IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2015

Nuclear Weapon and Fissile Material Stockpiles and Production

Eighth annual report of the International Panel on Fissile Materials

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On the cover: the map shows existing uranium enrichment and plutonium separation (reprocessing) facilities.

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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.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in more than one hundred locations. The total amount used for this purpose is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University. Its 31 members include nuclear experts from Brazil, China, France, Germany, India, Iran, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, 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.

IPFM's initial support is provided by grants to Princeton University from the John D. and Catherine T. MacArthur Foundation of Chicago and the Carnegie Corporation of New York.

Summary

The year 2015 marks the seventieth anniversary of the first production of fissile materials in quantities large enough to use for a nuclear weapon and of the first use of such weapons. The bomb that exploded over Hiroshima used uranium highly enriched in the isotope uranium-235 (HEU) and the weapon at Nagasaki used plutonium.

Global Fissile Material Report 2015 provides updated estimates for global and national stockpiles of HEU and plutonium, and recent developments in military and civilian fissile material production capabilities. This is the eighth *Global Fissile Material Report* by the International Panel on Fissile Materials.

In 2015, the global stockpile of nuclear weapons was estimated at over 15,800 weapons, with the United States and Russia together holding about 14,700 of these weapons and the other seven nuclear weapon states holding a combined total of about 1100 weapons.

The global stockpiles of HEU and plutonium presented in the report are for the end of 2014. This is because the most recent civilian plutonium holdings declared by the United States, United Kingdom, Russia, France, China, Japan and Germany are for the end of December 2014. These declarations are published as annual INFCIRC/549 reports by the International Atomic Energy Agency.

The global stockpile of HEU at the end of 2014 was about 1370 ± 125 tons, enough for more than 76,000 simple, first generation fission implosion weapons. About 99 percent of this material is held by the nuclear weapon states, mostly by Russia and the United States. The large uncertainty in the HEU estimate is due to a lack of official information about Russia's historical production of HEU. The uncertainty in the size of the Russian HEU stockpile is larger than the total HEU stocks held by all other states except for the United States.

In 2014, for the first time in about two decades, the global HEU stockpile stopped shrinking and remained nearly constant after Russia ended its down blending of HEU to low-enriched uranium for sale to the United States. Since 1995 Russia had been down-blending 500 tons of HEU that it had declared as excess to military needs at a rate of about 30 tons per year for shipment to the United States where it is used for power reactor fuel. December 2013 marked the final shipment in this program. No additional HEU has been declared excess by Russia since 1995.

The United States has about 40 tons of HEU remaining to be blended down of the 187 tons it has committed to dispose in this way. The down-blending of this material is scheduled to be completed by 2030. No additional HEU has been declared excess to military needs in the past decade by the United States.

The United States, United Kingdom, Russia, France and China all stopped producing HEU for weapons, in some cases decades ago. Today, only India, Pakistan and possibly North Korea are believed to be producing HEU for weapons purposes. But their programs are relatively small scale. In 2012, Russia announced that it would restart HEU production to meet the need for reactor fuel. It may be producing on the order of a few hundred kilograms per year, mostly for export to Europe as research reactor fuel.

The non-nuclear weapon states account for an estimated 15 tons of HEU, almost all of which was provided to them as research reactor fuel by the weapon states. This stockpile is declining as research reactors are closed down or converted to low-enriched uranium fuel and fresh and spent HEU fuel is returned to the country of origin, mostly the United States and Russia. As of the end of 2014, all HEU has been removed from 27 non-nuclear weapon states as part of these efforts.

The global stockpile of separated plutonium as of the end of 2014 was about 505 ± 10 tons. Less than half of this stockpile was produced for weapons. The majority of the global plutonium stockpile is the result of civilian programs in nuclear weapon states, some of it for foreign customers. As a result, about 98 percent of all separated plutonium is stored in the nuclear weapon states.

The stockpile of separated plutonium for weapons continues to increase because of continued production in Israel, India, and Pakistan. North Korea's plutonium production reactor showed signs of occasional periods of operation in 2014 and 2015. The other nuclear weapon states have ended production, in most cases decades ago.

As of late 2015, the United States and Russia have still not started verifiably disposing of the 34 tons of plutonium that each declared as excess to weapon purposes. These efforts were established under the Plutonium Management and Disposition Agreement (PMDA) of 2000. The U.S. program, which called for the plutonium to be turned into mixed plutonium-uranium oxide (MOX) power reactor fuel and irradiated, has faced rapidly increasing costs and delays and alternative options are now being considered.

There are about 53 tons of plutonium owned by the non-weapon states, most of which is in storage in France and the United Kingdom, and belongs to Japan. This plutonium, separated from power reactor spent fuel, was originally contracted to be returned as MOX fuel. In 2014, some non-weapon states chose to transfer the ownership to France and the United Kingdom so that it can be disposed of rather than returned. The operation of Japan's Rokkasho reprocessing plant continued to be delayed for technical problems and new safety rules put in place after the March 2011 Fukushima accident.

Nuclear Weapons

The first nuclear weapon was assembled 70 years ago by the United States and tested on 16 July 1945. There are today nine nuclear-weapon states: in historical order, the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan, and North Korea.

Figure 1. Decades of nuclear weapon design, development and testing has allowed for a many-fold decrease in warhead size while enabling large increases in destructive power. Left: the very first nuclear explosive ever tested (the Trinity test on 16 July 1945) had a yield of about 20 kilotons and was the basis for the simple first-generation fission bomb that destroyed Nagasaki on 9 August 1945; right: a mock-up U.S. W80-4 cruise missile thermonuclear warhead (scheduled for deployment in 2025) which will be an upgraded W80-1 warhead with a yield that can be as high as 150 kilotons. *Sources: Los Alamos National Laboratory and Sandia National Laboratory.*

The number of nuclear weapons worldwide peaked at over 60,000 in the 1980s. Since the end of the Cold war in 1990, the United States, Russia, the United Kingdom and France (the first four states to develop nuclear weapons) have been reducing their deployed arsenals from Cold War peaks that were in some cases many times larger than the respective arsenals today. China and Israel, the fifth and sixth states respectively to make nuclear weapons, did not produce such large weapons stockpiles and they are believed to have kept their arsenals roughly constant for the past few decades.

India and Pakistan, which carried out their first nuclear tests in 1974 and 1998 respectively, are building up their weapon stockpiles. North Korea, which carried out its third nuclear test in February 2013, also may be building up its arsenal. None of these states have indicated how many warheads they plan to make before their respective arsenal is considered to be of sufficient size.

Estimates of the current nuclear-weapon stocks held by the nine nuclear weapon states as of late 2015 are shown in Table 1. The United States and Russia together hold about 14,700 nuclear warheads, while the other seven nuclear weapon states hold together about 1100 warheads.

Country	Date of first nuclear test	Current nuclear warheads
United States	1945	~7200, of which about 2500 are awaiting dismantlement
Russia	1949	~7500, with a large fraction awaiting dismantlement
United Kingdom	1952	215
France	1960	Fewer than 300
China	1964	~260
India	1974	110 – 120
Israel	1979*	80
Pakistan	1998	120 – 130
North Korea	2006	fewer than 10

Table 1. Date of first nuclear test and estimated total nuclear-weapon stockpiles as of 2015.
Source: Federation of American Scientists, Status of World Nuclear Forces, updated September 2015.

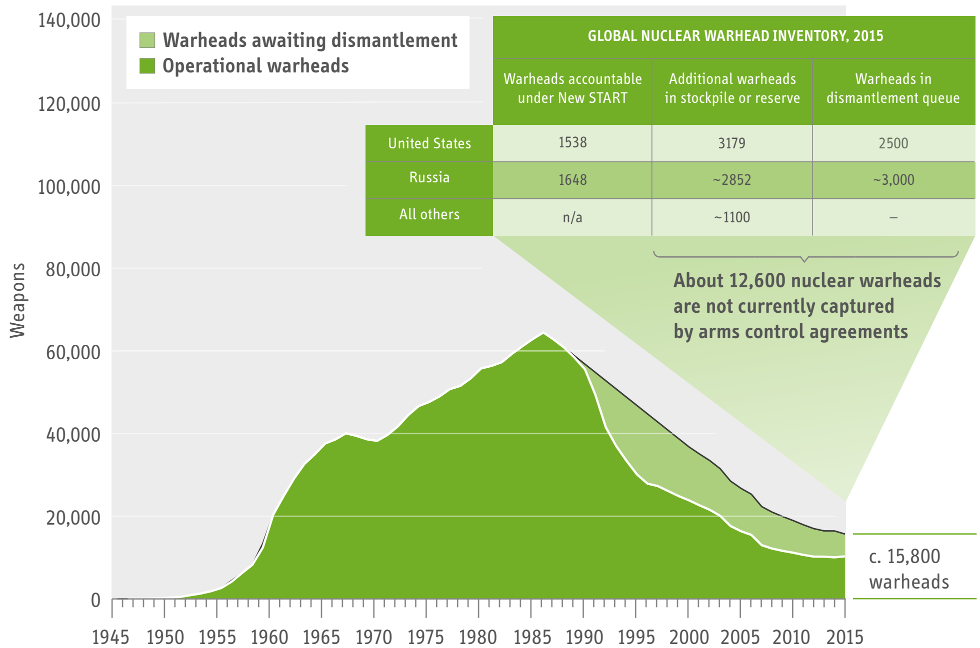
* Possible nuclear test by Israel in the Southern Indian Ocean on 22 September 1979.

United States and Russia

As of late 2015, the two countries continued to make uneven progress towards meeting the agreed limits on deployed strategic warheads and launchers set by the bilateral New START which entered into force in early 2011. Under New START, the United States and Russia agreed to limit themselves to a total of no more than 1550 strategic nuclear warheads on 700 deployed launchers by 2018. Launchers include deployed inter-continental ballistic missile, submarine launched ballistic missiles, and heavy bombers (which can be armed with nuclear-tipped cruise missiles or bombs).

New START declarations for 1 September 2015 show Russia had 1648 accountable warheads and 526 launchers, and the United States had 1538 warheads and 762 deployed launchers.[1] These deployed warheads are only a fraction of the total warheads held by each country. The number of warheads held as reserve by each country is significantly larger than the currently deployed warheads counted under New START. Both countries also have more warheads in the dismantlement queue than are currently deployed.

Figure 2 shows the rise and fall of the global nuclear weapons stockpile and the estimated number of Cold War legacy warheads awaiting dismantlement and those that are subject to international monitoring under New START.



GLOBAL NUCLEAR WARHEAD INVENTORY, 2015	Warheads accountable under New START	Additional warheads in stockpile or reserve	Warheads in dismantlement queue
United States	1538	3179	2500
Russia	1648	~2852	~3,000
All others	n/a	~1100	–

Figure 2. The evolution of global nuclear weapon stockpiles 1945 – 2015 and the numbers currently covered by international monitoring. The global stockpile peaked at the end of the cold war and has gradually decreased since. The rapid drop in the early 1990s led to the buildup of a dismantlement queue. Reductions in the global stockpile of nuclear weapons and in the size of the dismantlement queue have slowed significantly over the past decade. *Sources: Hans M. Kristensen and Robert S. Norris, "Global Nuclear Weapons Inventories, 1945 – 2013," Bulletin of the Atomic Scientists, 69 (5), 2013, 75 – 81; Federation of American Scientists, "Status of World Nuclear Forces," September 2015; and New START Treaty Aggregate Numbers of Strategic Offensive Arms, US State Dept. Bureau Of Arms Control, Verification And Compliance Fact Sheet, 1 October 2015.*

United States

In April 2015, speaking at the nuclear Non-Proliferation Treaty (NPT) Review Conference in New York, U.S. Secretary of State John Kerry announced that "As of September 2014, the number of nuclear weapons in our stockpile has fallen to 4717… with another approximately 2500 warheads retired and in the queue for elimination."[2] This declaration updated and improved on an official fact sheet "Transparency in the U.S. Nuclear Weapons Stockpile" issued in 2014 that had given the number of warheads as of September 2013 but referred only to "several thousand additional nuclear weapons [that] are currently retired and awaiting dismantlement."[3]

The 2014 fact sheet revealed that from 1994 through 2013 the United States dismantled a total of 9952 nuclear warheads, of which 239 warheads were dismantled in 2013 – close to the lowest number of warheads dismantled in any year over the past two decades. In his 2015 remarks, Kerry also made public that a further 299 warheads had been dismantled as of September 2014 and the United States would try to increase its annual warhead dismantlement rate by 20 percent in coming years.

The current slow pace of U.S. nuclear warhead dismantlement (about one-fifth the rate achieved in 1995, when 1393 warheads were dismantled) coincides with a policy of modernization of the nuclear arsenal, including upgrading warheads and developing new delivery systems, as well as renewing the nuclear weapons research and design and production complex. The cost of this effort has been projected as $350 billion in the decade from 2014 to 2023.[4] Many of these modernization programs will only complete their research and development phase by 2023, however. Most of the actual costs of buying the next generation intercontinental ballistic missiles, submarine-launched ballistic missiles and submarines, bombers and air-launched cruise missiles, will be incurred after 2023.

Russia

Unlike the United States, Russia has not declared the size of its nuclear warhead stockpile apart from the small portion covered by New START.

Russia also is modernizing its nuclear arsenal, in particular by replacing its Soviet-era delivery systems. This includes deployment of new silo based and mobile intercontinental ballistic missiles, with a shift towards greater reliance on mobile systems; new submarine launched ballistic missiles, and a class of nuclear-powered ballistic missile submarines; and a new nuclear-capable long-range bomber and long-range nuclear-armed cruise missile.[5] Russia also is upgrading some tactical nuclear weapons, as is the United States. This nuclear weapons modernization program is expected to have a very large cost.

United Kingdom

In January 2015, the U.K. government announced that it had "achieved our commitment to reduce the number of operationally available warheads to no more than 120."[6] This goal had been set as part of the 2010 Strategic Defence and Security Review which committed the United Kingdom to reduce its "operationally available warheads from fewer than 160 to no more than 120" and cut the "overall nuclear weapon stockpile to no more than 180."[7] This suggests the United Kingdom now has about 60 warheads in reserve (i.e., about half the number of its deployed warheads).

The United Kingdom is in the process of deciding whether and how to replace its fleet of four Vanguard class ballistic missile submarines, its only nuclear weapons platform. A decision is expected in 2016. On patrol each submarine now carries at most eight nuclear-armed Trident-2 D5 nuclear missiles, with a total of forty warheads on each boat. The missiles are leased from the United States while the nuclear warheads are produced by the United Kingdom.

The fissile material from dismantled U.K. warheads is returned to the Ministry of Defense stockpile. It has not been declared as excess for weapon purposes.

France

In 2015, President Francois Hollande reaffirmed that the planned reduction to 300 warheads meant France now had "half the total number of its weapons" previously, with nuclear warheads currently deployed on "three sets of 16 submarine-borne missiles and 54 ASMPA delivery systems" (Air-Sol Moyenne Portée-A air-launched cruise missiles).[8] France has declared previously that "All decommissioned weapons have been dismantled," and that "it possesses no non-deployed weapons. All its weapons are operational and deployed."[9]

France has not provided any information on the status of the fissile material recovered from the 300 warheads it has removed from service and dismantled. It is presumably retained in the military stockpile.

President Hollande also described France's nuclear arsenal modernization plans as involving deployment starting in 2016 of a new warhead (the Oceanic Nuclear Warhead) for its submarine launched ballistic missiles and the start of design work on the next generation submarine-launched ballistic missiles and the submarines to deploy them, as well as a follow-on cruise missile to replace the ASMPA.

China

The estimated 260 warheads held by China as of 2015 include 230 warheads that are deployed or available to be deployed (China does not keep warheads mated with its missiles under normal operating conditions).[10] A total of about 30 warheads are believed to be spares and warheads waiting dismantlement. As part of its nuclear arsenal modernization, it is possible that China may be increasing the number of warheads available to be deployed.

China's nuclear weapons modernization has focused on moving to longer-range and less vulnerable systems.[11] This includes replacing large liquid fueled missiles by solid fuel road mobile missiles, an improved submarine launched ballistic missile and new air-launched cruise missile. China also may have started to put multiple independently-targetable warheads on some of its DF-5 silo-based intercontinental ballistic missiles. France, Russia, the United Kingdom and the United States already deploy multiple warhead missiles.

Israel

A reassessment of Israel's nuclear arsenal in 2014 suggests it may have on the order of 80 nuclear warheads that can be delivered by aircraft, land-based ballistic missiles, and possibly sea-based cruise missiles.[12] Previous estimates have ranged from 75 warheads to more than 400 warheads. IPFM has previously assumed a range of 100–200 warheads which would be consistent with estimates for Israel's fissile material stockpile.

India

India continues to build up its nuclear arsenal and as of 2015 may have 110 to 120 nuclear warheads.[13] In late 2014, India began sea trials of its *Arihant* nuclear powered ballistic missile submarine.[14] Launched in July 2009, the submarine was supposed to begin sea trials in 2010 and be ready to be deployed by 2011.[15] The delay is explained as being due to caution on the part of the safety regulatory authority.[16] Work on a second nuclear submarine, INS *Aridaman*, is also several years behind schedule – it was originally planned to be ready for launch at the end of 2012 or in early 2013 – and a third vessel was under construction.[17]

In February 2015, India launched a program to build six nuclear-powered attack submarines.[18] India currently operates a Russian Akula-II nuclear-powered attack submarine on a 10-year lease and may acquire a second vessel of the same class.[19]

Pakistan

Pakistan also continued to develop its nuclear arsenal. In 2014 and 2015, it tested a ballistic missile with a range of 2750 km, an air-launched cruise missile with a range of 350 km, as well as a 60 km range nuclear-capable missile for use on the battlefield. It is uncertain which of these nuclear weapons systems will eventually be deployed.

Pakistan may be seeking nuclear armed cruise missiles that could be fired from ships or submarines.[20] Pakistan's Naval Strategic Force Command was established in 2012 and charged with development and use of a "2nd strike capability," but it is not known if this command has yet been issued any nuclear weapons.[21] In 2015, Pakistan agreed a deal with China for the supply of eight diesel-electric submarines.[22] Pakistan also may be working on a nuclear reactor for a possible nuclear-powered submarine to match Indian capabilities.[23]

North Korea

In 2015, North Korea claimed to have developed compact warheads that could be delivered by its ballistic missiles.[24] Previously, in February 2013, North Korea had carried out a test of a "miniaturized and lighter nuclear device with greater explosive force than previously."[25] There were earlier nuclear weapon tests in 2006 and 2009, and possibly one in 2010. North Korea also claimed to have successfully tested the underwater launch of a ballistic missile as part of its efforts to develop a submarine-launched ballistic missile capability.[26]

Highly Enriched Uranium

In 1944, the United States began the production of HEU as part of the Manhattan Project. Some of the first HEU produced was used in the Hiroshima bomb in August 1945. Since then the Soviet Union, United Kingdom, France, China, South Africa and Pakistan all have produced HEU for weapons.

It is possible that India and North Korea may have produced HEU for weapons since they have the capability to do so. Israel is believed to be alone among the weapon states in not having any significant domestic HEU production for weapons but may have a small HEU stockpile acquired from elsewhere. So far, no state has launched a purely civilian program to produce HEU. Table 2 gives the dates of HEU production by country. Appendix 2 lists operational enrichment plants.

	HEU	
	Production Start	**Production End**
United States	1944	1992
Russia	1949	1987–88 (2012–)
United Kingdom	1953	1963
China	1964	1987–89
France	1967	1996
South Africa	1978	1990
Pakistan	1983	Continuing
India	1992	Continuing
Israel	?	?
North Korea	?	?

Table 2. **HEU production histories.** Along with use in nuclear warheads, HEU also has been used as naval reactor fuel and as research reactor fuel. HEU production rates as of 2015 are estimated to be less than one percent of historical global peak production rates in the early 1960s.

HEU production rates peaked in the period 1960–1963, with the United States producing over 40 tons per year at the Portsmouth Gaseous Diffusion Plant and over 30 tons per year at the Oak Ridge Gaseous Diffusion Plant (for material enriched to over 90 percent in uranium-235, typical of that used for weapons).[27] Production of HEU for weapons by the United States ended in 1964, but production continued of HEU for naval reactor fuel. HEU production ended in 1992, soon after the end of the Cold War.

The Soviet Union produced significantly more HEU than the United States over all. Estimated Soviet production rates reached about 50 tons of HEU per year in the late 1960s and persisted through the 1970s. Although the Soviet Union announced an end to production of HEU for weapons in 1988–1989, production for non-weapon purposes continued until at least mid-2000s. In 2012, Russia announced it was resuming HEU production on a small scale for civilian reactor fuels.

The global stockpile of HEU has been declining since the early 1990s as Russia and the United States blended down HEU declared as excess for weapons and military purposes into low-enriched uranium (LEU) for use as fuel in power reactors (Figure 3).

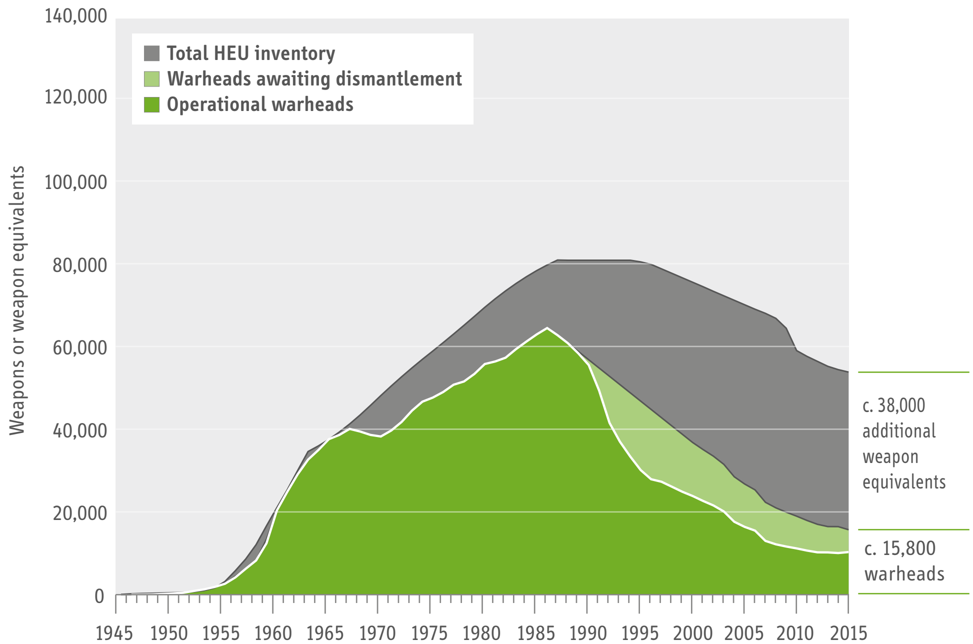


Figure 3. Global inventory of weapon-grade highly enriched uranium 1945 – 2015. A significant fraction of the global HEU inventory has been eliminated since the end of the Cold War; this includes 500 tons of Russian HEU that have been down-blended to low-enriched uranium and used as fuel in U.S. power reactors. Still, as of 2015, the HEU global stockpile is sufficient for about 55,000 nuclear weapons compared to about 16,000 that are in the nuclear arsenals. A large fraction of this overhang is reserved for future use in naval 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) releases an explosive yield of about 250 kt(TNT).

The most significant reduction has been due to Russia's blending down of 500 tons of HEU from its weapons – the equivalent of about 20,000 nuclear weapons – as a result of a deal with the United States.[28] The agreement was first suggested in 1991 by Thomas Neff.[29] It was signed by the two countries in 1993 and the first shipment of blended down Russian HEU took place in 1995. Russia completed this HEU blend down program in 2013. As of the end of 2014, Russia and the United States had together blended down over 660 tons of excess HEU. No additional HEU has been declared excess since the U.S. announcement of 2005, most of the 200 tons then declared excess was assigned to a naval fuel reserve.

The current global inventory of HEU is estimated to be about 1370 ± 125 tons. About 99 percent of this material is held by the nuclear weapon states, and most of it belongs to Russia and to the United States. This includes military HEU held by the nuclear weapon states and civilian HEU held both by the weapon states and the non-weapon states (see Figure 4).

The uncertainty in this estimate, of at least 120 tons, is larger than the combined HEU stockpiles of all the nuclear weapons 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 size 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 annually their respective civilian HEU stockpile. The other nuclear weapon states release no information on their HEU holdings.

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, or a possible second enrichment plant, is producing HEU.

Non-weapon states hold a small amount of HEU, estimated to be about 15 tons, which was provided to them as civilian research reactor fuel. In the case of South Africa, its HEU is the legacy of its nuclear weapons program, which ended in 1990. All the HEU in non-weapon states, including South Africa, is declared to and monitored by the International Atomic Energy Agency (IAEA).

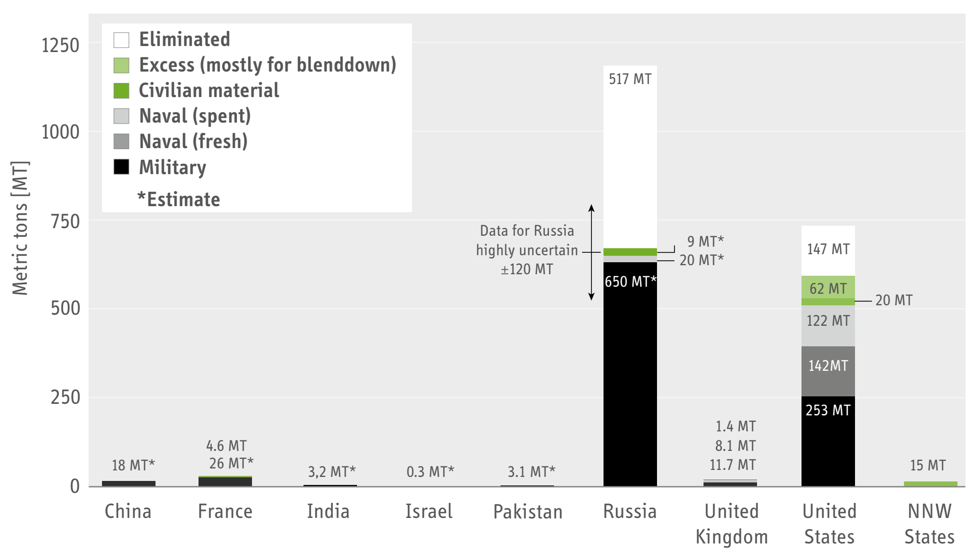


Figure 4. National stocks of highly enriched uranium as of the end of 2014. The numbers for the United Kingdom and United States are based on official publications and statements. The civilian HEU stocks of France and the United Kingdom are based on their public declarations to the IAEA. Numbers with asterisks are IPFM estimates, often with large uncertainties. A 20% uncertainty is assumed in the figures for total stocks in China and for the military stockpile in France, about 30% for Pakistan, and about 40% for India. The 517 tons of eliminated Russian HEU include 500 tons from the "megatons to megawatts" deal with the United States and 17 tons from the Material Consolidation and Conversion project. 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%.

Military HEU

The global stockpile of military HEU is estimated to be about 1257 ± 120 tons. This is material held by the nuclear weapon states and includes material in warheads and available for warheads, and reserved for naval fuel (and in spent naval fuel) This total does not include HEU for research reactor fuel or declared as excess for military purposes and to be downblended or otherwise disposed or HEU that weapon states have declared as civilian.

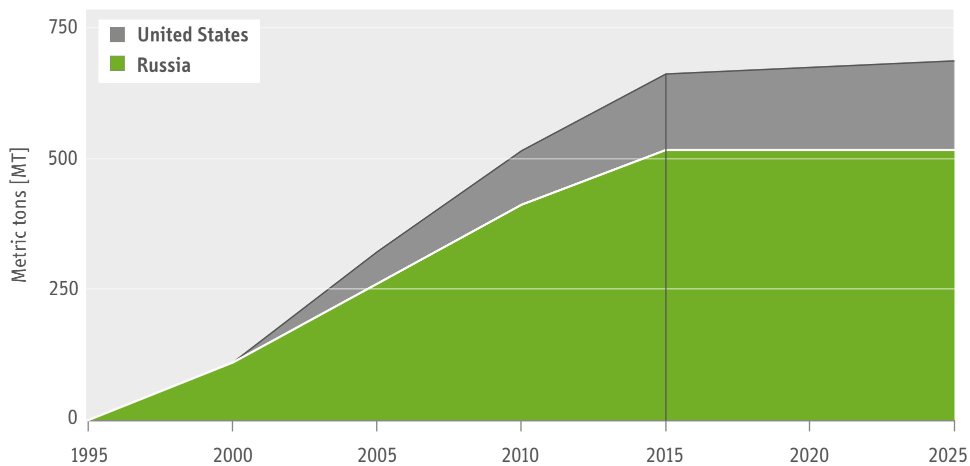


Figure 5. Annual blend down of HEU by Russia and the United States since 1995, and projection for the next decade (to 2025). Since 1995 Russia and the United States have together blended down about 662 tons of excess HEU into LEU, as of the end of 2014. While Russian blend down has ended, the United States plans to complete its much smaller blend program by 2030. Neither Russia nor the United States have announced any additional HEU excess in the past decade, the projection therefore assumes no additional HEU will become available for blend down other that the material already assigned.

Russia

As of the end of 2014, Russia had an estimated 650 tons of military HEU (90 percent HEU equivalent). Unlike the United States, there is no HEU stockpile that is declared or obligated as a naval fuel reserve or non-military material. Russia has an additional estimated 20 tons of HEU (8 tons 90 percent HEU equivalent) in the cores of operational submarines and military and civilian surface ships. The material in discharged naval cores is not included in the current stock since the enrichment of uranium in these cores is believed to be less than 20 percent uranium-235, so it is no longer classified as HEU. There is another 9 tons of HEU (6 tons 90 percent HEU equivalent) in various research facilities, which is considered civilian. In Russia, stored spent naval fuel, as well as stored spent research reactor fuel, is reprocessed.

In November 2013 Russia shipped the last batch of low-enriched uranium under the U.S.-Russian HEU-LEU program (also known as "Megatons to Megawatts"). The uranium was to be used to manufacture fuel for U.S. nuclear power plants. There are no indications of a follow-on arrangement to declare additional Russian HEU excess and to be blended down (Figure 5).

United States

The United States has a HEU stockpile estimated to be about 600 tons, of which 253 tons are believed to be in weapons or available for weapons. The United States stockpile is falling as it continues to dispose of the 187 tons of HEU it has declared excess and to be downblended into low-enriched uranium.[30] This amount includes 153 tons of HEU out of 175 tons declared excess in 1994 and 28 tons assigned for downblending from 200 tons of HEU declared excess in 2005, as well as 6 tons of other HEU, including U.S. origin HEU research reactor fuel that had been exported and has been returned as part of the effort to end the civilian use of such fuel. As of the end of December 2014, 146.6 tons of HEU had been down-blended or shipped for down-blending; of this total 146.1 tons had been down-blended and 0.5 tons had been shipped.[31]

According to the U.S. Department of Energy "The overall amount of HEU available for down-blending and the rate at which it will be down-blended is dependent upon decisions regarding the U.S. nuclear weapons stockpile, the pace of warhead dismantlement and receipt of HEU from research reactors, as well as other considerations, such as decisions on processing of additional HEU through H-Canyon, disposition paths for weapons containing HEU, etc."[32] The Department of Energy anticipates complete disposition of the excess HEU will be completed by 2030.[33] To meet this schedule for down blending the remaining 40 tons of HEU by 2030, an average down blending rate of about 2.5 tons of HEU per year would be required. Another 22 tons of excess HEU in spent fuel is awaiting geological disposal.

The United States has reserved 152 tons of HEU for naval fuel. This is material enriched to over 90 percent in uranium-235 and was previously in or available for weapons and in 2005 was declared excess for weapon purposes. It is estimated to be sufficient to last about 50 years at current rates of consumption in naval fuel. In January 2014, in a potentially significant shift, the U.S. Department of Energy's Office of Naval Reactors submitted to Congress a *Report on Low Enriched Uranium for Naval Reactor Cores* that concluded "recent work has shown that the potential exists to develop an advanced fuel system... [which] might enable either a higher energy naval core using HEU fuel, or *allow using LEU fuel*." [emphasis added].[34]

The Office of Naval Reactors has suggested a shift from HEU to LEU naval fuel would require a 10 to 15 year R&D program costing roughly a billion dollars. Since the U.S. Navy is currently building a generation of nuclear attack submarines with HEU fuel and is planning to build starting in the next decade a new generation of ballistic-missile submarines, any shift to LEU fuel may not happen until these vessels are ready for replacement, which may be many decades away.

The United States as of the end of 2014 had about 31 tons of spent naval HEU fuel in storage at the Expended Core Facility, part of the Naval Reactors Facility (NRF), and at the nearby Idaho Nuclear Technology and Engineering Center (INTEC), formerly known as the Idaho Chemical Processing Plant, at the Idaho National Laboratory. About 18 tons of this spent fuel were delivered between 1996 and the end of 2014.[35] There was already about 12 tons of spent naval fuel at the Idaho National Laboratory in 1996.[36] Naval spent fuel is to go to a geological repository.

United Kingdom

The United Kingdom is estimated to have stockpile of 19.8 tons of HEU as of the end of 2014. The U.K. declared a stockpile of 21.9 tons of HEU as of 31 March 2002, the average enrichment of which was not given. The United Kingdom uses HEU both for nuclear weapons and as fuel for naval nuclear propulsion for its fleet of four ballistic missile submarines.

The United Kingdom declared 1.4 tons of HEU as civilian (including irradiated material) as of 31 December 2014.[37]

France

France is estimated to have a military HEU stockpile of 26 tons but there is significant uncertainty in this estimate because of a lack of reliable public information about France's HEU production. France ended production of HEU in 1996 and has dismantled the Pierrelatte gaseous diffusion enrichment plant that was used for the production of weapon-grade uranium.

A new analysis in 2014 estimating HEU production rates with and without upgrades of the diffusion barriers suggests that Pierrelatte may have produced 18 – 21 tons of weapon-grade HEU in its 30 years of operation (1967 – 1996) if the barriers were upgraded and only 14 – 16 tons if there were no upgrades.[38] These estimates would leave France with a current inventory as large as 10 ± 2 tons and possibly as low as 6 ± 2 tons of HEU.

France also declared to the IAEA an additional civilian HEU inventory of 4.6 tons as of 31 December 2014.[39] This material includes domestic HEU and material received from the United States and Russia for research reactor fuel and irradiated material.

China

China is estimated to have 18 ± 4 tons of HEU in its stockpile, this updates earlier estimates of 16 ± 4 tons.[40] The revised estimate is based on new information suggesting that China's Heping gaseous diffusion plant operated from 1970 to 1987 to produce HEU, and not as previously assumed from 1975 to 1987. China's second military facility, the Lanzhou gaseous diffusion plant, operated from 1964 to 1979.

India

India is expanding its uranium enrichment capacity. Satellite imagery from 2014 suggests construction at the Rare Materials Plant (RMP) centrifuge facility in Rattehalli, Karnataka.[41] The plant is believed mainly to produce HEU to fuel the reactors of the Arihant class nuclear submarines that India is building. HEU from Rattehalli also has been used to fuel a land-based prototype of the *Arihant* submarine reactor. A core to reload the *Arihant* submarine after it has been in service for some years is reportedly "ready for shipping".[42]

The Arihant reactor power is estimated at around 80 MWth, with the core estimated to contain about 65 kg of uranium-235. The HEU fuel may be enriched to between 30 percent and 45 percent uranium-235. Assuming an enrichment level of 30 percent, India is estimated to have a stockpile of 3.2 ± 1.1 tons of HEU as of the end of 2014 with a uranium-235 content of 1.0 ± 0.3 tons.

A second enrichment plant, the Special Material Enrichment Facility, has been proposed for Chitradurga, also in Karnataka. According to Indian officials, this facility will be used for production of HEU for naval fuel and for production of low enriched uranium for nuclear power reactor fuel.[43] The new Karnataka enrichment plant may have a capacity "comparable to a few light-water reactors supply" according to the Chairman of India's Atomic Energy Commission.[44] However, currently there are no power reactors in India that require low enriched uranium from Indian enrichment plants, but design work has started on a 900 MWe light water reactor.[45] The initial purpose of the new facility may be to produce HEU for weapons and for naval fuel.

Plans for the new Chitradurga enrichment plant as well as other military facilities in the area have been challenged by local communities and environmentalists. In August 2013, India's National Green Tribunal, which has jurisdiction in environmental matters, ordered a stop to construction.[46]

Pakistan

As of the end of 2014, Pakistan is estimated to have a stockpile of 3.1 ± 0.4 tons of HEU and continues to produce HEU for its nuclear weapon program.[47] Uncertainty about Pakistan's uranium resources, and the operating history and enrichment capacity of its centrifuge plant at Kahuta and a possible second plant at Gadwal (which may be dedicated to HEU production) limits the reliability of the estimate.[48]

North Korea

Analysis of satellite imagery from 2013 and 2014 suggests North Korea is expanding its centrifuge enrichment plant at Yongbyon, possibly doubling its size.[49] It is not clear how many centrifuges DPRK may now have installed in this plant. North Korea revealed this plant in 2010 and claimed it was civilian, and as holding about 2000 centrifuges with a total enrichment capacity of 8000 SWU.[50] North Korea also may have a second as yet undeclared enrichment plant. There is as yet no firm evidence that North Korea has produced HEU.

Civilian Use of HEU

Civilian use of HEU is restricted to reactor fuels and as targets for use in isotope production, mostly for medical and industrial purposes. Nuclear weapon states and some non-weapon states have facilities that use HEU for such purposes. International efforts have been under way since the late 1970s to minimize civilian use of HEU and have become more urgent since 2001.

Reducing civilian use of HEU has been an important focus of the three international Nuclear Security Summits (Washington DC in 2010; Seoul in 2012; and The Hague in 2014). The final communique from The Hague Summit declared:

> "We encourage States to continue to minimise the use of HEU through the conversion of reactor fuel from HEU to LEU, where technically and economically feasible, and in this regard welcome cooperation on technologies facilitating such conversion."[51]

A fourth, possibly final, Nuclear Security Summit is planned for Spring 2016 and will be held in Washington, DC.

United States and Russia

Efforts by the United States and Russia to repatriate HEU supplied to other countries for research reactor fuel continues. All HEU material has been removed from the following 30 countries as of late 2015: Austria, Brazil, Bulgaria, Chile, Colombia, Czech Republic, Denmark, Georgia, Greece, Hungary, Iraq, Jamaica, Latvia, Libya, Mexico, Philippines, Portugal, Romania, Serbia, Slovenia, South Korea, Spain, Sweden, Switzerland, Taiwan, Thailand, Turkey, Ukraine, Uzbekistan and Vietnam. There remain 27 countries with at least one kilogram of HEU in civilian stockpiles.

United States

The United States still operates six HEU-fueled civilian and dual-use research reactors (there are an additional three military pulsed reactors and six military critical assemblies). The United States also continues to export fresh HEU for civilian research reactors in other countries, with shipments licensed in 2014 and 2015 for use as targets in Belgium, Canada, Czech Republic, France, Netherlands, and Poland.

Russia

In 2014, Russia converted a research reactor from HEU to LEU for the first time. The Argus reactor used 1.7 kg of 90 percent enriched uranium as fuel. The Argus was among the six Russian reactors that were to undergo conversion feasibility studies as part of an agreement with the United States announced in 2010.[52]

Russia's HEU fueled BN-800 fast neutron reactor reached criticality in 2014 and was expected to achieve full power in 2015.[53] It currently operates with a mixed core, about 100 of the 576 fuel assemblies contain HEU and the rest is plutonium-uranium oxide (MOX) fuel.

In January 2014 Russia opened the way for Rosatom to supply HEU for research reactors abroad. Under one agreement of this kind, reached in September 2013, Russia will supply HEU for the Jules Horowitz reactor in France, which uses 27 percent enriched fuel.[54] Russia in 2014 also agreed to supply HEU for the China Experimental Fast Reactor (CEFR).[55] It is not clear if Russia will require as a condition of supply that its customers for HEU research reactor fuel commit to convert the reactor to LEU fuel when such conversion becomes possible – this condition is applied by the United States in its exports of such HEU fuel.

There is some uncertainty as to the source of the HEU that Russia is exporting. In 1989, the Soviet Union had announced that it was "ceasing the production of highly-enriched uranium."[56] In 2012, Russia launched an HEU production cascade at the Electrochemical plant in Zelenogorsk, citing a need to produce the material for icebreakers and breeder reactors.[57] The HEU demands for fast reactor fuel for the BN-800 reactor or CEFR could be on the order of hundreds of kg or possibly tons of HEU per year, and could not be met from one cascade. Similarly, fuel requirements for Russia's old icebreakers, typically enriched from 20–90 percent, have been estimated as on the order of a few hundred kilograms per year.[58] These amounts could come from existing HEU stocks. Russia's new generation of icebreakers is believed to use LEU fuel.

It is possible that the new HEU is being produced for export for use in research reactor fuel.[59] If the HEU is intended as fuel for the Jules Horowitz reactor in France and the FRM-II reactor in Germany, annual production could be on the order of tens of kg of HEU per year, which would be possible with one centrifuge cascade.

China

China has not declared a civilian HEU stockpile even though it has received HEU fuel enriched to 64.4 percent from Russia for the Chinese Experimental Fast Reactor, which first achieved full power operation in December 2014.[60]

China also has been exporting very small amounts of HEU as fuel for its Miniature Neutron Source Reactors (MNSR). Reactors have been supplied to Ghana, Iran, Nigeria, Pakistan, and Syria, and each reactor has a core containing about 1 kg of HEU, enriched to 90 percent or greater. There are studies underway to convert these reactors to LEU fuel and plans to return the HEU to China

Civilian Uranium Enrichment Plants

There are civilian uranium enrichment plants in 11 countries: Argentina, Brazil, China, France, Germany, Iran, Japan, Netherlands, Russia, United Kingdom and the United States. North Korea claims that its enrichment plant at Yongbyon is to fuel its planned 100 MWth experimental light water reactor – this reactor was not completed as of mid-2015.[61]

United States

Plans for three new uranium enrichment facilities in the United States have encountered significant obstacles. The Global Laser Enrichment plant jointly owned by General Electric, Hitachi and Cameco, the American Centrifuge Plant owned by Centrus (previously known as USEC), and Areva's Eagle Rock centrifuge plant all now appear to be indefinitely delayed.

In 2014, the proposed $1 billion Global Laser Enrichment plant faced increased financial pressures leading to a decision to halt the project. Only three SILEX employees remain at the US office.[62] GLE had planned to construct and operate the laser enrichment facility on or near the Paducah Gaseous Diffusion Plant in Kentucky. Under a previous plan, GLE received an NRC license to construct and operate a uranium enrichment plant using laser technology in Wilmington, North Carolina.[63] The license allowed GLE to enrich uranium to 8 percent of uranium-235 for use in commercial nuclear power reactors. A spokesman for Global Laser Enrichment facility said "The supply for uranium is up, the demand is down, and that has caused us to slow down our pace of investment in this technology."[64]

The American Centrifuge Plant faced severe difficulty in 2014 when USEC filed for bankruptcy and gave control of the technology to the U.S. Department of Energy's Oak Ridge National Laboratory. In 2015, the Department of Energy cut funding by 60 percent, shut down the 120 centrifuge test cascade at the Piketon site in Ohio, and limited work to technology development at the Oak Ridge (Tennessee) site.[65] USEC, now renamed Centrus, is a subcontractor to Oak Ridge. USEC was originally the United States Enrichment Corporation, a government agency set up in 1992 to allow privatization of U.S. uranium enrichment. USEC was sold off in 1998.

Areva's planned Eagle Rock enrichment plant in Idaho Falls, Idaho, has been delayed indefinitely because of financial problems. The facility was to have an annual production capacity of approximately 3.3 million SWU. Work on the plant was supposed to start in 2011, but was pushed back to 2012, then 2013 and 2014. In 2015 Areva did not include the Eagle Rock enrichment facility in its list of core business interests.[66] Areva does not offer a possible date for the start of construction. The French government owns almost 90 percent of Areva.

The only operating uranium enrichment plant in the United States is owned by the European consortium Urenco, through its subsidiary Urenco-USA and is located at Eunice in New Mexico. In 2015, the Nuclear Regulatory Commission approved a license to expand the capacity of this enrichment plant possibly to 10 million SWU, but according to Urenco-USA "current plans are to expand to 5.7 million SWU and [...] be able to expand further when additional enriched uranium is required by the market."[67]

Russia

Russia continued to upgrade its enrichment facilities by installing 9th-generation centrifuges to replace older, less powerful machines. The first cascades with the new machines became operational in Zelenogorsk in 2012 and in Angarsk and Novouralsk in 2013. In April 2015, the Novouralsk plant added a second upgraded cascade, with a third cascade expected to be added by the end of the year. This modernization continues despite significant excess capacity in the Russian enrichment complex.

China

Civilian uranium enrichment in China has undergone a large expansion to meet the demand from its large and ambitious nuclear power program, which now includes the export of nuclear power reactors. This enrichment program is based on four Russian-supplied enrichment facilities as well as six constructed by China.

A new assessment in 2015 determined that China may have at least 4.5 million SWU of civilian enrichment capacity in operation and a further 2 million SWU under construction.[68] In addition, China may have an enrichment capacity of around 0.6 million SWU for naval fuel and other non-weapon military uses or dual (military/civilian) use. The Chinese centrifuges in operation today are believed to be derived from Russian machines.

Abdul Qadeer Khan, who led Pakistan's enrichment program from the mid-1970s until 2001, claimed to have shared with China the centrifuge technology he had acquired from Urenco and to have helped build a centrifuge plant there, at Hanzhong.[69] China had a pilot centrifuge plant in the 1980s (project 405-1) at Hanzhong, which reportedly did not perform well and China decided replace it with a Russian-supplied centrifuge facility (project 405-1A) at Hanzhong.[70]

France

Areva's George Besse II centrifuge enrichment plant reached a capacity of 6 million SWU in 2014.[71] Plans call for a production capacity of 7.5 million SWU as of 2016.[72] The plant was inaugurated in December 2010. Areva, however, is in financial crisis and this planned expansion of George Besse II is now uncertain.

The scale of uranium enrichment in France over the next decade may be determined by government success in implementing a policy to reduce dependence on nuclear electricity from the current 75 percent of total electricity generation to 50 percent by 2025.[73] This policy which formed part of the successful election platform of President Francois Hollande in 2012 was passed in 2015 by the French parliament.

Urenco

The four civilian enrichment plants owned by Urenco reached a combined total enrichment capacity of 18.1 million SWU at the end of December 2014.[74] Urenco is owned jointly by Germany, the Netherlands and the United Kingdom and has enrichment plants in each of these countries. It also owns the only operating enrichment plant in the United States. The enrichment capacity by Urenco site as of the end of 2014 is:[75]

- Urenco Nederlands – 5.4 million SWU
- Urenco U.K. – 4.9 million SWU
- Urenco Deutschland – 4.1 million SWU
- Urenco USA – 3.7 million SWU

Japan

Japan has been bringing online its new centrifuges at its Rokkasho enrichment plant to replace machines which had encountered technical problems. Since March 2010, a capacity of 75,000 SWU has been installed, all of which was reported to be operational as of December 2014.[76]

The original planned capacity of the Rokkasho enrichment plant was 1.5 million SWU, but problems with the centrifuges stopped the capacity growth at about 1 million SWU in 1998. As of 2010, JNFL had planned to install new machines and reach a capacity of 1.5 million SWU by 2020.[77] This was before the Fukushima disaster of 2011 and the shutdown of Japan's nuclear power reactors. It is now unclear what will be the final capacity of the enrichment plant after the replacement of the centrifuges.

Brazil

As of early 2014, Brazil's Resende uranium enrichment plant had an operating capacity of about 17,000 SWU.[78] This was made up of 4 centrifuge cascades, and there are plans for a total of 10 cascades by 2018. The plant supplies low enriched uranium fuel for Brazil's Angra nuclear power reactors.

Argentina

In February 2015, President Cristina Fernandez de Kirchner declared that "Argentina is back in the select club of 11 countries that can produce enriched uranium."[79] This followed the announcement in 2014 that Argentina planned to resume production at its Pilcaniyeu gaseous diffusion uranium enrichment plant, which was shut down in the 1990s. Argentine Planning Minister Julio de Vido told the Nuclear Suppliers Group meeting held in Buenos Aires in June 2014 that "In five weeks, the Pilcaniyeu plant will resume production of enriched uranium."[80] It is unclear if production has actually started and if so at what scale.

Iran

In July 2015, Iran agreed with the United States, United Kingdom, Russia, France and China, and Germany (known as the P5+1 or the E3/EU+3) a Joint Comprehensive Plan of Action to limit key aspects of its nuclear activities, including its uranium enrichment program.[81] The deal was subsequently approved unanimously by the United Nations Security Council.

The plan seeks to settle the more than decade-long dispute over Iran's enrichment program. The plan includes Iran reducing the number of its installed centrifuges from 19,000 to 6104 IR-1 machines – with only 5060 centrifuges enriching uranium at its Natanz facility – for a 10 year period; not enriching above about 3.7 percent uranium-235 for at least 15 years, capping its stockpile of low-enriched uranium to below 300 kg for a period of 15 years; and, building no new enrichment facilities for 15 years. Iran's Fordow facility will retain 1044 IR-1 centrifuges but will not enrich uranium. Iran plans eventually to increase its enrichment capacity to a scale sufficient at least to fuel its Russian-supplied Bushehr-I nuclear power reactor.

Separated Plutonium

The world's first plutonium production reactor, the Hanford B-reactor in the United States, started up in 1944, four years after plutonium was first created in a laboratory. The Hanford site grew to have 9 plutonium production reactors and the highest annual plutonium production rate of any site in the world, with annual production for weapons peaking at almost 5 tons in 1965.[82] This was higher than the combined annual production of the Soviet Union's three plutonium sites (Mayak, Seversk and Zheleznogorsk).[83]

In the period from 1963 through 1965, the Hanford site produced over 12.5 tons of weapon-grade plutonium, an amount that is larger than the estimated combined current stockpiles of all the other nuclear weapon states except Russia. The United States and the Soviet Union eventually produced roughly similar amounts of plutonium for weapons. Table 3 gives the period of plutonium production for weapons. Appendix 3 lists active reprocessing plants.

Plutonium		
	Production Start	**Production End**
United States	1944	1988
Russia	1948	1997
United Kingdom	1951	1995
China	1966	1991
France	1956	1992
Israel	1963 – 1964	Continuing
Pakistan	1998	Continuing
India	1960	Continuing
North Korea	1986	?

Table 3. Dates for plutonium production for weapons by country.

With the end of the Cold War, the United States and Russia reduced their arsenals and in 2000, Russia and the United States agreed 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 beginning by 2007 and a rate of 2 tons per year in each country. After failing to make progress, the agreement was amended in 2010 to allow the start of plutonium disposal to be delayed until 2018 and the rate of disposal was reduced to 1.3 tons/year.[84]

The United States also declared excess to its national security requirements an additional 20 tons of separated plutonium.

During the Cold War and in some cases continuing afterwards, the United States, the Soviet Union/Russia, the United Kingdom, France, Germany, Japan and India set up ambitious civilian nuclear power programs that included separating plutonium for use as fuel in breeder reactors. China also has started such a program. These programs have created civilian plutonium stockpiles that now are larger than the stockpile of plutonium created for military purposes (Figure 6).

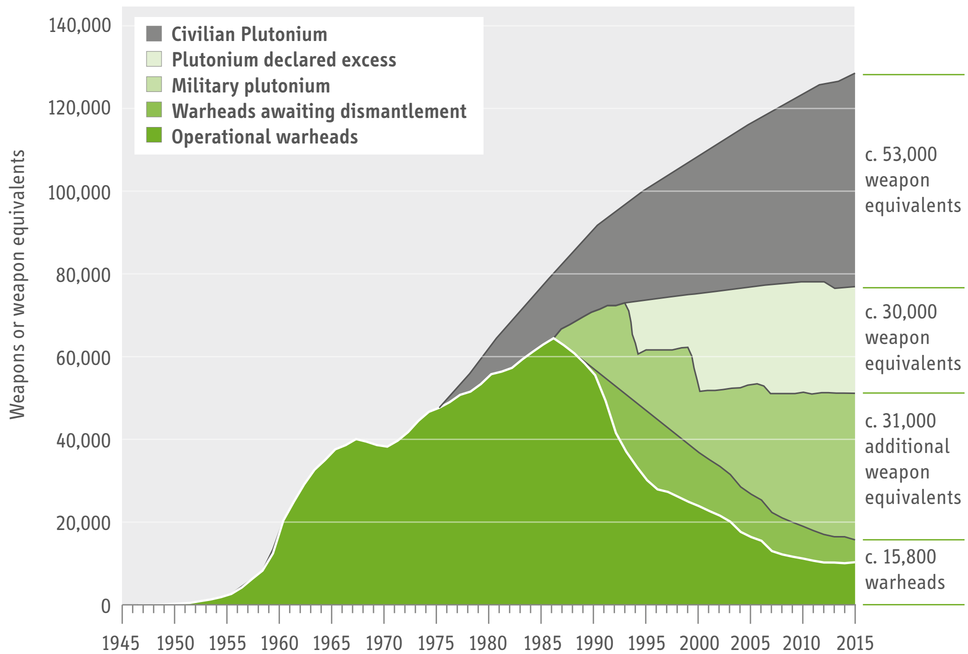


Figure 6. Growth of the global plutonium stockpile, 1945 – 2015. While the global stockpile of HEU has dropped since the end of the Cold War, the stockpile of separated plutonium has not. In fact, the startup of several large civilian reprocessing plants since the 1980s has led to a continuous increase in the global stockpile. At the same time, disposition of excess military plutonium has stalled. As of the end of 2015, the global stockpile of separated plutonium corresponds to about 130,000 weapon-equivalents. Weapon equivalents are assumed to be 3 kg of military (weapon-grade) plutonium and 5 kg of civilian (reactor-grade) plutonium.

The global stockpile of separated plutonium is estimated as 505 ± 10 tons as of the end of 2014. Russia and the United States have the largest stockpiles of plutonium produced for weapons.

The United Kingdom, France, and Russia, in that order, have the largest civilian plutonium stockpiles. Among the non-weapon states, Japan has the largest stockpile.

Weapons Plutonium

The global stockpile of military plutonium is estimated to be about 140 ± 10 tons as of the end of 2014 (Figure 7). This does not include material produced in weapon programs that was subsequently declared excess to weapon purposes. This excess material is not under international safeguards.

The United States has declared its history of production and use of weapons plutonium and provided an update in 2012 up to September 2009. The United Kingdom also has declared the size of its weapons plutonium stockpile in 2000 but has not updated the data or provided additional information since then. The other nuclear weapons states have not made declarations of their fissile material production histories and use. There remain significant uncertainties in estimates of Russia's stockpile.

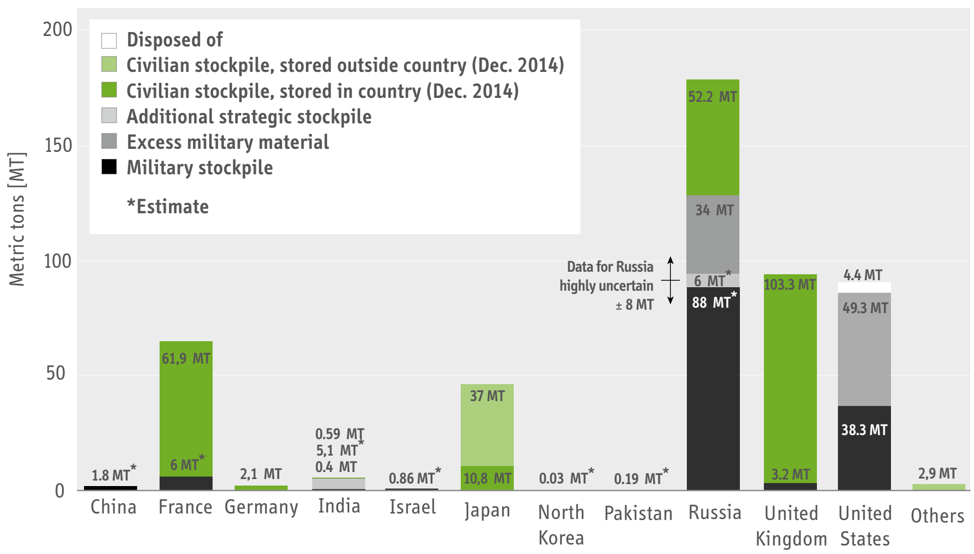


Figure 7. National stocks of separated plutonium as of the end of 2014. Military stocks are based on IPFM estimates except for the United States and United Kingdom whose governments have made declarations. Uncertainties in estimated military stockpiles for China, France, India, Israel, Pakistan, and Russia are on the order of 10–30%. Civilian stocks are based on the INFCIRC/549 declarations published in 2015, which report material as of 31 December 2014 and are listed by ownership, not by current location.

United States

The Obama Administration in 2014 announced plans to place the under construction MOX Facility at the Savannah River Site near Aiken, South Carolina into cold standby status and begin to look for alternative ways to dispose of the 34 tons of excess plutonium because of cost overruns and delays.[85] The MOX was to be made from excess weapon plutonium and used as power reactor fuel.

The Department of Energy's National Nuclear Security Administration (NNSA) had estimated in 2002 that the MOX plant would cost about $1 billion to design and build. Construction started in August 2007, with a then estimated total project cost of $4.8 billion and a scheduled completion date of September 2016. In 2015, a report for the Department of Energy concluded that about $5 billion had already been spent on construction of the facility and that an additional $27.2 billion (2014 dollars) would be required to complete the plant (assuming a budget cap of $0.5 billion per year).[86] This report observed that disposing of excess plutonium in the underground Waste Isolation Pilot Plant (WIPP) in New Mexico would be much less costly.

WIPP, which already holds 4.5 tons of plutonium, was shut down in 2014 after an accident that released radioactivity and is unlikely to become fully operational again until 2018, according to U.S. Secretary of Energy Ernest Moniz, and even that date "remains a little uncertain."[87] A 2015 official report attributed the accidental chemical reaction in a radioactive waste drum to systemic failures of procedures, lack of a hazard analysis, poor training of operators, and inadequate oversight and management.[88]

Russia

In 2014, Russia's BN-800 fast neutron reactor reached criticality. It is expected to achieve full power in 2015. It will be used in part to irradiate as MOX fuel the 34 tons of Russian plutonium declared excess for weapons. It currently operates with a core in which about 100 of the 576 fuel assemblies contain HEU and the rest is MOX fuel.

Israel

Israel is believed to still be operating the now 50 year old Dimona plutonium production reactor, built for it by France. The reactor may be operated now primarily for tritium production. As of the end of 2014, Israel may have a stockpile of about 860 kg of plutonium.

India

India currently produces weapon-grade plutonium at the 100 MWt Dhruva reactor at the Bhabha Atomic Research Centre (BARC), in Mumbai. During 2014, the reactor was reported to have operated at 80 percent capacity for most of the year.[89] The spent fuel from this reactor is reprocessed at the Trombay reprocessing plant (maximum capacity of 50 tons of spent fuel per year, commissioned in 1964) in the same complex.

As of the end of 2014, India is estimated to have a net stockpile of weapon-grade plutonium of 0.59 ± 0.20 tons. The upper estimate includes the possibility that some of the first discharges of unsafeguarded pressurized heavy water reactors that are primarily meant for producing electricity have been reprocessed and the resulting plutonium with low fractions of higher isotopes added to the weapons plutonium stockpile. The lower estimate assumes that Dhruva has operated at a power level significantly below the rated value.

Two new production reactors, with power levels of 125 MWt and 30 MWt, are being planned; according to the Indian government, construction of these reactors is "scheduled to commence" before 2017.[90]

India's unsafeguarded 500 MWe Prototype Fast Breeder Reactor, capable of producing on the order of 140 kg per year of weapon-grade plutonium in its blankets, continued to be delayed. The original expected start-up date was September 2010, but as of November 2015 it had still not started operation.

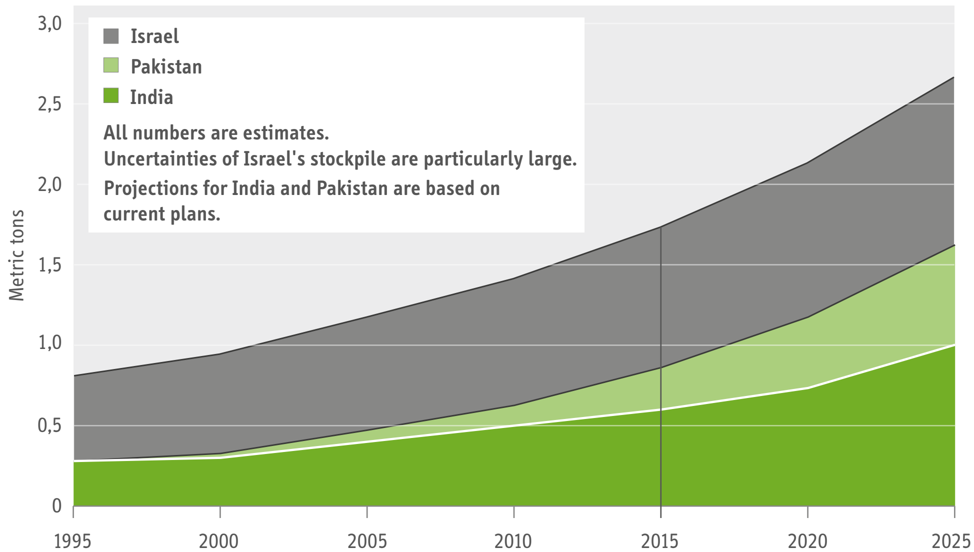


Figure 8. Projection of plutonium production for weapons purposes in non-NPT weapon states. Israel, India, and Pakistan all continue to operate plutonium production reactors, and production rates are expected to increase between now and 2025. Israel's Dimona reactor has been operating for more than 50 years, the longest-operating plutonium production reactor in history. India is planning construction of two new reactors, and Pakistan is moving toward plutonium-based weapons having brought online its fourth production reactor. Uncertainties of Israel's stockpile are particularly large as the power level and power history of its Dimona reactor is highly uncertain.

Pakistan

As of the end of 2014, IPFM estimates that Pakistan may have accumulated on the order of 190 kg of plutonium, from its Khushab-I and Khushab-II reactors.

Imagery from March 2013 and from December 2013 shows water vapor rising from some of the cooling towers of the third reactor at the Khushab site suggesting that it too had started up.[91] Satellite imagery from early 2015 suggested that Pakistan has started operating its fourth plutonium production reactor at Khushab, with steam seen coming from the cooling system.[92] Work on this reactor may have started in 2011. Spent fuel from these reactors may become available for reprocessing in 2015 and 2016 respectively.

New satellite imagery from December 2013 published by the Institute for Science and International Security suggests Pakistan may have completed major construction work on its Chashma reprocessing plant.[93] In 2012, a semi-official account of Pakistan's nuclear weapons program, *Eating Grass: The Making of the Pakistani Bomb*, started that "The commercial-scale reprocessing plant at Chashma is[…] nearing completion."[94] Work on the reprocessing plant started in 1974 when Pakistan signed a contract with the French company Saint-Gobain Techniques Nouvelles. In 1978, under U.S. pressure, France canceled the contract, but it is believed that significant design information and some technology may have been transferred.

The new reprocessing plant, when operating, will add to the capacity now available at the two small reprocessing plants at the New Labs site in Rawalpindi. This may allow Pakistan to reprocess all the fuel from its four plutonium production reactors at Khushab.

North Korea

Satellite imagery from late 2014 and 2015 suggests North Korea may have shut down and restarted its 5 MWe plutonium production reactor at Yongbyon.[95] The reactor resumed operation in August 2013 after having been shut-down in 2007 and having its cooling tower demolished as part of an agreed program to end production and disable the facility. It is estimated that North Korea may have about 30 kg of separated plutonium as of the end of 2014.

Civilian plutonium

The global stockpile of civilian plutonium is 271 tons as of the end of 2014. This estimate includes the civilian plutonium holdings declared as part of their annual INFCIRC/549 report to the IAEA by the United Kingdom, Russia, France, and China, as well as the plutonium holdings declared by Japan and Germany. It does not include United States military plutonium declared as excess or India's stockpile of unsafeguarded plutonium separated from spent power reactor fuel. This material is discussed below, however.

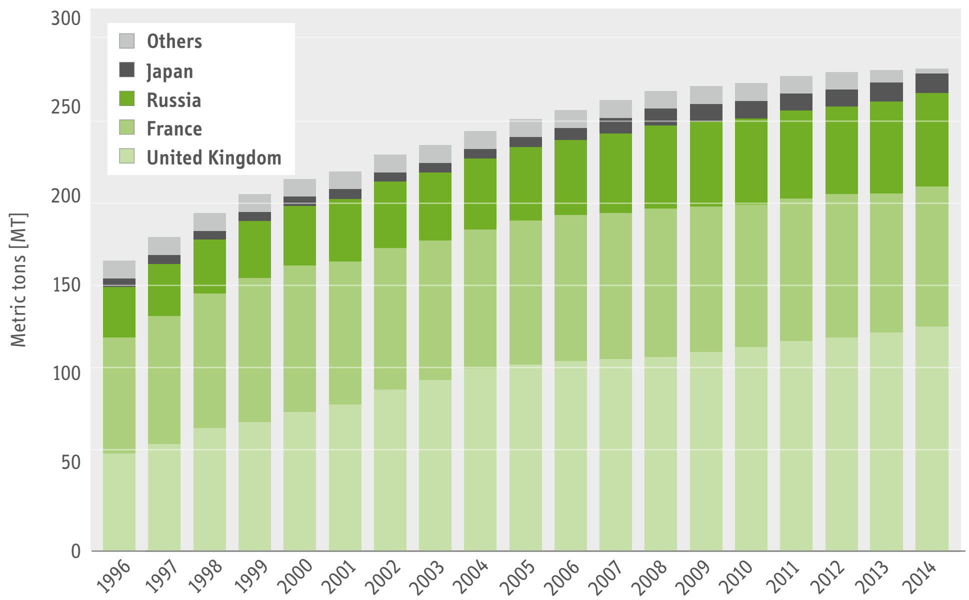


Figure 9. The civilian stockpile of separated plutonium continues to grow. These numbers are based on the INFCIRC/549 declarations for the respective years; stocks are listed by storage location, not by ownership. As of the end of December 2014, a total of 271 tons had been declared. The United Kingdom has accumulated the largest amount of civilian plutonium.

Belgium makes an INFCIRC/549 declaration but this has in recent years been of zero plutonium stocks. As of the end of 2014, Belgium held 900 kg of unirradiated MOX, all of which was foreign-owned.[96] This material may be at the Franco-Belgian Fuel Fabrication plant at Dessel, owned by Areva, which produces MOX fuel assemblies. Germany declared 2.1 tons of plutonium in MOX fuel as of the end of 2014.[97]

Some non-weapon states do not report their plutonium stockpiles even though they send spent fuel to be reprocessed in the United Kingdom and France, including Australia, Italy and the Netherlands which own civilian plutonium that is stored overseas. These plutonium stockpiles are estimated from the INFCIRC declarations by France and the United Kingdom which reprocess spent fuel from these countries.

Stocks of plutonium not belonging to non-reprocessing countries (that is excluding Japan) have fallen significantly. As of December 2010, France and the United Kingdom together held a total of 52.2 tons of foreign plutonium belonging to countries that did not themselves reprocess spent fuel. As of the end of 2014, the inventory of plutonium owned by non-reprocessing states and held in France and the United Kingdom was only 2.9 tons.

United States

The updated INFCIRC/549 declaration for civilian plutonium stocks as of the end of 2014 for the United States reported that the stockpile in 2014 remained the same size as for the end of 2013 (which was also the same for the end of 2012). No new civilian plutonium was separated in the United States or declared excess for weapon purposes and no additional excess plutonium was sent for final disposal to the WIPP since the facility is shut down because of an accident.

Russia

In its annual account of civilian plutonium stock, Russia reported that as of the end of 2014, it owned 51.2 tons of unirradiated separated plutonium at reprocessing plants, 0.9 tons more than was declared in 2013.[98] An additional 1.3 tons of plutonium was held elsewhere and 300 kg of plutonium were in unirradiated MOX.

In 2015, Russia launched a commercial MOX plant in Zheleznogorsk, formerly Krasnoyarsk-26. It produced its first MOX assemblies in 2014 and plans to reach its capacity of 400 assemblies per year in 2017.[99] The MOX fuel is initially intended for the BN-800 fast breeder reactor.

United Kingdom

The United Kingdom in 2014 announced that it will shut down its B205 reprocessing plant around 2020 – after fifty years of operation.[100] B205 began operation in 1964 and had a design throughput of 1500 tons of spent fuel per year and reprocessed spent fuel from the U.K.'s Magnox power reactors. The plutonium was intended to be used as start-up fuel for a fleet of breeder reactors, but these were never built. In 2000, it was announced that B205 would close by 2012 after all the Magnox spent fuel had been reprocessed but this deadline has been missed in part because B205 has failed to operate as well as expected.

The latest figures from Sellafield Ltd. show that both B205 and the U.K.'s Thermal Oxide Reprocessing Plant (THORP) have failed to meet targets for spent fuel reprocessing.[101] According to CORE, in 2013–2014 the B205 plant missed its annual target for the ninth successive year while the THORP plant in 2013–2014 processed only 346 tons of spent fuel against a target of 439 tons, less than 30 percent of its design rating of 1200 tons per year. THORP started operating in 1994 and is scheduled to end operation around 2018 but may do so sooner.

The U.K. has started a process of taking ownership of foreign plutonium separated at Sellafield because it has been unable to produce the MOX fuel for its reprocessing customers. In June 2014 Sweden allowed the nuclear power company OKG AB to transfer to the U.K. Decommissioning Authority ownership of 834 kg of separated plutonium stored at Sellafield.[102] Most of this plutonium was separated from Swedish spent fuel sent to Sellafield between 1975 and 1982 and was to have been returned as MOX fuel, but with the failure of the U.K. MOX facility Sweden can no longer expect to receive any fuel within the remaining lifetime of its nuclear reactors. This plutonium now will be managed together with U.K.-origin plutonium.

The U.K. has done other such swaps. In 2013, the U.K. took ownership of 750 kg of plutonium previously owned by certain German utilities, around 1850 kg of plutonium that was originally allocated to repay plutonium loans (to France) in relation to historic MOX fuel subcontracts, and 350 kg of material previously owned by a Dutch utility.[103] As a result of these swaps, the U.K. declaration of its civilian plutonium held domestically had increased to 103.3 tons as of the end of 2014 (from 96.4 tons as of the end of 2012).[104] The United Kingdom held a total of 126.3 tons of plutonium, of which 23 tons belonged to other countries.

France

In its declaration of civilian plutonium as of the end of 2014, France reported holding 61.9 tons of domestic unirradiated separated plutonium and 16.9 tons of foreign unirradiated plutonium.[105] The French state-owned company Areva that manages reprocessing and MOX fuel fabrication reported a loss of €4.8 billion ($5.2 billion) in its annual financial results for 2014, raising questions about its future.[106]

China

In its annual report of civilian plutonium holdings, China declared 25.4 kg of unirradiated separated plutonium "in product stores at reprocessing plants" as of December 31, 2014.[107] This is the first increase in China's declared civilian plutonium holdings since 2010, when it declared a stockpile of 13.8 kg produced by hot tests of its pilot reprocessing plant in 2010. The plant has a capacity of about 50 tons per year. The additional plutonium reported also may be from the 2010 tests.

The China National Nuclear Corporation (CNNC) is reported to have started preparations for a demonstration reprocessing plant with a capacity of 200 tons per year near Jiuquan city, Gansu province.[108] The French government owned company Areva continues its almost decade long effort to sell a very large (800 tons per year) reprocessing plant to China. In late 2014, Areva's Chief Executive Officer said "When these type of talks start, you never know when they will be completed."[109] A series of agreements have been signed but apparently with no commitment by China to buy the plant, in part because of the high price.[110] In 2015, Areva announced that it had reached an agreement that "defines the schedule for commercial negotiations."[111]

India

As of the end of 2014, India may have separated 5.5 ± 3.0 tons of plutonium from spent nuclear power reactor fuel, of which about 0.4 tons are under IAEA safeguards. This leaves a stockpile of 5.1 ± 3.0 tons outside safeguards.[112] The new estimate is considerably more uncertain than previous IPFM estimates.

This greater uncertainty is the result of reports suggesting India has faced problems producing sufficient separated plutonium to fuel the Prototype Fast Breeder Reactor (PFBR), possibly because of poor performance at the Tarapur and Kalpakkam reprocessing plants. It is possible, however, that the problem was not just the separation of plutonium but also in fabricating the mixed oxide fuel pins. These two scenarios allow for a lower and higher estimate of India's separated power reactor plutonium stockpile. Since this plutonium stockpile is reported to be intended for fast breeder reactor fuel, it is treated as civilian here even though it was kept out of safeguards under the 2005 Indian–US Civil Nuclear Cooperation Initiative and the safeguards agreement signed by the Indian Government and the International Atomic Energy Agency in 2009.

India has operated three plants for reprocessing spent fuel from pressurized heavy water power reactors: two at Tarapur (commissioned in 1977 and 2011) and one at Kalpakkam (commissioned in 1998), each of 100 tons of spent fuel per year capacity. A second 100 tons per year plant is under construction at Kalpakkam.[113]

The older Tarapur plant appears to have performed quite poorly in its first two decades. In the 1990s, it was reportedly running "substantially" below its design capacity, with an average throughput of 25 percent.[114] Similar reports of poor performance have continued.[115] It is used to "carry out aged Pu purification work", which presumably means that it is no longer used for reprocessing but rather to separate out americium-241 that builds up in the plutonium.[116] The Kalpakkam plant also may have performed poorly, but the evidence for this is indirect and is inferred from the long delay in startup of the PFBR being due to a lack of plutonium fuel. If the plutonium needed to produce all the fuel pins for the first PFBR core only became available in late 2013 or in 2014, as seems to the case, then both the Tarapur and Kalpakkam reprocessing plants must have operated quite poorly.

The PFBR core requires an initial inventory of 1.9 tons of plutonium.[117] At the beginning of the reactor's construction in 2004 it was expected to be commissioned in 2010. Since then the start–up date has been pushed back several times; in early 2012 it was reported the reactor would go critical in 2013.[118]

In 2012, insiders from India's Department of Atomic Energy (DAE) claimed that "The DAE has no plutonium stock in its inventory and this is causing the delay" in the start-up of the PFBR.[119] The 2014–15 Annual report of the DAE lends support to a possible low rate of plutonium separation; it mentions that it was in 2014 that "nuclear fuel material for the first fuel loading of PFBR was supplied to fuel fabrication facility."[120] In October 2014, the Director of the Bhabha Atomic Research Centre (BARC) announced that BARC had "been able to produce all the pins necessary for criticality of PFBR (Prototype Fast Breeder Reactor)."[121] In mid-2015, the date for PFBR criticality was pushed back to September 2015.[122] This deadline seems to have been missed.

Japan

According to its INFCIRC/549 report for the end of 2014, Japan had 10.8 tons of plutonium in country and 37 tons of plutonium outside its territory.[123] Of these 37 tons of separated plutonium, 16.3 tons was in France and 20.7 tons was in the United Kingdom.[124]

In March 2014, as part of the Nuclear Security Summit process, Japan announced that it would remove all foreign origin plutonium (and HEU) from the Fast Critical Assembly (FCA) at Tokai.[125] The Fast Critical Assembly uses 331 kg of plutonium, which according to the Japan Atomic Energy Agency, was supplied by three states - the United Kingdom (236 kg), the United States (93 kg) and France (2 kg).

The Japan Atomic Energy Agency (JAEA) announced in September 2014 that it will permanently shut down the head-end of the Tokai-mura reprocessing plant.[126] The decision to close the plant was prompted by cost estimates in excess of ¥100 billion ($915 million) that would be required to bring the plant into line with new regulatory guidelines established after the Fukushima disaster.[127] The plant operated from 1981–2006.

In September 2014, Japan Nuclear Fuel Limited (JNFL) announced that it had postponed commercial operation of the Rokkasho reprocessing plant until at least March 2016 and in 2015 it pushed the date back to 2018 or 2019.[128] It had been scheduled to begin operation in October 2014. When the construction of this plant started in 1993, it was expected that it will begin operations in 1997. Along with postponing the completion date of the Rokkasho reprocessing plant, the planned completion of a plant to manufacture MOX fuel was postponed to late 2019.[129] The original plan, announced in 1997, had called for 16 to 18 reactors to be using MOX fuel by 2010.

Nuclear Weapons, Fissile Materials and Transparency

The theme of *Global Fissile Material Report 2013* was the importance of increased transparency by the nuclear weapons states about the size of their arsenals and their fissile material stockpiles. The Final Document of the 2010 Nuclear Nonproliferation Treaty (NPT) Review Conference included a 64-point Action Plan in the areas of nuclear disarmament, nuclear nonproliferation, and peaceful uses of nuclear energy, which included commitments by the five nuclear weapon states that are parties to the NPT to be more transparent.

The five NPT weapon states submitted progress reports to the 2014 NPT Preparatory Committee Meeting, as required under the Action Plan, and some of these reports were updated during the 2015 NPT Review Conference. The 2015 Conference ended without a Final Document and the status of the Action Plan is uncertain. During 2014 and 2015, there was however little progress on the key obligations from the 2010 NPT Action Plan that bear on nuclear weapon and fissile material stockpiles.

As noted earlier in this report, there exist about 15,800 nuclear warheads as of late 2015, with the United States and Russia together holding more than 90 percent of that stockpile. The HEU and plutonium stockpile estimates presented here, which are partly based on official information and partly based on IPFM estimates, are about 1370 ± 125 tons of HEU and about 505 ± 10 tons of separated plutonium., again mostly held by the United States and Russia.

Since all of this fissile material is weapon-usable, it can be presented not in tons but in terms of weapon equivalents – that is the total number of weapons that could be produced from the fissile material available. It is estimated that the global fissile material stockpile today is sufficient for more than 200,000 simple implosion-type fission nuclear weapons, each with an explosive yield exceeding those of the Hiroshima and Nagasaki weapons.

The national fissile material stockpile estimates presented in this report also can be seen in another way. These national stockpiles can be aggregated into four broad categories of fissile material: material for nuclear weapon purposes, for naval fuel, declared as excess for military purposes and lastly material that is civilian. These stockpiles can be presented in terms both as tons of fissile material designated for each of these purposes worldwide as well as in terms of weapon-equivalents (Figure 10).

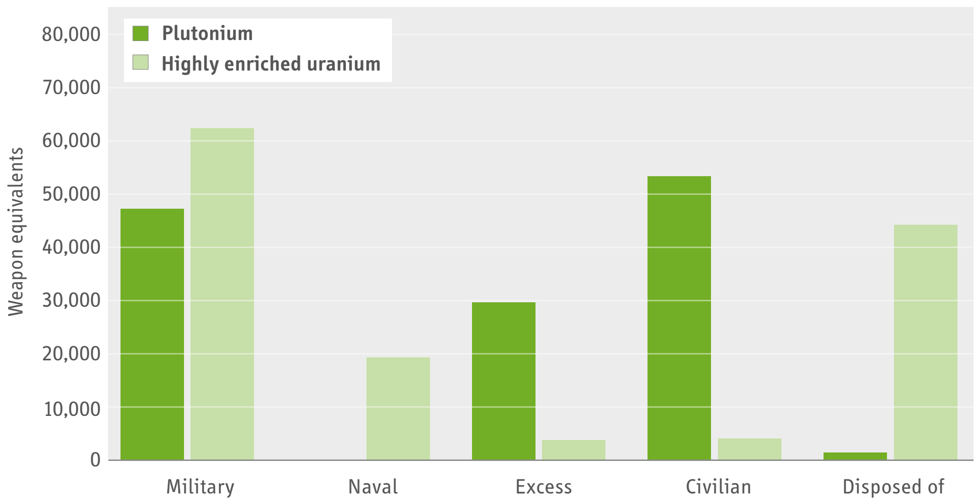


Figure 10. Fissile material stocks by category and their weapon-equivalents. The global stockpiles of plutonium and highly enriched uranium are sufficient for more than 200,000 nuclear weapons, assuming 3 kg of weapon-grade plutonium, 5 kg of reactor-grade plutonium, and 15 kg of highly enriched uranium per weapon-equivalent. The material currently reserved for weapons purposes today is equivalent to more than 100,000 nuclear weapons. This is in contrast to the less than 16,000 warheads in nuclear arsenals worldwide.

The HEU and plutonium currently reserved for weapon purposes together in terms of weapon-equivalents is sufficient for more than 100,000 simple fission warheads. Advanced thermonuclear weapons of the kind in arsenals of most nuclear weapon states are estimated to contain on average 3–4 kg of plutonium in the primary (fission stage), and 15–25 kg of HEU in the thermonuclear second stage of the weapon, where neutrons from fusion reactions drive fission events in the uranium (see Appendix). The fissile material estimated to be available for weapons today is sufficient for at least 45,000 modern two-stage nuclear warheads – i.e., about three times more warheads than are in nuclear arsenals today.

The very large amount of fissile material in the global stockpile reserved by nuclear weapon states for warhead purposes makes clear that nuclear arsenal reductions have not been matched by reductions in fissile material stockpiles. As such, nuclear arsenal reductions are reversible.

Reducing the stockpiles of HEU and plutonium for weapons to match what is actually required to sustain current nuclear arsenals would serve to make arsenal reductions more credible and more irreversible. It is estimated that on the order of 500–700 tons of HEU and 80–90 tons of weapons plutonium could be declared excess for weapon purposes today.

A better estimate of how many warheads there are in the world today and how much fissile material there is in the global stockpile will require much more openness by weapon states. The uncertainties in nuclear arsenal and the fissile material stockpiles are significant, especially for Russia. Baseline declarations of the size of the arsenal and the stockpiles of HEU and plutonium, such as the ones that the United States has provided, would be extremely useful and will likely be necessary to make any real progress towards nuclear disarmament.

Progress on some of the key obligations under the 2010 NPT Action Plan has been mixed (Table 4). Actions 2, 5, 16, 18, 19 and 21 are especially relevant. They offer opportunities for NPT weapons states (and the four non-NPT nuclear weapon states) to increase transparency about warheads and fissile materials stockpiles and establish a basis for progress towards deeper, more irreversible and verifiable nuclear arsenal and fissile material reductions.

	United States	Russia	United Kingdom	France	China
Number of total warheads	Approximate	No	Yes (upper limit)	Yes (upper limit)	Relative (out of date)
Number of deployed warheads	Yes (strategic only)	Yes (strategic only)	Yes (planned)	Yes	No
Dismantlements	Yes	No	Yes (no details)	Yes (no details)	No
Verification	Partial	Partial	No	No	No
Fissile material stockpiles	Yes	No	Yes (no details)	No	No
Production histories	Yes	No	No	No	No
Excess/Disposal	Yes (nothing new)	Yes (nothing new)	Yes (nothing new)	No	No
Verification	Partial	Partial (but no longer)	Partial (some plutonium)	No	No
International R&D activities	Yes	No	Yes	No	Some

Table 4. Nuclear Transparency Scorecard, 2015. Information on nuclear warhead and fissile material inventories and their status in NPT nuclear weapon states. At the 2010 Review Conference, as part of the Action Plan agreed in the Final Document, nuclear weapon states committed to more transparency and to regularly report progress on reductions in the stockpile of nuclear weapons (Actions 2 and 5) and to declare excess and offer for IAEA safeguards material no longer needed for military purposes (Action 16). This scorecard highlights relevant categories and areas (shown in green and in white) in which progress has been made.

The Draft Final Document of the 2015 NPT Review Conference called upon the nuclear-weapon states to provide regular reports on their nuclear disarmament and to report to the 2017 and 2019 sessions of the Preparatory Committee (for the 2020 NPT Review Conference), including:[130]

1. the number, type (strategic or non-strategic) and status (deployed or non-deployed) of nuclear warheads;
2. the number and the type of delivery vehicles;
3. the measures taken to reducing the role and significance of nuclear weapons in military and security concepts, doctrines and policies;
4. the measures taken to reduce the risk of unintended, unauthorized or accidental use of nuclear weapons;
5. the measures taken to de-alert or reduce the operational readiness of nuclear weapon systems;
6. the number and type of weapons and delivery systems dismantled and reduced as part of nuclear disarmament efforts;
7. the amount of fissile material for military purposes.

These reports were to be reviewed at the 2017 and 2019 sessions of the Preparatory Committee and the 2020 Review Conference. This Final Document was not adopted but some specific reports that the weapon states could prepare to make as part of this process, should they choose to do so, are offered below. These proposals build on some of the key Actions agreed at the 2010 NPT Review Conference.

Action 2 & 21: Irreversibility, Verifiability, Transparency.

All NPT nuclear weapon states have released some information about their nuclear arsenals, but with very different levels of detail and with no regularity.

As noted earlier in this report, in 2015 at the NPT Review Conference, the United States for the first time declared its total stock of operational warheads, including those that were retired and awaiting dismantlement. The U.K. has only repeated its planned upper limits on total and operational warheads; France has reiterated its declared upper limit on total warheads, all of which are operational and deployed; China has offered no new information on its stockpile nor repeated the claim that its warhead stockpile was smaller than those of the other NPT weapon states. Further progress in this area would require robust and regularly updated baseline declarations for nuclear warheads and warhead components.

Baseline declarations of historic and current fissile material stockpiles also are feasible, building on the example set by the United States and the United Kingdom.

Action 5: Rapid Irreversible Reductions.

Information made public about warhead dismantlements has been very uneven.

The United States still has warheads awaiting dismantlement that were retired in the 1970–1990s (W71 Spartan and W69 Poseidon), and has committed only to try to increase its annual warhead dismantlement rate by 20 percent in coming years; Russia and China do not provide official information on warhead dismantlement. The United Kingdom plans to cut its stockpile by 45 warheads by the mid-2020s, which corresponds to an average dismantlement rate of 3 warheads per year. France has said that it has no warheads in the queue for dismantlement.

As a step to meeting this obligation, weapon states could declare warhead dismantlements, including historical dismantlements and commit to timely dismantlement of retired warheads and provide regular updates.

Weapon states also could apply the principle of irreversibility to warhead dismantlement. The U.K. has already adopted this policy, with the Ministry of Defence stating in 2013 that "The main components from warheads disassembled as part of the stockpile reduction programme have been processed in various ways according to their composition and in such a way that prevents the warhead from being reassembled."[131] Other weapon states could follow suit.

Action 16: Declaration of Excess Fissile Material and Safeguards.

Despite very specific language in the 2010 NPT Final Document, no additional fissile material has been declared excess for military purposes and placed under safeguards. States could declare the status of fissile material from dismantled warheads and from warheads awaiting dismantlement, and when they might commit to declare this material as excess.

Action 18: Dismantling or Converting Fissile Material Production Facilities.

Some nuclear weapon states have declared the status of and plans for all their fissile material production facilities, notably, France, the United Kingdom and the United States. The others have not.

States also could initiate efforts to preserve fissile material production facilities, associated materials, and historic production records in a condition that would ultimately facilitate verification of fissile material declarations. No formal efforts are currently underway in this regard.

Action 19: Transparency and Verification for Nuclear Disarmament.

This called for cooperation aimed at increasing confidence, improving transparency and developing efficient verification capabilities related to nuclear disarmament is necessary.

The United States has recently re-vitalized research in this area and is considering declassifying information, which could significantly simplify disarmament verification. China has also launched a research program that covers "verification technologies of nuclear warheads dismantling and authentication, and the storage and disposition of nuclear components and nuclear material [...]"[132]

The next steps in establishing a firm technical foundation for the verification of nuclear disarmament could include:

1. Verifying Nuclear Warhead Dismantlement: Efforts to jointly develop and demonstrate practical warhead inspection systems.
2. Verifying Historic Fissile Material Production: Agreement on the most important types of fissile material production facility operating records to be preserved, on cataloguing, characterizing, and preserving waste materials from fissile material production, and demonstrating nuclear archaeological methods for uranium enrichment plants, plutonium production reactors and reprocessing plants.

Appendix 1 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 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 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.

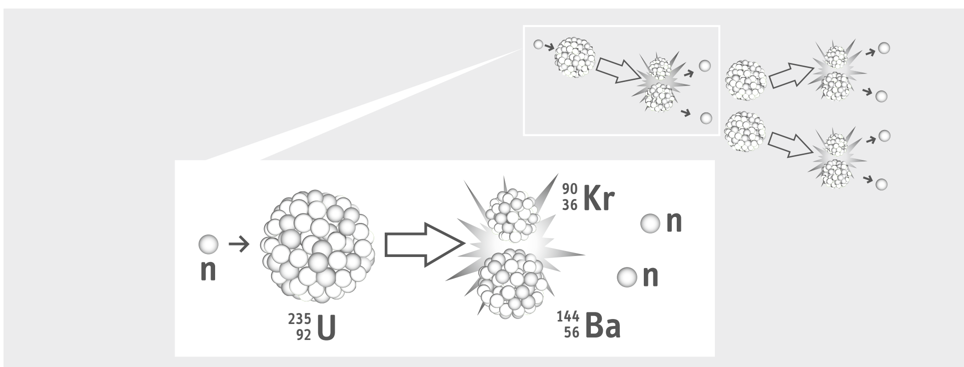


Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission 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 kg 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).

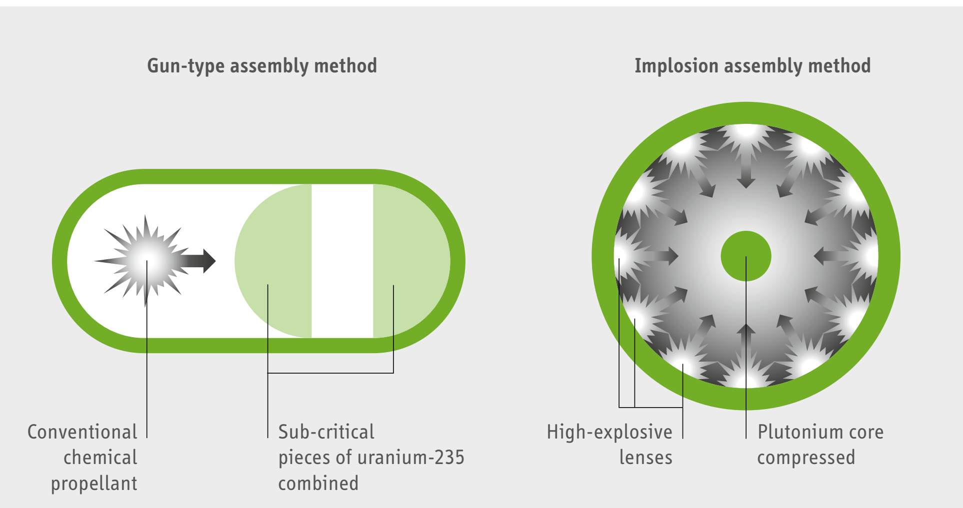


Figure A.2. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated "gun-type" method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow. 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 when the chain reaction is initiated in the fissile mass at the moment when it will grow most rapidly, i.e., when the mass is most super-critical. HEU can be used in either gun-type or implosion weapons. As 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 uranum-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 of about 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, 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.

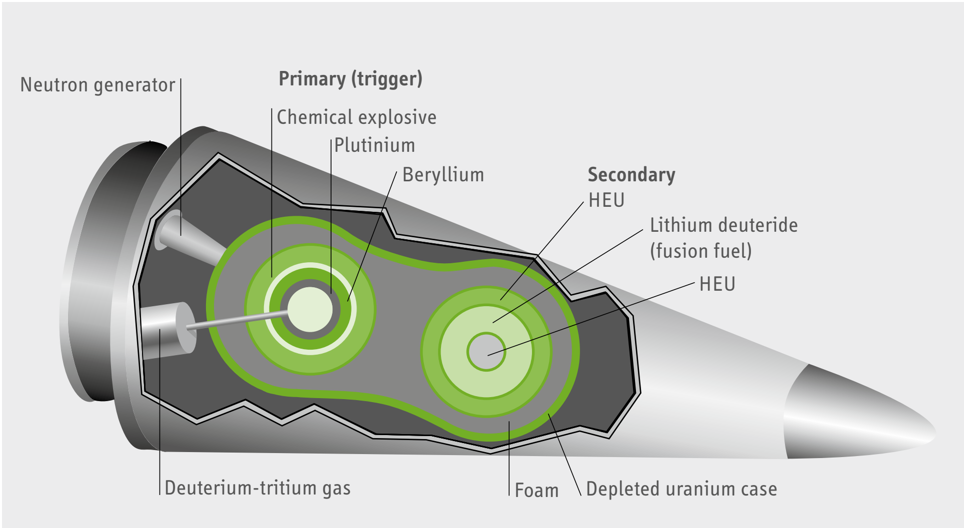


Figure A.3. A modern thermonuclear weapon usually contains both plutonium and highly enriched uranium. Typically, these warheads have a mass of about 200–300 kg and a yield of hundreds of kilotons of chemical explosive, which corresponds to about one kilogram per kiloton of explosive yield. For comparison, 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 conversion of the lithium-6 to tritium 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. Neutrons from thermonuclear reaction also induce fission in the uranium, 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.

	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
Two-stage high-yield weapon	3–4 kg Pu and 50+ kg HEU		1–10 MT	B83

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 highly enriched uranium. 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 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).

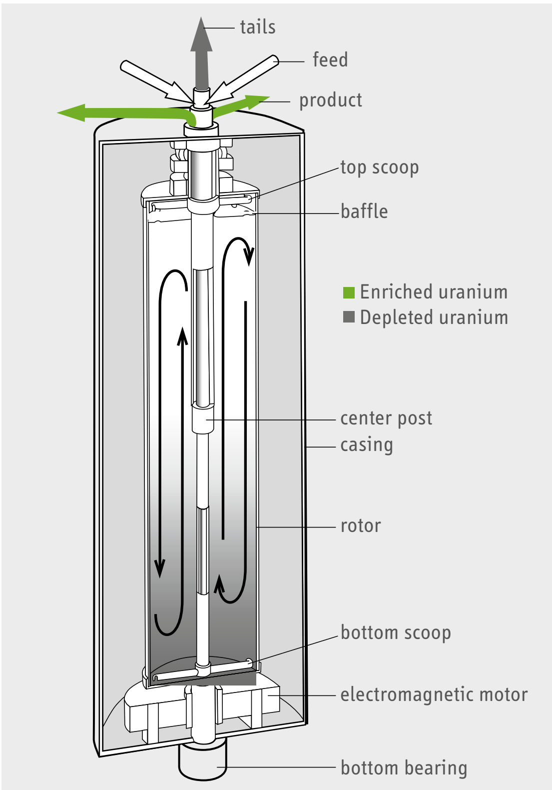


Figure A.4. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small 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 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 super-critical mass. In a Nagasaki-type design, even the earliest possible pre-initiation of the chain reaction would not reduce the yield below about 1000 tons TNT equivalent. That would still be a devastating weapon.

More modern nuclear weapon designs are insensitive to the isotopic mix in the plutonium. As summarized in a 1997 U.S. Department of Energy report: “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.”[133] 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 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. This makes its diversion or theft a rather unrealistic scenario. Separated plutonium can be handled without radiation shielding, but is dangerous when inhaled or ingested.

Appendix 2 Uranium Enrichment Plants

Facility	Type	Operational Status	Safeguards Status	Capacity [tSWU/yr]
Argentina				
Pilcaniyeu	Civilian	Resuming Operation	yes	TBD
Brazil				
Resende	Civilian	Expanding Capacity	yes	17–200
China				
Shaanxi	Civilian	Operating	(yes)	1000
Lanzhou II	Civilian	Operating	offered	500
Lanzhou (new)	Civilian	Operating	no	1000
France				
George Besse II	Civilian	Operating	yes	6000–7500
Germany				
Gronau	Civilian	Operating	yes	4100–4500
India				
Ratehalli	Military	Operating	no	15–30
Iran				
Natanz	Civilian	Limited Operation	yes	120
Fordow	Civilian	Limited Operation	yes	5 – 10
Japan				
Rokkasho	Civilian	Resuming Operation	yes	75–1500
Netherlands				
Almelo	Civilian	Operating	yes	5400–6200
North Korea				
Yongbyon	?	?	no	(8)
Pakistan				
Kahuta	Military	Operating	no	15 – 45
Gadwal	Military	Operating	no	Unknown
Russia				
Angarsk	Civilian	Operating	offered	4000
Novouralsk	Civilian	Operating	no	13,300
Zelenogorsk	Civilian	Operating	no	7900
Seversk	Civilian	Operating	no	3800
United Kingdom				
Capenhurst	Civilian	Operating	yes	4900
United States				
Eunice, NM	Civilian	Operating	offered	3700

Where a range of capacities is shown, the facility is expanding its capacity — except for Pakistan, where the range denotes uncertainty in estimated capacity.

Appendix 3 Reprocessing Plants

Facility	Type	Operational Status	Safeguards Status	Capacity [tHM/yr]
China				
Jiuquan	Civilian	Operating	(no)	50–100
France				
La Hague, UP2	Civilian	Operating	yes	1000
La Hague, UP3	Civilian	Operating	yes	1000
India				
Trombay	Military	Operating	no	50
Tarapur-I	Dual	Operating	no	100
ADD Tarapur-II	Dual	Operating	no	100
Kalpakkam	Dual	Operating	no	100
Israel				
Dimona	Military	Operating	no	40–100
Japan				
Rokkasho	Civilian	Starting up	yes	800
Tokai	Civilian	To be shutdown	yes	200
North Korea				
Yongbyon	Military	On standby	no	100–150
Pakistan				
Nilore	Military	Operating	no	20–40
Chashma	Military	Starting up	no	50–100
Russia				
RT-1	Dual	Operating	no	200–400
Seversk	Dual	Shutdown	no	6000
Zheleznogorsk	Dual	Shutdown	no	3500
United Kingdom				
B205	Civilian	To be shutdown after cleanup	yes	1500
THORP	Civilian	To be shutdown	yes	1200
United States				
H-canyon, SRP	Converted	Special Operations	no	15

Appendix 4 Civilian Plutonium Stockpile Declarations

	France (Addendum 5)		Japan (Addendum 1)		Russia (Addendum 9)		United Kingdom (Addendum 8)		United States (Addendum 6)	
1996	65.4	30.0	5.0	0.0	28.2	0.0	54.8	6.1	45.0	0.0
		0.2		15.1		0.0		0.9		0.0
1997	72.3	33.6	5.0	0.0	29.2	0.0	60.1	6.1	45.0	0.0
		<0.05		19.1		0.0		0.9		0.0
1998	75.9	35.6	4.9	0.0	30.3	0.0	69.1	10.2	45.0	0.0
		<0.05		24.4		0.0		0.9		0.0
1999	81.2	37.7	5.2	0.0	32.0	0.0	72.5	11.8	45.0	0.0
		<0.05		27.6		0.0		0.9		0.0
2000	82.7	38.5	5.3	0.0	33.4	0.0	78.1	16.6	45.0	0.0
		<0.05		32.1		0.0		0.9		0.0
2001	80.5	33.5	5.6	0.0	35.2	0.0	82.4	17.1	45.0	0.0
		<0.05		32.4		0.0		0.9		0.0
2002	79.9	32.0	5.3	0.0	37.2	0.0	90.8	20.9	45.0	0.0
		<0.05		33.3		0.0		0.9		0.0
2003	78.6	30.5	5.4	0.0	38.2	0.0	96.2	22.5	45.0	0.0
		<0.05		35.2		0.0		0.9		0.0
2004	78.5	29.7	5.6	0.0	39.7	0.0	102.6	25.9	44.9	0.0
		<0.05		37.1		0.0		0.9		0.1
2005	81.2	30.3	5.9	0.0	41.2	0.0	104.9	26.5	45.0	0.0
		<0.05		37.9		0.0		0.9		0.0
2006	82.1	29.7	6.7	0.0	42.4	0.0	106.9	26.5	44.9	0.0
		<0.05		38.0		0.0		0.9		0.0
2007	82.2	27.3	8.7	0.0	44.9	0.0	108.0	26.8	53.9	0.0
		<0.05		37.9		0.0		0.9		0.0
2008	83.8	28.3	9.6	0.0	46.5	0.0	109.1	27.0	53.9	0.0
		<0.05		37.8		0.0		0.9		0.0
2009	81.8	25.9	10.0	0.0	47.7	0.0	112.1	27.7	53.9	0.0
		<0.05		36.15		0.0		0.9		0.0
2010	80.2	24.2	9.9	0.0	48.4	0.0	114.8	28.0	53.9	0.0
		<0.05		35.0		0.0		0.9		0.0
2011	80.3	22.8	9.3	0.0	49.5	0.0	118.2	27.9	49.3	0.0
		<0.05		35.0		0.0		0.9		0.0
2012	80.6	22.2	9.3	0.0			120.2	23.8		
		<0.05		34.9				0.9		
2013	78.1	17.9	10.8	0.0	51.9	0.0	123	23.4	49.3	0.0
		<0.05		36.3		0.0		0.9		0.0
2014	78.8	16.9	10.8	0.0	52.8	0.0	126.3	23.0	49.3	0.0
		<0.05		37.0		0.0		0.0		0.0

Inventory held in country | Foreign-owned (included in local inventory)
Stored outside the country (not included in local inventory)

The annual inventories (as of December 31st of the respective year) listed in the table are in tons. The declarations give the fissile material stocks at reprocessing plants, fuel-fabrication plants, reactors, and elsewhere, divided into non-irradiated forms and irradiated fuel. Russia does not include in its declaration excess weapons plutonium, whereas the United States and U.K. do.

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A report published by
The International Panel on Fissile Materials (IPFM)
www.fissilematerials.org

Program on Science and Global Security
Princeton University
221 Nassau Street, 2nd Floor
Princeton, NJ 08542, USA

December 2015