Nuclear Weapons 1 - Technology, Materials, Testing and Monitoring

This learning unit examines the technical foundations of nuclear weapons, including fission and fusion processes, weapon designs, and the nuclear fuel cycle. It also explores disarmament challenges, verification methods, and the role of monitoring technologies in ensuring compliance with international non-proliferation agreements.

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1. Introduction

> It is important not to equate nuclear weapons with nuclear material.
>
> Rafael Mariano Grossi, IAEA Director General

If you ask people on the street, many will say that they consider nuclear weapons to be not only a major security threat, but even a threat to the survival of humanity. There is a reason that the International Campaign to Abolish Nuclear Weapons (ICAN) has gained enormous popularity in recent years – and even won the 2017 Nobel Peace Prize.

Obviously, nuclear weapons use nuclear materials as their main component. According to the International Panel on Fissile Material, the estimated global stock of weapon-ready highly enriched uranium is 1,245 metric tons, of which 1,100 tons is already in weapons or available for use in weapons programmes. [^1] But other forms of nuclear material are also used as fuel in nuclear power plants to generate clean energy. The climate crisis and the discussion on energy security have revived the debate on increasing the use of nuclear energy. The discussion about expanding the current nuclear reactor fleet and acquiring new nuclear energy systems has intensified not only in Europe but also beyond, making nuclear investment viable. In addition, every state has the right to the civilian use of nuclear energy as codified in the Non-Proliferation Treaty (see LU05) [/lu-05].

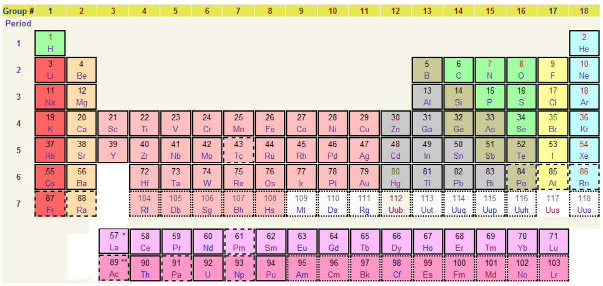
What are the main differences between nuclear materials to be used in a nuclear weapon and those intended for use as fuel in an energy system? How can the international community make sure that a state is not using the interest in nuclear energy to conceal a nuclear weapons programme? Can a state that engages in nuclear disarmament, dismantle their nuclear weapons and use the material as fuel for a nuclear power plant?

This unit provides an introduction to the physics of nuclear materials and what makes them useful in nuclear weapons. Chapter 2 starts with an insight into basic nuclear physics. Chapter 3 presents an overview of nuclear weapons, which includes the pathways to acquire nuclear material, different nuclear weapon designs, and the phases and effects of a nuclear explosion. Chapter 4 presents issues of armament and disarmament, such as stockpiles, nuclear tests and disarmament verification. Chapter 5 addresses monitoring in all its aspects related to the non-proliferation of nuclear weapons.

2. Basic Nuclear Physics

Introduction

Nuclear physics is the field of study that concerns the atomic nuclei, and some understanding of nuclear physics is needed to grasp the problems related to nuclear weapons. If you remember your chemistry or physics classes from school, you will know that the atom is the smallest part of an element, and an atom consists of a nucleus and an electron shell. There are two types of particles (of almost equal mass) that constitute the atomic nuclei: the proton, which is positively charged, and the neutron, which is electrically neutral. The number of protons defines a specific element, i.e. 6 protons make up the element carbon (chemical symbol C), and 92 protons make up the element uranium (chemical symbol U). All the elements, ordered based on increasing proton numbers, are commonly presented in the periodic table of elements.



Periodic table
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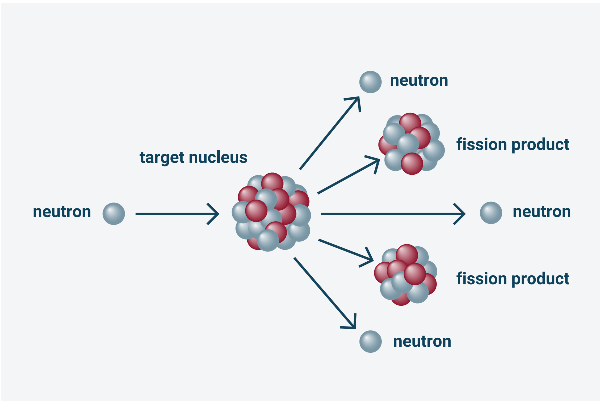
In addition to the protons, all nuclei with at least 2 protons also contain neutrons, and the number of neutrons can vary in atoms of the same element; these varieties are called isotopes. The isotopes are named after the total number of protons and neutrons, so for example carbon-12 has 6 protons and 6 neutrons, while carbon-14 has 6 protons and 8 neutrons. Isotopes of the same chemical element have the same chemical properties, but differ in mass and have different nuclear properties, such as radioactivity. One example is heavy water, which is water containing not normal hydrogen (with only 1 proton) but heavy hydrogen, so called deuterium (with 1 proton and 1 neutron).

For the heaviest element that exists on Earth – uranium – the two isotopes that occur naturally in more than trace amounts are uranium-235 (92 protons, 143 neutrons) and uranium-238 (92 protons, 146 neutrons). Uranium is interesting in this context because it is the starting point for creating nuclear weapons. The isotope of most interest in this respect is uranium-235. In naturally occurring uranium, only 0.7 percent (mass) is uranium-235, while 97.3 percent is uranium-238. The process of increasing the fraction of uranium-235 in a uranium sample is called enrichment. Enrichment can be carried out with various technologies, but the most common is the centrifuge technique which separates the isotopes based on their mass difference. First, a uranium gas is created, and when it is spun rapidly in a centrifuge drum, isotopes of different masses will follow different trajectories and can thus be separated.

Fission

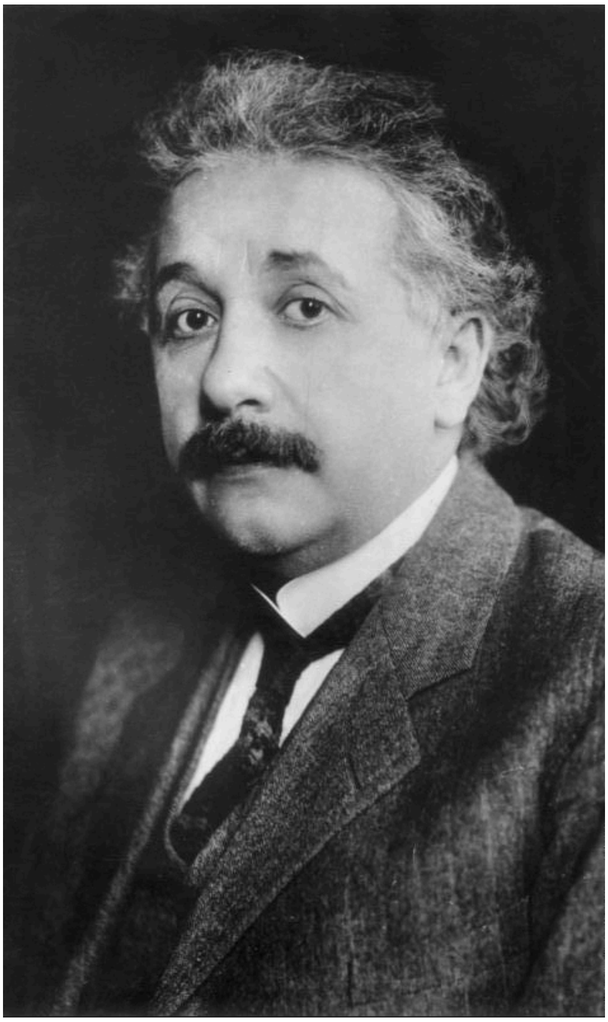
A nuclear reaction where a nucleus is split in two is called fission `[https://nrl.mit.edu/reactor/fission-process]`. Spontaneous fission occurs naturally in some very heavy elements, but is rather unusual in nature. Fission in nuclear technology applications, such as nuclear power or nuclear weapons, is always induced fission. This means that a catalyst is needed to cause the nucleus to split, and the catalyst in these cases is a free neutron. Isotopes that can be induced to split in this way are called fissile materials. Examples of fissile materials are uranium-235 and plutonium-239. The induced fission process will result in a large release of energy, 2 fission fragments and 2–3 new free neutrons, which can be used to split new fissile nuclei.



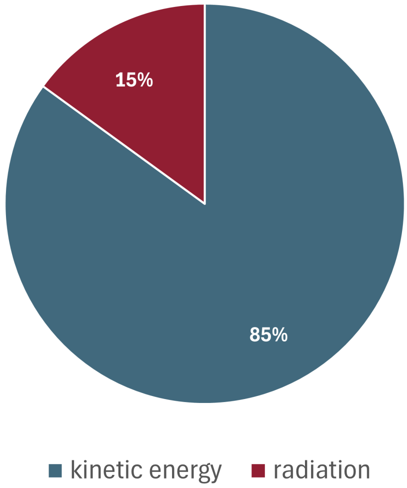
Nuclear fission
Grübelfabrik (CC BY NC)

When this happens, a chain reaction is possible, and this is a precondition for creating a self-sustaining reaction. This means that the neutrons released as a product of a fission reaction will interact with the neighbouring atoms and also produce fission.

The large release of energy associated with fission, more 100 MeV/fission, is due to the fact that the fission products together have a smaller mass than the precursor nucleus, and this mass difference is released as energy. This is in line with Einstein's famous formula E = mc2, basically stating that energy (E) and mass (m) are, in equivalents (c stands for the speed of light in vacuum, a very large number). The fission process releases around 85 percent of the energy as the kinetic energy of the fragments. The rest is released in the form of radiation. The energetic fission fragments collide with surrounding matter and their kinetic energy is thus converted to heat via friction. In a nuclear reactor, this heat is used to produce electricity. In a nuclear weapon, it is used to cause an explosion.

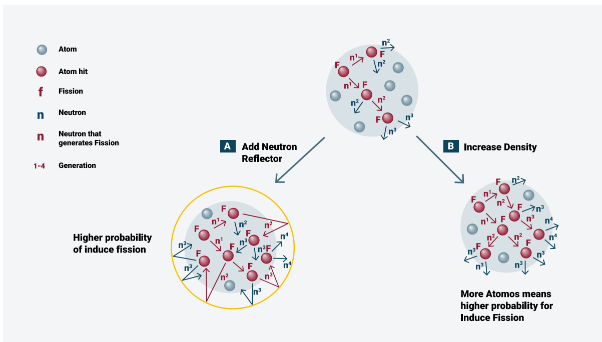


Albert Einstein
Bundesarchiv, CC-BY-SA 3.0



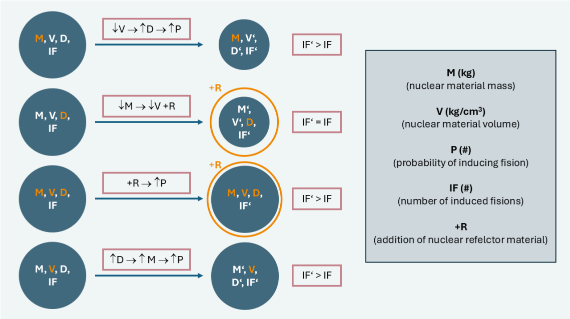
Distribution of the energy released during fission in terms of kinetic energy and radiation
PRIF, CC-BY-SA 4.0

A **critical mass** is defined as the smallest amount of fissile material needed to create a self-sustaining chain reaction of fission. However, the critical mass is not an absolute number, it depends on factors such as the geometry, the purity and density of the material, the temperature, and the presence or absence of a neutron reflector.
To build a nuclear weapon, an actor needs to find a balance between all these factors to calculate the final critical mass of the specific nuclear material needed. If we take the example of the geometry factor, the optimal shape for creating a critical mass is a sphere, since a sphere has the minimum possible surface area for a given mass. This not only makes it possible to acquire a smaller weapon but also contributes to minimising the leakage of neutrons. For example, the critical mass of a spherically shaped metallic uranium-235 is around 47 kilogrammes. This mass can be reduced if material to serve as a neutron reflector is placed around the spherical shapeor if the density of the material (number of atoms per volume) is increased .



Increasing nuclear fission probability by adding a neuron deflector or increasing density
Grübelfabrik, CC BY NS 4.0

How can the critical mass of nuclear material be modified according to changes in density, volume, and the addition of neutron reflector material?



Optimizing Nuclear Reactions: The Impact of Mass, Volume, Density, and Reflectors on Fission Efficiency
EU Non-Proliferation and Disarmament Consortium eLearning (CC BY-NC 4.0)

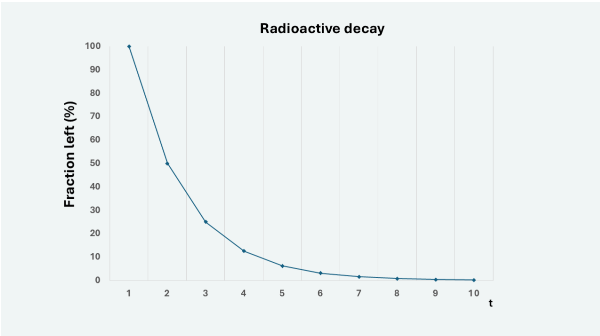
A) If the volume of nuclear material is decreased by compressing it, its density will increase, increasing the probability of inducing fission reactions for the same mass.
B) If the mass of nuclear material is decreased, keeping its density unchanged, the same level of induced fissions can be kept by adding a neutron material reflector around it.
C) If the volume, mass, and density of the nuclear material are unchangeable, the probability of inducing fission can be increased by the addition of neutron reflector material around it.
D) If the density of nuclear material is increased without changing its volume, the mass of nuclear material will increase along with the probability of inducing fission.

Radioactivity

Another topic of interest is radioactivity [`https://www.euronuclear.org/nuclear-basics/radioactivity/what-is-radioactivity/`]. Radioactivity occurs naturally and is a spontaneous process where a nucleus decays by the emission of ionising radiation. Of the elements in the periodic table, all have several isotopes and most have both stable and radioactive ones. The conditions within the nuclear structure that determine whether a nucleus is stable or radioactive are complex, but one of the factors that play a role is the relative number of protons and neutrons. In general, light elements have stable isotopes with equal or nearly equal numbers of protons and neutrons, but in heavy elements, there are substantially more neutrons needed for the formation of a stable nucleus. Heavy nuclei have more neutrons than protons, and this is why, when a heavy (uranium) nucleus splits into two lighter ones, the resulting fission products are left with too many neutrons to remain stable. This is the basis for the formation of highly radioactive products from fission.

A radioactive material decays with a unique half-life, i.e. the time it takes for half the radioactive nuclei in a sample to decay. After the decay, that particular nucleus has been transformed into an isotope of another chemical element, which can be stable or unstable (radioactive). If the resulting nucleus is stable, the decay stops here, but if it is unstable, the new nucleus will also decay according to its half-life. In some cases, there are long decay chains with many intermediate steps, until the final stable nucleus is reached.

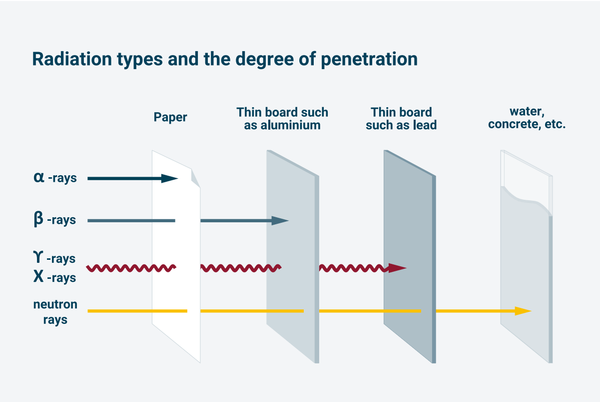
The decay curve is a negative exponential function (Figure: half-life) with the properties that after one half-life, 50 percent of the original amount remains, after two half-lives, 25 percent remains etc. After ten half-lives, less than 0.1 percent remains and this is generally regarded as the time it takes for a radioactive substance to be gone. Radioactive fission products are usually the starting points of long decay chains with several steps to the final stable element. The half-lives of these radioactive elements range from fractions of seconds to decades. Some isotopes that often are mentioned in nuclear technology applications are iodine-131 (half-life: 8 days) and caesium-137 (half-life: 30 years).



Radioactive decay
EU Non-Proliferation and Disarmament Consortium eLearning (CC BY-NC 4.0)

Radioactive decay comes in three forms – alpha, beta and gamma decay – with radioactive isotopes normally decaying either via alpha or beta decay, and the gamma decay following shortly after the initial alpha or beta. Alpha, beta, gamma and neutron radiation is all ionising, meaning it has enough energy to ionise atoms and molecules.

Alpha decay happens in isotopes of many heavy elements, such as radon, uranium and plutonium, and in the decay, an alpha particle is released. This is a heavy, charged particle that is, in fact, a helium nucleus consisting of 2 protons and 2 neutrons. Such a particle travels only short distances in air and even shorter in a denser material. Alpha particles can typically be stopped by skin or by a thin piece of paper.



Radiation Types and the Degree of Penetration
Grübelfabrik (CC BY-NC 4.0)

Most radioactive elements naturally present on Earth, as well as most fission products, decay via beta decay. The beta decay releases an electron and a neutrino, but only the electron interacts with matter and is regarded as ionising radiation. Being a much smaller particle, albeit charged, the beta particle has a longer range than an alpha particle and requires thicker material to be stopped.

The gamma particle that is released, often together with an alpha or beta particle, is a normal photon but with high energy. Gamma rays are similar to X-rays, but originate in an atomic nucleus, rather than in an atomic electron shell which is the origin of an X-ray. These particles have no mass and no charge, making them highly penetrable. They can travel a long way (at the speed of light) and require a dense material such as lead to be stopped.

The release of neutrons is particularly common for fission events but not a common natural form of radiation. Neutrons have mass, but no charge, and they can interact only with other atomic nuclei, not with electron shells.

3. Nuclear Weapons

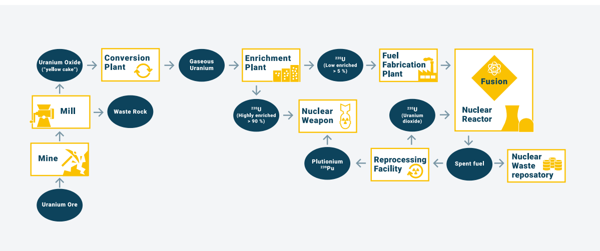
The energy generated by fission is around million times bigger than the energy generated by a chemical reaction. This happens because chemical reactions occur at the electron level of the atom, where a typical chemical bond stores energy in the order of 1 eV, while a nuclear bond is in the order of 1 MeV, as seen in Chapter 1.[1] This advantage is clear when comparing different options for the types of fuel that could be used for energy generation production for civilian purposes. For example, to generate 1GW in a year using a traditional fossil fuel plant would require eight train cars full of coal per day. While the same 1GW in a nuclear power plant would consume only half a train car of uranium-235 per year. The big difference in energy release per unit mass is also the main strategic advantage of a nuclear bomb. Imagine that one single nuclear bomb can destroy an entire city, while 100,000 bombs with conventional explosives would be needed to achieve the same result.

Proliferation pathways

There are primarily two nuclear materials that can be used in nuclear weapons: uranium-235 and plutonium-239. Creating one or both of these elements in a weapons-grade form, i.e. suitable purity for a successful weapon design, means following one or both of the two paths to nuclear proliferation, i.e. the uranium and the plutonium path. Both paths were developed and pursued simultaneously during the early years of nuclear weapons technology,[2] and each path requires specialised nuclear technologies and facilities. The technology and infrastructure used to produce nuclear material for a weapon is closely related to those necessary to produce nuclear energy. To understand this relation, we will have a look at the civilian fuel cycle steps and identify the main activities required to produce a nuclear weapon.

The nuclear fuel cycle

The nuclear fuel cycle as defined by IAEA[3], can be described as the various processing steps necessary to use nuclear fuel in the production of electricity or for producing weapons material.

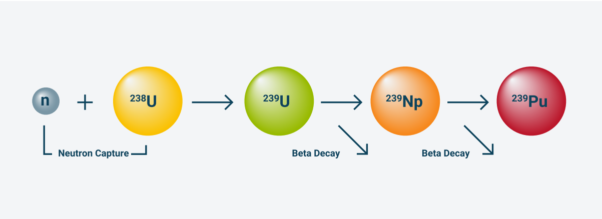


Nuclear Fuel Cycle
Grübelfabrik, CC BY NS 4.0

The cycle starts with the **mining** of uranium ore from the ground. In a mill, the uranium ore is crushed and ground to a fine slurry to allow the separation of uranium from the waste rock. The the uranium is recovered from the solution and precipitated as uranium oxide – yellow cake – in the **milling** step. Next, in the **conversion** step, the uranium oxide is then converted to a form suitable for enrichment. Since the most common enrichment process is gaseous diffusion*, the solid uranium oxide is converted to gaseous form. Natural uranium is composed mainly of uranium-238 (99.3%) and uranium-235 (0.7%). Therefore, to allow significant generation of energy from the fuel material, an **enrichment** process that increases the concentration of uranium-235 in the material is performed. Although there are nuclear reactors that run on natural uranium fuel, the majority need fuel with enrichment of around 3–5% of uranium-235. The enriched uranium gas is reconverted into solid uranium dioxide and sent to a **fuel fabrication plant**. Once inside the **nuclear reactor**, fissions occur in the uranium. After some time of the fuel being consumed (typically after three years), the number of neutrons generated by fission events are not enough to maintain a chain reaction and the fuel needs to be changed. The consumed fuel is called **spent fuel**. In a so-called "open fuel cycle", the spent fuel is treated as waste and deposited in an isolated and secure location for thousands of years. In a "closed fuel cycle", the spent fuel is sent to a **reprocessing** facility. In the reprocessing step, the spent fuel is chemically dissolved, uranium and/or plutonium are separated to be re-used as fuel, or sometimes, in the case of plutonium as weapons material.

For the **uranium path**, the creation of weapons-grade uranium requires creating a highly enriched uranium (HEU) with an enrichment level of at least 90% (i.e. 90% of the mass is uranium-235 and 10% uranium-238). This can be achieved in **enrichment plants** with large arrays of centrifuges; often several thousand units are needed to increase the fraction of uranium-235 from 0.7% (in natural uranium) to 90%.

For the **plutonium path**, the starting point is spent nuclear fuel, since plutonium is an element that is not present naturally on Earth in more than trace amounts. Hence, plutonium-239 has to be created by neutron irradiation of uranium inside a nuclear reactor. The process involves capture of a neutron in uranium-238 followed by two beta decays.



Plutonium-239
Authors' own illustration/Grübelfabrik, CC BY NS 4.0

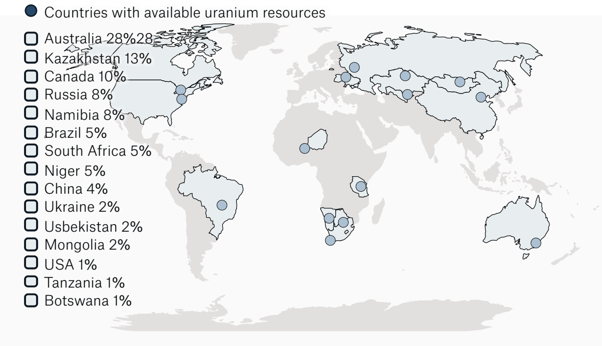
Both neutrons and uranium-238 are present in large amounts in a nuclear reactor, but in a reactor used for civilian purposes, plutonium is partly used as reactor fuel and the fraction of the relevant isotope, plutonium-239, decreases with reactor operation time. Nevertheless, civilian reactor are strictly monitored to prevent proliferation of plutonium (see LU05).

Reactors that are operated with the purpose of generating plutonium for a nuclear weapon are operated somewhat differently from civilian reactors, for instance by exchanging the fuel at shorter time intervals. Once plutonium intended for weapons production has been created in the reactor, it must be separated from the remaining uranium and fission products in the spent nuclear fuel. This is done by reprocessing that fuel.

There are several definitions of weapons-grade plutonium, but in general, it is considered that it should contain at least 93% plutonium-239, or less than 7% plutonium-240. It is important to note, however, that with suitable technology, even plutonium that does not fulfil the weapons-grade criteria can be used as weapons material so it can be difficult to assess exactly what plutonium product aspiring nuclear weapons builders need and want.

Nevertheless, the civilian fuel cycle activities, especially the enrichment, the nuclear reactor operation and reprocessing, are strictly monitored by international nuclear safeguards (for states that are part of the non-proliferation treaty) and security systems to guarantee that nuclear material and facilities are being used for peaceful purposes (see LU05) `[/LU-05/]`.

Uranium is not uncommon on Earth, but the ore deposits are unevenly distributed and their suitability fo



Global distribution of identified recoverable uranium resources
Data source: Piro, M./Lipkina, K. (2020): 8 - Mining and milling. In: Piro, M. (ed.): Advances in Nuclear Fuel Chemistry, Woodhead Publishing
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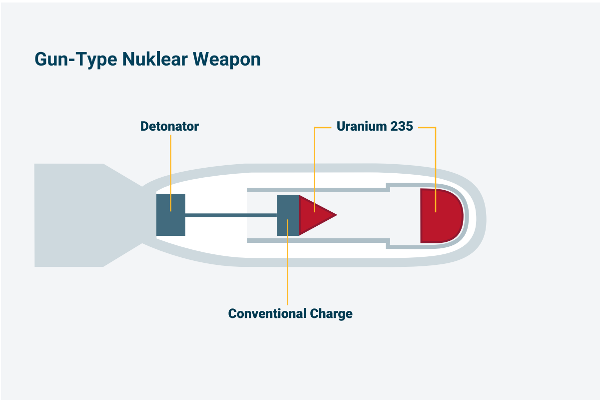
A country that pursues an indigenous and independent nuclear weapons programme might face uranium constraints and have to make choices on how to use the available uranium reserves to feed both or one of the proliferation pathways (and perhaps feed electricity-producing nuclear reactors as well). It might, for example, not be possible to feed both an enrichment plant for making HEU and a reactor for making plutonium. Some reactors (heavy water or graphite moderated) can run on natural uranium, removing the demand for enriched fuel, but they still consume uranium.

Different nuclear weapons designs

Over the years different models of nuclear warheads were invented to overcome the challenge of putting together, in one gadget, the necessary nuclear material mass that would lead to a supercritical stage at the correct time of detonation (but not beforehand!). The size or yields of nuclear weapons are often measured in kilotons. This unit relates to conventional explosives, with 1 kiloton corresponding to the yield of 1,000 tons of TNT (trinitrotoluene).

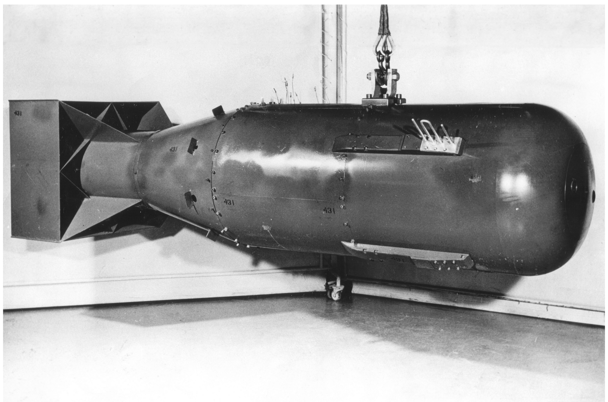
Gun-type weapons

This type of warhead is the easiest to produce and contains two subcritical pieces of uranium-235 and a detonator with a conventional explosive charge bringing the two pieces together. The design also contains an initiator which produces the neutrons to induce the fission chain reaction.



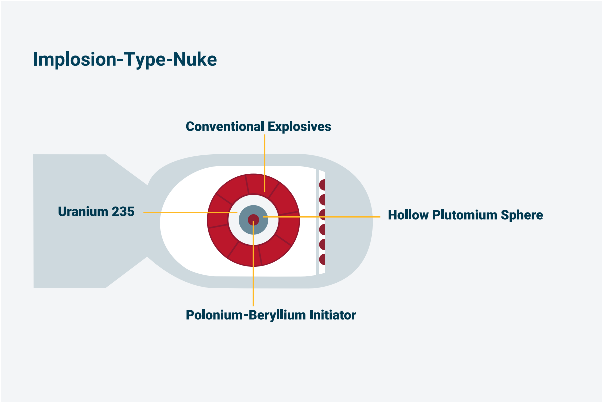
Gun-Type Nuclear Weapon
Grübelfabrik, CC BY NS 4.0

The Hiroshima bomb, "Little Boy" (15 kilotons), which contained 64 kg of HEU was also a gun-assembly type warhead



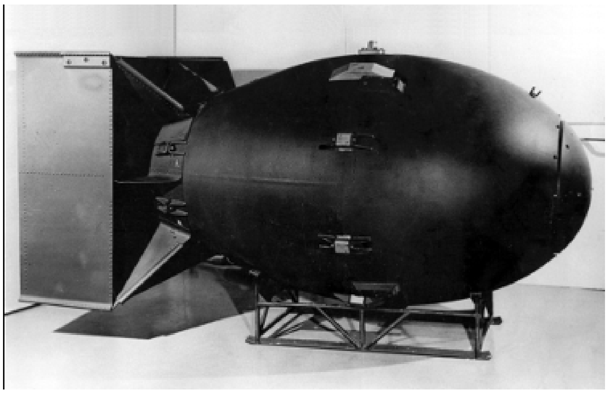
Little Boy
U.S. National Archives, ID 61-55, unrestricted use

Implosion-type weapons
For plutonium bombs, a slightly more complicated design is needed to assemble the critical mass at the time of detonation and it takes quite some craftsmanship to master it. The reason for this is that one of the plutonium isotopes inevitably present is plutonium-240, in which there is a fairly large chance of spontaneous fission occurring. This is a process that cannot be controlled, and risks setting off parts of the bomb material prematurely, due to the neutrons created by the spontaneous fission events. A much faster assembly time than can be achieved with gun-type warheads is necessary to be certain that the whole plutonium bomb will fission at the time of detonation. The solution is the implosion-type bomb.



LImplosion-Type Nuclear Weapon
Grübelfabrik, CC BY NS 4.0

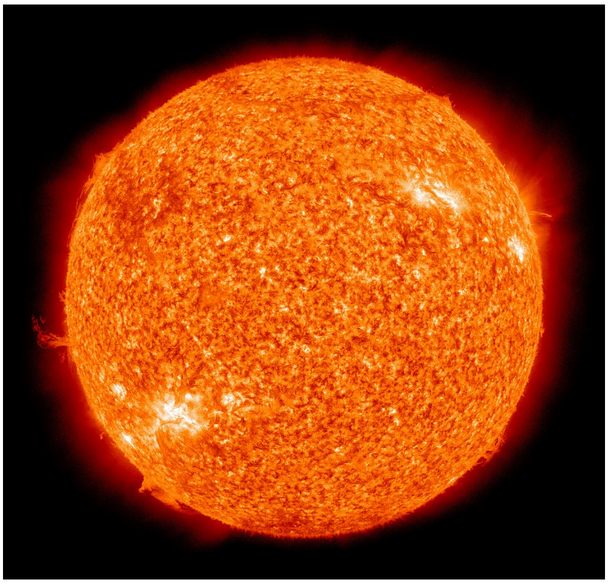
This bomb design contains a hollow sphere of plutonium that is rapidly compressed by a shockwave created by the ignition of the surrounding explosives. The resulting increase in density of the plutonium causes the sample to become critical and at the same time, neutrons from the initiator start the fission chain reaction. The second bomb the US released over Nagasaki in 1945 was called the “Fat Man” (21 kilotons) and contained 6.4 kg of plutonium.



'Fat Man' (mockup)
U.S. Department of Defense

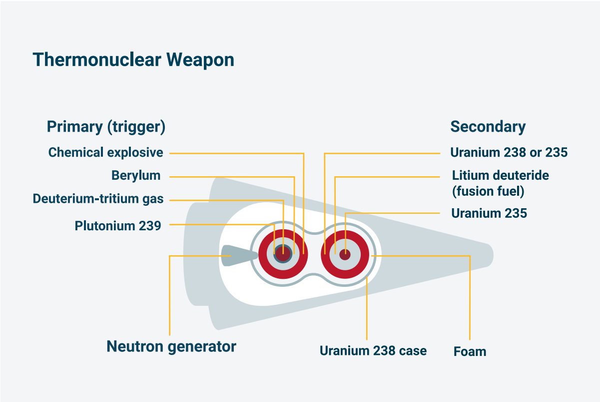
Note that plutonium has a much smaller critical mass than uranium-235, making it suitable for lighter bomb designs.

Thermonuclear weapons
A thermonuclear weapon is an even more advanced type of warhead than the gun-assembly and implosion-type described before. Another term for thermonuclear bomb is hydrogen bomb, indicating that this type of device relies not only on energy released from fission, but from fusion as well. Fusion is the nuclear reaction when two light atomic nuclei fuse together while releasing large amounts of energy. It is this process that takes place inside stars. Isotopes of the lightest element hydrogen – such as deuterium (hydrogen-2) or tritium (hydrogen-3) – can be made to fuse, if the temperature is high enough.



Fusion inside the sun
NASA/Wikimedia, public domain

A thermonuclear bomb works in a two-step process. The first step is the detonation a fission device with either HEU or plutonium (primary), which causes the temperature to rise to millions of degrees Celsius.



Thermonuclear Weapon
Grübelfabrik, CC BY NS 4.0

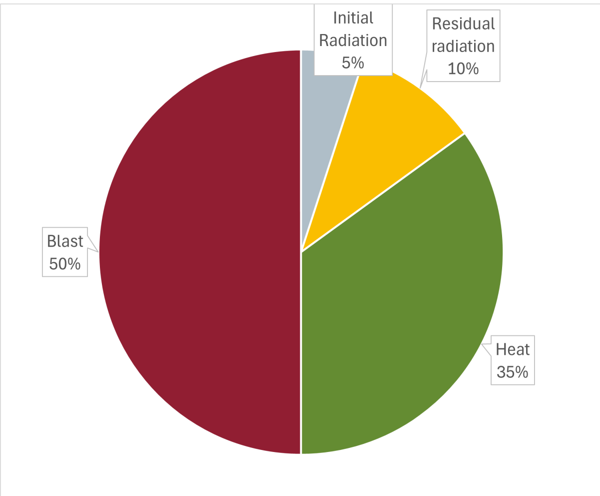
At this high temperature, much of the energy is released in the form of X-rays, which starts the second step, the compression and ignition of the secondary, setting off the fusion device.

Effects of nuclear explosions

It has been estimated that 140,000 people died in Hiroshima within months of the detonation of the first nuclear bomb and that another 74,000 people died in Nagasaki in 1945 after the second bomb was dropped. [4]

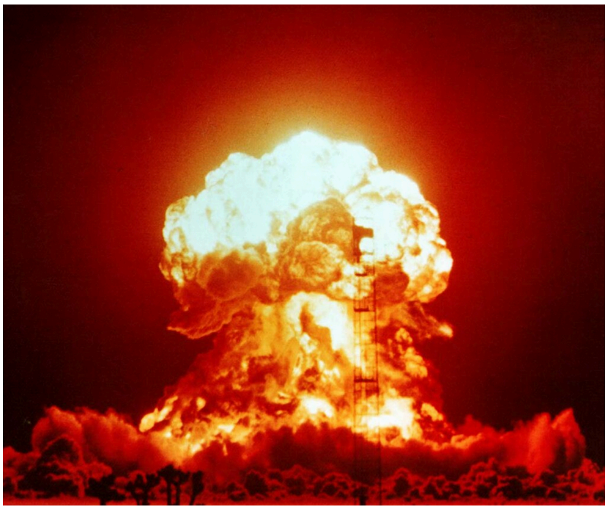
Physical effects

A nuclear explosion releases large amounts of energy in a very short time. The energy is divided into the blast, heat and radiation.



Effects of a Nuclear Explosion
EU Non-Proliferation and Disarmament Consortium eLearning, CC BY NS 4.0

The largest part of the energy is in the blast, which is a shock wave that can reach velocities of hundreds of kilometres per hour and cause severe injuries to humans and animals as well as raze structures and buildings to the ground.



U.S. 23 Kiloton Nuclear Test, 1953
Photo courtesy of National Nuclear Security Administration / Nevada Site Office

The heat wave also travels fast. In fact, the heat comes first since it consists of thermal radiation that travels at the speed of light. This heat can cause severe burns and even vaporise material. Radiation is released immediately at the time of the explosion (direct initial radiation), but also over a long period of time (residual radiation). The half-lives of radioactive isotopes produced in the nuclear fission or as a result of irradiation will determine how long the residual radiation lasts, but many commonly produced radioisotopes have half-lives of several years or decades.[5]

Fallout is a term used to describe radioactive material that "falls from the sky" after a nuclear detonation and it contains both fission products from the explosion itself and material that has become radioactive through the irradiation of neutrons from the fission processes. Here, the term radiation refers to either the particles that are released by radioactive decays (alpha, beta, gamma rays), or neutrons from the fission itself.

In this context, it should be noted that the highly penetrating particles will travel far, but also have a higher chance of travelling right through a biological body than the short-range particles (see Chapter 1). For example, ingesting or inhaling an alpha-emitting substance will probably mean that the particles will not exit the body but rather deposit all energy inside it, accompanied by any potential harm. Different particles also pose different dangers to biological systems; alpha particles are the most destructive, while beta and gamma are least destructive.

Biological effects

One of the biological effects of ionising radiation is that atoms in body tissues are ionised, which can cause chemical imbalance of the cells through the creation of chemically reactive ions, such as free radicals, which can be harmful. Another biological effect is that energetic particles (especially alpha particles) can physically break one or both strings of

DNA which can lead to mutations such as cancer. When subjected to a high dose of radiation at one time, the risk of severe damage is greater than if the same dose is received over a long time period. The reason is that the cell repair systems do not have time to respond if multiple cell injuries occur at the same time.

Nagasaki temple destroyed, 24.09.1945
U.S. Marine Corps/Wiki Commons CC

1. Segrè, Emilio. 1953 Experimental Nuclear Physics, Vol. 2. Wiley.
2. Manhattan Project. Available at: [https://www.osti.gov/opennet/manhattan-project-history/Events/1945/trinity.htm]
3. [https://www.iaea.org/topics/nuclear-fuel-cycle]
4. Bulletin of Atomic Scientists. 2020. Available at: [https://thebulletin.org/2020/08/counting-the-dead-at-hiroshima-and-nagasaki/]
5. [https://www.atomicarchive.com/science/effects/index.html]

4. Armament and Disarmament

Nuclear weapons production

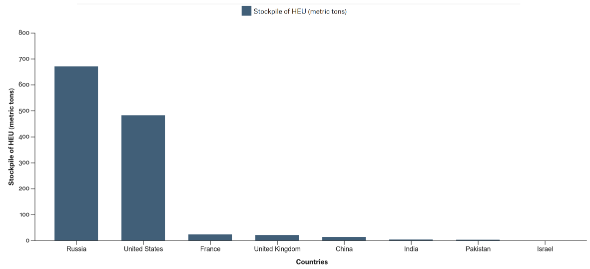
When a country decides to develop a nuclear weapons programme it needs to choose whether to enrich uranium, or to produce and separate plutonium. All the nuclear weapon states have produced weapons-grade uranium in the past, but the states under the Non-Proliferation Treaty (NPT) have ended HEU production for weapons (see LU05). Nowadays, HEU for military purposes is still produced by India, Pakistan and probably North Korea. The plutonium pathway is less costly than the uranium one. Moreover, plutonium has a lower critical mass than HEU. The United States, Russia, France, the United Kingdom, Japan, India, Israel, Pakistan and North Korea have reprocessing programmes for plutonium separation. Although all states under the NPT stopped separating plutonium for its use in weapons, the production of plutonium for military purposes is believed to be continued in India, Pakistan, North Korea and Israel.

Fissile material and weapons stockpiles

Fissile material stockpiles are divided into stockpiles of HEU and plutonium available for weapons. Since HEU is used in civil nuclear reactors, both military and civilian stocks of HEU are addressed. According to the International Panel on Fissile Materials (IPFM)[1], for HEU, the 2022 global inventory was 1,335 ± 125 metric tons, of which 99% is held by nuclear weapon states, mainly Russia and the USA.[2] Only the United States and the UK publish official statements regarding their military stockpiles, meaning that for other countries, figures are uncertain. This is particularly true for the Russian stockpiles. The current estimates of military stockpiles of HEU, based on the information provided by the International Panel in Fissile Material can be seen below.

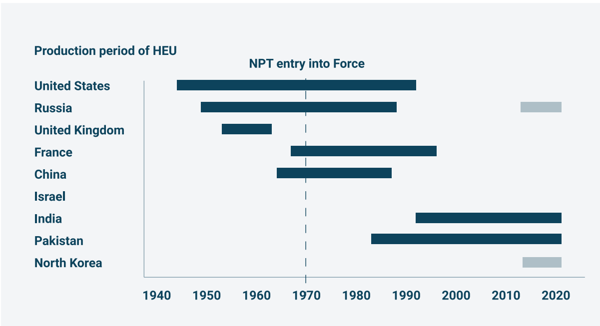
Table HEU. Stockpiles of HEU (IPFM, 2022)[3][4]

Country	Stockpile of HEU (metric tons)
Russia	672 ± 120
United States	483.4
France	24.6
United Kingdom	21.9
China	14.0
India	4.5
Pakistan	4.0
Israel	0.3



Stockpiles of HEU (IPFM, 2022)
Data: [Council on Strategic Risks] (https://councilonstrategicrisks.org/nolan/biodefense-budget-breakdown/), Graphic: PRIF

Note that the IPFM does not assign an HEU stockpile to North Korea. Other estimates suggest that North Korea could possess 0.5–2.1 metric tons of HEU.[5] The production of HEU has largely ended. Both the United States and Russia, along with other countries, stopped producing HEU between the 1970s and 1990s.

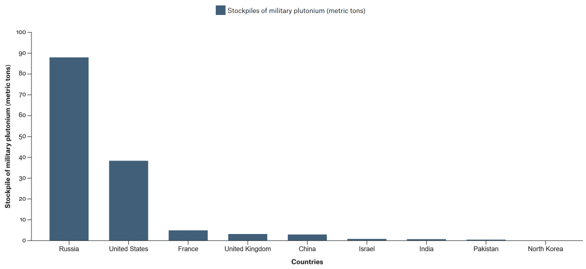


Production of HEU over time
Data: IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022, Diagram: Grübelfabrik, CC BY NS 4.0

The global stockpile of military plutonium is estimated to be 140 ± 10 metric tons (IPFM, 2022) Here, too, the majority of the material is held by Russia and the United States (see Table Pu).

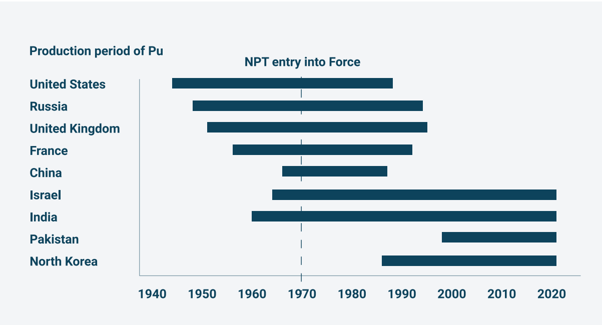
Stockpiles of Plutonium[6][7]

Country	Stockpile of HEU (metric tons)
Russia	88
United States	38.4
France	4.9
United Kingdom	3.2
China	2.9
Israel	0.83
India	0.71
Pakistan	0.46
North Korea	0.04



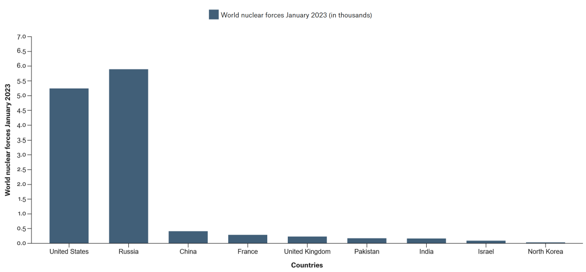
Stockpiles of Plutonium
Data: IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022, Diagram: PRIF

For plutonium production, the nuclear weapon states under the NPT all seized their production during the 1980s and 1990s, while India, Pakistan, Israel and North Korea still produce, see



Production period of Plutonium
Data: IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022, Diagram: Grübelfabrik, CC BY NS 4.0

The word "weapons stockpile" has different meanings in different countries and different contexts. Here we adopt the definition used by the Stockholm International Peace Research Institute (SIPRI) in their yearly report on the World's Nuclear Forces.[8] This definition includes all nuclear warheads that are deployed or in storage, as well as warheads that are retired but not yet dismantled, i.e. warheads that can be deployed with short preparation time. The existing warhead stockpiles based on this definition are shown here:



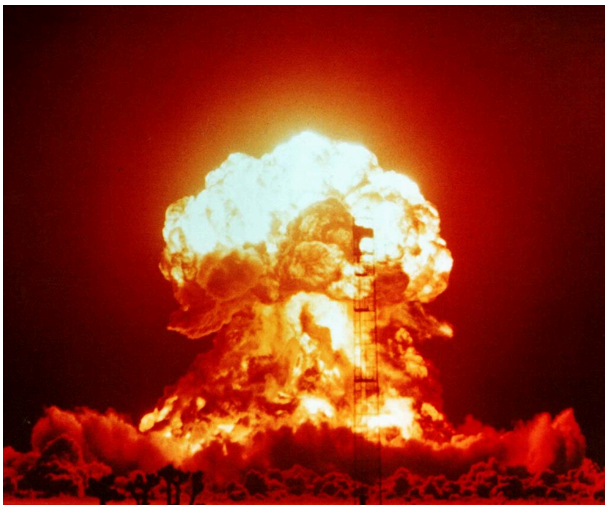
World Nuclear Forces in 2023
Data: Kristensen, H. 2023. 2023. SIPRI Yearbook 2023, 7. World nuclear forces, Stockholm International Peace Research Institute (SIPRI). Sweden. Available at: https://policycommons.net/artifacts/4313733/sipri-yearbook-2023-7/5123325/, Diagram: PRIF

The total number of warheads worldwide according to SIPRI is 12,512.

Nuclear weapons testing

A country that is developing a new nuclear weapons programme or a new design of nuclear weapon might perform a nuclear test explosion. The purpose of nuclear testing is to determine the performance and effect of a nuclear device. Even though there are experimental reasons to perform nuclear weapons tests, such as testing the detonation mechanism, the yield and other technical and physical parameters, nuclear testing has also been used extensively as a show of strength or for purely political and propaganda reasons.

For testing the physical parameters of a nuclear device, there are alternatives to full-scale detonations. One common technique is a cold or subcritical test, which is a test intended to produce zero yield by having less fissile material than a critical mass. Another method that has become increasingly important is computer simulations of nuclear explosions, which build on mathematical models of the physics involved.

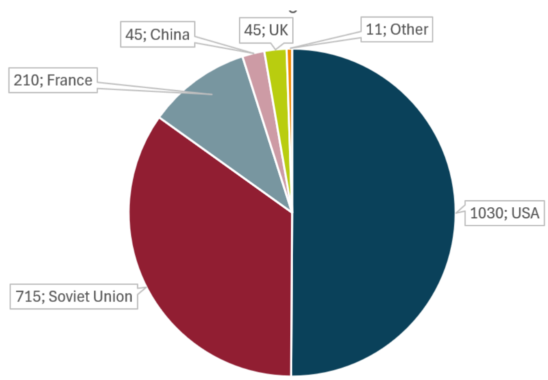


U.S. 23 kiloton nuclear test, 1953
Photo courtesy of National Nuclear Security Administration / Nevada Site Office

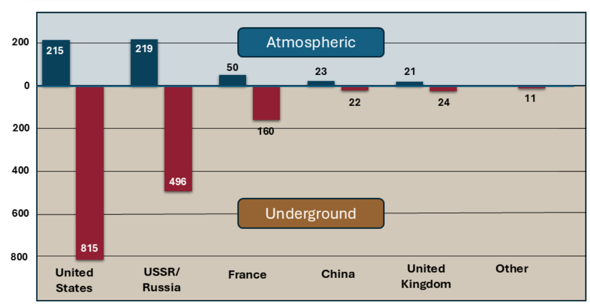
History of testing

The first nuclear test explosion took place in July 1945, and just one month later, two bombs were dropped on Hiroshima and Nagasaki in Japan, ending World War II in the east. As soon as the United States had demonstrated its ability to manufacture these weapons of mass destruction, other countries followed with nuclear bomb tests of their own – the Soviet Union (1949), the United Kingdom (1952), France (1960) and China (1964) – sparking an armament race. To prevent further proliferation, the Non-Proliferation Treaty (NPT) was negotiated in 1968, and since then, no new countries have been allowed to possess nuclear weapons under the NPT. Nevertheless, other states have produced their own nuclear devices, and three more countries have unambiguously performed nuclear weapon tests, those being India (1974), Pakistan (1998) and North Korea (2006). Israel is known to have nuclear weapons, but it has not been proven that they have tested a device. In total, more than 2,000 nuclear tests have been carried out worldwide since July 1945.

The overwhelming majority of all nuclear tests have been performed by the United States and the Soviet Union.



Nuclear testing per country
Data source and graphical inspiration: Arms Control Association, https://www.armscontrol.org/factsheets/nuclear-testing-tally

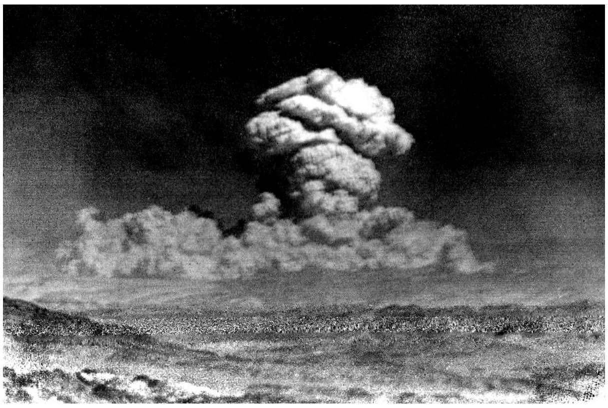


Bomb tests, a timeline of test showing atmospheric and underground tests
Data source and graphical inspiration: Arms Control Association, https://www.armscontrol.org/factsheets/nuclear-testing-tally

In the 1950s and early 1960s, most tests were performed in the atmosphere, creating nuclear fallout over large areas. The nuclear armament race continued, although from the first years of the 1960s, most of the tests were performed underground, which limits the fallout but also makes the tests more difficult to detect. Finally, after 1980, no more atmospheric nuclear tests were performed, and since the end of the Cold War in the 1990s, the total number of nuclear warheads in the world has been declining.

This is mainly due to the United States and the Soviet Union/Russian Federation reducing their arsenals.

The United States did most of their testing in the Nevada Desert, but also in the Pacific, in Alaska and in New Mexico. The testing procedures and the engineers and physicists that worked on creating the first American bomb are depicted in the *Oppenheimer* film.



Nuclear test near Las Vegas, Nevada. 100-kiloton bomb buried 650 feet underground. Explosion cloud was 3-5 miles wide and about 15,000 feet high.
US Government/Wiki Commons, public domain

The Soviet Union performed most tests in Kazakhstan and the Northern Test Site at Novaya Zemlya. The UK tested in the Montebello Islands in western Australia and also in Maralinga in the southern central part of Australia. France has tested in Algeria and the Mururoa Atoll in French Polynesia, and China tested nuclear weapons in Lop Nur, Xinjiang. India, Pakistan and North Korea have performed underground tests domestically. It has not been proven that Israel has performed any nuclear test explosions.

Test ban treaties

Several international treaties to limit or completely ban nuclear testing have been negotiated, starting with the Partial **Test Ban Treaty (PTBT)** in 1963. The full name of this treaty is the Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water, and it bans all nuclear test explosions except those underground. The PTBT was both signed and ratified by the United States, Soviet Union and United Kingdom, but not by France and China. The PTBT had a significant effect as nearly all nuclear tests moved underground once it had come into force. This treaty is still in effect.

Another important treaty is the **Threshold Test Ban Treaty (TTBT)**, which was adopted between the United States and the Soviet Union in 1974. The full name of this treaty is Treaty on the Limitation of Underground Nuclear Weapon Tests and it limits the yield of a test device to 150 kilotons. This was a bilateral treaty between the United States and the Soviet Union and was signed and ratified by both. As with the PTBT, the TTBT is still in effect.

In 1996, the United Nations General Assembly adopted the **Comprehensive Test Ban Treaty (CTBT)**. This treaty bans all nuclear test explosions including peaceful testing. It has been signed and ratified by the majority of the Earth's nations, but has not entered into force since not all the required states have ratified it. In its Annex II, there is an agreed list of 44 countries that must sign and ratify the treaty for it to enter into force. Of these "Annex II states", eight signatures and/or ratifications are still missing: China, Egypt, India, Iran, Israel, North Korea, Pakistan, Russia and the United States. The United States and Russia have both signed but not ratified the treaty.

In preparation for the CTBT to enter into force, an extensive verification regime has been developed in order to monitor compliance with the Treaty. This is handled by the Comprehensive Test Ban Treaty Organization [https://www.ctbto.org/]. The verification regime includes three components:

1. The IMS – the International Monitoring System which is a network of monitoring stations based on different detection technologies and with stations detecting seismic disturbances (seismic), soundwaves in the ocean (hydroacoustics), infrasound and radionuclides. For more details on the monitoring systems, see Chapter 5.
2. The IDC – the International Data Centre in Vienna where the CTBTO headquarters is located. This centre receives and processes data from the IMS and distributes it to the CTBTO member states.
3. OSI – on-site inspections will make it possible to collect data on the ground, once the CTBT enters into force.

It should be noted that the IMS and the CTBT successfully detected the nuclear weapons tests performed by North Korea in 2006, 2009, 2013 and 2016.

Nuclear disarmament

While the NPT prohibits the development of nuclear weapons by non-nuclear weapon states, the five recognised nuclear weapon states – the United States, Russia, France, China and the United Kingdom are exempt from this prohibition. Nevertheless, it is important to remember that Article VI of the NPT requires that the nuclear weapon states

> pursue negotiations in good faith on effective measures relating to cessation of nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control.
>
> Treaty on the Non-Proliferation of Nuclear Weapons (NPT), Article VI

Nuclear disarmament is the process of reducing or eliminating nuclear weapons.

Nuclear weapons dismantlement

Dismantlement is one phase of the disarmament process. It refers to the physical separation of the weapons components, such as high explosives and nuclear material, so it can no longer produce a nuclear yield. The dismantlement of nuclear weapons reached its peak in the 1990s, when the US alone dismantled weapons at a rate of 1,000 per year.[9] But with the shift of resources, the US started to invest in maintenance and life extension programmes for the existing warheads instead.[10] The US has one operational weapon disassembly facility at Pantex, Texas. Russia has two such facilities at Lesnoy and Trekhgorny. Typically, disassembly facilities are also weapon assembly facilities, which makes sense in terms of the type of machinery and experience needed to handle a particular nuclear weapon. The steps involved in the dismantlement of a nuclear weapon depend on the type of weapon.

In general terms, the steps followed in dismantlement are[11]:

1. Removal of the weapon from the delivery system
2. Removal of the weapon from its outer shell and other components
3. Separation of high explosives and fissile material core
4. Destruction, storage or reuse of various weapon components

Verification

Verification will be an essential part of any disarmament treaty that comes into force. Verification can be defined as

> iterative and deliberative processes of gathering, analysing, and assessing information to enable a determination of whether a State Party is in compliance with the provisions of an international treaty or agreement".
>
> International Partnership for Nuclear Disarmament Verification

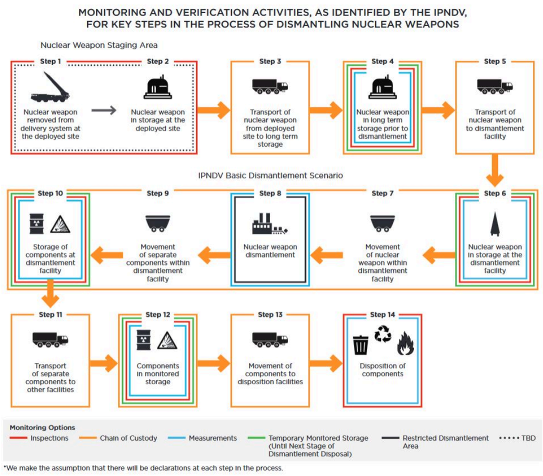
Verification develops confidence among and between states, increasing transparency and encouraging states to engage in future agreements. The verification of the arms control treaty between the Russian Federation and the United States, "New START", which came into force in 2011, was conducted indirectly. The warheads were counted indirectly, via the number of delivery vehicles that were associated with these weapons. A disarmament treaty that imposes limits on the number of weapons in an arsenal will require a different verification system, since it might require the verification of individual nuclear warheads in storage or entering the dismantlement queue (for more information, see Learning Unit 05 or Learning Unit 20).

Verification of the dismantlement of a nuclear weapon is an important element of securing a transparent and irreversible nuclear weapons reduction process. The verification of individual nuclear weapons is tricky, since the design of a nuclear weapon is highly classified information that cannot be revealed to international inspectors, even in the event of dismantlement. Therefore, the verification methods used should not reveal classified information so as to keep the host party information secret and to fulfil non-proliferation requirements. The verification methods applied in a disarmament verification treaty should enable a compromise between reliably verifying that the inspected warhead is authentic and not disclosing information about its design.

Individual institutional research groups, such as the Massachusetts Institute of Technology (MIT), have been performing research on the development of methods to assist the inspection of nuclear weapons dismantlement and destruction.[12] The group of MIT scientists proposed a verification method using neutron beams and an isotopic information barrier filter to inspect certain properties of the warhead without revealing confidential information on the warhead design. Initiatives such as the International Partnership for Nuclear Disarmament Verification (IPNDV) [https://www.ipndv.org] work on identifying challenges related to nuclear disarmament verification and developing procedures and technologies to address these challenges.
The IPNDV was started in December 2014 based on cooperation between the U.S. Department of State and the Nuclear Threat Initiative (NTI) [https://www.nti.org/]. Later, the IPNDV incorporated different countries, with and without nuclear weapons, reaching 25 states in 2024.
The main goals of the IPNDV are:

- to identify gaps and technical challenges associated with monitoring and verifying nuclear disarmament throughout the nuclear weapons life cycle;
- to build and diversify international capacity and expertise on nuclear monitoring and verification.

To better understand the verification of a nuclear dismantlement process, the IPNDV developed a 14-step model, from the removal of nuclear weapons from its delivery system to their disposition in separate components.



IPNDV's 14-step Nuclear Weapons Dismantlement Lifecycle
Courtesy of IPDNV, all rights reserved

The IPNDV partners worked with this 14-step nuclear weapons dismantlement life cycle to propose different procedures and technologies for monitoring and inspecting the various processes. Measurement technologies applied in some of these steps include radiation detection equipment, calorimeters and explosive identification systems. Elements that could be part of the chain of custody procedure include container assessment technologies, tamper indicating devices and seals. Monitoring procedures suggested by the IPNDV for some of the steps are surveillance technologies and portal monitors.

Weapon material disposal
To make sure that weapons material is not used to make new nuclear weapons, different approaches to dispose of weapons-grade uranium and plutonium are discussed. The options under discussion are processing the material in current and future reactors, vitrification of the material with high-level nuclear waste for disposal in an engineered repository or even launching the material in packages into solar orbit from the Earth. Due to economic, environmental and non-proliferation reasons (protecting the material from terrorist groups or rogue nations that might attempt to acquire it for use in nuclear weapons), the use of nuclear weapons material demands strict measures, imposing limitations on its application for energy production.[13] For example, to use weapons-grade plutonium in a reactor, the material would need to be used to fabricate mixed-oxide fuel (MOX). However, the costs related to this process would be much higher than those for fabricating LEU. And since there are just a few reactors that are designed to use MOX, there will be the costs of the secure shipping and storage of the material as well

1. The International Panel on Fissile Materials (IPFM) is an independent group of arms control and non-proliferation experts from both nuclear weapon and non-nuclear weapon spates.
2. IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022
3. IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022
4. Please note that Russia's stockpiles are given as 672 +/- 120
5. Christopher, Grant/Wingo, Hailey. 2023. North Korean Operations of the Experimental Light Water Reactor. Vertic. Available at: [https://www.vertic.org/wp-content/uploads/2023/07/TV172-REV2.pdf#page=7], Trust & Verify Issue 172
6. IPFM. Global Fissile Material Report 2022. Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy. A report of the International Panel on Fissile Material, July 2022
7. Please note that Russia's stockpiles are given as 88 +/- 8.
8. Kristensen, H. 2023. 2023. SIPRI Yearbook 2023, 7. World nuclear forces, Stockholm International Peace Research Institute (SIPRI). Sweden. Available at: [https://policycommons.net/artifacts/4313733/sipri-yearbook-2023-7/5123325/]
9. [https://open.defense.gov]. The Trump Administration has not disclosed stockpile and dismantlement numbers for 2018.
10. Kristensen, Hans M. "Obama Administration Announces Unilateral Nuclear Weapon Cuts", in: Federation of American Scientists 11, January 2017. Available at: [https://fas.org].
11. Bunn M. 2008. – Reykjavik Revisited: Steps Toward a World Free of Nuclear Weapons, Chapter 5: Transparent and Irreversible Dismantlement of Nuclear Weapons. Available at: [https://www.hoover.org/sites/default/files/uploads/documents/9780817949211_ch5.pdf]
12. "How to dismantle nuclear bombs" in MIT News. 2019. Available at : [https://news.mit.edu/2019/verify-dismantle-nuclear-bombs-0927]
13. Berkhout, F./ Diakov, A./Feiveson, H./ Hunt, H./ Lyman, E./Miller, M./von Hippel, F.: "Disposition of Separated Plutonium", in: Science and Global Security 3 (3–4), March 1993: pp. 161–214;
Von Hippel, F./Miller, M/Feiveson, H/Diakov, A./Berkhout, F.: "Eliminating Nuclear Warheads", in the Scientific American, 269, pg. 4-49, Aug. 1993.

5. Monitoring

Introduction

What is monitoring?
Monitoring is the act of observing and checking the progress, quality and state of something over time — in other words, maintaining regular surveillance over something.

What type of monitoring?
The activity of interest for monitoring depends on the type of treaty or agreement in place. In the context of nuclear non-proliferation, examples are treaties and agreements that guarantee the peaceful use of nuclear energy, ban nuclear tests, control the proliferation of nuclear weapons or nuclear disarmament. For instance, if there is a nuclear test ban treaty in place, the activity of interest to be monitored would be the execution of a nuclear explosion. Under the NPT, fuel cycle activities that can indicate the use of nuclear material for non-peaceful purposes are of interest, including the construction of facilities that are not declared or the modification of the current facilities.

The nuclear fuel cycle activities that are most relevant for monitoring in the context of non-proliferation are those related to the paths to acquire material that could be used in a nuclear weapon. The two nuclear materials that could be used in a nuclear weapon discussed in Chapter 3 were uranium, enriched to above 90% in the isotope 235, and plutonium. Considering that the main process to acquire enriched uranium is the enrichment process, and that to acquire plutonium, uranium needs to be fed into a nuclear reactor and later separated in a reprocessing facility, here, we will discuss the monitoring of the enrichment, reprocessing and the operation of the nuclear reactor itself.

How to monitor

The type of monitoring method chosen is highly dependent on the purpose of the monitoring. Some well-established methods are satellite imagery, environmental sampling and analysis, infrasound, hydroacoustic, seismic signals and other nuclear safeguards procedures.

Satellite imagery: Visible light imagery can monitor facility construction and demolition activities at known sites, as well as the operation of nuclear reactors equipped with vapor-emitting cooling towers. [1] Satellites capable of thermal infrared imagery can also be used to detect water flowing from nuclear reactors into rivers or the ocean.[2] Satellite technology cannot, however, unambiguously identify uranium enrichment when it is performed by gas centrifuges or reprocessing activities.

Infrasound: Acoustic waves with very low frequency are called infrasound. Explosions in the atmosphere and underground can generate infrasound waves, and these waves are able to travel long distances with low dissipation. Infrasound waves can come from many sources, such as volcanic eruptions, earthquakes, aircraft and large chemical explosions. Since the sound propagates efficiently, it can be detected at large distances from its origin.

Hydroacoustic: To monitor hydroacoustic waves means recording signals that show changes in water pressure generated by sound waves in the water. Hydroacoustic monitoring is used to localise and differentiate between signals generated by nuclear explosions and signals from other sources.

Seismic signals: Seismic signals are waves transmitted through the Earth, and can have many different sources. Seismic signals can be used to detect underground nuclear explosions. Seismic technology is very efficient, since seismic waves can travel very fast and long distances. Seismometers, usually arranged as an array, detect seismic waves amplifying the seismic signal against the seismic background. In so doing they provide information on the location, depth and magnitude of an event.

Environmental sampling: To sample means to collect a small part of air, water, solid or biota from the ambient environment. The sample is analysed for indicators, such as traces of chemical components, specific elements or radiation. There are many techniques for the detection and analysis of radioactive particles and noble gases. Examples of these techniques include gamma spectroscopy, detection of gamma-beta coincidences, and mass spectroscopy.[3] In the monitoring of nuclear explosions, for instance, samples of aerosol particles collected on air filters are tested for the presence of radionuclides via gamma spectroscopy. In addition to this, radioactive noble gasses are also collected and the relative abundance of different noble gas isotopes is measured.

Other nuclear safeguards procedures: The objective of the international nuclear safeguards system created by the International Atomic Energy Agency (IAEA) is to deter the spread of nuclear weapons. Developed to ensure that the states under the NPT are honouring their legal obligations, the IAEA safeguards enable the performance of independent verification that nuclear facilities and materials are not misused and are not diverted from peaceful uses. Among the technical measures used by the IAEA, different systems for monitoring nuclear facilities and material include satellite images, the collection of environmental samples and remote monitoring. For example, unattended monitoring systems (UMSs) run

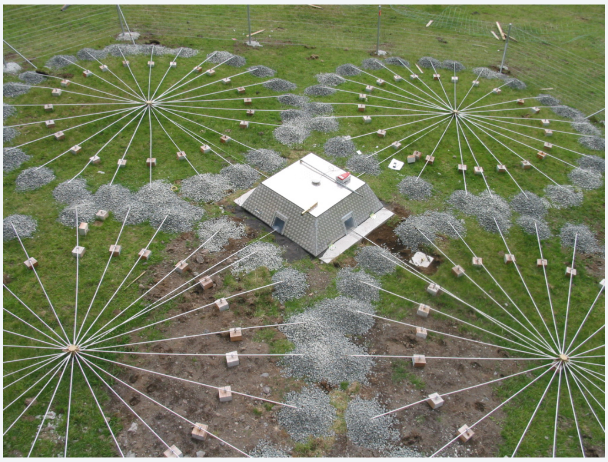
24 hours a day, 365 days a year without requiring the presence of an inspector in the field.

Monitoring of nuclear test explosions and subcritical tests

Nuclear explosions

The monitoring of a nuclear explosion would be part of the Comprehensive Nuclear Test Ban Treaty (CTBT), adopted in 1996, once it enters into force. The four sensor technologies that are part of the CTBT verification regime are seismic, infrasound, hydroacoustic and radionuclide detection. Examples of CTBT monitoring stations can be seen here.

Auxiliary seismic station in Ushuaia, Argentina
Courtesy of CTBTO



Infrasound station array at Tristan da Cunha, UK
Courtesy of CTBTO

Infrasound station array at Tristan da Cunha, UK
Courtesy of CTBTO

The different International Monitoring Stations are set up in such a way that signals from several of the monitoring techniques must be detected at the same time to indicate a test explosion.
Radionuclide detection is the only technique that can confirm whether an explosion detected and located by the other three techniques is indicative of a nuclear test. The Partial Test Ban Treaty (PTBT), adopted in 1963, was the first treaty to use environmental sampling for verification purposes. The radionuclide stations detect both radioactive particles that are collected on filters, and radioactive noble gases collected from the atmosphere. In total there are 337 IMS facilities around the globe:

CTBTO International monitoring system
Courtesy of CTBTO

Subcritical tests instead of explosions

A subcritical nuclear weapons test uses quantities of fissile material that are lower than the subcritical mass, so there is no self-sustaining nuclear chain reaction. The fissile material used is generally plutonium-239. Subcritical tests release less than one ton of TNT equivalent and are more difficult to detect, especially if performed underground. Nowadays, there is no regime for the international observation of subcritical tests. Researchers are investigating how to perform monitoring and verification of such tests and are also exploring measures to ensure transparency related to subcritical tests under the CTBT.[4]

Monitoring of enrichment and reprocessing activities

The detection of clandestine weapons-grade uranium production and plutonium production and separation is one of the main goals in verifying the compliance of non-nuclear weapon states with the Non-Proliferation Treaty (NPT) and the compliance of nuclear weapon states with future fissile material cutoff treaties, such as the Fissile Material Cutoff Treaty (FMCT).

States under the NPT are subject to international nuclear safeguards inspections and monitoring by the IAEA.

The Global Fissile Material Report from 2007 shows the detectability of different steps of the enrichment and plutonium production processes by satellite imaging and environmental sampling.[5]

Monitoring nuclear facilities via satellite
Grübelfabrik, CC BY NS 4.0

According to the report, the production of weapon-usable fissile materials, such as plutonium and highly enriched uranium (HEU), varies significantly in how easily it can be detected by remote monitoring methods. Some technologies, like nuclear reactors and gaseous diffusion facilities, are generally more visible through satellite imagery and thermal detection. Others, such as reprocessing plants, conversion facilities, and especially centrifuge enrichment, are far more difficult to identify without direct access. Environmental sampling can help in some cases, but its effectiveness is often limited to large-scale operations. These differences highlight the challenges in reliably detecting and monitoring nuclear proliferation activities from a distance.

Plutonium production and separation

To be used in a weapon, plutonium needs to be generated inside a nuclear reactor and then separated from the spent nuclear fuel.

Undeclared nuclear reactors that are readily detected via satellite images, open source information or nuclear safeguards inspection. Changes in the reactor operation to produce plutonium is more challenging to monitor but can be identified if the facility in question is subject to nuclear safeguards.

New undeclared reprocessing facilities, operating on a large scale with the aim of being profitable, can be detected via satellite image, open data assessment, etc. The two most challenging scenarios when it comes to detecting an undeclared reprocessing facility are if a common industrial facility is remodelled to function as a quick and simple reprocessing plant, or if a declared reprocessing facility is used to divert material to produce plutonium. In the first case, the monitoring of material in the undeclared facility could indicate illegal activity. In the second case, on-site monitoring could be used to detect such an attempt.

A reprocessing plant has many characteristic features that could be identified during a managed-access inspection, visually and/or with appropriate instruments, without revealing sensitive information.[6] These include:

- heavy walls for gamma radiation shielding, typically 1–2 metres thick and made of metal aggregate containing concrete. Ultrasonic gauges calibrated for wall thickness of up to 1.3 metres are commercially available;
- very high gamma-ray radiation levels inside spaces where spent fuel has been dissolved and fission products separated from the Pu. A simple dosimeter that measures only gamma-ray dose and not its energy spectrum could verify the radiation levels;
- release of volatile radionuclides during the dissolution of spent fuel. The fission product detected furthest downwind from a reprocessing plant is Kr-85. This product is produced in 0.3% of fissions of U-235, has a half-life of 11 years and is not reactive, thus remaining in the atmosphere. Unless it is removed and contained inside the facility, it should be possible to detect Kr-85 outside the site fence of an operating reprocessing facility.

Highly enriched uranium production

Enrichment via gaseous diffusion requires large-scale facilities that usually have a specific shape and use a lot of energy, allowing detection via both visible and thermal satellite imaging. Enrichment via centrifuges cannot be detected via the satellite imaging or environmental sampling techniques considered in the GFM report. Monitoring systems that are placed inside the facility might be required. Nuclear safeguards procedures are applied in enrichment facilities declared under the NPT to ensure that the uranium enrichment level is kept under the allowed limit, which usually means low-enriched uranium (LEU) used as fuel in nuclear power reactors. Gamma-ray spectroscopy and weighting are examples of techniques used by nuclear safeguards to monitor fuel enrichment. In the case of the FMCT, where states agreed to stop the production of HEU, facilities that were used to produce military HEU were converted to produce civil LEU. The challenge in such facilities is to distinguish HEU particles that were produced in the past from present production particles. For this purpose, techniques to identify the isotopic signature and the age of such particles are applied.

1. [https://edition.cnn.com/2023/09/22/asia/nuclear-testing-china-russia-us-exclusive-intl-hnk-ml/index.html]
2. Park, Sulgiye/Puccioni, Allision/Verille, Francesca. 2024. Thermal satellite imagery for the detection and monitoring of nuclear weapons: Early approaches for automating imagery analysis. Available at: [https://hai.stanford.edu/events/thermal-satellite-imagery-detection-and-monitoring-nuclear-weapons-early-approaches]
3. Kuhn, E./Fisher, D./Ryjinski, M. 2001. Environmental Sampling for IAEA Safeguards: A Five Year Review. IAEA-SM-367/10/01. Available at: [https://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%2010/Paper%2010-01.pdf]
4. Jones, S. L./von Hippel, F. N. (1997): "Transparency measures for subcritical experiments under the CTBT", in: Science & Global Security 6(3): 291–310; Hruby, J. (2023): Remarks by NNSA Administrator Jill Hruby at the CTBT: Science and Technology Conference 2023, [https://www.energy.gov/nnsa/articles/remarks-nnsa-administrator-jill-hruby-ctbt-science-and-technology-conference-2023]
5. GFMR. 2007. International Panel on Fissile Materials, Global Fissile Material Report, 2007. Available at: [https://fissilematerials.org/library/gfmr07.pdf]
6. International Panel on Fissile Materials, Global Fissile Material Report, 2007. Available at: [https://fissilematerials.org/library/gfmr07.pdf]

6. Summary

Since their origins during World War II, with the evolution of technology, nuclear weapons have become more precise, reliable, destructive and smaller.

Although nuclear weapons testing has historically been a key aspect of developing and validating new weapon designs, subcritical tests and computer simulations have largely replaced live tests, allowing for the continued refinement of nuclear arsenals without actual detonations. Even though the Comprehensive Nuclear Test Ban Treaty (CTBT) has not yet fully entered into force, it has led to a de facto moratorium on nuclear testing by major powers.

The primary materials used in nuclear weapons are plutonium-239 and highly enriched uranium (HEU). The production of these materials involves complex processes, including uranium enrichment and plutonium reprocessing. Beyond the control and monitoring of nuclear weapons, the control and monitoring of nuclear materials and activities is essential for arms control and non-proliferation. International frameworks like the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and organisations such as the International Atomic Energy Agency (IAEA) and EURATOM play crucial roles in verification and compliance.

Currently, there are five recognised nuclear weapon states – the United States, Russia, France, the United Kingdom and China – and four other states with nuclear weapon capabilities – India, Pakistan, Israel and North Korea. Although the real numbers of nuclear weapons are considered national secrets by the states, the global military stockpile is estimated to be higher than 12,000 nuclear warheads. Nuclear disarmament seems to be out of reach, as states are still investing a lot of money in maintaining and modernising their nuclear arsenals.

While the near future of nuclear weapons technology will likely focus on further advancements in delivery systems, advances in technology promise enhanced monitoring and verification capabilities for treaties and agreements on nuclear weapons control and disarmament in the more distant future.

Further information

- International Panel on Fissile Materials (IPFM) – fissilematerials.org `[https://fissilematerials.org]`
  This site brings together top scientists and technical experts to analyze global stocks of fissile material and options for securing or eliminating them. Its research is technical, accessible, and central to understanding the nuts and bolts of disarmament.
- James Martin Center for Nonproliferation Studies (CNS) – nonproliferation.org `[https://nonproliferation.org]`
  CNS offers detailed technical and open-source analysis of nuclear weapons programs, with a strong focus on innovation in verification and monitoring. Their tools and satellite imagery work are particularly valuable for students.
- Federation of American Scientists (FAS) – fas.org `[https://fas.org]`
  FAS provides data-rich reports and analysis on nuclear arsenals, delivery systems, and the science behind arms control. Their Nuclear Notebook series is a must-read for technically inclined disarmament followers.
- Los Alamos National Laboratory – lanl.gov `[https://lanl.gov]`
  While not focused on disarmament, LANL is a key player in U.S. nuclear science and often publishes technical papers on verification and detection technologies. It's essential for understanding the capabilities and limits of current monitoring methods.
- Sandia National Laboratories – sandia.gov `[https://sandia.gov]`
  Sandia conducts cutting-edge work on nuclear security, warhead dismantlement, and verification tech. Great for diving into engineering-level discussions on disarmament tools.
- Arms Control Wonk – armscontrolwonk.com `[https://armscontrolwonk.com]`
  A technical blog and podcast run by experts that breaks down nuclear tests, satellite imagery, missile tracking, and more. Informal but incredibly detailed, it's perfect for students who want both depth and real-world application.
- IAEA (International Atomic Energy Agency) – iaea.org `[https://iaea.org]`
  The IAEA is the heart of international nuclear verification. Its publications and safeguards reports give direct insight into how civilian nuclear programs are monitored—tech-heavy and indispensable.
- NTI (Nuclear Threat Initiative) – nti.org `[https://nti.org]`
  NTI bridges technical depth with accessible tools and datasets, including their Nuclear Security Index. It's ideal for understanding global vulnerabilities and efforts to reduce nuclear risks.
- Science & Global Security (SGS) Journal – scienceandglobalsecurity.org `[https://scienceandglobalsecurity.org]`
  This peer-reviewed journal is packed with technical studies on disarmament verification, nuclear weapons physics, and policy-relevant science. A goldmine for students looking to publish or understand high-level debates.

More information on how each of the CTBTO stations work can be found here:

- Infrasound: [https://www.youtube.com/watch?v=GVWOA5pZG6o&t=2s]
- Seismic: [https://www.youtube.com/watch?v=bx9YKVxvJ00]
- Hydroacoustic: [https://www.youtube.com/watch?v=IFomVoL92oM]
- Radionuclide: [https://www.youtube.com/watch?v=HDyU6nsUJqA]

Terms

Megaelectronvolt
Unit of measurement for energy: megaelectronvolt =1 million electronvolts. MeV It is a unit particularly used in nuclear physics since the SI unit for energy (Joule) is way too large. 1 MeV is ca 10^(-13) Joule.