Chapter 15
Nuclear Fuel Cycle and Proliferation

OVERVIEW

There is a close relationship between the technology and infrastructure necessary for a nation to produce nuclear energy for peaceful purposes and those necessary to produce nuclear weapons. History shows that most proliferating nations rely on their own nuclear weapons development programs to produce the essential components for a nuclear weapon. Some nations prefer to advertise their intent to develop nuclear weapons. Other nations prefer to hide their proliferation activities until they have produced usable weapons. Analyzing a proliferant nation's weapons development program and its ability to produce nuclear weapons capabilities depends on understanding the nuclear fuel cycle and how it relates to the major activities required to produce a nuclear weapon. This chapter describes the steps a proliferating nation would need to take, either overtly or covertly, and to develop a nuclear weapons program and covers subjects including: nuclear fuel-cycle requirements; the basic principles of nuclear engineering; and the process to develop, produce, and weaponize a nuclear energy program.
* The United States does not produce spent nuclear fuel, including mixed-oxide (MOX) fuel.
Any proliferating nation that desires to successfully develop a nuclear weapon must engage in two basic essential activities: 1) a process to produce fissile material and from that a fissile component, and 2) a process to develop and produce all of the required non-fissile (non-nuclear) components required to produce a nuclear weapon. Figure 15.1 shows four basic paths to produce fissile material and then a fissile component. It also lists the required major non-fissile components that must be developed and produced in a process called weaponization.

The first path to a fissile component is to use an enrichment process with natural uranium (NU) as the basic material to be transformed into fissile material, shown as Path 1 in Figure 15.1. The enrichment process produces weapons-grade highly enriched uranium (WG-HEU) as the fissile material, which is put through a fabrication process to create a fissile component. A second possible path is to run a sufficiently large heavy-water reactor (HWR) with natural uranium as the reactor’s nuclear fuel. The reactor’s operation process converts a small portion of the nuclear fuel to the fissile material plutonium (Pu). The spent fuel is reprocessed to extract the fissile plutonium from the other materials in the

1 Most of the weaponization components listed are essential for any of the four basic nuclear weapon designs. Some may be required for one design, but not another. Others may be desired but not essential to produce a nuclear detonation, depending on the design.
spent fuel. The extracted plutonium is put through a fabrication process to create a fissile component (Path 2). A third possible path is to run a sufficiently large light-water reactor (LWR) with low-enriched uranium (LEU) as the reactor’s nuclear fuel.\(^2\) The reactor converts a small portion of the nuclear fuel to the fissile material plutonium. The spent fuel is reprocessed to extract the fissile plutonium from the other materials in the spent fuel, and the plutonium is fabricated into a fissile component (Path 3). A fourth possible path uses a thorium-fueled reactor producing uranium-233 as the fissile material (Path 4). This process is rarely used because thorium (Th) as a nuclear fuel is less efficient than either natural uranium in a heavy-water reactor or low-enriched uranium in a light-water reactor. Additionally, the uranium-233 produced is less efficient as a fissile material than plutonium. For these reasons, Path 4 in Figure 15.1 is shown grayed-out.

Because there are three practical paths to produce fissile material, there is no single path or single activity that is mandatory for a nuclear weapons program, including nuclear testing, which makes detecting illicit proliferation more difficult. Further details about these first three paths to a fissile component, each of the major components produced in weaponization, and the issue of nuclear testing are described later in this chapter.

Nuclear Fuel Cycle and Fissile Material

Fissile material is a necessary element of any nuclear weapon; therefore, a nation attempting to achieve a nuclear weapons capability must decide how to obtain fissile material. In most cases, proliferating nations prefer to produce their own fissile material as a by-product of nuclear energy production rather than rely on a foreign supplier. The process required to obtain nuclear fuel for use in a nuclear reactor is called the “nuclear fuel cycle,” and normally refers to the requirements for reactors used as power plants to generate electrical power, generally referred to as power reactors. The process is almost identical for reactors that serve to produce fissile material for nuclear weapons, generally referred to as production reactors. Most production reactors serve both functions, i.e., to produce fissile material for a weapons program and to generate electricity, again making detection more difficult if a nation wants to obscure its intent to proliferate.

Figure 15.2 shows the process to enrich uranium and produce WG-HEU, one common type of fissile material. Steps A through F represent a proliferating nation’s path to WG-HEU with no outside foreign assistance to obtain fissile materials. In Step F, the enrichment process must enrich uranium beyond LEU and non-weapons-grade highly enriched uranium (HEU). It also shows the

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\(^2\) It is possible to use natural uranium in a graphite-moderated light-water reactor to produce plutonium and generate electricity. Very few of the world’s total nuclear reactors are in this category.
paths to produce plutonium, the other most common fissile material, using natural uranium in heavy-water or graphite-moderated reactors under Step E or using LEU in light-water reactors under Step F.

If the decision in Step B is to use a foreign source for uranium ore, natural uranium, or converted uranium, the path can go from Step B to either Step D, E, or F accordingly. It is also possible that the proliferating nation procures uranium at any level of enrichment from a foreign source. History shows that proliferating nations rarely, if ever, procure from a foreign source any significant amount of HEU or WG-HEU for their nuclear weapons.

**EXPLORATION**

Exploration is the first phase of any new nuclear fuel cycle. Step A in Figure 15.2 shows the process of beginning exploration and obtaining data through research and assessment about nuclear physics, engineering, economic costs, manufacturing requirements, safe handling and transport requirements, and potential foreign suppliers. Step B is the decision to choose a path to obtaining fissile material—produce fissile material indigenously or purchase and import uranium ore, or uranium already extracted from ore (usually in the form of yellowcake), or converted uranium (usually uranium hexafluoride).

**MINING**

Step C in Figure 15.2 depicts the mining process for uranium ore. Conventional mining removes ore from the earth, which is processed above ground to extract the desired minerals, such as uranium. In situ mining, also called leach mining,
processes the ore while still in the ground by dissolving the ore in-place and extracting only the desired minerals. The leach solution which contains the desired minerals is pumped to the surface and the minerals are separated above ground in a subsequent process. In situ is usually more cost-effective than conventional mining because there is much less movement, handling, and disposal of wasted ore tonnage (sometimes called tailings), and it is more environmentally friendly because there is much less destruction of the natural surface of the terrain and less waste for disposal.

**MILLING**
In Step D, the uranium ore is transported to a milling facility to separate the natural uranium from all other minerals. This usually involves grinding the ore to a specified particle size and extracting the uranium using a chemical leaching process. The extracted uranium is usually in the form of a yellow, dry, coarse powder with a distinct odor, called yellowcake. Typically, yellowcake consists of mostly tri-uranium oxide ($\text{U}_3\text{O}_8$), and other uranium oxides such as uranium dioxide ($\text{UO}_2$) and uranium trioxide ($\text{UO}_3$).

**CONVERSION**
In Step E, the yellowcake uranium is transported to a conversion facility to further modify the chemical form of the uranium. This is required because the intended use of the uranium is for either manufacturing the uranium into a fuel pellet for a reactor that will use natural uranium, or to be put into a process to enrich the uranium. Either process requires that the uranium be in a different chemical form. The most common conversion is to uranium hexafluoride ($\text{UF}_6$), which is suitable for use in most reactors and also suitable to enter an enrichment process. The uranium may be converted to uranium dioxide ($\text{UO}_2$), which is the preferred form for some less-common reactors, such as the Canadian CANDU reactors.

**FUEL PELLET FABRICATION**
Certain types of less-common reactors, such as heavy-water or graphite-moderated reactors, are designed to use natural uranium without enrichment. In these cases, the natural uranium can be converted into the fuel pellet form required,

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3 The common name is tri-uranium oxide, but the technically correct term in chemistry is tri-uranium octaoxide.

4 CANDU (Canadian deuterium uranium) reactors are pressurized, heavy-water reactors using uranium as the fissionable fuel and heavy water as a neutron moderator (i.e., to slow down the neutrons and increase the fission cross-section, which is the probability that the neutron will interact with a heavy nucleus and cause a fission event). The term deuterium is used because heavy-water molecules contain deuterium atoms (the second isotope of hydrogen, which has one proton and one neutron in the nucleus) rather than the common form of hydrogen, which is called protium, and has one proton but zero neutrons.
and can be used in the reactor without enrichment as shown at the bottom of Step E. These reactors can be used as power reactors to generate electricity, or as production reactors to produce plutonium for nuclear weapons.

**ISOTOPES OF URANIUM**

Natural uranium consists of three isotopes shown in Figure 15.3. Of these three isotopes, only U-235 is fissile.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>99.2745</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>0.7200</td>
</tr>
<tr>
<td>Uranium-234</td>
<td>0.0055</td>
</tr>
</tbody>
</table>

Figure 15.3  Natural Uranium Isotopes and Percentages

**URANIUM ENRICHMENT**

Uranium enrichment is the process of isotope separation increasing the percentage of uranium-235 atoms in any given amount of uranium and decreasing the percentage of the sum of all other isotopes. Uranium enrichment does not create fissile atoms, but rather removes most of the non-fissile U-238 atoms, leaving a larger percentage of the fissile U-235 atoms in a much smaller quantity of uranium.

In Figure 15.4, Step A shows natural uranium moved to an enrichment apparatus. The gray area represents the atoms of the non-fissile isotopes and the black dots represent the atoms of the fissile uranium-235, which is only 0.72 percent of the total as shown in Figure 15.3 above. In Step B the uranium is subjected to a force or process applied by the apparatus. This causes the uranium atoms to separate in a manner that causes more of the heavier atoms to go one way and more of the lighter atoms to go in a different direction. This results in one portion of the uranium having a lower percentage of U-235 atoms, called depleted uranium, as shown in Step C at the top of the apparatus. The other portion of the uranium is enriched, i.e., having a higher percentage of U-235 atoms, as illustrated at the bottom of the apparatus.

All three steps in Figure 15.4 occur sequentially in one apparatus, which is called a *stage* when it is a part of a series of enrichment devices. At each stage, the separation process causes only a slight difference in the percentages of U-235 between the depleted and enriched portions. For most enrichment methods, this difference is usually only a small fraction of 1 percent.

The right portion of Figure 15.4 shows a list of different methods of creating the force or process to cause isotope separation. The current gold-standard of uranium enrichment is gas centrifuge technology. However, there are several
feasible and practical alternative methods that have either been implemented for commercial or weapons programs or that have been demonstrated at smaller scales for isotope separation. A proliferating nation may attempt to pursue a less widely used enrichment method.

In order to enrich uranium to a level where the percentage of U-235 is increased significantly, many enrichment stages are required. Multiple apparatuses are configured in a series, called a cascade, where each stage enriches the uranium to a higher level. The flow of uranium going through stages for higher levels of enrichment is referred to as moving downstream. Depleted uranium moving to earlier stages is called moving upstream. Figure 15.5 depicts a cascade of three enrichment stages.

In Stage 1, natural uranium undergoes isotope separation with the depleted uranium (A) sent upstream to the previous stage.\(^5\) The enriched uranium (B)
moves downstream to Stage 2. Uranium returning from Stage 2 (C) to Stage 1 has the same level of enrichment as the uranium processed in Stage 1. The apparatus at Stage 2 receives uranium enriched at Stage 1 (B) moving downstream and uranium depleted at Stage 3 (E) moving upstream. The Stage 2 apparatus combines the incoming uranium, separates the isotopes, and passes the more enriched downstream and the less enriched upstream.\(^6\) The apparatus at each stage performs the same functions, but at each successive stage going downstream, the level of enrichment is slightly higher. The level of uranium enrichment is defined as the percentage of U-235 atoms in the uranium, e.g., 3 percent enriched uranium contains 3 percent U-235 atoms of the total uranium atoms.

**Depleted Uranium**

Depleted uranium (DU) is uranium containing less than 0.72 percent U-235 atoms. DU is a by-product of an enrichment process where the primary product is enriched uranium and the DU is the by-product depleted of U-235 atoms. DU has many uses, e.g., serving as a heavy substitute component instead of a fissile component in nuclear weapons flight tests (that cannot use “live” nuclear weapons), being used as a heavy, dense material in conventional weapons relying on kinetic energy, or for certain types of scientific research, etc. Figure 15.6 shows the categories of uranium enrichment levels.

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depleted Uranium (DU)</td>
<td>Less than 0.72 percent U-235</td>
</tr>
<tr>
<td>Natural Uranium (NU)</td>
<td>0.72 percent U-235</td>
</tr>
<tr>
<td>Low-Enriched Uranium (LEU)</td>
<td>&gt; 0.72 &lt; 20.00 percent U-235</td>
</tr>
<tr>
<td>Highly Enriched Uranium (HEU)</td>
<td>20.00 to 89.99 percent U-235</td>
</tr>
<tr>
<td>Weapons-Grade HEU (WG-HEU)</td>
<td>= / &gt; 90.00 percent U-235</td>
</tr>
</tbody>
</table>

**Figure 15.6 Categories of Uranium Enrichment**

**Low-Enriched Uranium**

LEU is uranium enriched to any level above natural uranium, but less than 20 percent enrichment. Low-enriched uranium may serve several purposes, including use in medical or other scientific research, as fuel for nuclear reactors (usually light-water reactors), or feed material for higher levels of enrichment. Normally, it takes hundreds of stages to enrich natural uranium to the level required for light-water reactors (usually between 3 and 5 percent LEU). The exact number of stages required depends on the exact level of enrichment.

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\(^6\) By technical definition, depleted uranium has a lower percentage of U-235 than natural uranium. In common discussion, at each stage, the portion with the smaller percentage of U-235 is referred to as depleted. However, after Stage 1, these portions of uranium should be called “less-enriched” because they have a higher percentage of U-235 than natural uranium, not lower.
required, the method of enrichment used by the enrichment apparatus, and the “operational efficiency of the design of the apparatus. LEU has such a small percentage of fissile U-235 atoms that it cannot serve as the fissile material in a nuclear weapon.

**Highly Enriched Uranium**

HEU is uranium enriched to at least 20 percent, but less than 90 percent. HEU may be used in medical or other scientific research, or for industrial purposes. Usually, it requires many hundreds or even more than one thousand stages to reach 20 percent enrichment. HEU normally cannot serve as the fissile material in a nuclear weapon. HEU enriched to the highest levels of the category could be usable, but would be much less efficient than weapons-grade HEU.

**Weapons-Grade Highly Enriched Uranium**

WG-HEU is uranium enriched to 90 percent or higher. WG-HEU may serve as the fissile material in a nuclear weapon. It may also be used in small naval propulsion reactors or in breeder reactors. It would be rare to find a valid justification for using WG-HEU in medical or other scientific research, or for industrial purposes, even if only in trace amounts.

Figure 15.7 illustrates the results of the enrichment process. Step A represents a large amount of natural uranium entering the process. Step B shows that approximately half way through the process, the level of enrichment has reached 50 percent, with approximately half of the non-fissile U-238 atoms removed, but the amount of uranium has decreased significantly. Step C depicts the stage at which the enrichment has reached 90 percent. Approximately 90 percent of the U-238 atoms have been removed, and the small amount of remaining uranium is 90 percent fissile U-235 atoms. In a typical enrichment process with average efficiency, it may take one ton or more of natural uranium input to enrich one kilogram (kg) (approximately 2.2 pounds) of 90 percent enriched WG-HEU.
WG-HEU may be used as the fuel for research reactors and is typically used as the fuel for propulsion reactors. Several nations’ intelligence agencies and international organizations like the International Atomic Energy Agency (IAEA) track various aspects of research and propulsion reactor fuel. Some of the aspects that are evaluated are accounting for material, security of the material in storage and transit, safe handling, and any indicators that the fissile fuel could be for sale on the international black market. Additionally, there are ongoing efforts to develop technical solutions allowing for the replacement of WG-HEU fuel with LEU fuel. Thus far, no terrorist organization has come into possession of propulsion reactor fuel and assembled it into a nuclear weapon, although the international community must continue monitoring for that possibility.

**ENRICHMENT FACTORS**

The process to enrich natural uranium in a large enough quantity to produce sufficient WG-HEU for even a small number of nuclear weapons would require several resources, including:

- a modern industrial facility to accommodate the several acres required for the thousands of enrichment devices (one at each stage) laid out in one extremely long cascade, or more likely, several shorter cascades of a few hundred enrichment devices in each cascade. Space would be required for technicians to have access to each device for routine maintenance, repair, or replacement with reserve “float” enrichment devices;
- a huge amount of electrical energy to power each of the enrichment devices and all of the other activities of a modern manufacturing plant—which may be more electricity on a continuous basis than required to support a large city;
- security to prevent sabotage or theft of valuable materials or equipment. If a proliferating nation is attempting to hide their nuclear weapons program from sophisticated foreign intelligence sources, it may require extraordinary and expensive additional measures, such as constructing facilities underground and disguising the activities in and around each facility;
- persons with the required technical knowledge and skills; and
- funding to procure or build the facility, hire a work force of skilled and semi-skilled technicians, purchase or produce the required electrical energy, provide the required security, and provide the necessary support activities.

**NUCLEAR REACTORS**

Most nuclear reactors are structures as large or larger than a small house, containing radioactive nuclear fuel configured to achieve a controlled, sustained chain reaction of fission events. The normal basic reactor design has the nuclear
fuel in small cylindrical pellets, arranged in a line called a fuel rod. Many fuel rods are grouped into large three-dimensional fuel rod assemblies, which are further grouped into a three-dimensional “pile” that is the reactor core. The core will have neutron-absorbing control rods, a cooling/heat transfer system, and an interactive electrical control system. There are several ways of categorizing nuclear reactors; the most basic way is by purpose/intended function, in which case there are four basic categories of nuclear reactors: research, propulsion, power, and production.

**Research Reactors**
Research reactors are nuclear reactors intended for scientific or medical research. They are usually very small compared with other categories of reactors. They may have a configuration similar to most other reactors, or they may have unique configurations that do not resemble a standard nuclear reactor. Research reactors are small enough that any fissile material produced would be in such small quantities that it would not be enough for a fissile component in a nuclear weapon.

**Propulsion Reactors**
Propulsion reactors are nuclear reactors that are intended to provide the power for ship propulsion and other power needs to operate the ship. They are usually larger than research reactors, but much smaller than power reactors. They are almost always of a basic design that uses a pile arrangement as the reactor core, and the nuclear fuel is usually uranium enriched to 90 percent or more.

**Power Reactors**
Power reactors are nuclear reactors that are intended solely for the production of electrical energy. They are usually very large reactors with a basic design that uses a pile arrangement as the reactor core. Most of the more than 400 operational reactors worldwide are power reactors, and they all produce significant amounts of fissile plutonium. The material accountability, security, safety, and political control of power reactors are a concern.

**Production Reactors**
If a nuclear reactor is intended to produce electrical energy and also to produce fissile material for nuclear weapons, it is categorized as a production reactor. They are usually relatively large in order to produce significant quantities of

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7 Some research reactors do not use nuclear fuel configured in a pile, e.g., a neutron flux reactor may consist of two separated subcritical fissile components that operate by using gravity to slide one component past the other creating a brief moment of supercriticality and a large flux of neutrons produced by the supercritical fission events. This type of reactor uses but does not produce fissile material.

8 In the 1990s, the U.S. nuclear reactor community evaluated a “triple-play” reactor design that would consume fissile material without producing any other fissile material, produce electrical energy, and produce tritium needed for nuclear weapons programs. The then-Secretary of Energy terminated the program before a comprehensive evaluation of the advantages and disadvantages was completed.
fissile materials. Within the category of production reactors, most are light-water reactors, but a significant number are heavy-water reactors. A few have been thorium-fueled reactors.

**Light-Water Reactors.** LWRs use LEU (usually between 3 and 5 percent enriched) as nuclear fuel in the reactor core and natural water (light water) to moderate (slow down) neutrons for increased fission efficiency. Thermal (slow) neutrons have a higher probability of producing fission events and producing a more efficient chain reaction than using unmoderated faster neutrons to produce subsequent fission events. The light water is also used to cool the reactor core, and usually to transfer heat to drive a turbine and generator to produce electricity.

Within the reactor core of LEU fuel, 95 percent or more of the uranium atoms are non-fissile U-238 atoms. As the reactor operates, some of these U-238 atoms absorb or capture a neutron. When this occurs, it becomes a U-239 atom with one more neutron than the U-238. U-239 has a short half-life of only 23.47 minutes. When the U-239 atom decays, it emits a beta particle from the nucleus, which in effect changes one neutron to a proton. With one more proton and one less neutron it becomes neptunium-239 (Np-239). Np-239 has a relatively short half-life of 2.355 days. When the Np-239 atom decays, it also emits a beta particle from the nucleus, and becomes plutonium-239 (Pu-239).

Figure 15.8 illustrates how this process of U-238 atoms capturing neutrons and transmuting to neptunium, then to plutonium, is continually ongoing while the reactor is operational.

![Figure 15.8  U-238 Neutron Capture and Transmutation to Plutonium](image)

**LWR Production Factors.** The process to operate a light-water production reactor to produce plutonium in sufficient quantities for a nuclear weapons program would require associated infrastructure and resources, to include:

- a modern industrial capability to design, construct, and operate a large nuclear reactor. Normally the acreage required would be less than that required to enrich uranium to weapons grade;
• procurement or production of LEU enriched to the required level for the reactor design;
• a significant water source to provide water to be passed through the core serving as the moderator, coolant, and to drive a turbine. Most large reactors pass through tens of millions to a billion gallons of water per day.
• persons with the required technical knowledge and skills;
• security to prevent sabotage or theft of valuable materials or equipment. If a proliferating nation is attempting to hide their nuclear weapons program from sophisticated foreign intelligence sources, it may require extraordinary and expensive additional measures, such as constructing facilities underground and disguising the activities in and around each facility; and
• significant funding to procure or build the reactor, produce or procure LEU, maintain a highly skilled workforce, provide the security, and provide all the necessary support activities. While the capital investment required is significant, and may be as much as the investment required for an enrichment program, unlike the enrichment program, the reactor will generate electricity that could help offset the total cost of the nuclear weapons program.

Plutonium

Plutonium-239 is the most efficient of all the fissile isotopes producible in large quantities. It has a relatively long half-life of 24,100 years and a low incidence of spontaneous fission. Therefore, it is the preferred fissile isotope for most proliferating nations. As the Pu-239 begins to increase in quantity in the reactor core, two things happen that interfere with a steady build-up of plutonium. First, because it is so efficient as a fissile material, most of the Pu-239 atoms will fission when struck with a neutron. These Pu-239 fission events add to the reactor’s operation and output, but it hampers the build-up of large quantities of Pu-239, which occurs slowly over a period of many months or years.

Second, some of the Pu-239 atoms that do not fission will capture neutrons and become heavier isotopes of plutonium. These heavier isotopes are disadvantageous as fissile material. Pu-240 is not a fissile isotope and cannot contribute to a multiplying chain reaction of fission events in a nuclear weapon. More importantly, Pu-240 has a much higher incidence of spontaneous fission

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9 All known fissile isotopes that can be produced in significant quantities are subject to some low level of spontaneous fission. This is a concern because the spontaneous fission events reduce the number of fissile atoms, and the neutrons produced can cause subsequent fission events and further loss of fissile atoms.
than the fissile isotopes, thereby making it an impurity to the overall plutonium as a fissile material.

Some of the Pu-240 atoms will capture neutrons and become Pu-241 atoms. Pu-241 is a fissile isotope with a low incidence of spontaneous fission, but it has a short half-life of 14.4 years and will decay with higher frequency than longer half-life isotopes. When Pu-241 atoms decay, they emit beta particles and strong gamma radiation. The gamma rays have the potential to interact with surrounding material and cause the material to increase in temperature, making it less desirable for use in a weapon. This heating effect can cause high explosive (HE) compounds (necessary to implode the fissile material to cause a sustained chain reaction) to change their molecular arrangement and become less efficient for symmetrical implosion, reducing the weapon’s efficiency and yield, and the heat could make the HE unstable and unsafe. Some of the Pu-241 atoms will capture neutrons causing an increase in plutonium isotopes heavier than Pu-241, but these isotopes have less effect on the overall characteristics of the plutonium as a fissile material.

Unlike uranium enrichment, the production of plutonium in reactors has the opposite effect. In uranium enrichment, only a small percentage of the uranium reaches high levels of enrichment, but the more enriched it is, the more it approaches weapons grade. The production of plutonium in reactors has a continuing increase in the amount of plutonium, but a continuing decrease in the quality of isotope distribution.

At the beginning of reactor operations, there is no plutonium in the nuclear fuel. As the reactor continues operations the amount of plutonium increases, but the quality of the plutonium decreases as it becomes hotter with increased heavy isotopes above Pu-239. As the amount of plutonium builds up, it becomes less pure as a fissile material, and is hotter in both temperature and in the amount of hazardous gamma radiation emitted.

**Weapons-Grade Plutonium**

As the amount of plutonium is increasing in the reactor core, it has very little of the undesirable heavier isotopes. It is considered weapons-grade plutonium (WG–Pu) as long as the percentage of heavier isotopes is not greater than 7 percent and the percentage of Pu-239 is at least 93 percent. This quality of plutonium is the most fissile efficient of all isotopes that can be produced in sufficient quantities for a nuclear weapon, and its radiation emissions are low enough for safe handling for short periods of time.

Unlike uranium, the common terminology for plutonium does not use the level of purity, but instead uses the level of undesirable isotopes to distinguish levels
of plutonium. For example, very pure plutonium that has only 3 percent heavier isotopes would be referred to as “3 percent plutonium,” not 97 percent. Figure 15.9 shows the categories of plutonium.

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weapons-Grade Pu (WG-Pu)</td>
<td>= / &lt; 7 percent Pu-240, 241, etc. (= / &gt; 93 percent Pu-239)</td>
</tr>
<tr>
<td>Reactor-Grade Pu (RG-Pu)</td>
<td>&gt; 7 &lt; 15 percent Pu-240, 241, etc. (&lt; 93 &gt; 85 percent Pu-239)</td>
</tr>
</tbody>
</table>

Figure 15.9 Categories of Plutonium

**Reactor-Grade Plutonium**

When the heavier isotopes build-up to more than 7 percent, the plutonium is considered to be reactor-grade plutonium (RG-Pu). At that point it remains a fissile material and can be used in a nuclear weapon. However, as it approaches higher levels of reactor grade (probably between 9 and 14 percent plutonium depending on the weapon design, peacetime configuration, and the nation’s health risk standards for radiation workers, if any) it is too radioactive to handle safely and too hot to be next to a high explosive component.

Light-water reactors vary in their efficiency producing fissile plutonium due to several factors including the design of the reactor, the level of enrichment of the LEU reactor fuel, and especially the managed operations of the reactor. The longer the reactor operates before replacing the spent fuel, the hotter the plutonium will become.

**High-Level Waste**

With long reactor operational cycles, the heavier isotopes of plutonium build up in the reactor, and eventually will exceed 15 percent and become high-level waste, i.e., having a high-level of radioactivity, which makes it radioactive waste. It would be hot enough in radiation emissions that it would be unsafe for humans to handle and would be hot enough in temperature that it would be unsafe to put it next to or near a high explosive component. High-level waste plutonium is not safe to be used in nuclear weapons. However, high-level waste is often processed as spent fuel to extract fissile uranium and plutonium to be used as nuclear fuel for power reactors. Plutonium is considered to be high-level waste when the percentage of heavier isotopes reaches 15 percent.

Light-water reactors are less efficient than heavy-water reactors at producing weapons-grade plutonium. Because of that fact, there have been assertions made that light-water reactors are “proliferation resistant” and cannot produce fissile material. This is false and will be discussed at the end of the section on heavy-water reactors.
**Heavy-Water Reactors**

HWRs use natural uranium as nuclear fuel in the reactor core and specially produced heavy water to moderate (slow down) neutrons for increased fission efficiency and usually to cool the core. The heated heavy water may also be used to drive a turbine for electricity generation. Heavy-water reactors are more efficient at producing weapons-grade plutonium than light-water reactors.

**Heavy Water**

Heavy water is natural water (usually seawater) that has been processed to remove all salt and other minerals as well as the $^1$H protium atoms from the water molecules, which are replaced with $^2$H deuterium atoms (also shown in science literature as $^2$D). Figure 15.10 illustrates the nuclei particles for light-water and heavy-water molecules. When used in a reactor, heavy water, containing two more neutrons than light/natural water, will have a higher probability of being struck by neutrons and slowing their velocity, and will be more efficient for producing fission events in the chain reaction. Because the heavy-water reactor uses natural uranium for the same size reactor, the nuclear fuel contains more U-238 atoms, which are the fertile isotopes that transmute to form Pu-239.

As shown in Figure 15.10, a light-water molecule (natural water) consists of one oxygen atom and two hydrogen atoms. The hydrogen atoms are approximately 99.9844 percent $^1$H protium atoms (the first isotope of hydrogen with a nucleus of one proton and zero neutrons). In the symbol $^1$H, the 1 indicates only one particle in the nucleus, i.e., the proton. The other 0.0156 percent of hydrogen atoms in natural water are $^2$H deuterium atoms that have one proton and one neutron in the nucleus. For every one million hydrogen atoms in naturally occurring seawater, only 156 are $^2$H deuterium atoms.

The process to produce heavy water uses a cascade of devices (usually using either distillation or electrolysis) to separate heavy from light molecules in a manner similar to the process to enrich uranium. Often the heavy water is referred to as enriched water. Most heavy-water reactors require the water to be enriched to
levels between 99.7 and 99.97 percent. This is a resource-intensive process and, in some cases, can be almost as expensive as enriching uranium to LEU levels.

**HWR Production Factors**
The process to operate a heavy-water production reactor to produce plutonium in large enough quantities for a nuclear weapons program would require several resources similar to a light-water production reactor, including a modern industrial capability, skilled personnel, enhanced security, and funding. The significant differences are that the heavy-water reactor requires the production or procurement of heavy water, not LEU. In most cases the heavy water would serve as a coolant eliminating the need for a significant water source at the reactor site.

As the heavy-water reactor operates, it will have a similar conversion of U–238 to plutonium as in the light-water reactor discussed above. It will also have a similar build-up of the undesirable heavier isotopes as shown in Figure 15.9.

**HWR vs LWR for Plutonium Production**
Because HWRs moderate neutrons more efficiently and have a larger percentage of U–238 atoms in the uranium fuel, they are more efficient for producing weapons-grade plutonium than LWRs. However, some people misunderstand and misrepresent the capabilities of the less-efficient LWRs. Assertions that light-water reactors are “proliferation resistant” and cannot produce fissile material are false. While an LWR may take longer to produce a given amount of weapons-grade plutonium, it can produce enough fissile weapons-grade plutonium for a weapons program. The efficiency and capacity varies with different reactor designs and operations. The shorter the operational cycle (before extracting the spent fuel and replacing it with new nuclear fuel) the less plutonium produced, but the plutonium will be more pure with a lower percentage of the undesirable heavier isotopes. The same size HWR can produce 50 percent more nuclear weapons in a decade. The LWR produces fewer—but not zero.

**Summary of Fissile Component Feasibility**
For use as fissile material, uranium must be enriched to near 90 percent, i.e., weapons grade. Figure 15.11 shows that the WG-HEU will have a long shelf-life, usually many decades. Enrichment at lower levels, less than weapons grade, will not function as fissile material to produce a nuclear detonation in a weapon-size device, illustrated in the second column. The third column represents weapons-grade plutonium as a good fissile material with a long shelf life. The fourth column shows reactor-grade plutonium usable as a fissile material in a nuclear weapon, but with a shorter shelf life.

If the RG-Pu is 7.1 percent Pu or 7.2 percent Pu—just above the definitional threshold beyond weapons grade—it would still have a shelf life of decades, but
less than WG-Pu. However, if RG-Pu is at a much higher level, e.g., 11 percent or 12 percent, it would have a significantly reduced shelf life. At 15 percent it becomes dangerous in proximity to a high explosive component for even a short period of time.

**REPROCESSING**

After fissile plutonium is produced in the reactor core as a part of the process of reactor operation, it is mixed with a variety of radioactive spent fuel. Reprocessing is the activity to extract the plutonium from the remainder of the spent fuel. Normally, this is accomplished using a chemical process. Because the spent fuel includes some of the original natural uranium or LEU, it would also be extracted for its monetary value as a by-product of the weapons program.

The process of enriching natural uranium to WG-HEU levels requires a reconversion to return it to its metal form. This is the reverse process of the activity used to create the UF6 for the enrichment process. There is no universal term for this activity, but it is not referred to as reprocessing.

Compared with other key activities in the overall nuclear weapons development program, neither plutonium reprocessing nor uranium reconversion are difficult or very expensive.

**FISSILE COMPONENT FABRICATION**

After fissile material is produced, it must be formed into a component with the required size and shape. The process of component fabrication is different between uranium and plutonium.

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10 In a power reactor program, the primary purpose of reprocessing would include extracting both uranium and plutonium to be used as mixed oxide as nuclear fuel for future reactor use.
**Uranium Fissile Component Fabrication**

If the fissile material is either WG-HEU (one of the most commonly used fissile materials) or U-233 (produced in a thorium-fueled reactor but rarely used, if ever),\(^\text{11}\) the uranium is relatively easy to return from the gaseous form to uranium used in manufacturing to fabricate a hard, heavy metal component that retains its size and shape at ambient temperatures\(^\text{12}\) with normal handling. Normally, this would be one of the least difficult activities of a nuclear weapons program.

**Plutonium Fissile Component Fabrication**

If the fissile material is plutonium, regardless of the reactor type used to produce it, the plutonium has among the most unique chemical properties of all known elements. At a minimum, plutonium has two different component fabrication challenges. First, plutonium has six different chemical phases at normal pressures. This means that a given amount of plutonium can have different densities depending on its chemical phase. Density is one of the essential factors affecting criticality. Most nations with nuclear weapons treat the detailed information about plutonium phases as classified and do not share it with other nations.

A second challenge is that pure plutonium in its most common phases does not readily retain normal heavy metal characteristics. It must be chemically stabilized by mixing some other material with the plutonium to form a plutonium compound that will allow the plutonium to be fabricated into a heavy metal component that will hold its size and shape. This can require research and experimentation to find an adequate stabilizing agent and a process in which to apply it. The types of materials used and the processes to stabilize plutonium normally are not shared with other nations.

**Weaponization**

Weaponization includes all of the activities required to research, develop, test, evaluate, produce, and maintain nuclear weapons components, including those that will interface with weapon system delivery vehicles, other than the production of fissile materials and the fissile component. There are at least ten non-fissile components that are either essential or beneficial in a nuclear weapon.

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\(^{11}\) Some organizations promoting the use of thorium-fueled reactors have made assertions that the spent fuel has either no fissile material or fissile material that is less fissile than plutonium, and not appropriate for a nuclear weapon. This is inaccurate. The uranium-233 produced in a thorium-fueled reactor is more efficient than HEU and is easier to fabricate into a nuclear component than plutonium.

\(^{12}\) Ambient temperatures for nuclear weapons and components are the temperatures in the expected temperature range spectrum for normal activities including handling, storage, transport, and employment.
ARMING DEVICE
An arming device is an essential component that, at the proper time or proper condition, will change the weapon from a safe condition to a condition ready for firing, explosion, or detonation. Any prudent design of a nuclear or other weapon will include an arming device. This will preclude arbitrary initiation of the lethal force of the weapon that could be triggered by impact, temperature change, a nearby lightning strike, or stray electromagnetic radiation (e.g., radiation transmitted by hand-held electrical devices and relayed by cell towers). Conventional munitions use arming devices based on set-back during launch, setting an internal timer, barometric pressure, or other means as the impetus to arming. An arming component is neither technologically difficult nor expensive relative to other aspects of a nuclear weapons program.

CASING
The casing is an essential component that is the outside of any munition or weapon; it contains all the other components. It may be as simple as a single cast iron container or as complex as two or more components made of titanium or other compounds that screw or bolt together. The casing is neither relatively expensive nor technically difficult.

DETONATORS
Detonators are small, essential components containing explosive material intended to produce a detonation wave to ignite a high explosive compound. In some nuclear weapon designs there may be a single detonator to initiate the high explosive. Detonators are also used in conventional weapons. They are relatively inexpensive, very reliable, and readily available to almost any nation with conventional weapons.

EXPLOSIVE
An explosive compound is an essential component that will either move a subcritical component into another subcritical component or compress a subcritical component to cause a supercritical mass in a nuclear weapon. If used as a propellant, there are many such compounds in conventional weapons useful for nuclear weapons. To create an inward exploding compound that is near-perfectly symmetrical would be one of the more difficult elements of a nuclear weapons program to achieve/acquire. The time it would take to perfect an inward exploding compound is likely more of an obstacle than the cost.

FIRING DEVICE
In a nuclear weapon, a firing device is an essential component that either converts or stores and releases electrical or chemical energy to detonate the system. A crude firing device from a conventional weapon could work, but most
nations would try to produce a more sophisticated firing device that would have extremely high reliability. This would be moderately difficult to achieve compared with other components, but is relatively low cost.

**FUZE**
A fuze is an essential component that provides a signal to the firing device at the proper time to fire the weapon. A fuze from a conventional weapon could suffice, but refinement of the conventional fuze for use in a nuclear weapon would be necessary to ensure high reliability. This would be moderately difficult to achieve and in the moderate cost range.

**NEUTRON GENERATOR**
A neutron generator is an essential component that produces a flux of neutrons at the precise moment when the fissile material reaches its designed supercriticality. There is no comparable component in conventional weapons. Neutron generators are used in industry for geological neutron-sounding, for example, but they are almost always large devices. It would be very difficult to take a commercial design and miniaturize it to meet the limited allocation for volume/space and weight in a nuclear weapon. This component would be very difficult and moderately expensive compared with other components to develop or acquire. Neutron generators would most likely use short-life radioactive material, and be a limited-life component (LLC) requiring periodic replacement.

**POWER SOURCE**
A power source is a component that stores and releases energy to power the warhead’s imbedded electrical components and sub-components such as the arming device, firing device, the fuze, and possibly a safing component. The power source may be as simple as a good commercial battery or it could be a specially designed and produced, one-of-a-kind item using unique electrical parameters for security. Unless the power source uses nuclear isotopes, such as PU-238 in a radioisotopic thermoelectric generator (RTG), it will be a LLC requiring periodic replacement.

**REFLECTOR**
A reflector is a component that reflects neutrons back into the supercritical mass at the moment of detonation. This returns escaping neutrons into the fissile material to increase the design efficiency. A nuclear weapon can work without a neutron reflector, but it would be very inefficient (meaning it would require more fissile material). Designing and producing a reflector component would not be technically difficult or costly.
**Safing Device**
A safing device is a component that may provide increased safety. Safing devices are not essential for a first-generation weapon; it is unnecessary in order to produce a nuclear detonation and it would require significant space and weight. The most important function of a safing device is to preclude the weapon from unintended detonation. Other safety functions could be to prevent fissile material from scattering in an accident or to reduce ionizing radiation hazards to weapon handlers. The most sophisticated safing devices could require significant space and weight, and would be very difficult to design and moderately costly to produce.

**Tamper**
A tamper is a component that will tamp or restrict the explosive component from releasing its energy in all directions. This adds efficiency to the weapon design. It may also assist in holding the supercritical mass together longer, adding to weapon design efficiency. Many basic designs combine the functions of the tamper, reflector, and casing into one component, which would have little technical difficulty or cost.

**Security Device**
A security device is a component that locks the warhead in the safe mode until unlocked with a security code. This prevents unauthorized nuclear weapon employment or detonation. A security device built into the warhead is optional, and many nations, including the United States, first fielded nuclear weapons without security devices. A security device could be as simple and crude as a mechanically-operated padlock (which could be overcome by a heavy-duty bolt cutter) or as sophisticated as electrical components embedded in the warhead requiring a multi-digit code to unlock and limited to only two or three unsuccessful attempts before permanently locking. Most proliferating nations will bypass a security feature that would take valuable space and weight, and could reduce the warhead availability/reliability if the security device were to malfunction, denying authorized use.

**Special Handling Equipment**
Special handling equipment must be designed and produced to allow personnel to handle a warhead which could weigh several tons, i.e., warhead equipment for lifting, repositioning, transporting, and disassembling. Special tools would be required for warhead maintenance, removing, and replacing LLCs (e.g., power source, neutron generator, or boosting gas). The special handling equipment is relatively easy to design and produce, and not costly.
**Delivery System Interface**

Nuclear warheads are designed and produced to interface with the intended weapon delivery system (e.g., manned aircraft, ballistic missile, submarines). The interface includes physical attachment, electrical compatibility, preclusion of mutual interference, and a practical solution for physically joining the warhead with the delivery system.

- **Casing** – The casing must be designed to mate with the delivery system in a practical manner. If the warhead weighs two tons and it must be screw-attached to a missile, it would be impossible for a team of handlers to lift the warhead and screw it onto the missile without the proper handling equipment.

- **Electrical Components** – The arming, fuzing, and firing components must be electrically compatible with the delivery system. Voltage, electrical coded signals, and even the plugs and electric receptacles must be designed for compatibility.

It is possible to design different adaptation kits/devices that do all interface requirements between a warhead and two or more different delivery systems, using one type of adaptation kit for each type of delivery system. A single given type of warhead could be compatible with several types of aircraft and several types of missiles with the use of well-designed adaptation kits.

**Basic Nuclear Warhead Design Types**

The first nuclear warhead designs resided in *Little Boy*, a uranium gun-type fission bomb, and *Fat Man*, a plutonium implosion-type fission bomb. A fission weapon is a nuclear weapon because the primary energy release comes from the nuclei of fissile atoms. Fusion weapons are called hydrogen bombs or H-bombs because isotopes of hydrogen are used to achieve fusion events that increase the yield of the detonation. Fusion weapons are also called thermonuclear weapons because high temperatures and pressure are required for the fusion reactions to occur.\(^\text{13}\)

Figure 15.12 describes the basic types of nuclear weapon designs detailed in *Chapter 13: Basic Nuclear Physics and Weapons Effects*.

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\(^{13}\) The term *thermonuclear* is also sometimes used to refer to a two-stage nuclear weapon.
<table>
<thead>
<tr>
<th>Weapon Type</th>
<th>Key Characteristics</th>
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| Gun Assembly (GA) Weapon   | • Propellant drives one subcritical mass into another subcritical mass, forming one supercritical mass and nuclear detonation  
                             | • Less technically complex than other designs, but less efficient  
| Implosion Weapon           | • Compression/implosion of one subcritical fissile component to achieve greater density and supercritical mass  
                             | • More technically complex than gun assembly type and more efficient  
| Boosted Weapon             | • Fusionable material (e.g., deuterium, tritium) placed inside core of fission device, producing large number of fusion events, thereby increasing yield  
                             | • More technically complex than GA or implosion design and more efficient  
| Staged Weapon              | • Boosted primary stage and secondary stage to produce significantly increased yield  
                             | • Most technically complex; produces larger yields than other designs  

**Figure 15.12 Basic Types of Nuclear Weapons**

**Nuclear Weapon Design Factors**

There are many considerations that affect the decision to select a specific nuclear weapon design and its size and weight.

**Weapon Size**

Generally, the smaller the size (volume, dimensions, and weight) of the warhead, the more challenging it is to design to function properly to produce a nuclear detonation, and the harder it is to achieve a higher yield. As illustrated in Figure 15.13, for a given level of technical knowledge and capability, a very large size nuclear weapon will have less technical difficulty and can produce a very high yield. A very small nuclear weapon will have significantly increased technical difficulty and will produce a much lower yield.

![Figure 15.13 Size, Technical Difficulty, and Yield](image)

Because the boosted and two-staged designs are significantly more difficult than the gun assembly or implosion design, they are not practical candidates for any nation’s first generation nuclear weapon. There is no evidence that any nuclear-capable nation was able to produce either of these as their first workable warhead.
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.\(^\text{14}\) This is probably because, unlike the situation in the early 1940s, today most nations (and even some non-state actors) possess some type of air defense, which render non-stealth, large cargo, or passenger aircraft ineffective at penetrating to potential adversary targets. Therefore, it is highly likely that the first generation weapons developed by proliferating nations would be low-yield weapons, typically between one and 10 kilotons (kt).\(^\text{15}\)

While the United States pursued both the GA and the implosion designs in the Manhattan Project, other nations that have become nuclear-capable (with one exception), have focused on the implosion design for several 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. Figure 15.14 compares warhead types for a given size where the left side compares yield and the right side compares technical difficulty.

The right side of Figure 15.14 includes a column showing the relative difficulty for a developing nation to design and manufacture one million automobiles; even a gun assembly weapon would be more difficult. The relative cost could be similar to the technical difficulty, with the easiest and least expensive nuclear weapons program more costly than producing a million autos, which would be in the billions of U.S. dollars.

\(^{14}\) Typically, the maximum weight for a warhead to be compatible with a high-performance jet aircraft would be approximately 1,000 to 1,500 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.

\(^{15}\) 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.