Lecture 3: Nuclear Energy Basics, Part 1: Fission, Fusion, and the Bomb

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QUESTIONS TO BE ADDRESSED:

I. **What are the basics of nuclear fission?**

II. **What were the first nuclear bombs and how did they work?**

III. **How did single-stage fission bombs change after 1945?**

IV. **What are multiple-stage fusion weapons designs and how do they work?**

Fission Basics and the First Nuclear Bombs

FISSION BASICS

The Atom's Components and Isotopes

The Nucleus

An atom is made up of protons, neutrons, and electrons. Protons and neutrons are bound together at the atom's center to form what is known as the atom's nucleus (see figure 1A).

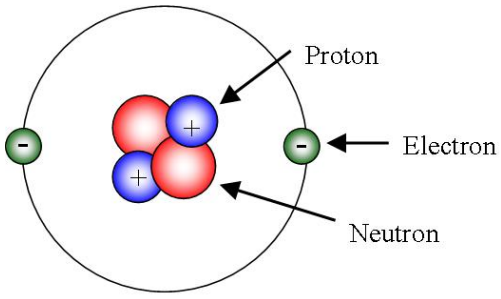
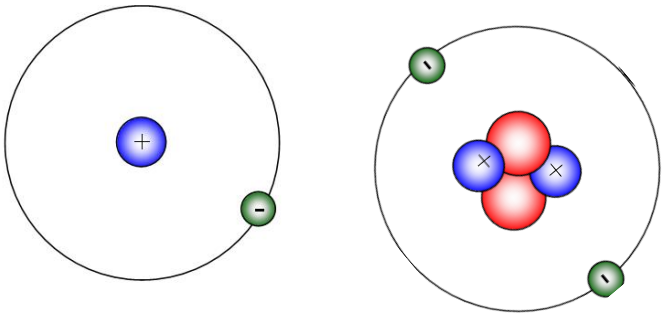


FIGURE 1A
The Atom

Protons

Protons are positively charged (+). A chemical element is defined by the number of protons in the atom's nucleus. The number of protons in any element is balanced by an equal number of electrons in the exterior of the atom. For example, hydrogen atoms have one proton and one electron. Helium atoms have two each (see figure 1B).



Hydrogen Atom (H) **Helium Atom (He)**

FIGURE 1B

A handy reference number for each chemical element is known as the atomic number, which equals the number of protons found in that element's atom. Thus, hydrogen has an atomic number of one and helium an atomic number of two. Atomic numbers ought not to be confused with atomic weight, or atomic mass, which are numbers representing the mass of all the atom's component parts, almost all of which is in the nucleus.

Neutrons

Besides protons, the nuclei of most atoms also contain neutrons, which have a slightly greater mass than a proton but have no electrical charge. The number of neutrons in an atom is usually the same as the number of protons but frequently will vary with the heavier elements. For example, 99.3 percent of the uranium found in nature has 92 protons and 146 neutrons in its nucleus and is identified as uranium-238 (92 + 146 = 238). The remaining 0.7 percent of the uranium found in nature has 92 protons and 143 neutrons, rather than 146, and is identified as uranium-235 (92 + 143 = 235). Uranium-238 (U^{238}) and uranium-235 (U^{235}) have a different number of neutrons in their nuclei and are two different isotopes of uranium.

Electrons

Electrons have negligible mass, a negative electrical charge, and orbit about the nucleus of the atom. Generally, the number of electrons in an atom matches the number of its protons producing a neutral charge for the atom as a whole. Electrons orbit about the nucleus in various levels of energy or shells. The first of these electron shells can accommodate no more than two electrons, the second eight (and with each succeeding shell the number increases). Atoms do not like their electron shells to be incomplete. Thus, if an atom has only few electrons it needs to fill its outermost electron shell, the atom tends to let this small number of electrons be torn off (producing a positive ion of the element). Conversely, if an atom has most of the electrons it needs to fill its outermost electron shell, the atom tends to seek electrons. Atoms that want to complete their electron shells explain what are known as chemical reactions. Chemical reactions, which only involve the combining of different electron shells of different elements into compounds, are quite different than atomic reactions. The latter involves the splitting and

fusing of the nuclei of atoms. Chemical reactions in contrast, only involve the electrons in the electron shells of elements.

Chemical Reactions

Most hydrogen atoms in nature have one proton (which is considered to have a mass of one and is positively charged) in its nucleus and one electron orbiting about the nucleus with a negative charge and (for our purposes) a negligible mass (see figure 2).

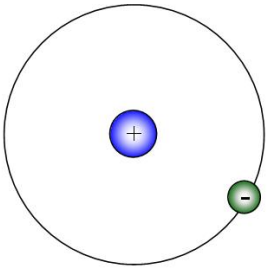


FIGURE 2
The Element Hydrogen (H)

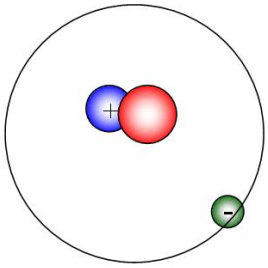


FIGURE 3
Deuterium—a Hydrogen Isotope

Some hydrogen in nature also has a neutron (which has a mass of one and is neutrally charged) attached to the proton in its nucleus. This isotope of hydrogen, known as deuterium, has the same number of protons, and hence the same atomic number as common hydrogen, but deuterium has an atomic weight or mass nearly twice as great as hydrogen (see figure 3).

Because hydrogen has only one electron in its outermost electron shell (see figure 4), it seeks one more electron to fill it out, for example, by sharing an electron with another hydrogen atom that also seeks an electron to fill its outermost electron shell (see figure 5).

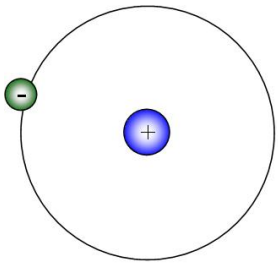


FIGURE 4
Hydrogen Atom

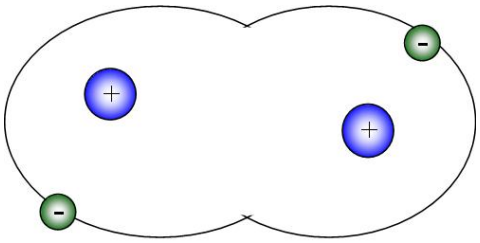


FIGURE 5
Two Hydrogen Atoms Sharing Electrons

Chemical Bonds and Conventional Explosives

Chemical Stability

When atoms share electrons as hydrogen does, they create molecules of an element or, if the atoms are of different elements, molecules of a chemical compound. The reason these bonds are made is that each atom's electron shell seeks the chemical stability that comes with being complete. The first electron shell needs two electrons to be complete, and the second shell requires 8. Helium (which has two electrons that complete the first electron shell) and neon (which has ten electrons, eight of which complete the second electron shell), both have a very low chemical reactivity with other elements—i.e., they have no need for additional electrons to fill their outermost electron shells, and so they do not seek to share electrons with other atoms and are, consequently, quite stable or inert (see figures 6 and 7).

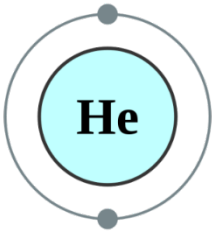


FIGURE 6
Helium Atom

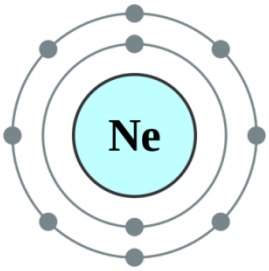


FIGURE 7
Neon Atom

Chemical Reactions and the Release of Energy

Physics tells us that systems seek greater stability by going to lower energy states. Thus, systems that have parts held together by weak forces will naturally want to move toward more stable ones. Whenever a less stable physical, chemical, or atomic system moves to a more stable state, the transition to greater stability is occasioned by the release of energy.

Consider the example of a house of cards that collapses when given a nudge: The cards fallen flat on the table are in a much more stable state than before (i.e. they are less likely to be rearranged by small amounts of force than when they were assembled in an unstable, upright house). This increase in stability is attended by the release of energy, i.e., when the cards fall and hit each other and the table, the movement and collision of the cards with one another and the table releases kinetic energy, causing a movement in the air, which produces a slight, audible, sound.

This release of energy also pertains to chemical systems. When hydrogen and oxygen combine to form water, a small amount of energy is supplied, H_2O is created and, because this reaction produces a chemical compound with a more complete set of electron shells, the system is

chemically more stable and energy is released in the form of light and heat (sees Figures 8 & 9).

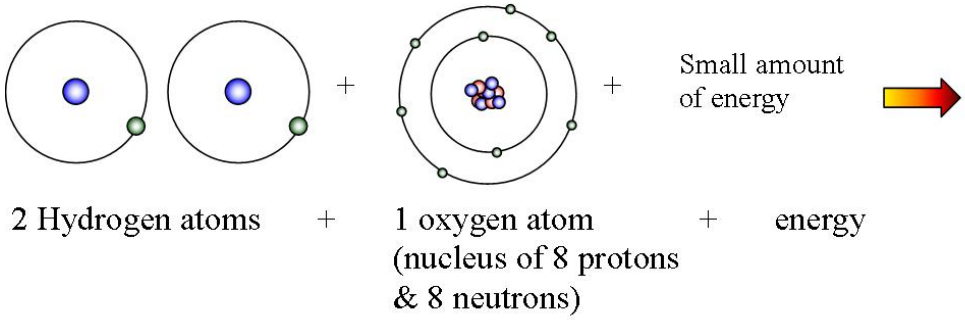


FIGURE 8

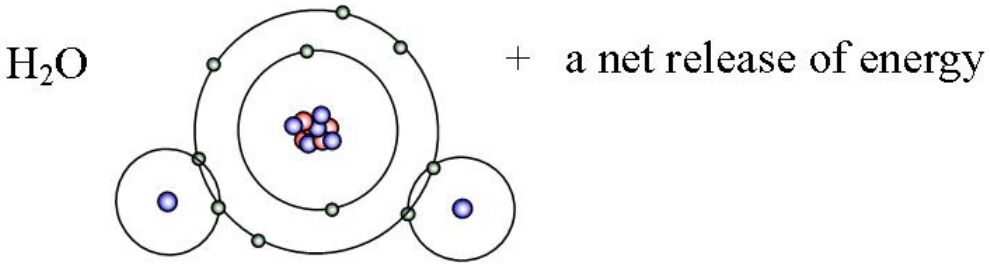


FIGURE 9

This hydrogen-oxygen reaction is the same sort of reaction that occurs in the combustion of most carbon-based fuels (e.g., the burning of wood or gasoline). Carbon atoms are combined with oxygen (O_2) molecules to form a more chemically stable compound, CO_2. In this compound the carbon atom's outer electron shell, which normally has four electrons in it, shares electrons with the two oxygen atoms. In this way, the combined system completes all of the outer electrical shells, moves to a more stable state than when the constituents are separate, and so releases energy (see Figure 10).

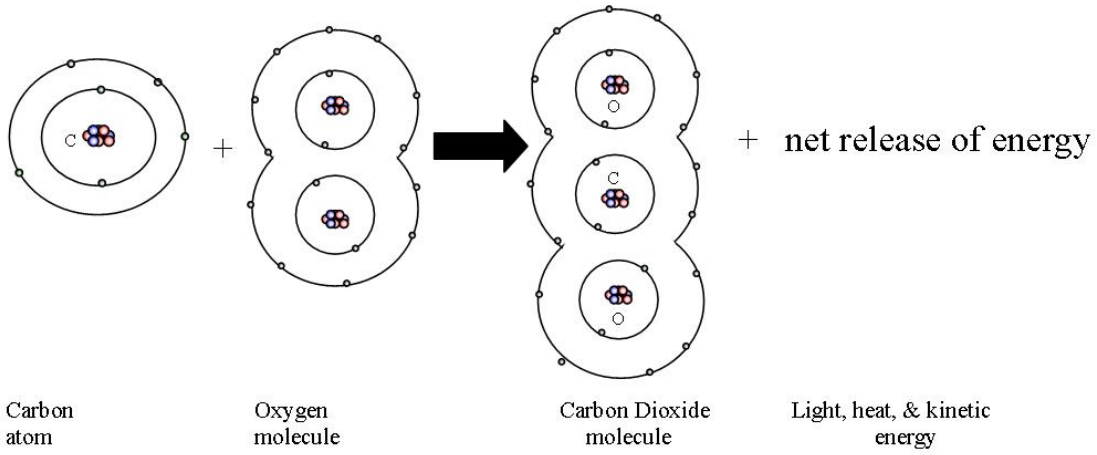


FIGURE 10

Binding Energy and Atomic Transmutations

The energy released in a chemical reaction only involves the rearrangement of the chemical bonds between atoms' electrons. The nucleus of the atoms is not disturbed. In fact, up until the turn of the century it was assumed that matter could never be destroyed or lost, that it could only be transformed from one state to another (e.g., solid, liquid, gas) or brought in or out of one or another chemical combinations (e.g., C + O_2 to produce CO_2 or CO_2 + energy to produce C and O_2). A corollary to this law was that energy was never lost; it was only altered from one form to another (e.g., heat to electricity as in coal-fired electrical production plants). Contrary to these "laws," we now know that a proton or neutron on its own weighs more than it does when it is in an atomic nucleus (approximately one octillionth of a gram - 1/1027) more. Neutrons and protons weigh less when they are present in an atom's nucleus because some of their mass is given up to supply the energy necessary to bind the protons to the neutrons and vice versa. That energy is referred to as binding energy. In any case, energy can be and is lost and turned into matter and matter can be and is lost resulting in a release of energy.

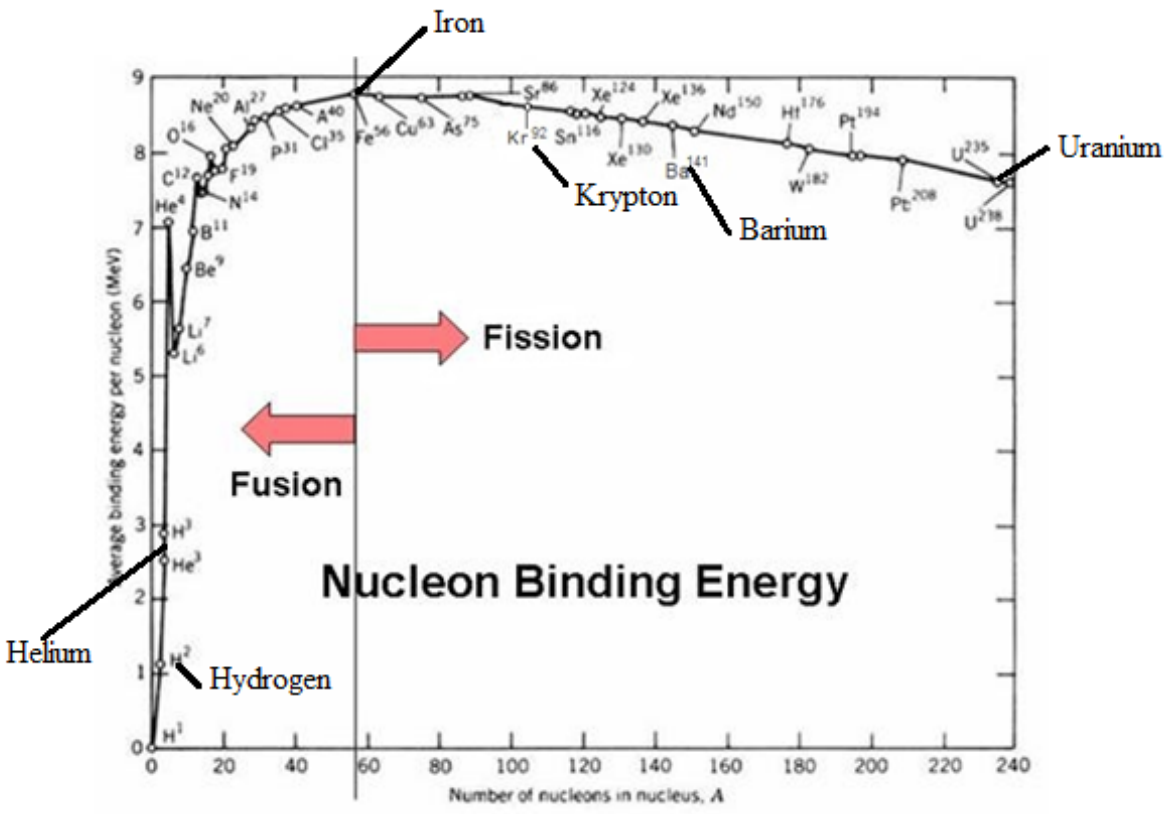


FIGURE 11
The Curve of Binding Energy
http://www.mpoweruk.com/nuclear_theory.htm

Thus, it is possible for heavy nuclei like uranium to be split, or to fission, into lighter ones like those of barium and krypton (which have a higher binding energy than uranium), and hydrogen nuclei can join together, or fuse, to form helium nuclei (which has a higher binding energy than hydrogen), with a consequent release of nuclear energy.

Transmutations

To move up the curve of binding energy—by decreasing the atomic mass of an atom's nucleus for all the elements weighing more than iron—requires that the mass of the nucleus of the atom be altered or transmuted. To alter the nucleus first requires getting to it by getting past the negatively charged outer electron shells of the targeted atom and dealing with the positive charge of the protons in the nucleus's center. To use protons for this task, then, requires penetrating past the attractive negative charge of the atom's electron shells and then to overcome the repulsive positive forces of the protons in the targeted atom's nucleus. More energy, generally, is necessary to transmute the atom with such positively charged particles than

might be released by the subsequent increase in the targeted nucleus' binding energy and mass. Thus, when Ernest Rutherford first transmuted nitrogen atoms into oxygen atoms in 1919 by bombarding nitrogen with positively charged alpha (α) particles (helium nuclei consisting of two protons bound to two neutrons); he did so only by supplying his alpha particles with tremendous energies. Once he did, however, atomic transmutations did result and were occasioned by the release of energy. Later in the 1930s, several transmutation experiments were conducted using protons and magnetic accelerators known as cyclotrons (see figure 12).[1]

FIGURE 12
An Early Cyclotron from the 1930s
Source: LBNL

By alternating positive and negative magnetic-electric fields, these machines could accelerate protons or alpha particles and shoot them into a target material. In the transmutation experiments of the 1930s almost all the elements targeted were transmuted into heavier isotopes. More important, when alpha particles were accelerated with cyclotrons against beryllium targets, new particles emerged, known as neutrons. The discovery of neutrons was critical to inducing and sustaining the nuclear fissioning of uranium and plutonium.

Fission

Unlike chemical reactions, Rutherford's early nuclear transmutations did not continue on their own (i.e. energy released from the initial reaction did not generally prompt further reactions); they failed to be self-sustaining. As a result, until the late 1930s the production of significant amounts of nuclear energy seemed unlikely. What changed scientific opinion regarding the possibility of producing large amounts of nuclear power were transmutation experiments that used neutrons to irradiate one of the heaviest known elements, uranium. In addition to splitting into smaller pieces, the uranium nucleus also emitted two to three neutrons that could continue the nuclear reaction by then fissioning other uranium nuclei.

1. You can read more about Ernest Rutherford here: "Ernest Rutherford: father of nuclear science," available from http://media.newzealand.com/en/story-ideas/ernest-rutherford-father-of-nuclear-science/.

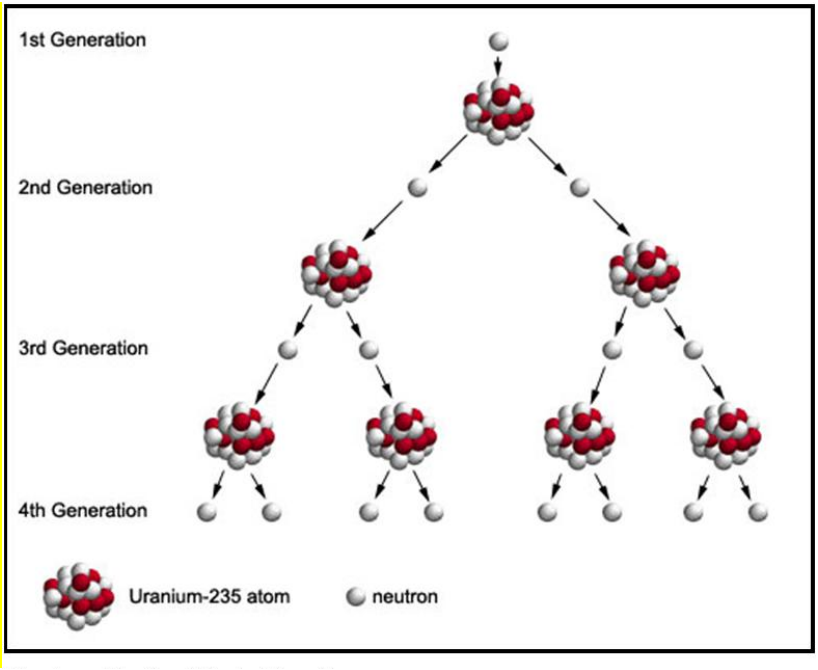


FIGURE 13
Nuclear Fission Chain Reaction with Uranium-235 Atoms
Source: atomicarchive.com

The uranium isotope most prone to fission is rare. Almost all, 99.3 percent, of uranium found in nature consists of the uranium isotope U^{238} (which is not very prone to fission). Almost the entire balance, or 0.7 percent, consists of the isotope U^{235} (which is quite prone to fission). When U^{235} does fission, it releases at least two neutrons and, therefore, the fissioning of U^{235} can sustain a chain reaction (see figure 13).

$E=mc^2$

The amount of atomic energy released from the fissioning of an element, such as uranium, depends on how much mass is lost in the course of the fissioning of the material—i.e., the difference in mass between the original uranium atom and that of the fission products that result after it fissions. Einstein determined that energy (E) equals mass (m) times the speed of light squared (c2). The speed of light (c) equals 300,000 kilometers per second (km/sec) or 3 x 10^{10} centimeters per second (cm/sec). Thus:

$$E = mc^2$$
$$E = m\,(3 \times 10^{10})^2$$
$$E = m\,(3 \times 10^{10})(3 \times 10^{10})$$
$$E = m\,(9 \times 10^{20})$$

To compute the amount of atomic energy produced here, we need only know m, or the quantity of mass in grams lost in the fissioning of uranium. This quantity is the difference between the mass of uranium before it is fissioned and the sum of the masses of its immediate fission fragments. In the case of U^{235} we know that when 1 kilogram (2.2 pounds) of uranium undergoes

fission, slightly less than 1 gram of mass is lost. Thus, the amount of energy released equals (1 gram)(9 x 10^{20} cm/sec). To get E, or energy expressed in terms of calories (a measure of heat), we simply divide our figure by the constant, 4.2 x 10^{7}:

$$E = \frac{9 \times 10^{20}}{4.2 \times 10^{7} \text{ calories}}$$

$$E = 2.1 \times 10^{13} \text{ calories}$$

To put this figure into some perspective, the largest U.S. conventional high explosive bomb recently used in Afghanistan, the GBU-43/B MOAB (Massive Ordinance Air Blast), had an explosive yield of 10 metric tons (22,000 pounds) of high explosives. The first atomic bomb to be used in war against the Japanese at Hiroshima released energy equivalent to approximately 16,000 tons of high explosive, or 1,500 times the amount of energy released by the MOAB. This 16-kiloton (kt) yield, it should be noted, was the result of the fissioning of about 1 kg of U^{235}.

Atomic Weapons Design Basics

Critical Size and Critical Mass

To achieve the energy release of a nominal uranium atomic weapon—i.e., of approximately 10 to 20 kt— 3 x 10^{24} atoms of U^{235} must fission. When one atom of U^{235} captures a neutron, fissions, and releases at least two neutrons, in 80 generations enough neutrons would be produced to fission all of the atoms in one kilogram of U^{235} and a 20 kt yield would be achieved. If 10^{-8} seconds pass for each generation, release of all 20 kt of yield would take less than one millionth of a second. (see figure 14).

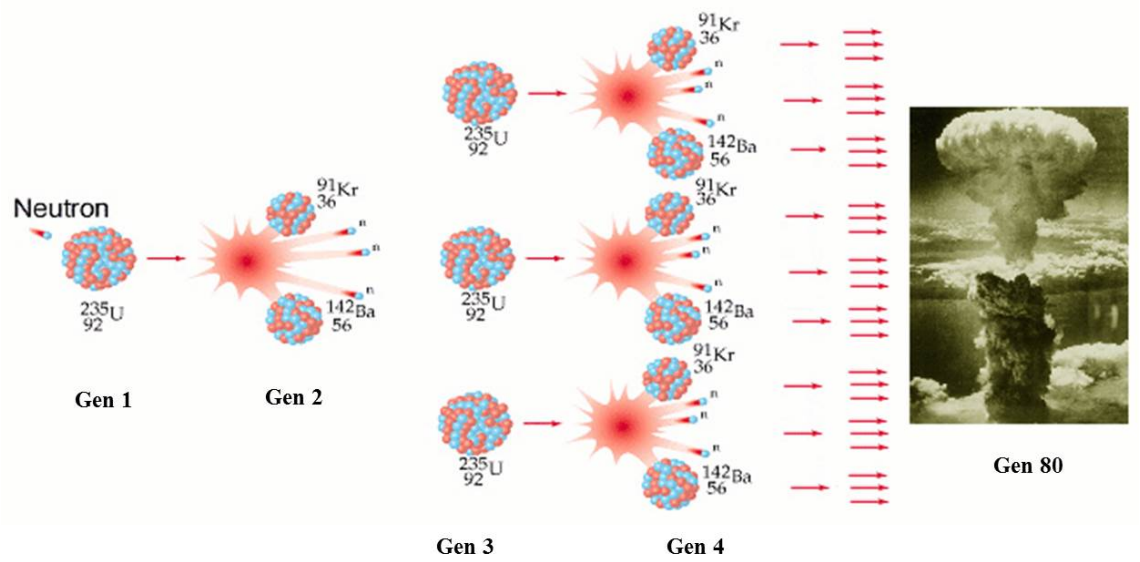


FIGURE 14

A Nominal Weapon Requires the Neutrons from 80 Generations of U^{235} Fission

Source: modified from https://edu.glogster.com/glog/nuclear-radiation-project/1mtdaaamhhp

All this, though, assumes that every neutron that is generated from fissioning material is absorbed to produce more fissioning. Assuming that every neutron will be absorbed, though, is overoptimistic. Often neutrons miss their target and escape the uranium altogether (see figure 15).

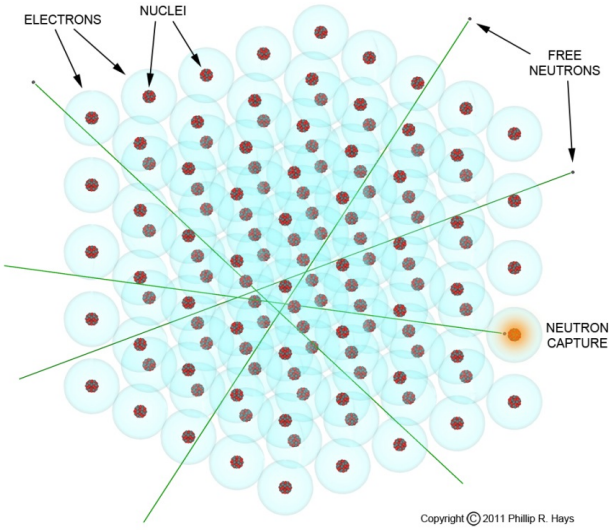


FIGURE 15

Neutron Capture by U^{235} Atoms

Source: http://www.okieboat.com/How%20nuclear%20weapons%20work.html

To achieve the energy release of a nominal bomb, then, it is necessary to ensure that the neutrons generated from a fissioned U^{235} atom are absorbed by another U^{235} atom. To ensure this, there must be sufficient bomb material. Lacking this, many neutrons will pass out of the mass of fissionable material without hitting enough nuclei to fission one kilogram of material. To fission one kilogram of weapons material, then, you need more than one kilogram of it (see figure 16).

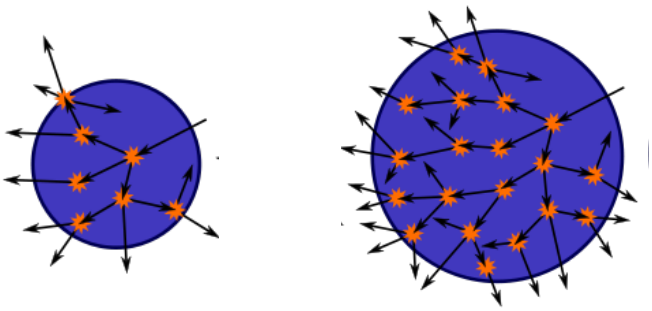


FIGURE 16

Neutron Escape

Diagrammatic representation of effect of size of fissionable material on relative loss of neutrons by escape.

In the case of the critical size of material in the diagram on the right, the material is of the same density as that on the left but there is a much smaller ratio of surface area to volume with the larger sphere and, hence, an increased likelihood that many more fissionings will take place.

To achieve critical size in the case of U^{235} without using any additional weapons designs techniques to enhance fissioning, you would need approximately 50 kilograms of material just to get a sustained chain reaction. It is possible, though, to use far less material to make a reliable nominal yield bomb.

Reducing Critical Size and Critical Mass

To reduce the critical size or mass to achieve a given yield one could:

1. Surround the device with a neutron reflector such as beryllium so neutrons that passed through the weapons material could be reflected back and, thus, increase the likelihood of achieving additional fissioning. This can reduce the critical mass by a factor of two to three.

2. Squeeze the weapons material to make it denser at the time of detonation. This would bring the atoms of uranium or plutonium closer together and, thus, increase the likelihood of them being hit by generated neutrons. A doubling of the density increases

the expected yield of a given amount of nuclear weapons material four-fold or allows one quarter of the amount of material to be used to produce a given yield.

3. Increase the speed with which the nuclear weapons material is brought to criticality. Before one detonates a nuclear weapon, one wants to make sure that the weapons material is in a subcritical mass or masses, otherwise just a few stray neutrons might set off a significant amount of fissioning before you wanted to set off the weapon. Not paying sufficient attention to the need to bring these masses together quickly, also, risks having the material begin to fission on its own and blow apart, pre-detonate, or "fizzle" before a sufficient number of atoms have a chance to fission and produce the desired yield. Conversely, increasing the speed at which the subcritical masses are assembled into a critical mass, increases the yield for any given amount of nuclear weapons material or reduces the amount of fissile material needed to produce a given yield

4. Decrease the bomb's early tendency to blow apart by encasing it with a heavy metal casing, like steel, and a tamper such as tungsten-carbide or U^{238} that will resist this tendency (by increasing the inertia of the bomb's exterior) increasing the amount of fissioning occurs before the bomb blow itself apart

5. Increase the number of neutrons that start the reaction at the time the bomb is set off. This can be done by having a neutron source or generator release neutrons shortly after the bomb's detonators are set off or by injecting tritium and deuterium gas into the center of the bomb shortly before fissioning begins. In the latter case, the tritium and deuterium will undergo fusion releasing additional neutrons, which in turn, will induce more fissioning.

Basic Aspects of Uranium and Plutonium Bomb Designs

Some of the techniques noted above were used in the United States' first two weapons employed against Japan. These atomic bombs were different from one another. The Mark-1 "Little Boy" design bomb dropped on Hiroshima used U^{235} as weapons material and employed a gun-barrel design to assemble this material to into a critical mass. In contrast, the Mark-3 "Fat Man" bomb dropped on Nagasaki used plutonium and an implosion design to bring this material to criticality.[2]

2. Atomic Heritage Foundation, "Little Boy and Fat Man," available from http://www.atomicheritage.org/history/little-boy-and-fat-man, accessed on March 14, 2016

Why did the United States use two different weapons materials and two different bomb designs? First, it is a general practice of American weapons research to pursue several possible paths in developing new capabilities. Second, each material and design have their own unique advantages. Uranium-235 by itself emits very few neutrons spontaneously (i.e., it has very low neutron background). This reduces the possibility of pre-detonation caused by stray neutron emissions when subcritical masses of the material are being brought together to produce a detonation. This, in turn, allows use of a relatively simple method of bringing the subcritical masses together—the gun method—about which more will be said later.

On the negative side, U^{235} is difficult to produce. U^{235} is quite scarce in nature and, because it is an isotope of uranium, it cannot be separated chemically from the more common, less easily fissionable U^{238}. To produce a significant amount of U^{235} from the uranium found in nature, you must use technically demanding physical separation processes that separate the main isotopes. One of the most successful early methods of uranium enrichment was gaseous diffusion. To build such a plant is a major engineering and construction undertaking. Also, to operate a gaseous diffusion plant requires large amounts of electrical power. When all three U.S. uranium gaseous diffusion enrichment plants were operating in the early 1950s, they consumed nearly ten percent of all the electricity produced in the United States.

This set of production challenges was a key reason why the Manhattan Project also pursued a bomb design that used plutonium. Plutonium is produced in reactors when a U^{238} nucleus captures a neutron. This transmutes the U^{238} into U^{239}, which is unstable and decays in 23 minutes into neptunium 239 (NP^{239}) which, in turn, is unstable and decays into plutonium 239 (Pu^{239}) in 2.3 days. Plutonium, being a different element from uranium, can then be separated from uranium in the reactor using a relatively simple chemical process called chemical separation or reprocessing. The most desirable isotopes of plutonium for bomb purposes are the odd isotopes, Pu^{239} and Pu^{241}, which throw off the least heat and emit fewer neutrons simultaneously than Pu^{240} and Pu^{242}. Plutonium is generally produced in nuclear reactors fueled with natural uranium or uranium that has been slightly enriched. Figures 17 and 18 show schematics of the reactions describing the transmutation of U^{238} into Pu^{239}.

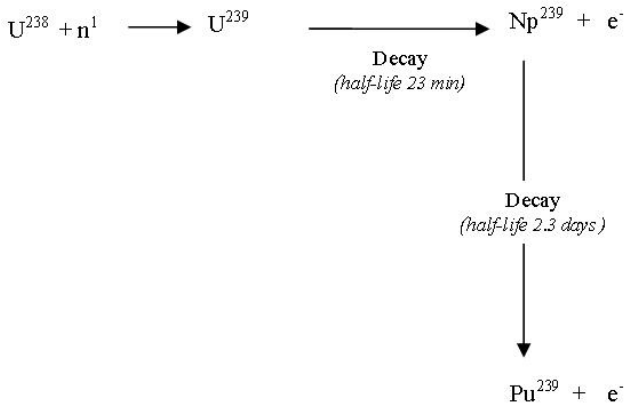


FIGURE 17
Transmutation of U^{238} into Pu^{239}

Np^{239} represents neptunium and Pu^{239} plutonium. The symbol e^- designates an electron. As noted above, uranium-238 cannot be used as the basic fuel for a self-sustaining chain reaction because it can only be fissioned by very high-energy or "fast" neutrons and most fission neutron have insufficient energy to accomplish this. However, the artificially created element plutonium has isotopes, Pu^{239} and Pu^{241} do. Pu^{240} and Pu^{242} are formed when Pu^{239} absorbs neutrons. In 1945, using Pu^{240} or Pu^{242} in nuclear weapons was more challenging than using Pu^{239} because the even isotopes of plutonium (240 and 242) are much more prone to spontaneous fission and so release more neutrons than the odd isotopes of plutonium (239 and 241). These challenges, however, can largely be overcome with several nuclear weapons engineering fixes of the sort noted above.[3]

In the case of Pu^{239}, if it sits long enough in a reactor, it will absorb neutrons and transmute into Pu^{240}. The absorption of a neutron is portrayed below in figure 18.

3. For more on this, see Bruce Goodwin's presentation in the Appendix on p. 48.

As noted, the presence of Pu^{240} (and Pu^{242}) in a weapon's core can induce fissioning in crude

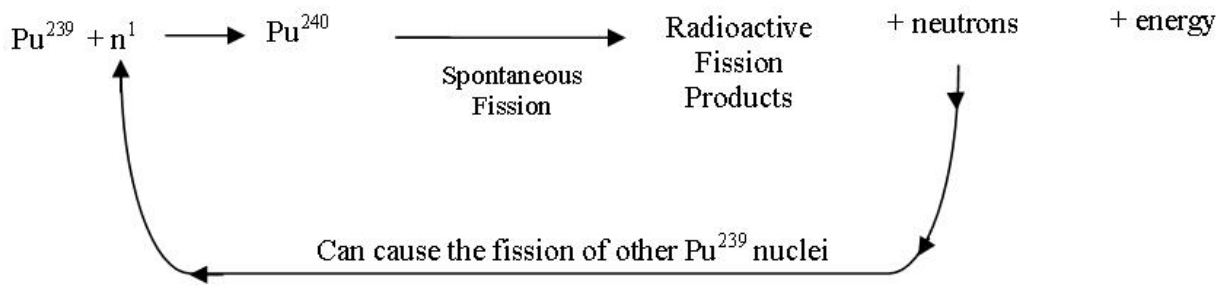


FIGURE 18
Decay of Pu^{239} into Pu^{240}

designs before the material is brought to a critical enough state to get the desired explosive yield. This will reduce the expected yield of the weapon. Because of this "predetonation" problem associated with plutonium, Manhattan Project bomb designers determined that the gun-barrel design was impractical for setting off a reliable plutonium bomb and they had to come up with another way to bring the subcritical masses of plutonium together much faster.

This limitation does not apply to U^{235}. Because of that material's relatively low level of neutron emissions, it is possible to use conventional gun barrel ballistics to bring subcritical masses together to create a large explosion. The Mark-1 uranium bomb "Little Boy" dropped over Hiroshima used a gun-barrel design to slam a subcritical slug of U^{235} into another machined, subcritical, cylindrical doughnut of the material (see figure 19 on the next page).

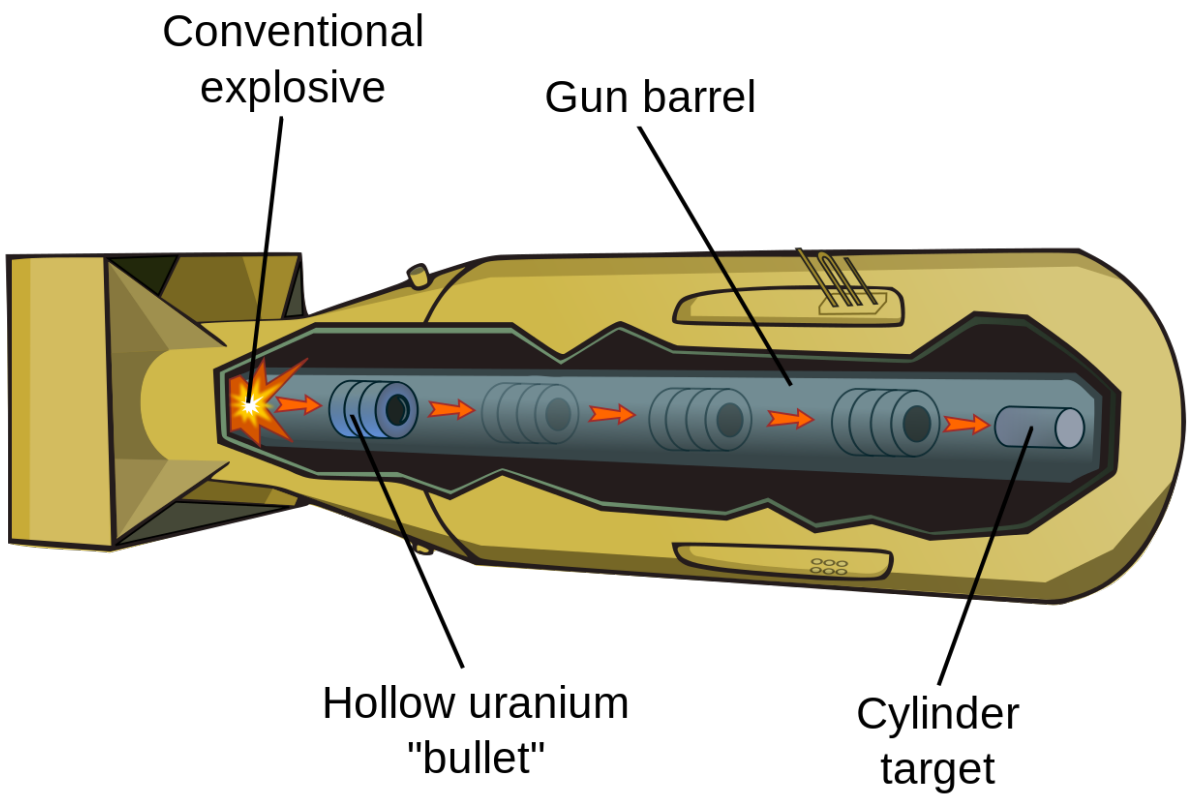


FIGURE 19
Basic Gun Barrel Design

For plutonium, the Los Alamos National Laboratory came up with a new bomb assembly concept called implosion. Rather than use high explosives to shoot one subcritical mass into another, the Mark-3 used high explosives to crush a subcritical sphere of plutonium creating a dense super-critical ball. The effectiveness of the implosion approach effectively overcame the plutonium predetonation problem. It also reduced the amount of fissile material needed to produce a given yield. This was the case whether one used plutonium or uranium to fuel the bomb. As a result, the gun-barrel design was all but abandoned in future U.S. uranium and plutonium bomb production efforts.

Generally, the amount of plutonium required to make a critical mass increases as the proportion of even isotopes of plutonium present in the material becomes greater. Similarly, the more U^{238} that is present in comparison to U^{235} in the uranium used in a weapon, the greater the amount of material required to make a uranium bomb. You want more of the uranium to be U^{235} and more of the plutonium to be the isotopes Pu^{239} and Pu^{241} in order to reduce the amount of material necessary to make a bomb. That said, it is possible with efficient implosion designs to make a plutonium bomb out of any isotopic mixture of even and odd isotopes of plutonium. This

is not the case, however, with uranium. As the U^{235} content declines to roughly 20-40% (and the amount of U^{238} increases to 60-80% content) it becomes physically impractical to make a workable bomb as the critical mass amount and the needed amounts of explosives to assemble it become excessively large. This is represented in figure 20, which shows the amount of plutonium and uranium required in a very basic implosion device.

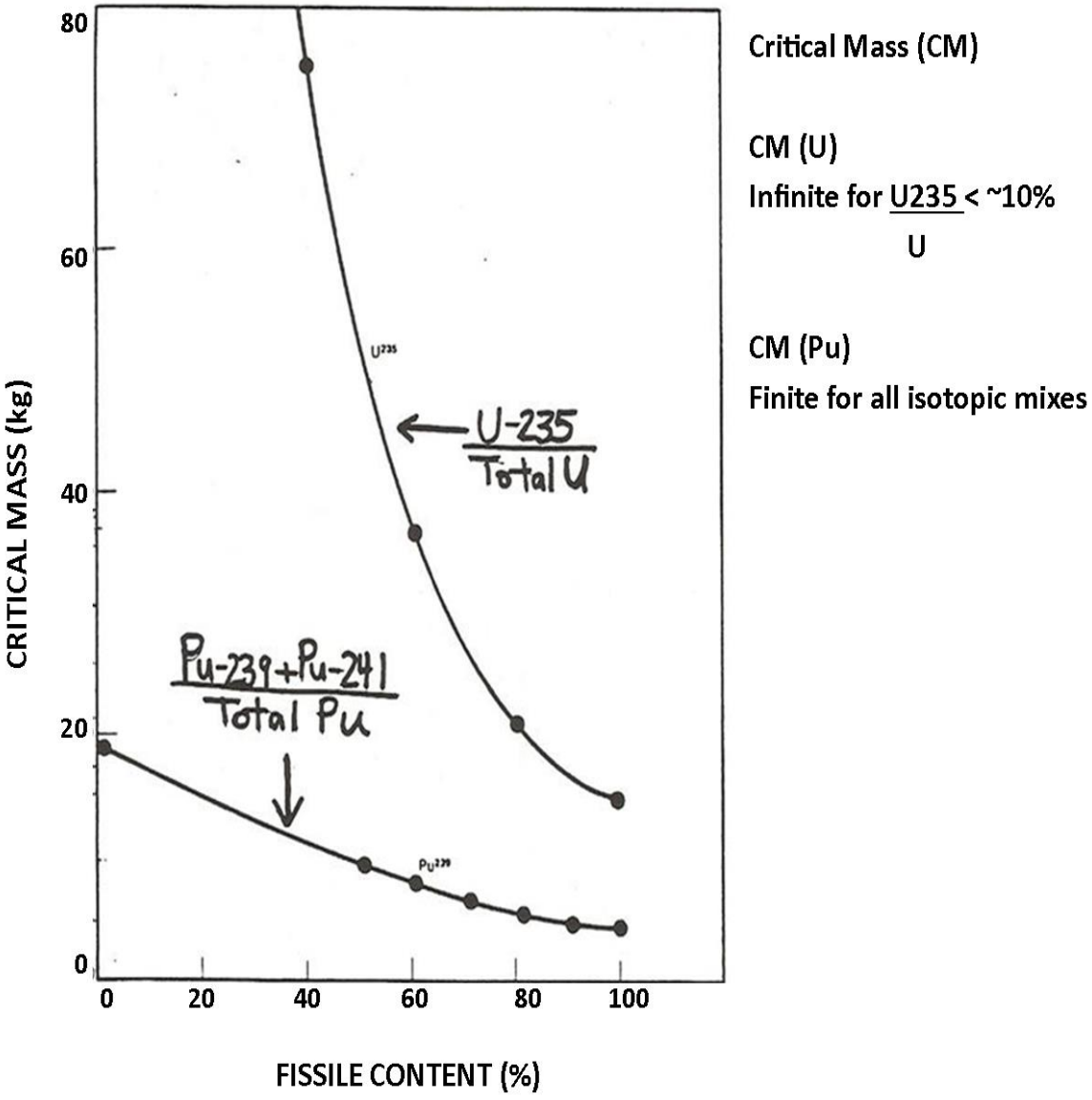


FIGURE 20

Critical Mass of Uranium and Plutonium as a Function of Isotopic Mix.

***Assumes the use of a neutron reflector and a heavy casing**

THE FIRST NUCLEAR BOMBS

The first nuclear weapons ever developed—the Mark-1 uranium gun-barrel design "Little Boy" and the Mark-3 plutonium implosion design "Fat Man" were fission bombs.

Gun-barrel Design

The gun-barrel design, referred to as the Mark-1, was the first of two bomb designs developed by the scientists of the Manhattan Project during World War II.

The gun-barrel design brings two subcritical masses of fissile material together very rapidly to form a supercritical mass that will fission in a self-sustaining chain reaction. The bomb has a long tubular shape with a high explosive at one end that shoots a subcritical piece of material (the "bullet" or "projectile" consisting of U235 rings or disks) down a barrel into another subcritical piece of material (a cylindrical "target") held at the opposite end of an interior channel of the barrel. Because the speed at which the two pieces of fissile material were brought together was relatively slow, only enriched uranium was a suitable fuel for gun-barrel designs.[4]

The Mark-1 bomb used highly enriched uranium (HEU) for the subcritical projectile and target components. The uranium target consisted of six U^{235} rings or disks backed by a tungsten-carbide disk with a steel backplate, which served as a neutron reflector. A detonator at the end of the barrel set off a conventional explosive (cordite), which propelled the U^{235} projectile down the length of the barrel and into the U^{235} target. (see figure 20).

4. Plans for a plutonium-fueled gun barrel design, the Mark-2 bomb "Thin Man," were made during the Manhattan Project. Because plutonium has a higher spontaneous fission rate than uranium, a higher velocity was necessary to assemble the two subcritical plutonium components. The estimated length necessary to allow the plutonium projectile to reach a suitable velocity was 18 feet (5.5 meters); the length of the Mark-2 bomb made it aerodynamically unstable. In addition, the plutonium actually produced for the bomb by the Hanford reactors had a higher rate of spontaneous fission than anticipated, which increased the risk of pre-detonation. None of the bombers in existence at the time were capable of carrying a bomb with a gun barrel long enough to achieve the velocity necessary to avoid pre-detonation. As a result, plans for the Mark-2 were shelved and work increased on the implosion method design. For more information, see http://en.wikipedia.org/wiki/Thin_Man_(nuclear_bomb).

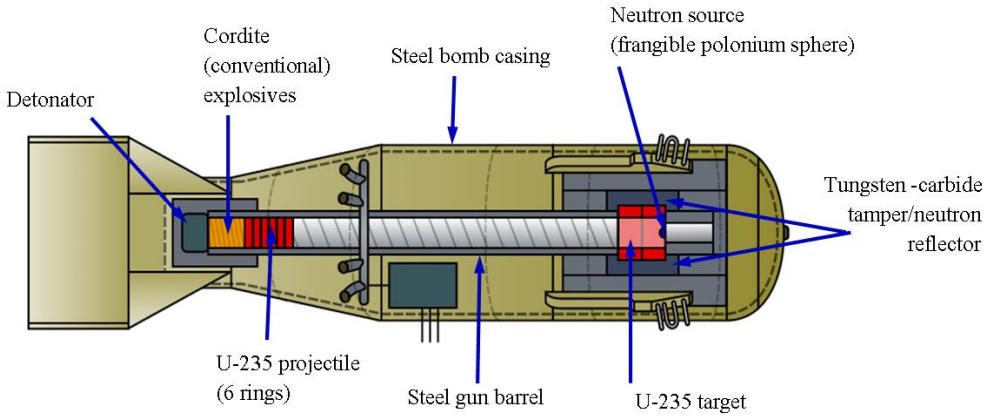


FIGURE 21

The Mark-1 Bomb

Gun-barrel assembly with U^{235} projectile and target

To reduce the tendency of the bomb blowing apart too early, a tamper made of tungsten-carbide was installed. A tamper is a layer of dense material surrounding the fissile material. The tamper slows down the expansion of material from the fission reaction, allowing more time for the neutrons to react with other nuclei. In the early weapons designs, the tamper surrounded and was bonded with the core of fissile material to form the weapon pit. A neutron reflector reflects neutrons to increase the amount of fission the fissile material undergoes before the bomb is blown apart. Often the tamper doubles as the reflector.

In addition to having a heavy steel casing and a tamper/neutron reflector, both the gun barrel and the implosion Manhattan Project designs had a crude neutron source to help get the atomic reaction going at the optimal moment once the weapons material was brought together to form a supercritical mass. To produce a small surge of neutrons, the early bombs used a small sphere of beryllium and polonium-210. When beryllium and polonium are crushed, it increases the surface area of the material significantly. This, in turn, creates a slight surge in neutron emissions as alpha particles from the polonium impinge more readily on the beryllium, releasing more neutrons than would otherwise be the case.

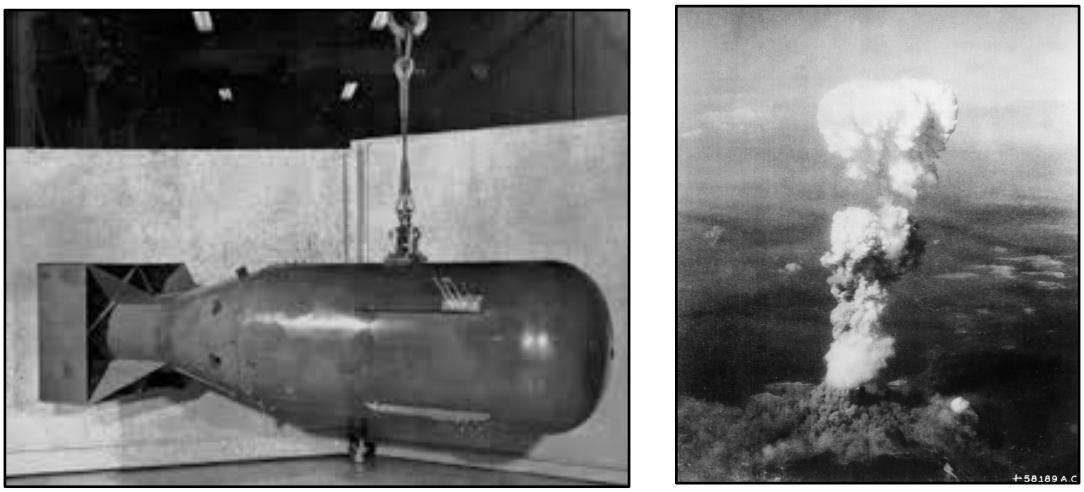


FIGURE 22
The First Mark-1 Bomb: "Little Boy"
It was 10 feet long, had a diameter of 28 inches, and weighed 4,400 kg.

The bomb dropped on Hiroshima on August 6, 1945, was a Mark-1 weapon nicknamed "Little Boy." It contained 64 kilograms (kg) of HEU and had a yield of approximately 15 kilotons (kt) (see figure 22). Even in 1945, the design was considered relatively simple, and the scientists who developed the bomb felt confident enough in its success that the design was not tested before "Little Boy" was dropped on Hiroshima.[5]

Implosion Design

As noted above, to overcome the risk of pre-detonation caused by spontaneous neutron emissions from plutonium, the scientists of the Manhattan Project developed a second method—implosion—to bring a subcritical mass of fissile material to criticality.

The implosion design uses a shell of high explosive lenses (shaped changes), arranged into a sphere, to create a shockwave that compresses a subcritical sphere of fissile material into a supercritical mass. The material becomes critical much faster than the gun barrel design, reducing the opportunity for spontaneous neutron emissions to trigger fission before the critical mass has been achieved. Because of this, both plutonium and uranium are suitable fuels for implosion designs.

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5. Atomic Archive, "The Story of Hiroshima: Designs of Two Bombs," available from http://www.atomicarchive.com/History/twocities/hiroshima/page2.shtml.

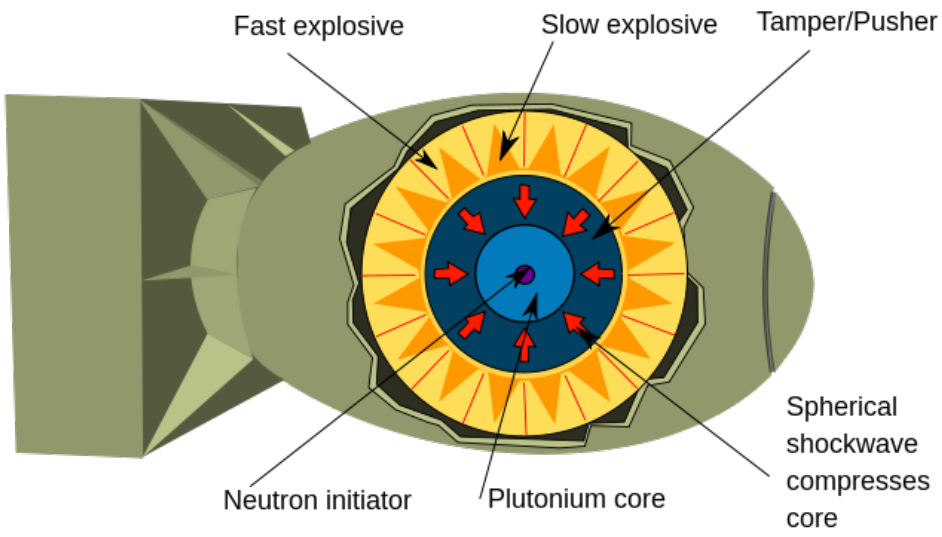


FIGURE 23
Mark-3 Implosion Bomb
Core was a solid sphere of plutonium

The first implosion design, known as the Mark-3 (see figure 23), used a solid, subcritical sphere of plutonium surrounded by a tamper/reflector consisting of a thick layer of U^{238} in a configuration known as the solid-pack design. The plutonium core used two Pu-239 hemispheres. Again, a polonium-beryllium neutron initiator—similar to that used in the Mark-1 bomb—was placed in a small pocket at the center of the plutonium; when crushed by the imploding material, the neutron initiator released enough neutrons to boost the chain reaction.

The uranium U^{238} tamper increased the efficiency of the bomb by holding the fissioning material in the core together a bit longer before the bomb blew apart (so that more material could fission, resulting in a higher yield).

The tamper doubled as a neutron reflector in the Mark-3 design. As discussed in the section on fission, U^{238} does not readily absorb the regular (slower speed) neutrons generated by most fission reactions. As a result, neutrons that escape the fissioning plutonium core are "reflected" off the surrounding layer of U^{238} back towards the core, increasing the chance they will be absorbed by the fissioning core and contribute to the chain reaction.

The Mark-3 design also had a "pusher" located between the U^{238} tamper and the outer shell of high explosives. Pushers can be made out of aluminum, beryllium or an alloy of the two. The pusher's purpose is to modulate the shock wave created by the explosive shell. The pusher

allows the shockwave created by the explosion of the weapon's high explosive "lenses" (see below) to remain spherical in shape and so compress the core material uniformly.

A series of 32 high explosive lenses, arranged in a soccer-ball pattern, formed the outer shell of the weapon (see figure 24). The explosives were detonated simultaneously, creating the shockwave that traveled inward to the weapon's core. The shockwave created by the explosives compressed the core, increasing its density and resulting in the supercritical mass necessary for the fission reaction to occur.

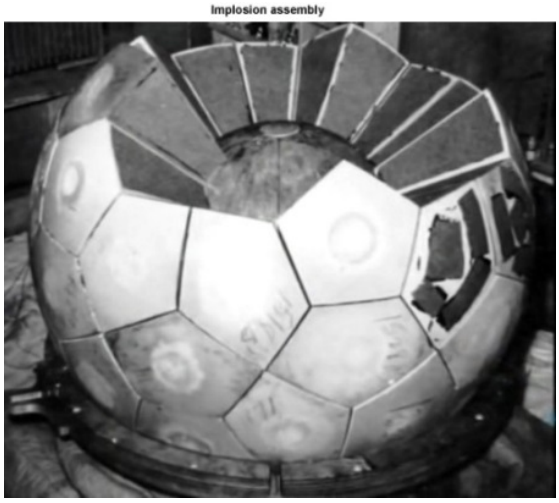


FIGURE 24
High Explosive Lenses
Arranged in the typical "soccer ball" pattern

The explosive shell of the bomb contains several layers. At the outermost level are the detonators, which are triggered by a high-speed switches known as krytrons. The detonators, also known as initiators, are attached to high velocity explosives. The high velocity explosive then sets off a lower velocity explosive. This changes the shape of the shockwave so that it hits all points of the weapon's core simultaneously and creates a spherical implosion (see figures 25 and 26).

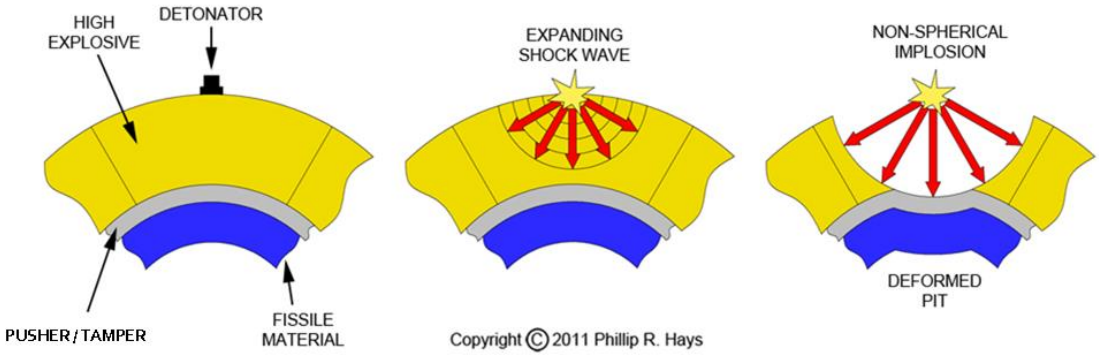


FIGURE 25

High Velocity Explosives Only

Modified from Source: http://www.okieboat.com/How%20nuclear%20weapons%20work.html

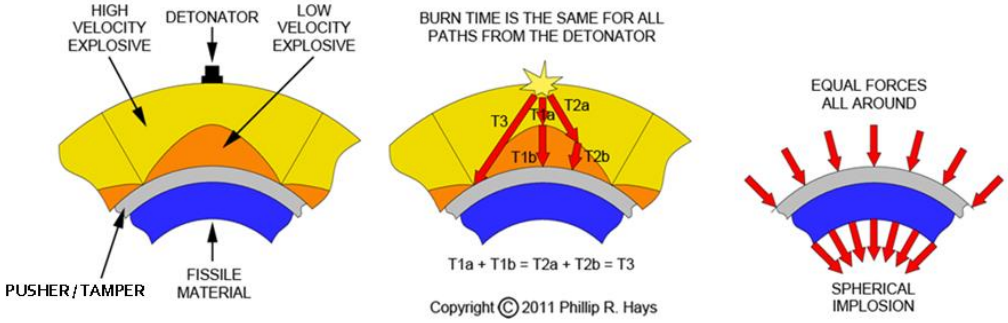


FIGURE 26

Combination of High and Low Velocity Explosives

Modified from Source: http://www.okieboat.com/How%20nuclear%20weapons%20work.html

The complete system of the fissile core, tamper/reflector, pusher, explosives and detonators—i.e. everything required to make the weapon explode—is known as the physics package. The physics package is then placed inside the bomb casing to form the final weapon (see figures 27 and 28).

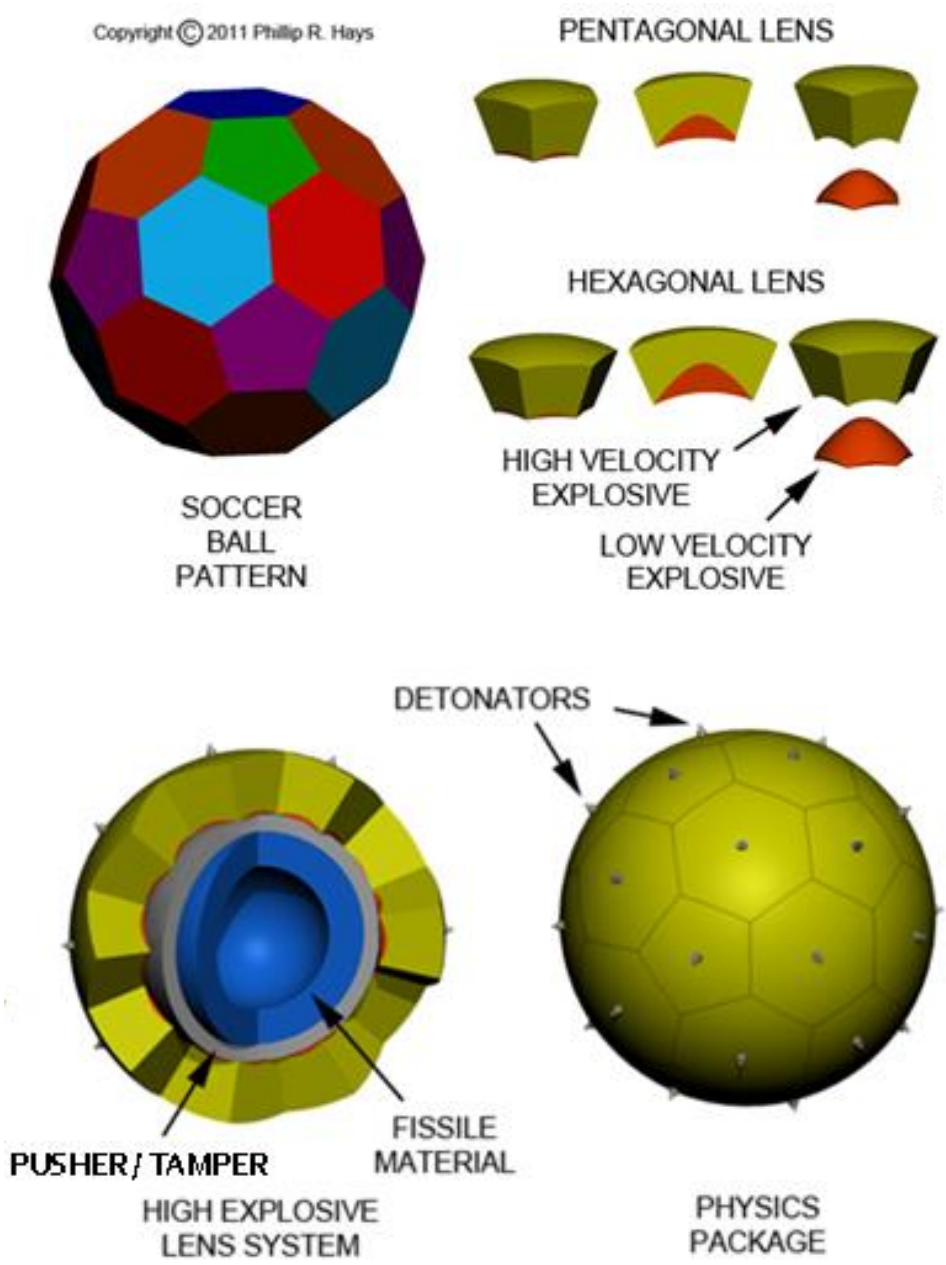
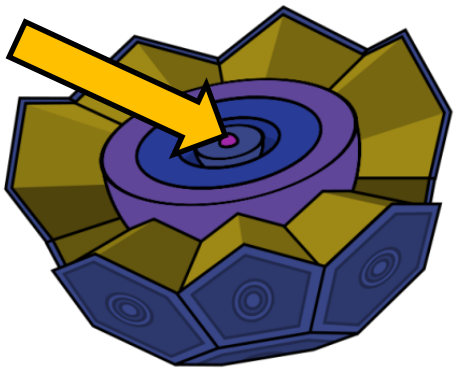


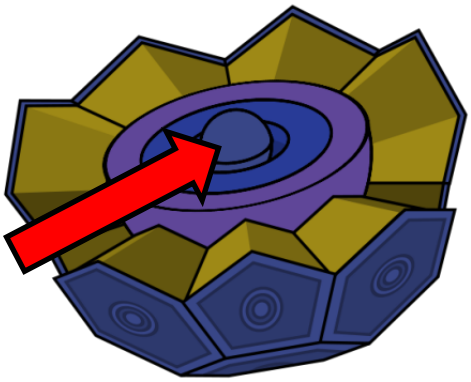
FIGURE 27

Nuclear Weapon Physics Package

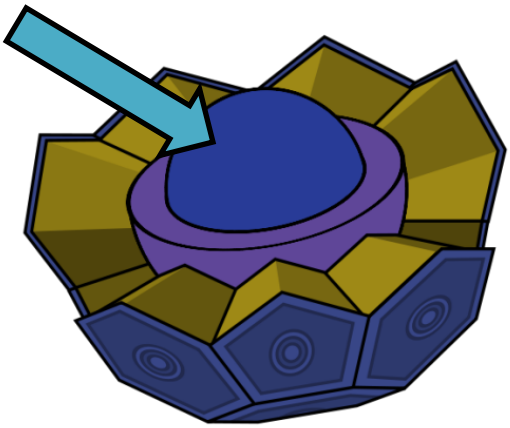
Modified from Source: http://www.okieboat.com/How%20nuclear%20weapons%20work.html



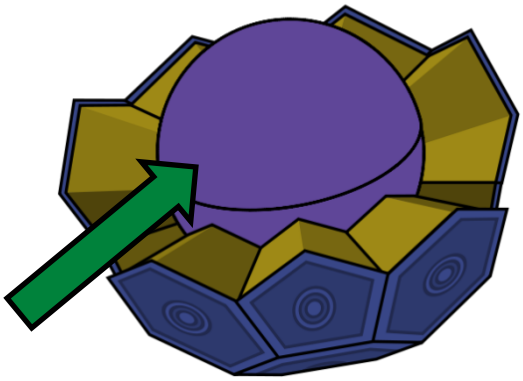
A: Neutron initiator



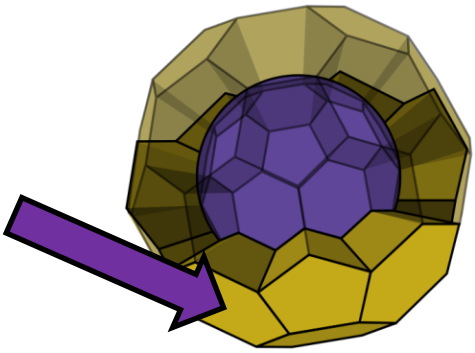
B: Plutonium Core



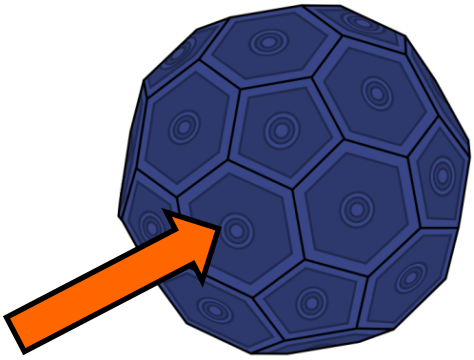
C: Tamper



D: Pusher



E: Explosive lenses



F: Outside plates and detonators

FIGURE 28
Nuclear Explosive Components of a Mark-3 Bomb

FIGURE 29

The Gadget

Many of the wires seen in the photo above are connected with detonators/initiators that are triggered by krytrons.

The Mark-3 design was used in a device known as the "Gadget" (see figure 29) for the world's first nuclear test at the Trinity site in New Mexico on July 16, 1945. This design was also used in the bomb "Fat Man," (see figure 30) which was dropped on Nagasaki on August 9, 1945. The "Fat Man" bomb used a core with 6.2 kg plutonium and had a yield of approximately 21 kt.[6]

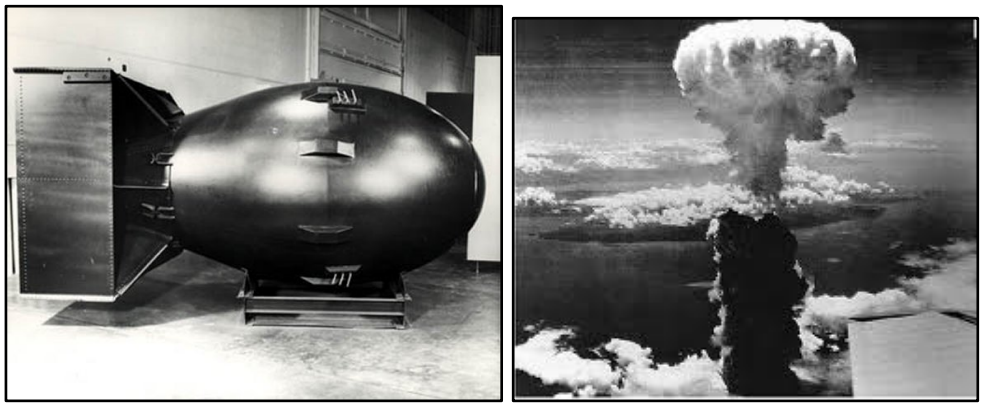


FIGURE 30

The Mark-3 Bomb "Fat Man"

It was 10 feet 5 inches long, had a diameter of 5 feet, and weighed 4,600 kg.

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6. More about the Trinity testing site can be found here: "Trinity Site: History," available from http://www.wsmr.army.mil/PAO/Trinity/Pages/TrinitySiteHistoryAcopyofthebrochuregiventositevisitors.aspx.

Post-1945 Designs

SINGLE-STAGE FISSION IMPLOSION DESIGNS

As noted above, single-stage nuclear weapons designs refer to any nuclear weapon in which a majority of the yield is derived from fission reactions. Below are some of the key design upgrades that were made to the original Mark-3 implosion design.

Levitated Pit with a Solid Core

The first major improvement on the Mark-3 design was to put a space between the fissile core of the weapon and the tamper. Instead of having the explosive lenses, neutron reflector and tamper/pusher all bonded directly to one another and the solid core (as in a "solid-pack design"), the levitated pit design created a space between the fissile core and the tamper/pusher, neutron reflector and explosive lenses. It did this by mounting the fissile core on small cones/tubes or by suspending the fissile core on wires such that there was a space between the fissile core and the pusher/tamper. (See figure 31).

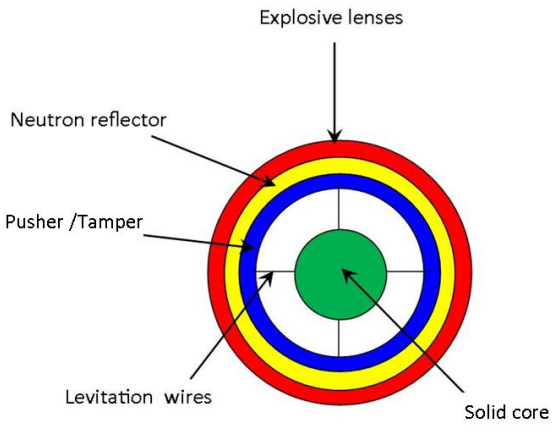

FIGURE 31
Levitated Pit with Solid Core Design

This empty space between the tamper and core causes the high explosive shockwave to accelerate along with the pusher/tamper before hitting the core, thus improving the rate of compression and the efficiency of the weapon. The effect is similar to how a hammer hits a nail: Placing a hammer directly on the nail and pushing provides less leverage than swinging the hammer through an empty space before hitting the nail's head.

Increasing the compression on the pit meant that levitated pit would implode faster and become even denser and so could generate a given yield using less fissile material. Or, the same amount of fissile material could be used to reach a greater yield than with a solid-pack design.

The levitated pit design was used by the United States in 1948 in a Mark-4 design in a series of three tests known as Operation Sandstone.[7]

Levitated Pit with a Hollow Core

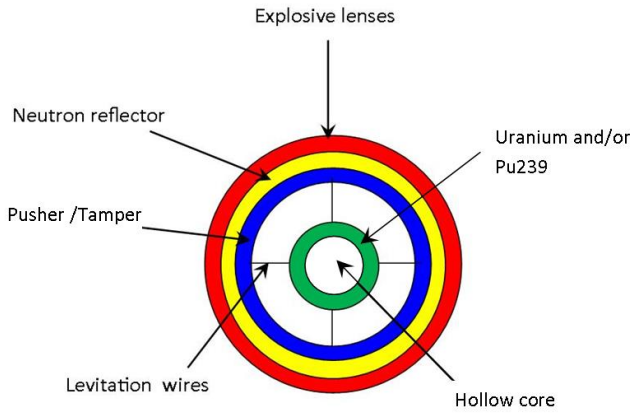

FIGURE 32
Levitated Pit with Hollow Core Design

The Operation Sandstone tests all tested devices with a solid core. A hollow core design is different. It uses a subcritical, hollow sphere of plutonium (or a plutonium-uranium composite) as the core. The benefit of the hollow core is that it requires far less tamper and fissionable materials, and explosives. The reason why is similar to the advantages of levitating the pit. By having a hollow space in its center, it is possible to increase the speed of assembly of the plutonium even further. This, in turn, allows the bomb to use a smaller U^{238} tamper, less plutonium fuel, and less explosive to produce a given yield as compared to solid-pack design. As a result, the bomb can be made smaller and lighter than solid-pack designs.

The hollow core design also enables multiple crits (critical masses) worth of fissionable material to be used in the core without going critical before detonation, thus allowing a greater yield.

The levitated pit and hollow core design was originally contemplated as the first device for the Manhattan Project. The solid-pack design, however, required less sophisticated tampers and explosives and was employed instead. After the Sandstone nuclear tests, though, the United

7. Nuclear Weapons Archive, "Operation Sandstone," available from http://nuclearweaponarchive.org/Usa/Tests/Sandston.html.

States no longer tested any solid core designs. Great Britain's first nuclear test ("Operation Hurricane" on October 3, 1952) employed a levitated pit hollow core design.

High Yield Pure Fission

As noted before in the discussion of the hollow core levitated pit, a high yield single-stage weapon can be made without boosting by using more than one critical mass of fissile material in a hollow core design.

The Mark-18 high yield pure fission bomb developed by the United States, sometimes known as the Super Oralloy[8] Bomb (SOB), was a hollow core implosion design that contained 60 kg of HEU, an amount equal to at least four critical masses. The presence of so much fissionable material increased the risks of accidental detonation. Neutron absorbing chains made of aluminum and boron were inserted into the hollow cavity of the core to prevent the collapse of the core in the event of an accident—such as one of the high explosives detonating early. The bomb was armed by removing the chains.

FIGURE 33
Exterior of Weapons Casing for Violet Club

This design was tested by the United States only once; the "King" shot of Operation Ivy was successfully made on November 16, 1952, in the Pacific. At a yield of 500 kt, it was the largest pure fission bomb ever tested by the United States. Fewer than 100 weapons of this design were built.[9]

The British built a similar device as an interim measure to achieve a megaton yield while their fusion weapons were being developed. Known as "Violet Club" (see figure 33), this design used over 70 kg of HEU and had a system of 72 high explosive lenses. It was not tested but had an estimated yield of 500 kt (or 0.5 mt), so was considered a megaton weapon.[10]

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8. Oralloy: The Manhattan Project codeword for enriched uranium. Short for "Oak Ridge alloy."

9. Defense Threat Reduction Agency, "Operation IVY Factsheet," available from http://www.dtra.mil/Portals/61/Documents/NTPR/1-Fact_Sheets/13_IVY.pdf.

10. More about the Violet Club and the challenges it presented the UK: Robert Uhlig, "N-bombs 'could have gone off by accident'," *The Telegraph,* June 28, 2001, available from

Boosted Fission

Another method of increasing the yield and/or the efficiency of a weapon is to use nuclear fusion reactions to "boost" the number of neutrons working to fission the fissile material in the core. Boosted weapons do not derive a significant fraction of their energy from the fusion reaction, but instead use the neutrons from fusion to create more fissioning of U^{235} or Pu^{239}. Boosted fission weapons are not considered to be true multiple-stage thermonuclear fusion weapons or H-bombs.

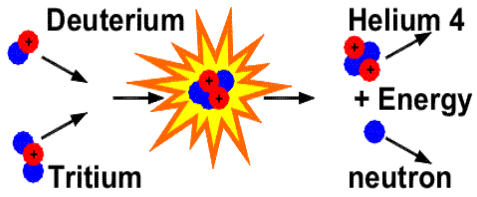

FIGURE 34
Boosting to Produce Additional Neutrons for Fission Weapons

In a boosted weapon, a small amount of deuterium/tritium gas is introduced into the hollow core of an implosion weapon just before detonation. The high explosives in the shell are then used to create the shockwave that implodes the core, causing the initial fission reaction. The resulting heat and pressure from the fission reaction initiates fusion in the deuterium/tritium gas, which releases a large number of high-energy neutrons that feed the ongoing fission reaction (see figure 34). This increases the rate of fission in the core, allows a higher percentage of material to fission before the core blows apart and so produces a higher yield than an un-boosted weapon of a similar weight.

The gas is stored externally and is introduced into the weapon's pit just before implosion (see figure 35). The tritium has a half-life of 12.3 years and must be periodically replenished in order to remain effective as fuel. By storing the gas externally, the fuel can be accessed more easily and replaced. The amount of tritium injected can be modulated to vary the weapon's yield.

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http://www.telegraph.co.uk/news/science/science-news/4764479/N-bombs-could-have-gone-off-by-accident.html.

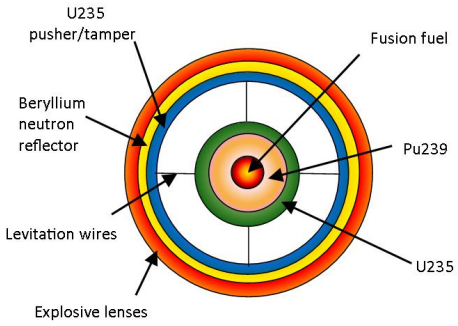

FIGURE 35
Boosted Fission Design

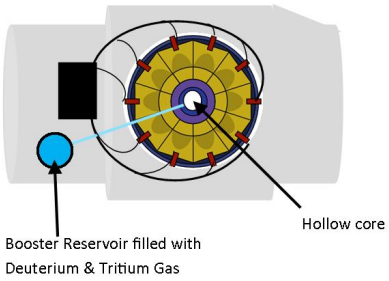

FIGURE 36
Boosted Fission Weapon
Source: adapted from image by Phillip R. Hays
http://www.okieboat.com/How%20nuclear%20weapons%20work.html

FIGURE 37
Greenhouse Item
Boosting Device

The first test of a boosted fission device was the "Item" shot of the Operation Greenhouse (see figure 37). It was tested on May 25, 1951, at Enewetak Atoll. It had a yield of 45.5 kt, more than twice the yield of the un-boosted, solid-pack implosion bomb "Fat Man."[11]

11. Atomic Archive, ""George" Shot Is Pivotal," available from http://www.atomicarchive.com/History/hbomb/page_12.shtml.

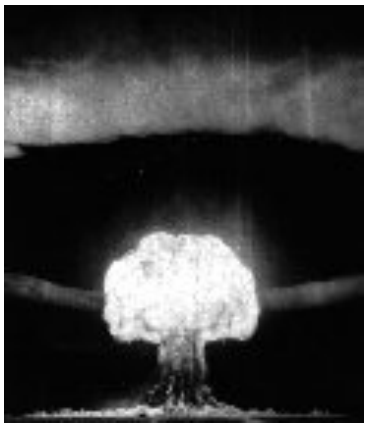

FIGURE 38
Joe-4 Test

Yet another weapons concept that used deuterium and tritium reactions was the layer-cake design. The Soviets tested such a design in their Joe-4 test of August 1953. It was the Soviet's first attempt to produce a true thermonuclear two-stage weapon. In this regard, it was a failure. Nonetheless, it produced a yield of 400 kt. The Soviet layer-cake weapon design (called "Sloika") had a fissile core surrounded by a layer of lithium-6 deuteride. This material was then surrounded by a layer of depleted uranium. Some versions had several alternating layers of these materials. After the highly enriched uranium or plutonium core is set off and fissions, it creates neutrons, some of which strike the atoms of lithium-6, creating tritium. Given the high temperatures created by fission in the core, tritium and deuterium can undergo fusion releasing high-energy neutrons without a high level of compression. These high-energy neutrons, in turn, can be used to fission an outside jacket of U-238, which is what produced most of the Joe-4's yield.

Two-point (Ellipsoid) Design

The next major advance in the implosion design after the appearance of hollow core designs and boosting was the two-point implosion design. Prior to this design the majority of implosion designs were based on variations of the Mark-3 "Fat Man" style bomb, which had an outer shell of 32 high explosives lenses arranged as a sphere. The two-point design reduced the number of explosive lenses to only two, which meant a smaller implosion mechanism was necessary to detonate the bomb. The two-point design also meant the shape of the bomb changed from a sphere to an ellipsoid, which had a much smaller diameter. These two features—the smaller implosion mechanism and the smaller diameter—meant that the two-point design was much smaller and more efficient than the previous designs.

The two-point "linear" implosion technique was first developed in the 1950s. The United States started testing linear implosion techniques in 1955 during the test series known as Operation Teapot. The Swedish were also working on this design for their first nuclear weapon.[12]

12. See Robert Standish Norris and Thomas B. Cochran, "United States Nuclear Tests: July 1945 to 31 December 1992," NWD 94-1, *Natural Resources Defense Council*, February 1, 1994. https://fas.org/nuke/cochran/nuc_02019401a_121.pdf

The two-point design also had a safety feature: the one-point safety test. The ignition of only one of the two explosive points would create an uneven compression of the weapon pit, preventing it from reaching criticality, resulting in no nuclear yield.

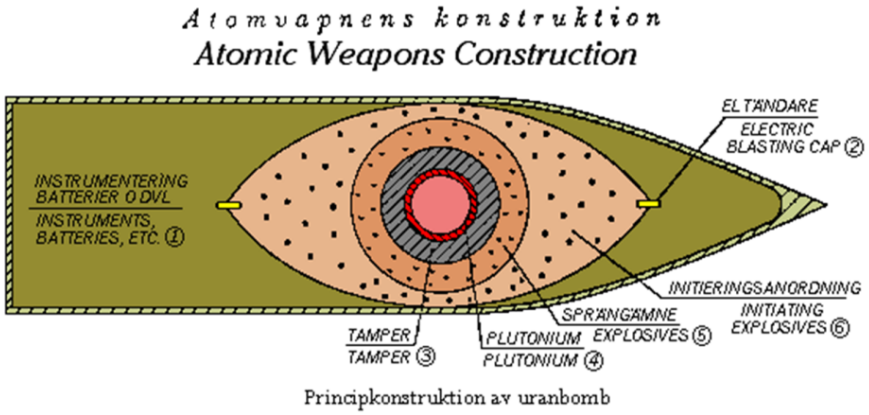

FIGURE 39
Two-point (Ellipsoid) Design
1956 Sketch from the Swedish Nuclear Weapons Program

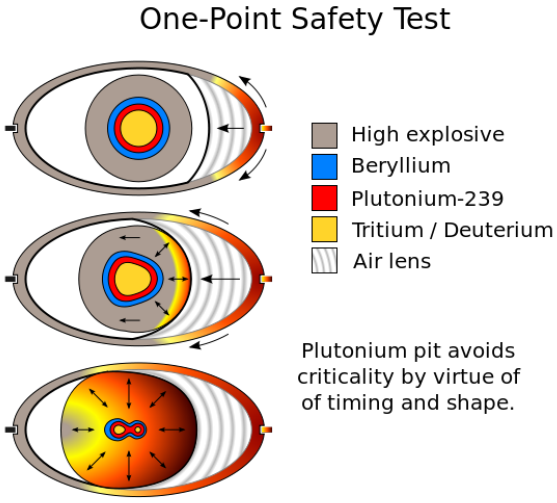

FIGURE 40
One-point Safety Test

Swan Device

The Swan Device—first tested in the "Inca" shot of Operation Redwing on June 21, 1956—was the first design to incorporate all of the advanced implosion features: two-point, levitated pit, hollow core, fusion boosted. It was first tested as a standalone device, but it quickly became the common design used for both single-stage fission bombs and for use as the primary stage of multiple-stage fusion weapons. The Swan's small dimension (diameter of 29.5 cm and 58 cm long) was important for its use as the primary stage of fusion weapons and was a vital advancement in the development of nuclear warheads.[13]

MULTIPLE-STAGE FUSION WEAPONS DESIGNS

The weapon designs discussed so far have all been single-stage weapons, i.e., most of the energy they release comes from fission reactions. Multiple-stage weapons use the heat and radiation pressure generated by a single-stage fission bomb, known as the primary, to initiate fusion reactions in a separate stage of the weapon. Half or more the energy released from a multiple-stage weapon is generally the result of fusion, hence these designs are also known as fusion weapons, or sometimes as hydrogen weapons or H-bombs for the hydrogen fusion reactions that multiple-stage designs exploit.

Fusion Reactions

Like fission, fusion also involves the exploitation of binding energy. In fusion, however, the goal is to combine the nuclei of two atoms to get one with a higher binding energy and heavier atomic weight. The mass of the heavier atom is less than the combined masses of the two lighter atoms. The difference in mass is released as energy.

The energy released by the sun is created by the nuclear fusion reactions at its core, where light elements such as hydrogen nuclei undergo fusion to form helium nuclei. When the hydrogen nuclei fuse and become helium, the mass of the helium nuclei is less than the combined mass of the hydrogen. This corresponds with a jump up the curve of binding energy, and the difference in mass is converted to energy.

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13. Nuclear Weapons Archive, "Operation Redwing," available from http://nuclearweaponarchive.org/Usa/Tests/Redwing.html.

In the case of nuclear weapons, the hydrogen reaction entails the fusing of deuterium and tritium to create helium. These fusion reactions (involving deuterium, lithium 6, tritium) release three to four times more energy per mass of reacting material than a comparable mass of fissioning uranium.

Hydrogen atoms are common in fusion reactions because they are very light and, therefore, easier to fuse together. In order for two nuclei to fuse, they must overcome the electrical repulsion from the protons in the other particle's nucleus. This requires extremely high temperatures and pressure. A fission device is used as a trigger for the fusion reaction. The high temperatures, X-ray radiation, and pressures generated by the explosion of the fission trigger (called the primary) and the ablation on the secondary's uranium tamper is intense enough to force the fusion fuel in the secondary to undergo fusion. Due to the immense temperatures required to ignite the fusion fuel, weapons that obtain a significant part of their energy from fusion reactions are also known as "thermonuclear."

The easiest fusion reaction to initiate is with the heavy hydrogen isotopes deuterium and tritium. Deuterium fuel is relatively abundant in nature—it can be found in ordinary water—but tritium must be produced, either from lithium that has been bombarded with neutrons in a reactor or the fusion of two deuterium nuclei.

Deuterium is considered a "heavy" hydrogen isotope because it possesses one proton and one neutron per atom, whereas more common hydrogen only has one proton and no neutrons.

Two atoms of deuterium can fuse together and produce an atom of tritium (radioactive hydrogen) and a common hydrogen atom. Alternatively, a reaction between deuterium and tritium can be fused to produce 4He (helium isotope), a free neutron, and energy.

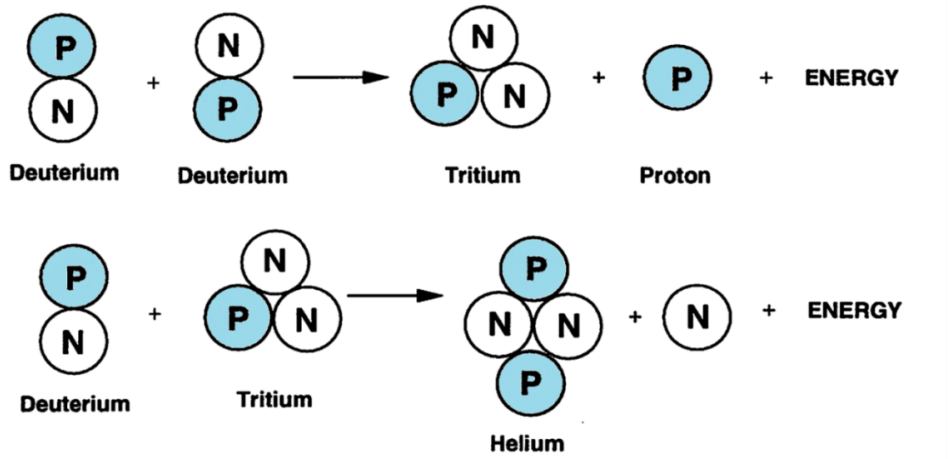

FIGURE 41

Fusion of Deuterium and Tritium

Source: A Nuclear Proliferation Primer. L-00933D TASC, Reading, Mass., January 21, 1992.

Deuterium and tritium are used as fuel in fusion weapons and both exist as gases at room temperature. Gaseous deuterium and tritium are difficult to contain and handle when building a fusion weapon. Although deuterium is a naturally occurring substance, tritium has a half-life of only 12.3-years (i.e., the time required for half of the tritium to decay or transmute itself into another element) and so it does not readily exist in nature and must be produced and replenished for use in weapons.

Lithium-6 deuteride (^{6}Li-D) is a solid at room temperature and can be used to make deuterium and tritium. In the compound ^{6}Li-D, deuterium atoms are chemically bound to the lithium-5 molecules. Lithium-6 basically consists of an alpha particle (the nucleus of a Helium atom—^{4}He) and a deuteron (^{2}H, also referred to as "D") that are bound together. When lithium-6 is hit with neutrons, it releases tritium (^{3}H, also shown as "T").

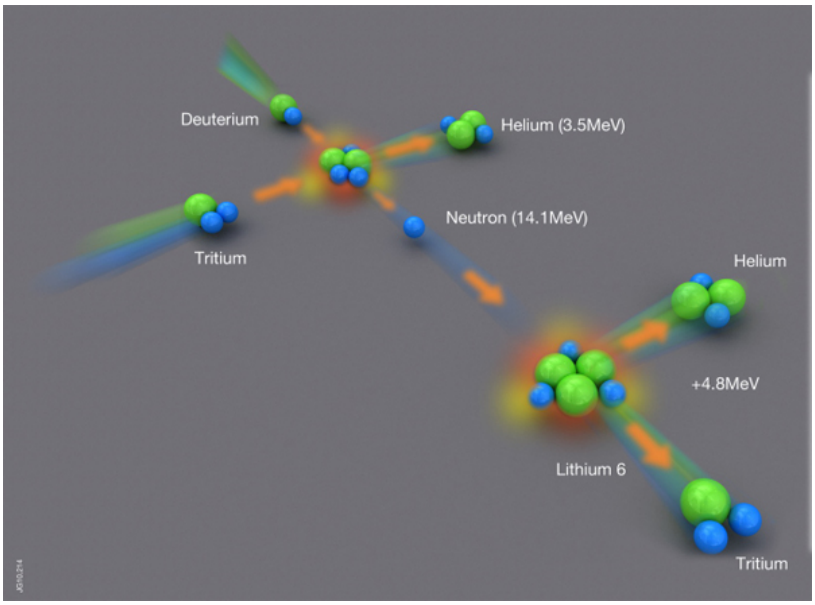

FIGURE 41B

Fusion of Deuterium and Tritium

Source: Steve Cowley, "Hot Fusion," *Physics World*, October 1, 2010.

$^{6}Li + Neutron = {}^{3}H + {}^{4}He + Energy$

The tritium then fuses with the deuterium atoms and produces helium atoms, as well as excess neutrons and energy.

$^{2}H + {}^{3}H = {}^{4}He + n + 17.6\ MeV$

--- or ---

$D + T = {}^{4}He + n + 17.6\ MeV$

Two-stage Fusion Weapons Designs

Most fusion weapons consist of two stages. The first stage consists of a primary (often a standard fusion boosted implosion design using a plutonium-only core to enhance lightness and reduce warhead size and, alternately, sometimes with a composite plutonium/uranium core). Multiple-stage fusion weapons involve the same principles of neutron breeding as boosted single-statue weapons. The difference is that with two-stage weapons, more than half of the explosive yield is a result of the fusion reaction. It is far more powerful than a fission bomb of comparable size.

Teller-Ulam Design

The modern two-stage fusion weapon is based off the Teller-Ulam design developed in 1951. This design is also known as a staged radiation implosion bomb. The primary stage has a fissile core, which may or may not be boosted. The secondary stage contains fusion fuel—usually a form of lithium deuteride—with a uranium or plutonium "spark plug" of fission fuel at the center (see figure 42).

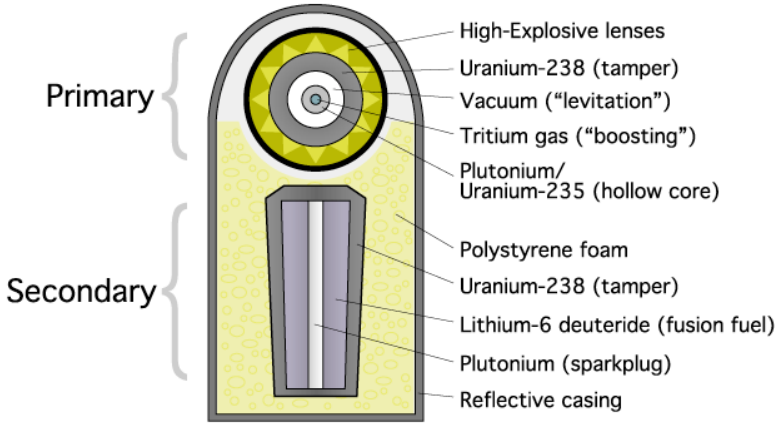

FIGURE 42
Two-stage Fusion Weapon
Based on Teller-Ulam design

When the primary explodes, it creates X-ray radiation, which is captured and contained within the reflective casing that surrounds the nuclear components of the bomb. The radiation heats up the polystyrene foam lining the interior of the reflective casing and turns it into plasma. The radiation is then absorbed by the outer tamper surrounding the secondary component, which heats up and ablates (boils away). This causes the secondary component to implode, and the fission plutonium spark plug at the center to compress. When the spark plug is compressed into a critical mass, it starts a fission reaction that creates the heat and pressure necessary to ignite the fusion fuel.

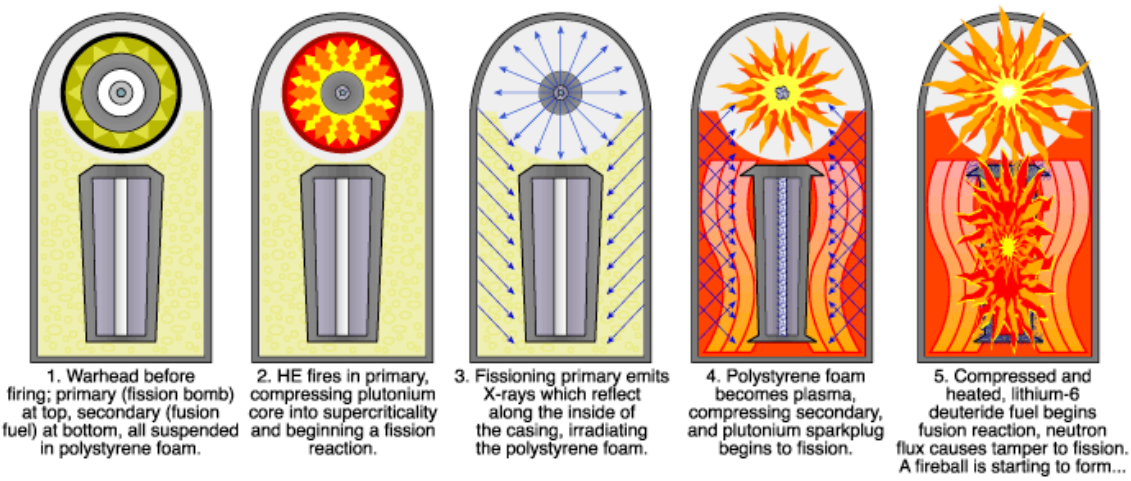

FIGURE 43
Detonation of a Two-stage Fusion Design

"Ivy Mike" was the first successful test of a multi-megaton fusion weapon. It was tested by the United States on November 1, 1952, at Elugelab, Enewetak Atoll. It had a yield of 10.4 megatons. The first mass produced fusion weapon deployed by the United States was the Mark-17 bomb.[14]

FIGURE 44
Mark-17
2-stage fusion weapon

14. Nuclear Weapon Archive, “Operation Ivy,” available from http://nuclearweaponarchive.org/Usa/Tests/Ivy.html.

Clean vs. Dirty Fusion Bombs

Fusion weapons can either release most of their energy directly from fusion—in which case they are called fission-fusion weapons—or they can use the high energy, or fast neutrons created by the fusion reaction to fission an additional "jacket" of fissionable material, such as U^{238}, surrounding the secondary — in which case, they are called fission-fusion-fission weapons. The fission-fusion-fission weapon is not to be confused with a true three-stage fusion weapon, which has an additional, separate fusion stage, the tertiary, which is ignited by the secondary (see discussion and diagram below).

Unlike fission, fusion reactions do not directly produce any radioactive products, so weapons that release most (fifty percent or more) of their energy as fusion create less radioactive fallout than bombs where the fission reactions account for fifty percent or more of the weapon's energy. Weapons without the fissionable jacket release most of their energy from fusion and are considered relatively "clean" bombs. Weapons that use a fissionable jacket obtain more of their yield from fission and hence have a higher fallout of fission products; these weapons are considered "dirty." "Salted weapons" such as the cobalt bomb design use a jacket of cobalt to increase the radioactive fallout from a weapon. The United States developed this cobalt design but never deployed it.

Three-stage Fusion Weapons Designs

The radiation created by the secondary stage can be used to compress and ignite a third, or tertiary, stage. In theory there is no limit to the number of stages it might have (see Figure 46).

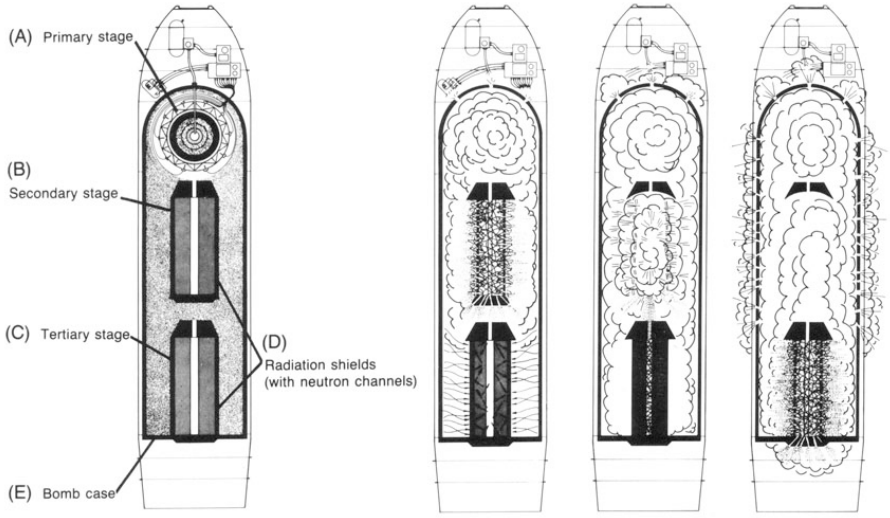

FIGURE 45
Schematic of a Three-stage Fusion Weapon
Source: Chuck Hansen, Nuclear Weapons: A Secret History, available from http://blog.nuclearsecrecy.com/2012/09/12/in-search-of-a-bigger-boom/

The first test of a three-stage fusion device was conducted by the United States on May 27, 1956, in the Redwing Zuni test. It had a yield of 3.5 megatons (mt).

The version of the three-stage fusion weapon that was actually deployed was the Mark-41 design (see figure 47). At a yield of 25 mt, it was the highest yield nuclear weapon ever deployed by the United States. It was also the only three-stage fusion weapon ever developed by the United States, and with a weight of 4,500 kg, it achieved the highest yield-to-weight ratio of any U.S. weapons design.

FIGURE 46
Mark-41 Three-stage Fusion Weapon

A more notable example of a three-stage fusion weapon is the Soviet Union's "Tsar Bomba." The Tsar Bomba was the largest fusion device detonated. It was tested on October 30, 1961, and had a yield of 50 mt. It could have produced a yield of 100 mt but was detuned by the Soviets to allow the bomb to be set off without destroying the bomber and bombing crew that dropped it.[15]

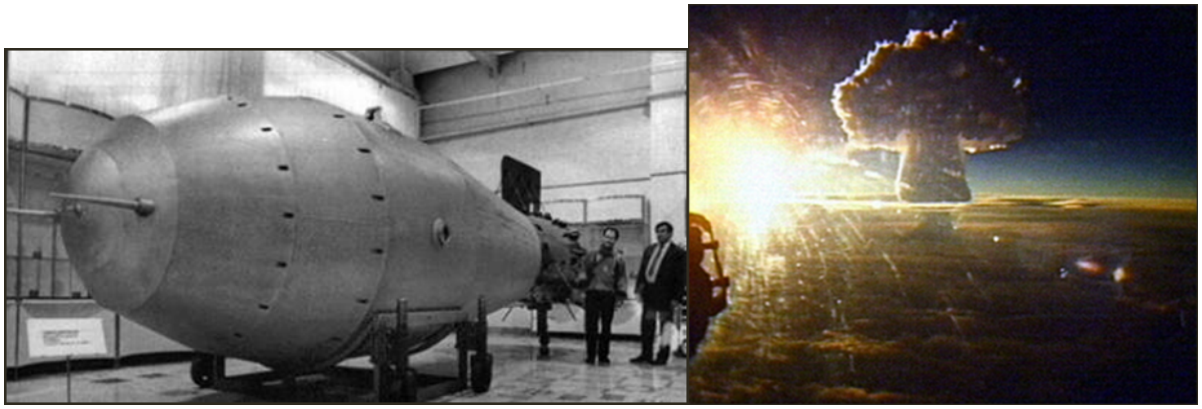

FIGURE 47
Tsar Bomba

Additional Variations on Fusion Weapons Designs

Enhanced Radiation Weapon (Neutron bombs)

Enhanced radiation weapons (ERW), also known as "neutron bombs," are two-stage fusion weapon designed to minimize the amount of explosive energy (blast and thermal) and to maximize the output of lethal nuclear radiation. Enhanced radiation weapons allow the high energy neutrons generated by the fusion reaction of the secondary to escape, unlike standard fusion weapons that absorb the neutrons.

Neutron bombs typically have a lower yield than standard nuclear weapons and are designed to release the greatest percentage of their energy as fast energy neutrons. Although these weapons still cause blast and thermal damage, the high dose of neutron radiation they release is intended to cause a large number of human casualties.

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15. Paul Richard Huard, "The 'Tsar Bomba' Was a 50-Megaton Monster Nuke," *Medium,* April 1, 2015, available from https://medium.com/war-is-boring/the-tsar-bomba-was-a-50-megaton-monster-nuke-6855dcaeb618

Neutrons are capable of penetrating tank armor and other shielding that could withstand the blast and thermal effects of a standard nuclear weapon (e.g. blast resistant military command centers). The lethal area of the neutron radiation extends much further than the lethal blast area against objects.

The neutron bomb was intended for use as a tactical anti-tank weapon (due to the ability of the neutrons to penetrate armor and incapacitate the crew) and as a strategic anti-missile weapon. The United States produced three neutron warheads: W66, W70 Mod 3, and the W79. All have been retired. The Chinese tested such a device but are thought not to have deployed it. The French and Soviets developed such weapons as well.

Cobalt Bomb (and Other "Salted" Weapons)

Another variation on the two-stage design is intended to maximize the radioactive fallout of a nuclear weapon, rather than increase the explosive force. These weapons are a type of dirty fusion bomb and are referred to as "salted."

This design uses a non-fissionable jacket of elements that become radioactive when they capture the neutrons generated by the fusion reaction of the secondary stage. For example, a two-stage bomb with a jacket made of cobalt-59 would absorb the neutrons generated by the fusion reaction and release the radioactive isotope cobalt-60, which has a half-life of about five years and emits penetrating gamma radiation when it decays.

The cobalt bomb, which was developed by the United States in the early 1960s but not deployed, is probably the most well-known example of a "salted" bomb design. But other salting isotopes could be used. The length of the fallout effect, or how long an area is contaminated by radiation, is determined by the isotope chosen as the salting agent: Gold would cause fallout lasting only days, tantalum and zinc would last months, and cobalt would last years.

Variable Yield Weapons

Variable yield designs give operators the option to adjust the desired yield of a nuclear weapon, allowing a single type of weapon to be used in various scenarios. Most modern nuclear weapons have a variable yield capability.

In a two-stage Teller-Ulam weapons design, there are a couple ways to vary the weapon's yield. One is by increasing the primary's yield by boosting with fusion fuels. The amount of deuterium-tritium gas that is introduced into the core as the primary's pit is collapsing may be adjusted to increase or decrease the yield of the weapon depending on the amount of gas used. It is also possible to shut down the secondary (fusion) reaction, either by exploding the primary at a yield

too low to compress and ignite the secondary, or by blocking the transfer of energy from the primary to the secondary by using mechanical shutters or a similar device. This allows the primary's energy to disperse before the secondary can detonate.

Currently, the U.S. deploys three types of variable yield weapons: the **B-61** and **B-83** gravity bombs, and the **W-80** warhead that is found on the AGM-86 Air-Launched Cruise Missile (ALCM). The B-61 and B-83 fusion bombs are unguided gravity bombs. They can be delivered by a variety of U.S. and NATO aircraft, including the B-2A Spirit stealth bomber and the F-16 (see Figure 48).

	B61 Gravity Bomb 	**B83 Gravity Bomb** 	**W80 Warhead** 
Yield	0.3 – 340 kt	Low kt – 1.2 mt	5-150 kt
Length	3.56 m	3.7 m	80 cm
Diameter	33 cm	46 cm	30 cm
Weight	320 kg	1,100 kg	130 kg
Delivery	Aircraft	Aircraft	AGM-86 ALCM

FIGURE 48
Currently Deployed Variable Yield Weapons

APPENDIX

How Much Fissile Material Is Needed to Fuel Different Nuclear Weapons Designs

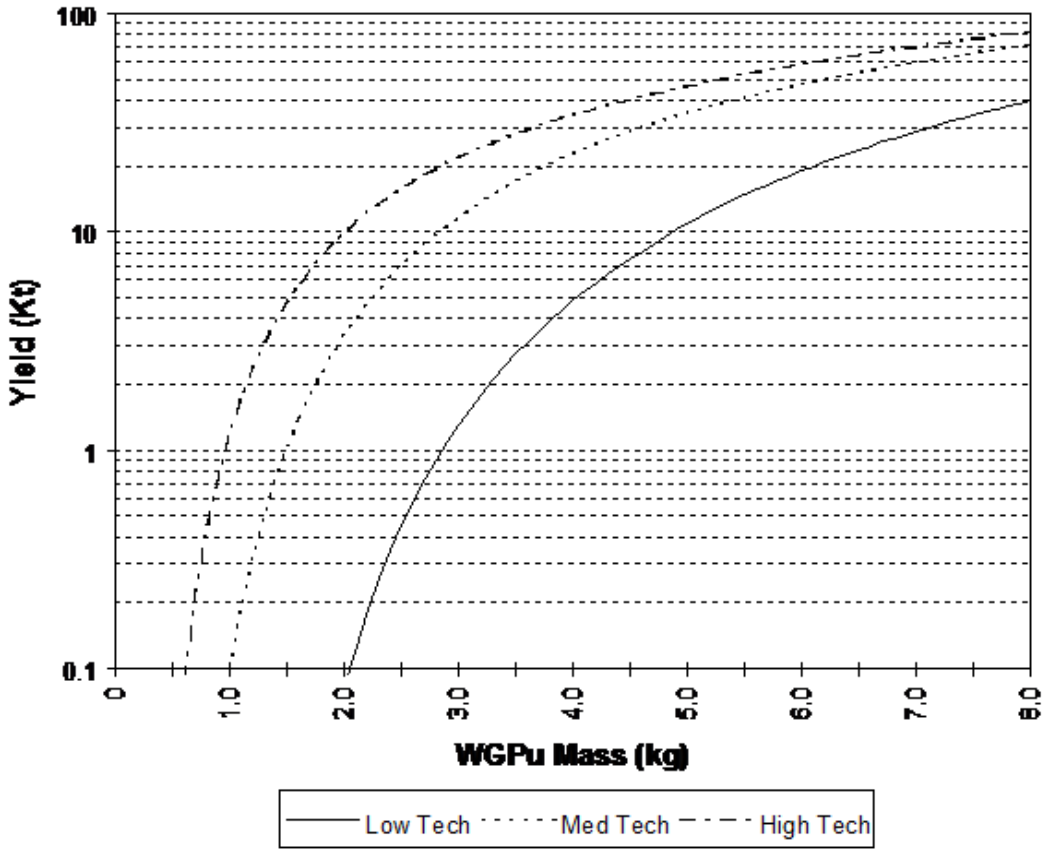

FIGURE 49

Nuclear Weapon Yield Versus Plutonium Mass for Pure Fission Weapons

Source: Thomas B. Cochran, "Technical Issues Related to Proliferation," NRDC.

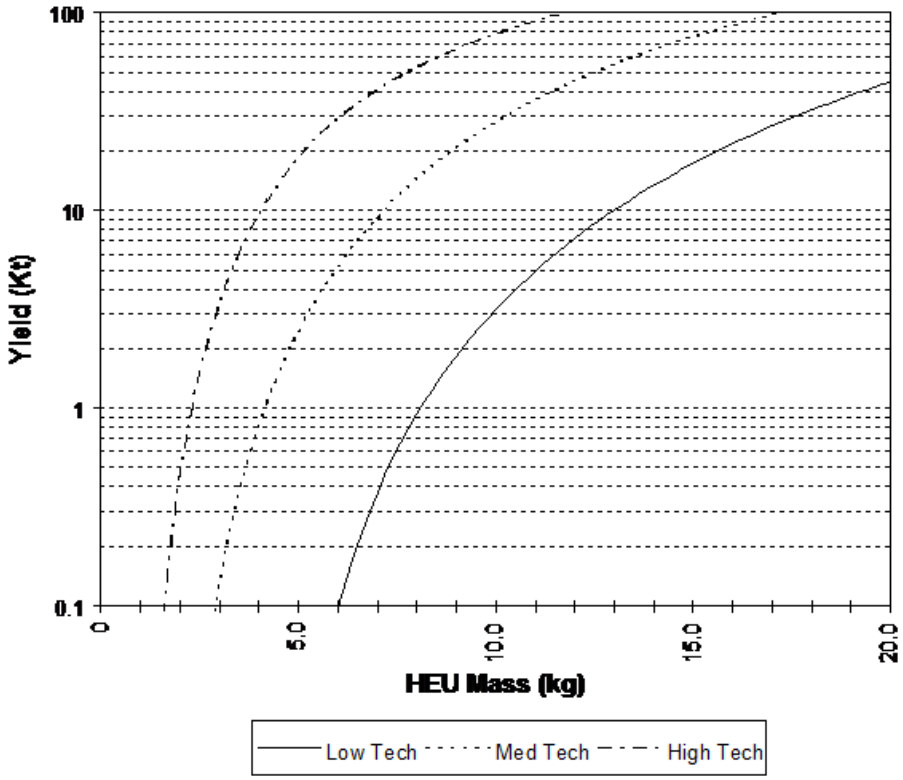

FIGURE 50

Nuclear Weapons Yield Versus HEU Mass for Pure Fission Weapons

Source: Thomas B. Cochran, "Technical Issues Related to Proliferation," NRDC.

	WEAPON-GRADE PLUTONIUM (KG)			HIGHLY-ENRICHED URANIUM (KG)		
Yield	**Technical Capability**			**Technical Capability**		
(kt)	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5

** Values rounded to the nearest 0.5 kilogram*

FIGURE 51

Approximate Fissile Material Requirements for Pure Fission Nuclear Weapons

Source: Thomas B. Cochran, "Technological Issues Related to Proliferation," NRDC.