Manhattan Project

A deep dive into the physics and history behind the atomic bombs project.

Ammar S. Alfaifi & AbdulElah Hakami

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جامعة الملك فهد للبترول والمعادن
King Fahd University of Petroleum & Minerals

Contents

Origin

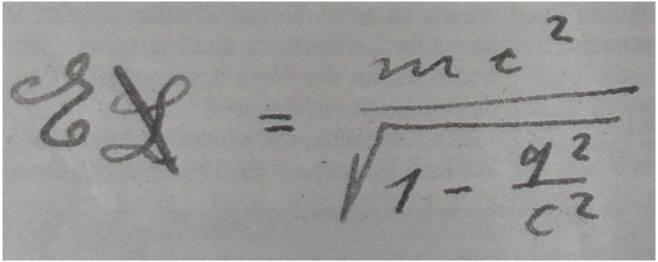

Figure 1: The equation in Albert Einstein's own handwriting from 1912

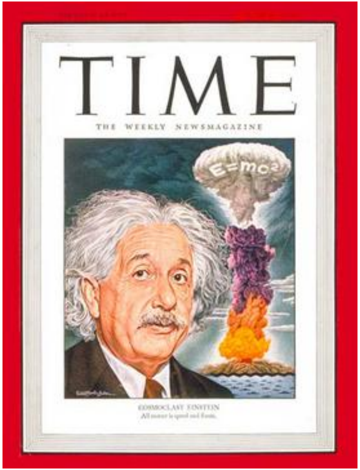

Figure 2: The cover of Time magazine in July 1946.

DOES THE INERTIA OF A BODY DEPEND UPON ITS ENERGY-CONTENT?

By A. EINSTEIN

September 27, 1905

If a body gives off the energy L in the form of radiation, its mass diminishes by L/c^2. The fact that the energy withdrawn from the body becomes energy of radiation evidently makes no difference, so that we are led to the more general conclusion that

The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by $\mathrm{L}/9 \times 10^{20}$, the energy being measured in ergs, and the mass in grammes.

$$m = \frac{L}{c^2}$$

$$E = mc^2$$

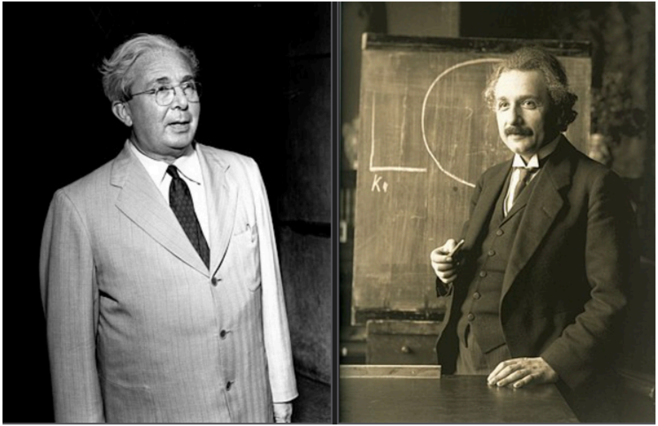

Figure 3: Leo Szilard and Albert Einstein.

Manhattan Project

Introduction

- In 1942, before the Manhattan Project, Robert Oppenheimer held conferences where physicists discussed nuclear bomb design issues.
- A gun-type design was initially chosen, where two sub-critical masses of plutonium would be brought together by firing a "bullet" into a "target".
- The alternative implosion-type design, suggested by Richard Tolman, was considered far more complex and received scant consideration.

Thin Man

- In early 1943, Oppenheimer prioritized the gun-type weapon but created the E-5 Group at Los Alamos to investigate implosion as a hedge against predetonation.
- Implosion-type bombs were determined to be more efficient in terms of explosive yield per unit mass of fissile material due to compressed fissile materials reacting more rapidly and completely.
- However, the plutonium gun-type bomb received the bulk of the research effort due to less uncertainty involved, with the assumption that the uranium gun-type bomb could be easily adapted from it.

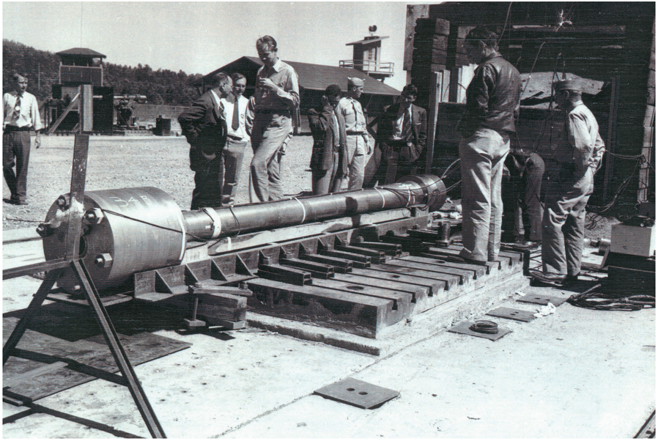

Figure 4: A prototype of the "Thin Man" gun being tested at Anchor Ranch, at Los Alamos.

- "Thin Man" was an early nuclear weapon design proposed before plutonium breeding.
- It assumed plutonium could be assembled by a gun-type method, requiring a "bullet" speed of at least 910 m/s.
- Dimensions: 5.2 m long, 0.97 m wide tail and nose, 0.58 m midsection.
- Weight: approximately 3,600 kg.
- No USAAF aircraft could carry it without modifications.
- Avro Lancaster (10 m bomb bay) or modified Boeing B-29 Superfortress were suggested.
- B-29 modification involved removing part of the bulkhead and oxygen tanks (Serial No. 42-6259).

Figure 5: A USAAF B-29 Superfortress. B-29s dropped the atomic bombs on Hiroshima and Nagasaki, the only aircraft ever to drop nuclear weapons in combat.

Predetonation

- Experiments in April 1944 by Emilio G. Segrè's group at Los Alamos showed reactor-produced plutonium contained the isotope plutonium-240.
- Plutonium-240 has a high spontaneous fission rate, increasing the risk of predetonation.
- This meant the plutonium would likely predetonate and blow itself apart during critical mass formation.
- The distance required to avoid predetonation would need an impractically long gun barrel for any bomber.

- The only viable option was the more difficult implosion method.[?]
- At a meeting on July 17, 1944, it was agreed that gun-type work would focus on the `Little Boy` uranium design.
- Almost all Los Alamos research was re-oriented toward solving the implosion problems for the `Fat Man` plutonium bomb.

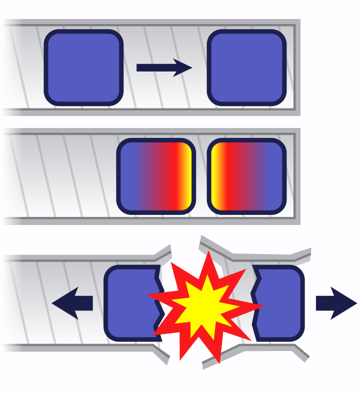

Figure 6: If two pieces of subcritical material are not brought together fast enough, nuclear predetonation can occur, whereby a smaller explosion than expected will blow the bulk of the material apart.

Pu-239 Production

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

Neutrons from the fission of uranium-235 are captured by uranium-238 nuclei to form uranium-239; a beta decay converts a neutron into a proton to form neptunium-239 (half-life 2.36 days) and another beta decay forms plutonium-239.[?]

Isotope	Decay mode	Half-life (years)	Spontaneous fission n $(1/(g \cdot s))$
^{238}Pu	alpha to ^{234}U	87.74	2600
^{239}Pu	alpha to ^{235}U	24100	0.022
^{240}Pu	alpha to ^{236}U	6560	910

Little Boy

- The gun-type uranium bomb, code-named "Little Boy", was much simpler than the plutonium implosion design.
- Its smaller size allowed it to fit into the B-29 bomb bay without difficulty.
- Design specifications were completed in February 1945, with components manufactured at different plants.
- The bomb (except uranium payload) was ready by early May 1945.
- The enriched uranium projectile and target were completed in June and July 1945, respectively.
- No full test of the gun-type bomb was conducted before the Hiroshima bombing.

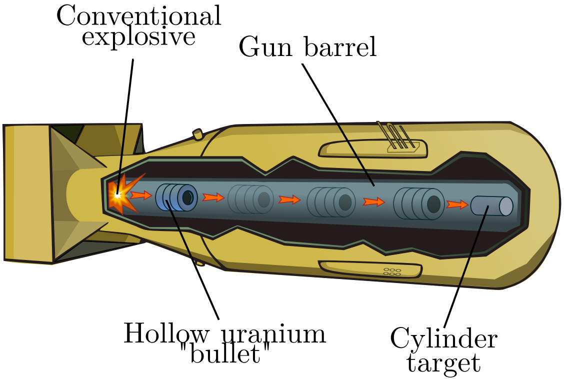

Figure 7: The "gun" assembly method. When the hollow uranium projectile was driven onto the target cylinder, a nuclear explosion resulted.

- Little Boy had an estimated yield of 15 kilotons based on data from instruments dropped by parachute.
- A rule of thumb was developed: the "5 psi lethal area" where overpressure ≥ 34 kPa would be fatal.
- At Hiroshima, this lethal area had a diameter of 3.5 km.
- Three main effects: blast, fire, and radiation.

Blast

- Everything within 1 km was destroyed except reinforced concrete buildings.
- Severe blast damage followed the 34 kPa overpressure contour at 1.8 km radius.
- Fuel for fires was created by blast damage to structures.

Fire

- Fireball surface temperature was $6,000°C$, igniting fires across the destruction zone.
- Fires merged into a 3.2 km diameter firestorm within 20 minutes.
- An estimated 60% of immediate deaths were from fires.

Radiation

- No local fallout since it was an air burst.
- Lethal radius of 1.3 km from initial radiation.
- 30% of immediate deaths from direct radiation exposure.
- 30% of survivors had radiation injuries, increasing cancer risk.

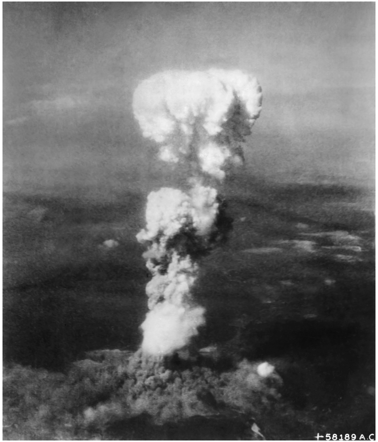

Figure 8: The mushroom cloud over Hiroshima after the detonation of Little Boy on 6 August 1945.

- After falling for 44.4 seconds. Detonation occurred at an altitude of 600 ± 15 m.
- It was less powerful than the Fat Man bomb dropped on Nagasaki.
- However, damage and casualties in Hiroshima were higher due to its flat terrain.
- Published figures in 1945 stated 66,000 people killed and 69,000 injured.
- Later estimates put the death toll as high as 140,000.

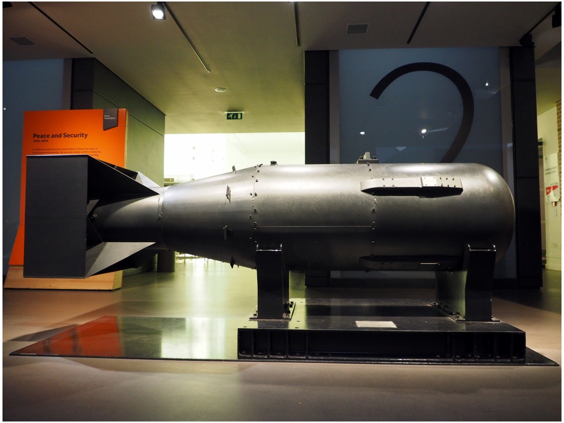

Figure 9: One of five casings built for the Little Boy bomb used on Hiroshima on display at the Imperial War Museum in London during 2015

Fat Man

- The idea of using shaped charges as 3D explosive lenses came from James L. Tuck and was developed by John von Neumann.
- Precision in the inward motion of the explosive plates was crucial, achieved using exploding-bridgewire detonators invented by Luis Alvarez and Lawrence Johnston.
- Robert Christy's calculations showed that a solid plutonium sphere could be compressed to a critical state, simplifying the task.
- The bomb size was constrained by the available aircraft; (maximum length: 3.4 m, width: 1.5 m, weight: 9,100 kg).
- Drop tests led to modifications, including the addition of a "California Parachute" stabilizer for a stable descent.
- The final wartime Y-1561 design was assembled with 90 bolts and yielded approximately 100 TJ (25 kilotonnes) in the Trinity test on July 16, 1945.

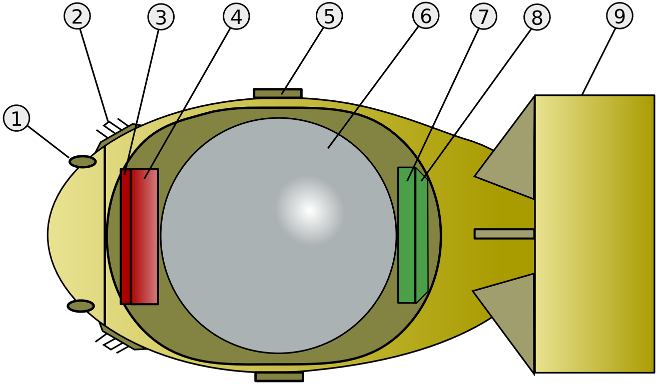

Figure 10: Fat Man external schematic.

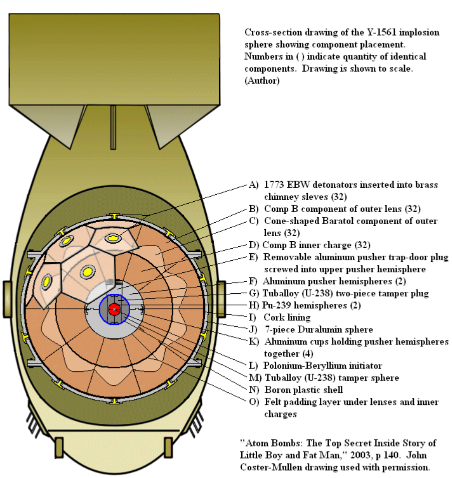

Figure 11: Fat Man internal schematic

The Implosion

https://upload.wikimedia.org/wikipedia/commons/0/05/ImplosionShapedCharge.gif

The Urchin

- The neutron initiator design typically combines beryllium-9 and polonium-210, separated until activation.
- The alpha source isotope must have strong alpha emissions and weak gamma emissions.
- It consisted of a beryllium pellet (0.8 cm diameter), beryllium shell (2 cm outer diameter, 0.6 cm wall thickness) with grooves, and polonium-210 (50 curies, 11 mg) deposited between them.

- Gold and nickel coatings shielded the beryllium from polonium's alpha particles.
- Upon implosion, the shock wave mixed the beryllium and polonium, allowing alpha particles to bombard beryllium and emit neutrons (1 neutron every 5-10 ns).
- The neutrons triggered the chain reaction in the compressed plutonium core.

https://youtube.com/clip/UgkxPCbwqQO4_6HBbKd4qxSKm2mrt0CYYnDy?si=m5m0Mrrw2ZoW0jmk

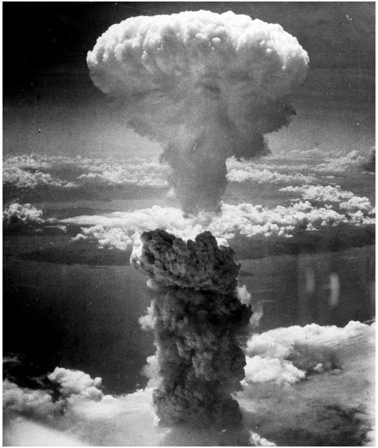

Figure 12: Mushroom cloud after Fat Man exploded over Nagasaki on 9 August 1945

References & Conclusion

References

Thank you for listening.