Appendix C
Basic Nuclear Physics

C.1 Overview

This appendix offers a basic overview of nuclear physics, which is the study of the properties of the atomic nucleus—the very tiny object at the center of every atom. This short tutorial is meant to be neither an authoritative nor a comprehensive examination of the subject. Instead, the purpose of this appendix is to provide background information useful in understanding the basic technical aspects of the U.S. nuclear stockpile, which are significant considerations for many important programmatic decisions. This appendix also serves to provide an understanding of the complexity of the science behind nuclear weapons and how this complexity affects weapon design, component production, and post-fielding issues.

C.2 Atomic Structure

Matter is the material substance in the universe that occupies space and has mass. All matter in the observable universe is made up of various combinations of separate and distinct particles. When these particles are combined to form atoms, they are called elements. An element is one of over 110 known chemical substances, each of which cannot be broken down further without changing its chemical properties. Some examples are hydrogen, nitrogen, silver, gold, uranium, and plutonium. The smallest unit of a given amount of an element is called an atom. Atoms are composed of electrons, protons, and neutrons. For the purpose of this book, there is no benefit in discussing a further breakout of sub-atomic particles.

Nuclear weapons depend on the potential energy that can be released from the nuclei of atoms. In the atoms of the very heavy elements that serve as fissile material in nuclear weapons, the positively charged protons and electrically neutral neutrons (collectively known as nucleons) form the enormously dense nucleus of the atom that is located at the center of a group of shells of orbiting, negatively charged electrons. See Figure C.1 for an illustration of the structure of an atom. Electron interactions determine the chemical characteristics of matter, and nuclear activities depend on the characteristics of the nucleus. Examples of chemical characteristics include: the tendency of elements to combine with other elements (e.g., hydrogen and oxygen combine to form water); the ability to conduct electricity (e.g., copper and silver are better conductors than sulfur); and the ability to undergo chemical reactions, such as oxidation (e.g., iron and oxygen combine to form iron oxide or rust). On the other hand, nuclear characteristics are based on an element's tendency to undergo changes at the nuclear level, regardless of the number of electrons it contains. Examples of nuclear characteristics include: the tendency of a nucleus to split apart or fission (e.g., atoms of certain types of uranium will undergo fission more readily than atoms of iron) and the ability of a nucleus to absorb a neutron (e.g., the nuclei of certain types of cadmium will absorb a neutron much more readily than beryllium nuclei). An important difference between chemical and nuclear reactions is that there can neither be a loss nor a gain of mass during a chemical reaction, but mass can be converted to energy in a reaction at the nuclear level. In fact, this change of mass into energy is what is responsible for the tremendous release of energy during a nuclear explosion.

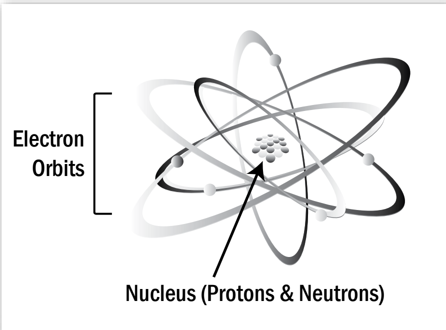

Figure C.1 Diagram of an Atomic Structure

The number of protons in an atom identifies the element to which it belongs. For example, every atom with eight protons belongs to the element called oxygen, and every oxygen atom has eight protons. There are 92 naturally occurring elements. In addition to these, modern technology has enabled scientists to increase the number of elements to more than 110 by artificially producing them. The periodic table is a tabular method of displaying the chemical elements, first devised in 1869 by the Russian chemist, Dmitri Mendeleev. Mendeleev intended the table to illustrate recurring ("periodic") trends in the properties of the elements; hence, this listing of elements became known as the periodic table. See Figure C.2 for an illustration of the periodic table.

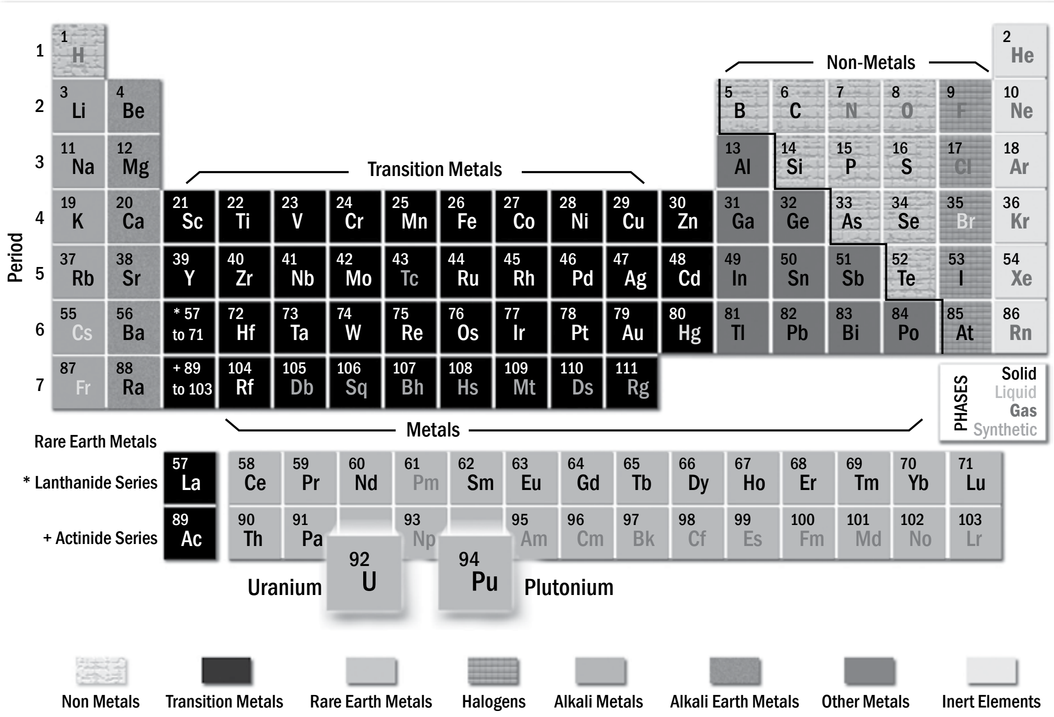

Figure C.2 Periodic Table

Atoms are electrically neutral when the number of negatively charged electrons orbiting the nucleus equals the number of positively charged protons within the nucleus. When the number of electrons is greater than or less than the number of protons in the nucleus, atoms are no longer electrically neutral; instead, they carry a net-negative or net-positive charge. They are then called ions. Ions are chemically reactive and tend to combine with other ions of opposite net charge. When atoms are combined in molecules, they may share electrons to achieve stability of the electron shell structure.

The term *atomic number* (Z) describes the number of protons in a nucleus, and because the number of protons determines the element, each different element has its own atomic number. Atoms of different elements have different numbers of protons in their nuclei.

The total number of protons and neutrons in an atomic nucleus is referred to as the *atomic mass* or *atomic weight* (A). A method of denoting atomic structure that is often used is $^{A}_{Z}X$, where X is the chemical symbol of the element. Another common format uses the name of the element followed by a dash and the atomic weight, e.g., uranium-233 (U-233). This information is typically not included in a periodic table, but it can be determined from a chart of the nuclides, which details specific nuclear properties of the elements and their isotopes. Isotopes are atoms that have identical atomic numbers (same number of protons) but a different atomic mass (different numbers of neutrons). This distinction is important because different isotopes of the same element can have significantly different nuclear characteristics. For example, when working with uranium, U-235 has significantly different nuclear characteristics than U-238, and it is necessary to specify which isotope is being considered. See Figure C.3 for an illustration of two of the 23 currently known isotopes of uranium.

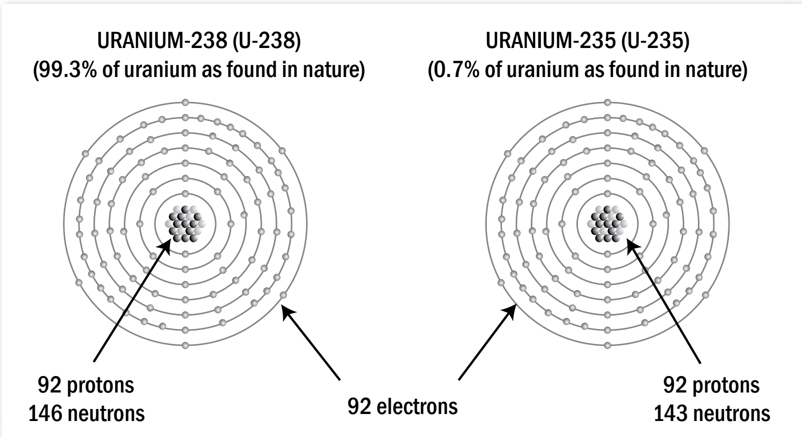

Figure C.3 Isotopes of Uranium

C.3 Radioactive Decay

Radioactive decay is the process of nucleus breakdown and the resultant particle and/or energy release as the nucleus attempts to reach a more stable configuration. The nuclei of many isotopes are unstable and have statistically predictable timelines for radioactive decay. These unstable isotopes are known as radioisotopes. Radioisotopes have several decay modes, including alpha, beta, and gamma decay and spontaneous fission. The rate of decay is often characterized in terms of "half-life," or the amount of time required for half of a given amount of the radioisotope to decay. Half-lives of different isotopes range from a tiny fraction of a second to billions of years. Rate of decay is also characterized as activity, or the number of decay events or disintegrations that occur in a given time.

C.4 Nuclear Reactions

The splitting apart of atoms, called fission, and the fusing together of atoms, called fusion, are key examples of nuclear reactions or reactions that can be induced in the nucleus. Fission occurs when an element with a very large nucleus, such as plutonium, is split into smaller pieces. This may occur spontaneously, or it may occur when a sub-atomic particle, such as a neutron, collides with the nucleus and imparts sufficient energy to cause the nucleus to split apart. The fission that powers both nuclear reactors and nuclear weapons is typically the neutron-induced fission of certain isotopes of uranium or plutonium. Fusion occurs when the nuclei of two atoms, each with a small nucleus, such as hydrogen, collide with enough energy to fuse two nuclei into a single larger nucleus. Fusion occurs most readily between nuclei with just a few protons, as in the isotopes of hydrogen.

C.4.1 Fission

During nuclear fission, a nucleus splits into two or more large fission fragments, which become the nuclei of newly created lighter atoms, and which are almost always radioactive (prone to radioactive decay). Fission releases a large amount of energy—millions of times more energy than the chemical reactions that cause conventional explosions. The fission process will almost always release some number of neutrons that can, in turn, cause other nuclei to fission; this is known as a *chain reaction*. See Figure C.4 for an illustration of a fission event.

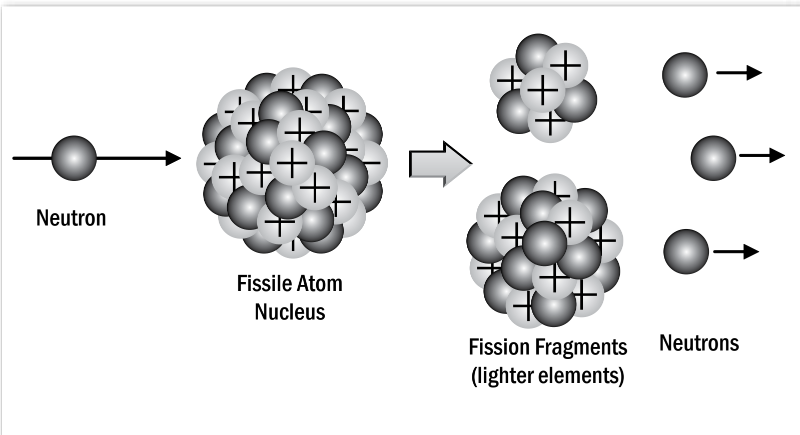

Figure C.4 Fission Event

Criticality describes whether the rate of fission increases (supercritical), remains constant (critical), or decreases (subcritical) in a particular situation. See Figure C.5 for an illustration of a sustained chain reaction of fission events. In a highly supercritical configuration, the fission rate increases very quickly, which results in the release of tremendous amounts of energy in a very short time, causing a nuclear detonation. For this reason, the fissile material in a nuclear weapon must remain subcritical until detonation is required.

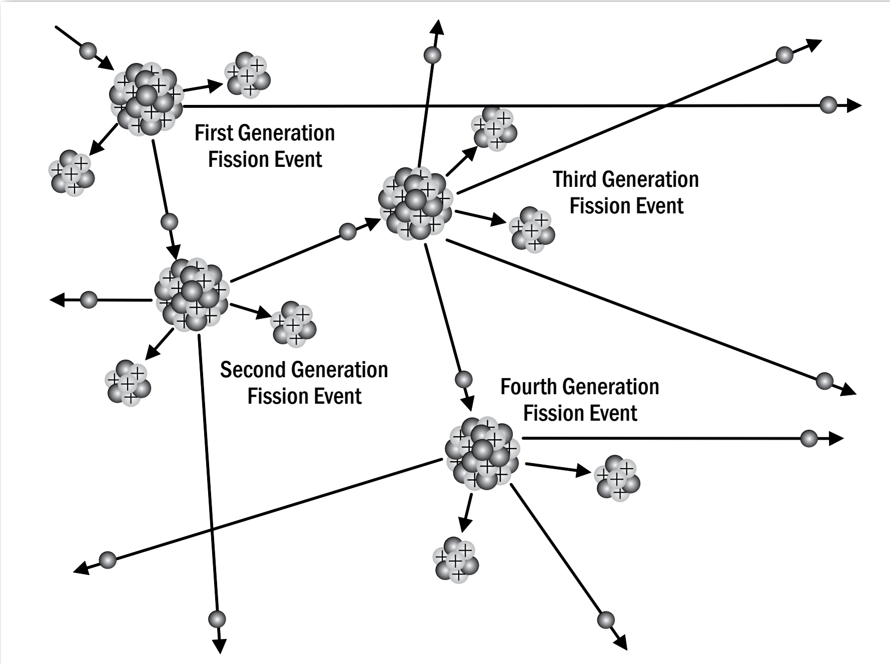

Figure C.5 Sustained (Critical) Chain Reaction

There are seven factors that affect criticality: the type of fissile material, the amount of fissile material, the enrichment of the material, the purity of the material, the shape of the material, the density of the material, and the environment. Different types of fissile isotopes have different probabilities of fission when their nuclei are hit with a neutron (called "cross-section") and produce a different average number of neutrons per fission event. These are the two primary factors in determining the material's fissile efficiency. Generally, the larger the amount of fissile material in one mass, the closer it is to approaching criticality if it is subcritical, and the more effectively it can sustain a multiplying chain reaction if it is supercritical. Enrichment is a term that indicates the percentage of the fissile material that is a more fissile efficient isotope than the other isotopes in that material. For this reason, using the words uranium or plutonium to describe some material as fissile material does not provide enough information to determine its isotopic distribution within that material. The purity of fissile material is important because either production of the fissile material or radioactive decay within the material can cause the material to contain atoms that act as neutron absorbers, which will decrease the material's fissile efficiency. Shape is important because some shapes (for example, a sphere) will increase the probability of neutrons meeting nuclei within the material, causing a subsequent fission event, and other shapes (for example, material in a long thin line) will decrease the probability that neutrons produced from one fission event can interact with another nucleus to cause another fission event. Density is important because the closer the fissile nuclei are, the more likely the neutrons are to interact with those nuclei before they can escape to the perimeter of the material. The environment in which the fissile material is contained is important because if a neutron-reflecting material immediately surrounds the fissile material, then neutrons that would otherwise escape at the perimeter of the material will be reflected back into the fissile material to cause other fission events. Additionally, if the fissile material is immediately surrounded by a huge amount of material, such as being buried deeply underground, then the surrounding material "tamps" the fissile material, keeping it together for a longer period of time (only a small fraction of a second) before it can explosively separate.

Only a handful of isotopes can support a chain reaction. The most important of these fissile isotopes are uranium-235 (U-235) and plutonium-239 (Pu-239); these are the only fissile isotopes that currently exist in large quantities. Obtaining significant quantities of fissile material has historically been the greatest challenge to a country seeking to build nuclear weapons.

Natural uranium consists of approximately 99.3 percent U-238, approximately 0.7 percent U-235, and very small amounts of other uranium isotopes. For use in weapons, the U-235 fraction must be enriched relative to the more abundant U-238 isotope. There are several different ways to enrich uranium, but all of them require significant technical expertise and energy. Figure C.6 depicts the typical uranium enrichment process. The process begins with a large amount of natural uranium converted to a form that can be processed for enrichment; currently, the gaseous compound uranium hexafluoride (UF6) is the most commonly used form. At each stage, the UF6 is subjected to a force that separates the UF6 with the heavier U-238 atoms from the UF6 with the lighter U-235 atoms by a small fraction of a percent. The portion of the UF6 with more of the fissile isotope U-235 is called enriched; the portion with more of the non-fissile U-238 is called depleted. By putting the enriched UF6 through successive stages, it becomes slightly more enriched at each stage. Initially, it is considered low enriched uranium (LEU). When it reaches 20 percent U-235, it is called highly enriched uranium (HEU). After thousands of enrichment stages, it can be enriched to approximately 90 percent U-235, which is considered to be weapons-grade HEU and can be configured into a weapon-sized package to produce a nuclear detonation.

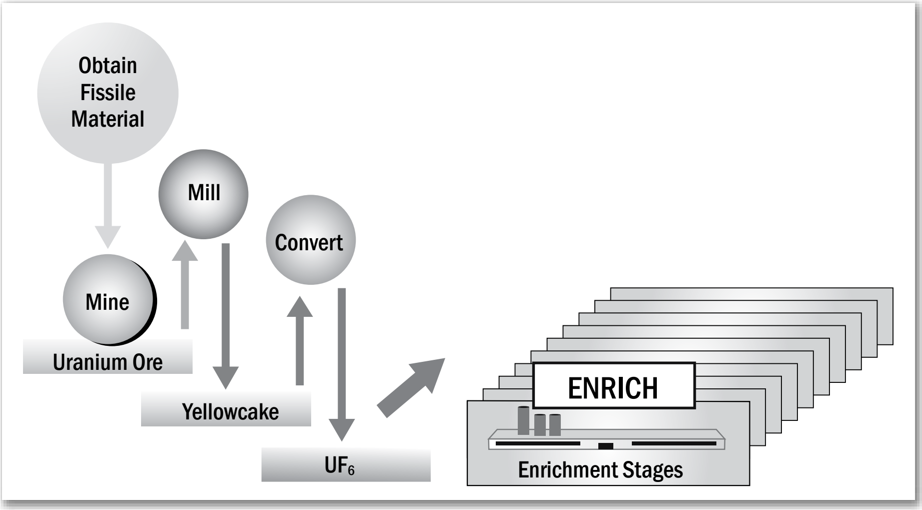

Figure C.6 Uranium Enrichment Process

By the end of the process, the very large amount of natural uranium has had most of the U-238 stripped away from the fissile U-235, leaving only a small fraction of the original quantity of uranium, but that small quantity has a much larger percentage of U-235. The U-235 has not been created or produced; it has only been separated away from most of the non-fissile U-238.

Plutonium is another fissile material used in nuclear weapons; it does not occur naturally in practical quantities. Plutonium is produced in nuclear reactors when U-238 nuclei absorb a neutron and become U-239. The resulting nuclei decay (via beta decay) to neptunium-239 and then to Pu-239, which is the plutonium isotope desired for nuclear weapons. As the reactor operates, the amount of plutonium increases and gradually becomes contaminated with undesirable isotopes due to additional neutron absorption.

Over time, the percentage of the undesirable isotopes, especially Pu-240 and Pu-241, increase. These heavier isotopes have shorter half-lives than Pu-239, making the material “hotter” for gamma radiation emissions. While the percentage of the undesirable isotopes is 7 percent or less, it is considered to be weapons-grade Pu. When that percentage becomes greater than 7 percent, it is considered to be reactor-grade Pu, and when the percentage exceeds 15 percent, it is considered “high-level waste” plutonium, with a high level of radioactivity that precludes it from being handled safely with the normal procedures for weapons-grade Pu.

This means that for the plutonium to be weapons-grade, the “spent” fuel containing Pu-239 must be removed more frequently. If the reactor is serving to both produce electricity and plutonium, this results in additional costs and less efficient power production. The plutonium must be chemically separated from the other elements in the "spent" nuclear fuel and extracted if it is to be used as fissile material for a nuclear weapon. This reprocessing step is an additional challenge for those who wish to divert weapons-grade plutonium from reactors that produce electricity.

C.4.2 Fusion

In general, fusion may be regarded as the opposite of fission. Nuclear fusion is the combining of two light nuclei to form a heavier nucleus. For the fusion process to take place, two nuclei must be forced together by sufficient energy so that the strong, attractive, short-range, nuclear forces overcome the electrostatic forces of repulsion. Because the positively charged protons in the colliding nuclei repel each other, it takes a large amount of energy to get the nuclei close enough to fuse. It is, therefore, easiest for nuclei with smaller numbers of protons, such as the isotopes of hydrogen, to achieve fusion. One of the most important fusion reactions occurs between two isotopes of hydrogen, deuterium (H-2) and tritium (H-3), resulting in helium-4 (HE-4) plus one high-energy free neutron (a neutron unattached to a nucleus), which can be used in a nuclear weapon to cause another fission event. Fusion also releases millions of times more energy than a chemical reaction does. See Figure C.7 for an illustration of a fusion event.

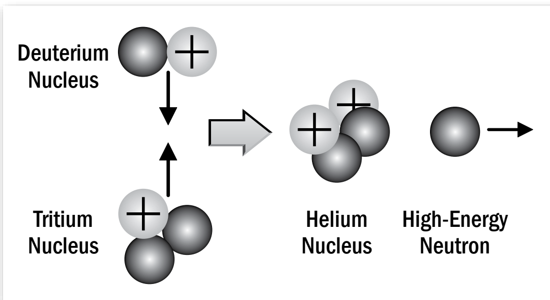

Figure C.7 Fusion Event

C.5 Basic Weapon Designs

All current nuclear weapons use the basic approach of producing a very large number of fission events through a multiplying chain reaction and releasing a huge amount of nuclear energy in a very short period of time (typically dozens of generations of fission events in a nuclear detonation will take only approximately one millionth of a second).

A variety of names are used for weapons that release energy through nuclear reactions—atomic bombs, hydrogen bombs, nuclear weapons, fission bombs, fusion bombs, and thermonuclear weapons. Therefore, it is necessary to address terminology.

The earliest name for a nuclear weapon was *atomic bomb* or *A-bomb*. These terms have been criticized as misnomers because all chemical explosives generate energy from reactions between atoms. Specifically, when exploded, conventional explosives release chemical molecular binding energy that had been holding atoms together as a molecule. Technically, a fission weapon is a "nuclear weapon" because the primary energy release comes from the nuclei of fissile atoms; it is no more "atomic" than any other weapon. However, the name is firmly attached to the pure fission weapon and is well-accepted by historians, the public, and by some of the scientists who created the first nuclear weapons.

Fusion weapons are called *hydrogen bombs* or *H-bombs* because isotopes of hydrogen are the principal components of the large number of fusion events that add significantly to the nuclear reactions involved. Fusion weapons are also called *thermonuclear weapons* because high temperatures and pressure are required for the fusion reactions to occur.[1] Because the distinguishing feature of both fission and fusion weapons is that they release energy from the transformations of the atomic nucleus, the best general term for all types of these explosive devices is *nuclear weapon*.

C.5.1 Achieving Supercritical Mass

To produce a nuclear explosion, a weapon must contain an amount of fissile material (usually either HEU or plutonium) that exceeds the mass necessary to support a critical chain reaction; in other words, a supercritical mass of fissile material is required. A supercritical mass can be achieved in two fundamentally different ways. One way is to have two subcritical components positioned far enough apart so that any stray neutrons that cause a fission event in one subcritical component will not begin a sustained chain reaction of fission events between the two components. At the same time, the components must be configured in such a way that when the detonation is desired, one component can be driven toward the other to form a supercritical mass when they are joined together. A second approach is to have one subcritical fissile component surrounded with high explosives (HE). When the detonation is desired, the HE is exploded with its force driving inward to compress the fissile component, causing it to go from subcritical to supercritical. Each of these approaches can be enhanced by using a proper casing as a tamper to hold in the explosive force, by using a neutron reflecting material around the supercritical mass, and by using a neutron generator to produce a large number of neutrons at the moment that the fissile material reaches its designed supercriticality, so that the first generation of fission events in the multiplying chain reaction will be a larger number of events.

Currently, nuclear weapons use one of four basic design approaches: gun assembly, implosion assembly, boosted, or staged. (This list is in order of simplest to most sophisticated—and thus most difficult to successfully produce.)

[1] The term *thermonuclear* is also sometimes used to refer to a two-stage nuclear weapon.

C.5.2 Gun Assembly Weapons

Gun assembly (GA) weapons use the first approach described above to producing a supercritical mass and rapidly assemble two subcritical fissile components into one supercritical mass. This assembly may be structured in a tubular device in which an explosive is used to drive one subcritical mass of fissile material from one end of the tube into another subcritical mass held at the opposite end of the tube. When the two fissile components are brought together, they form one supercritical mass of fissile material capable of sustaining a multiplying chain reaction of fission events.

In general, the GA design is less technically complex than other designs. It is also the least efficient.[2] Figure C.8 illustrates how a GA weapon achieves supercriticality.

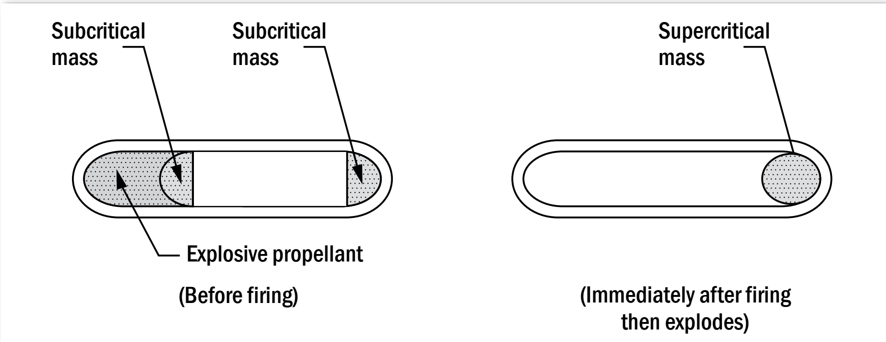

Figure C.8 TCG-NAS-2 Unclassified Illustration of a GA Weapon

C.5.3 Implosion Assembly Weapons

Implosion assembly (IA) weapons use the second method of achieving a supercritical mass, imploding one subcritical fissile component to achieve greater density and a supercritical mass. Here, a subcritical mass of HEU or weapons-grade Pu is compressed (the volume of the mass is reduced) to produce a supercritical mass capable of supporting a multiplying chain reaction. This compression is achieved by the detonation of specially designed high explosives surrounding a subcritical sphere of fissile material. When the high explosive is detonated, an inwardly directed implosion wave is produced. This wave compresses the sphere of fissile material. The decrease in the surface-to-volume ratio of this compressed mass plus its increased density are then sufficient to make the mass supercritical because the fissile nuclei will be much closer together. The proximity of the fissile nuclei increases

2 *Technical efficiency* is measured by the amount of energy produced for a given amount of fissile material. Less efficient devices require a lot of material to produce a relatively smaller sized nuclear detonation.

the probability that any given neutron will cause a fission event while simultaneously decreasing the probability that a neutron will escape the critical mass rather than cause a fission event. See Figure C.9 for an illustration of an implosion assembly weapon.

In general, the implosion design is more technically complex than the GA design, and it is more efficient.

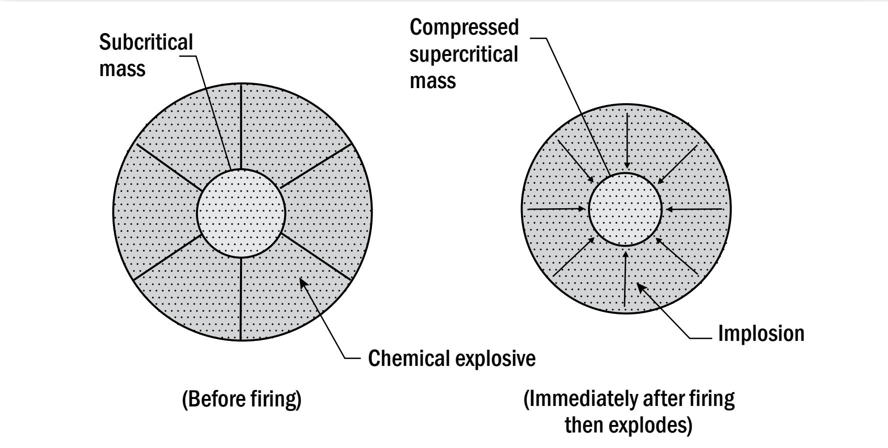

Figure C.9 TCG-NAS-2 Unclassified Illustration of an IA Weapon

C.5.4 Boosted Weapons

It is possible to increase the efficiency and yield for a weapon of the same volume and weight when a small amount of material suitable for fusion, such as deuterium or tritium gas, is placed inside the core of a fission device. The immediate fireball, produced by the supercritical mass, has a temperature of tens of millions of degrees and creates enough heat and pressure to cause the nuclei of the light atoms to fuse together. A small amount of fusion gas (measured in grams) in this environment can produce a huge number of fusion events. Generally, for each fusion event, there is one high-energy neutron produced. These high-energy neutrons then interact with the fissile material (before the weapon breaks apart in the nuclear explosion) to cause additional fission events that would not occur if the fusion gas were not present. This approach to increasing yield is called “boosting” and is used in most modern nuclear weapons to meet yield requirements within size and weight limits.

In general, the boosted weapon design is more technically complex than the implosion design, and it is also more efficient.

C.5.5 Staged Weapons

A more powerful and technically complex version of a boosted weapon uses both fission and fusion in stages. In the first stage, a boosted fission device called the primary releases the energy of a boosted weapon in addition to a large number of X-rays. The X-rays produced by the primary stage transfer energy to the secondary stage, causing that material to undergo fusion, which releases large numbers of high-energy neutrons. These neutrons, in turn, interact with the fissile and fissionable material to cause a large number of fission events, thereby significantly increasing the yield of the whole weapon. See Figure C.10 for an illustration of a staged weapon.

In general, the two-stage weapon design is more technically complex than the boosted weapon design. The two-stage design can produce much larger yields.

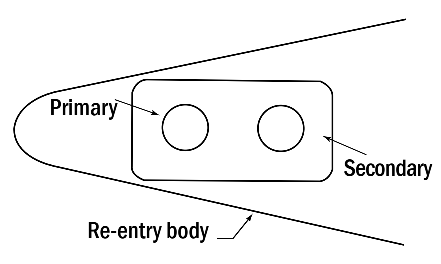

Figure C.10 TCG-NAS-2 Unclassified Illustration of a Staged Weapon

C.5.6 Proliferation Considerations

Generally, the smaller the size (volume, dimensions, and weight) of the warhead, the more difficult it is to get the nuclear package to function properly to produce a nuclear detonation, and the harder it is to achieve a higher yield.

The simplest and easiest design is the gun assembly design, followed by the implosion design. Because the boosted and two-staged designs are significantly more difficult, they are not practical candidates for any nation's first generation of nuclear weapons. There is no evidence that any nuclear-capable nation was able to produce either of these as their first workable warhead.

While the United States pursued both the GA and the implosion designs in the Manhattan Project, with one exception, other nations that have become nuclear-capable have focused on the implosion design for a number of reasons. First, the GA design is the least efficient design for producing yield per amount of fissile material. Second, the GA design has inherent operational disadvantages that are not associated with the other designs. Third, Pu is susceptible to predetonation in a GA design, requiring HEU for the GA weapon; however, HEU is extremely expensive because of the cost of the enrichment process. Pu, on the other hand, is produced in a reactor that can also be used for the simultaneous production of electrical power, which could positively affect a nation's economy in contrast to the economic drain associated with a costly enrichment process.

Up to this time, nations that have pursued a nuclear weapons capability have been motivated to design warheads to be small enough to be delivered using missiles or high-performance jet aircraft.[3] This is probably because, unlike the situation in the early 1940s, today almost all nations (and even some non-government actors) possess some type of effective air defense system, which render non-stealth, large cargo, or passenger aircraft ineffective at penetrating to almost any potential adversary's target. For this reason, it is highly likely that the first generation weapons developed by proliferating nations will be low-yield weapons, typically between one and 10 kilotons (kt).[4]

[3] Typically, the maximum weight for a warhead to be compatible with a high-performance jet aircraft would be approximately 1,000 to 1,500 kilograms (kg) (2,200 – 3,300 pounds), and approximately 750 to 1,000 kg (1,650 – 2,200 pounds) for the typical missile being proliferated, e.g., NODONG or SCUD-variant missiles.

[4] The *Fat Man* and *Little Boy* weapons had respective yields of 21 and 15 kt but were approximately 10,000 pounds each, and had dimensions much larger than today's modern warheads.