NUCLEAR WEAPONS TECHNOLOGY 101

FOR POLICY WONKS

BRUCE T. GOODWIN

Center for Global Security Research
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About the Author

Bruce Goodwin is a senior laboratory fellow at the Center for Global Security Research at Lawrence Livermore National Laboratory (LLNL). Prior to joining CGSR, he was LLNL's associate director-at-large for national security policy and research. From 2001 to 2013 he was the principal associate director for LLNL's nuclear weapons program. In this latter role, Dr. Goodwin led the process to certify LLNL's nuclear weapons and was responsible for establishing priorities, developing strategies, and designing and maintaining LLNL's nuclear weapons. From 1981 to 2001, he worked as a nuclear weapons designer at Los Alamos and at Lawrence Livermore, and authored five nuclear weapons tests. For this work he received the Department of Energy E.O. Lawrence Award for innovative weapons science. Goodwin received his bachelor's degree in physics from City College of New York and his master's and doctorate in aerospace engineering from the University of Illinois at Urbana Champaign.

Introduction

Policymaking for nuclear security requires a strong grasp of the associated technical matters. That grasp came naturally in the early decades of the nuclear era, when scientists and engineers were deeply engaged in crafting policy. In more recent decades, the technical community has played a narrower role, one generally limited to implementing policies made by others. This narrower role has been accentuated by generational change in the technical community, as the scientists and engineers who conceived, built, and executed the programs that created the existing U.S. nuclear deterrent faded into history along with the long-term competition for technical improvements with the Soviet Union. There is thus today a clear need to impart to the new generation of nuclear policy experts the necessary technical context.

That is the purpose of this paper. Specifically, to: introduce a new generation of nuclear policy experts to the technical perspectives of a nuclear weapon designer, explain the science and engineering of nuclear weapons for the policy generalist, review the evolution of the U.S. approach to nuclear weapons design, explain the main attributes of the existing U.S. nuclear stockpile, explain the functions of the nuclear weapons complex, and show how all of this is integrated to sustain future deterrence.

I wish to acknowledge Thomas Ramos, Richard Ward, and Jacek Durkalec for their invaluable contributions to this paper. Without them, it could not have been written.

The Revolution in Physics That Led to the Bomb

First, a little history. I will use some technical terms in this section that may not be familiar. I beg your patience as I lay out the nuclear revolution. Following this, I will define these technical terms in excruciating detail before I describe the physics of nuclear weapons. You can also consult the glossary at the end of the paper.

Nuclear weapons came into being from the scientific advancements that occurred in the five decades from 1895 to 1945. It begins with Roentgen's 1895 discovery of radiation in the form of X-rays. Then in 1905, Albert Einstein developed his Special Theory of Relativity positing that matter and energy could change from one form to the other. The next necessary technical advance was Chadwick's 1932 discovery of the neutron. The final technical step was the discovery in 1938-1939 of fission by Otto Hahn and Lisa Meitner. This final development led Niels Bohr to quietly voice concerns to the UK government over the possibility of atomic weapons development by Nazi Germany. Thus, the MAUD committee was created to study the feasibility of an atomic bomb. This group wrote the UK MAUD report and transmitted that report to the U.S. government in 1941. It was given to the United States as it was realized that only America had the industrial capacity to produce the nuclear materials needed to determine if an atomic (i.e. a fission) bomb was feasible. By the way, some have hypothesized that the codename MAUD stood for the **M**ilitary **A**pplication of **U**ranium **D**etonation. This is not true. In fact, Maud was the name of Niels Bohr's housekeeper.[1]

Things then began to move very quickly. In February 1941, Glenn Seaborg discovered plutonium (Pu), the first manmade fissionable element, thus doubling the possible paths to a bomb. He did this by bombarding uranium-238 with neutrons.

After Pearl Harbor brought the U.S. into World War II in December 1941, the Manhattan Engineering District (a code name), under the direction of General Leslie Groves, was formed in May of 1942 to develop the atomic bomb. This was followed by the establishment of the Los Alamos Scientific Laboratory on November 25, 1942, under the direction of Dr. J. Robert Oppenheimer of the University of California, Berkeley. The first manmade fission chain reaction was achieved on December 2, 1942, by Enrico Fermi's team in the first nuclear reactor (a graphite pile reactor) under the grandstands of The University of Chicago stadium.

Thus, all of the technical elements for a fission explosive were in place and these pieces had to be put together in a practical design for a bomb. Two designs

1 Atomic Heritage Foundation, "Britain's Early Input – 1940-41." https://www.atomicheritage.org/history/britains-early-input-1940-41. Accessed April 15, 2021.

were developed, one for a uranium-235 bomb, the other for a plutonium-239 bomb. The plutonium design was exploded in the first nuclear test code named “Trinity” at Alamogordo, New Mexico on July 16, 1945.

Three weeks later, on August 6, 1945, a uranium “gun” weapon (Little Boy) destroyed the city of Hiroshima in Japan. On August 9, 1945, a plutonium implosion weapon (Fat Man) destroyed the Japanese city of Nagasaki, ending World War II.

The Nuclear Arms Race Begins

With the U.S. as the sole nuclear power at the end of World War II, a nuclear arms race was on. The next country to build an atomic bomb was the USSR, which exploded a fission device on August 29, 1949. This was about four years faster than intelligence agencies had estimated.[2] That speed was largely due to the multiple Soviet espionage penetrations of the Manhattan Project (accomplished by recruiting Project staff as spies). Those recruits included Claus Fuchs, Theodore Hall, Lona and Morris Cohen, David Greenglass, Julius and Ethel Rosenburg, and many others. These spies delivered the designs for the bombs and for the material production plants to the Soviets, greatly accelerating their atomic weapon program. In fact, Lavrentiy Beria, the head of the KGB and person in charge of Soviet bomb efforts, told the Soviet scientists that if they changed one detail of the American designs, they and their family members would be executed. Truly, a motivational manager.

The test of the Soviet bomb led President Truman to order the development of the thermonuclear (i.e. hydrogen) bomb. The conflict between Oppenheimer, the chair of the State Department Panel of Consultants on Disarmament, and Edward Teller over developing and testing the hydrogen bomb ultimately led to the founding of Lawrence Livermore National Laboratory on September 2, 1952. Edward Teller was a brilliant Hungarian-American physicist prominent in the Manhattan Project and known as the father of the hydrogen bomb.

The United Kingdom tested its first fission device on October 3, 1952. The U.S. tested the first hydrogen explosive on November 1, 1952 and the USSR exploded its first hydrogen bomb on August 12, 1953. The UK then exploded a hydrogen device on November 8, 1957. France tested its first fission device in Algeria on February 13, 1960. China tested it first fission device on October 16, 1964 followed quickly by a hydrogen device on June 14, 1967. France then tested a hydrogen device on August 23, 1968. This completes the first nuclear testing events of the P-5 nuclear states as defined in the Nuclear Non-Proliferation Treaty.

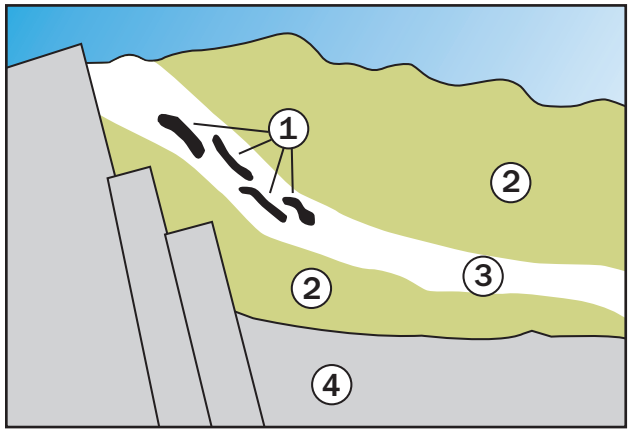
Next to join the nuclear “club” was India which exploded a fission device on May 18, 1974. An “anomalous” double flash event was detected by a U.S. Vela Hotel nuclear explosion detection satellite on September 22, 1979 near the Prince Edward Islands in the Indian Ocean. This has been hypothesized by some to be a South African nuclear test as all previous 41 Vela signals were, in fact, nuclear tests. In 1991, South Africa ratified the Nuclear Nonproliferation Treaty, becoming the first country to have had nuclear weapons and given them up. Pakistan exploded a fission device on May 28, 1998 and finally, North Korea exploded a nuclear device on October 9, 2006.

2 Donald P. Steury, "How the CIA Missed Stalin's Bomb," *Studies in Intelligence* 49, no. 1 (2005).

Fission and Fusion are "Natural" Processes

Manmade fission reactors first operated 75 years ago at The University of Chicago. There is a general belief that fission and fusion are manmade processes. This is simply not true. Nature operated 16 natural uranium reactors that went critical at Oklo, Gabon in Africa 1.7 billion years before that. They periodically ran for a few hundred thousand years. This was possible because rising oxygen levels during the aging of the Earth allowed uranium to be dissolved and transported with groundwater to places where a high enough concentration could accumulate to form rich uranium ore bodies. A uranium-rich mineral deposit became inundated with groundwater that acted as a neutron moderator, and a nuclear chain reaction took place. A moderator slows neutrons, making them more likely to induce fission in uranium-235 (U-235). The heat generated from the nuclear fission caused the groundwater to boil away, which slowed or stopped the reaction. After cooling of the mineral deposit, the water returned, and the reaction restarted, completing a full cycle about every three hours. The fission reaction cycles continued for hundreds of thousands of years and ended when the depletion by fission of the fissile materials would no longer sustain a chain reaction.

A key factor that made the natural reactor possible was that at the time the reactors went critical 1.7 billion years ago, the fissile isotope U-235 made up about 3.1% of natural uranium, which is comparable to the amount used in some of today's reactors. (The remaining 96.9% was non-fissile U-238.) Because U-235 decays with a half-life of about 700 million years, the current abundance of U-235 in natural uranium is only about 0.72%, making a natural nuclear reactor no longer possible without heavy water or graphite moderators. Of course, fusion has naturally powered the Sun from the beginning of the solar system.



Geological situation in Gabon leading to natural nuclear fission reactors

1. Nuclear reactor zones
2. Sandstone
3. Uranium ore layer
4. Granite

Figure 1. Geology of natural uranium reactors in Gabon
https://www.iaea.org/newscenter/news/meet-oklo-the-earths-two-billion-year-old-only-known-natural-nuclear-reactor

The Basics of the Operation of Nuclear Explosives

Nuclear weapons are mechanically complex, as you can see in the picture of a disassembled B-61 bomb below. The B-61 is a strategic and tactical nuclear weapon that entered the stockpile in 1966 and has undergone 12 modifications. While mechanically complex, the underlying physics of nuclear explosives is fairly simple.

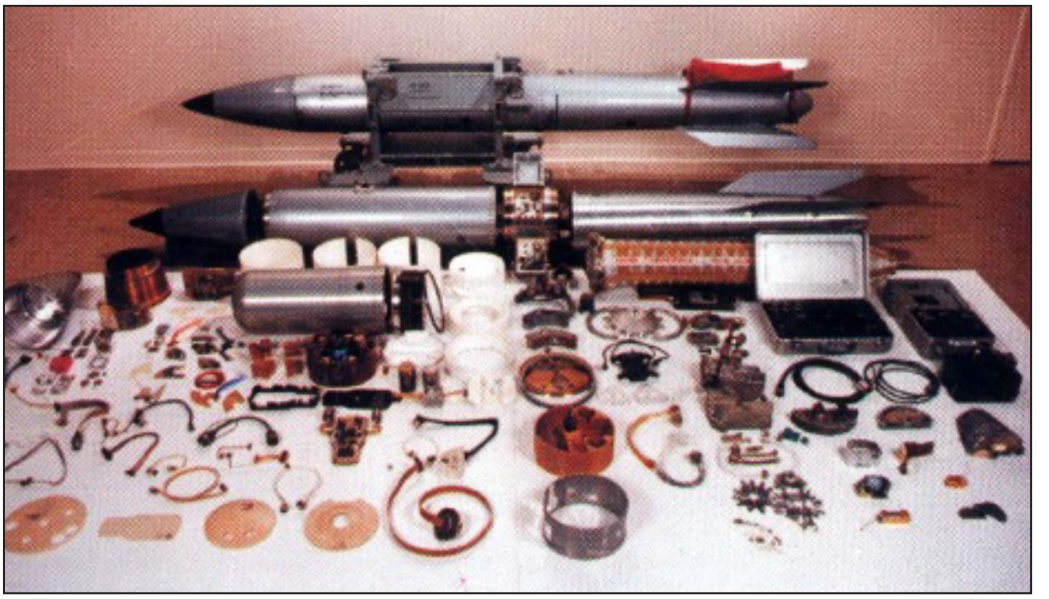


Figure 2. Components of B-61 nuclear bomb (Sandia National Laboratory photo)

The nuclear explosive is in the relatively small, gray metallic cylinder just left of center at the midline of the photo. The rest of the objects in this photo are components that control the delivery of the bomb to the target and so are not "nuclear."

In this section, I'll explain basic nuclear-design principles. First, I explain the physical basis for nuclear fission and fusion, the processes that enable atomic and hydrogen bombs. Next, fission weapons will be described, followed by the "boosting" process. I'll then describe thermonuclear (or hydrogen) weapons. Finally, I'll wrap up this section by describing the materials used for these processes in order to understand how the Nuclear Explosive Package (often shortened to NEP) works. Many older documents refer to the NEP as the Nuclear Assembly System (NAS).

But first, I'll need to define some terms by answering the following questions. What is an atom? What are they made of? What are neutrons, protons, and electrons? What is an ion? What are isotopes of elements? What is fission? What is a chain reaction? What is critical mass and supercriticality? And finally, what is fusion?

Only then can one get to how a nuclear weapon works. If you are familiar with these terms, skip ahead to the **Types of Nuclear Weapons** section. There is also a glossary of technical terms at the end of this paper.

The Atom

Atoms are the smallest particle of any given chemical element. They are made of protons, neutrons, and electrons. Protons are electrically positive, charged particles that reside in the nucleus of atoms. Neutrons are electrically neutral (i.e. uncharged) particles that reside in the nucleus of atoms. Electrons are electrically negatively charged particles that orbit the nucleus of atoms.

As an example, this is an atom of beryllium-9 ($_4Be^9$). In this notation for elements, the leading subscript is the number of protons in the nucleus (the atomic number) while the superscript is the total number of protons and neutrons in the nucleus (the atomic weight). Beryllium is a lightweight metal. It has four protons and five neutrons, a total of nine particles in the nucleus. The electron's weight is negligible compared to that of a proton or neutron. Thus, the atomic weight is defined as the sum of the nuclear particles. Atoms want to be electrically neutral, thus the number of protons generally equals the number of electrons. Chemical reactions rearrange the electrons orbiting the nucleus. Nuclear reactions add or subtract protons and/or neutrons in the nucleus, hence the name "nuclear." Ions are atoms with one or more electrons removed, leaving them electrically charged.

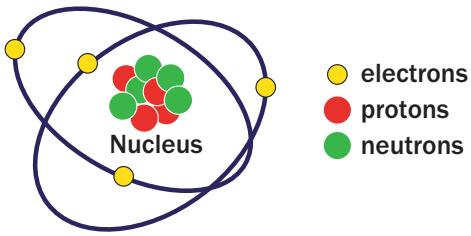


Figure 3. Beryllium Atom

Isotopes

Isotopes are atoms with the same number of protons, hence the same element since the number of electrons present equal the proton number. Remember, the electrons determine the chemical characteristics of elements. So, atoms with the same number of protons (equal to the number of electrons) have the same chemical properties. Different isotopes of an element have different numbers of neutrons in the nucleus, hence different atomic weight. While the electrical charge is the same (hence the chemical behavior is the same), the nuclear weight difference gives different isotopes different nuclear reaction properties since nuclear reactions depend upon adding or subtracting protons and neutrons from the nucleus.

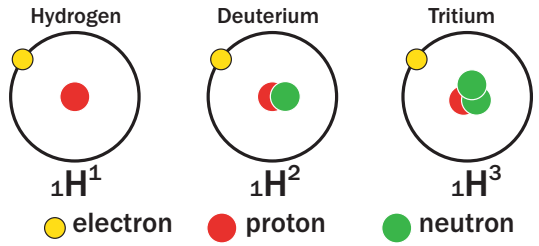


Figure 4. The three isotopes of hydrogen: hydrogen, deuterium, and tritium

The deuterium and tritium isotopes of hydrogen are one key to nuclear weapons technology.

The isotopes of hydrogen are hydrogen, deuterium, and tritium. Hydrogen is the simplest atom and contains only a proton in its nucleus. Deuterium has a proton and a neutron in its nucleus, hence "deu" for two nuclear particles. Tritium has a proton and two neutrons in its nucleus, hence "tri" for three nuclear particles.

Consider also the isotope of uranium-235 ($_{92}U^{235}$) which has 92 protons and 143 neutrons in its nucleus and 92 electrons orbiting that nucleus. It is key to uranium fission. The other fissile element of weapons interest is plutonium-239 ($_{94}Pu^{239}$) which has 94 protons and 145 neutrons in the nucleus and 94 electrons orbiting that nucleus.

Half-life

Some atomic nuclei are unstable and will emit nuclear particles and thereby "decay" into a different atomic element or isotope. The average length of time that an unstable atom exists before decaying is referred to as its half-life. This is the time that it takes for half of the atoms of an unstable material to decay and so transform into a different material. $_{94}Pu^{239}$ is unstable and has a half-life of about 24,000 years. Hence, Pu is not found in nature—any that had existed has all decayed by now. $_{92}U^{235}$ has a half-life of about 700 million years and so, while rare, it is found in natural uranium in a very low percentage. Similarly, the hydrogen isotope tritium has a half-life of about 12 years and emits an electron, converting one of its neutrons into a proton, thereby changing the tritium atom into helium-3 ($_{2}He^{3}$), an isotope of the element helium. Hence, tritium is not found in nature as it has all decayed. As a result, it must be manufactured.

Fission

Fission is a nuclear process that splits atoms. Certain atoms release extra energy when they fission. The ones of most interest for nuclear weapons are uranium and plutonium. The story of fission begins in 1938 in Germany when Otto Hahn discovered that new, lower nuclear weight elements were produced when he bombarded uranium atoms with neutrons. He subsequently received the Nobel Prize in Chemistry in 1944 for this discovery. In 1939, Lise Meitner, working in Sweden (whence she had emigrated since she was Jewish and had to escape Nazi Germany), identified this process as fission.

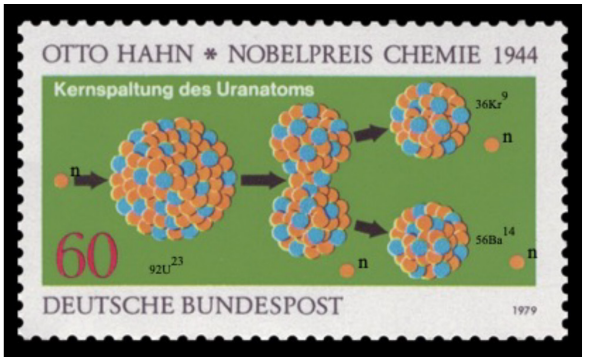


Figure 5. German postage stamp commemorating Hahn's Nobel Prize in Chemistry for fission (German-stamps.org)

Now I'll define fission, the process that makes the atomic bomb work. Fission occurs when a nucleus of fissionable material (e.g. U^{235}, Pu^{239}) absorbs a neutron, becomes

unstable, and splits into two smaller atoms and emits between two and three energetic neutrons. A fissionable element is one wherein the nucleus becomes unstable and splits into two smaller nuclei when it absorbs a neutron. A non-fissionable element absorbs a neutron to become a stable isotope with an atomic weight one higher than before the absorption or an unstable isotope that decays by some means other than fission.

Below is a schematic of the fission of uranium-235 into atoms of krypton-91 and barium-142 plus two to three neutrons released along with about 180 million electron volts (MeV) of energy. The atoms produced vary. Krypton and barium are one of a number of possible atoms produced in this fission process.

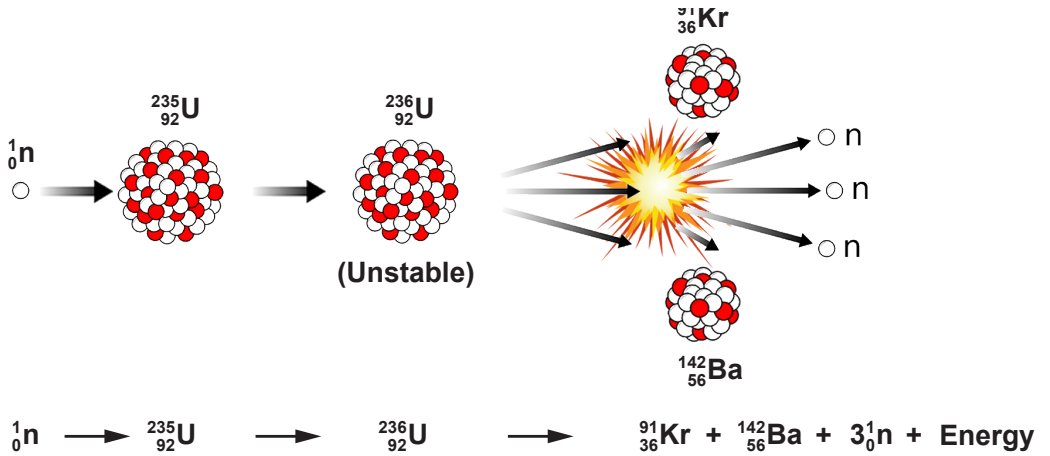


Figure 6. Fission process for uranium-235 (from *https://commons.wikimedia.org/wiki/File:Nuclear_fission_reaction.svg,* Author Mike Run, June 2017)

Chain Reaction

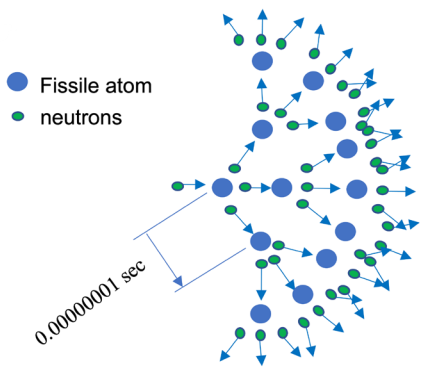


Figure 7. First three fission steps in a chain reaction

A chain reaction is a self-sustaining sequence of fission reactions caused by the additional neutrons emitted in a fission reaction if the fission reaction occurs in a critical mass of fissionable material.

Each step in the chain reaction takes about one hundred millionth of a second. One gets a quadrillion (1 followed by 15 zeros) fissions from 50 chains (x 10^{-8} secs) in a microsecond. That's a lot of fissions and so a lot of energy released in a very short time. Hence, a fission explosion.

Critical Mass

A **critical mass** of fissionable material is a piece of material large enough to sustain the fission chain without losing the neutrons that drive the fissions, the loss of which would stop the reactions. There are five characteristics that determine critical mass.

Type: First, the kind of fissile material. For example, Pu has a higher neutron cross section than uranium. Since a higher cross section makes it more likely to fission, the critical mass or amount of Pu needed to make a critical mass of Pu is lower than for U. The concept of a cross section is a physics metaphor. The notion is that since an atom of Pu is more likely to absorb a neutron, it looks bigger to the neutron than an atom of uranium. In fact, to complete the metaphor, the unit of cross section that physicists use to measure cross section is the "barn," as in "hitting the broad side of a barn." A barn is 10^{-24} cm^2, a very small area.

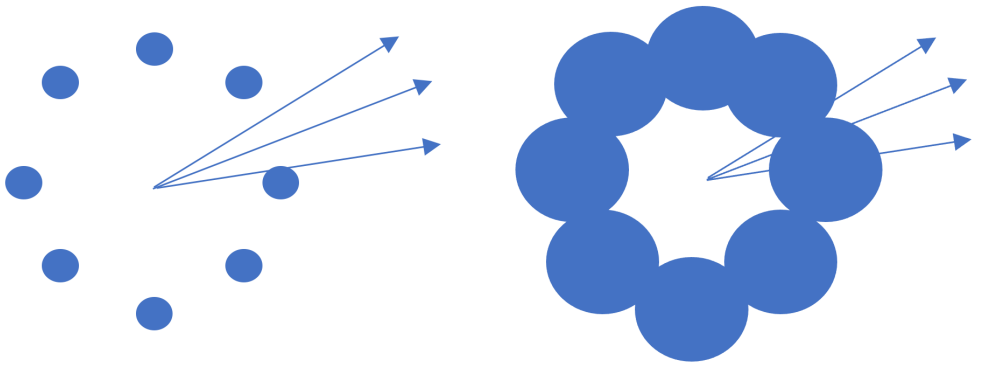


Figure 8. Cross-section effect on fission process

In this illustration, the cross sections of the atoms are represented by disc size (area) and the neutrons by arrows. It is clear that a larger disc (atomic cross section) is more likely to intercept a neutron (and fission as a result) than the smaller discs (atomic cross section) where the neutron is more likely to pass between them and escape without causing a fission event.

Mass: Second, the amount or mass of material.

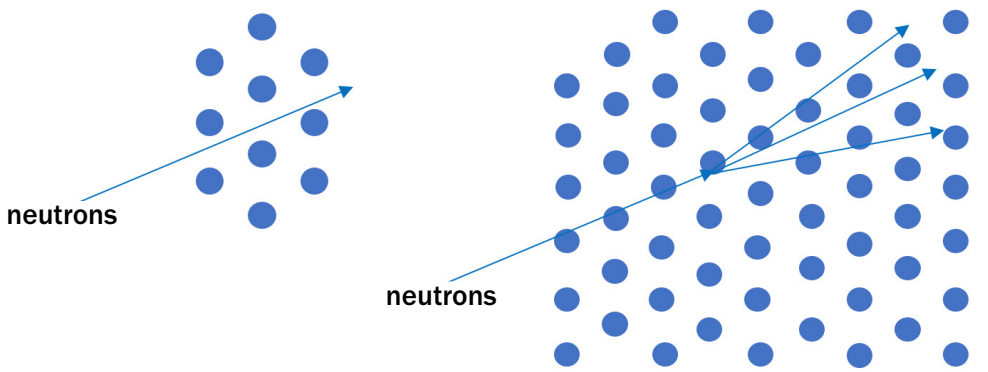


Figure 9. Size effect on fission process

In Figure 9, the group of atoms on the left is too small to sustain a chain reaction because the neutron is unlikely to cause a fission chain reaction to start before escaping the material. In the group of atoms on the right, a neutron can't avoid causing a fission chain reaction before escaping the material.

Implosion: Third, implosion or compressing the material to force the atoms closer together. By imploding and so compressing the material, the atoms are forced closer together and fission neutrons are less likely to escape the material without causing additional fission events, hence a chain reaction. See Figure 10 below.

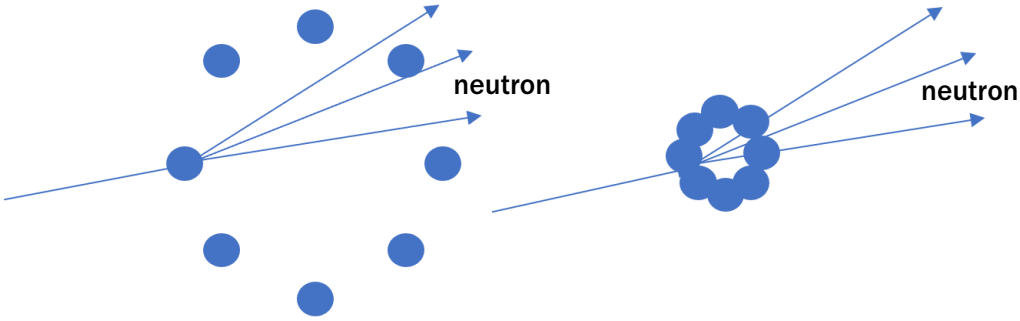


Figure 10. Implosion effect on fission process

Shape: Fourth, the shape of the material affects the likelihood of a neutron escaping or not escaping.

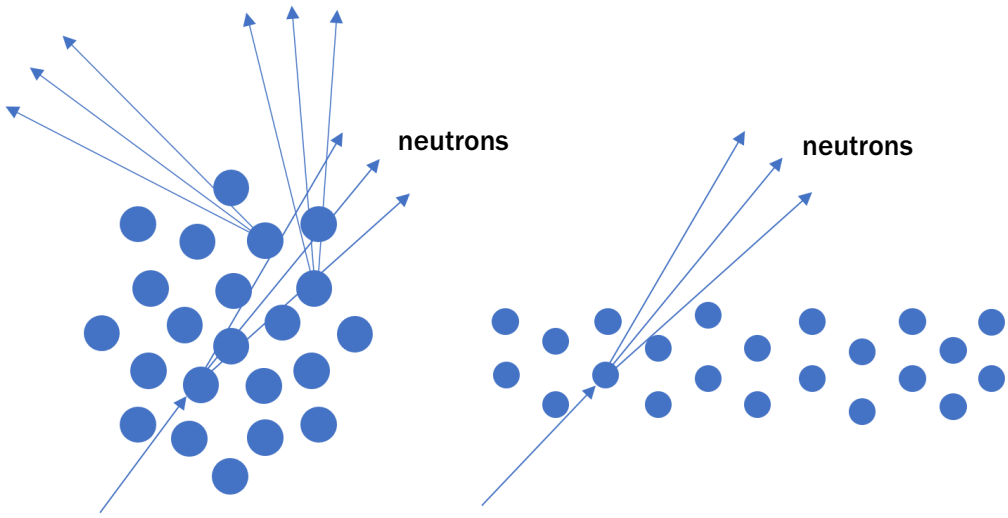


Figure 11. Shape effect on fission process

A sphere is the optimal shape for a critical mass. This is because the neutrons escape through the surface of a material and a sphere has the smallest surface area for a given volume of any geometric figure, hence the smallest means of escape for the neutrons. It is thicker in any direction (see Figure 11 on left above) than a sheet of metal foil (see Figure 11 on right above) that has a very short path to the surface throughout the material.

Reflector: Fifth, a "blanket" of material around the critical mass also known as a reflector. A neutron reflector blanket reflects neutrons (that would otherwise escape the material) back into the material to cause additional fissions. Thus, a subcritical

mass might be made supercritical by the addition of a neutron-reflecting material around the mass.

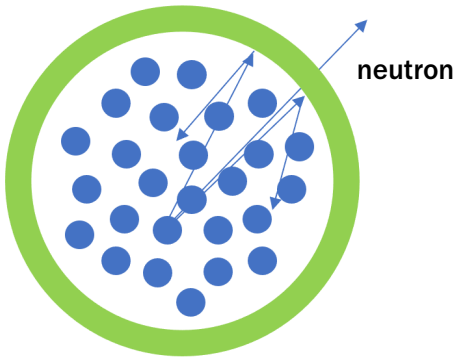


Figure 12. External reflector effect on fission process

Fusion

The other process that enables nuclear explosives operation is nuclear fusion. Whereas fission uses neutrons to split atoms at the upper range of nuclear size, fusion uses extreme heat (hence the "thermo" in thermonuclear) to force the smallest atoms to merge together, or fuse, to produce nuclear energy. This is the process that enables the hydrogen bomb.

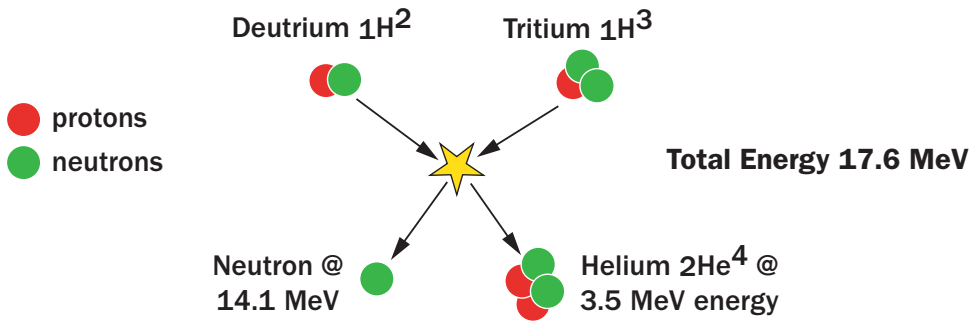


Figure 13. Deuterium/tritium fusion reaction

At extremely high temperature, deuterium and tritium atoms move very fast. So when they collide, they merge—or fuse—to form a single helium atom and emit a high energy neutron. The total energy produced in each fusion reaction is 17.6 million electron-volts (MeV).

Fission and fusion energy produced is gigantic compared to everyday experience. An eV is an electron-volt. That is the energy gained by an electron if it is accelerated through a 1-volt electric field. In comparison, room temperature is ~0.025 eV and a chemical high-explosive detonation temperature is ~0.5-1.0 eV, whereas a fission reaction produces 180 MeV and a fusion reaction produces 17.6 MeV. For a further comparison, burning a kilogram of coal would produce enough energy to burn a 10-watt lightbulb for about 83 hours. If a kilogram of uranium fissions, it would light the

same bulb for about 25,000 years. This is one reason why nuclear electric power is so attractive.

Compare chemical explosives with nuclear explosives. A gram of trinitrotoluene (TNT) produces $2.6x10^{16}$ MeV, so 180 MeV in a fission reaction may not seem like much in comparison. But there are three thousand-billion-billion atoms in a gram of uranium. Thus, fission energy in one gram of uranium is about 20 tons of TNT equivalent. Nuclear weapons take advantage of the enormous amounts of energy in these nuclear reactions to produce their devastating effects.

Types of Nuclear Weapons

Nuclear weapons can be grouped into three categories:

1. **Pure fission weapons**—the kind of weapon used to destroy Hiroshima and Nagasaki.

2. **Boosted fission weapons**—a fission explosion causes a small fusion reaction that reacts back onto the fissioning material with fusion neutrons to "boost" the fission explosion yield.

3. **Thermonuclear weapons**—the X-ray energy from a primary fission stage implodes a separate (secondary) thermonuclear (fusion) stage. This is the "H-bomb."

All of these weapon types use materials that can be fissioned. However, there are two kinds of material that can be fissioned: fissile material versus fissionable material. Fissile nuclei are nuclei that fission after absorbing a zero-energy (slow) neutron and so are most easily fissioned. Both U^{235} and Pu^{239} are fissile materials. Fissionable nuclei are nuclei that can only fission by absorbing an energetic (fast) neutron. U^{238} is such a fissionable material. Table 1 below lists common fissile and fissionable materials. U^{235}, Pu^{239}, and U^{238} are the materials most commonly used in nuclear explosives.

Isotope	Density (gm/cm^3)	Critical Mass (kg)	Neutron emission (n/kg/sec)	Heat (watts/kg)
U^{233}	18.64	16.1	0.82	0.3
U^{235}	**18.84**	**48.1**	**0.3**	**0.0**
Pu^{239}	**19.50**	**10.5**	**22**	**1.9**
Pu^{241}	19.66	12.8	49	13
U^{234}	18.72	153	5.0	0.2
U^{238}	**19.04**	**∞**		**0.0**
Pu^{238}	19.41	10.	$2.6x10^6$	553 used in Thermoelectric Generators (RTGs)
Pu^{240}	19.58	37.3	$1.0x10^6$	6.9
Pu^{242}	19.74	86.2	$1.7x10^6$	0.11
Np^{237}	20.40	58.8	0.14	0.02

Table 1. Common fissile and fissionable materials and their salient physical characteristics

Fission weapons use plutonium and uranium. All Pu in existence is manmade by irradiating uranium in a nuclear reactor with neutrons and chemically separating out

the plutonium from the spent fuel. The nuclear reaction creating the Pu is

$$(n, {}_{92}U^{238} > {}_{92}U^{239} > {}_{93}Np^{239}, e^{-} > {}_{94}Pu^{239}, e^{-})$$

In this process an atom of natural uranium ($_{92}U^{238}$, i.e. 92 protons and 146 neutrons) absorbs a neutron to become U^{239} (i.e. 147 neutrons) which then emits a beta particle (better known as an electron) that turns the extra neutron in the U^{239} nucleus into a proton and thus converting the U^{239} to neptunium-239 (i.e. 93 protons and 146 neutrons). This atom is unstable and emits another beta particle, converting a neutron into a proton to become plutonium-239 (i.e. 94 protons and 145 neutrons) which is a relatively long-lived element (a half-life of about 24,000 years).

While ^{239}Pu is the desired material, ^{240}Pu (half-life = 6,560 years) and other isotopes are produced in the reactor as the Pu-239 created captures additional neutrons. The time the fuel is left in the reactor determines the amount of other Pu isotopes produced. Weapons-grade plutonium contains less than 7% Pu^{240} and requires short reactor times and frequent fuel reprocessing. Higher percentages of Pu^{240} (reactor grade, typically more than 18% Pu^{240}) can be used in a weapon with a somewhat higher personnel hazard.

U^{235} has a half-life of 704 million years and so it naturally occurs in uranium at a low level of 0.7%. Thus, to be used in reactors it has to be artificially enriched to a low enrichment of at least a few percent. Highly Enriched Uranium (HEU) is uranium enriched to greater than 20%, while weapons-grade uranium is enriched to greater than 85% U^{235}.

Enriching uranium is a difficult process because U^{235} and U^{238} are chemically indistinguishable and their masses are nearly identical. There are four ways to separate 235 from 238 to enrich uranium. The Manhattan Project developed and used two enrichment technologies: electromagnetic separation and gaseous diffusion separation.

Electromagnetic separation used large cyclotrons (a cyclotron is an apparatus in which charged atomic and subatomic particles are accelerated by an alternating electric field while following an outward spiral or circular path in a magnetic field). The slightly heavier mass of the isotope U^{238} caused it to spin in a larger circle where it could be scooped off, leaving the U^{235} to be harvested from the smaller circle. These cyclotrons were called Calutrons (**Cal**ifornia **U**niversity Cyclo**trons**) and were developed by Ernest Lawrence at the University of California, Berkeley. They were built on a large scale for use at the Y-12 plant in Oak Ridge, Tennessee.

The other enrichment technology developed for the Manhattan Project was gaseous diffusion. Gaseous diffusion uses semi-permeable membranes. The uranium is made into a gaseous form by reacting it with fluorine gas to make uranium hexafluoride (UF_6). The gaseous uranium is then pressurized and forced through a series of membranes. At each membrane stage, the lighter U^{235} has a slight advantage in diffusing through the membrane. A series of such stages will thus enrich the gas in $U^{235}F_6$. The technique was developed by Francis Simon and Nicholas Kurti at the Clarendon Laboratory in the UK at the tasking of the MAUD committee and then transferred to the U.S. for further development and commercialization. The diffusion stages were built for large-scale use at

the K-25 plant in Oak Ridge, Tennessee and provided enriched uranium (known as oralloy, short for **O**ak **R**idge **Alloy**) for the Little Boy uranium bomb. Until recently, this was the sole source of enriched uranium for the U.S. nuclear industry.

Since the Manhattan Project, two new and better, more electrically efficient methods for enrichment have been developed. Gas centrifuge technology spins gaseous uranium (UF_6) at very high rates in long metal cylinders. Centripetal force accelerates molecules so that different masses are physically separated in a gradient along the radius of the rotating cylinder. Separation efficiency depends on mass difference between the two isotopes. A high degree of isotopic separation relies on using many individual centrifuges arranged in a cascade that achieve successively higher concentrations by passing the slightly enriched uranium gas from one centrifuge to the next. The gas centrifuge system yields higher concentrations of U^{235} while using much less energy when compared to gaseous diffusion (see photo of an Iranian centrifuge cascade below).

Figure 14. Iranian centrifuge cascade

The most recent enrichment technological development is Atomic Vapor Laser Isotope Separation (AVLIS). In this process, a frequency tunable dye laser is used to preferentially ionize U^{235} atoms, but not U^{238} atoms. Ionization is a process wherein a negatively charged electron is ejected from an atom by stimulating it with the highly selective laser light, leaving the atom with a net positive charge. Again, the laser energy is selective and only ejects the electron from U^{235} atoms making U^{235} ions. The positively charged ions of U^{235} can then be moved and so separated by an electromagnetic field that acts on the charged atoms. As the U^{238} atoms are not ionized by the laser, they are not moved by the electromagnetic field. AVLIS achieves very high rates of separation in a single step. A large demonstration project was built at Lawrence Livermore National Laboratory (LLNL) in the 1980s, but the method has not been generally adopted by the nuclear industry. Centrifuges had already come to dominate enrichment and AVLIS was simply too late.

Returning to fusion, as noted, the deuterium and tritium atoms will have enough velocity to collide and fuse to make energy when at a very high temperature. They make energy because the sum of the masses of the deuterium atom and the tritium atom going into the reaction is greater than the sum of the masses of the resulting helium atom and neutron. That difference in mass is converted to energy in

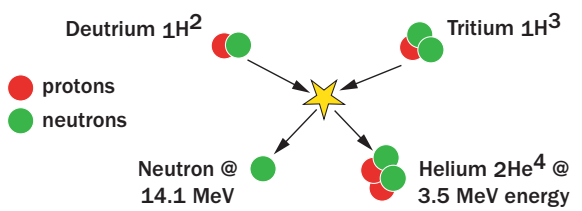


Figure 15. Deuterium-Tritium fusion reaction

accordance with Einstein's equation $E=MC^2$ where E is the energy that can be made from a mass M times C^2 which is the speed of light squared. Hence, the fusion of two grams of deuterium and three grams of tritium produces 400 tons of TNT equivalent energy at 100% efficiency. That's 80 kilotons per kilogram for fusion as compared to 17.4 kilotons per kilogram for fission. Thus, the advantage of a fusion weapon (hydrogen bomb) versus a fission weapon. The H-bomb has much greater yield for a given weight.

How do you get deuterium and tritium for fusion? Deuterium occurs naturally in water in very small amounts as D_2O and can be separated from water by either chemical exchange, distillation, or electrolysis. Tritium does not occur in nature because it is unstable and decays with a 12.3-year half-life. It must therefore be produced in nuclear reactors using neutrons. The reaction to make tritium uses the lithium-6 isotope of lithium. You bombard the ${}_3Li^6$ in a reactor with neutrons which splits the Li^6 atom into normal helium (${}_2He^4$) and tritium.

$$\mathbf{{}_3Li^6 + n \rightarrow {}_2He^4 + {}_1T^3}$$

As pointed out, tritium is unstable with a half-life of 12.3 years, so tritium must be periodically renewed in any weapon that uses D/T fusion for yield.

Finally, How Nuclear Weapons Work

Fission Explosives

The sequence of a nuclear fission explosion begins with assembling a supercritical mass of fissile material (${}_{94}Pu^{239}$ and/or ${}_{92}U^{235}$). Neutrons are then injected into the supercritical assembly to start a fission chain reaction. Because the assembly of fissile material is supercritical, the number of fission reactions grows exponentially. The yield of the explosion then depends upon how many fissions occur before the assembly disassembles (i.e. blows itself apart). The assembled critical mass will begin to disassemble when the fission energy produced begins to exceed the energy used to assemble the supercritical assembly (e.g. the energy delivered by the chemical high explosive to the implosion).

There are two ways to assemble a fission weapon supercritical mass of fissile material. First, I'll describe a gun-assembled fission device such as the Little Boy bomb dropped on Hiroshima on August 6, 1945.

As illustrated in the cartoon below left, in a gun-assembled weapon, two subcritical parts of a supercritical assembly of fissile material are placed at either end of a gun barrel. When the two halves are separated, each is subcritical. One of the halves has a charge of explosive propellant behind it, as one might use in a conventional gun. When the propellant is fired, it drives one of the halves down the barrel and onto the other half, forming a supercritical mass. At the optimum time, a source of neutrons is introduced to the supercritical assembly to initiate an exponentially increasing chain reaction causing a nuclear explosion.

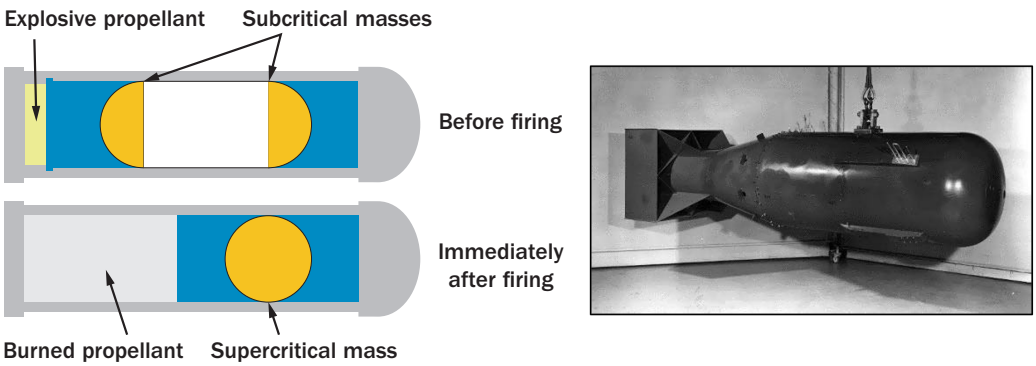


Figure 16. Schematic of gun-assembled critical mass with photo of Little Boy bomb at right

This is how the Little Boy bomb (shown above right) worked that was used at Hiroshima. It was an oralloy weapon and it exploded with about 15 kilotons of yield.

Second, I'll describe an implosion-assembled fission device such as the Fat Man bomb dropped on Nagasaki on August 9, 1945. As illustrated in Figure 17 below, a subcritical sphere of plutonium is surrounded by a sphere of high explosive. The surface of the high explosive is covered with a layer of explosive lenses (not shown) which create a spherically-shaped, inwardly-directed shockwave that precisely detonates the outer surface of the high explosive sphere. This drives an inwardly-directed chemical explosive detonation which then pushes on and so implodes the subcritical sphere of plutonium. The compression of the plutonium resulting from the implosion forces the atoms of plutonium closer together, driving the plutonium to supercriticality. At the optimal time, a source of neutrons is introduced to the now supercritical assembly to initiate an exponentially increasing fission chain reaction causing a nuclear explosion.

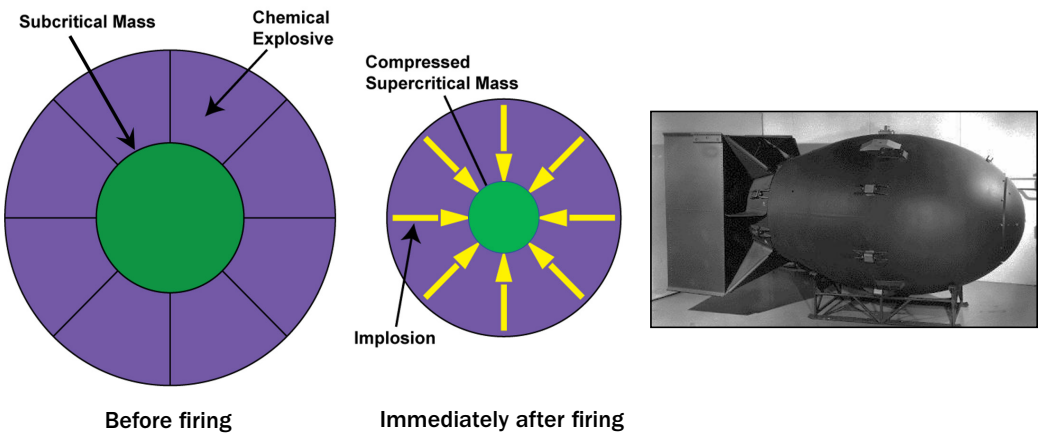


Figure 17. Schematic of implosion-assembled critical mass with photo of Fat Man bomb

This is how the Fat Man bomb (shown above) that destroyed Nagasaki worked. It was a plutonium weapon and exploded with about 20 kilotons of yield. Both Fat Man

and Little Boy are commonly known as atomic (i.e. fission) bombs.

Trinity was the codename for the first nuclear test of a nuclear explosive (nicknamed the "Gadget") at Alamogordo, New Mexico on July 16, 1945. The gadget is the roughly spherical object at the lower right (Figure 18) below. The wires around the gadget are the high voltage cables that delivered the electrical energy to fire the explosive lenses. It was fired atop the tower shown at top left, with a close up of the test object as it was prepared to be hoisted to the tower top at bottom left. The photo at top right is of the Little Boy and Fat Man bombs. The picture in the middle is the mushroom cloud from the Trinity detonation as it began to rise.

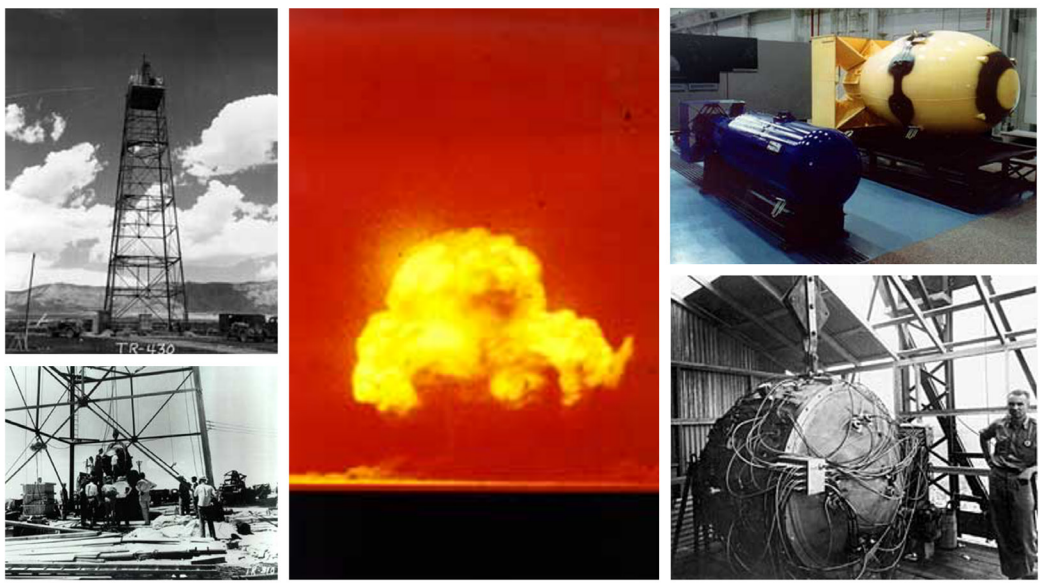


Figure 18. Trinity test tower (upper left), Trinity device (lower right), device to be hoisted up tower (lower left), Little Boy and Fat Man bombs (upper right), Trinity test mushroom cloud (center)

The yield of a pure fission device is sensitive to the timing of the neutrons injected into the supercritical assembly to start the fission chain reaction. This is known as the neutron-initiation pulse. Neutrons must be injected at a precise time in the implosion—not too early and not too late. Some yield may be produced without deliberate neutron initiation because of spontaneous neutrons coming from the fissile materials themselves. Note from the fission materials table above that Pu^{239} spontaneously produces 22 neutrons per kilogram per second. It was because of these spontaneous neutrons that an implosion system was developed. Plutonium cannot be used in a gun weapon because gun weapon assembly time is too long and would lead to premature neutron self-initiation and thus a low and unpredictable yield. The extremely fast implosion assembly time solves this problem.

Figure 19 illustrates why the timing of the initiation pulse is important to yield. As a supercritical mass is being assembled, by either gun or implosion, it will go through first criticality and have a positive neutron multiplication factor known as alpha (rising through zero at the left below) and then increase in supercriticality until it reaches a

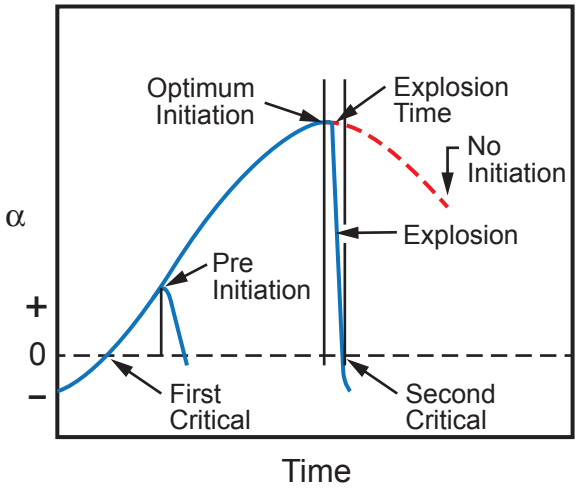


Figure 19. Notional criticality versus time plot

maximum of criticality. If no nuclear chain reaction occurs, it will then disassemble and so decrease in criticality back to zero and return to subcritical. While the assembly is supercritical, it is possible to start a chain reaction. The unit of neutron multiplication is generations per microsecond, hence if you multiply that number by the length of time, you get total generations of neutrons which is the same as the total number of fissions which is the yield generated before the heat of fission causes the assembly to come apart. Thus, the area under the curves is the yield of the explosion. If the neutrons start too soon, say at zero alpha, the area under the triangle at the left is proportional to the relatively low yield. If the neutrons are introduced at peak alpha, the larger triangle in the middle is the yield. That yield is the optimum, largest yield.

Fusion Explosives

The current strategic stockpiles (e.g. in the P-5, weapons states as defined by the Non-Proliferation Treaty—U.S., Russia, UK, France, and China) consist of thermonuclear devices. These are popularly known as hydrogen bombs, because the use of the fusible isotopes of hydrogen (i.e. deuterium and tritium) through the reaction shown below to make their explosive yield. Fusion of light elements occurs most efficiently at a high temperature, hence the term “thermonuclear” (think the center of the Sun). Fusion releases a lot of energy from a relatively small mass (weight) of material. This is what makes the H-bomb attractive from a military point of view.

Modern (e.g. P-5) nuclear weapons employ both fission and fusion to achieve their explosive yield. These weapons typically use a “boosted” fission first stage (a "primary")

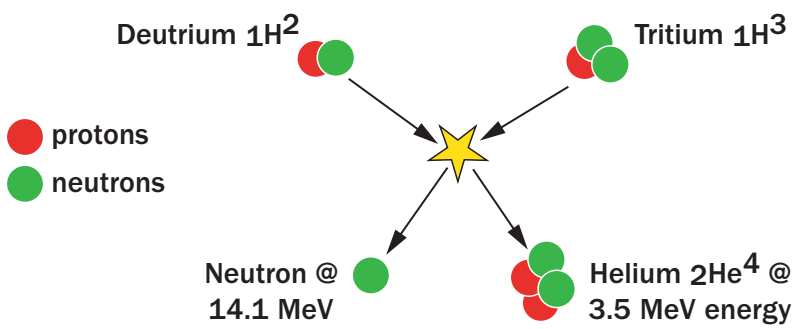


Figure 20. Deuterium-Tritium fusion reaction

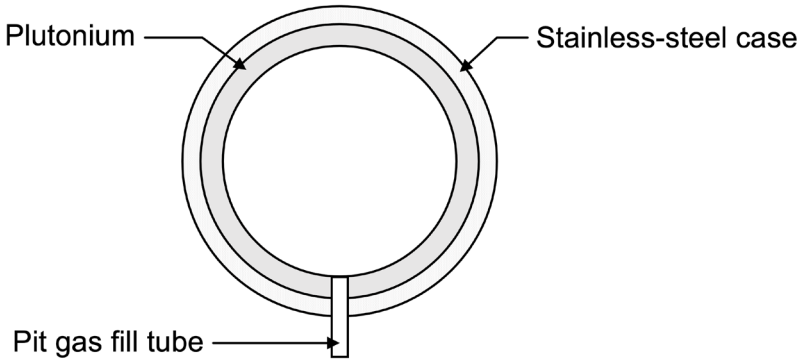


Figure 21. Notional boosted fission assembly geometry

to drive (i.e. implode) a thermonuclear second or main yield-producing "secondary" stage. Boosted fission weapons significantly reduce weight and fissile material used.

Boosting is achieved by placing a small amount of deuterium and tritium (DT) into a fission weapon's imploding core as shown schematically in Figure 21. Upon weapon implosion, the initial small fission yield is used to compress and heat the DT gas in its core to fusion detonation. The small fusion yield in the core then generates 14 MeV fusion neutrons that react back on the initial supercritical fission assembly and increase (i.e. boost) its fission yield. Thus, the first stage uses a fission/fusion/fission process to generate a first stage yield in a low-weight device. One of the key measurements made in a nuclear test is the efficiency of boost.

Staged Thermonuclear Explosives: the H-bomb

The concept for the two-stage thermonuclear explosive was first published in a

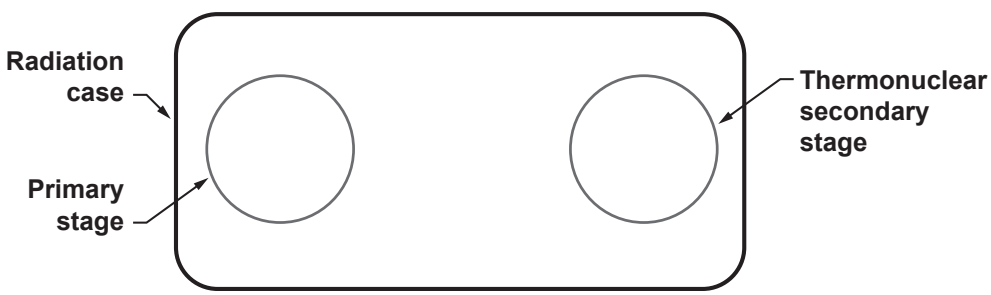


Figure 22. Schematic of a thermonuclear explosive

paper by Edward Teller and Stanislaus Ulam in March 1951. Ulam conceived the idea of staging. Teller conceived the idea of using the X-rays emitted by the very hot first stage (known as the primary) to implode the secondary or thermonuclear fusion stage. This approach uses the fact that the primary gets so hot from fission that it glows, not red or white hot, but glows in the X-ray spectrum. If those X-rays can be contained by a radiation case, they will be used to compress the secondary, resulting in a

thermonuclear detonation, producing the enormous yield of the H-bomb. Teller's X-ray coupling concept placed the explosive components inside of a heavy metal case that is opaque to X-rays. This is known as the radiation case. A key measurement made in a nuclear test is energy balance, the understanding of how much of the radiation is coupled to the secondary.

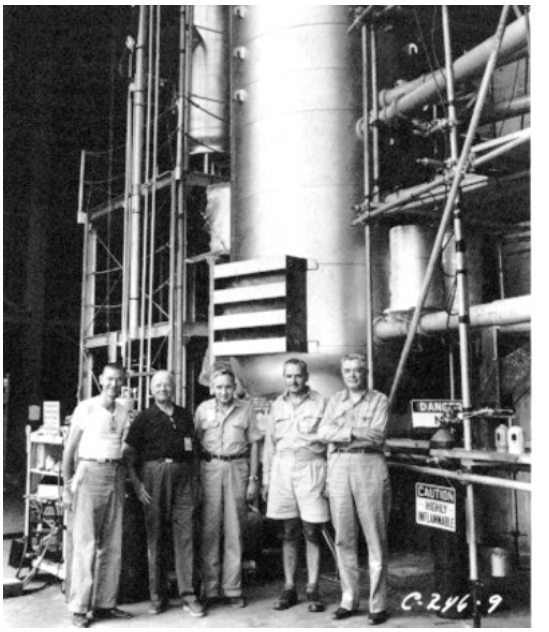


Figure 23. First thermonuclear explosive tested on November 1, 1952.

The first H-bomb was detonated on November 1, 1952 by Los Alamos Scientific Laboratory (LASL)—later renamed Los Alamos National Laboratory (LANL)—using the Teller/Ulam concept and gave 10.4 megatons of explosive yield. The device used to prepare for the test is shown in Figure 23. The explosive is the large vertical cylinder directly behind the second person on the right. It used a very large, unboosted primary at the bottom to implode a large cylinder of liquid deuterium. It weighed 82 tons and required a separate refrigeration plant to produce the cryogenic deuterium needed for the secondary stage. The device was designed by Richard Garwin, a student of Enrico Fermi. The deuterium reactions employed were:

$$6_1D^2 > 2\ {}_2He^4 + 2_1H^1 + 2n$$

yielding 43.2 MeV per reaction. This device was clearly not a weapon. In fact, Russian scientists sarcastically referred to it as an "installation,"[3] but it was a great breakthrough in nuclear weapon technology that led to H-bombs.

3 Gregg Herken, *Brotherhood of the Bomb* (New York: Henry Holt & Co, 2002), notes for Chapter 14 - #4.

The Modern, Miniature Hydrogen Bomb

The first H-bombs were gigantic. See below, for example, a U.S. H-bomb next to a B-36 strategic bomber (at the time the world's largest aircraft). In 1953, the world's first Russian H-bomb was the world's first deliverable and deployed H-bomb.

Figure 24. B-36 bomber with hydrogen bomb.

Even during the Manhattan Project, Teller was working on fusion concepts while all others were working on fission. With the end of World War II, Teller immediately campaigned to develop the thermonuclear bomb. This brought him into direct conflict with Oppenheimer, the chair of the State Department Disarmament Panel, and led to Teller leaving Los Alamos to work with Fermi at The University of Chicago. During this time, Teller also began lobbying the Air Force through Lieutenant General James Doolittle to create a second nuclear lab dedicated to thermonuclear research.[4] So as to keep nuclear weapons research firmly within the Atomic Energy Commission (AEC), the AEC asked Ernest Lawrence to open a second weapons lab. This lab opened on September 2, 1952 on the one square mile site of an abandoned World War II naval aviation training base in Livermore. It was conveniently located less than an hour's drive from Lawrence Berkeley National Laboratory. Ironically, the lab opened two months before Los Alamos tested the first thermonuclear bomb on November 1, 1952.

4 Thomas Ramos, *Those Upstarts Who Ushered in the Thermonuclear Age and Averted a Nuclear War* (Naval Institute Press, forthcoming), pre-print (2021), p56.

So, what was this thermonuclear lab to do? Lawrence directed that Livermore could do any weapons research it deemed important to national defense. Livermore could not, however, do any research occurring at Los Alamos. Teller dominated Livermore's first efforts, effectively acting as Livermore's unofficial chief scientist. He went down paths for thermonuclear weapons different from the original Teller-Ulam H-bomb idea since that idea was being done at Los Alamos. There was a push at this time to close the Livermore Lab. For example, Professor Isadore Rabi at Columbia University, a colleague of Oppenheimer's, was part of the campaign to close LLNL, likely related to Teller's involvement in the Oppenheimer/AEC security violations hearing that stripped Oppenheimer of his clearance. It did not help that Livermore's first three Nevada nuclear tests (code named Ruth, Rae, and Koon), based upon these alternate Teller ideas, failed catastrophically. Relations between the new lab at Livermore and Los Alamos became so bad that when the Ruth test explosion failed to demolish the Nevada testing tower, Los Alamos distributed photos of the tower and sarcastically referred to it in Washington as Livermore's invention of the "reusable test tower" (see photo in Figure 25).[5]

Figure 25. Post-test remains of the Ruth event test tower.

Lawrence then gave the technical lead to three brilliant young physicists: John Foster, Harold Brown, and Herbert York.[6] Their innovations saved Livermore and led to the invention of the miniature H-bomb. These physicists worked within a lab with an approach that was very different from the approach at Los Alamos. From its very beginning, Livermore Lab took a computational-simulation approach to the design of nuclear weapons as opposed to the experimentally-based approach of Los Alamos. One of Livermore's first acquisitions was the world's fastest (at the time) supercomputer. Large-scale, multidimensional

5 Ibid., p75-84.

6 Ibid., p89.

numerical simulation became (and has remained) the foundation of all research at Livermore.[7]

The first Livermore innovation of a nuclear weapon was created by John Foster. In his work to develop a nuclear howitzer shell, Foster invented the first miniature atomic bomb. At a time when atomic bombs were as much as five feet in diameter, successfully demonstrating in the nuclear test code named Tesla in March 1955, a howitzer-sized nuclear explosive was a groundbreaking achievement. This nuclear test is another example of the strained relationship between the two labs. At that time, all of the equipment at the test site was maintained by Los Alamos. When it came time to plan the event, Los Alamos informed Foster that the test would have to be delayed nine months as the busy Los Alamos testing schedule did not allow them to provide the nuclear-rated crane needed (to lift the nuclear device to the top of the test tower) until that time. Undeterred, Foster knew that he needed no crane as his miniature design could be carried by hand to the top of the tower. The solution was to put the device into two suitcases, add two leather handles to each for two-man nuclear safety, and have engineers carry the device to the top to the tower and install it. In Figure 26, the engineer is eating a sandwich on top of the suitcases containing the device as the Ford two-door ranch wagon transported it to the testing tower. There was no delay, and the test went off successfully. This photo demonstrated Livermore's invention of the "suitcase nuke."

The miniature atomic bomb was not Foster's only invention. As a student at Berkeley, after World War II service, he worked with the physicist Hugh Bradner of the University of California, Berkeley and Lawrence Berkeley National Lab (also formerly of LASL) to develop and market the first Neoprene wetsuit. See brochure and photos in Figure 27. Dr. Foster is the wetsuit model in each of the pictures.

The next step on the path to the miniature H-bomb came in August 1956 at the Navy's anti-submarine warfare conference in Woods Hole, Massachusetts. The conference was codenamed Project Nobska after the nearby lighthouse at Nobska Point. The Navy planned to enter the strategic nuclear weapons arena and so invited, for the first time to these conferences, two staff from each of the nuclear labs. Los Alamos sent Harold Agnew and Carson Mark (its chief scientist) and Livermore sent Edward Teller and Johnny Foster. At this

Figure 26. Tesla test device in suitcases at Nevada Test Site en route to test tower

7 Ibid., p68-69.

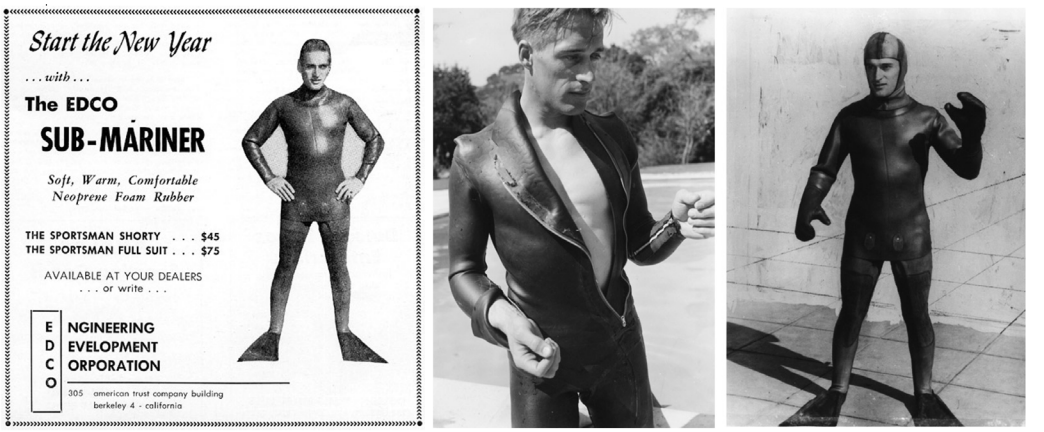


Figure 27. Dr. John Foster modeling wetsuit he developed

conference, the Navy showed its plans for a special giant submarine that would carry three liquid-fueled Jupiter missiles (each missile with one nuclear warhead). Despite having worked with the Army to reduce the size of the Army Jupiter missile from 60 feet down to 45 feet, the large missiles still spanned from bottom of the hull to the top of the sail. As the missiles were fueled with liquid oxygen, the boat would have to surface to elevate, load liquid oxygen and fuel into each missile, and launch. This process would take about 30 minutes and had a dangerous conduct of operation from both the fueling and also the defensive exposure point of view. The Navy planned to deploy the boats in 1965 since the big, special submarines had yet to be designed and built.

The Navy presented its needs to the nuclear lab representatives. The range of the Jupiter missile limited the weight of the warhead to no more than 3,000 pounds. The accuracy of the missile required at least a megaton of yield. This was a significant reduction in yield-to-weight from state-of-the-art 1955. Los Alamos said by 1965 that they could meet these warhead characteristics. Teller, aware of Foster's success and of the work that Brown and York were doing to miniaturize the thermonuclear secondary, did the arithmetic in his head and promised the Navy a 30-fold yield-to-weight improvement over state-of-the-art 1955. He added that Livermore could do this by 1963 ("turning the knife" on Carson Mark). He did this, despite the fact that only one of the three new technologies needed had been tested. The chairman of the Nobska Conference, Admiral Arleigh Burke, awarded the project to Livermore on the spot.[8]

The Navy immediately realized that such a small warhead could be launched by the much safer solid rocket-motored Polaris missile and that the Polaris missile could be launched underwater, dramatically improving the conduct of operations for missile deployment and launch. Hence, the planned giant submarines were not needed because attack submarines already under construction could contain the 29-foot Polaris missile within their pressure hull. In November 1957, construction of the #6 Skipjack class attack sub SSN-589 Scorpion was paused. Conversion to the first ballistic missile submarine,

8 Ibid., p113-114.

the SSBN-598 George Washington, started in January of 1958. The boat was cut in half behind the sail, the propulsion section was moved back, a 133-foot long, 16-missile launch tube section was inserted behind the sail, and the hull was welded back together (see Figure 28 for images of the Jupiter and Polaris SSBNs). The George Washington went on sea trials in July 1960. In October 1960, the first Polaris SSBN-598 deployed with 16 Polaris missiles each carrying a Livermore W-47 warhead. The first modern, miniature thermonuclear weapon was deployed to the boats and the boats were actively defending the nation four years early—only four years after Teller's audacious promise.

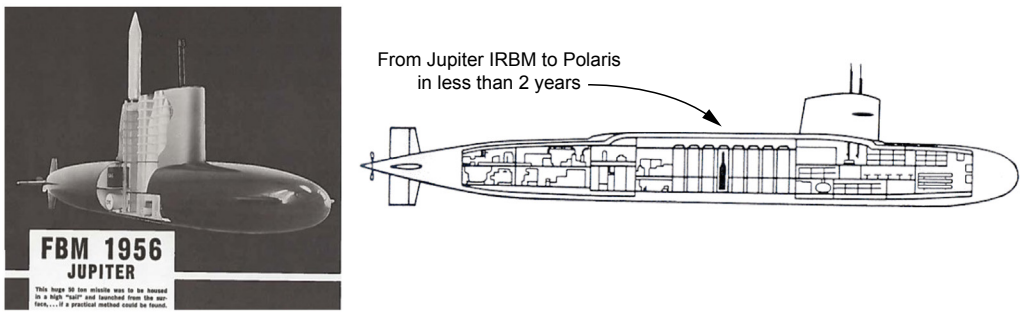


Figure 28. Proposed Jupiter Fleet Ballistic Missile submarine (left), schematic of Polaris Missile submarine (right)

This did not happen without challenges. In the fall of 1958, President Eisenhower and Soviet Premier Khrushchev agreed to a Gentleman's Nuclear Testing Moratorium to start at the end of October 1958. While Foster's idea was thoroughly tested by then (and testing was essential to deployment), Brown's ideas had had only one test by August 1958 and so could not be used until further testing under various deployment conditions was completed.

Hence, the first sixteen W-47/Mk0 warheads went to sea in October 1960 aboard the SSBN George Washington with some old-style technology that gave only half yield (i.e. ~15-fold improvement over state-of-the-art 1955). The Navy was satisfied despite this limitation.

The USSR then broke out of the Gentleman's Test Moratorium in 1961 using as an excuse the first French nuclear test conducted in Algeria in February 1960 (codenamed Gerboise Bleue, or Blue Desert Rat). The Soviets then executed 57 tests in the last four months of 1961 and 78 tests in 1962. They clearly had been preparing to break out. One is led to speculate as to why the USSR opted into the moratorium and then opted out in such an extreme way? The USSR may have agreed to the moratorium because they thought that they had achieved nuclear technological parity with the United States. Both countries had deployed fission and thermonuclear weapons. In fact, the USSR was first to deploy a thermonuclear weapon in 1953. A major issue in the 1960 U.S. Presidential campaign was the "missile gap." The United States lagged the USSR in missile throw weight capability. This became evident when the Soviets launched Sputnik, the first Earth satellite, in October 1957. While this may have been a space race issue, from a nuclear weapons point of view, it was a false issue. The United States

didn't need large missiles for its nuclear forces. Our thermonuclear weapons were miniaturized. The Soviet warheads were huge and, therefore, so were their missiles. When the Polaris SSBN deployed in October 1960 with megaton-class warheads small enough to fit on a Polaris missile, the Soviets noticed. In fact, the Navy ensured that they noticed by arranging for the October 1960 *CBS News* special "Year of the Polaris" where the new capability was fully displayed for the U.S. public and the Soviets to see. To quote Dr. Strangelove, "The whole point of the doomsday machine…is lost if you keep it a secret." It was true then and remains so today. It became clear to the Soviets that they did not have technological parity and that may have led them to return to testing.

After the Soviet breakout, the United States returned to testing in 1961. This enabled testing of the Brown and York concepts to be completed and incorporated into the megaton-class W-47/Mk1. In May 1962 the Frigate Bird test of the Polaris system was the only U.S. test of an operational ballistic missile with a live warhead. It was launched by the Ethan Allen (SSBN-608) from southeast of the Big Island of Hawaii. The W-47 warhead detonated at 11,000' altitude, 480 nautical miles (nm) east northeast of the UK's Christmas Island. The image of the Frigate Bird mushroom cloud (left) was taken from the periscope of the USS Carbonero (SS-337) near ground zero.

Figure 29. Frigate Bird test mushroom cloud

The American nuclear advantage became starkly apparent during the Berlin Crisis of 1961. With Polaris submarines on station, President Kennedy knew that they would survive a massive, surprise nuclear strike with enough power to retaliate and destroy the Soviet Union. As a result, Kennedy faced down Khruschev's threat of massive land war in Europe over Berlin.

Did the small thermonuclear warhead carried on Polaris make a difference in the Berlin Crisis? Did it add backbone to Kennedy when he stood up to Khrushchev? Kennedy's national security advisor, McGeorge Bundy, who was at the center of the crisis and helped determine the response, said that it did in his book *Danger and Survival: Choices About the Bomb in the First Fifty Years*. In March 1962, Kennedy himself came to Lawrence Berkeley National Lab to personally thank the Livermore physicists who helped him to avert thermonuclear war. The president set the stage himself when he offered his thanks to his weapons scientists before a crowd of 85,000 spectators. The photo below shows Kennedy with the inventors of the modern miniature thermonuclear weapon. From right to left are Harold Brown, Secretary of Defense Robert McNamara, Edward Teller, President Kennedy, Chairman of the AEC Glenn Seaborg, Berkeley Lab Director Edwin McMillan, John Foster, and Los Alamos

Figure 30. Kennedy at Lawrence Berkeley National Lab with developers of the modern H-bomb
(Photo from *Those Upstarts …*, Thomas Ramos, pre-print, Naval Institute Press, 2021.)

Director Norris Bradbury. The only one not smiling in this picture is Bradbury. This may be because he chose to ignore Foster's new technology in 1955 when his hydrotest leader Max MacDougal recommended that Los Alamos adopt it.[9]

The W-47 warhead was just the beginning of the innovation of the H-bomb. In the early 1960s, the USSR was developing nuclear tipped anti-ballistic missile (ABM) systems. With nuclear ABM, an inexpensive ABM defeats a large, expensive ballistic missile. This is an economic game that cannot be won by the attacker, as more big missiles are easily overcome by more cheap ABMs. The solution to ABM is MIRV (Multiple Independently targetable Reentry Vehicle). With MIRVs, a large number of ABMs are needed to defeat one MIRVed missile with many nuclear warheads aboard. This is an economic game the defender cannot win.

At this time, Livermore stepped up to the MIRV challenge since it had the miniaturization technology required. In 1964, Livermore tested the technology that became the MIRVed W-68 Poseidon warhead. This enabled another more than four-fold size reduction and brought strategic re-entry vehicles to their zenith of miniaturization. The figure below shows the reductions from the state-of-the-art 1955 B-18 to the 1960 W-47 to the 1964 W-68.

9 Ibid., p93.

The size of the W-68 defined the number of MIRV warheads required aboard a Poseidon missile. This is the reverse of the usual approach. Poseidon was deployed

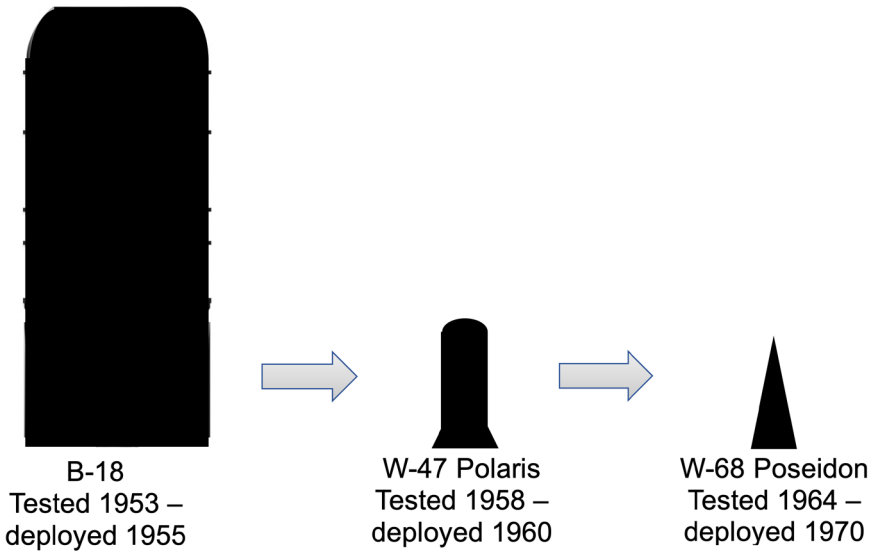


Figure 31. Relative sizes of weapons from the 1950s-1970s.

in 1970. The next generation of Navy warheads, the W-76 for Trident, was assigned to Los Alamos not because they had a better design, but rather because the AEC wanted to get them back into the strategic warhead business. As a result, in 1973, the AEC directed Livermore to transfer its miniaturization technology to Los Alamos and that the Livermore W-68 designers teach this technology at Los Alamos—so that it could once again compete in strategic nuclear weapons development.

Intrinsically Safe Nuclear Weapons

A series of accidents, some spreading nuclear materials into the environment, led to fundamental changes in nuclear weapons technology. A few examples of these accidents include (see figures below):

Palomares, Spain, January 1966: A B-52 nuclear bomber and a KC-135 tanker aircraft collided while refueling. Four of the 11 crew members survived. Four B-28 nuclear weapons fell from the bomber. Two inadvertently deployed parachutes. One sank to 2,900 feet in the Mediterranean and was recovered by the U.S. Navy four months later. Three fell onto the farming village of Palomares, Spain. The two without deployed parachutes detonated their conventional high explosives on impact, spreading nuclear materials across five square kilometers of farmland. One thousand four hundred tons of contaminated soil had to be packaged and removed to the United States.

Thule, Greenland, November 1968: A B-52 flying code name alert “Chrome Dome" over the Arctic developed a fuel leak. The leak ignited in the navigator’s area. The pilot ordered five crew members to bail out in Greenland’s Arctic winter while he attempted to land at Thule Air Base. The B-52 crashed seven miles short of the runway. All of the

nuclear weapons aboard were destroyed, spreading nuclear material on the fjord ice and snow. Seven thousand four hundred tons of contaminated ice and snow had to be packaged and removed to the United States.

There were more incidents and so reason to make weapons intrinsically safe. A near miss occurred in September 1980. In a Titan missile silo located in Damascus, Arkansas, a maintenance technician dropped an eight-pound socket that pierced the missile fuel tank. The fuel ignited and mortared the warhead out of the silo. It landed fusion stage down in the mud and did not detonate its high explosive charge.

Figure 32. Contamination footprint in Palomares, Spain (left - from BBC.com), B-28 bomb recovered from Mediterranean off Palomares, Spain by U.S. Navy (right).

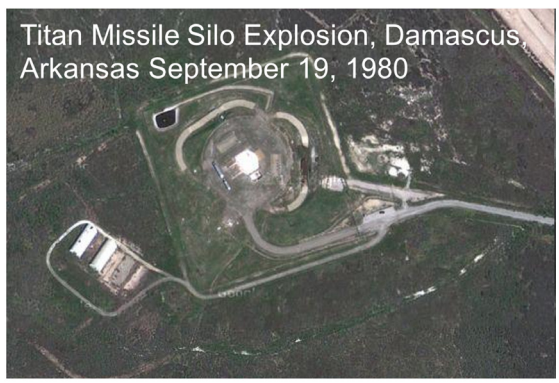


Figure 33. Aerial view of Titan missile silo installation (U.S. Air Force photo).

The Air Force asked for intrinsically safe weapons and defined an intrinsically safe nuclear weapon for the nuclear labs. It should:

1. Survive a high-speed impact without high explosive detonation
2. Survive a fuel fire without high explosive detonation or release of nuclear materials
3. Survive a lightning strike without high explosive detonation

The scenario suggested by these criteria is a bomber crash during a thunderstorm. The two labs engaged on this problem. Los Alamos developed the best insensitive high explosive (IHE) but did not fully understand the "Foster" miniaturization technology essential to using IHE. Hence their first nuclear tests failed. Livermore copied Los Alamos' IHE and successfully tested it to demonstrate the practicality of intrinsically safe nuclear weapons. Livermore added fire safety technology to the nuclear materials to create fire safe pits. Thus, without two competing nuclear design labs, the United States would not have intrinsically safe nuclear weapons today.

IHE has been tested to demonstrate that it does not easily burn. When it is forced to burn under an external flame, it burns like charcoal in that when the flame is removed, IHE goes out. However, unlike charcoal, IHE does not smolder, it just goes completely out. In addition, it does not react during supersonic impact and does not react when struck by multiple high velocity rifle rounds. It truly is an insensitive and thus a very safe high explosive.

Underground Testing

The modern stockpile was developed utilizing underground testing after the Limited Test Ban Treaty (LTBT) was signed in 1963. It prohibited the testing of nuclear weapons in outer space, underwater, or in the atmosphere. Most tests were done in vertical holes in Nevada. The drilling of a vertical testing hole is illustrated in the first image ("Hole Drilling," all test illustrations from LLNL archive) at left in Figure 34. Drilling time for a hole usually took three to 12 weeks. Typical hole depths in the valley at the Nevada Test

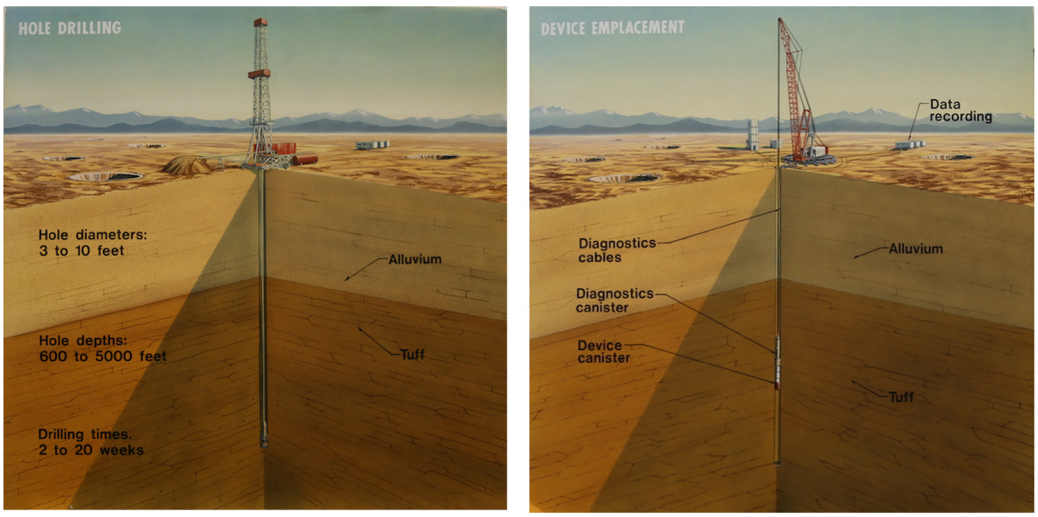


Figure 34. Drilling a test hole (left), lowering test canister into test hole (right)
(Pictures from LLNL National Security Vault displays.)

Site (NTS) ranged from 600 to 2,200 feet depending upon yield. The minimum depth of burial of 600 feet was to ensure that no radioactive materials would escape to the atmosphere in the event of a complete failure. Tests in the valley at NTS were in the hundreds of kiloton range. Megaton class tests were conducted at other sites, such Amchitka Island in the Aleutian Islands in Alaska and other unique locations. These took place at depths up to 6,000 feet. Hole diameters ranged from 36" to 120".

The diagnostic canister holding the test device and measurement equipment was lowered into the hole as shown in the second illustration (Device Emplacement) at right above. The hole was then filled with materials such as fly ash, sand, gravel, and plastic plugs to prevent radiation leakage as shown in the third illustration (Stemming for Containment) on the lower left in Figure 35. Hundreds of coaxial and fiber-optic cables connected the canister diagnostic measuring equipment to recorders located in trailers at a distance from the hole.

When the device is detonated (see illustration "Device Detonation" at right in Figure 35), the canister and the rock immediately surrounding the detonation is

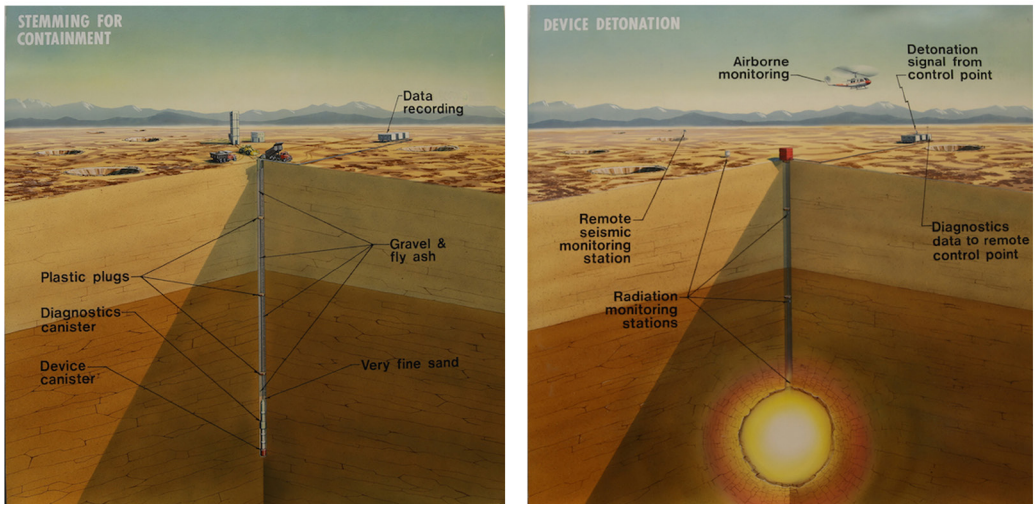


Figure 35. "Stemming" the test hole (left), detonating the nuclear explosive (right)
(Pictures from LLNL National Security Vault displays.)

vaporized. Beyond that, the shockwave from the detonation fractures the rock. All of the measurements of the test must be made by the canister test equipment and the data sent up the cables to the recording trailers before the canister is vaporized.

After the explosion, the plasma in the cavity created by the explosion cool to a gas and then condense to a liquid much like lava and flows to the bottom of the cavity to form a puddle. When sufficient condensation has occurred, the pressure in the cavity drops and can no longer hold up the fractured rock in the ceiling. The ceiling begins to collapse and caves in from the bottom to the surface forming a subsidence crater on the surface above the test point (see illustration titled "Post-Detonation Recovery of Radioactive Debris Samples" in Figure 36). When the area is deemed safe, a crew returns to drill down to what is now a rock puddle of cavity material to recover radioactive rock core samples. These samples contain reaction products of the explosion. The cores are returned to the lab that executed the test (either LLNL or LANL) where they are permanently stored for future reference. Tests of the reaction products are used to determine the yield of the explosion. During atmospheric testing, the size of the explosion fireball was a direct measure of the yield. Underground, the fireball cannot be measured. Instead, the radiochemistry of the rock cores reveals the yield, hence the drill back to recover cores.

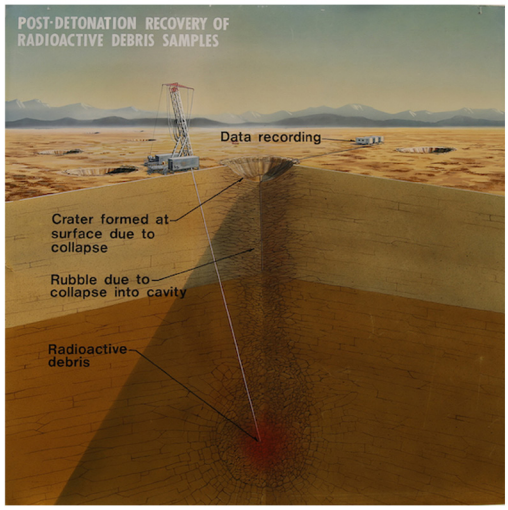


Figure 36. Drill back to retrieve rock core samples for explosive yield determination
(Picture from LLNL National Security Vault displays.)

Figure 37 below shows the temporary final test assembly structure with cranes and the many kilometers of coaxial diagnostic cable laid out on the desert floor that connect the canister to the recording trailers. The photo below right (Figure 38) shows a test canister (blue) suspended over the hole inside of a temporary assembly structure. The photo at bottom left (Figure 38) shows the temporary structure removed and a large crane about to lower the canister into the test hole.

The U.S. carried out 1,054 nuclear tests between 1945 and 1992, most of those at NTS. A comprehensive listing of the nuclear tests may be found in a document titled “United States Nuclear Tests July 1945 through September 1992."[10] A map of NTS showing the locations of the tests (Figure 39), a map of Nevada (Figure 40) showing the location of NTS within the Nellis Air Force Test Range, and a photo of the Yucca Valley at NTS (Figure 41) are featured on the next page. The many subsidence craters shown in the photo form at the surface above the cavity created by an underground nuclear explosion after it collapses.

Figure 37. Temporary structure holding test canister for final assembly of nuclear test. Coaxial cables to transmit measurements lie on the ground. Crane holds canister over hole.

Figure 38. Test canister about to be lowered into test hole (left), canister over hole in temporary assembly structure (right).

10 U.S. Department of Energy, Nevada Nuclear Security Administration Nevada Field Office, "United States Nuclear Tests July 1945 through September 1992" (September 2015). https://www.nnss.gov › docs › doe_nv-209_rev16. Accessed June 25, 2021.

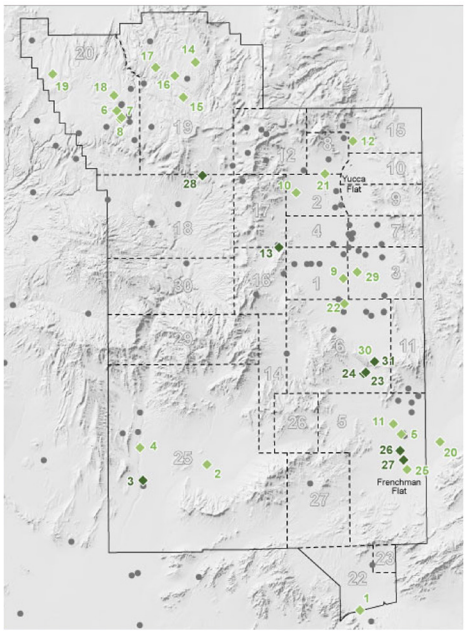


Figure 39. Map of NTS showing locations of tests

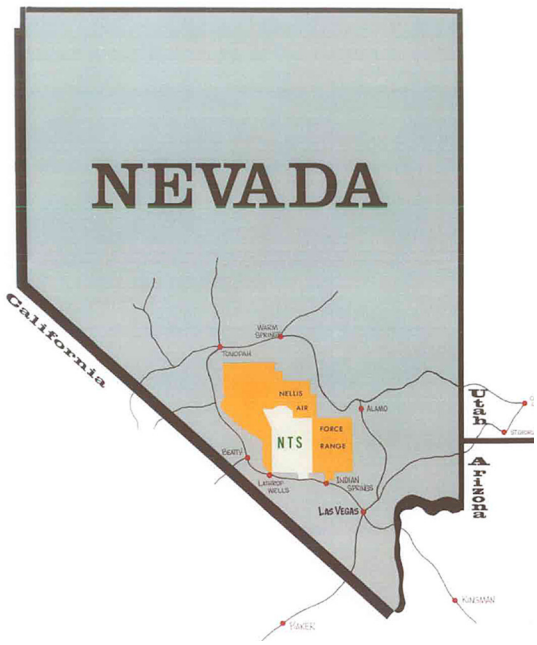


Figure 40. Location of NTS in Nevada

Figure 41. Aerial view of post-test subsidence craters at NTS.

The End of Nuclear Testing and the Advent of Science-Based Stockpile Stewardship

All of the technology and the weapons described so far were invented, developed, and certified by the traditional "cut-and-try" ad hoc experimental methods of nuclear testing. From the 1970s until 1992, modern "miniature" design was applied to the stockpile by both labs. While these scientists did conduct significant work in understanding the underlying physics of weapons operation, they primarily focused on weapons development and deployment. Nuclear testing enabled them to accomplish the design, development, certification, and deployment of these weapons.

Nuclear testing came to an abrupt halt in September 1992. President George H.W. Bush reluctantly signed a bill ending testing after a proposed 15 final tests. He signed the bill because it was attached to funding for a giant Super-Conducting, Super-Collider particle accelerator to be built in Texas. He then lost the 1992 election and the 15 tests never happened—nor was the accelerator built. The nuclear weapons enterprise had to then rapidly shift from a nuclear testing basis to a simulation and non-nuclear testing basis for weapon sustainment and any possible future development. This became the Stockpile Stewardship Program. It was believed by some that the end of testing would lead to the inevitable degradation of the weapons in the stockpile and prevent the design and development of new nuclear weapons. The Stockpile Stewardship Program has proved them wrong.

Historically, developing a complex, engineered, technological device without testing was not unheard of. There are many large, engineered structures that cannot be tested, especially not tested to failure, before they are built. It is clear that the builders of Roman arched bridges and Gothic vaulted cathedrals understood how to do this.

A classic example is suspension bridges, which are built without full system testing. One cannot test a suspension bridge to failure. The testing of these structures begin the day they are opened to traffic. The approach—used since ancient times—is called "engineering safety factors" (ESF). For nuclear weapons, the methodology is called "Quantification of Margins and Uncertainty" (QMU). QMU was developed by LLNL and adopted by NNSA to guide stockpile program decisions. In both ESF and QMU, the most stressing combination of factors that a system must face in its deployed lifetime is assumed to determine the worst-case forces acting upon a system. Then the system is designed to be significantly stronger than needed to sustain itself under those combined conditions. That extra capability is called "margin to failure."

For a suspension bridge, these combined stresses might include having a century of corrosion present on a day when there are fully loaded tractor trailer trucks stopped in traffic in both directions during a major hurricane when a Richter Scale 8

earthquake shakes the bridge. A good engineer will have designed the bridge to be able to sustain more than the combination of these forces. Good engineers are also humble and so assume that they may not have anticipated all future conditions and may have underestimated some stresses. Thus, they ensure that there is significant extra margin to failure. A classic example of this is shown in the picture of the Golden Gate Bridge in Figure 42. On the 50th anniversary of its opening, the bridge was closed to traffic so that the public could walk on it. It was not anticipated that 300,000 people would come and crowd shoulder to shoulder on the bridge deck. This was the largest load the bridge ever experienced. In fact, the bridge sagged seven feet at mid-span and each tower leaned in by six inches at the top. The bridge sustained the unanticipated load because there was significant margin to failure built into its design.

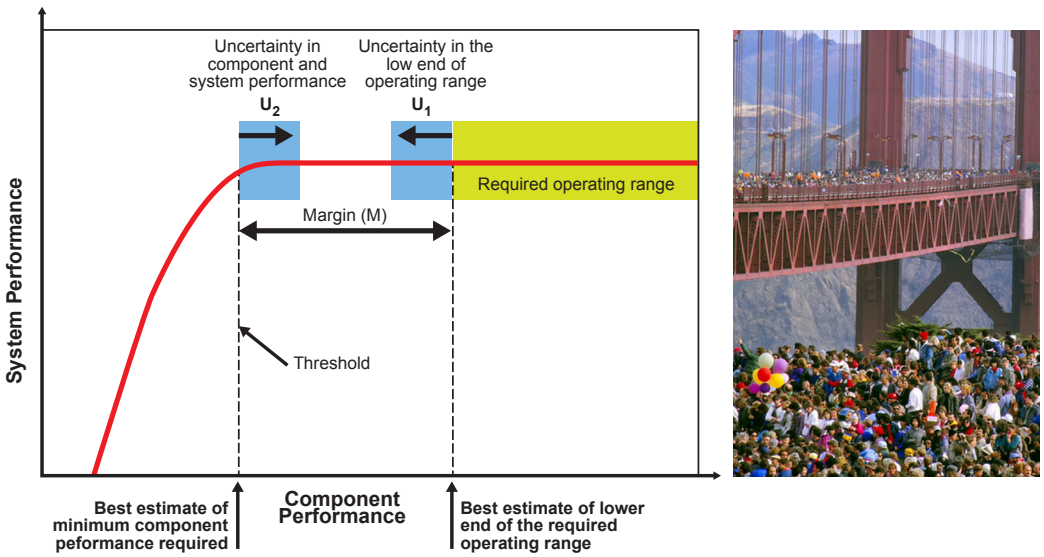


Figure 42. Schematic engineering safety factor graph (left), Golden Gate Bridge's largest load in 1989 (right) (photo *Marin Independent*).

In the notional, generic QMU diagram in Figure 42, the red line describes the behavior of a general system, perhaps a bridge, an airplane, or a nuclear weapon. For a bridge, the system performance vertical axis might be whether the bridge stands or collapses, while the component performance horizontal axis might be the strength of the cables holding the bridge up. The daily operating conditions of the bridge are shown where the red line is in the yellow block. Where the red line exits the yellow block at the left should define the estimates of the worst-case stress that the bridge will ever experience. The engineers then add extra margin (blue block at the right) for uncertainties about those stresses. They also add extra margin at the knee of the red curve because there is little experience of bridge failure. A well-designed system should have significant white space between the blue blocks as extra margin to failure to ensure that the bridge never fails.

For nuclear weapons, a QMU chart can be calibrated with more than a thousand nuclear tests, as there is extensive data on weapon performance to define the curves and the knee in the curve. Additionally, Uncertainty Quantification (UQ) in simulation is a computational keystone of stewardship wherein simulated performance exploring uncertainties are added to calibrate the chart for the system. Thus, significant margin to failure is built into the stockpile and life extension programs for the stockpile. Through this methodology, combined with non-nuclear hydrodynamic testing (i.e. implosion testing with surrogate, non-fissionable material), new design without nuclear testing has become possible.

Stockpile Stewardship Today

What fundamentals do we need to understand in order to steward the stockpile? Where do we stand today? Returning to what nuclear tests told us about the functioning of nuclear weapons at the highest level, we measured many things, many of which can be used to analyze boost efficiency and energy balance.

We can do experimental measurements at nuclear conditions without nuclear testing at High Energy Density facilities such as the National Ignition Facility.

The principal goal of Science-Based Stockpile Stewardship (SBSS) has been to determine these two factors without nuclear testing via non-nuclear experiments and high-resolution, large-scale numerical simulation. QMU has succeeded in localizing and reducing the blue uncertainty blocks. Through non-nuclear experiments at facilities like the Dual Axis Radiographic Hydrodynamic Test facility (DARHT) and the National Ignition Facility (NIF), energy balance has been resolved, and boost efficiency is close at hand. Thus, despite the hopes of some that the end of testing would bring an end to nuclear weapons and so to the stockpile, the indefinite sustainment of modern stockpile weapons and the design and deployment of new weapons can be achieved without resorting to nuclear testing. The stockpile modernization program today uses the methods of the SBSS to update the weapon designs of the 1980s based upon three decades of surveillance data while using modern manufacturing techniques.

Appendix 1: The Nuclear Weapons Complex

It takes the entire nationwide complex to design and build the nuclear weapons stockpile (see Figure 43). In addition to the already mentioned LLNL, LANL, and NNSS, the Sandia National Laboratory campuses in Livermore, California and Albuquerque, New Mexico design the non-nuclear components in LLNL and LANL weapons respectively. The Tonopah Range performs delivery system testing on facilities such as rocket sleds. The Kansas City, Missouri plant manufactures non-nuclear components. Uranium component production is performed at the Y-12 plant in Oak Ridge, Tennessee. Tritium is produced at the Savannah River plant in South Carolina. Finally, all of these components come together at the Pantex plant in Amarillo, Texas where weapon assembly and disassembly is performed.

Many of these places have visitor centers for nuclear tourists. Los Alamos National Laboratory in New Mexico has a museum, bookstore, and the Los Alamos Boys Ranch House that was the original building at the lab in 1942. Kirtland Air Force Base in Albuquerque, New Mexico is home to The National Museum of NNSS (formerly NTS) Nuclear Science and History. The Trinity site of the first nuclear test at the Alamogordo Bombing Range in White Sands, New Mexico is open to visitors two days each year (the first Saturday in April and October). The Oak Ridge National Laboratory in Tennessee is the site of the first plutonium production reactor, the X-10 Nuclear Pile. Hanford, near Richland, Washington, has a facility for the tour of the original Plutonium reactors and the "B" reactor. It is a very interesting tour with an excellent museum for understanding the earliest days of the weapons program. Tours of NNSS (formerly NTS) can be arranged at www.nv.doe.gov/nts/tours.htm#Tour%20Dates. While there, in Las Vegas there is the Atomic Testing Museum (www.atomictestingmuseum.org/). Finally, LLNL maintains a photographic archive of LLNL atmospheric nuclear tests at https://www.youtube.com/playlist?list=PLvGO_dWo8VfcmG166wKRy5z-GIJ_OQND5.

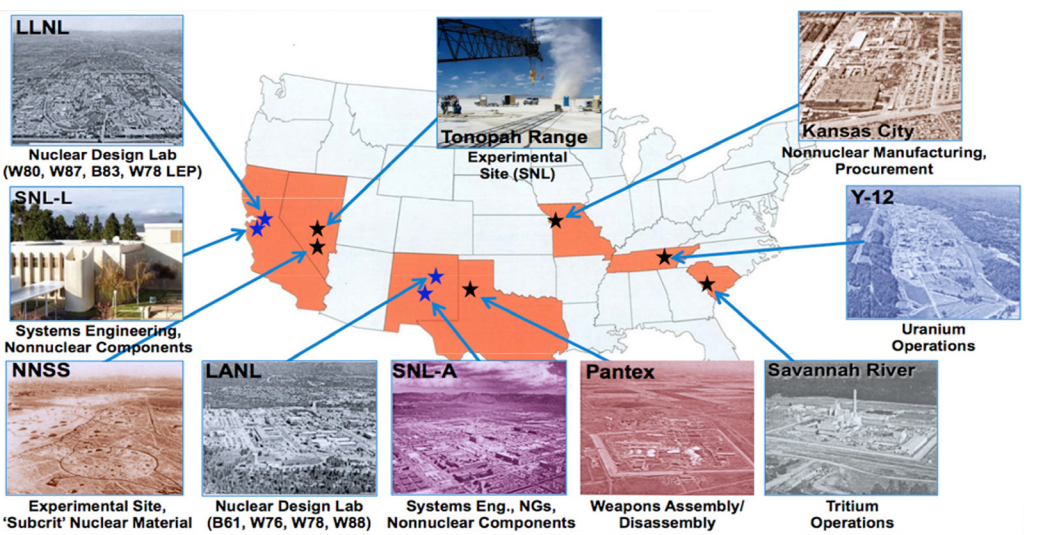


Figure 43. Locations of major nuclear enterprise facilities in the United States

Appendix 2: Current U.S. Stockpile Weapons

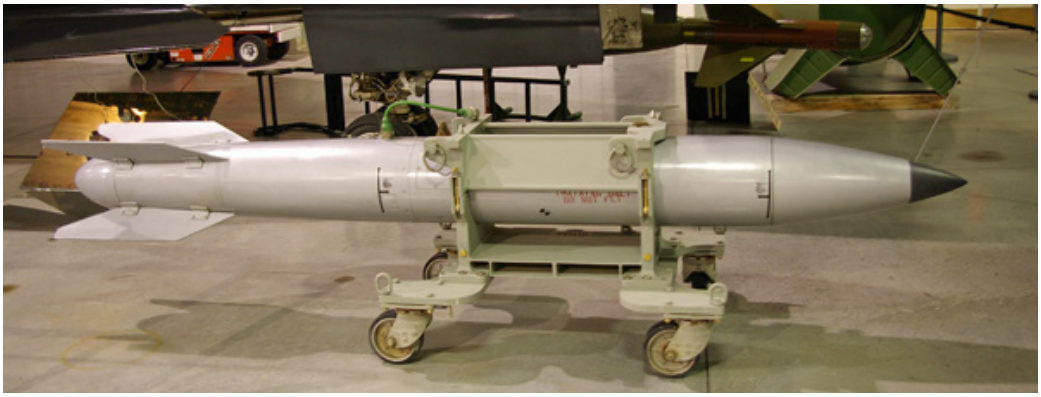


Figure 44. B-61 Strategic & Tactical Bomb. They are deployed on strategic and dual capable tactical bombers.

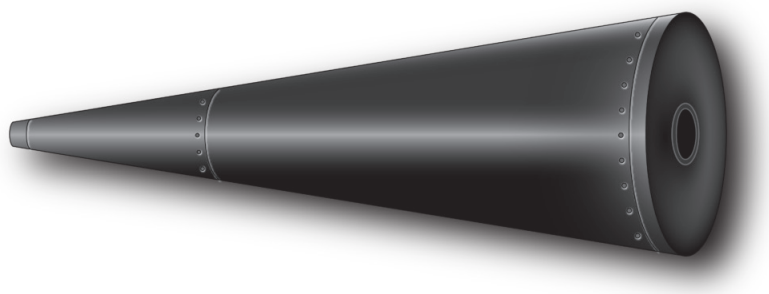


Figure 45. W-76 Warhead. They are deployed aboard Ohio-class submarines armed with Trident Ballistic Missiles.

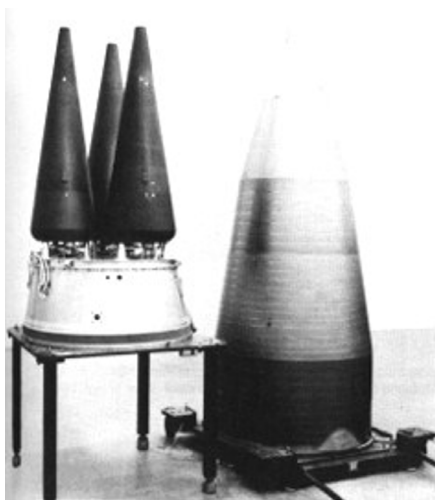


Figure 46. W-78 Warhead. Deployed on Minuteman III missiles, they are reaching end of life and are to be replaced by W-87-1 warheads.

Figure 47. W-80 Warhead. They are deployed on Air Launched Cruise Missiles aboard strategic bombers. In 2021, they are undergoing life extension to be deployed on the future Long Range Stand-Off missile.

Figure 48. B-83 Modern Strategic Bomb. They are deployed aboard strategic bombers. Physically, they are the largest weapon in the stockpile and have the largest yield.

Figure 49. W-84 Ground-Launched Cruise Missile Warhead. They are not currently deployed because the Ground Launched Cruise Missile went away in the Intermediate Nuclear Forces Treaty. The warhead is currently sustained in storage.

Figure 50. W-87 Warhead. It was deployed originally on the MX Missile (shown here), and is now deployed on the Minuteman III missile.

Figure 51. W-88 Warhead. It is deployed on Trident Ballistic Missiles aboard Ohio-class submarines.

Glossary of Terms

Atom Elements are made up of atoms. Atoms are made up of protons, neutrons, and electrons. Protons and neutrons are located in the nucleus (core of atom), while electrons orbit the nucleus.

Boosting A process used to increase the yield of fission weapons. A small fission explosion drives a small fusion reaction which makes many fusion neutrons that "boost" the fission process.

Chain Reaction A self-sustaining sequence of fission reactions caused by the additional neutrons emitted in a fission reaction. Requires a critical mass of fissionable material.

Critical Mass The amount of fissionable material required to sustain a fission chain reaction without losing the additional neutrons without which the reactions would stop.

Deuterium An isotope of hydrogen with one neutron. Used in fusion processes.

Electron A negative electrically-charged, sub-atomic particle. Also called a beta particle.

Fissile A material that fissions when absorbing a zero energy (slow) neutron.

Fission The nuclear process where a heavy element atom absorbs a neutron, becomes unstable, and splits into two smaller atoms, resulting in the emission of energetic neutrons.

Fissionable A material that only fissions when absorbing a sufficiently energetic (fast) neutron.

Fusion The process that uses extremely high temperature to accelerate light atoms to velocity sufficient to cause their nuclei to collide and merge into a combined, heavier nucleus. Deuterium and tritium fuse to produce a helium atom, an energetic neutron, and 17.4 MeV energy per reaction.

Half-life The time it takes for half of a material consisting of unstable atoms to decay into other atoms.

Hydrogen	The lightest element. It has one proton, one electron, and no neutrons.
Ion	An atom with one or more electrons removed, leaving the atom positively electrically charged.
Isotope	Atoms with the same number of protons, but different numbers of neutrons. Isotopes are chemically identical because the electrons determine its chemical properties and the number of electrons equals the number of protons.
Neutron	An electrically neutral, sub-atomic particle.
Primary	The first stage of a staged, thermonuclear weapon.
Proton	A positive electrically-charged, sub-atomic particle.
Radiation Case	An X-ray opaque case that surrounds the two stages of a thermonuclear weapon containing the X-rays that implode the second stage.
Secondary	The second or fusion stage of a staged, thermonuclear weapon.
Supercritical Mass	A mass of material able to support a significantly faster chain reaction than a simple critical mass.
Subcritical Mass	A mass of material unable to support a chain reaction.
Tritium	An isotope of hydrogen with two neutrons. Used in fusion processes and is manmade.

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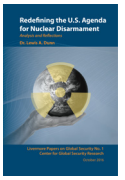

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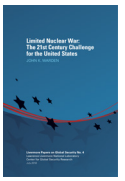

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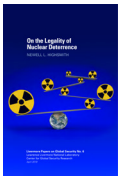

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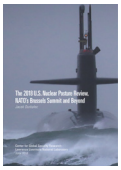

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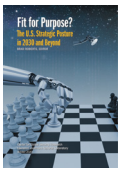

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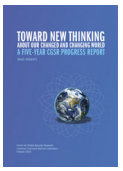

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