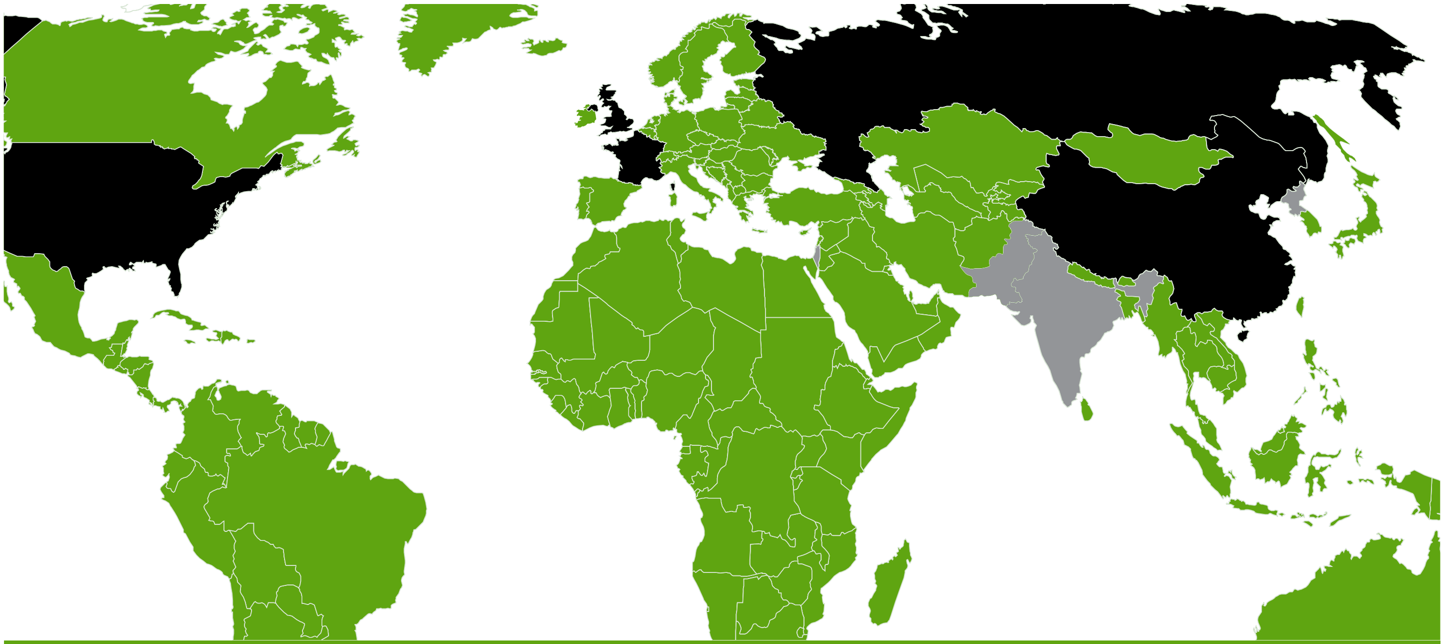

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2022

Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy

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www.fissilematerials.org

On the cover: the map shows the five NPT nuclear weapon states (black), the other four states possessing nuclear weapons (grey), and the 186 non-weapon states in the NPT (green).

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from seventeen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

The Panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University. Previously, it was co-chaired by Jose Goldemberg of the University of Sao Paolo, Brazil (2006-2007), R. Rajaraman of Jawaharlal Nehru University, New Delhi, India (2007-2014), and Frank von Hippel of Princeton University (2006-2014).

Its members include nuclear experts from Brazil, Canada, China, France, Germany, India, Iran, Japan, the Netherlands, Norway, Pakistan, Russia, South Africa, South Korea, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

Princeton University's Program on Science and Global Security provides administrative and research support for the IPFM.

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Overview

This Global Fissile Material Report focuses on the Treaty on the Non-Proliferation of Nuclear Weapons (commonly known as the nuclear Non-Proliferation Treaty, or NPT) and the 50 years since it entered into force in 1970.[1] It looks at the achievements and limits of the treaty over this period in three interlinked areas: nuclear weapons, the fissile materials that are the key ingredients for nuclear weapons, and nuclear energy. All three areas have been the subject of earlier reports by the International Panel on Fissile Materials.

Part 1 of this report provides an overview of global and national nuclear weapon stockpiles and related arms control and disarmament issues over the 50 years of the NPT. Part 2 surveys the evolution and current status of stockpiles of separated plutonium and highly enriched uranium (HEU), the fissile materials that fuel nuclear weapons and play a central role in the NPT effort at limiting proliferation. Part 3 assesses the global experience with the peaceful use of nuclear energy that the NPT supports, especially in developing countries.

Part 4 of the report offers brief country profiles of the nine states that today possess nuclear weapons. Five are parties to the NPT (the United States, Russia, United Kingdom, France, and China) and four states are not NPT parties (Israel, India, Pakistan, and North Korea). Each national profile summarizes the situation with regard to nuclear weapons, fissile material stockpiles and production, and nuclear energy safeguards. An appendix to the report provides a short technical overview on nuclear weapons and fissile materials.

Nuclear Weapons

Of the 191 states in the NPT, only five are nuclear weapon states. From 1970 until 1992, only the United States, the Soviet Union (and then Russia) and the United Kingdom were NPT weapon-states parties. In 1992, China and France joined the treaty. Under the definition used in the NPT, Israel, India, Pakistan, and North Korea cannot join as nuclear weapon states since they had not manufactured and tested a nuclear weapon before 1967. Israel, India, Pakistan have not signed the treaty and North Korea withdrew from it. The goal of universalization of the treaty, agreed to be an 'urgent priority' and the first item in the program of action agreed at the 1995 Review and Extension Conference, has not advanced.

The NPT effort to prevent transfer of or control over nuclear weapons (Articles I and II) has not addressed the continuing hosting of U.S. nuclear weapons by Belgium, Germany, Italy, Netherlands, and Turkey. U.S. and Soviet weapons have been removed from other host states and there are no additional states that host nuclear weapons.

Article VI of the NPT calls for "effective measures to end the nuclear arms race at an early date and to nuclear disarmament." As of the beginning of 2021, the global nuclear weapon stockpile was estimated to be about 13,080 weapons, about one-third of what it was 50 years ago. Even after the NPT entered into force, nuclear arsenals continued to increase. The global inventory of nuclear warheads has been shrinking since the late 1980s, mostly because of reduction measures agreed between the United States and Russia – the UK, France, and China have not joined reduction negotiations. The overall rate of decline has slowed, while some nuclear arsenals have been growing, including that of China, and those of the non-NPT nuclear-armed states.

Key arms control measures that have gained consensus support in the five-yearly NPT Review Conferences, such as entry into force of a treaty banning nuclear weapons testing and a treaty ending production of HEU and separated plutonium for weapons, have failed to be implemented. Although no NPT member state has tested nuclear weapons since 1996, the 1996 Comprehensive Nuclear-Test-Ban Treaty is not in force and substantive talks have yet to begin on a Fissile Material Cutoff Treaty (FMCT).

Many non-weapon states have responded with efforts to foster progress on disarmament using the NPT Review process and other measures. This has included establishing regional nuclear weapon free zones, as envisaged under Article VII of the NPT. As of 2021, there are five such zones encompassing 112 countries. Following collective recognition at the 2010 NPT Review Conference of the "catastrophic humanitarian consequences of any use of nuclear weapons," a sustained campaign and a 2016 United Nations General Assembly resolution led in 2017 to a United Nations conference to negotiate the Treaty on the Prohibition of Nuclear Weapons. At the end of the conference, 122 countries agreed to the draft treaty text. The five NPT nuclear weapon states did not join the process and have declared their opposition to the treaty. The Treaty on the Prohibition of Nuclear Weapons entered into force in 2021.

Fissile Materials

Article III of the NPT requires application of a system for international safeguards in non-weapon states on the production and use of fissile materials, in practice separated plutonium and HEU, to prevent their diversion from peaceful to military use. The safeguards are managed by the International Atomic Energy Agency (IAEA). The NPT weapon states have, through voluntary offer agreements, accepted limited safeguards on some civilian sites and materials. Entry into force of the NPT did not stop production of separated plutonium or HEU for weapons, or end civilian programs producing or using weapon-useable fissile materials.

The Soviet Union, United Kingdom and United States continued plutonium production for weapons for about two decades after becoming members of the NPT. France and China ended production about the time they became NPT members. The UK and Russia were the last of the NPT weapon states to end production of plutonium for weapons. India, Israel, Pakistan, and North Korea are believed to be continuing production of plutonium for weapons.

The global stockpile of plutonium for weapons as of 2021 is estimated to be 140 ± 10 tons, with an additional almost 90 tons declared as excess for weapon purposes by the United States and Russia.* Despite the year-2000 Plutonium Management and Disposition Agreement between Russia and the United States (now defunct), no significant reductions in stockpiles of weapons plutonium (except in waste) have taken place in the 50 years since the NPT came into force.

Large-scale separation of civilian plutonium, which also is weapon-usable, started after NPT entry into force. In 2021, the global stockpile of civilian plutonium was 317 tons – larger than the military stockpile. Most of the civilian plutonium stockpile and separation is in the NPT weapon states. Japan is the only NPT non-weapon state with a significant plutonium separation program and stockpile.

The NPT nuclear weapon states all produced HEU for weapons and other military purposes even after the treaty's entry into force, except the UK, which receives HEU transfers for military purposes from the United States. All these states have ended HEU production for

* All tons are metric tons in this report.

weapons. HEU currently is being produced only by India, Pakistan, Russia and probably North Korea. The current global inventory of HEU is estimated to be about 1,335 ± 125 tons, with most of it belonging to Russia and the United States. Civilian stocks of HEU total about 42 tons, less than four percent of the global HEU stockpile. All of this has been produced by the weapon states, except for several hundred kilograms in the diminishing legacy stockpile in South Africa from its former nuclear weapons program and kilogram quantities produced by Iran starting in 2021.

The global stockpile of HEU peaked in the 1980s. After the end of the Cold War, as nuclear weapon arsenals declined, the United States and Russia declared large amounts of HEU excess and began downblending it to produce low-enriched uranium fuel for nuclear power reactors. About 680 tons of HEU have been eliminated as of 2021.

Despite large reductions in the 1980s of their nuclear arsenals from their Cold War peaks by four of the five NPT nuclear weapon states and despite commitments at NPT Review Conferences, most of the plutonium and HEU made excess by these reductions has not gone under safeguards.

Nuclear Energy

A vision for an expanded global role for nuclear energy for peaceful purposes is reflected in NPT Article IV. When the NPT entered into force in 1970, 14 countries operated grid-connected nuclear power reactors. Fifty years later, only 31 countries out of the 191 NPT states have operational nuclear power reactors. Of these 31 countries, nine have either nuclear phase-out, no-new-build or no-program-extension policies in place. The five NPT nuclear weapon states together have over half of the operating power reactors in the world. India and Pakistan also have nuclear power programs, but are not NPT parties. The spread of nuclear power has taken place at a significantly slower pace and on a smaller scale than anticipated in 1970, with about the same number of power reactors operating today as 30 years ago.

Under Article III of the NPT, each non-nuclear-weapon state undertakes to accept International Atomic Energy Agency safeguards "with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices." At the time the NPT was negotiated and when it entered into force in 1970, there was no 'comprehensive safeguards' system. A model comprehensive safeguards agreement to meet the NPT goal was developed in 1972. Problems with detection of undeclared nuclear material and activities in Iraq and North Korea in the early 1990s led in 1997 to a Model Additional Protocol to the comprehensive safeguards agreement with additional reporting and inspection requirements. The Additional Protocol is not mandatory under the NPT.

The NPT does not require nuclear weapon states to conclude any safeguards agreement with the IAEA, but there are voluntary offer safeguards agreements between the IAEA and the five NPT weapon states. Out of 717 nuclear facilities worldwide that are under safeguards, however, only 11 are covered under such voluntary offer agreements.

The amount of nuclear material under IAEA safeguards has increased almost 500-fold since 1970. Most of this growth has come from the operation of civilian nuclear power programs. Despite the growing stockpile of materials and number of facilities under and available for safeguards, funding for IAEA safeguards has not kept pace.

Nuclear Weapons and the NPT

In 2020, the Treaty on the Non-Proliferation of Nuclear Weapons (commonly known as the nuclear Non-Proliferation Treaty, or NPT) marked 50 years since it entered into force in 1970. This was made possible by a 1995 decision under Article X of the treaty, whereby a majority decision could be made 25 years after entry into force on whether the treaty could be extended indefinitely. In 1995, as part of a set of decisions including agreement on the "Principles and Objectives for Nuclear Non-Proliferation and Disarmament," the NPT was extended indefinitely. With 191 states parties as of 2020, the NPT has become a defining feature of the international nuclear order, entrenching there "its basic principle that nuclear weapons are intrinsically illegitimate everywhere and for all time."[2]

The NPT's preamble makes clear the motivation for the treaty is the threat to humankind from nuclear weapons. The preamble begins:

> "Considering the devastation that would be visited upon all mankind by a nuclear war and the consequent need to make every effort to avert the danger of such a war and to take measures to safeguard the security of peoples,
>
> Believing that the proliferation of nuclear weapons would seriously enhance the danger of nuclear war…"

The origins of the treaty lie in the Irish resolution introduced at the United Nations in 1958 recognizing that "the danger now exists that an increase in the number of States possessing nuclear weapons may occur, aggravating international tension and the difficulty of maintaining world peace" and seeking to address it.[3] The United States believed the Irish initiative to be "potentially dangerous" and "disruptive," and sought to dissuade Ireland from moving ahead with it.[4] The U.S. position was that it was "unable [to] accept any provision calling upon nuclear powers not to make nuclear weapons available to other countries" and furthermore could not support "singling out nuclear weapons for separate treatment" since this "would strengthen [the] Soviet campaign for prohibition of these weapons."[5]

Growing concerns about the spread of nuclear weapons eventually overcame this opposition, however. In October 1960, during the U.S. presidential election debate, John F. Kennedy expressed his fear that "10, 15, or 20 nations will have a nuclear capacity, including Red China, by the end of the Presidential office in 1964."[6] In 1961, with Kennedy as President, the United States joined supporters of the Irish resolution at the General Assembly in a unanimous vote in favor, to enable the negotiations that led to the NPT, which opened for signature in 1968.

Capping and reducing the number of states with nuclear weapons was a key goal of the NPT. It also sought to restrict the transfer of nuclear weapons or control over such weapons to non-weapon states, and allowed for the establishment of regional nuclear weapon free zones.

Under Article VI, the treaty expressed an ambition to achieve universal disarmament. It obliged "Each of the Parties to the Treaty" to work towards "effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament." If realized, such measures would have ended the development and production of new nuclear weapons, reduced the number of existing nuclear weapons, and led to the elimination of nuclear weapons in the nuclear weapon states that were parties to the treaty.

Non-weapon states have used the NPT's review process to seek progress towards disarmament. NPT Article VIII requires the parties to hold a conference after five years for "assuring that the purposes of the Preamble and the provisions of the Treaty are being realized" and allowed for "further conferences with the same objective of reviewing the operation of the

Treaty" every five years. A major feature of the review conferences has been disputes between the weapon states and many non-weapon states over interpreting and implementing Article VI obligations. The review conferences in 1975, 1985, 1995, 2000, and 2010 concluded with some agreement, including in 2000 and 2010 substantive commitments to pursue specific arms control measures, but the review conferences in 1980, 1990, 2005, and 2015 did not reach consensus.[7] The tenth review conference, scheduled to be held in 2020, was delayed due to the COVID pandemic.

Nuclear Weapon States

There were five countries with nuclear weapons during the period from 1965 to 1968 when the NPT was negotiated, the United States, Soviet Union/Russia, United Kingdom, France, and China. The NPT recognizes these five countries as nuclear weapon states by adopting, under Article IX, a 1 January 1967 cut-off date for when states had manufactured and tested a nuclear weapon or explosive device as the basis for defining a nuclear weapon state for the purposes of the treaty.

The five NPT weapon states have not all been parties to the treaty since it came into force in 1970 (Figure 1). Until 1992, only three nuclear-armed states were NPT members – the depository states: the Soviet Union/Russia, the United States and the United Kingdom. Following the end of the Cold War, in March 1992 China joined the NPT, trailed in August 1992 by France. Along with the five nuclear weapon states, there are today 186 non-weapon states parties to the NPT.

Five additional countries have made nuclear weapons: Israel, India, South Africa, Pakistan, and North Korea. South Africa dismantled its nuclear weapons, and in 1993 joined the NPT as a non-nuclear weapon state. The other four states – Israel, India, Pakistan, and North Korea (DPRK) – are not members of the NPT. North Korea joined the NPT in 1985 but announced its withdrawal in 2003, becoming the only country to exercise the Article X right of withdrawal from the NPT. South Sudan is the only other country currently not a member of the NPT.

Almost all member states of the United Nations are members of the NPT. Twelve countries joined the NPT even before becoming UN members.[8] Two NPT members are not members of the UN (Holy See and the State of Palestine).

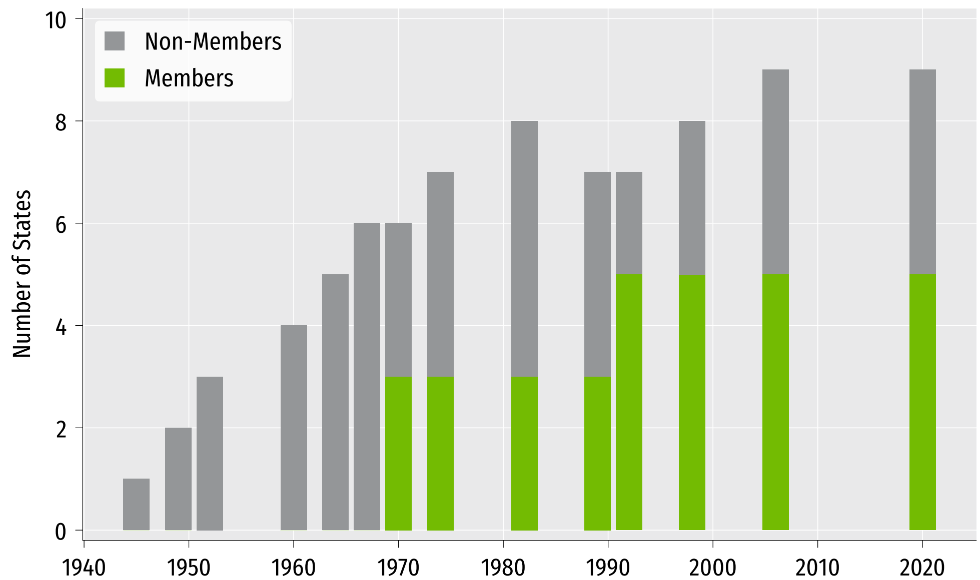

Figure 1: NPT membership of countries with nuclear weapons. The figure shows bars only for years in which numbers changed.

Under NPT Article I, weapon-states commit not to "transfer" or give "control over" nuclear weapons "directly, or indirectly" to non-weapon states, or "in any way to assist, encourage, or induce" them to get such weapons. In Article II of the NPT, non-nuclear weapon states make a reciprocal commitment not to seek to acquire or exercise control over or make nuclear weapons or seek help in doing so. Nonetheless, some nuclear weapon states have deployed nuclear weapons on the territory of non-weapon states.

As of 2021, five countries (all NPT non-weapon states) host U.S. nuclear weapons under nuclear sharing agreements: Belgium, Germany, Italy, Netherlands, Turkey. Other countries that have hosted U.S. nuclear weapons in the past include Canada, Greece, Greenland (owned by Denmark), Iceland, Japan, Morocco, Philippines, Republic of Korea, Spain, as well as Taiwan.[9]

During the Cold War, the Soviet Union deployed nuclear weapons in Cuba, the German Democratic Republic, Czechoslovakia, Hungary, and Poland.[10] In addition, it is generally assumed that nuclear weapons were deployed in the Soviet Republics: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. All are now independent states and none host nuclear weapons.

While most of the Soviet republics hosted only tactical nuclear weapons, Belarus, Kazakhstan, and Ukraine had strategic nuclear weapons on their territories as well.[11] After the breakup of the Soviet Union, these three countries became parties to the START I treaty along with Russia and the United States but transferred their nuclear weapons to Russia. This made it possible for them to join the NPT as non-nuclear weapon states while Russia became the Soviet Union's successor as the nuclear-weapon state party to the NPT. The transfer of nuclear weapons was completed in November 1996.[12] Today, Russia does not deploy nuclear weapons outside its borders.

The United States and the Soviet Union agreed in their private bilateral talks in 1966 that existing nuclear weapon sharing agreements would be permitted under a future NPT.[13] Other states have disputed the legitimacy of nuclear sharing. Mexico questioned NATO nuclear sharing at the 1995 NPT Review and Extension Conference, prompting a nuclear weapon host state (Germany) to complain that the issue of nuclear sharing within the NPT had never previously been questioned.[14] In 2015, at the NPT Review Conference, Russia for the first time argued that NPT Articles 1 and 2 "are violated during so called 'nuclear sharing'" when NATO non-nuclear weapon state forces are trained to use nuclear weapons and participate in nuclear war planning.[15] In 2019, the Non-Aligned movement, a group that includes 120 states, declared "nuclear-weapon sharing by States Parties constitutes a clear violation of non-proliferation obligations under Articles I and II of the Treaty."[16] This suggests the future status of nuclear sharing arrangements within the NPT may be uncertain.

Nuclear Weapon Stockpiles

As of 2021, nuclear weapons were believed to be present in 14 countries – the nine nuclear-armed states and the five European states hosting nuclear weapons belonging to the United States. Weapons are deployed on nuclear weapons delivery systems on land and at sea (on missiles and as bombs to be used by aircraft), and stored at military bases and central storage facilities. As nuclear weapons require refurbishment, some weapons are at weapon assembly and disassembly facilities.[17]

As of the beginning of 2021, the global nuclear weapon stockpile held an estimated 13,080 nuclear weapons.[18] The U.S. and Russia held 90 percent of these weapons. The global stockpile in 1970, when the NPT entered into force, has been estimated at about 38,200 weapons, almost three times larger than the stockpile in 2021.[19] Overall, the global inventory of nuclear warheads has been in decline, as the United States and Russia continue dismantling legacy Cold War era warheads that have been retired, with the United States in 2021 having about 2,000 warheads awaiting dismantlement.[20] The rate of dismantlement has slowed significantly since the early 1990s. Figure 2 shows the estimated historical development of the nine national nuclear weapons stockpiles.

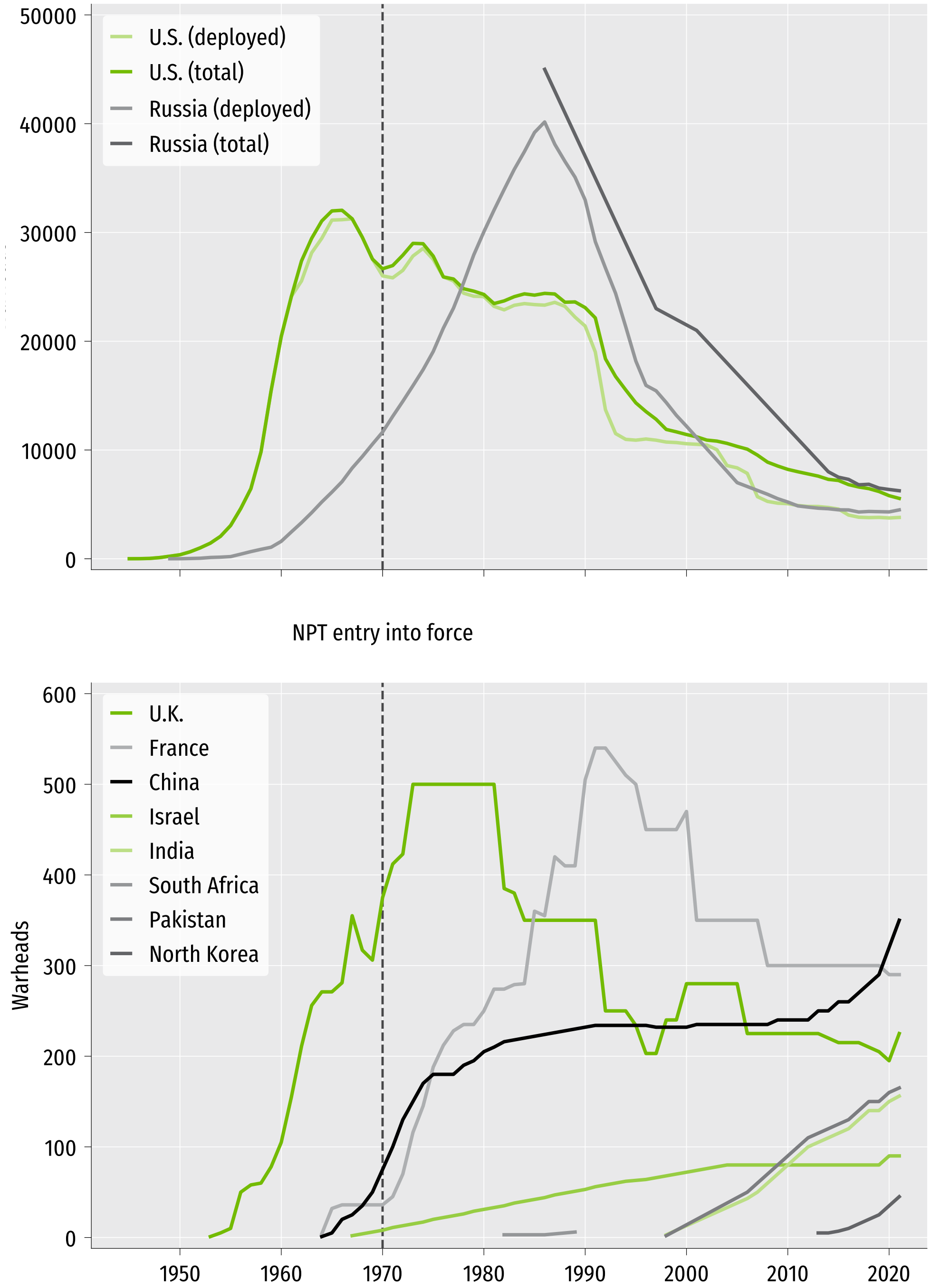

Figure 2: Estimated number of nuclear weapons over time. Data prepared based on initial figures provided by Hans Kristensen and Matt Korda, July 15, 2020. The total number of Russian weapons is estimated only from 1986 onwards.

In 2021, the United States nuclear stockpile contained about 5,550 nuclear warheads. The arsenal peaked in 1966 with more than 32,000 warheads. The production peak occurred during 1959 and 1960 when the United States produced approximately 5,000 new weapons per year. In 1970, when the NPT entered into force, the U.S. arsenal contained two-thirds of all existing nuclear weapons. After the United States joined the NPT in 1970, its arsenal continued to grow for several years. In 1974, the U.S. nuclear weapon stockpile began to decline.

Russia owned an estimated 6,255 nuclear warheads in 2021. Its stockpile (as the Soviet Union) peaked in 1986, with about 45,000 weapons. Its peak production was over 2,000 weapons per year, and came in the late 1970s-1980s, well after the Soviet Union had joined the NPT. Since the late 1980s, this stockpile has been declining.

The nuclear weapon stockpiles of the United Kingdom and France show a similar pattern. They continued to increase after the NPT entered into force in 1970 and peaked at round 500 warheads each but have since declined. France's stockpile for 2021 was estimated at about 290 warheads and the United Kingdom's at 225 weapons. China's stockpile in 2021 was estimated to be about 350 nuclear warheads and growing.

The nuclear-armed states outside the NPT have the smallest arsenals. In 2021, Israel was believed to have about 90 nuclear warheads. The arsenals of India (156 warheads) and Pakistan (165 warheads) have been increasing as they continue to develop new more capable nuclear warhead delivery systems. North Korea, with material for an estimated 40-50 warheads as of 2021, also is assumed to be building up its arsenal.

Nuclear Weapon Testing

The NPT uses nuclear testing by January 1967 as part of the treaty definition of a nuclear weapon state. In its preamble, the NPT recalls the goal "to achieve the discontinuance of all test explosions of nuclear weapons for all time."

Eight of the nine nuclear-armed states have confirmed that they have tested nuclear weapons; Israel has not.[21] It is estimated that 2,056 nuclear tests have been conducted altogether.[22] Tests have been conducted on land, in the air (atmospheric tests), in space, under water, and in underground tunnels and shafts, with varying degrees of harm to the environment and public health.

Article V of the NPT recognized "potential benefits from any peaceful applications of nuclear explosions" and sought to ensure any such benefits "be made available to non-nuclear weapon States Parties ... on a non-discriminatory basis", at modest cost and possibly on a bilateral basis. A U.S. initiative, it proved to be contentious.[23] There have been over 150 nuclear tests reported to be for peaceful purposes, most of which were carried out by the Soviet Union, with the last one in 1988.[24] Technically such peaceful nuclear explosions are not significantly different from nuclear weapon tests. Table 1 shows the total number of nuclear tests conducted by decade since the 1940s.

Nuclear weapon tests have been conducted within some weapon state national territories as well as at sites elsewhere in the world. The majority of U.S. tests took place on American soil, but the United States conducted more than 60 tests in the Marshall Islands in the Pacific.[25] The main Soviet test site was in Semipalatinsk, in today's Kazakhstan. Some tests were conducted on the Novaya Zemlya archipelago and at the Totsk test site in the Ural Mountains.[26] The U.K. tested initially on Australian islands, later on islands part of Kiribati and finally in the United States. No British tests were conducted in mainland Britain.[27] France tested nuclear weapons in Algeria and French Polynesia. No French tests were conducted in mainland France.[28] China tested its weapons on Chinese soil close to the borders of Mongolia and Kazakhstan.[29] India, Pakistan and North Korea have conducted all their tests in country. Israel is believed to have conducted a nuclear test in the atmosphere in the southern Atlantic in 1979.[30]

The United States, Russia and the U.K. ended testing in 1992. France and China joined the moratorium in 1995 and 1996 respectively. The Comprehensive Test-Ban Treaty (CTBT) opened for signature in 1996. By establishing an obligation “not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control” the CTBT recognized that there was no longer support for peaceful nuclear testing or its possible benefits as imagined in NPT Article V. The CTBT has yet to enter into force.

Today, NPT nuclear weapon states continue nuclear-weapon sustainment, modernization, design, and development, without explosive nuclear weapon tests. They do hydrodynamic and subcritical tests, which are understood to be permissible under the CTBT. In addition, a significant amount of effort is put into computer simulations of nuclear weapon detonations and explosions. India, Pakistan, and North Korea have carried out explosive nuclear weapon tests, the last test was by North Korea in 2017.

Decade	Nuclear Weapon Tests
1945-1949	7
1950-1959	291
1960-1969	706
1970-1979	550
1980-1989	439
1990-1999	57
2000-2009	2
2010-2020	4

Table 1: Nuclear weapon tests per decade.

Nuclear-Weapon-Free Zones

Article VII of the NPT supports the establishment of regional nuclear-weapon-free zones by recognizing “the right of any group of States to conclude regional treaties in order to assure the total absence of nuclear weapons in their respective territories.”

The idea of a nuclear-weapon-free zone emerged with a Soviet proposal in 1956 to the United Nations to prohibit nuclear weapons 'in the territory of both parts of Germany' and neighboring states, and a subsequent initiative in 1957 by Poland at the United Nations General Assembly to establish a Central European zone free of nuclear weapons that would cover both parts of Germany, Czechoslovakia and Poland.[31] In 1961, in response to French nuclear testing in the Sahara Desert, the United Nations General Assembly adopted a resolution calling for respecting Africa as a denuclearized zone and refraining from testing, stationing, storing or transporting nuclear weapons on Africa territory.[32] In the same year, Brazil proposed the creation of a Latin American zone free of nuclear weapons.

In 1967 several states agreed a regional treaty to form what became the Latin America and the Caribbean nuclear-weapon-free zone (NWFZ). Other regions followed (Figure 3) with nuclear-weapon-free zones in the South Pacific (1985), South East Asia (1995), Africa (1996) and Central Asia (2006). The treaties differ in specifics, but in general prohibit member states from owning or hosting nuclear weapons. The NWFZs in the Antarctic, Latin America, South Pacific and South East Asia include significant maritime regions. The other zones cover only coastal waters.

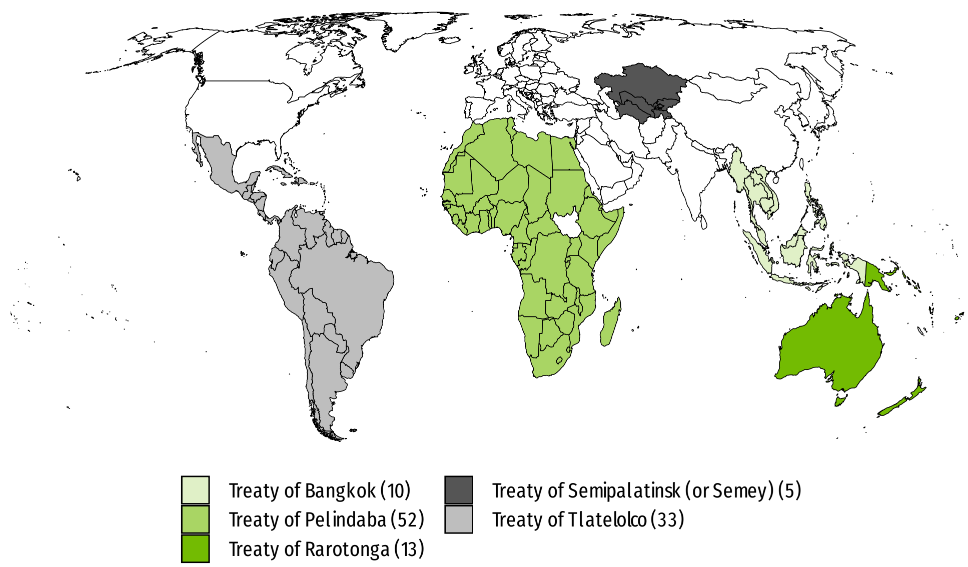

Figure 3: Nuclear-weapon-free zone coverage of the Earth.

The United Nations General Assembly in 1974 agreed on the goal of the establishing a Middle East NWFZ, following a proposal by Iran and Egypt. In 1995, as part of the package that supported the indefinite extension of the NPT, the NPT Review Conference called on all parties "to exert their utmost efforts with a view to ensuring the early establishment by regional parties of a Middle East zone free of nuclear and all other weapons of mass destruction and their delivery systems."[33] There was limited progress, however. In December 2018, the United Nations General Assembly agreed to hold an annual conference for "elaborating a legally binding treaty establishing a Middle East zone free of nuclear weapons and other weapons of mass destruction." The first of these conferences was held in 2019, with 23 states from the region and four observer states (Britain, China, France, and Russia). The United States did not attend. Israel, not a party to the NPT, also did not attend.

Arms Control and Disarmament

The NPT's Article VI obligation for "each Party to the Treaty" includes negotiations on "effective measures to end the nuclear arms race at an early date and to nuclear disarmament". In 1996 the International Court of Justice issued a unanimous advisory opinion that under the NPT, nuclear-weapon states have "an obligation to pursue in good faith and bring to a conclusion negotiations leading to nuclear disarmament in all its aspects."[34]

Since 1970, there have been a number of formally negotiated arms control agreements to set limits on the number and type of nuclear weapon delivery systems (missiles and bombers) and on warhead numbers. These have addressed only U.S. and Soviet/Russian nuclear weapons. Agreed in 2010, the most recent U.S.-Russia arms control treaty, New START, was extended for five years in 2021 after the United States and Russia failed to agree a follow-on treaty and just before it expired. Table 2 shows the limits under the six major agreements since 1970.

In parallel to nuclear weapons limitation agreements, the U.S. and Russia negotiated the Anti-Ballistic Missile (ABM) Treaty, which limited anti-ballistic missile defenses. The aim was to reduce a possible driver of an offense-defense arms race that would create incentives to build additional or different kinds of nuclear weapons. The ABM Treaty remained in force until 2002, when the United States withdrew, becoming the first country to withdraw from a nuclear arms control treaty. Keeping the ABM treaty in force was a recurring part of NPT Review Conference decisions, including the 2000 Review Conference.

These arms control treaties did not achieve the goal of ending the nuclear arms race, since the U.S. and Russia, like the other NPT nuclear weapon states, have extensive programs for modernizing their nuclear arsenals.[35]

Treaty	Date		Numerical Limit on Deployed Warheads[36]
	Entry into Force	Implementation	
SALT I	1972	-	No stockpile increase
INF Treaty	1988	1991	0
PNI	1991	2001	No specific limit
START	1994	2001	6000
SORT	2003	2011	2200
New START	2011	2018	1550

Table 2: Warhead limits in major U.S.-Russia nuclear arms control agreements, including deployed warheads at implementation date.

The United Kingdom, France, and China have not participated in negotiations on measures to cap or reduce their nuclear arsenals. Any arsenal reductions they have undertaken or limits they have set have been unilateral national measures. In 1994, China proposed to the other four NPT nuclear-weapon states a draft treaty on the no first use of nuclear weapons.[37] It received no support. China and Russia agreed on a bilateral no first use commitment.

One proposed arms control measure that has featured often at NPT review conferences has been the negotiation of a Fissile Material Cutoff Treaty (FMCT) to ban production of plutonium and HEU and possibly other fissile materials for weapons. This treaty was one of the measures agreed in the "Principles and Objectives for Nuclear Non-Proliferation and Disarmament" accepted by all NPT parties in the 1995 Review Conference package of decisions allowing the indefinite extension of the treaty.[38] The United Nations General Assembly in 1993, in a consensus decision, agreed to Resolution 48/75L recommending negotiation of a "non-discriminatory, multilateral, and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other explosive devices." Despite the commitments made at the 1995 NPT Review and Extension Conference, and agreement at the United Nations Conference on Disarmament in 1995 on a negotiating mandate, there have yet to be substantive negotiations towards an FMCT.[39]

NPT non-weapon states have sought to advance nuclear disarmament measures as a way to meet their Article VI obligations, and respond to the lack of progress by the nuclear weapon states. The New Agenda Coalition, comprising Brazil, Egypt, Ireland, Mexico, New Zealand, South Africa, and Sweden, proposed a series of 13 "practical steps for the systematic and progressive efforts to implement article VI" that were adopted at the 2000 NPT Review Conference.[40]

The 2010 NPT Review Conference in its consensus Final Document expressed "deep concern at the catastrophic humanitarian consequences of any use of nuclear weapons and reaffirms the need for all States at all times to comply with applicable international law, including international humanitarian law."[41] This was followed by a series of international Conferences on the Humanitarian Impact of Nuclear Weapons, organized by Norway (2013), Mexico (2014) and Austria (2014). The 2014 conference generated a Humanitarian Pledge, supported by 127 countries, "to cooperate ... in efforts to stigmatise, prohibit and eliminate nuclear weapons in light of their unacceptable humanitarian consequences and associated risks."[42]

In 2016, the United Nations General Assembly agreed resolution 71/258 "to convene in 2017 a United Nations conference to negotiate a legally binding instrument to prohibit nuclear weapons, leading towards their total elimination."[43] A United Nations negotiating conference was established, and on 7 July 2017, with support from 122 countries, it adopted the Treaty on the Prohibition of Nuclear Weapons.[44] The treaty entered into force in January 2021 after it had been ratified by 50 countries.

Fissile Materials and the NPT

Central to the NPT approach to preventing the proliferation of nuclear weapon states is control of the production, transfer, and use of fissile materials, in practice separated plutonium and HEU, the key ingredients in nuclear weapons (see the Appendix to this report). This approach is codified in Article III of the treaty, which imposes restrictions "on all source or special fissionable material in all peaceful nuclear activities" in non-weapon states and a system of safeguards to be managed by the International Atomic Energy Agency (IAEA).

While Article III requires IAEA safeguards, the details of such a system were left to be worked out after the NPT entered into force. The IAEA Board of Governors set up a special committee to draw up a safeguards system for the NPT and in 1972 agreed what became the basis for the Comprehensive Safeguards Agreements (INFCIRC/153) for non-weapon states to cover all declared fissile materials and declared production facilities.[45] This system, with significant modifications, also provided the basis for the more limited Voluntary Offer Agreements on safeguards accepted by the United States and United Kingdom in 1976, France in 1978, the Soviet Union in 1985 and China in 1988.[46] These voluntary offer agreements apply to certain civilian facilities or materials and the IAEA has chosen to inspect only a small number of the facilities and stocks offered by the weapon states. Fissile materials in nuclear weapon complexes and related programs are excluded, as are fissile material used for other purposes such as fueling naval propulsion reactors.

Most of the global stockpile of fissile material is in the possession of the NPT nuclear weapon states. All these states produced fissile material before the NPT entered into force in 1970 for use in weapons. For the United States, the United Kingdom and the Soviet Union, NPT membership had little impact on their production of fissile material for weapons and naval propulsion reactors. The three countries continued production until after the end of the Cold War. China and France ended their production of fissile materials for weapons after they joined the NPT during the decade after the Cold War. The nuclear weapon states not parties to the NPT, Israel, Pakistan, India, and North Korea, continue to produce fissile materials for weapon purposes.

Plutonium

The global stockpile of military plutonium as of 2021 is estimated to be 140 ± 10 tons (Figure 4). This does not include material produced in weapon programs that was subsequently declared excess to weapon purposes.

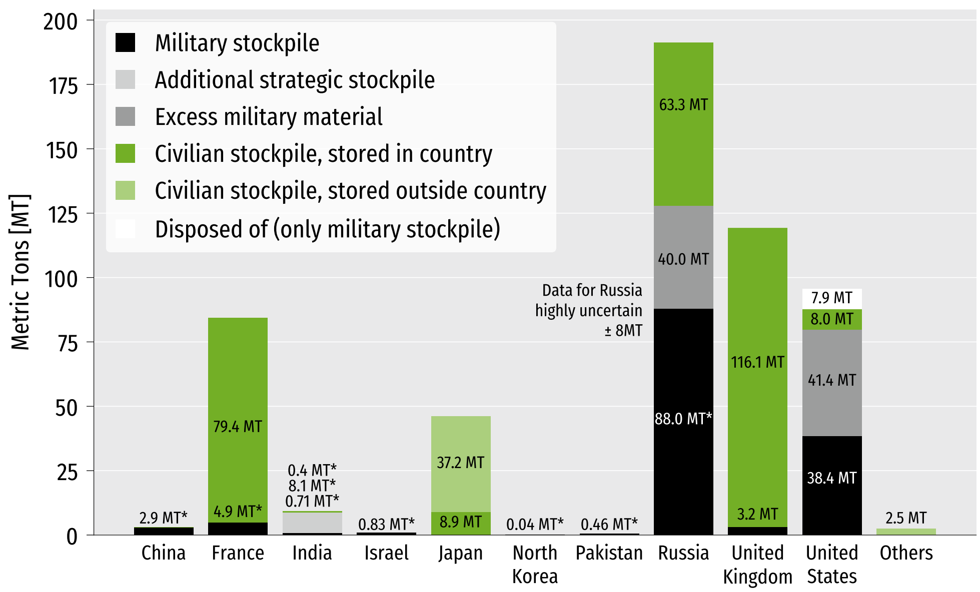

Figure 4: National stocks of separated plutonium as of the end of 2020. Military stocks are based on IPFM estimates except for the United States and United Kingdom whose governments have made declarations. Uncertainties in estimated military stockpiles for China, France, India, Israel, Pakistan, and Russia are on the order of 10 – 30 percent. Civilian stocks are based on the INFCIRC/549 declarations published in 2021, which report material as of 31 December 2020, except for China, which has not updated its report since the end of 2016.

The Soviet Union, United Kingdom and United States continued plutonium production for weapons for about two decades after becoming members of the NPT (Figure 5). France and China ended production about the time they became NPT members. The U.K. and Russia were the last of the NPT weapon states to end production of plutonium for weapons. India, Israel, Pakistan, and North Korea are believed to be continuing production of plutonium for weapons.

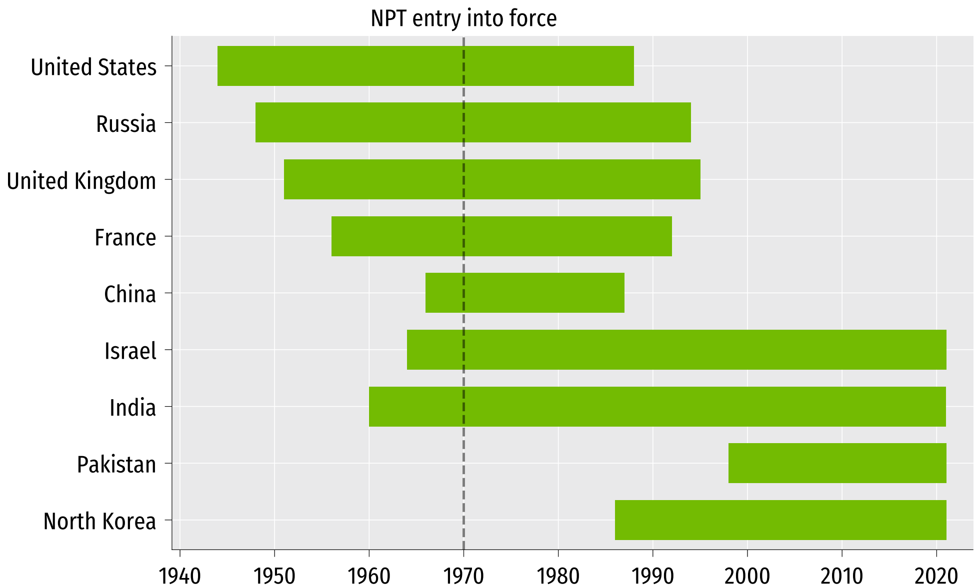

Figure 5: Periods of plutonium production for weapons by country.

The global rate of production and separation of plutonium for weapon purposes peaked prior to the entry into force of the NPT (Figure 6). The stockpile of plutonium produced for weapon purposes by the Soviet Union/Russia and the United States peaked in the 1990s at 230 tons, including military plutonium declared excess for weapon purposes. As can be seen in Figure 6, most reductions in weapon plutonium stocks have been declaratory, a change of designation rather than the result of physical disposition.

As of 2021, the United States and Russian stocks of separated plutonium included 89.4 tons declared as material in excess of military requirements. With the end of the Cold War, the United States and Russia reduced their warhead stocks and, in 2000, Russia and the United States agreed on a bilateral Plutonium Management and Disposition Agreement (PMDA) that committed each to verifiably dispose of at least 34 tons of plutonium from nuclear weapon programs, with IAEA monitoring. After the two countries failed to make progress on disposition, the agreement was amended in 2010, and then suspended by Russia in 2016.

Comparing military plutonium stockpiles to the amount required to support the existing number of warheads, Russia and the United States could declare much more plutonium excess. Current weapon plutonium stockpiles would be sufficient to produce about three times as many nuclear weapons as countries possess.

Figure 6 shows global plutonium stockpile evolution, and that no significant physical reductions in stocks of weapons plutonium have taken place in the 50 years since the NPT came into force. The United States has discarded 7.9 tons of plutonium in various forms in waste. Also, an estimated 8.6 tons of plutonium were used in nuclear weapon tests.

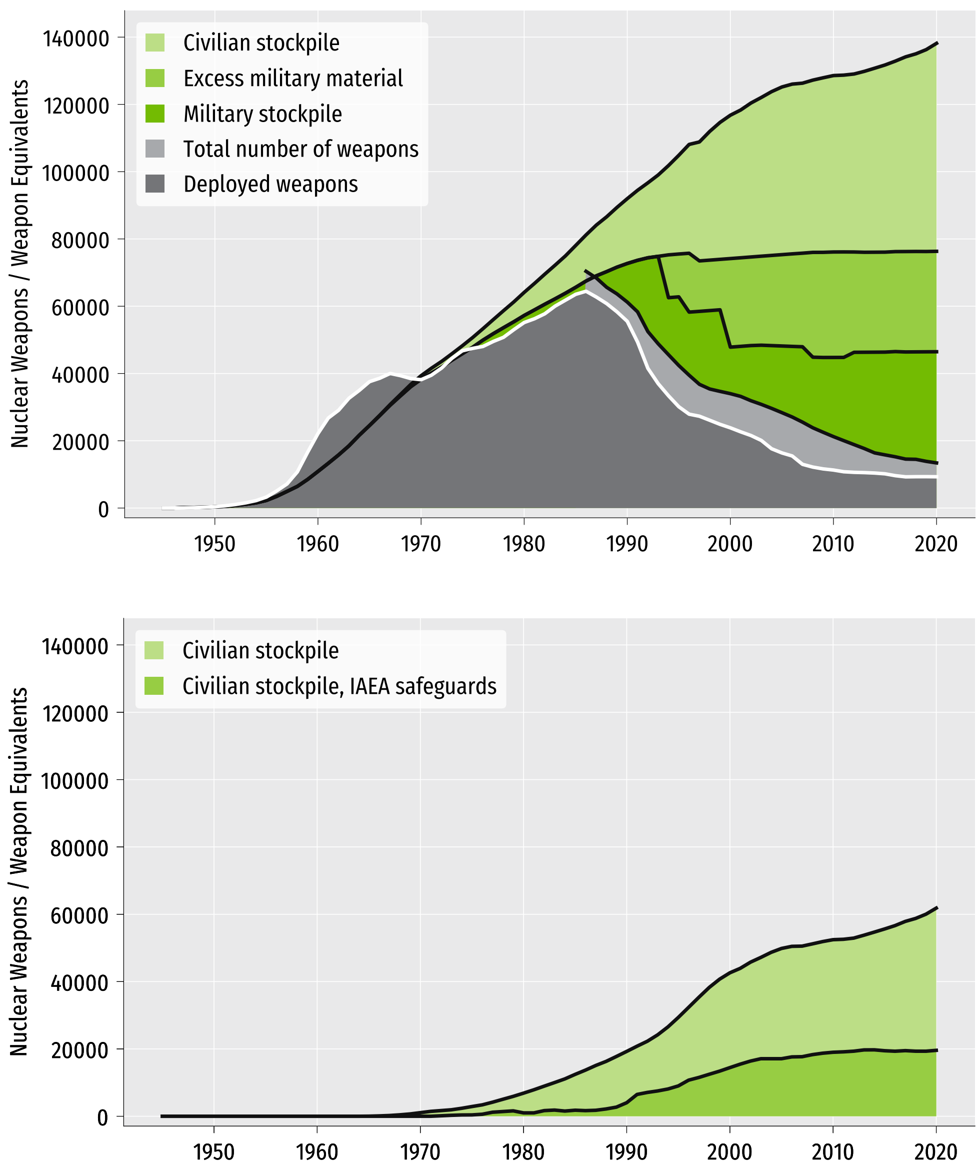

Figure 6: Growth of global plutonium stockpiles, 1945 – 2020. The global stock of separated plutonium has not dropped since the end of the Cold War. Indeed, the startup of several large civilian reprocessing plants since the 1980s has led to a continuous increase in the global stock. During the same period, essentially no disposition of excess military plutonium occurred. As of the end of 2020, the total global stock of separated plutonium corresponds to about 140,000 weapon-equivalents. Weapon equivalents are assumed to be 3 kg of military (weapon-grade) plutonium and 5 kg of civilian (reactor-grade) plutonium. The total number of Russian weapons is estimated only from 1986 onwards. The bottom figure shows the total civilian stock and the portion reported by the IAEA as under safeguards.

The global stock of separated civilian plutonium was 317 tons as of 2021 (Figure 4). Significant civilian plutonium separation started only after the NPT entered into force. The largest civilian stocks of separated plutonium are owned by the United Kingdom, France, and Russia. Among the non-weapon states, only Japan has a significant stock.

Civilian separated plutonium stockpiles continue to grow. The buildup will slow in the near future, however, due to the end of the United Kingdom's reprocessing operation.[48] The global stockpile could increase much more quickly if Japan begins to operate its Rokkasho reprocessing plant[49]. Japan currently has a publicly stated policy not to increase its stocks of separated plutonium.[50]

As a transparency measure, since 1996 nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and United States) have annually declared stocks of civilian plutonium to the IAEA (INFCIRC/549).[51] China stopped reporting after 2016 and Russia does not include its excess weapons plutonium in its declaration, while the U.S. does. Countries also declare stocks of separated plutonium at reprocessing plants, fuel fabrication plants, reactors, and elsewhere, and in spent fuel.

All plutonium in NPT non-weapon states is under IAEA safeguards. For the end of 2020, the Agency reported safeguards covered 12,237 "significant quantities" (for plutonium, this is set as 8 kg) or 99.8 tons of separated plutonium outside of reactors: of which about 10 tons were in non-weapon states – presumably almost all in Japan – and the remainder was due to voluntary offers by weapon states – mostly France and the U.K. This is about one third of existing global separated civilian plutonium.

The largest military reprocessing facilities were in the U.S. and Soviet Union, built long before NPT entry into force. India, Pakistan, North Korea built their facilities later and China built its facilities after entry into force but before becoming an NPT member state. Most civilian facilities became operational after the NPT was negotiated.

Ten countries have operated civilian reprocessing plants: Belgium, China, France, Germany, India, Italy, Japan, Russia, United Kingdom and the United States (Appendix 1.1). In addition, eleven countries that did not operate domestic fuel cycle facilities sent some spent fuel abroad for reprocessing. These countries include Switzerland, Sweden, Spain, the Netherlands, Armenia, Bulgaria, Finland, Hungary, Ukraine and the former states of Czechoslovakia and East Germany. Belgium, Germany, and Italy, countries with domestic plants, also shipped fuel abroad for reprocessing after domestic operations ceased.

Highly Enriched Uranium

The current global inventory of HEU is estimated to be about 1,335 ± 125 tons. Nearly 99 percent of this material is held by the nuclear weapon states, and most belongs to Russia and the United States. This includes military HEU held by the nuclear weapon states and civilian HEU held both by the weapon states and non-weapon states (Figure 7).

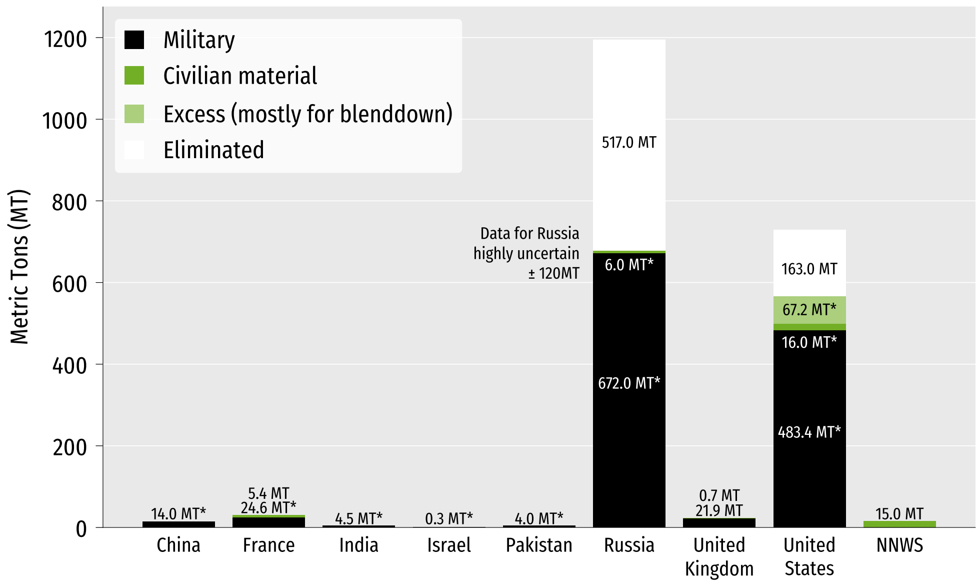

Figure 7: National stocks of highly enriched uranium as of the end of 2020. The numbers for the United Kingdom and United States are based on official publications and statements. The civilian HEU stocks of France and the United Kingdom are based on their public declarations to the IAEA. Numbers with asterisks are IPFM estimates, often with large uncertainties. A 20 percent uncertainty is assumed in the figures for total stocks in China and for the military stockpile in France, about 30 percent for Pakistan, and about 40 percent for India. A revised IPFM estimate suggests France may only have 10 tons of military material (see chapter on France). The 517 tons of eliminated Russian HEU include 500 tons from its "megatons to megawatts" deal with the United States and 17 tons from the U.S. Material Consolidation and Conversion program. HEU in non-nuclear weapon (NNW) states is under IAEA safeguards. About 10 tons of the HEU in non-nuclear weapon states is irradiated fuel in Kazakhstan with an estimated enrichment of about 20 percent.

The uncertainty in this estimate, at least 120 tons, is larger than the combined HEU stockpiles of all the states other than Russia and the United States. It is due mostly to a lack of accurate public information about Russian HEU production and consumption (for details, see Global Fissile Material Report 2010).

The United States and United Kingdom have declared the sizes of their total HEU stockpiles (as of 1996 and 2004 for the United States, and as of 2002 for the United Kingdom). The U.K. and France declare their respective civilian HEU stocks annually. The other nuclear weapon states release no information on their HEU holdings.

Beginning in the 1970s, there has been an effort to address proliferation risks from HEU fuel for research reactors. Civilian stocks of HEU total roughly 42 tons, less than four percent of the global total stock. The largest civilian stock is held by the United States. Non-weapon states hold about 15 tons provided to them as civilian research reactor fuel. South Africa's

HEU is a legacy of its nuclear-weapon program, which ended in 1990. All the HEU in non-weapon states, including South Africa, is declared to and monitored by the IAEA.

A series of four Nuclear Security Summits, in the United States in 2010 and 2016, South Korea in 2012, and the Netherlands in 2014, sought to encourage efforts to minimize HEU use with a special focus on conversion of research reactors and targets for the production of medical radioisotopes from HEU to low enriched uranium (LEU) fuel and repatriation of spent and unused HEU fuel from research reactors in non-weapon states. Most of this HEU had been supplied by the United States and Soviet Union (Russia). Naval reactors were not covered. Naval propulsion accounts for the largest number of HEU-fueled reactors worldwide and the largest annual use of HEU as fuel.[52] The United States, Russia, the United Kingdom and India fuel their naval propulsion reactors with HEU.

The United States began the production of HEU in 1944 as part of the Manhattan Project (Figure 8). Most of its World War II HEU production was used on 6 August 1945 in the Hiroshima bomb. Since then, the Soviet Union, United Kingdom, France, China, South Africa, Pakistan and potentially North Korea have all produced HEU for weapons. It is not clear whether Israel has produced HEU for weapons.

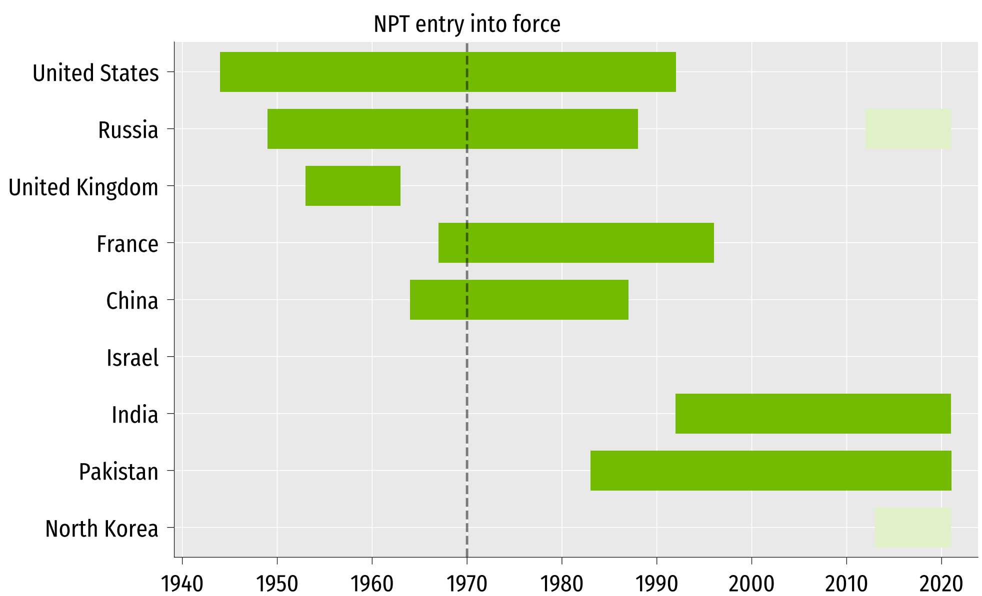

Figure 8: HEU production histories in states possessing nuclear weapons today. Along with use in nuclear warheads, HEU also is used in naval and research reactor fuel. In 2012, Russia announced it was resuming HEU production on a small scale for civilian reactor fuel (light green). This may reflect the fact that Russia's excess weapons HEU contains levels of reactor-produced Uranium-236 that are unacceptable for its foreign customers (China and Germany). North Korea has operated a uranium enrichment facility since 2013 but it is unclear whether it produces HEU (light green).

Although the United States and Russia continued to enrich HEU after the NPT entered into force, this was mostly for naval reactor fuel. France and China continued uranium enrichment for military HEU after 1970, however they only became NPT member states in 1992. Around that time, both countries ended military HEU production. It is believed that both China and France fuel their naval reactors with LEU fuel.

Pakistan and India are currently producing HEU. North Korea in 2010 disclosed a uranium enrichment centrifuge plant, but it is not known whether this plant and a possible second enrichment plant, are currently producing HEU.

The global stock of HEU peaked shortly before the end of the Cold War (Figure 9). After 1990, both the United States and Russia set in motion programs to eliminate significant amounts of HEU, mostly by mixing it with natural and slightly-enriched uranium to produce low-enriched uranium to fuel power reactors. Down-blending in Russia was supported by the United States through purchase of low-enriched uranium from the downblending of 500 tons of HEU to be used in civilian power reactor fuel and financial support for down-blending an additional 17 tons from civilian facilities. To date, 680 tons of HEU have been eliminated. In recent years, reduction activities have stalled, however, and Russia has even produced new HEU for foreign customers.

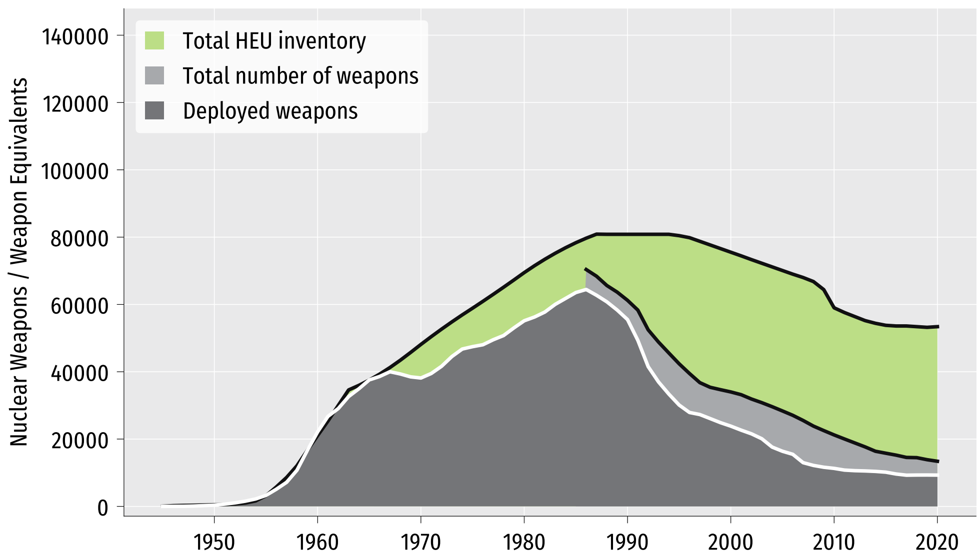

Figure 9: Global inventory of weapon-grade highly enriched uranium 1945 – 2020 in weapon-equivalents. A significant fraction of the global HEU inventory has been eliminated since the end of the Cold War. This includes 500 tons of Russian HEU that have been down-blended to low-enriched uranium and used to fuel U.S. power reactors. As of 2021, the estimated global HEU stock is sufficient for about 55,000 nuclear weapons more than three times the estimated 16,000 in the nuclear arsenals. A large fraction of the overhang is reserved for future use in naval reactor fuel. The figure assumes an average of 25 kg of HEU per warhead; less material is sufficient to make a nuclear weapon, but this figure has been used by the Megatons-to-Megawatt program. Advanced nuclear weapon states use HEU primarily in the second stage of thermonuclear weapons; fissioning about half of the uranium assumed per warhead (12.5 kg) would release an explosive yield equivalent to that of about 250,000 tons of TNT chemical explosive. The total number of Russian weapons is estimated only from 1986 onwards.

Fourteen countries built enrichment facilities (Appendix 1.2). With the exception of Argentina, all continue to enrich uranium. This is true even for Germany, which will phase-out all nuclear energy production in 2022. Its domestic enrichment facility, which is owned by URENCO, a German-Netherlands-U.K. controlled multinational, currently has an operating license of unlimited duration. Iran is currently the only non-weapon state to produce HEU.[53]

APPENDIX

Appendix 1.1: Reprocessing Plants

Major civilian and military reprocessing plants in the world.[54] The table includes operating and shutdown facilities.

Country	Plant	Military/civilian	Design Capacity (tons HM/year)	Years of Operation
Belgium	Eurochemic	Civilian	30	1966-75
China	Jiuquan pilot plant	Civilian	50	2010-
	Jiuquan intermediate pilot plant	Military	100	1968-1970
	Jiuquan reprocessing plant	Military	250-300	1970-1987
	Guangyuan reprocessing plant	Military	250-350	1976-1987
France	UP1	Military	400	1958-97
	UP2	Civilian (formerly Dual-Use)	1000	1966-
	UP3	Civilian	1000	1989-
Germany	WAK	Civilian	35	1971-90
India	Tarapur I	Dual-Use	100	1982-
	Tarapur II	Dual-Use	100	2011-
	Kalpakkam	Dual-Use	100	1996-
	Trombay	Military	50	
Israel	Dimona	Military	40-100	
Italy	EUREX	Civilian	40	1970-83
	ITREC	Civilian	5	1975-1978
Japan	Tokai	Civilian	200	1977-2014
	Rokkasho	Civilian	800	2006-8, 2022?
North Korea	Yongbyon	Military	100-150	
Pakistan	Chasma	Military	50-100	2015-
	Nilore	Military	20-40	2000-
Soviet Union/Russia	RT1	Civilian	400	1976-
	EDC, Zheleznogorsk	Civilian	250	Starting up
	Zheleznogorsk	Military	3500	1958-2010
	Seversk	Military	6000	1955-2013
	Mayak Plant B	Military		1948-1960
	Mayak Plant BB	Military		1959-1987
United Kingdom	B204	Civilian	300	1952-1973
	B205	Civilian	1500	1964-2022
	THORP	Civilian	1200	1994-2018
United States	Savannah River Site, H-Canyon	Civilian (was military)	15 (was 2400)	1954, civilian operation ongoing
	Savannah River Plant, F-Canyon	Military	1600	1954-2002
	Hanford, T-Plant	Military	550	1944-1956
	Hanford, B-Plant	Military	550	1945-1957
	Hanford, REDOX	Military	4400	1952-1967
	Hanford, PUREX	Military	4800	1956-1972 1983-1988
	Idaho Chemical Processing Plant	Military		1953-1992
	West Valley	Civilian	300	1966-72

Appendix 1.2: Enrichment Plants

Major civilian and military enrichment plants in the world. The table includes operating and shutdown facilities.

Country	Facility	Civilian/Military	Enrichment Process	Capacity (kSWU/yr)	Operational Status
Argentina	Pilcaniyeu	Civilian	GD	20	2015-
Brazil	Resende	Civilian	GC	35	2006-
China	Lanzhou	Civilian (was military)	GC	2600	1964-1980 (military) 1980-2000 (civilian)
	Hanzhong (Shaanxi)	Civilian	GC	2000	1990s-
	Emeishan	Civilian	GC	1060	2013-
	Heping	Dual-Use	GD	230	1970-
France	Pierrelatte	Military	GD	100-300	1964-1996
	Georges Besse I		GD	10800	1979-2012
	Georges Besse II	Civilian	GC	7500	2011-
Germany	URENCO Gronau	Civilian	GC	3900	1985-
India	Rattehalli	Military	GC	15-30	1990-
Iran	Natanz	Civilian	GC	3.5-8	2002-
	Qom (Fordow)	Civilian	GC	..	2011-
Japan	Rokkasho	Civilian	GC	75	1992-
Netherlands	URENCO Almelo	Civilian	GC	5200	1973-
North Korea	Yongbyon	Uncertain	GC	8	2013-
Pakistan	Gadwal	Military	GC	..	
	Kahuta	Military	GC	15-45	1980-
Russia	Angarsk	Civilian (was military)	GC (was GD)	4000	1957-
	Novouralsk	Civilian (was military)	GC (was GD)	13 300	1949-
	Seversk	Civilian (was military)	GC (was GD)	3 800	1953-
	Zelenogorsk	Civilian (was military)	GC (was GD)	7900	1962-
U.K.	Capenhurst	Civilian	GC	4600	1973-
	Capenhurst	Military	GD	400	1954-1982
USA	URENCO Eunice	Civilian	GC	4900	2010-
	Oak Ridge		GD	8500 peak	1945-1985
	Paducah		GD	11300	1954-2013
	Portsmouth		GD	7400	1956-2001
	K-25	Military	GD		1945-1985
	K-27	Military	GD		1946-1985
	K-29	Military	GD		1951-1985
	K-31	Military	GD		1951-1985
	K-33	Military	GD		1955-1985

Nuclear Energy and the NPT

Visions of a nuclear-powered future date back to the beginning of the atomic age. The first nuclear power reactor to supply electricity to a national grid was in Obninsk in the Soviet Union, which started only six months after President Eisenhower's "Atoms for Peace" speech at the UN General Assembly in December 1953. The subsequent growth in nuclear energy capacity and capabilities did result in some countries using their ostensibly civil nuclear energy program to further their quest to acquire nuclear weapons capacity.

It was recognized that states could, should they decide to do so, use civilian nuclear energy programs to achieve a latent nuclear weapon capability; some countries were even designated virtual nuclear weapon states.

The promise of nuclear energy is a fundamental feature of the NPT, especially through Article IV. The second part of that article includes the commitment to "the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty, with due consideration for the needs of the developing areas of the world." This was in keeping with the expectation that nuclear power would expand significantly and provide cheap electricity for economic development in poorer countries.

One lesson from the past seven decades of commercial nuclear energy, however, is that nuclear electricity is expensive and is not seen by most developing countries as an aid to development.

Soon after the NPT entered into force in 1970, projections for nuclear power started growing. David Fischer recalls in his *History of the International Atomic Energy Agency*:

> "The 1970s showed that the NPT would be accepted by almost all of the key industrial countries and by the vast majority of developing countries. At the same time the prospects for nuclear power improved dramatically. The technology had matured and was commercially available, and the oil crisis of 1973 enhanced the attraction of the nuclear energy option. (...) The 1970s also saw a sudden upturn in the prospects for nuclear power characterized by a stream of orders for nuclear power plants, first in North America, then in Europe and then, more tentatively, in the developing world."[55]

The strong belief in the rapid global expansion of nuclear power also resulted in a number of countries (including Belgium, France, Germany, Italy, Japan, the Netherlands, Russia, the U.K., and the U.S.) launching significant investments into commercial spent fuel reprocessing and fast breeder reactors. The dream of a machine that could produce more fuel – plutonium – than it consumed (namely a "breeder reactor") was particularly captivating, but the experiences of building these in many different countries has shown that the assumptions driving the pursuit of breeder reactors have proven to be wrong.[56]

During the 1970s, projections by international agencies envisioned rapid expansions of nuclear power. The 1974 IAEA projection envisaged up to 5,300 GW of installed nuclear capacity for the year 2000, with a "most likely" scenario of 3,600 GW. The OECD was similarly optimistic. Both international organizations were off by more than one order of magnitude, as nuclear power grew much more modestly.

In contrast to projections, only 350 GW were installed and operating by 2000 (see Figure 10). That number has hardly moved over the past two decades with 366 GW operating by 2020.

The slowdown in the growth of nuclear power has affected the growth of uranium enrichment and reprocessing around the world, arguably the most important elements in the acquisition of nuclear weapons or latent capabilities. In his history of the Nuclear Non-Proliferation Treaty written in the 1970s, Mohammed Shaker points out:

> "Uranium enrichment is currently taking place only in the five nuclear-weapon States, and is so far being jointly developed by only three European States, i.e., the FRG, the Netherlands, and the UK, whereas plutonium production is widespread all over the world, wherever there is a nuclear-power plant or a nuclear-research reactor. As Pu-239 chemical separation from the spent fuel of a reactor has become a widely known technology and a financially feasible operation for many countries, its control is the most immediate goal of any non-proliferation scheme. By 1980, the total annual production of plutonium is expected to reach the figure of about 130 tons, one-third of which would be produced in non-nuclear [weapon] states."[57]

Had the envisioned growth of nuclear power occurred, the spread and availability of separated plutonium would be far greater than is the case today.

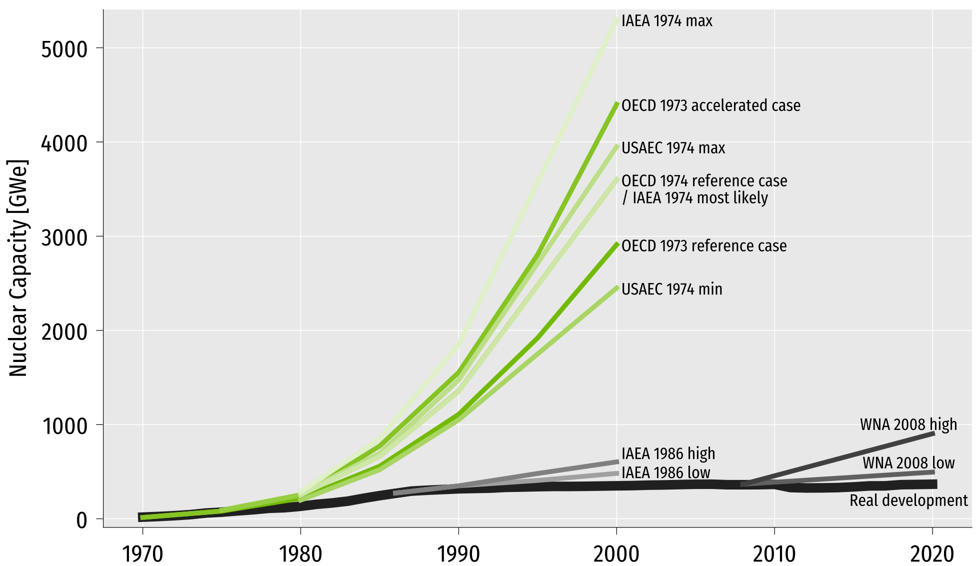

Figure 10. Operating nuclear capacity projections by U.S. and international organizations. Early projections covered time frames until 2000, later projections and development until 2020 shown for comparison.[58]

Nuclear Reactor Construction

Construction of nuclear reactors has not proceeded uniformly and most of the reactors operating around the world were constructed before the 1990s. The number of annual construction starts peaked as early as 1976 (see Figure 11).[59]

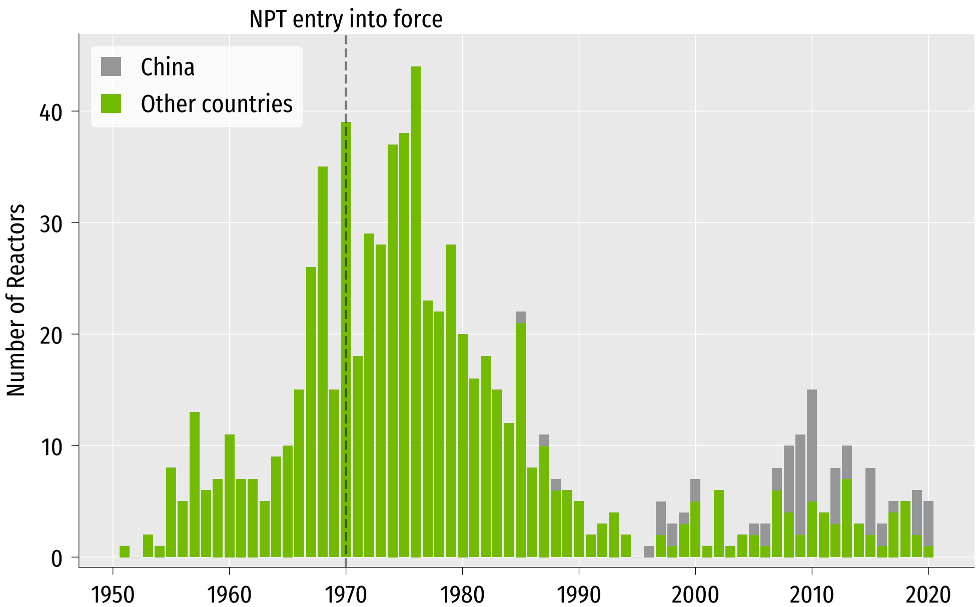

Figure 11. Construction starts of commercial nuclear reactors in the world 1951–2020.[60]

In 1995, the year of the NPT Review and Extension Conference, for the first time since 1952, no nuclear construction project was launched anywhere in the world. Until the second half of the 2000s, when China started its new-build program, the number of construction starts was negligible. But even China has not accelerated its nuclear reactor construction program in the manner that was envisioned.

In 2011, China's decision-makers, responding to the nuclear disaster at Fukushima in Japan, froze authorizations for new constructions. Construction starts went from 10 in 2010 – out of 15 worldwide – to zero in 2011. Seven units got underway in 2012 and 2013 under pre-existing licenses. None in 2011, 2014, and 2018. It was only in 2015 that new construction licenses were given out, but the overall program had been downsized dramatically. With 47.5 GW operating as of the end of 2020 and 15.7 GW under construction, China missed its 5-Year-Plan targets for 2020 that had planned for 58 GW operating and 30 GW under construction.

The cumulated number of reactors listed as "under construction" peaked in 1979 with 234 units, of which 48 were never connected to the grid. Over 250 reactor orders were cancelled around the world since the 1970s and at least 93 construction projects – about one in eight – were abandoned at some point, from early stages of advancement to completed building. The reasons to abandon projects included economics (by far the dominant reason, as numerous utilities got into serious financial difficulties or even went bankrupt over cost-escalating nuclear projects, especially in the United States), safety concerns (e.g. in Germany) or public pressure (e.g. in Austria).

Figure 12 illustrates the spread of nuclear power throughout the world took place at a significantly slower pace and smaller scope than anticipated in the 1970s:

- Fourteen countries had operating nuclear power reactors (grid connected) when the NPT entered into force in 1970.

- Sixteen additional countries operated power reactors by 1985.

- Six additional countries (Mexico, China, Romania, Iran, UAE, Belarus) started up power reactors over the past 30 years.

- The number of countries operating power reactors in 1996-1997 reached 32. It took another 23 years to reach a new peak at 33 countries.

- Three countries (Italy, Kazakhstan, Lithuania) abandoned their nuclear programs.

- Nine of the current 33 nuclear countries have either nuclear phase-out, no-new-build or no-program-extension policies in place.

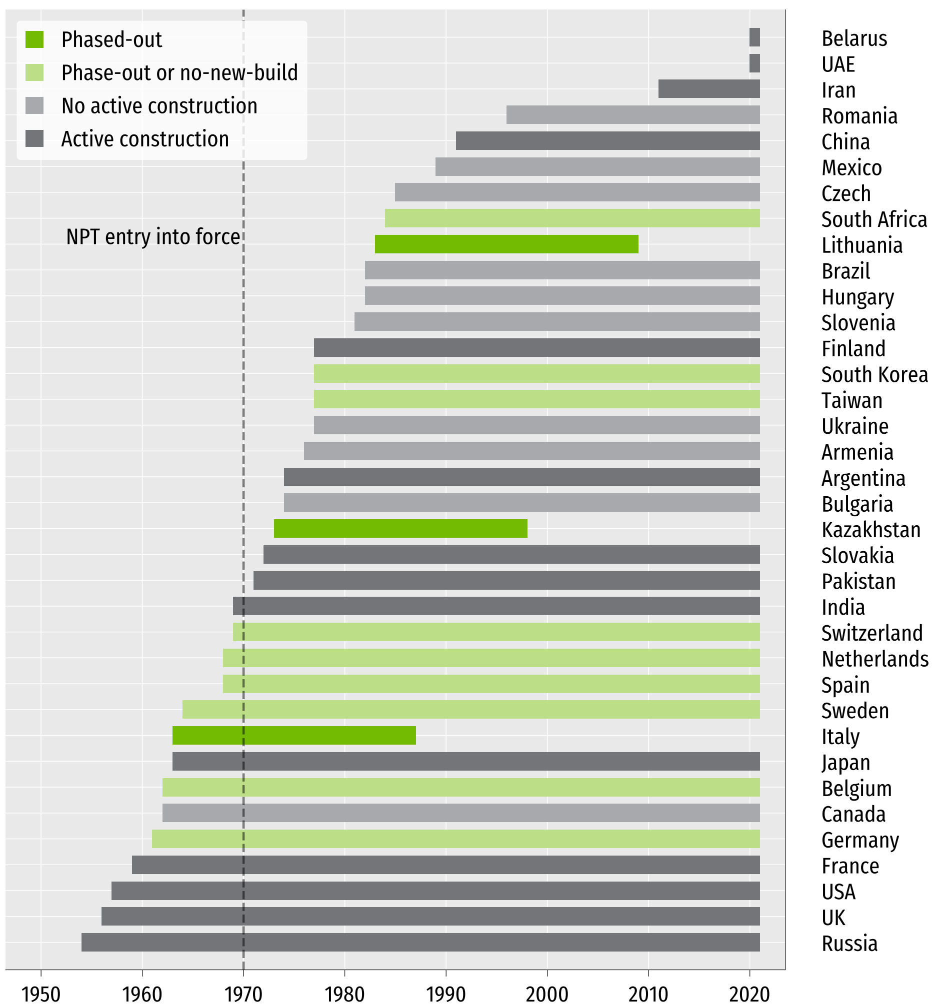

Figure 12. The spread of national nuclear power programs 1954–end of 2020. Although South Korea has a long-term nuclear phase-out policy, it has four reactors under construction as of 1 January 2021. The figure lists South Korea in the category "Program Limitation or Phase-out".[61]

The NPT had 191 states parties as of January 2021. As Figure 12 shows, only 34 of these states engaged in nuclear power programs (plus India and Pakistan; Italy, Kazakhstan and Lithuania abandoned their programs). The NPT's often cited "Third Pillar", the promotion of peaceful uses of nuclear technology, did not reflect and failed to create wide support among other countries, particularly in developing countries.

The number of annual startups peaked at 33 in 1984–85, that is 6 times more than the five units connected to the grid in 2020. Over the decade 2011–2020, 63 new units were started up in the world of which 37 (59 percent) were in China, while 61 units were closed – all outside China. In other words, in the rest of the world, with only 26 grid connections in a decade – two and a half per year – closures were exceeding startups by 35. The global decline, ongoing for years, continued in 2020 with another negative annual startup/closure balance.

As of January 2021, there were 411 reactors operating in the world, five less than 30 years ago, and 27 units below the historic peak of 438 in 2002 (Figure 13). A total of 28 reactors were in Long-Term Outage (LTO), of which 25 were in Japan, and one each in China, India and South Korea. As of 2020, the NPT nuclear weapon states had a combined total of 247 operating power reactors out of the global total of 411 units.[62]

After a significant drop following the Fukushima events in 2011, in 2020, the operating net nuclear capacity recovered almost the level of the historic maximum of 2006, which was also the year when nuclear power generation peaked. In 2020, nuclear power production dropped by a historic margin (with the exception of post-Fukushima years 2011–2012) by almost 4 percent. Meanwhile, the share of nuclear power in the commercial electricity mix in the world has declined from a maximum of 17.5 percent in 1996 to just above 10 percent in 2020.[63] Renewable sources of energy, even without including large hydropower plants, contributed more electricity.

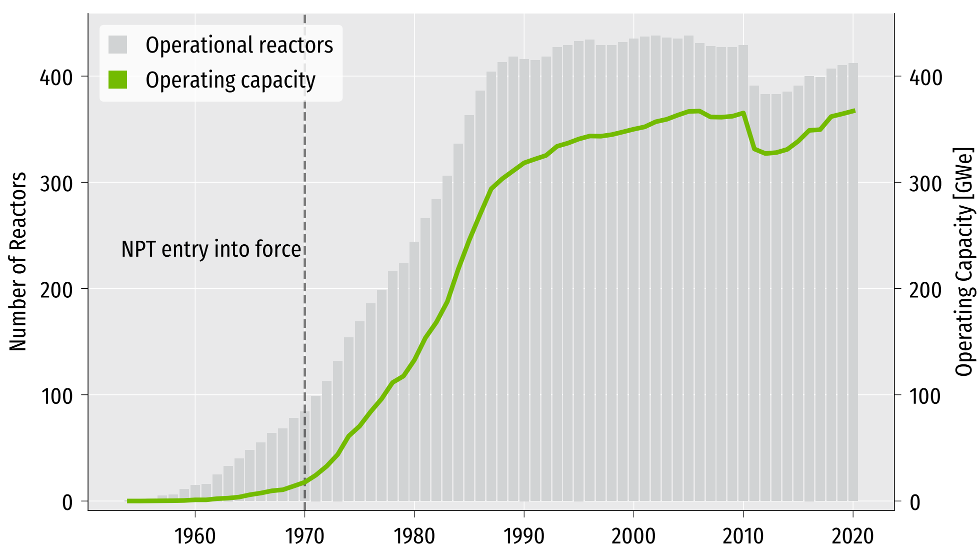

Figure 13. Operating reactors and their net operating capacity worldwide.[64]

Nuclear power plant construction as of early 2021 continues in China with 17 units, followed by India with seven active construction projects. In addition, only Russia and South Korea are building on several sites at the same time. Thirteen of the 17 countries currently building new reactors have only one site with one to three units under construction. Two of these are "newcomer" countries building their first nuclear power plant, Bangladesh and Turkey.

Safeguards

The spread of nuclear energy has been accompanied by the growth of safeguards to try to prevent the acquisition of nuclear weapons capabilities. Under Article III of the NPT:

> "Each non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards, as set forth in an agreement to be negotiated and concluded with the International Atomic Energy Agency in accordance with the Statute of the International Atomic Energy Agency and the Agency's safeguards system, for the exclusive purpose of verification of the fulfilment of its obligations assumed under this Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices. Procedures for the safeguards required by this Article shall be followed with respect to source or special fissionable material whether it is being produced, processed or used in any principal nuclear facility or is outside any such facility. The safeguards required by this Article shall be applied on all source or special fissionable material in all peaceful nuclear activities within the territory of such State, under its jurisdiction, or carried out under its control anywhere".

Safeguards Arrangements

The nature of safeguards arrangements has evolved with time. In a report on the legal framework for IAEA safeguards, Laura Rockwood lays out the early history:

> "The first Safeguards Document (INFCIRC/26) was developed by interested Member States and the Secretariat in 1959 and 1960 and approved by the IAEA's Board of Governors on 31 January 1961. It contained the principles and procedures for the application of safeguards to small reactors. This document was extended to cover larger reactors by decision of the Board on 26 February 1964. In 1964 and 1965, a completely revised Safeguards Document was worked out by a group of Member State experts and approved by the Board after unanimous concurrence by the General Conference in September 1965 (INFCIRC/66). Annex I to INFCIRC/66 (published in INFCIRC/66/Rev.1), which contains provisions for reprocessing plants, was approved by the Board in 1966, and Annex II (published in INFCIRC/66/Rev.2), which contains provisions for safeguarded nuclear material in conversion and fuel fabrication plants, was approved by the Board in 1968. With its two annexes, the Safeguards Document is now referred to as INFCIRC/66/Rev.2."[65]

The arrangement was too late to apply to India, which obtained the CIRUS reactor from Canada. The problem was apparent to Canadian officials well before India conducted its first nuclear test in 1974. In 1960, Canadian diplomat Harry Williamson told U.S. State Department official Robert Winfree that "the safeguards were essentially a handshake deal: Canada and India agreed that the reactor would be used for peaceful purposes only and the Indian Atomic Energy Commission would 'exercise self-inspection'".[66] The only condition in the agreement that "Only plutonium produced from the Canadian fuel elements will be audited," was evidently unworkable because both "Indian and Canadian fuel elements" were being used in the reactor and there was "no way of telling what plutonium comes from what elements".

Although many Canadian officials tried to get India to accept some kind of voluntary controls or safeguards on the spent fuel produced, Indian interlocutors, led by Homi Bhabha, the physicist who oversaw the creation of the nuclear program in India, adamantly refused.[67] But when it came to power reactors, Bhabha was open to safeguards. In 1956, at a conference on the IAEA's statute, Bhabha laid out his strategy of using international assistance to further India's weapon and civilian applications of nuclear power. "[T]here are," Bhabha said, "many states, technically advanced, which may undertake with Agency aid, fulfilling all the present safeguards, but in addition run their own parallel programmes independently of the Agency in which they could use the experience and know-how obtained in Agency-aided projects, without being subject in any way to the system of safeguards".[68]

At the time when the NPT was negotiated or when it entered into force in 1970, there was no 'comprehensive safeguards' system for non-nuclear weapon states (NNWS). In 1970, the IAEA's "Board of Governors established a Safeguards Committee (Committee 22) to advise it on the contents of safeguards agreements to be concluded between the NNWSs party to the NPT and the IAEA" and this Committee "developed a document entitled 'The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons'" (INFCIRC/153 (Corr.)), which the Board, in 1972, approved and requested the Director General to use as the basis for negotiating safeguards agreements under the NPT. A model agreement based on INFCIRC/153 (Corr.) was eventually developed and published in 1974 as GOV/INF/276, Annex A. Agreements concluded on the basis of that model are commonly referred to as 'full scope' or 'comprehensive' safeguards agreements". [69]

Because the NPT does not require Nuclear Weapon States (NWS) to conclude any safeguards agreement, "INFCIRC/153 (Corr.) also provided the framework for the voluntary offer agreements (VOAs) of the five NPT NWSs".[70] Worldwide, only 272 power reactors are under IAEA safeguards as of 2021, of which 246 are in NPT member states. One power reactor is under IAEA safeguards in China. The other four NPT weapon states' power reactors are not under IAEA safeguards (Table 5).[71]

Country	Power Reactors	Under IAEA Safeguards
China	63	1
France	57	0
India	29	19
Israel		0
North Korea		0
Pakistan	7	7
Russia	41	0
United Kingdom	17	0
United States	96	0

Table 5 Operational power reactors and power reactors under construction and their IAEA safeguards status in nuclear-armed states. Here, operational reactors are counted according to the IAEA's definition, which includes reactors in long-term outage.[72]

Such comprehensive safeguards agreements are the dominant arrangements by which most nuclear facilities around the world are covered. As of 2021, ten NPT states had yet to bring into force such agreements, and 681 of the 717 facilities under safeguards were covered by comprehensive safeguards agreements.[73] Of the remaining, 25 facilities in India, Israel, and Pakistan were covered under INFCIRC/66 type agreements, and 11 facilities covered under voluntary offer agreements.

Growth in Safeguards

Even though the early projections of nuclear power growth did not materialize, there has nevertheless been an increased need for safeguards to ensure that fissile materials not be diverted for use in nuclear weapons.

This increase can be examined using multiple metrics, starting with the number of facilities safeguarded. Figure 14 shows the development of safeguarded facilities over time, based on IAEA Annual Reports. The IAEA lists different categories, including power reactors, research reactors, fuel cycle front- and backend, storage facilities, as well as other facilities. Most of the increase happened in the 1970s and the numbers have stabilized in the past decade. Given the trends in nuclear energy development, the number of power reactors is unlikely to change significantly in the future.

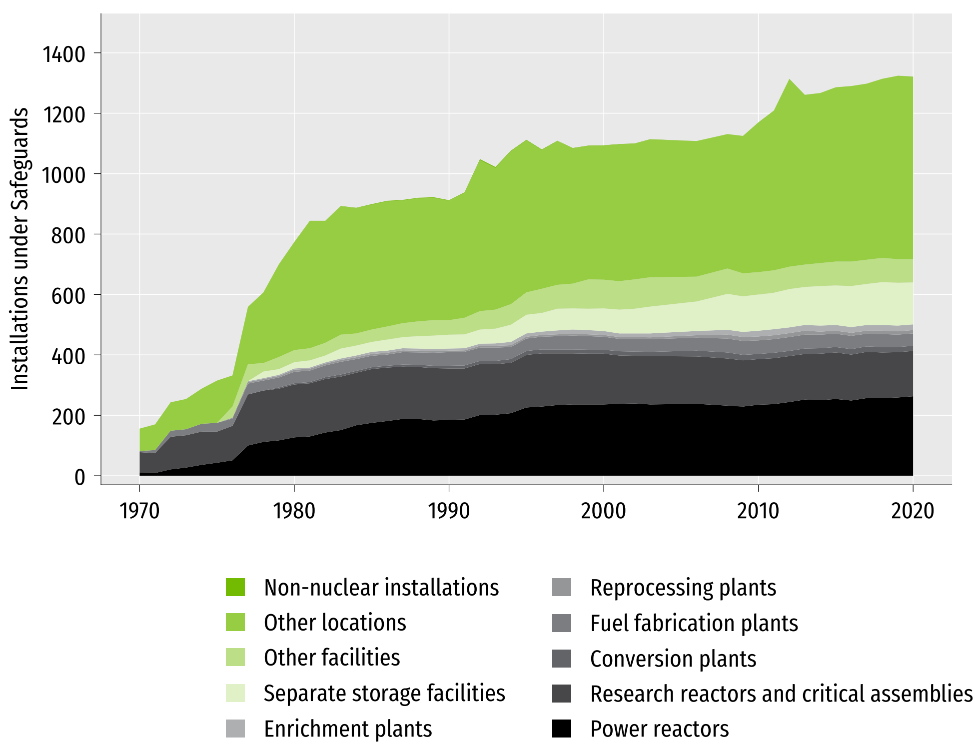

Figure 14: Installations under IAEA safeguards during respective years. Data from IAEA Annual Reports since 1970. No data available for 2003, 2004, 2005 and 2007. Prior to 1979, the reports listed fewer categories of installations. For a small number of facilities in the category "Power reactors," the IAEA counts two power reactors as one facility (17 facilities in 2020). The plot shows the numbers as provided by the IAEA.

However, one metric in safeguarding nuclear activities and facilities has continued to increase: the number of significant quantities (SQ). The change is shown in Figure 15. In the beginning of 1970 (December 31, 1969), there were only 163 SQs of material under IAEA safeguards.[74] That figure went up to 172,180 SQs by the end of 2010 and to 221,432 SQs by the end of 2020.[75] In other words, nearly 25 percent of the SQs being safeguarded currently were added within the last decade.

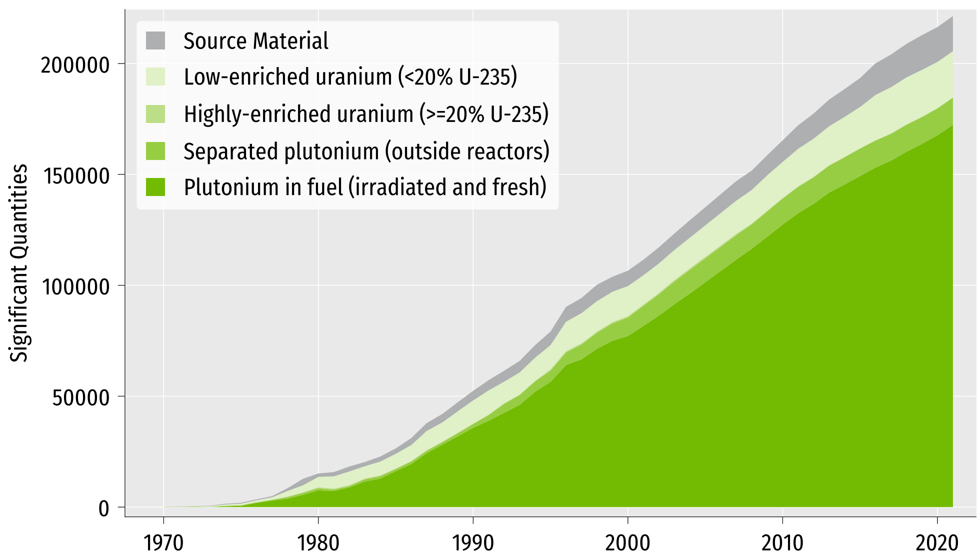

Figure 15: Significant Quantities under IAEA safeguards shown for the beginning of each year. Data from IAEA Annual Reports. No data available for 2004 and 2005.

The increase is for a simple reason. As long as a nuclear power plant continues to operate, it will require uranium to be mined, milled, converted, enriched (in any nuclear reactor design that doesn't operate with natural uranium), and fabricated into fuel. The irradiated fuel discharged from the reactor will have to be safeguarded for decades, possibly longer, in the absence of any operating geological repository to bury it in. Thus, even though nuclear power capacity may not be growing, the requirement for safeguards is growing.

What has not been growing concomitantly is the IAEA's budget for safeguards. In 2008, the U.S. Pacific Northwest National Laboratory calculated that in constant year (2008) dollars, the IAEA budget increased from around $10 million in 1970 to around $100 million in 1990, but had more or less plateaued since then except for the period between 2000 and 2005 when it increased by about 20 percent.[76] In 2020 dollars, those figures are around $12 million in 1970 and $120 million in 1990. Expenditures on safeguards have increased in the past decade.[77]

In summary, despite the expectations reflected in the NPT, over the past 50 years nuclear power did not grow into a major source of electricity. Only a small fraction of all the signatories of the NPT have operating nuclear power plants. Funding for international safeguards to address concerns about possible proliferation through diversion from civil nuclear programs has not kept pace with the growing stockpile of materials and facilities that actually needed to be safeguarded and are available for safeguards.

The failure of nuclear energy to meet early expectations about its future role is due to multiple reasons: the inability to economically compete with other sources of energy, the risks and consequences of severe accidents such as Chernobyl and Fukushima, the generation of radioactive nuclear waste products that remain hazardous for millennia, and unfavorable public opinion.[78] Despite the nuclear industry's current attempts to offer itself as a solution to climate change, the outlook for nuclear power suggests it will continue to have diminishing importance.

Nuclear-Armed States and the NPT

This section of the report provides country profiles for the nine states that possess nuclear weapons as of 2021. The profiles are organized on the basis of when each state acquired nuclear weapons. The first five states (the United States, Russia, United Kingdom, France and China) are parties to the NPT, having manufactured and tested nuclear weapons before 1 January 1967, the date set in the NPT for creating the treaty category of nuclear weapon state.

The other four states profiled here (Israel, India, Pakistan, and North Korea) are not parties to the NPT. North Korea signed the NPT as a non-weapon state in 1985 and withdrew in 2003. South Africa is not included since it dismantled its nuclear arsenal and signed the NPT as a non-weapon state.

A number of other countries, notably Iraq, Libya, and Syria, have sought nuclear weapons capability covertly while parties to the NPT, without success. The status and direction of Iran's nuclear program is currently problematic and unresolved following US withdrawal in 2018 from the 2015 Joint Comprehensive Plan of Action and Iran's response of limiting its compliance with the Plan and constraining IAEA monitoring

Each of the nine profiles covers briefly the respective state's nuclear history, the size of its nuclear arsenal, the production and stockpiles as of 2020 of HEU and separated plutonium, current fuel cycle activities related to uranium enrichment and reprocessing, and the situation with regard to IAEA safeguards.

The profiles do not cover current nuclear weapon activities. All nine of the nuclear-armed states, whether parties to the NPT or not, have been pursuing policies to maintain and modernize their nuclear arsenals.

United States

Background

The United States nuclear-weapon program was launched during World War II. After the first Soviet nuclear test in 1949, the U.S. developed thermonuclear weapons and built up to a peak of 31,255 operational warheads in 1967. As of September 30, 2020, the official number was down to 3,750 operational warheads plus about 2,000 additional warheads awaiting dismantlement.[79]

The United States conducted 1,054 nuclear tests starting 16 July 1945 through 23 September 1992, including 24 jointly with the United Kingdom on the U.S. Nevada test site starting in 1962. Some of the tests involved multiple simultaneous underground nuclear explosions in the same filled-in shaft or tunnel. The total number of detonations was 1,149.[80] The United States signed the Comprehensive Nuclear-Test-Ban Treaty on 24 September 1996 but has not ratified it.

The United States ratified the Nuclear-Nonproliferation Treaty on 5 March 1970.

Highly Enriched Uranium

The United States ended production of HEU for weapons in 1964 and for naval reactor fuel and all other purposes in 1992. In 2001, the United States declared that, as of September 30, 1996, a net total of 851 tons of HEU had been produced with an average enrichment of 87.6 percent uranium-235, and the remaining inventory was 740.7 tons.[81] In 2006, 152 tons of HEU were placed in a reserve for future use in U.S. and U.K. naval reactor fuel.[82] In 2015, it was estimated that no additional enrichment for naval fuels would be required before 2060.[83]

The amount of HEU remaining available for nuclear weapons is estimated as 216-240 tons enriched to an average of about 93 percent uranium-235.[84] At 25 kg per warhead, the amount of HEU in the approximately 4,000 warheads in the U.S. nuclear stockpile would contain about half of this material. Most of the remaining material is in reserve fusion-fission warhead “secondaries,” referred to as “canned subassemblies,” stored in the Highly Enriched Uranium Materials Facility in the U.S. Department of Energy’s Y-12 complex in Oak Ridge, Tennessee.

As of 2021, the United States has a HEU stockpile estimated to be about 566 tons. In 2016 it declared that, as of 30 September 2013, its HEU inventory was 585.6 tons, of which 499.4 tons was declared to be for "national security or non-national security programs including nuclear weapons, naval propulsion, nuclear energy, and science." The remaining 86.2 tons was composed of 41.6 tons "available for potential down-blend to low enriched uranium or, if not possible, disposal as low-level waste," and 44.6 tons in spent reactor fuel.[85] Between September 2013 and September 2019 the United States down-blended an additional 19 tons of HEU.[86] The remaining HEU available for blend-down is to be down-blended to produce U.S.-origin LEU to fuel U.S. tritium-production reactors.[87] The amount available for use had been reduced from 499.4 to about 476 tons, mostly by irradiation in naval reactors. The irradiated fuel is still HEU, and as such included in the stockpile estimate.

Plutonium

Between 1944 and 1988, the nine graphite-moderated, water-cooled reactors at the U.S. Hanford Site in the State of Washington and the five heavy-water-moderated and cooled reactors at the Savannah River Site in South Carolina produced a total of 90.6 tons of weapon-grade plutonium. In addition, between 1964, the year the U.S. warhead stockpile peaked, and 1982, the Hanford reactors produced 12.9 tons of non-weapon-grade plutonium for the U.S. breeder-reactor program. The U.S. also received: 5.8 tons of mostly fuel-grade separated plutonium from foreign countries, 1.8 tons from the reprocessing of spent U.S. research and power reactor fuel, and 0.7 tons in spent power-reactor fuel that was never reprocessed. Of the total weapon-grade plutonium, 3.4 tons were expended in nuclear tests and the Nagasaki bombing, 1.3 tons were fissioned or transmuted into other transuranic elements in reactors, 1 ton was transferred to U.S. industry and foreign countries for breeder reactor research and development programs, and 2.4 tons are unaccounted for – probably some in waste and some that never existed because of overestimates of the amount produced in production reactor fuel. As of the end of September 2009, the U.S. government possessed a total inventory of 81.3 tons of weapon-grade and 14.1 tons of fuel-grade and reactor-grade plutonium.[88]

In 1993, the U.S. declared 38.2 tons of weapon-grade plutonium excess for military purposes.[89] In 2007, an additional 9 tons of weapon-grade plutonium were declared excess.[90] Most of the weapon-grade plutonium remaining in the U.S. military stockpile that is not in weapons is in reserve pits stored at DOE's Pantex warhead assembly/disassembly plant in Amarillo, Texas. Some is also at the Los Alamos National Laboratory's plutonium facility where efforts are being made to reestablish a national capability for producing plutonium "pits" for the fission "primaries" of US nuclear weapons.

All U.S. government-owned fuel-grade plutonium has been declared excess for military purposes. In 2016, the U.S. took ownership of 0.4 tons of separated plutonium from Japan, Germany, and Switzerland. As of 2021, the total excess is 61.7 tons of plutonium. Of that material, 7.8 tons remains in spent fuel, and 4.5 tons had been disposed of in the DOE's deep-underground Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico in chambers mined out of bedded salt.[91] That leaves 49.4 tons of unirradiated plutonium declared excess.

Of the unirradiated plutonium, 4 tons is in fuel from the Idaho National Laboratory's Zero Power Physics Reactor, which DOE's Office of Nuclear Energy has not yet decided to release for disposal. Further, nearly 40 tons is in metal form, including 33.3 tons in the form of surplus weapon "pits." The remainder is stored in the form of oxide powder – some of it impure.[92]

US plans for the disposal of its excess weapon-grade plutonium were originally formed in the context of the year-2000 Plutonium Management and Disposition Agreement (PMDA) with Russia according to which each country would dispose of 34 tons of weapon-grade plutonium with IAEA verification. The U.S. plan at that time was to fabricate 25.6 tons into plutonium-uranium mixed oxide (MOX) fuel for light water reactors and immobilize the remaining 8.4 tons in glassified reprocessing waste for disposal.[93] In 2002, the Bush Administration decided to dispose all of the plutonium in MOX. This decision was formalized in 2010 by the Obama Administration and Russia in a revised PMDA.[94]

After the estimated costs of completion of construction of its MOX Fuel Fabrication Facility grew by an order of magnitude, however, the Obama Administration opted instead for conversion of the plutonium metal to oxide, dilution of the oxide with chemicals from which the plutonium would be difficult to separate, and disposal of the mix in WIPP in cans piled in tubes centered on the axes of insulating barrels for protection. Currently, however, DOE has only a small capacity (hundreds of kilograms per year) to convert plutonium metal to oxide at the Los Alamos National Laboratory and to dilute plutonium oxide at the Savannah River Site for disposal. The U.S. Department of Energy's (DOE's) proposed budget for fiscal year 2021 included a plan to install at the Savannah River Site a capacity for blending down 1.5 tons of plutonium oxide per year starting in 2028.[95]

Russia has not agreed to the unilateral U.S. change of plans for the disposal of the 34 tons of weapon-grade plutonium covered by the PMDA. In part because of this unilateral U.S. action and in part because of U.S. sanctions imposed on Russia after its seizure of Crimea and support of an insurgency in eastern Ukraine, in 2016, President Putin suspended co-operation under the PMDA.[96]

In summary, as of 2021, the United States has 38.4 tons of plutonium available for weapons, and owns an additional 49.4 tons of separated plutonium declared excess for military purposes.

Current Fuel Cycle Activities

Currently, the only enrichment plant operating in the United States is owned by URENCO and located in Eunice, New Mexico. In 1993, the U.S. Department of Energy turned over the operation of its two remaining operating gaseous-diffusion enrichment plants to a newly-established private company, U.S. Enrichment Corporation (USEC). USEC also launched the development of more competitive enrichment technologies: first laser enrichment and then large gas centrifuges. USEC went bankrupt in 2013, however, when the last of U.S. gaseous diffusion plants ended operation.

After about 2040, however, the U.S. will need low-enriched uranium to fuel the reactors in which it produces tritium for its nuclear weapons,[97] and, after about 2060, it will run out of excess Cold War HEU to fuel its naval reactors.[98] The U.S. government argues it cannot buy enriched uranium from URENCO or any other foreign enrichment supplier because of peaceful-use agreements. This position has been disputed by URENCO – at least with regard to the LEU fuel required for U.S. tritium production.[99] DOE's Office of Nuclear Energy has placed a controversial contract with Centrus, the successor of USEC, to install 16 centrifuges in a test facility at the DOE's shutdown gaseous diffusion enrichment facility in Portsmouth, Ohio to demonstrate that it can produce uranium enriched to up to 19.75 percent to be used in some of the new generation of "small modular power reactors" DOE is promoting for commercialization.[100]

The U.S. ended its brief foray into commercial reprocessing of spent power-reactor fuel in 1972.[101] The Department of Energy continues to operate the 1950s-era H-canyon reprocessing plant at its Savannah River Site for a number of purposes, however, including recovering HEU from irradiated aluminum-clad research reactor fuel for blend-down to low-enriched uranium and disposing of the Fast Critical Assembly (FCA) plutonium fuel it received from Japan.[102] The plutonium will go into the site's liquid high-level waste tanks for glassification with fission products and eventually disposal in a deep-underground repository. In the recent past, the H-canyon has also been used to convert plutonium metal into oxide.[103]

IAEA Safeguards

The U.S. has made a voluntary offer of all of its civilian nuclear facilities for IAEA safeguards.[104] The IAEA has taken advantage of these offers primarily for training purposes. It has also verified the storage of some HEU and plutonium that the U.S. has declared excess for military purposes and the blend-down of some excess U.S. HEU to LEU. The URENCO-USA plant and three LEU fuel-fabrication plants in the U.S. report their production and shipments to the IAEA but are not subject to inspection.[105] Currently, the only U.S. nuclear materials under IAEA safeguards are three tons of stored excess plutonium at the Savannah River Site.[106] In the Russia-US Plutonium Management and Disposition Agreement, the two countries agreed that the disposal of the 34 tons of weapon-grade plutonium that each had declared excess would be subject to IAEA safeguards. In 2016, then Secretary of Energy Moniz offered to subject to IAEA monitoring the disposal of an additional six tons of excess U.S. non-PMDA plutonium stored at the Savannah River Site.[107] As of late-2021, however, arrangements for monitoring had not been completed.

Russia

Background

In February 1943, the Soviet Union established a relatively small research program on nuclear weapons with significant input from intelligence on the U.S. program. A large, high-priority nuclear-weapon development effort was launched in August 1945, shortly after the United States used nuclear weapons in Hiroshima and Nagasaki.[108] The program produced its first nuclear weapon in 1949 and subsequently developed thermonuclear weapons. At its peak, in the mid-1980s, the Soviet arsenal of nuclear weapons is estimated to have included more than 40,000 weapons.[109] After the breakup of the Soviet Union, Russia assumed control over all Soviet nuclear weapons and became the USSR's legal successor in nuclear arms control treaties. As of 2021, Russia had an estimated 4,500 weapons in its nuclear stockpile plus perhaps 1,760 weapons in the dismantlement and disposition queue.[110]

The Soviet Union conducted 715 nuclear tests from 29 August 1949 to 19 October 1989. The number of explosive devices detonated in these tests is 969.[111] Russia signed the Comprehensive Nuclear-Test-Ban Treaty on 24 September 1996 and ratified it on 30 June 2000.

As a legal successor of the Soviet Union, Russia is a nuclear weapon state member of the Nuclear Non-proliferation Treaty. The Soviet Union ratified the treaty on 5 March 1970.

Highly Enriched Uranium

The Soviet Union ended production of HEU for weapon purposes by 1989, but it appears that the production of HEU for other needs, such as naval, research, and fast neutron reactors continued after that. It is estimated that by the late 1980s the Soviet Union had produced almost 1,500 tons of HEU (90 percent HEU equivalent). About 300 tons of this material have been used in naval reactor fuel, plutonium production reactors, and nuclear tests.[112] An additional 517 tons were downblended, 500 during 1995-2013 as part of the HEU-LEU agreement with the United States[113] and 17 tons as part of the Material Consolidation and Conversion project. Taking these removals into account, the amount of HEU in Russia's inventory is estimated to be 678 ± 120 tons of 90 percent HEU equivalent. About 25 tons of this material is in use in the naval fuel cycle, primarily in the cores of operational naval reactors. About 6 tons of HEU is in use in various research facilities.[114]

About 130 tons of HEU appear to be contained in assembled nuclear weapons: 90 tons in the active stockpile and 40 tons in weapons awaiting dismantlement. The rest is available for military as well as civilian applications. Russia can therefore consider as much as 580 tons of HEU as material in excess of defense needs. None of this material, however, is covered by an obligation not to use it for military purposes.

Russian naval reactors are believed to use HEU with enrichments from 21 percent to about 60 percent. It is possible that Russia continues to produce some of this material. Substantial quantities of HEU are also used to fuel two operating fast-neutron reactors.[115]

The Soviet Union built four large enrichment facilities: in Novouralsk, Seversk, Zelenogorsk, and Angarsk. Initially, the enrichment was done by gaseous diffusion, but in the 1960s, a shift to gas centrifuges began. The transition to centrifuge enrichment was complete in 1993. Most of HEU was produced by enriching uranium recovered from spent fuel of plutonium production reactors.[116] In 2012, Russia resumed production of HEU at the Novouralsk plant to provide HEU for export. The production line was apparently expanded in 2019.[117]

Plutonium

The Soviet Union produced kilogram quantities of plutonium for its nuclear weapon program in 1948 in a dedicated production reactor in what is now known as the Mayak plant in Ozersk, in the Urals region. By 1964, the Soviet fleet of dedicated plutonium-production reactors – all graphite-moderated – included 12 reactors at three sites: Ozersk and two sites in Siberia, Seversk, and Zheleznogorsk.[118] These three sites also operated dedicated reprocessing facilities that separated plutonium from the irradiated natural-uranium fuel of the production reactors.

The total amount of weapon-grade plutonium produced by these reactors is estimated to be 145 tons. With various removals accounted for, the amount of weapon-grade plutonium in Russia's inventory is estimated at 128 ± 8 tons.[119]

Russia shut down its last plutonium production reactor in April 2010. In accordance with a U.S.-Russian agreement, plutonium separated after September 1997 cannot be used for military purposes and is stored in a facility that is regularly monitored by U.S. inspectors.[120] About 15 tons of weapon-grade plutonium covered by this obligation are stored in Zheleznogorsk.[121] All reprocessing facilities associated with the production reactors have been shut down and are being decommissioned.

In a separate agreement, the Plutonium Management and Disposition Agreement (PMDA), which was finalized in 2010, the United States and Russia agreed to eliminate 34 tons of weapon-grade plutonium each.[122] The material Russia designated for disposition includes 25 tons of metal weapon-origin plutonium and 9 tons of plutonium from the post-1997 stock stored in Zheleznogorsk. The weapon-origin PMDA plutonium is stored in a dedicated Fissile Material Storage Facility at Mayak, Ozersk. Russia was planning to eliminate this material by using it to produce fuel for fast-neutron reactors. In 2016, Russia suspended its participation in the PMDA but confirmed its commitment not to use the plutonium covered by the agreement for any military purpose.[123] This material remains in storage as Russia has been using plutonium from its civilian stock to produce plutonium-based fuel for its fast-neutron BN-800 reactor.

Taking these commitments and obligations into account, about 88 tons of weapon-grade plutonium produced by dedicated production reactors is potentially available for weapons in Russia. Of this amount, an estimated 26 tons is in assembled weapons – 18 tons in active stockpile and 8 tons in weapons awaiting dismantlement.

The total amount of weapon-grade plutonium that is excess to the current nuclear arsenal requirements is 110 tons, of which 40 tons are covered by a commitment not to use the material for military purposes.

In addition to the plutonium produced in dedicated plutonium-production reactors, Russia has declared a stock of 63.5 tons of civilian plutonium as of the end of 2020.[124] Most of this material is reactor-grade plutonium separated from spent fuel of power reactors in a continuing reprocessing program.

The total plutonium stock in Russia therefore includes about 191 tons, of which 88 tons remain in the military program, about 40 tons are weapon-grade plutonium that is not available for military purposes, and 63 tons of civilian plutonium.

Current Fuel Cycle Activities

As of 2021, Russia operates four gas-centrifuge uranium enrichment facilities to provide enrichment services for Russian and foreign reactors. Rosatom is deploying new centrifuges in Novouralsk and Zelenogorsk. The facilities in Seversk and Angarsk may be phased out, although they remain in operation as of today and no specific plans to discontinue enrichment there have been made public.

The main civilian reprocessing facility, RT-1 plant at Mayak, Ozersk, has been in operation since 1976. Although its design capacity is 400 tons/year, it has been processing about 100-130 tons of spent fuel annually, mostly from VVER-440 light-water reactors. It also reprocesses research and naval reactor fuel. In recent years the plant was modified so it can now reprocess all types of spent fuel, including that of VVER-1000 reactors and its design capacity was increased to 500 tons/year.

Russia also is developing a new reprocessing center in Zheleznogorsk. The new center already has large wet and dry spent fuel storage facilities and new reprocessing and fuel fabrication facilities.[125] Construction of the reprocessing facility is being carried out in two phases. A Pilot Demonstration Center will include a reprocessing facility with the capacity of 250 tons/year and a MOX fabrication facility that will produce fuel for the BN-800 fast-neutron reactor. The reprocessing facility successfully completed its first test run in June 2018.[126] The MOX fuel fabrication facility was launched in 2015 and produced its first fuel assemblies for the BN-800 reactor in August 2019.[127]

IAEA Safeguards

The Soviet Union concluded a voluntary offer agreement with the IAEA in 1985.[128] In 2000 Russia and the IAEA concluded an additional protocol to that agreement, which entered into force in 2007.[129] Russia currently has only one facility under IAEA safeguards – the LEU fuel bank in Angarsk, which is operated by the multinational International Uranium Enrichment Center.[130]

United Kingdom

Background

During World War II, as the scale of the effort required to develop and produce nuclear weapons became obvious, the United Kingdom's nuclear-weapon program was absorbed into the U.S. Manhattan Project. After the war, however, the United Kingdom was cut off from the expanding U.S. effort and began an independent effort in 1947. This included the construction of two plutonium production reactors at the Windscale Site, which became operational in 1951 and provided the plutonium for the first British nuclear weapons test in October 1952. Throughout the 1950s and 1960s, the United Kingdom built a series of additional production facilities, some of them dual-use, to make the plutonium and HEU for its expanding weapons program.

By the time the NPT came into force in 1970, the U.K. arsenal contained an estimated 375 nuclear warheads. For the past decade, the U.K. was estimated to have about 225 warheads – all for its ballistic-missile submarines.[131] After years of intending to reduce its stockpile to not more than 180 warheads by the mid-2020s, the U.K. government announced last year in a strong policy reversal that it will now move to an overall stockpile ceiling of 260.[132]

Overall, the United Kingdom conducted 45 nuclear tests from 1952 to 1991, with 24 tests from 1961 to 1991 conducted at the U.S. Nevada Test Site under the 1958 U.S.–U.K. Mutual Defense Agreement.[133] The U.K. signed the Comprehensive Nuclear-Test-Ban Treaty in September 1996 and ratified it in April 1998.

In April 1995, in advance of the vote to indefinitely extend the Nonproliferation Treaty at the fifth NPT Review Conference, the United Kingdom announced that it "had ceased the production of fissile material for explosive purposes."[134] In the years following the production stop, the U.K. made some basic declarations concerning its fissile material stockpiles and nuclear-weapon inventories. Since 2006, when it published data for 2002,[135] the United Kingdom has not provided new or updated information on its military fissile material stockpile. In fact, most of the existing reports have vanished from government websites and are only available in archived form elsewhere.

Highly Enriched Uranium

The United Kingdom acquired HEU from two major sources: domestic production in its gaseous diffusion plant at Capenhurst (until 1962) and from the United States pursuant to the 1958 Mutual Defense Agreement, which remains in effect to this day.[136] In 2006, the United Kingdom declared that it had produced a total of 26.36 tons of HEU as of 2002. The total audited stock at that time was 21.9 tons.[137] The history of HEU production and transfers associated with the U.K. stockpile was reviewed in an IPFM assessment in 2010.[138]

Domestic production. The Capenhurst gaseous-diffusion enrichment plant produced HEU between 1954 and 1962. The cascade was then reshaped for civilian but unsafeguarded LEU production, largely to provide fuel for Britain's fleet of advanced gas-cooled reactors. All enrichment operations there ended in 1982 and the plant has been undergoing decommissioning and demolition. The U.K. Nuclear Decommissioning Authority (NDA) reported the maximum capacity of the Capenhurst gaseous diffusion plant was 400,000 kg SWU/yr. On that basis, the total production of HEU at Capenhurst has been estimated as 9–13 tons.

Transfers from the United States. Little is known about the specific transfers of fissile materials between the United States and the United Kingdom. In one set of transactions, the United Kingdom bartered 5.4 tons of its separated plutonium for 7.5 tons of HEU and 6.7 kg of tritium from the United States. The United Kingdom also sent low-enriched uranium produced in the first centrifuge enrichment plant at Capenhurst (A3) to the United States and received an "equivalent" amount of weapon-grade HEU for naval fuel in return. Combined with information that can be gleaned from U.S. HEU declarations, one can estimate that on the order of 15 tons of HEU had been transferred to the United Kingdom by the early 2000s. This is consistent with information about total acquisitions and the estimate of total domestic production above. It is possible, however, that the United Kingdom received additional U.S. HEU for its naval reactors since 2002.

Removals. The 2006 declaration specified that, as of 2002, the United Kingdom had consumed a total of 4.72 tons of HEU. An estimated 3.3 tons was used as fuel in submarine propulsion reactors, 0.7 tons in nuclear weapon tests, and 0.7 tons in research-reactors fuel. An additional 3.3 tons would be in submarine spent fuel for a total of about 8 tons. Assuming annual use of 14 kg by each of the seven attack submarines and 22 kg for each of its four ballistic-missile submarines, the additional use since 2002 would have been 3.4 tons for a total of 11.4 tons or about half of its pre-2002 total acquisitions. Of this about 5 tons would be in submarine spent fuel.

Today, assuming an arsenal of 225 warheads, the United Kingdom uses about 2.7 tons of HEU for weapon purposes. New stockpile requirements announced in 2021 would raise this number to about 3.1 tons. The United Kingdom also uses 0.2 tons of HEU for naval purpose per year. Thus, the current HEU stockpile is enough to cover all the weapons needs and 40 to 60 years of supplies of HEU naval fuel, assuming the United States would stop shipments.

On the civilian side, after proceeding to transfer "around 700 kg" of unirradiated HEU to the United States between 2016 and 2019,[139] the United Kingdom now reports an inventory of 500 kg of unirradiated and 137 kg of irradiated HEU (as of December 31, 2020).[140]

Plutonium

The main production site for U.K. military plutonium was the Sellafield complex, which has hosted all U.K. reprocessing operations. Sellafield also hosted a total of six production reactors: the two Windscale Piles and the four Calder Hall reactors. The United Kingdom also operated four additional dual-use reactors at the Chapelcross power plant in southwest Scotland, whose fuel was sent to Sellafield for reprocessing. When the United Kingdom announced in 1995 that it had stopped production of fissile material for military purposes, arrangements were made to bring most of its military fuel cycle under Euratom and, in some cases, IAEA safeguards.

In 1998, the United Kingdom declared a military inventory of 7.6 tons of plutonium. This amount was later reduced to 3.2 tons, when 4.4 tons, including 0.3 tons of weapon-grade plutonium, were declared excess. The United Kingdom requires about one ton of plutonium for its current nuclear arsenal, leaving about two tons of plutonium as a reserve, some of which could be declared excess.

Civilian Plutonium

The United Kingdom has also pursued an extensive program of reprocessing spent fuel from power reactors with minimal plutonium recycle. This has resulted in the largest stockpile of civilian plutonium in the world, including 116.1 tons of U.K. and 24.1 tons of foreign-owned (almost all Japanese) separated plutonium stored in the United Kingdom as of the end of 2020.[141]

Current Fuel Cycle Activities

In November 2018, after 25 years of separating plutonium from domestic and foreign spent fuel from nuclear power reactors, Britain's Thermal Oxide Reprocessing Plant at Sellafield moved to a clean-out program as part of the plant's final shutdown. This is a prelude to the plant's decommissioning and the treatment, disposal and management of its various remnants.[142]

Britain's other reprocessing plant, B205, which in 1964 began reprocessing fuel from Britain's first-generation Magnox power reactors, completed its operations in July 2022 once all of the Magnox fuel had been reprocessed.[143] With both plants shutting down, the United Kingdom is expected to stop all reprocessing activities as of 2022.[144]

With regard to civilian uranium enrichment, Urenco U.K. continues to operate the Capenhurst plant, which had a production capacity of 4,600 tSWU/year in 2021.[145]

IAEA Safeguards

The United Kingdom has voluntarily accepted IAEA and Euratom safeguards on "all source or special fissionable material in facilities or parts thereof within the United Kingdom, subject to exclusions for national security reasons only, with a view to enabling the Agency to verify that such material is not, except as provided for in this Agreement, withdrawn from civil activities."[146] As of 2021, one civilian uranium enrichment and two separate storage facilities are under safeguards. The IAEA does not safeguard any other civilian facility, neither reactors nor reprocessing sites. Due to its withdrawal from the European Union, the United Kingdom is no longer a part of Euratom and has established new bilateral safeguards arrangements with the IAEA.[147]

France

Background

France's nuclear engagement started during World War II with the involvement of a number of French scientists in the U.S. nuclear-weapon project. Immediately after the war, France established an Atomic Energy Commission (*Commissariat à l'Energie Atomique*, CEA), which, during the 1950s, began secretly pursuing nuclear weapons.[148] The weapon program was only given official status by the government in 1958.[149] Given the extensive preparations, it then proceeded rapidly. On 13 February 1960, France detonated its first nuclear weapon in the then French-Algerian Sahara Desert.

France did not develop separate civilian and military facilities and fuel cycles. The 1973 CEA annual report asserted that, "in order to limit costs, the CEA must adapt the production of military nuclear material to rapidly changing needs by taking advantage of technical progress and civilian programs, which themselves have greatly benefited from military programs."

In August 1992, France became the last nuclear-armed state to join the NPT as a Nuclear-Weapon State (China had joined in March that year). At that time, its weapons stockpile had reached its historic peak of about 540 warheads.[150] France ceased large-scale production of plutonium for military purposes the same year, but continued to produce HEU. France announced the end of its production of fissile material for weapons purposes on 22 February 1996. The gaseous diffusion enrichment plant at Pierrelatte stopped producing HEU by the end of June 1996.[151] France has since started decommissioning its military fissile materials production complex.

France ended its nuclear testing program in January 1996, signed the Comprehensive Nuclear-Test-Ban Treaty, and shut down its test site in the South Pacific. Overall it conducted 210 nuclear experiments, with 17 conducted from 1960 to 1966 in Algeria and 193 (including fifteen safety tests) conducted from 1966 to 1996 in Polynesia.[152]

As of 2021, France has not made public any information about its military fissile-material stockpiles. France also has not officially declared any fissile material as excess for military purposes. France has been a supporter, however, of a Fissile Material Cutoff Treaty, publishing its own draft treaty in 2015.[153] France's naval reactors are fueled with LEU, with the most recent nuclear attack submarine being fueled with uranium at "civilian enrichment levels," i.e. less than 6 percent uranium-235.[154]

Highly Enriched Uranium

France produced HEU at a dedicated enrichment complex near Pierrelatte at the Tricastin site on the Rhone River. Construction of the Pierrelatte plant began in 1960. It was composed of four main units called usines ("plants") with each unit representing a squared-off enrichment cascade increasing enrichment but decreasing separative work capacity. The first unit to come online was the *low* plant in 1964, and production of HEU started in the *very high* plant in early 1967. While operations at the Pierrelatte enrichment were linked to a second, much larger plant on the same site, the Eurodif Plant that came online in 1979 to produce low-enriched uranium for nuclear power plants, Pierrelatte's HEU output was constrained by the capacity of the unit producing high-assay uranium (up to 95 percent uranium-235). HEU production at Pierrelatte ended in June 1996.[155]

The capacity of the Pierrelatte plant (and its individual units) has never been declared, but earlier studies suggest it was over 100,000 SWU/yr and could have been as high as 300,000

SWU/yr.[156] Recent archival findings consistent with an independent analysis modelling Pierrelate's cascades arrangement suggests that the plant was designed to produce 800 kg of enriched uranium per year, including 700 kg of weapon-grade HEU (greater than 95 percent uranium-235). Given that the compressors in the very-high-enrichment unit operated for a total of about 205,000 hours over their lifetime, Pierrelatte would have produced a total of 16–18 tons of weapon-grade HEU.[157]

France has consumed a significant fraction of its HEU stockpile. The main removals were due to the operation of the two HEU-fueled Célestin tritium-production reactors, which were also used for production of plutonium and special-isotope. The lifetime HEU use of the Célestin reactors has been estimated as 5–7 tons.[158]

Nuclear weapon tests have also consumed HEU. While, France conducted a total of 210 tests in the 1960-1996 period, none involved HEU before the 1968 Polynesia atmospheric test series when weapon-grade uranium from Pierrelatte finally became available. Atmospheric testing ended in 1974. Based on public information about the 1968-1974 tests, it is estimated that France consumed about 0.5 ± 0.1 tons of weapon-grade uranium in atmospheric tests.[159] CEA officials told an independent panel of experts assessing the underground contamination of the French Polynesia test sites that an additional 0.35 tons of weapon-grade uranium had been used in the 1975-1996 underground tests.[160] Altogether therefore, France consumed an estimated 0.8–1 tons of HEU in nuclear tests.[161]

These estimates would leave France with a current inventory of 10 ± 2 tons of HEU. Today, assuming an arsenal of 300 warheads, France uses about 3.6 tons of HEU for weapons purposes. Assuming a strategic reserve of 50 percent for the weapon stockpile and an annual use of 50 kg of uranium-235 by the six attack submarines and 135 kg for the four ballistic-missile submarines and one aircraft carrier (the latter equipped with 2 reactors), France's current inventory covers all its weapons need and about 30 years of supplies for naval fuel via blend-down to high assay LEU.[162] Military enriched uranium needs for nuclear propulsion at enrichment levels above 6 percent should significantly decrease within the next 20 years, with the introduction of new classes of submarines with reactors functioning at civilian enrichment levels.

Plutonium

Large-scale plutonium production for military purposes in France started in 1956 and ceased in 1992. To support its weapons program, France built a series of dedicated reactors (G1, G2, and G3) at its Marcoule Site. It also produced additional weapon-grade plutonium (and tritium) in several civilian reactors owned and operated by Electricité de France (EDF).[163]

Significant weapon-grade plutonium production began in the 46 MWt G1 reactor, which operated from 1956 to 1968. The bulk of France's military plutonium stockpile was produced in the G2 and G3 dedicated production reactors, however, which came online in 1958 and 1959. These two identical reactors were carbon-dioxide-cooled and achieved thermal power levels of 250–350 MWt each. In total, G1, G2 and G3 produced an estimated 3.9-4 tons of weapon-grade plutonium.[164]

France also operated two dedicated tritium-production (Célestin) reactors at Marcoule. These identical 190 MWt heavy-water reactors came online in 1967 and 1968, but it soon became clear that their tritium-production capacity was greater than needed by the French nuclear arsenal. The mission of the Célestin reactors then broadened to include the production of plutonium and special radioisotopes for both civilian and military purposes. When France decided to discontinue production of plutonium in 1992, the Célestin reactors began to operate in an alternating mode, with only one reactor operating at a time. Both reactors were finally shut down in December 2009. Overall, the Célestin reactors may have contributed another 0.6–0.9 tons of plutonium to the weapons stockpile.

France operated a number of other reactors that likely had some military role. This includes, in particular, the fast-neutron reactor Phénix, which went critical in mid-1973. Operating also at Marcoule, the reactor could have produced 0.3–0.4 tons of plutonium. In total, the Marcoule site produced an estimated 4.8–5.3 tons of plutonium.

Additional production might have taken place in civilian gas-cooled graphite-moderated power reactors at Chinon, Saint-Laurent, Bugey, and Vandellos (Spain). In principle, these could have been used to provide up to 1.7 tons of additional weapon-grade plutonium to the stockpile.[165]

Overall, the total estimated French production of weapons plutonium was 5.9 ± 1.1 tons. Between 1960 and 1996, France conducted 210 nuclear weapon tests, which would have consumed about 1 ton of plutonium.[166] The estimate for the current stockpile is therefore 4.9 ± 1 tons.

With a declared arsenal of 300 warheads today, France uses about 1.2 tons of plutonium for military purposes. Assuming an extra fifty percent reserve for process and strategic purposes, if the production estimate presented here is correct, France could declare up to 3 tons of weapon-grade plutonium as excess to military requirements.

Civilian Plutonium

France carried out large-scale separation of plutonium for both military and civilian purposes between 1958 and 1997 at the UP1 plant at the military Marcoule site. Reprocessing of gas-graphite reactor fuel started at UP2 at La Hague in Normandy in 1966 and ended in 1987. Around 4,900 tons of metal fuel were reprocessed during this period. In 1974, the CEA also started reprocessing fuel from EDF's gas-graphite reactors at UP1, including fuel with higher burnups than needed for military uses. UP1 stopped the separation of plutonium for military purposes in 1993. By 30 September 1997, when reprocessing at Marcoule ended, a total of 13,330 tons of gas-graphite fuel had been reprocessed at UP1. In total, CEA/COGEMA reprocessed over 18,000 tons of spent gas-graphite fuel at UP1 and UP2. The La Hague UP2 plant started reprocessing oxide fuel from LWRs in 1976. A first major extension, called UP3, started operating in 1989 and a second enlargement, named UP2-800, followed in 1994. The nominal capacity of the La Hague site was thus increased by more than a factor of four to 1,700 tons per year.

Between 1976 and the end of 2018 a total of over 35,000 tons of LWR fuel were put through La Hague. Fuel of French, German, and Japanese origin dominated the throughput (70 percent, 16 percent, and 8 percent, respectively) but additional smaller contracts existed with Belgium, Italy, the Netherlands, and Switzerland.[167] Since 2005, Areva (now Orano) added a head-end for the processing of research reactor fuel, and contracts to process small quantities of such fuels have been signed with Australian, Belgian, and French clients.

In its civilian plutonium stockpile declaration to the IAEA, France reported holding (as of 31 December 2020) 79.4 tons of domestic unirradiated plutonium. French holdings also include 15.6 tons foreign-owned unirradiated plutonium. The total stock includes 30.5 tons of plutonium in MOX fuel.[168]

The distribution of the physical form of the separated plutonium held in France has changed significantly over time. The amount of separated plutonium in MOX fabrication facilities (as oxide or in semi-final products like fuel pellets) reached a maximum in 2002 of 15 tons and was reduced to about 9 tons in 2021. The decreases were offset, however, by an increase of unirradiated plutonium in fresh MOX or "other fabricated products," which increased from 1.8 tons in 1994 to 27.2 in 2009 and has stayed roughly constant for the past 10 years. The reasons for the increase appear to be an accumulation of unused fuel fabricated for breeder reactors that were shut down or never operated and scrap from shutdown MOX plants, and France's operating Melox MOX-fuel fabrication plant.[169]

With the phasing out of reprocessing and MOX fuel fabrication for foreign utilities, the amount of foreign plutonium stored in France decreased between 2000 and 2021 from 38.5 to 15.6 tons. This remaining material is owned by Japan, whose MOX usage plans have been delayed for a decade by public opposition and the 2011 Fukushima accident.

It remains unclear how and in what timeframe the substantial backlog of French civilian unirradiated plutonium is supposed to be absorbed and whether, with the end of France's fast-neutron reactor program, its spent MOX fuel will be redirected to France's deep repository instead of being mined for plutonium for fast reactors.

Current Fuel Cycle Activities

In addition to reprocessing civilian nuclear fuel, France operates the front end of the fuel cycle from uranium mining activities, to conversion and enrichment. The French uranium enrichment plant, George Besse II, operates gas centrifuge cascades. It reached its full production capacity of 7.5 million SWU per year in 2016.[170]

The French state-owned company, formerly named Areva, which manages nuclear fuel cycle activities was saved from bankruptcy by the government, downsized and restructured, and renamed Orano.[171] The company remains massively indebted.[172] The company is hoping to sell a large civilian reprocessing plant to China. The government believes this contract would save the company.[174]

IAEA Safeguards

France voluntarily offered to subject certain civilian nuclear materials to IAEA safeguards under a trilateral agreement with Euratom and the IAEA, which came into force in 1981.[175] This arrangement provides the IAEA with the means to "verify end-use in order to ensure that nuclear materials subject to its supervision are not diverted from civil uses."[176] It is unclear, however, how this agreement would apply to LEU being removed from Georges Besse II for naval fuel fabrication. As of 2021, all of France's civilian uranium enrichment and reprocessing facilities are under safeguards.

China

Background

China launched its nuclear-weapon program in 1955 and began producing HEU and plutonium in 1964 and 1966, respectively.[177] China exploded its first fission device (HEU-based) on October 16, 1964 and detonated its first hydrogen bomb on June 14, 1967. Since its first nuclear explosion, China has maintained a nuclear policy featuring a no-first-use pledge. China ratified the Nuclear Nonproliferation Treaty on March 9, 1992.

China has kept secret information about its fissile materials and nuclear weapons stocks. It is estimated that China had about 360 warheads in 2020, slowly increasing over recent decades.[178] The U.S. missile-defense program is a major driver of China's nuclear-weapon modernization, which includes an expansion of its nuclear arsenal and more and improved intercontinental ballistic missiles.[179]

China conducted 45 nuclear tests from 1964 to 1996 at its Lop Nor site in Xinjiang. Its last nuclear test was in July 1996. In September 1996, China signed the Comprehensive Nuclear-Test-Ban Treaty but has not yet ratified it. Most likely, China is waiting to see if the U.S. will ratify.

Highly Enriched Uranium

China produced its HEU for weapons at the Lanzhou and Heping gaseous diffusion plants (GDPs). Construction of the Lanzhou plant (Plant 504) with assistance from Soviet experts began in 1958. In August 1960, however, Moscow withdrew all its experts, forcing China to become self-reliant. In January 1964, Lanzhou began to produce 90-percent-enriched uranium (weapon-grade), making possible China's first nuclear test, in October 1964. It appears that Lanzhou stopped production of HEU for weapons in 1980, shifting to making LEU for civilian power reactors and possibly for naval reactors. The plant was shut down on December 31, 2000 and demolished in 2017. While it was making HEU, the Lanzhou GDP produced an estimated 1.2 million SWU.

In 1965, as part of China's "third line" program, to produce redundancy in its military industrial base in case of war, a site was selected for the Heping GDP (plant 814). Construction started in 1966 and it began operating in June 1970. China's nuclear industry actively pursued military to civilian conversion beginning in the early 1980s and the Heping plant is believed to have ended HEU production for weapons purposes in 1987. Since then, it is believed to have produced enriched uranium products for non-weapon military and/or civilian purposes. This GDP was likely closed by 2019. Plant 814 also operates a pilot centrifuge enrichment plant (CEP) near Emeishan that is likely producing enriched uranium for naval fuel and civilian use. The Heping GDP produced an estimated 2.2 million SWU while it was producing HEU.

Of the total 3.4 million SWU China's two gaseous diffusion plants produced during their HEU-production periods, roughly 0.5 million SWU were used for non-weapon purposes (research and naval reactor fuel) and for re-enriching irradiated natural uranium. This would have left an estimated 2.9 million SWU, sufficient to produce about 15 tons of weapon-grade HEU.

China's nuclear tests may have consumed about 0.75 tons of HEU. An additional 90 kg could have been lost during processing. These reductions result in an estimated current inventory of about 14 ± 3 tons of HEU in and available for weapons. China has not declared any excess HEU.

Plutonium

China produced plutonium for weapons at two nuclear complexes, Jiuquan (Plant 404) and Guangyuan (Plant 821), each with a single natural uranium-fueled, graphite-moderated, water-cooled production reactor with an original design power of 600 MWt. These reactors also produced tritium.

Construction of the Jiuquan plutonium-production reactor began in 1960. The reactor achieved criticality in October 1966 and reached its design power in mid-1975. A great deal of effort went into increasing its plutonium-production rate, which rose 20 percent by 1979. During the 1980s, production declined and the reactor was shut down by November 1986. Decommissioning began after 1990. The Jiuquan reactor could have produced about 2 tons of weapon-grade plutonium.

In 1969, Beijing began building a second plutonium-production complex at Guangyuan. The reactor achieved criticality in December 1973 and design power by October 1974. Its plutonium production rate increased by 30 percent by 1978. The reactor was probably shut down in 1984. Decommissioning began after 1990. The Guangyuan reactor could have produced a total of 1.4 tons of weapon-grade plutonium

Together therefore, the Jiuquan and Guangyuan reactors could have produced 3.4 tons of weapon-grade plutonium. Allowing for the fact that China used some of this capacity to produce tritium, the Jiuquan and Guangyuan reactors produced an estimated 3.2 ± 0.6 tons of weapon-grade plutonium.

Allowing for the plutonium consumed in nuclear tests and lost in reprocessing and fabrication, China's current inventory of plutonium for weapons is estimated to be about 2.9 ± 0.6 tons, which is significantly larger than the previous estimate made for the IPFM Global Fissile Material Report 2015. China has not declared any excess military plutonium.

Current Fuel Cycle Activities

China's use of HEU for non-weapons purpose is expected to be very limited. Its new generation of naval reactors likely continues to use LEU fuel and future HEU use in its research reactors will not be significant. China has not released any information about its non-weapons HEU stock but could have produced a large stock since 1987 when it ended HEU production for weapons. The Heping GDP and the pilot CEP of Plant 814, both assumed to be dual-use, could each produce more than 1 ton of 90 percent enriched HEU per year.

China leads the world in new reactor construction. Since 2010, to meet the expected rapid increase of the associated requirements for low-enriched uranium, China National Nuclear Corporation (CNNC), which is responsible for enrichment services in China, significantly expanded its indigenous centrifuge enrichment capacity at several sites.[180] Currently, China operates three centrifuge enrichment plants at Hanzhong (Shaanxi province, Plant 405), at Lanzhou (Gansu province, Plant 504), and at Emeishan (Sichuan province, the Emeishan civilian facility of Plant 814) to produce LEU for civilian purposes. CNNC has said that it maintains a policy of "self-sufficiency" in the supply of enrichment services for China. CNNC experts state that China has a capacity to build 1 million SWU/year of centrifuge capacity annually. It is estimated China has reached a total estimated enrichment capacity of about 7.8 million SWU per year, which is large enough to meet its reactors' demands of 7.5 million SWU annually.[181]

China has pursued a closed fuel cycle policy since 1983.[182] In December 2010, it began testing civilian reprocessing in a pilot plant at its Jiuquan complex with a design capacity of 50 tons of spent fuel per year. The plant has been shut down most of the time, however, to fix technical problems. Based on China's last (INFCIR/549) declaration to the IAEA, as of the end of 2016, it had separated only 40.9 kilograms of plutonium.[183] The pilot plant has reportedly entered normal operation since 2017.[184] If so, it could separate about 0.5 tons of plutonium per year.

The Jiuquan complex also hosts a pilot MOX fuel fabrication facility (0.5 tons year capacity). Its purpose is to supply fuel for China's 20 MWe Experimental Fast Reactor (CEFR). The CEFR reached criticality in July 2010 but had not used any MOX fuel as of 2019. Its initial core provided by Russia contains about 240 kg of 64.4 percent enriched uranium. A new fuel batch was delivered by Russia in July 2019.[185]

In July 2015, the China National Nuclear Corporation (CNNC) started construction of a demonstration reprocessing plant with a design capacity of 200 tons/yr at Jinta in Gansu Province. Completion is planned for about 2025. Since 2018 CNNC has also been building a demonstration MOX fuel fabrication line with a capacity of 20 tons/year near the demonstration reprocessing plant. The plant is to be commissioned by 2025.[186] China is believed to have started the construction of a second 200 tons/year reprocessing plant at the same site in late 2020 or early 2021. The plant could be commissioned before 2030.[187] CNNC also has been negotiating with France's Orano (formerly Areva) for the purchase of a commercial reprocessing plant with a capacity of 800 tons/yr.

In December 2017, CNNC began construction on a demonstration fast-neutron reactor CFR-600 (600 MWe) at Xiapu, Fujian with plans to commence operation in 2023.[188] Construction started on another CFR-600 at the Xiapu site in December 2020. The two 200 tons/year reprocessing plants would supply plutonium for MOX fuels for the CFR-600. Russia is to supply an initial HEU core and HEU reloads during the first seven years of the first reactor's operation.[189] However, it is not clear whether the HEU supply is only for the first CFR-600 or both.

CNNC's China Institute of Atomic Energy has proposed to design 1000 MWe or 1200 MWe commercial fast-neutron reactors based on the experience to be gained from the CFR-600, with pre-conceptual designs by 2020, and construction to start in 2028.[190]

IAEA Safeguards

Since 1988 China has voluntarily offered a few of its civilian nuclear facilities for IAEA safeguards, including the Russian supplied centrifuges at Hanzhong plant, a Qinshan heavy-water power reactor, and a research reactor. China signed the Additional Protocol to its IAEA Safeguards Agreement in December 1998. The protocol entered into force in March 2002.

Israel

Background

Israel launched its nuclear weapons program in the 1950s. It relied primarily on a French-supplied plutonium-production reactor and associated reprocessing plant at Dimona in the Negev Desert.[191] Formally known today as the Shimon Peres Negev Nuclear Research Center, the site is also home to other weapon-related activities, including the production of tritium and possibly also of enriched uranium.

The most detailed information about the technical operations at Dimona was supplied by Mordechai Vanunu, who was employed as a technician there from November 1976 until October 1985. Much of that information was first published in the London-based *Sunday Times* in 1986.[192] Vanunu provided notes about operations at Dimona and about sixty color photographs taken on two consecutive nights in the facility in September 1985.[193] Vanunu was kidnapped by Israeli intelligence agents and taken to Israel where he was tried in secret and sentenced to 18 years in prison. Today, there is broad agreement that the information Vanunu provided on the activities underway at Dimona between 1977 and 1985 was genuine and consistent.

Israel may have carried out a nuclear weapon test in 1979. Based on estimates from 2020 and 2021, Israel may have around 90 nuclear warheads, which may be stored in a partially unassembled state for deployment on aircraft, and on land-based and sea-based missiles.[194] Israel is not a party to the NPT.

Highly Enriched Uranium

It is not clear whether Israel ever produced HEU for weapons or other military purposes. As the discussion below suggests, however, Israel likely requires enriched uranium to fuel the Dimona reactor as part of a strategy that enables concurrent plutonium and tritium production.[195] A 1974 U.S. Special National Intelligence Estimate noted that, “for over ten years, the Israelis have been doing research and development work on the gas centrifuge method of uranium enrichment.”[196] According to Vanunu, the production of enriched uranium at Dimona using gas centrifuges and lasers both started around 1980.[197] There is extensive additional circumstantial evidence – but no definitive proof or official acknowledgement – that Israel has had and may still have an active uranium enrichment program.[198]

The uranium enrichment capacity needed make slightly enriched fuel (up to about 1.5 percent enriched in uranium-235) for the Dimona reactor could be relatively small. If natural uranium is used as feedstock, the capacity could be on the order of 10,000–50,000 SWU/yr. A much smaller capacity would be sufficient, however, if recycled uranium is primarily used instead. Re-enriching uranium recovered from discharged fuel would only require 1,000-2,500 SWU/yr depending on the depletion level of the tails. These enrichment capacities are very small compared to commercial requirements, and a plant of this size could easily be accommodated somewhere on the Dimona site.

Another possible early source of enriched uranium was NUMEC, a nuclear fuel facility in the United States near Pittsburgh. The allegation that hundreds of kilograms of weapon-grade uranium were secretly transferred from the NUMEC plant to Israel in the 1960s, with the cooperation of the plant’s owner, Zalman Shapiro, has been the subject of intense investigation and speculation.[199] If this material was indeed diverted to Israel’s weapons program, it could have been used directly for weapons purposes. It is also possible, however, that the material was used as blend-stock to make slightly enriched fuel for Dimona at a time when a domestic enrichment capability had not yet been established. For example, one could blend 300 kg of weapon-grade uranium (93 percent uranium-235) with natural uranium to obtain enough slightly enriched fuel to operate Dimona for more than two years.

Israel has kilogram quantities of HEU under IAEA safeguards. This material is used as MTR-type fuel in the 5-MW research reactor (IRR1) at the Soreq Nuclear Research Center (SNRC).[200] Since the early 2000s, there have been plans to permanently shut down the reactor, but these plans have apparently been postponed until a new experimental facility comes online in or around 2023. In 2009, irradiated HEU fuel from the reactor was returned to the United States, which has supplied this fuel since the 1960s.

Weapons Plutonium

It is reasonable to assume that Israel's nuclear weapons program is primarily based on plutonium-based weapons produced at the Dimona reactor. Plutonium production in a reactor is primarily determined by its thermal power and the type and enrichment of the fuel. The Dimona reactor is listed with a power of 26 MW thermal in the IAEA Research Reactor Database, consistent with the original declared design power rating.[201] There is strong evidence that the reactor was operated at a power level of about 40 MW shortly after being commissioned; this was possible by using a third (spare) coolant loop available in the original reactor design.

The power level likely increased to 70–90 MW later on to enable a new target plutonium production rate of 20 kg/yr. This is consistent with information provided by Vanunu based on his observations until 1985, and it is plausible to assume that this production rate has been maintained for many years. Unless the reactor has been completely redesigned and uses driver fuel with much higher enrichment today, it would be difficult to reduce the power level of Dimona significantly, while maintaining tritium production rates sufficient to sustain a stockpile of about 100 tritium-boosted nuclear warheads, which together require about 50–60 grams per year of new tritium to offset tritium decay.[202] If the Dimona reactor is currently operated primarily for tritium production, Israel could be reprocessing its spent fuel and separating and stockpiling the plutonium, but not using it to make weapons. Apart from one or more possible nuclear weapon tests in 1979,[203] there are no obvious removals from Israel's plutonium stockpile except for small amounts lost as waste during plutonium pit production.

Overall, as of December 2020, it is estimated that Israel produced a total of 830 ± 100 kg of plutonium at Dimona. If all this plutonium were used for weapon purposes, with no working stock, it could be sufficient for about 150–190 warheads, assuming that each device contains on the order of 5 kg of plutonium.[204] This by far exceeds the independent estimates of Israel's current nuclear arsenal of 80–85 weapons.

Civilian Plutonium

Israel has not publicly declared any stocks of civilian plutonium.

Current Fuel Cycle Activities

All major fuel-cycle activities in Israel appear to be located at the Dimona site; as discussed, these include irradiated fuel reprocessing and, potentially, uranium enrichment. The site is also used for storage of low-level, intermediate-level, and high-level waste, which is currently stored above ground near the site pending further processing and disposal. Israel is apparently considering deep borehole disposal of this waste near Dimona.[205]

In late 2018 or early 2019, significant new construction began at the Dimona site; this construction was first observed in commercial satellite imagery obtained in early 2021.[206] The most prominent new construction is in the immediate vicinity of the buildings that house the nuclear reactor and the reprocessing plant. Imagery from 2021 shows that the construction has expanded and appears to be actively underway with multiple construction vehicles present. At this stage, the construction appears to be centered around an excavation area of 140 meters by 50 meters. The purpose of this construction is unknown.

IAEA Safeguards

In Israel, only the 5-MW HEU-fueled IRR1 research reactor at the Soreq Nuclear Research Center is under safeguards. The reactor was originally supplied by the United States as part of the Atoms for Peace Program. The safeguards agreement is facility-specific and based on INFCIRC/66 (Rev. 2).[207] IRR1 fresh fuel is 93 percent enriched and is removed from the core when the burnup is 50–60 percent.[208] In January 2010, more than one hundred spent fuel assemblies from the reactor were returned to the Savannah River Site, USA.[209] The reactor is to be shut down and replaced by an accelerator. The Soreq Applied Research Accelerator Facility is under construction and expected to be completed in 2023.[210] Israel has not signed an Additional Protocol.

India

Background

India's nuclear program was launched in 1940s, in the aftermath of the U.S. bombing of Hiroshima and Nagasaki and just as the country gained independence from British colonial rule, Officially the nuclear program was only for peaceful purposes, i.e., aimed at producing electricity for development, but its leaders never lost sight of the possibility that the facilities constructed and expertise gained in this process could be used for military purposes. Eventually India's Department of Atomic Energy started designing nuclear weapons, testing them in 1974 and then again in 1998.[211]

There are no official figures on the size of India's nuclear arsenal. But independent estimates suggest that it is still growing. The latest figures from the Federation of American Scientists are based on publicly available information about India's delivery vehicles and strategy; according to this estimate, the country might have 150 nuclear warheads as of 2021.[212] India's delivery platforms include nuclear powered submarines.

India first conducted a nuclear weapon test in May 1974. It followed this test 24 years later with five nuclear explosions in May 1998. Plans to conduct nuclear tests in the early 1980s and 1995 were cancelled.[213] It has not conducted any nuclear weapon tests since 1998 and has declared a moratorium, but has not signed the Comprehensive Nuclear-Test-Ban Treaty.

India has not signed the Nuclear Non-Proliferation Treaty or any other major nuclear-weapons-related multilateral treaties since it signed the 1963 Partial Test Ban Treaty.

Highly Enriched Uranium

India has a uranium enrichment program based on centrifuge technology. Assuming an enrichment level of 30 percent, India is estimated to have produced 5.6 ± 1.9 tons of HEU as of the beginning of 2021 with a uranium-235 content of 1.7 ± 0.6 tons, for naval fuel.

It has been estimated that India's nuclear-powered submarine reactor cores each require 65 kg of uranium-235. The first submarine was deployed in 2018 and in December 2021, and India may be preparing a third nuclear submarine for deployment.[214] In addition to the cores for these three submarines, the core for a land-based prototype and a re-load core for the first submarine, *Arihant*, have also been fabricated.[215] Assuming that only five cores have been fabricated, a little under 1.1 tons of HEU (enriched to 30 percent) could have been used so far. Allowing for production and removal, it is estimated that, as of early 2021, India's HEU stockpile was 4.5 ± 1.9 tons with a uranium-235 content of 1.4 ± 0.6 tons.

Plutonium

India's nuclear weapons are primarily, if not solely, based on plutonium. India has produced weapon-grade plutonium in the 40 MWt CIRUS production reactor and the 100 MWt Dhruva production reactor, both located in the Bhabha Atomic Research Centre complex near Mumbai. CIRUS is a heavy-water-moderated, light-water-cooled, natural-uranium-fueled reactor based on the design of Canada's NRX reactor. CIRUS became critical in 1960 and fully operational in 1963. It was shut down in 2010. Dhruva, was commissioned in 1985, but had operating problems during its first few years. It is reported to have begun normal operations in 1988.[216]

Another source of India's weapon-grade plutonium may be the first spent fuel discharges from India's pressurized heavy water power reactors, which would contain only small concentrations of the higher isotopes of plutonium, making them easily usable in nuclear weapons. Such low burnup spent fuel would have been discharged from twelve unsafeguarded 220 MWe Pressurized Heavy Water Reactors (PHWRs) and two 540 MWe PHWRs. Together these reactors may have produced slightly over 100 kg of weapon-grade plutonium. Because of uncertainty about whether India did add such plutonium to its weapons-plutonium stockpile, this source of weapon-grade plutonium is included in the higher but not the lower estimate.

It is estimated that India produced 0.71 ± 0.14 tons of weapon-grade plutonium as of the beginning of 2021. The largest removal of weapon-grade plutonium from this stock was for the initial core of the Fast Breeder Test Reactor, which was constructed before any unsafeguarded reactor-grade plutonium was available in the country. It is estimated that this core would have required about 50 kg of weapon-grade plutonium. It also is estimated that a total of about 25 to 30 kg of weapon-grade plutonium would have been used to construct the devices exploded during the 1974 and 1998 nuclear weapon tests. In all, India would have removed 75 to 80 kg of weapon-grade plutonium from its stock.

Accounting for the production and removal figures, as of the beginning of 2021, India's weapon-grade plutonium stockpile would be 0.63 ± 0.14 tons. India has not declared any of this inventory as excess to its weapons requirements.

India also has a stockpile of separated reactor-grade plutonium that is not under IAEA safeguards, produced by reprocessing the spent fuel from a fleet of unsafeguarded PHWRs. As of the beginning of 2021, India's reprocessing plants together might have separated 8.1 ± 4.3 tons of reactor-grade plutonium, of which about 0.4 tons are under IAEA safeguards.

Current Fuel Cycle Activities

The primary purpose of India's uranium enrichment program is to produce HEU for naval reactors for the *Arihant*-class submarines India is building. India started pilot-scale uranium enrichment only in the mid-1990s and a larger centrifuge facility called the Rare Materials Plant has been operating since 1990 in Rattehalli in southern India. The enrichment capacity at the beginning of 2021 is an estimated 16,000 to 31,000 SWU/yr. A second enrichment facility called the Special Material Enrichment Facility is being constructed in Chitradurga, also in southern India.[217] The facility will reportedly start operating by 2025.[218] India reportedly enriches uranium to somewhere between 30 percent and 45 percent uranium-235. While this qualifies as HEU, it may not be directly usable in the primary of a practical nuclear weapon.

India operates three reprocessing plants. The oldest is the Trombay reprocessing plant, whose nominal reprocessing capacity is 50 tons per year. The other plants, PREFRE and the Kalpakkam Reprocessing Plant, each with a nominal capacity of 100 tons per year, are designed to treat PHWR spent fuel.

IAEA Safeguards

India has a total of ten PHWRs and four LWRs under safeguards. Of these, eight PHWRs were offered for safeguards after the Nuclear Suppliers Group waived its restrictions on India in 2008. A total of eight PHWRs remain outside IAEA safeguards.[219] In addition, the PREFRE reprocessing plant in Tarapur and a number of facilities at the Nuclear Fuel Complex in Hyderabad are safeguarded whenever they are dealing with fuel for or from reactors that are under safeguards. The same is true of the Away-From-Reactor Storage Facility and the Nuclear Material Store. India has entered into an Additional Protocol to the Safeguards Agreement with the IAEA.[220]

Pakistan

Background

Pakistan's plan to acquire nuclear weapons started in 1972 after its military was overwhelmed by India's conventional forces in the December 1971 war. Later, following India's first nuclear weapon test in May 1974, Pakistan committed significantly greater resources to its nuclear weapon program.

The initial focus of the fissile material effort was on uranium enrichment using ultracentrifuge technology smuggled in from Europe by A. Q. Khan. Pakistan's production of fissile materials expanded later to include weapon-grade plutonium using dedicated heavy water moderated production reactors and chemical reprocessing of the irradiated fuel.

As with most weapon states, no public official information about the production rates of Pakistan's fissile materials exists. Estimates of Pakistan's uranium enrichment capacity, the power ratings of its plutonium-production reactors and the capacities of its reprocessing plant(s) are based on assumptions.[221]

Pakistan tested its nuclear weapons in 1998 in the hills and desert of Balochistan, claiming to conduct five tests on 28 May, and one test on 30 May (matching the total number of tests by India). Pakistan has since declared a moratorium on further testing, conditional on no further tests by India. The six test explosions may all have been HEU devices, since by that time Pakistan is believed to not have separated significant amounts of weapon-grade plutonium.

Pakistan's stockpile as of 2021 has been estimated at 165 warheads.[222] It has shown no inclination to cease or even slow the production of weapon grade fissile material. Pakistan also has been strongly resisting negotiations on a Fissile Material Cutoff Treaty at the UN Conference on Disarmament unless previous stocks are explicitly included in the scope of the Treaty talks, citing a fissile material gap relative to India. Its nuclear posture rests on a threat of use of nuclear weapons in the event its conventional forces are overwhelmed by an adversary (which is currently only India), or its existence is threatened by any other means.[223]

Pakistan has not acceded to the Nuclear Non-Proliferation Treaty and refuses to sign as a non-weapon state as long as India does not also do so.

Highly Enriched Uranium

Pakistan's HEU production started at Kahuta in the early 1980s using simple P1 centrifuges based on a URENCO design. The first HEU (90 percent or higher uranium-235) is believed to have been produced in 1983. The plant had an initial enrichment capacity estimated at about 3,000 SWU/year. Since then, improved centrifuges (P2, P3, and P4) have been introduced.[224] Pakistan also operates a recently-identified enrichment plant in Gadwal and a second plant inside the Kahuta complex.[225]

As of the end of 2020, Pakistan is estimated to have produced 4.1 ± 0.4 tons of HEU. Of this, about 100 kg could have been used in the 1998 tests. The remaining stock would be sufficient for 160 ± 16 HEU implosion weapons.

Pakistan has been interested in nuclear powered submarines since the turn of the century.[226] It is reported to have been working on a prototype naval reactor since 2001.[227] The submarine reactors would require enriched uranium fuel. It aims to put nuclear weapons on its submarines.[228]

Plutonium

Pakistan produces plutonium for nuclear weapons at four dedicated reactors. Its first heavy-water-moderated, light-water-cooled production reactor with an estimated capacity of 40-50 MWt was established in the Khushab Complex in the 1990s, and is believed to have started operation in 1998. Three more production reactors, each with a thermal power estimated to be about 40-50 MWt, seem to have become operational in 2010, 2013 and 2015, respectively, all at this Khushab complex.

A pilot plant to separate plutonium from spent nuclear fuel was established in the early 1980s at the 'New Labs' in Nilore near Islamabad by Saint-Gobain Techniques Nouvelles of France and Belgonucleaire of Belgium, with a capacity to handle 20 – 40 tons of spent fuel per year.[229] Pakistan has since built another reprocessing plant of the same size. There are reports of completion in 2015 and possible start-up a larger reprocessing plant at the Chashma Nuclear Complex, the site of an incomplete reprocessing plant being built by France in the mid-1970s but abandoned due to international pressure over proliferation concerns.[230]

Pakistan's first weapon-grade plutonium is believed to have been separated in the year 2000. By the end of 2020, Pakistan's weapon-grade Pu stock was an estimated 460 ± 160 kg. There are no reports of Pakistan reprocessing spent fuel from its safeguarded Canadian supplied heavy-water power reactor or its four Chinese supplied light-water power reactors.

Current Fuel Cycle Activities

Pakistan is currently fueling (with natural uranium) only its aging Canadian 125 MWe pressurized heavy water power reactor in Karachi, recently derated to 100 MWe. Its other power reactors, four 300 MWe light water reactors and two 1,100 MWe light water reactors, were all supplied together with fuel by China. There is no indication spent fuel from these reactors will be reprocessed.

Pakistan has expressed its intent to set up a centrifuge enrichment plant with 300,000 SWU per year capacity under IAEA safeguards to produce 4-5 percent enriched LEU to fuel light water power reactors.[231] Faisalabad has been identified as the proposed site. This project appears to have been postponed, however, for want of financial resources. In order to enrich uranium on this scale to produce reactor fuel indigenously, Pakistan will need to purchase natural uranium from the world market. This will require approval from the Nuclear Suppliers Group, which adds a large uncertainty to the whole project.

IAEA Safeguards

All of Pakistan's seven power reactors are under IAEA safeguards as are its two research reactors, PARR-1 and PARR-2. The PARR-1 reactor was initially a 5 MWt HEU-fueled reactor (93 percent enriched). The U.S. supplied the HEU fuel from 21 December 1965, and supported conversion to LEU (19.99 percent) and a power upgrade to 10 MWt in 1992. China now supplies the LEU fuel.[232] Activities around the production of medical isotopes in PARR1 and PARR-2 are safeguarded, as is the plant that produces heavy water for KANUPP.

Power reactor spent fuel remains stored in on-site ponds. A dry storage facility is being planned for the spent fuel from the soon to be decommissioned, heavy water reactor, which also would be safeguarded. Pakistan's enrichment plants, production reactors, fuel production facilities and reprocessing plants are not subject to international safeguards.

North Korea

Background

North Korea's nuclear program can be traced back to the early days of the Kim Il Sung era (1948 – 1994). Kim thought the country needed nuclear weapons to deter U.S. attack. The former Soviet Union began training North Koreans on nuclear matters in the early 1950s and, in 1965, provided the DPRK with the 2 MWt light-water-moderated IRT-2000 research reactor.

North Korea launched its nuclear-weapon program in the early 1980s when it started building a 5 MWe graphite-moderated reactor, which was used to irradiate natural-uranium fuel from which plutonium was later extracted.[233] North Korea acquired gas-centrifuge technology from Pakistan during the 1990s and may have produced HEU.[234] It is estimated in 2021 that North Korea so far may have produced fissile material for 40-50 nuclear weapons but assembled perhaps only 10 to 20 warheads.[235]

North Korea has conducted six nuclear tests since October 2006. The yield of the test in September 2017 has been estimated to be 140-250 kilotons, in the range of thermonuclear warheads. Although North Korea ratified the NPT in 1985, it did not accept a comprehensive IAEA safeguards agreement until 1992.[236] It withdrew from the NPT in 2003.

Highly Enriched Uranium

In November 2010, a North Korean chief engineer stated to an American delegation including Siegfried Hecker visiting Yongbyon that the Yongbyon centrifuge facility contained 2,000 centrifuges. Hecker was told that the facility had been completed shortly prior to the visit and was producing 3.5 percent LEU destined for the experimental LWR under construction nearby at the time. A Yongbyon official claimed that the facility had a capacity of 8,000 kg-SWU/year. In late 2013, the floor area of the building housing the centrifuges was approximately doubled, which is assumed to be associated with a doubling of the number of centrifuges. North Korea may have additional undeclared enrichment facilities at Yongbyon or elsewhere.[237]

Although there is no firm evidence that North Korea has produced HEU, it is believed that it has been operating its uranium enrichment facility on a consistent basis since 2013. Extrapolation using assumptions and estimates made by various authors suggests that by the end of 2020 North Korea could have produced between 230 and 1,180 kg of HEU. These values assume that North Korea is operating between 2,000 and 8,700 P2-type centrifuges in Yongbyon and at least one other undisclosed location. This estimate is based on projecting to 2020 three earlier estimates.[238] The minimum value given here reflects the lowest stockpile estimate combined with the lowest estimated production rate, and the maximum value relies on projecting the highest estimate combined with the highest production rate.

Plutonium

The 5 MWe (20-25 MW thermal) plutonium production reactor at Yongbyon began operation in 1986. The reactor is graphite-moderated and fueled with natural uranium metal. The fuel rods are placed in channels in the graphite moderator and cooled by CO_2 gas. The reactor is similar in design to but with a much lower power rating than the British Calder Hall reactors and could produce up to 6 kg of weapon-grade plutonium per year operating on average at 70 percent of capacity.[239] The reactor was shut down in 1994, in accordance with the US–DPRK Agreed Framework. North Korea resumed operation of the reactor in

February 2003 after the breakdown of the Framework in December 2002. The reactor has operated intermittently since, depending on progress or setbacks in its diplomacy with the United States. It seems that the reactor was likely not operated in 2019 and 2020.[240] The IAEA reported that the reactor went back in operation around July 2021.[241]

During the late 1980s, North Korea constructed the Radiochemical Laboratory (a reprocessing facility) in Yongbyon. In 1994, the reprocessing facility had a design capacity to reprocess 220-250 tons of Magnox spent fuel per year (operating 24 hours per day, 300 days per year, using both PUREX processing lines). At that time, the second reprocessing line was nearing completion. The reprocessing facility may actually have a capacity of about 110 tons/year. This is consistent with information that North Korea might have been able to reprocess a full-core load (50 tons) from June to December 2005.[242]

Operation of the reprocessing facility started in 1989. Since that time, North Korea is believed to have reprocessed a full core of irradiated uranium fuel from the 5 MWe reactor five times: in 2003, 2005, 2009, 2016 and 2018.[243] In 2021 the facility has been operated for 5 months which is consistent with the reprocessing of a full core from the 5 MWe reactor.[244]

In 2008, North Korea declared it had extracted 31 kilograms of plutonium from spent nuclear fuel using its reprocessing facility and had used 2 kilograms of that amount in its October 2006 nuclear test. In 2017, it was estimated that North Korea possessed between 23.2 and 37.3 kg of separated weapon-grade plutonium.[245] Taking into account plutonium used in nuclear tests conducted by North Korea, estimates are of a current stockpile of 36.5 ± 11.5 kg of separated plutonium in metallic form.[246] Recent studies using reactor modelling estimate a stockpile of 40.4 ± 8 kg.[247]

The DPRK's Experimental Light-Water Reactor (ELWR) under construction in Yongbyon is a potential source of plutonium in the future. During a 2010 visit to Yongbyon, his North Korean hosts told Hecker that the reactor is designed to produce 25-30 MWe (corresponding roughly to 100 MWt).[248] The reactor would be fueled with uranium dioxide fuel enriched to 3.5 percent uranium-235. It is estimated that the ELWR could produce roughly 20 kg of weapons-grade plutonium per year if operated with a 70-80 percent capacity factor, or that it could produce roughly 10-15 kg of plutonium annually. The reactor has not yet been reported to be in operation.[249]

IAEA Safeguards

The first agreement between North Korea and the IAEA, concluded in 1977, related to safeguards on North Korea's IRT-2000 research reactor. North Korea joined the NPT in 1985 and, in 1992, the original facility-specific safeguard agreement was replaced with an NPT Safeguard Agreement covering all of North Korea's nuclear activities. North Korea provided the IAEA with its initial nuclear declaration and the Agency's first inspection started in 1992. Because of inconsistencies in North Korea's declaration of its plutonium stocks, the IAEA asked several times for access to two potential undeclared reprocessing waste sites without success.

In March 1993, North Korea announced its withdrawal from the NPT but suspended withdrawal a day before it would have entered into force. The crisis was resolved in 1994 with the Agreed Framework which collapsed in 2002 on suspicions that North Korea was engaged in an undeclared uranium enrichment program. North Korea withdrew from the NPT in January 2003.

The IAEA states that it was never able to "verify the correctness and completeness of the DPRK's declarations" in connection with North Korea's 1992 Safeguards Agreement. The Agency notes also that it was unable to engage in any form of safeguards activities between the end of 2002 and July 2007 and since April 2009 when IAEA inspectors were expelled.[250]

Fissile Materials and Nuclear Weapons

Fissile materials are essential in all nuclear weapons, from simple first-generation bombs, such as those that destroyed Hiroshima and Nagasaki more than sixty years ago, to the lighter, smaller, and much more powerful thermonuclear weapons in arsenals today. The most common fissile materials in use are uranium highly enriched in the isotope uranium-235 (HEU) and plutonium. This Appendix describes briefly the key properties of these fissile materials, how they are used in nuclear weapons, and how they are produced.

Explosive Fission Chain Reaction

Fissile materials in quantities that substantially exceed a fast-neutron critical mass can sustain an explosive fission chain reaction. When the nucleus of a fissile atom absorbs a neutron, it will usually split into two smaller nuclei. In addition to these "fission products," each fission typically releases two to three neutrons that can cause additional fissions, leading to a chain reaction in a "critical mass" of fissile material (see Figure A.1). The fission of a single nucleus releases one hundred million times more energy per atom than a typical chemical reaction. A large number of such fissions occurring over a short period of time, in a small volume, results in an explosion. About one kilogram of fissile material – the amount fissioned in both the Hiroshima and Nagasaki bombs – releases an energy equivalent to the explosion of about 18 thousand tons (18 kilotons) of chemical high explosives.

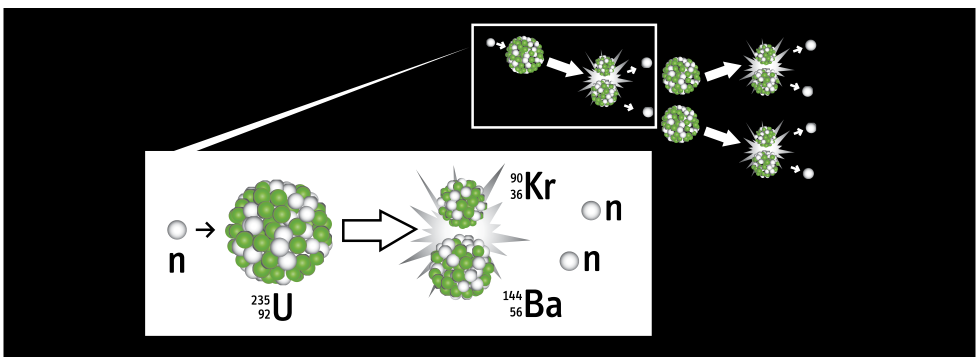

Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission products, which separate at high velocities. Additional neutrons are released in the process, which can set off a chain reaction in a critical mass of fissile materials. The chain reaction proceeds extremely fast; there can be 80 doublings of the neutron population in a millionth of a second, fissioning one kilogram of material and releasing an energy equivalent to 18,000 tons of high explosive (TNT).

The minimum amount of material needed for a chain reaction is defined as the critical mass of the fissile material. A "subcritical" mass will not sustain a chain reaction, because too large a fraction of the neutrons escape from the surface rather than being absorbed by fissile nuclei. The amount of material required to constitute a critical mass can vary widely – depending on the fissile material, its chemical form, and the characteristics of the surrounding materials that can reflect neutrons back into the core. Along with the most common fissile materials, uranium-235 and plutonium-239, the isotopes uranium-233, neptunium-237, and americium-241 are able to sustain a chain reaction.

Nuclear Weapons

Nuclear weapons are either pure fission explosives, such as the Hiroshima and Nagasaki bombs, or two-stage thermonuclear weapons with a fission explosive as the first stage. The Hiroshima bomb contained about 60 kilograms of uranium enriched to about 80 percent in chain-reacting uranium-235. This was a "gun-type" device in which one subcritical piece of HEU was fired into another to make a super-critical mass (Figure A.2, left). Gun-type weapons are simple devices and have been built and stockpiled without a nuclear explosive test. The U.S. Department of Energy has warned that it might even be possible for intruders in a fissile-materials storage facility to use nuclear materials for onsite assembly of an improvised nuclear explosive device (IND) in the short time before guards could intervene.

The Nagasaki bomb operated using implosion, which has been incorporated into most modern weapons. Chemical explosives compress a subcritical mass of material into a high-density spherical mass. The compression reduces the spaces between the atomic nuclei and results in less leakage of neutrons out of the mass, with the result that it becomes super-critical (Figure A.2, right).

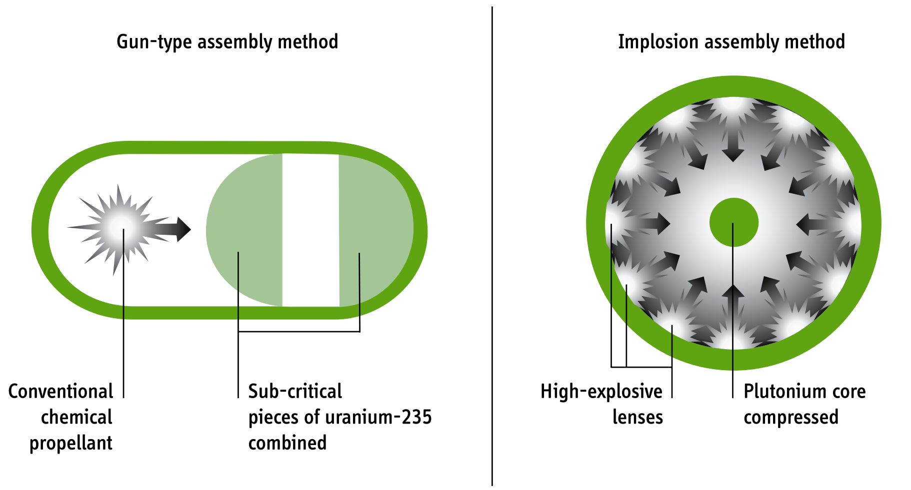

Figure A.2. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated "gun-type" method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow. For plutonium, the faster "implosion" method used in the Nagasaki bomb is required. This involves compression of a mass of fissile material. Much less material is needed for the implosion method, because the fissile material is compressed beyond its normal metallic density. For an increase in density by a factor of two, the critical mass is reduced to one quarter of its normal-density value.

For either design, the maximum yield is achieved if the chain reaction is initiated in the fissile mass at the moment a when it will grow most rapidly, i.e., when the mass is most supercritical. HEU can be used in either gun-type or implosion weapons. As is explained below, plutonium cannot be used in a gun-type device to achieve a high-yield fission explosion.

Because both implosion and neutron-reflecting material around it can transform a subcritical into a supercritical mass, the actual amounts of fissile material in the pits of modern implosion-type nuclear weapons are considerably smaller than a bare or unreflected critical mass. Experts advising the IAEA have estimated "significant quantities" of fissile material, defined to be the amount required to make a first-generation implosion bomb of the Nagasaki-type (see Figure A.2, right), including production losses. The significant quantities are 8 kg for plutonium and 25 kg of uranium-235 contained in HEU, including losses during production. The Nagasaki bomb contained 6 kg of plutonium, of which about 1 kg fissioned. A similar uranium-based first generation implosion weapon could contain about 20 kg of HEU (enriched to 90 percent uranium-235, i.e. 18 kg of uranium-235 in HEU).

The United States has declassified the fact that 4 kg of plutonium is sufficient to make a more modern nuclear explosive device. As the IAEA significant quantities recognize, an implosion fission weapon requires about three times as much fissile material if it is based on HEU rather than plutonium. This suggests a modern HEU fission weapon could contain only about 12 kg of HEU.

In modern nuclear weapons, the yield of the fission explosion is typically "boosted" by a factor on the order of ten by introducing a mixed gas of two heavy isotopes of hydrogen, deuterium and tritium, into a hollow shell of fissile material (the "pit") just before it is imploded. When the temperature of the fissioning material inside the pit reaches about 100 million degrees, it ignites the fusion of tritium with deuterium, which produces a burst of neutrons that increases the fraction of fissile material fissioned and thereby the power of the explosion.

In a thermonuclear weapon (Figure A.3), the nuclear explosion of a fission "primary" generates X-rays that compress and ignite a "secondary" containing thermonuclear fuel, where much of the energy is created by the fusion of the light nuclei, deuterium and tritium. The tritium in the secondary is made during the explosion by neutrons splitting lithium-6 into tritium and helium.

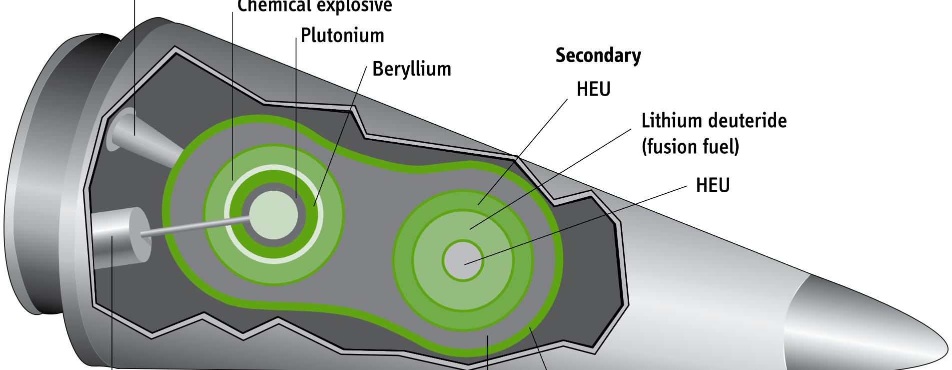

Figure A.3. A modern thermonuclear weapon usually contains both plutonium and highly enriched uranium. Typically, these warheads have a mass of about 200-300 kg and a yield of hundreds of kilotons of chemical explosive, which corresponds to about one kilogram per kiloton of explosive yield. For comparison, the nuclear weapons that destroyed Hiroshima and Nagasaki weighed 300 kg per kiloton. Source: Adapted from Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China, U.S. House of Representatives, Washington, DC, 1999. See Volume I, Chapter 2, "PRC Theft of U.S. Thermonuclear Warhead Design Information," p. 78.

Modern nuclear weapons generally contain both plutonium and HEU (Figure A.3). The primary fission stage of a thermonuclear weapon can contain either plutonium or HEU or both (the last is known as a composite core or pit). HEU also is often added to the secondary stage as a 'spark-plug' to generate neutrons from a fission chain reaction to begin the production of tritium from the lithium-6 to and to increase its yield. Natural or depleted uranium is also used in the outer radiation case, which confines the X-rays from the primary while they compress the thermonuclear secondary. Fast neutrons from thermonuclear reaction also induce fission in the U-238, which can contribute one-half of the energy yield of the secondary.

A rough estimate of average plutonium and HEU in deployed thermonuclear weapons can be obtained by dividing the estimated total stocks of weapon fissile materials possessed by Russia and the United States at the end of the Cold War by the numbers of nuclear weapons that each deployed during the 1980s: about 4 kg of plutonium and 25 kg of HEU. Many of the older U.S. and Russian strategic weapons had yields in excess of 1 MT and may have contained more than 25 kg HEU. The lower yield thermonuclear weapons deployed today (typically around 100–500 kt) could contain 10-20 kg of HEU (Table A.1).

	Plutonium	HEU	Yield	Example
IAEA Significant Quantity (SQ)	8 kg	25 kg*		
1st-generation gun-type weapon	n/a	50-60 kg	20 kt	Hiroshima
1st-generation implosion-type weapon	5-6 kg	15-18 kg	20 kt	Nagasaki (6 kg Pu)
2nd-generation single-stage weapon	4-5 kg	12 kg	40-80 kt	(levitated or boosted pit)
Two-stage low-yield weapon	3-4 kg Pu and 4-7 kg HEU		100-160 kt	W76
Two-stage medium-yield weapon	3-4 kg Pu and 15-25 kg HEU		300-500 kt	W87/W88

Table A.1. Nuclear weapon generations and estimated respective fissile material quantities. Warhead types are U.S. warhead-designations. The estimates assume about 18 kt per kilogram of nuclear material fissioned, a fission-fraction of 50 % for a 2nd-generation and two-stage weapon, and a yield fraction of 50 % in the secondary from fission in the two-stage weapon. *The significant quantity specifies uranium-235 contained in highly enriched uranium.

Production of Fissile Materials

Fissile materials that can be directly used in a nuclear weapon do not occur in nature. They must be produced through complex physical and chemical processes. The difficulties associated with producing these materials remains the main technical barrier to the acquisition of nuclear weapons.

Highly Enriched Uranium (HEU)

In nature, uranium-235 makes up only 0.7 percent of natural uranium. The remainder is almost entirely non-chain-reacting uranium-238. Although an infinite mass of uranium with a uranium-235 enrichment of 6 percent could, in principle, sustain an explosive chain reaction, weapons experts have advised the IAEA that uranium enriched to above 20 percent uranium-235 is required to make a fission weapon of practical size. The IAEA therefore considers uranium enriched to 20 percent or above "direct use" weapon-material and defines it as HEU. To minimize their masses, however, actual weapons typically use uranium enriched to 90-percent uranium-235 or higher. Such uranium is sometimes defined as "weapon-grade."

The isotopes uranium-235 and uranium-238 are chemically virtually identical and differ in weight by only about one percent. To produce uranium enriched in uranium-235 therefore requires sophisticated isotope separation technology. The ability to do so on a scale sufficient to make nuclear weapons or enough low-enriched fuel to sustain a large power reactor is found in only a relatively small number of nations.

In a uranium enrichment facility, the process splits the feed (usually natural uranium) into two streams: a product stream enriched in uranium-235, and a waste (or "tails") stream depleted in uranium-235.

All countries that have built new enrichment plants during the past three decades have chosen centrifuge technology. Gas centrifuges spin uranium hexafluoride (UF6) gas at enormous speeds, so that the uranium is pressed against the wall with more than 100,000 times the force of gravity. The molecules containing the heavier uranium-238 atoms concentrate slightly more toward the wall relative to the molecules containing the lighter uranium-235. An axial circulation of the UF6 is induced within the centrifuge, which multiplies this separation along the length of the centrifuge, and increases the overall efficiency of the machine significantly (see Figure A.4 for an illustration).

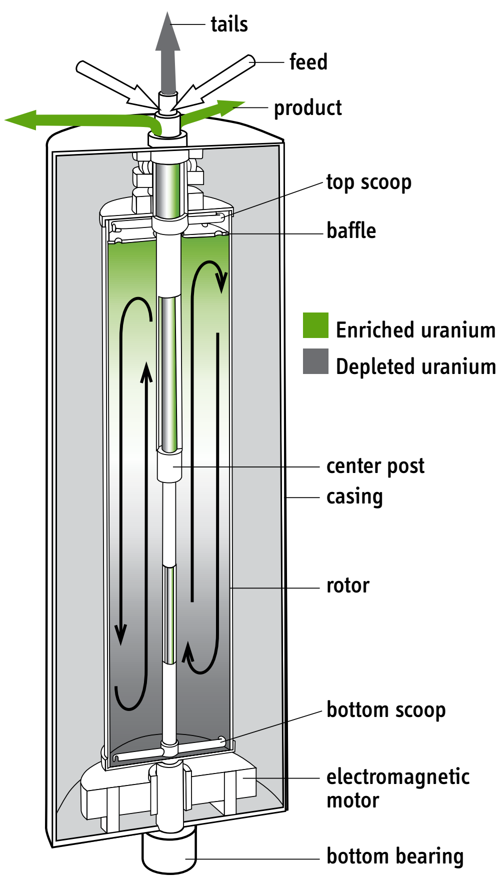

Figure A.4. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small scale prior to and during World War II, but the technology only became economically competitive in the 1970s. Today, centrifuges are the most economic enrichment technology, but also the most proliferation-prone.

Gaseous diffusion enrichment, invented during the Manhattan Project, exploits the fact that, in a uranium-containing gas, the lighter molecules containing uranium-235 move more quickly through the pores in a barrier than those containing uranium-238. The effect is only a few tenths of a percent, however, and the molecules have to be pumped through thousands of barriers before HEU is produced.

A third enrichment method, electromagnetic separation, involves introducing a beam of uranium-containing ions into a magnetic field and separating it into two beams by virtue of the fact that the path of the electrically charged ions containing the heavier uranium-238 atoms is bent less than that of the lighter U-235 ions by the magnetic field. This method of enrichment was used by the United States during the World War II Manhattan Project and attempted by Iraq in the late 1980s. It is no longer in use.

Plutonium

Plutonium is an artificial isotope produced in nuclear reactors after uranium-238 absorbs a neutron creating uranium-239. The uranium-239 subsequently decays to plutonium-239 via the intermediate short-lived isotope neptunium-239.

The longer an atom of plutonium-239 stays in a reactor after it has been created, the greater the likelihood that it will absorb a second neutron and fission or become plutonium-240 – or absorb a third or fourth neutron and become plutonium-241 or plutonium-242. Plutonium therefore comes in a variety of isotopic mixtures.

The plutonium in typical power-reactor spent fuel (reactor-grade plutonium) contains 50–60 percent plutonium-239, and about 25 percent plutonium-240. Weapon designers prefer to work with a mixture that is as rich in plutonium-239 as feasible, because of its relatively low rate of generation of radioactive heat and relatively low spontaneous emissions of neutrons and gamma rays (Table A.2). Weapon-grade plutonium contains more than 90 percent of the isotope plutonium-239 and has a critical mass about three-quarters that of reactor grade plutonium.

Isotope	Bare Critical Mass [kg]	Half Life [years]	Decay Heat [watts/kg]	Neutron Generation [neutrons/g-sec]
Pu-238	10	88	560	2600
Pu-239	10	24,000	1.9	0.02
Pu-240	40	6,600	6.8	900
Pu-241	13	14	4.2	0.05
Pu-242	80	380,000	0.1	1700
Am-241	60	430	110	1.2
WPu (94% Pu-239)	10.7		2.3	50
RPu (55% Pu-239)	14.4		20	460

Table A.2. Key properties of plutonium isotopes and Am-241 into which Pu-241 decays. Data from: U.S. Department of Energy, "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems," in *Technological Opportunities to Increase the Proliferation Resistance of Global Nuclear Power Systems*, TOPS, Washington, DC, U.S. Department of Energy, Nuclear Energy Research Advisory Committee, 2000, www.ipfmlibrary.org/doe00b.pdf, p. 4; see also, J. Kang et al., "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel," *Science & Global Security*, Vol. 13, 2005, p. 169. WPu is typical weapon-grade plutonium, and RPu is typical reactor-grade plutonium.

For a time, many in the nuclear industry thought that the plutonium generated in power reactors could not be used for weapons. It was believed that the large fraction of plutonium-240 in reactor-grade plutonium would reduce the explosive yield of a weapon to insignificance. Plutonium-240 fissions spontaneously, emitting neutrons. This increases the probability that a neutron would initiate a chain reaction before the bomb assembly reached its maximum supercritical state. This probability increases with the percentage of plutonium-240.

For gun-type designs, such “pre-detonation” reduces the yield a thousand-fold, even for weapon-grade plutonium. The high neutron-production rate from reactor-grade plutonium similarly reduces the probable yield of a first-generation implosion design – but only about ten-fold, because of the much shorter time for the assembly of a supercritical mass. In a Nagasaki-type design, even the earliest possible pre-initiation of the chain reaction would not reduce the yield below about 1,000 tons TNT equivalent. That would still be a devastating weapon.

More modern tritium-boosted nuclear weapon designs are insensitive to the isotopic mix in the plutonium. As summarized in a 1997 U.S. Department of Energy report:[251] “Virtually any combination of plutonium isotopes ... can be used to make a nuclear weapon.” The report recognizes that “not all combinations, however, are equally convenient or efficient,” but concludes that “reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states.”

For use in a nuclear weapon, the plutonium must be separated from the irradiated uranium and the highly radioactive fission products that it contains. Separation of the plutonium is done in a chemical “reprocessing” operation, behind heavy shielding and with remote handling. Reprocessing requires both resources and technical expertise. Detailed descriptions of the standard PUREX separation process have been available in the published technical literature, however, since the “Atoms for Peace” Conferences of the 1950s and 60s.

Spent fuel can only be handled remotely, due to the very intense radiation field generated by the fission products that it contains. This makes its diversion or theft a rather unrealistic scenario. Separated plutonium can be handled without radiation shielding, but is extremely dangerous if inhaled.

Endnotes

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The NPT entered into force in 1970.
It is part of the international effort to address the threat from existing nuclear weapon arsenals and to halt proliferation of nuclear weapons to additional states, including through the diversion of nuclear energy and materials from peaceful uses to nuclear weapons.

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