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How Nuclear Bombs Work

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Hiroshima Peace Memorial stands as a visible reminder of the day the Japanese city was bombed on Aug. 6, 1945. After that fateful day, the structure was the only thing still standing in the vicinity of the explosion.
STEVE ALLEN/GETTY IMAGES

The first nuclear bomb meant to kill humans exploded over Hiroshima, Japan, on Aug. 6, 1945. Three days later, a second bomb detonated over Nagasaki. The death and destruction wrought by these weapons was unprecedented and might have, in another world with another race of beings, ended the nuclear threat right then and there.

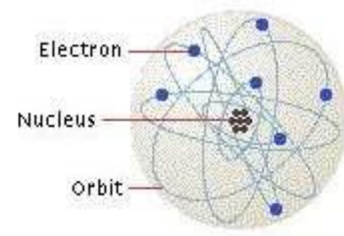
But the events in Japan, although they brought a close to World War II, marked the beginning of the Cold War between the United States and the Soviet Union. Between 1945 and the late 1980s, both sides invested huge amounts of money in nuclear weapons and increased their stockpiles significantly, mostly as a means to deter conflict. The threat of catastrophic destruction from The Bomb loomed over everyone and everything. Schools conducted nuclear air raid drills. Governments built fallout shelters. Homeowners dug bunkers in their backyards.

During the 1970s and '80s, tensions began to ease somewhat. Then the Berlin Wall fell in 1989, followed by the collapse of the Soviet government itself two years later. The Cold War officially ended. As relations between the two countries improved, a commitment to limit nuclear arsenals emerged. A series of treaties followed, with the latest going into effect in February 2011. Like its predecessors, the new Strategic Arms Reduction Treaty (START) aims to further reduce and limit strategic arms. Among other measures, it calls for an aggregate limit of 1,550 warheads [source: the White House].

Unfortunately, even as Russia and the U.S. step tentatively away from the brink, the threat of nuclear warfare remains. Nine countries can now deliver nuclear warheads on ballistic missiles [source: Fischetti]. At least three of those countries -- the U.S., Russia and China -- could strike any target anywhere in the world. Today's weapons could easily rival the destructive power of the bombs dropped on Japan. In 2009, North Korea successfully tested a nuclear weapon as powerful as the atomic bomb that destroyed Hiroshima. The underground explosion was so significant that it created an earthquake with a magnitude of 4.5 [source: McCurry].

While the political landscape of nuclear warfare has changed considerably over the years, the science of the weapon itself -- the atomic processes that unleash all of that fury -- have been known since Einstein. This article will review how nuclear bombs work, including how they're built and deployed. Up first is a quick review of atomic structure and radioactivity.

Atomic Structure and Radioactivity



An atom, in the simplest model, consists of a nucleus and orbiting electrons.

Before we can get to the bombs, we have to start small, atomically small. An **atom**, you'll remember, is made up of three subatomic particles -
- **protons**, **neutrons** and **electrons**. The center of an atom, called the **nucleus**, is composed of protons and neutrons. Protons are positively charged, neutrons have no charge at all and electrons are negatively charged. The proton-to-electron ratio is always one to one, so the atom as a whole has a neutral charge. For example, a carbon atom has six protons and six electrons.

It's not that simple though. An atom's properties can change considerably based on how many of each particle it has. If you change the number of protons, you wind up with a different element altogether. If you alter the number of neutrons in an atom, you wind up with an **isotope**. For example, carbon has three isotopes: 1) carbon-12 (six protons + six neutrons), a stable and commonly occurring form of the element, 2) carbon-13 (six protons + seven neutrons), which is stable but rare and 3) carbon-14 (six protons + eight neutrons), which is rare and unstable (or radioactive) to boot.

As we see with carbon, most atomic nuclei are stable, but a few aren't stable at all. These nuclei spontaneously emit particles that scientists refer to as **radiation**. A nucleus that emits radiation is, of course, **radioactive**, and the act of emitting particles is known as **radioactive decay**. If you're particularly curious about radioactive decay, you'll want to peruse How Nuclear Radiation Works. For now, we'll go over the three types of radioactive decay:

1. **Alpha decay:** A nucleus ejects two protons and two neutrons bound together, known as an **alpha particle.**

2. **Beta decay:** A neutron becomes a proton, an electron and an **antineutrino**. The ejected electron is a **beta particle.**
3. **Spontaneous fission:** A nucleus splits into two pieces. In the process, it can eject neutrons, which can become neutron rays. The nucleus can also emit a burst of electromagnetic energy known as a **gamma ray.** Gamma rays are the only type of nuclear radiation that comes from energy instead of fast-moving particles.

   Remember that fission part especially. It's going to keep coming up as we discuss the inner workings of nuclear bombs.

Nuclear Fission

Nuclear bombs involve the forces, strong and weak, that hold the nucleus of an atom together, especially atoms with unstable nuclei. There are two basic ways that nuclear energy can be released from an atom. In **nuclear fission** (pictured), scientists split the nucleus of an atom into two smaller fragments with a neutron. **Nuclear fusion** -- the process by which the sun produces energy -- involves bringing together two smaller atoms to form a larger one. In either process, fission or fusion, large amounts of heat energy and radiation are given off.

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We can attribute the discovery of nuclear fission to the work of Italian physicist Enrico Fermi. In the 1930s, Fermi demonstrated that elements subjected to neutron bombardment could be transformed into new elements. This work resulted in the discovery of slow neutrons, as well as new elements not represented on the periodic table. Soon after Fermi's discovery, German scientists Otto Hahn and Fritz Strassman bombarded uranium with neutrons, which produced a radioactive barium isotope. They concluded that the low-speed neutrons caused the uranium nucleus to fission, or break apart, into two smaller pieces.

Their work sparked intense activity in research labs all over the world. At Princeton University, Niels Bohr worked with John Wheeler to develop a hypothetical model of the fission process. They speculated that it was the uranium isotope uranium-235, not uranium-238, undergoing fission. At about the same time, other scientists discovered that the fission process resulted in even more neutrons being produced. This led Bohr and Wheeler to ask a momentous question: Could the free neutrons created in fission start a chain reaction that would release an enormous amount of energy? If so, it might be possible to build a weapon of unimagined power.

And it was.

Nuclear Fuel

Officials from the Manhattan Project, the code name for the U.S. plan to develop atomic weapons, inspect the detonation site of the Trinity atomic bomb test. That's Dr. Robert J. Oppenheimer in the white hat.

LOS ALAMOS NATIONAL LABORATORY/TIME LIFE PICTURES/GETTY IMAGES

In March 1940, a team of scientists working at Columbia University in New York City confirmed the hypothesis put forth by Bohr and Wheeler -- the isotope **uranium-235**, or **U-235**, was responsible for nuclear fission. The Columbia team tried to initiate a chain reaction using U-235 in the fall of 1941, but failed. All work then moved to the University of Chicago, where, on a squash court situated beneath the university's Stagg Field, Enrico Fermi finally achieved the world's first controlled nuclear chain reaction. Development of a nuclear bomb, using U-235 as the fuel, proceeded quickly.

Because of its importance in the design of a nuclear bomb, let's look at U-235 more closely. U-235 is one of the few materials that can undergo **induced fission**. Instead of waiting more than 700 million years for uranium to naturally decay, the element can be broken down much faster if a neutron runs into its nucleus. The nucleus will absorb the neutron without hesitation, become unstable and split immediately.

As soon as the nucleus captures the neutron, it splits into two lighter atoms and throws off two or three new neutrons (the number of ejected neutrons depends on how the U-235 atom happens to split). The two lighter atoms then emit gamma radiation as they settle into their new states. There are a few things about this induced fission process that make it interesting:

- The probability of a U-235 atom capturing a neutron as it passes by is fairly high. In a bomb that is working properly, more than one neutron ejected from each fission causes another fission to occur. It helps to think of a big circle of marbles as the protons and neutrons of an atom. If you shoot one marble -- a single neutron -- into the middle of the big circle, it will hit one marble, which will hit a few more marbles, and so on until a chain reaction continues.
- The process of capturing the neutron and splitting happens very quickly, on the order of picoseconds (0.000000000001 seconds).
- In order for these properties of U-235 to work, a sample of uranium must be **enriched**; that is the amount of U-235 in a sample must be increased beyond naturally occurring levels. Weapons-grade uranium is composed of at least 90 percent U-235.

In 1941, scientists at the University of California at Berkeley discovered another element -- element 94 -- that might offer potential as a nuclear fuel. They named the element **plutonium**, and during the following year, they made enough for experiments. Eventually, they established plutonium's fission characteristics and identified a second possible fuel for nuclear weapons.

Fission Bomb Design

If you think of critical mass in terms of marbles, the tight formation of marbles represents critical mass and the three lone marbles stand in for neutrons.
ISTOCKPHOTO/THINKSTOCK

In a fission bomb, the fuel must be kept in separate **subcritical** masses, which will not support fission, to prevent premature detonation. **Critical mass** is the minimum mass of fissionable material required to sustain a nuclear fission reaction. Think about the marble analogy again. If the circle of marbles are spread too far apart -- subcritical mass -- a smaller chain reaction will occur when the "neutron marble" hits the center. If the marbles are placed closer together in the circle -- critical mass -- there is a higher chance a big chain reaction will take place.

Keeping the fuel in separate subcritical masses leads to design challenges that must be solved for a fission bomb to function properly. The first challenge, of course, is bringing the subcritical masses together to form a **supercritical** mass, which will provide more than enough neutrons to sustain a fission reaction at the time of detonation. Bomb designers came up with two solutions, which we'll cover in the next section.

Next, free neutrons must be introduced into the supercritical mass to start the fission. Neutrons are introduced by making a **neutron generator**. This generator is a small pellet of polonium and beryllium, separated by foil within the fissionable fuel core. In this generator:

1. The foil is broken when the subcritical masses come together and polonium spontaneously emits alpha particles.
2. These alpha particles then collide with beryllium-9 to produce beryllium-8 and free neutrons.
3. The neutrons then initiate fission.

Finally, the design must allow as much of the material as possible to be fissioned before the bomb explodes. This is accomplished by confining the fission reaction within a dense material called a **tamper**, which is usually made of uranium-238. The tamper gets heated and expanded by the fission core. This expansion of the tamper exerts pressure back on the fission core and slows the core's expansion. The tamper also reflects neutrons back into the fission core, increasing the efficiency of the fission reaction.

Fission Bomb Triggers

The simplest way to bring the subcritical masses together is to make a gun that fires one mass into the other. A sphere of U-235 is made around the neutron generator and a small **bullet** of U-235 is removed. The bullet is placed at the one end of a long tube with explosives behind it, while the sphere is placed at the other end. A barometric-pressure sensor determines the appropriate altitude for detonation and triggers the following sequence of events:

1. The explosives fire and propel the bullet down the barrel.
2. The bullet strikes the sphere and generator, initiating the fission reaction.
3. The fission reaction begins.
4. The bomb explodes.

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Little Boy, the bomb dropped on Hiroshima, was this type of bomb and had a 14.5-kiloton yield (equal to 14,500 tons of TNT) with an efficiency of about 1.5 percent. That is, 1.5 percent of the material was fissioned before the explosion carried the material away.

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The second way to create a supercritical mass requires compressing the subcritical masses together into a sphere by implosion. **Fat Man**, the bomb dropped on Nagasaki, was one of these so-called **implosion-triggered bombs**. It wasn't easy to build. Early bomb designers faced several problems, particularly how to control and direct the shock wave uniformly across the sphere. Their solution was to create an implosion device consisting of a sphere of U-235 to act as the tamper and a plutonium-239 core surrounded by high explosives. When the bomb was detonated, it had a 23-kiloton yield with an efficiency of 17 percent. This is what happened:

- The explosives fired, creating a shock wave.
- The shock wave compressed the core.

- The fission reaction began.
- The bomb exploded.

Designers were able to improve the basic implosion-triggered design. In 1943, American physicist Edward Teller invented the concept of boosting. **Boosting** refers to a process whereby fusion reactions are used to create neutrons, which are then used to induce fission reactions at a higher rate. It took another eight years before the first test confirmed the validity of boosting, but once the proof came, it became a popular design. In the years that followed, almost 90 percent of nuclear bombs built in America used the boost design.

Of course, fusion reactions can be used as the primary source of energy in a nuclear weapon, too. In the next section, we'll look at the inner workings of fusion bombs.

Fusion Bombs

Fission bombs worked, but they weren't very efficient. It didn't take scientists long to wonder if the opposite nuclear process -- fusion -- might work better. Fusion occurs when the nuclei of two atoms combine to form a single heavier atom. At extremely high temperatures, the nuclei of hydrogen isotopes deuterium and tritium can readily fuse, releasing enormous amounts of energy in the process. Weapons that take advantage of this process are known as **fusion bombs**, **thermonuclear bombs** or **hydrogen bombs**. Fusion bombs have higher kiloton yields and greater efficiencies than fission bombs, but they present some problems that must be solved:

- Deuterium and tritium, the fuels for fusion, are both gases, which are hard to store.
- Tritium is in short supply and has a short half-life.
- Fuel in the bomb has to be continuously replenished.
- Deuterium or tritium has to be highly compressed at high temperature to initiate the fusion reaction.

Scientists overcome the first problem by using lithium-deuterate, a solid compound that doesn't undergo radioactive decay at normal temperature, as the principal thermonuclear material. To overcome the tritium problem, bomb designers rely on a fission reaction to produce tritium from lithium. The fission reaction also solves the final problem. The majority of radiation given off in a fission reaction is **X-rays**, and these X-rays provide the high temperatures and pressures necessary to initiate fusion. So, a fusion bomb has a two-stage design -- a primary fission or boosted-fission component and a secondary fusion component.

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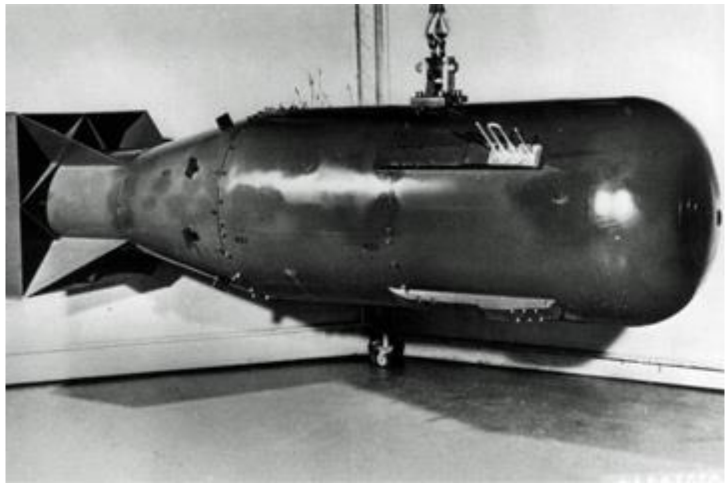
To understand this bomb design, imagine that within a bomb casing you have an implosion fission bomb and a cylinder casing of uranium-238 (tamper). Within the tamper is the lithium deuteride (fuel) and a hollow rod of plutonium-239 in the center of the cylinder. Separating the cylinder from the implosion bomb is a shield of uranium-238 and plastic foam that fills the remaining spaces in the bomb casing. Detonation of the bomb causes the following sequence of events:

1. The fission bomb implodes, giving off X-rays.
2. These X-rays heat the interior of the bomb and the tamper; the shield prevents premature detonation of the fuel.
3. The heat causes the tamper to expand and burn away, exerting pressure inward against the lithium deuterate.
4. The lithium deuterate is squeezed by about 30-fold.
5. The compression shock waves initiate fission in the plutonium rod.
6. The fissioning rod gives off radiation, heat and neutrons.
7. The neutrons go into the lithium deuterate, combine with the lithium and make tritium.
8. The combination of high temperature and pressure are sufficient for tritium-deuterium and deuterium-deuterium fusion reactions to occur, producing more heat, radiation and neutrons.
9. The neutrons from the fusion reactions induce fission in the uranium-238 pieces from the tamper and shield.
10. Fission of the tamper and shield pieces produce even more radiation and heat.
11. The bomb explodes.

All of these events happen in about 600 billionths of a second (550 billionths of a second for the fission bomb implosion, 50 billionths of a second for the fusion events). The result is an immense explosion with a 10,000-kiloton yield -- 700 times more powerful than the Little Boy explosion.

Nuclear Bomb Delivery



An atomic bomb of the 'Little Boy' type that was detonated over Hiroshima Japan

MPI/GETTY IMAGES

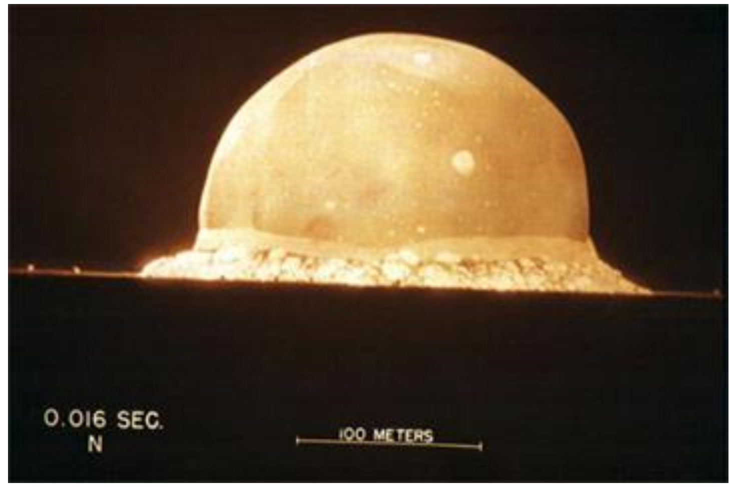
It's one thing to build a nuclear bomb. It's another thing entirely to deliver the weapon to its intended target and detonate it successfully. This was especially true of the first bombs built by scientists at the end of World War II. Writing in a 1995 issue of Scientific American, Philip Morrison, a member of the Manhattan Project, said this about the early weapons: "All three bombs of 1945 -- the [Trinity] test bomb and the two bombs dropped on Japan -- were more nearly improvised pieces of complex laboratory equipment than they were reliable weaponry."

The delivery of those bombs to their final destination was improvised almost as much as their design and construction. The USS Indianapolis transported the parts and enriched uranium fuel of the Little Boy bomb to the Pacific island of Tinian on July 28, 1945. The components of the Fat Man bomb, carried by three modified B-29s, arrived on August 2. A team of 60 scientists flew from Los Alamos, N.M., to Tinian to assist in the assembly. The Little Boy bomb -- weighing 9,700 pounds (4,400 kilograms) and measuring 10 feet (3 meters) from nose to tail -- was ready first. On August 6, a crew loaded the bomb into the Enola Gay, a B-29 piloted by Col. Paul Tibbets. The plane made the 750-mile (1,200-kilometer) trip to Japan and dropped the bomb into the air above Hiroshima, where it detonated at exactly 8:12 a.m. On August 9, the nearly 11,000-pound (5,000-kilogram) Fat Man bomb made the same journey aboard the Bockscar, a second B-29 piloted by Maj. Charles Sweeney. Its deadly payload exploded over Nagasaki just before noon.

Today, the method used in Japan -- gravity bombs carried by aircraft -- remains a viable way to deliver nuclear weapons. But over the years, as warheads have decreased in size, other options have become available. Many countries have stockpiled a number of ballistic and cruise missiles armed with nuclear devices. Most **ballistic missiles** are launched from land-based silos or submarines. They exit the Earth's atmosphere, travel thousands of miles to their targets and re-enter the atmosphere to deploy their weapons. **Cruise missiles** have shorter ranges and smaller warheads than ballistic missiles, but they are harder to detect and intercept. They can be launched from the air, from mobile launchers on the ground and from naval ships.

Tactical nuclear weapons, or **TNWs**, also became popular during the Cold War. Designed to target smaller areas, TNWs include short-range missiles, artillery shells, land mines and depth charges. Portable TNWs, such as the Davy Crockett rifle, make it possible for small one- or two-man teams to deliver a nuclear strike.

Consequences and Health Risks of Nuclear Bombs



A photograph shows the first atomic bomb test on July 16, 1945, at 5:30 a.m., at the Trinity Site in New Mexico.
JOE RAEDLE/GETTY IMAGES

The detonation of a nuclear weapon unleashes tremendous destruction, but the ruins would contain microscopic evidence of where the bombs' materials came from. The detonation of a nuclear bomb over a target such as a populated city causes immense damage. The degree of damage depends upon the distance from the center of the bomb blast, which is called the **hypocenter** or **ground zero**. The closer you are to the hypocenter, the more severe the damage. The damage is caused by several things:

- A wave of intense **heat** from the explosion
- **Pressure** from the shock wave created by the blast
- Radiation
- **Radioactive fallout** (clouds of fine radioactive particles of dust and bomb debris that fall back to the ground)

At the hypocenter, everything is immediately **vaporized** by the high temperature (up to 500 million degrees Fahrenheit or 300 million degrees Celsius). Outward from the hypocenter, most casualties are caused by burns from the heat, injuries from the flying debris of buildings collapsed by the shock wave and acute exposure to the high radiation. Beyond the immediate blast area, casualties are caused from the heat, the radiation and the fires spawned from the heat wave. In the long term, radioactive fallout occurs over a wider area because of prevailing winds. The radioactive fallout particles enter the water supply and are inhaled and ingested by people at a distance from the blast.

Scientists have studied survivors of the Hiroshima and Nagasaki bombings to understand the short-term and long-term effects of nuclear explosions on human health. Radiation and radioactive fallout affect those cells in the body that actively divide (hair, intestine, bone marrow, reproductive organs). Some of the resulting health conditions include:

- Nausea, vomiting and diarrhea
- Cataracts
- Hair loss
- Loss of blood cells

These conditions often increase the risk of leukemia, cancer, infertility and birth defects.

Scientists and physicians are still studying the survivors of the bombs dropped on Japan and expect more results to appear over time.

In the 1980s, scientists assessed the possible effects of nuclear warfare (many nuclear bombs exploding in different parts of the world) and proposed the theory that a **nuclear winter** could occur. In the nuclear-winter scenario, the explosion of many bombs would raise great clouds of dust and radioactive material that would travel high into Earth's atmosphere. These clouds would block out sunlight. The reduced level of sunlight would lower the surface temperature of the planet and reduce photosynthesis by plants and bacteria. The reduction in photosynthesis would disrupt the food chain, causing mass extinction of life (including humans). This scenario is similar to the asteroid hypothesis that has been proposed to explain the extinction of the dinosaurs. Proponents of the nuclear-winter scenario pointed to the clouds of dust and debris that traveled far across the planet after the volcanic eruptions of Mount St. Helens in the United States and Mount Pinatubo in the Philippines.

Nuclear weapons have incredible, long-term destructive power that travels far beyond the original target. This is why the world's governments are trying to control the spread of nuclear-bomb-making technology and materials and reduce the arsenal of nuclear weapons deployed during the Cold War. It's also why nuclear tests conducted by North Korea and other countries draw such a strong response from the international community. The Hiroshima and Nagasaki bombings may be many decades past, but the horrible images of that fateful August morning burn as clear and bright as ever.

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