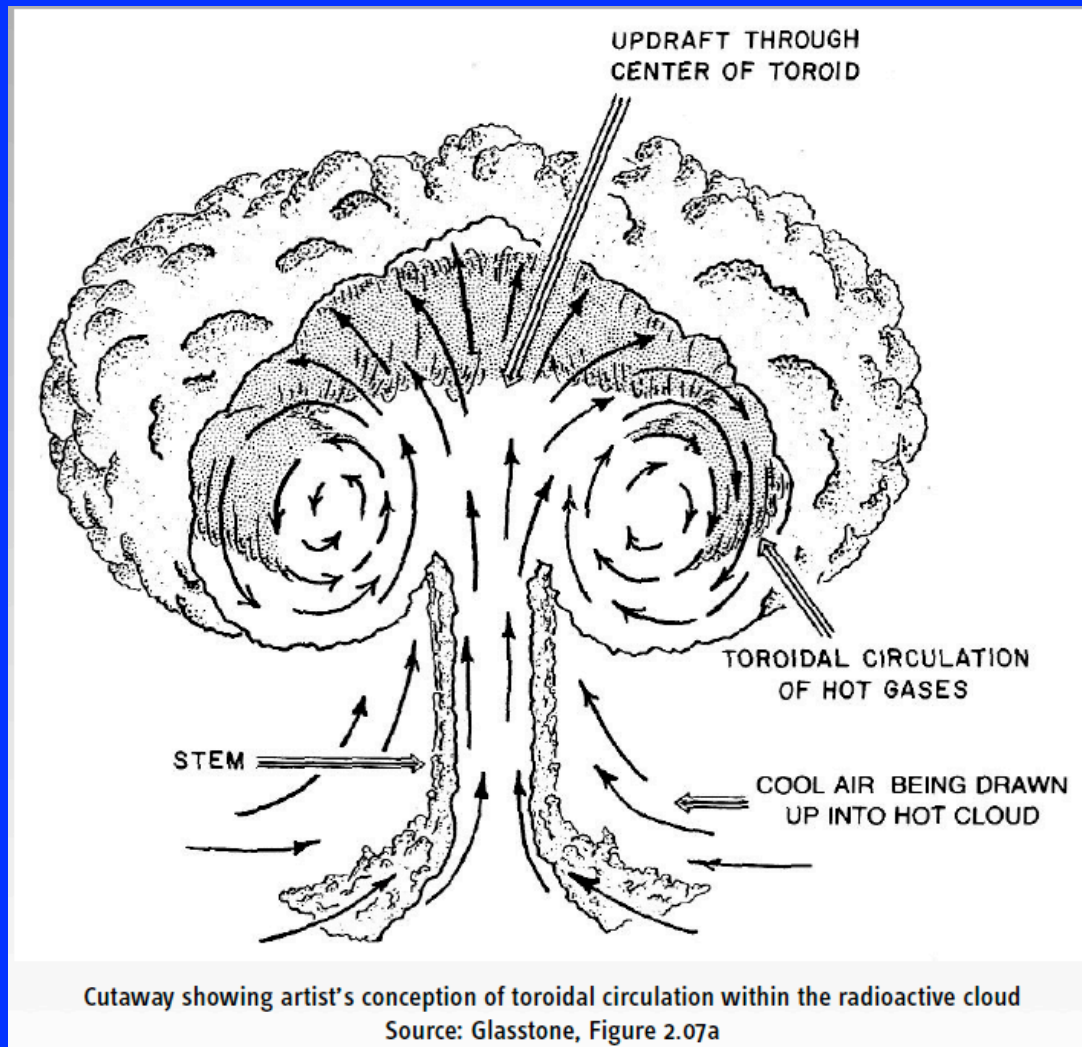
Source: *LIFE*, photographer: Bernard Hoffman

# Nuclear fireball: the Trinity test



Source: Alexander Glaser, Princeton University; Los Alamos

# The mushroom cloud



# Range of nuclear weapons effects

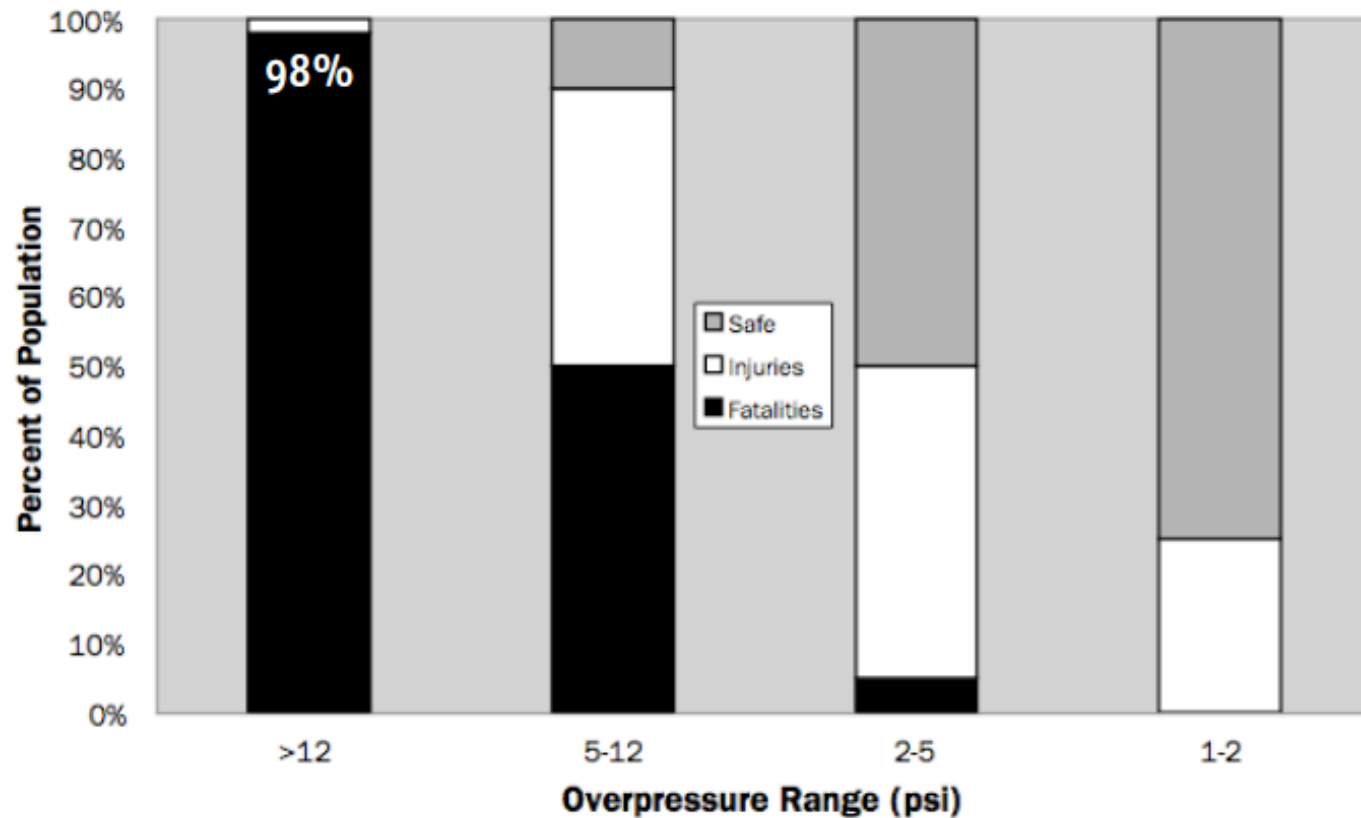
	Radius (approximate)		
Effect	1 kiloton	10 kilotons	100 kilotons
Fireball	80 m	200 m	500 m
5-psi blast	500 m	1,000 m	2,000 m
500 rem prompt	1,100 m	1,500 m	1,800 m
4-5 calories/cm <sup>2</sup>	600 m	1,700 m	4,700 m

- ◆ Radiation radius:  $\sim Y^{0.19}$
- ◆ Blast radius:  $\sim Y^{0.33}$
- ◆ Thermal radius:  $\sim Y^{0.41}$

# Area of nuclear weapons effects

	Area of Potentially Lethal Effects (surface burst, square kilometers)		
Effect	1 kiloton	10 kilotons	100 kilotons
Fireball	0.02	200 m	500 m
5-psi blast	0.66	1,000 m	2,000 m
500 rem prompt	3.8	1,500 m	1,800 m
2 <sup>nd</sup> degree burns	1.1	1,700 m	4,700 m
500-rem 48-hr fallout	3		

# Percentage of population killed or injured



Source: NRDC, *The U.S. Nuclear War Plan: A Time for Change* (Original source: OTA, *The Effects of Nuclear War*, 1979)