Plutonium and Highly Enriched Uranium 2015
INSTITUTE FOR SCIENCE AND INTERNATIONAL SECURITY

Military Highly Enriched Uranium and Plutonium Stocks in Acknowledged Nuclear Weapon States[a]

End of 2014

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November 3, 2015

Plutonium and highly enriched uranium (HEU), called "fissile materials," were first produced in large quantities for use in nuclear weapons. Starting in World War II, and for over two decades afterwards, almost all the plutonium and HEU in the world was produced for these immensely destructive weapons. This production was centered almost exclusively in five states: Britain, China, France, Russia, and the United States.

In the Nuclear Non-Proliferation Treaty (NPT) these five countries are designated as "nuclear-weapon states" because all five had manufactured and exploded a nuclear weapon prior to January 1, 1967. To this day, they remain the only acknowledged nuclear weapon states. Although other countries possess nuclear weapons, the acknowledged states have gained a special status in international affairs. As part of that status, however, these five states also committed to work towards nuclear disarmament, in particular steps accompanied by the elimination of their own stocks of fissile material for nuclear weapons.

At the end of 2014, these five states had military stocks totaling about 238 tonnes of plutonium and 1,330 tonnes of HEU, mostly weapon-grade uranium (WGU is defined as HEU enriched over 90 percent). Table 1 provides a summary of the results. Tables 2 and 3, located at the end of the report, provide official declarations or detailed estimates of each country's military plutonium and HEU holdings. These tables provide extensive endnotes describing official declarations, other sources, and the derivation of the various estimates. In addition to aggregate totals, tables 2 and 3 provide partial information about the various types of military stocks held by these five countries, including fissile material dedicated to nuclear weapons activities and naval propulsion programs, and declared excess to defense requirements.

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[a] This report is part of a series on national and global stocks of nuclear explosive materials in both civil and military nuclear programs. This work was generously funded by a grant from the Nuclear Threat Initiative (NTI). This work builds on earlier work done at ISIS by one of the authors.

Table 1. Military Highly Enriched Uranium and Plutonium Stocks in the Acknowledged Nuclear Weapon States, end of 2014

Country	Plutonium	HEU	Total Fissile Material
United States	95.4	544	639
Russia	128	712	840
United Kingdom	7.6	25	32.6
France	5.3	30.5	35.8
China	1.9	19.4	21.3
Total	**238**	**1,330 (rounded)**	**1,570 (rounded)**

A crude measure of the number of weapons that could be built with these materials is derived by assuming that a nuclear weapon would contain 25 kilograms of HEU or 8 kilograms of plutonium. Using those values, the five nuclear weapon states have the equivalent of roughly 80,000 nuclear weapons. These five states in fact possess far fewer nuclear weapons, likely about 15,000 according to the Federation of American Scientists.[b] Nonetheless, this value provides a measure of how large these military stocks remain.

Figures 1 and 2 compare the worldwide amounts of military fissile material to their respective civilian stocks while figures 3 and 4 illustrate the amounts of military fissile material in the five acknowledged nuclear weapon states.

Much of the stocks are dedicated to nuclear weapons programs, including weapons, reserves, and other related categories. With existing information, however, it is difficult to accurately determine the amount of fissile material strictly dedicated to nuclear weapons, including amounts held in strategic reserves for such weapons. In the case of the United States, the data imply that this stock holds about 225 tonnes of HEU. Another 110 tonnes of fresh HEU are held in reserve for future use in naval propulsion reactors, but this stock could be used for nuclear weapons as well. In table 3, this stock of 335 tonnes is identified as the primary military HEU stock. A similar HEU break down in the case of the other nuclear weapon states was not possible due to a lack of authoritative or official information. However, their stocks' sheer size suggests that the amount of HEU needed for their nuclear weapons and a reasonable reserve is significantly less than their total military HEU given in the first column of table 3.

It is important to note that in addition to the military fissile material dedicated to nuclear weapons, there is a substantial amount of plutonium and HEU that is not in stocks dedicated to nuclear weapons programs. As mentioned above, in the case of HEU, there are large stocks of this material under the authority of other military programs, namely naval programs. The United States has almost 100 tonnes of HEU in mostly irradiated forms, particularly in reactor cores, under the authority of the naval propulsion program and another 28 tonnes of HEU in spent naval

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[b] "Status of World Nuclear Forces," Federation of American Scientists, September 28, 2915, http://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.

fuel awaiting geological disposal. There are also HEU stocks leftover in plutonioum and tritium production reactor spent fuel and declared excess to defense requirements. This last category, namely excess fissile material, represents commitments to nuclear arms reductions and efforts to reduce the security risks posed by these materials.

Since the end of the Cold War, stocks of military HEU have diminished overall. As of the end of 2014, almost 650 tonnes of military HEU have been blended down into low enriched uranium (LEU), a form not usable in nuclear weapons. Another 116 tonnes are declared excess and awaiting downblending to LEU or ultimate disposal in a geological depository, (e.g. HEU in US naval spent fuel). Since the end of the Cold War, about 38 percent of the post-Cold War HEU stock has been blended down to LEU or is awaiting downblending or disposal.

In the case of plutonium, there are also substantial excess stocks in addition to stocks dedicated to the nuclear weapons programs. About 111 tonnes of plutonium are slated for disposal in geological repositories or irradiation in civil nuclear reactor fuel and then disposition. About 47 percent of the plutonium in military stocks at the end of the Cold War has been committed to civil purposes or disposal as waste. However, plutonium disposition programs have encountered serious delays and little of this plutonium has been used in civil programs or disposed.

Information about the military stocks has been gathered from official declarations and other open sources. Both Britain and the United States have provided detailed declarations of their stocks of plutonium and HEU for weapons purposes. However, China, France, and Russia have provided little official information about their military stocks of plutonium and HEU. These stocks are estimated in this report, although these estimates have relatively large uncertainties.

Overall, greater transparency is needed about these stocks, particularly in states that have not declared them. Moreover, as of the date of this publication, Britain and the United States could usefully update their declarations. The last US HEU declaration was published in 2006, covering the stock as of 2004. Similarly, Britain’s plutonium and HEU declarations are at least that old.

This task, even in states that declare, is complicated by the age, or lack, of production records, the sheer amount in these inventories, and inaccurate accounting of these materials that ended up in waste. After all, most of this material was produced decades ago when material accounting standards and capabilities were far less than today.

A critical, on-going priority is ensuring that none of these stocks are stolen or otherwise diverted. The sheer enormity of these stocks, measured in hundreds of tonnes, stands sharply against the reality that only kilograms are needed to make a nuclear weapon. For example, with the proliferation of civil unrests in the Middle East and North Africa, the risk of terrorists groups, or more generically non-state actors, seeking fissile material is likely to grow. The chance of them acquiring a nuclear weapon, either through theft of a functioning nuclear weapon, or of nuclear explosive material followed by the manufacturing of a crude nuclear explosive, is assessed as low. However, the consequences of a nuclear weapon in the hands of terrorists would be disastrous, and extraordinary efforts need to be waged to ensure that the risk becomes even lower. Therefore, countries need to constantly improve their security over nuclear weapons and fissile materials, against both external and insider threats.

Another priority is negotiating a verified fissile material cutoff treaty (FMCT). Although all of these five countries have ended their production of plutonium and HEU for nuclear explosive purposes, a negotiated, verified treaty would provide confidence that no more stocks are produced for nuclear weapons in these states. A FMCT would also stimulate more transparency of the existing stocks. By involving other states with nuclear weapons, a FMCT would cap stocks in those countries, all of which still produce plutonium and HEU for nuclear weapons.

Another priority is reducing the amounts of plutonium and HEU in nuclear weapons as part of nuclear disarmament obligations. It is important for the five acknowledged states to officially declare more of their stocks of plutonium and HEU excess to defense requirements and take steps to render the material unusable in nuclear weapons.

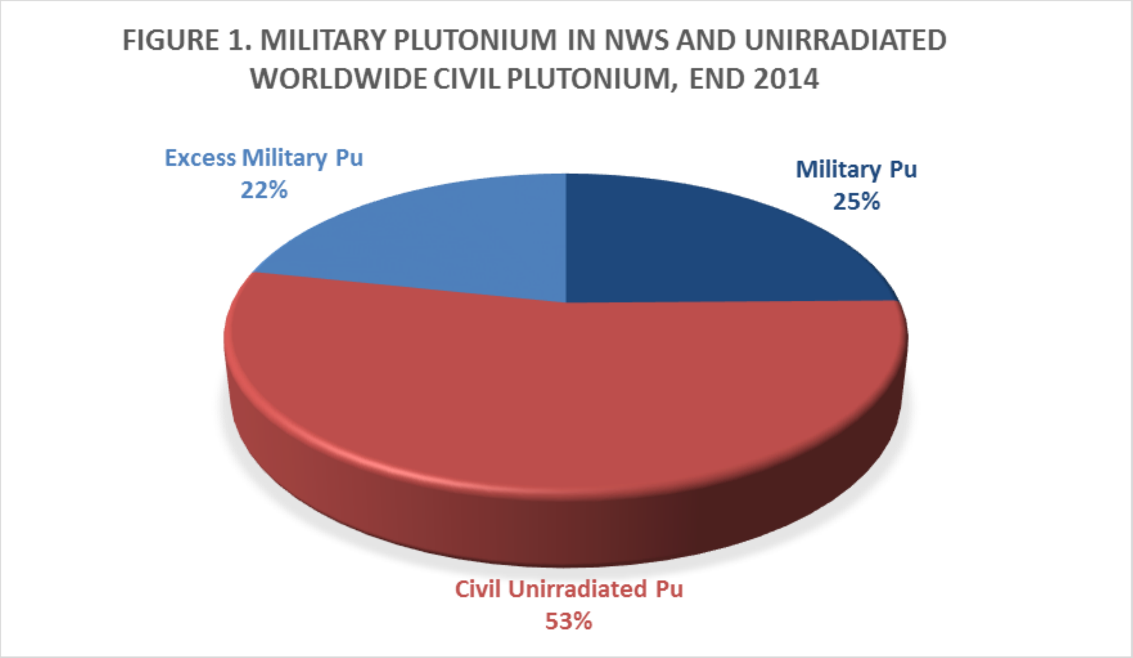


FIGURE 1. MILITARY PLUTONIUM IN NWS AND UNIRRADIATED WORLDWIDE CIVIL PLUTONIUM, END 2014

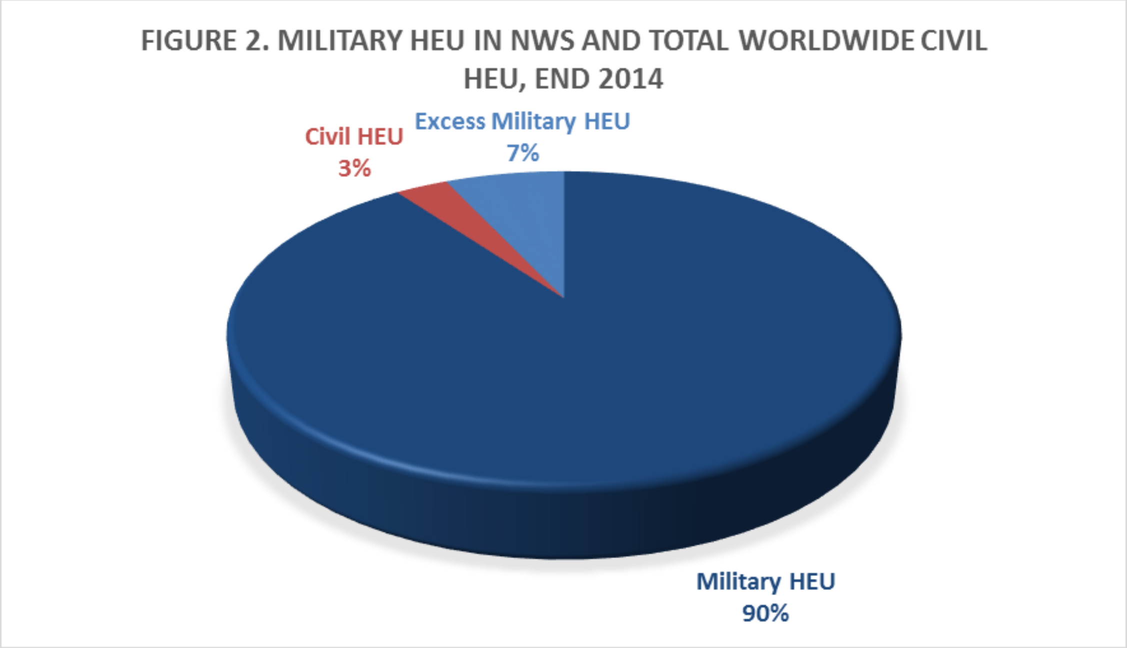


FIGURE 2. MILITARY HEU IN NWS AND TOTAL WORLDWIDE CIVIL HEU, END 2014

Note: Excess HEU and plutonium is considered part of the military stocks in these figures.

FIGURE 3. MILITARY PLUTONIUM IN NWS, END 2014

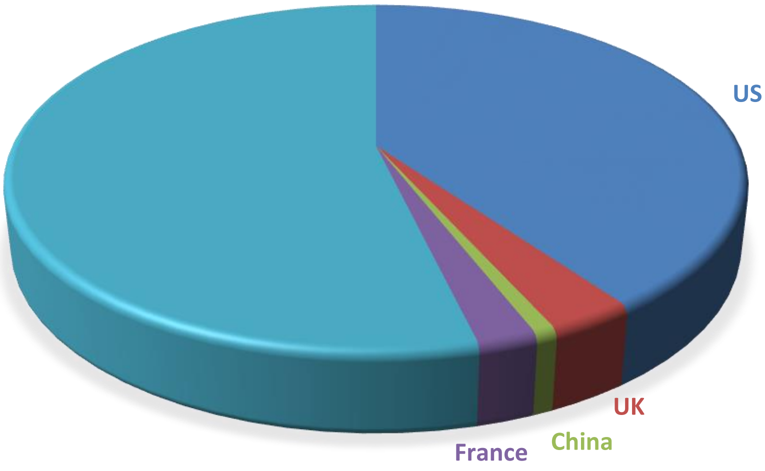


FIGURE 4. MILITARY HEU IN NWS, END OF 2014

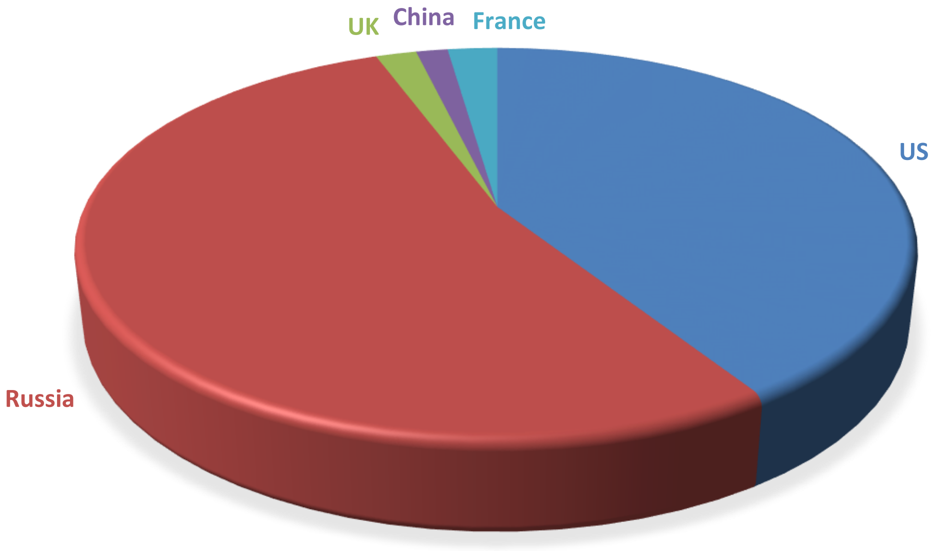


Table 2. Military and Excess Stocks of Plutonium in the Acknowledged Nuclear Weapon States, end of 2014 (tonnes)

Country	Total[a]	Military Stock[b]	Declared Excess
State Declarations			
United Kingdom[c]	7.6	3.2	4.4
United States[d]	95.4	33.9	61.5[e]
ISIS Estimates of Stocks			
China[f]	1.9 (1.6-2.4)	1.9	0
France[g]	5.3 (4.1-6.4)	5	0
Russia[h]	128 (120-136)	78-88[i]	40-50[j]
Total	**238 (229-248)**	**127 ±5**	**111 ±5[k]**

Table 3. Estimated Military and Excess Stocks of Highly Enriched Uranium (HEU) in the Acknowledged Nuclear Weapon States, end of 2014 (in tonnes)[l]

Country	Military Stocks, in Weapons, Reserves, including naval reserves[m]	Naval Programs, Military Reactors[n]	Production Reactors[o]	Excess for Disposition, via Downblending or Disposal[p]		Total (median)
				Original	Remaining	
United Kingdom[q]	19-20	5.5-6.2	0	0	n.a.	**25**
China[r]	19.4 (± 5)	Small	none?	0	n.a.	**19.4**
France[s]	24 (± 6)	1[t]	5.5[u]	0	n.a.	**30.5**
Russia	660 (±100)[v]	40-60[w]	?[x]	500[v] 15.2[v]	0 2	**712**
U.S.	335 (±10)[y] Subset of total in nuclear weapons program: 225 (±5)[y]	90-100[z]	--[aa]	239[bb] Naval spent fuel: 28[z] (7 tonnes overlap)	93[bb,cc] Naval spent fuel: 28[z] (7 tonnes overlap)	**544[cc]**
Total (median)	**1,058**	**152**	**5.5**		**116[p]**	**1,331**

Notes and Comments for Tables 2 and 3

(a) The values in the parentheses represent the range of the total estimated stock.

(b) Only the central estimates are used in this column.

(c) See "Plutonium and Aldermaston – An Historical Account," United Kingdom Ministry of Defense, 2000; and "The Strategic Defense Review White Paper," United Kingdom House of Commons Defense Select Committee, October 15, 1998.

(d) As of 2009, the United States' total production and acquisitions of plutonium amounted to 111.7 metric tonnes of plutonium. Of this, 103.4 tonnes came from production, 0.7 tonnes from research reactors, 5.8 tonnes were imported from the United Kingdom, and 1.8 tonnes were produced by industry. However, 16.4 metric tonnes were removed. About 3.4 tonnes were used in weapons testing, 0.5 tonnes were lost due to radioactive decay, 1.3 tonnes were lost to fission and transmutation, 7.8 tonnes were downgraded to waste, 0.2 tonnes were exported, and 0.8 sent to industry. Additionally, an inventory difference of 2.4 tonnes is included in these removals. See *The United States' Plutonium Balance, 1944-2009*, Department Of Energy/NNSA, June 2012.

(e) As of December 2013, a total of 61.5 metric tonnes of government owned plutonium were declared excess to national security needs. See *Communication Received from the United States of America Concerning its Policies Regarding the Management of Plutonium*, INFCIRC/549/Add.6/17, October 6, 2014. This stock, totaling 61.5 tonnes, is comprised of 49 tonnes or unirradiated plutonium and 7.8 tonnes in spent fuel, 4.5 tonnes disposed as waste, and 0.2 tonnes lost to radioactive decay since September 1994, when the last declaration happened.

(f) Although considerable amounts of information have emerged about the Chinese nuclear weapon program over the last three decades, great uncertainty surrounds its military plutonium stocks. Further complicating any analysis, China still treats details about a key plutonium production reactor as secret. Unlike the other declared nuclear weapon states, China has yet to officially state that its production of fissile materials for weapons has ended. However, unofficial Chinese statements indicate that such production ended by about 1991, likely earlier.

This study builds on a 2005 ISIS study and work done by Jeffrey Lewis, who uncovered a range of new information about the Chinese plutonium production program. See David Albright and Corey Hinderstein, *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, ISIS, June 30, 2005. http://isis-online.org/uploads/isis-reports/documents/chinese_military_inventories.pdf and Jeffrey Lewis *Paper Tigers: China's Nuclear Posture* (Adelphi Book 446), International Institute for Strategic Studies (Oxon and New York: Routledge, 2014). The amount of plutonium in this current estimate is significantly less than the 2005 estimated quantity. It reflects new information that the power of the main plutonium production reactors at Jiuquan and Guangyuan was less than originally assessed.

The plutonium estimate uses a simple formula that predicts plutonium production in reactors, where variables in this formula are given as ranges of values. This equation is evaluated using Crystal Ball® software. Rather than decide on a best estimate of a specific parameter, such as reactor power, a frequency distribution of possible values is derived for use in the software. Distributions representing key parameters in a formula are then sampled using a Monte Carlo approach to derive a distribution of results. In essence, a variable’s range is treated as a probability distribution, often a uniform distribution where each value is equally likely. The advantage of this software is that the results represent many more possibilities where the exact value of the variable is relatively poorly known, leading to a more rigorous uncertainty analysis. Although judgments are still necessary in any uncertainty analysis, they can be applied in a more transparent manner with this software, and many more simulations are considered.

The plutonium (Pu) production formula is:

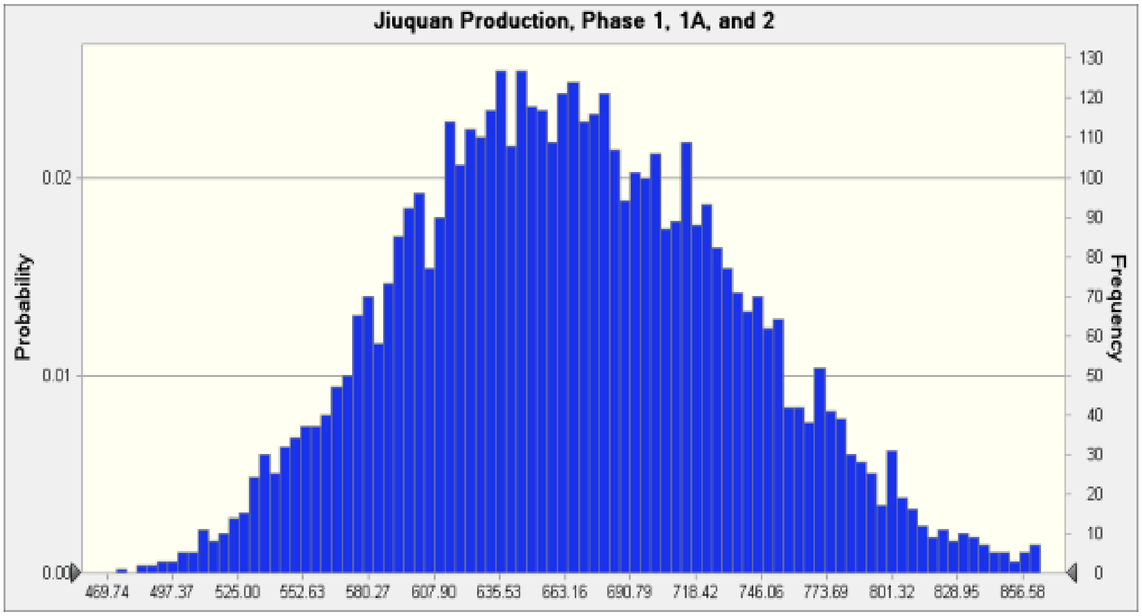
$$\textit{Pu = Power x Capacity Factor x Years in Operation x Plutonium Conversion Factor x (0.001)}$$

where the Plutonium Conversion factor is the amount of weapon-grade plutonium in the discharged fuel per unit of energy produced in the uranium fuel, taken here as 0.85 grams of weapon-grade plutonium per MWth-d. The last factor converts from grams to kilograms. The most sensitive parameters in this estimate are the power of the reactors and the average capacity factors. In this estimate, the operation of each reactor is divided into different phases, reflecting available operational information.

For the Jiuquan reactor, the periods of weapon-grade plutonium production, along with estimates of reactor power and capacity factor, are:

Years	Power (MWth)	Capacity Factor
1966-1975 (phase 1)	100-200	0.2-0.5
1976-1979 (phase 1A)	250-350	0.4-0.6
1980-1984 (phase 2)	300-400	0.5-0.7

The reactor was shut down in 1984, ending any further plutonium production. Under these assumptions, the median of total amount of weapon-grade plutonium produced in the Jiuquan reactor is 0.66 tonnes with a full range of 0.46 to 0.93 tonnes. The distribution is:

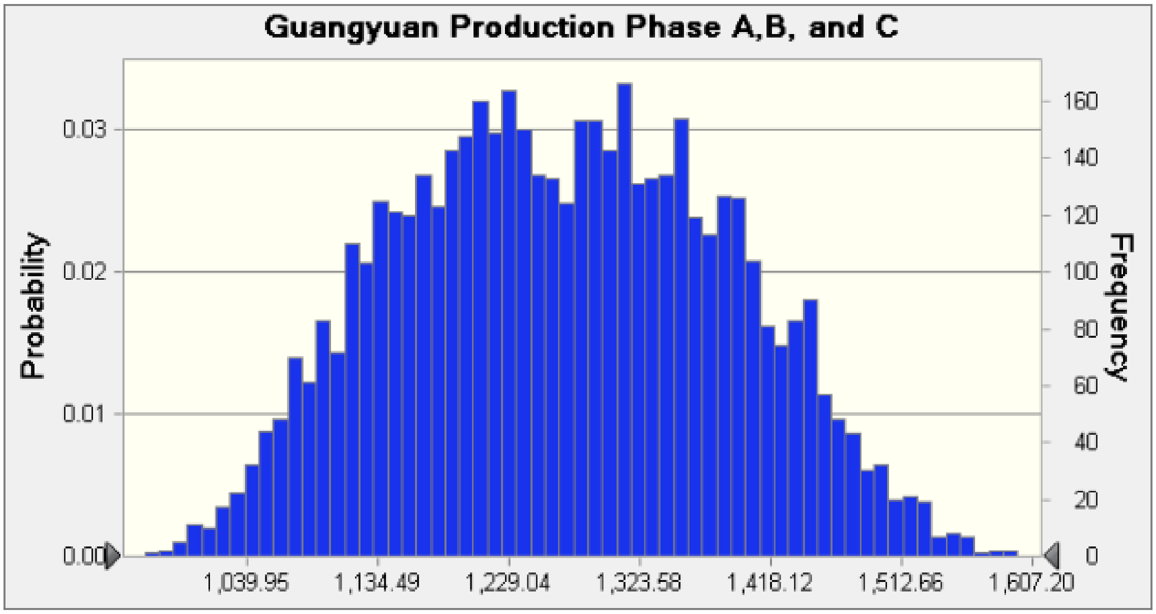


For the Guangyuan reactor, the periods of weapon-grade plutonium production, along with estimates of reactor power and capacity factor, are:

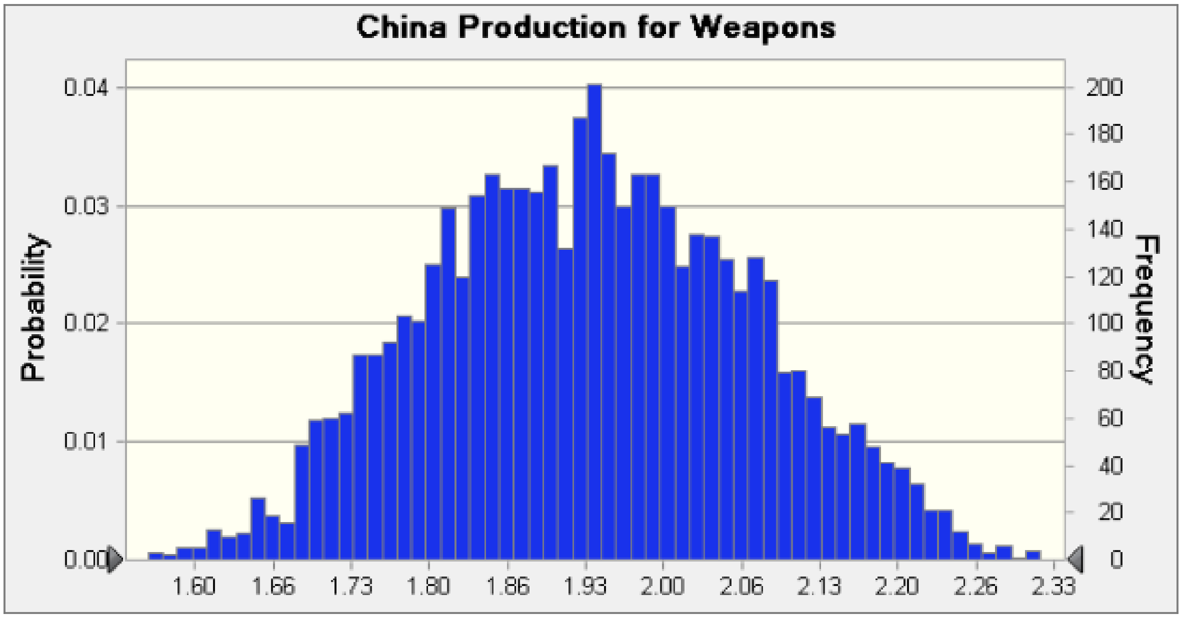
Years	Power (MWth)	Capacity Factor
1973-1976 (phase A)	200-300	0.3-0.5
1977-1980 (phase B)	200-400	0.4-0.6
1981-1990 (phase C)	350-500	0.7-0.8

It is unknown if the Guangyuan reactor shut down in 1990 or continued to operate afterwards. If so, it likely produced non-weapon-grade plutonium. However, it is not possible to do an estimate of the amount of this plutonium without more information.

Under these assumptions, the median of total amount of weapon-grade plutonium produced in the Guangyuan reactor is 1.27 tonnes with a full range of 0.97 to 1.60 tonnes, respectively. The distribution is:



Total plutonium production in the two reactors is 1.93 tonnes, with a full range of 1.6 to 2.4 tonnes. The standard deviation is 0.14 tonnes, but reflecting the uncertainties, the full range is used. The distribution is:



China used some of this plutonium in nuclear tests and undoubtedly had processing losses. However, given the uncertainties in estimating both total plutonium production and the size of the relatively small drawdowns, these drawdowns are ignored here.

(g) The estimate is from David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford: Oxford University Press, 1997), p. 68. However, the value for Chinon-1, -2, and -3, St. Laurent-1 and -2, and Bugey-1 has been modified to a range of 1-2 tonnes.

(h) See *Global Fissile Material Report 2010*, Fifth Annual Report of the International Panel on Fissile Material, http://fissilematerials.org/library/gfmr10.pdf.

(i) The value in the Global Fissile Material 2010 (op. cit) is 88 tonnes. However, the 78-88 tonnes range reflects that Russia has committed to declaring excess up to 50 tonnes of plutonium. See footnote (j).

(j) The declared plutonium excess is up to 50 tonnes. At the 1996 Moscow Summit, Russia committed to releasing up to 50 tonnes of weapon grade plutonium from its military program. This commitment was later reconfirmed at the 41th Session of the IAEA General Conference in 1997, where Victor Mikhailov, Minister of the Russian Federation for Atomic Energy, read a statement from President Boris Yeltsin announcing that Russia would begin the staged withdrawal of up to 500 tonnes of HEU and up to 50 tonnes of plutonium from military programs, the pace depending on the dismantling of nuclear weapons and the construction of necessary storage facilities. See "Unofficial Summaries of Statements, September 1997, http://www.iaea.org/About/Policy/GC/GC41/Statements/30septam.html. However, technical and financial difficulties relative to the disposition of plutonium arose. A Joint Steering Committee was created and worked out the Plutonium Management and Disposition Agreement (PMDA) which was signed in the year 2000. Both the United States and Russia committed to dispose of 34 tonnes of its excess weapon grade plutonium by loading it into MOX fuel and subsequently irradiating it in civil nuclear reactors. However, the practical implementation of the agreement was delayed because of liability and financial difficulties. A new plan for the disposition of the 34 tonnes of plutonium was agreed upon in 2007 and modified in 2011. According to the modified agreement, both the United States and Russia agreed to start the disposition process in 2018. See A. Diakov1 and V. Rybachenkov2, "Disposition of Weapon Grade Plutonium: New Developments," January 13, 2014, http://armscontrol.ru/pubs/en/disposition-of-excess-weapon-grade-plutonium-new-developments-en.pdf. However, additional delays continue. The 15 tonnes of plutonium produced in Russian production reactors since 1994 are committed to non-nuclear weapons use. However, according to the *Global Fissile Material Report 2010,* about 9 tonnes of this 15 tonnes are included in Russia's 34 tonnes that are firmly committed to MOX irradiation. The remaining 6 tonnes are added to the excess, resulting in a total of 40 tonnes in this category in *Global Fissile Material Report 2010*. The original commitment is for up to 50 tonnes, so a range of 40-50 tonnes is used in this table. If 50 tonnes were used for non-nuclear weapons purposes, the military stock value of 88 tonnes would be reduced to 78 tonnes.

(k) Rounded values.

(l) This table presents highly enriched uranium (HEU) stocks in nuclear weapons programs and associated reserves, naval propulsion programs and military reactors, and defunct production reactor programs that made plutonium and tritium for nuclear weapons, as well as HEU stocks declared excess to defense requirements. The HEU is in many chemical forms and shapes, including warhead parts, metals, oxides, process residues, compounds, solutions, unirradiated and irradiated fuel, hold-up materials in facilities, sources, standards, and waste.

(m) This column lists estimates of the primary, or "maintained," military stocks that contain HEU, mostly weapon-grade, assigned to nuclear weapons, reserves, or in the case of at least the United States, slated for future use in naval propulsion, other military programs or a limited number of civil reactors. The values in the parentheses are the uncertainty ranges of the total estimated stock. The British value is an official declaration, and no uncertainty was provided by the government.

(n) The values in this column represent inventories in naval reactors under the control of defense departments or ministries. In some cases, as noted in endnotes, the HEU may be in land-based military or naval reactors. In some countries, this category may include all the HEU in spent naval reactor fuel slated for eventual disposition or recycling. However, in the case of the United States, the bulk of the HEU in naval spent fuel is listed under excess stocks.

(o) This column includes mainly HEU used in military production reactors. See relevant endnotes for more details.

(p) This column is focused on Russia and the United States, which have made public announcements that formerly military HEU stocks are excess to defense requirements and slated for downblending or disposition, such as in spent fuel slated for geological disposal. In the case of the U.S. HEU in naval spent fuel slated for geological disposal, the amount overlaps by 7 tonnes with the 93 tonnes in excess, so the total of these two values is 93 + 28 -7 = 114 tonnes. See endnotes (z) and (cc).

(q) The British values are based on earlier British declarations. In 2006, Britain declared that it had an audited stock of 21.86 tonnes of HEU as of March 31, 2002. See Ministry of Defense, *Historical Accounting for UK Defense Highly Enriched Uranium,* March 2006. The average enrichment level of the HEU was not specified. The Ministry also declared that based on an evaluation of historical records, the UK had produced in total 26.36 tonnes of HEU for defense programs. It further stated that 4.72 tonnes had been removed, leaving an estimated stock of 21.64 tonnes of HEU as of this date. The difference between the audited and estimated stocks is 0.22 tonnes, which is attributed to missing historical production records and other uncertainties associated with a re-creation of the historical production and use of HEU. The report says that the removed HEU was used in naval nuclear reactors, military test reactors, and nuclear weapon tests and experiments. Some HEU ended up in waste. One uncertainty is whether the quantity of the removed HEU represents its initial mass or is decreased to account for the fissioning and transmutation of uranium 235 in reactors. Here, we assume it is the initial mass of the HEU. This view is consistent with earlier British declarations of HEU, where the declared stock reportedly did not account for the fission and transmutation of the contained uranium 235 in reactors, particularly naval reactors.

Much of the HEU used in reactors ended up in spent fuel; some was reprocessed and the HEU recycled. A fraction of the HEU was consumed in British nuclear tests. Earlier, we estimated that British nuclear tests used about one tonne of HEU. See Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford: Oxford University Press, 1997), p. 121.

Britain has not made any subsequent HEU declarations, so it is necessary to estimate the additional HEU used in naval propulsion reactors from 2002 through 2014 to obtain a more recent estimate. The International Panel on Fissile Materials (IPFM) estimated that each year the UK submarine fleet has consumed about 100 kilograms of uranium 235, and thus requires about 140 to 200 kilograms of uranium 235, assuming a burnup of 50-70 percent. See IPFM, *Global Fissile Material Report 2010*, pp. 75 and 179. At an enrichment level of 97.4 percent, the total HEU annual requirement is 145-205 kilograms of HEU, or a total of 1.74-2.46 tonnes of HEU from 2002 to the end of 2014.

As of the end of 2014, the total removals are estimated at 6.46-7.18 tonnes of HEU and the military stock would be reduced to 19.18-19.9 tonnes of HEU (rounded to 19-20 tonnes). As in the 2002 inventory removals, about one tonne had been consumed in nuclear tests, leaving 5.46-6.18 tonnes HEU (initial mass) largely in spent fuel, recovered HEU, and military reactor cores (rounded to 5.5-6.2 tonnes).

Britain has not declared any of this HEU excess to military requirements. Any HEU not required for nuclear weapons would reportedly be reserved for its naval propulsion program, any military reactors, or ultimate disposal.

(r) Although considerable amounts of information have emerged about the Chinese nuclear weapon program over the last three decades, great uncertainty surrounds plutonium and highly enriched uranium (HEU) stocks. Further complicating any analysis, China still treats details about a key plutonium production reactor and an enrichment plant as secret. Unlike the other declared nuclear weapon states, China has yet to officially state that its production of fissile materials for weapons has ended. However, unofficial Chinese statements indicate that such production ended by about 1991, likely earlier.

An estimate of the Chinese weapon-grade uranium (WGU) stock is derived by modeling the enrichment output in separative work units (swu) and determining the drawdowns, including the use of HEU in nuclear testing and the need for enriched uranium in civil and military reactors. It builds on an earlier ISIS study and work done by Jeffrey Lewis, who uncovered a range of new information about the

Chinese enrichment program. See David Albright and Corey Hinderstein, *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, ISIS, June 30, 2005. http://isis-online.org/uploads/isis-reports/documents/chinese_military_inventories.pdf and Jeffrey Lewis *Paper Tigers: China's Nuclear Posture* (Adelphi Book 446), International Institute for Strategic Studies (Oxon and New York: Routledge, 2014)

Crystal Ball® software is used to calculate distributions of estimated separative work and WGU values based on ranges of key variables. Rather than decide on a best estimate of a specific parameter, such as enrichment plant separative capacity, a frequency distribution of possible values is derived for specified time periods. The time periods are defined by the availability of information providing the separative power, or swu/year, of the plants. Distributions representing key parameters in a formula are then sampled using a Monte Carlo approach to derive a distribution of results. In essence, for specific time periods, the separative power is treated as a uniform probability distribution, where each value is equally likely. The advantage is that the results represent all possibilities in a situation where the exact value of separative power is poorly known, leading to a more rigorous uncertainty analysis. Although judgments are still necessary in any uncertainty analysis, they can be applied in a more transparent manner with this software, and many more simulations are considered.

In this calculation, the key parameter is the separative power of the plant and the efficiency of production. Several different periods are considered. The production in the Lanzhou gaseous diffusion plant is estimated to have been somewhere in the range of 20,000-50,000 swu per year from 1964 until the end of 1974. After improvements in the equipment, the capacity is estimated to have increased to about 75,000-180,000 swu per year from 1975 to somewhere between 1980 and 1982, the exact date is in some dispute. Here a date of end of 1981 is used. During the third period, after 1981, the capacity is estimated to have reached about 200,000-300,000 swu per year for the rest of the plant's operation, but the plant is not believed to have produced weapon-grade uranium during this latter period but instead low enriched uranium for civil use. It is reported that the plant shut down in the late 1990s.

The range of separative power does not explicitly include a capacity factor, although it does implicitly include one. The range of values for separative work include a consideration that the plant's output fluctuated. Nonetheless, this notion of a capacity factor is further included by considering another important variable, namely the time the plant operated at these separative powers given in this range. For the period from 1964-74, or 11 years, the range of full-power equivalent separative work output is estimated to be in the range of 7-10 years, where at least for the equivalent of one year (and up to four years) the plant effectively did not operate while in the other years it effectively operated at its the full value, as given by a specific separative work rate. In this period, the addition of this capacity factor means that for a specific separative work output in the range, its actual value after including a capacity factor was about 65-90 percent of the given output. For the second period, which lasts 7 years, these numbers are estimated to be higher, namely 6-7 years, or equivalently 85-100 percent, reflecting overall better experience in operating the plant.

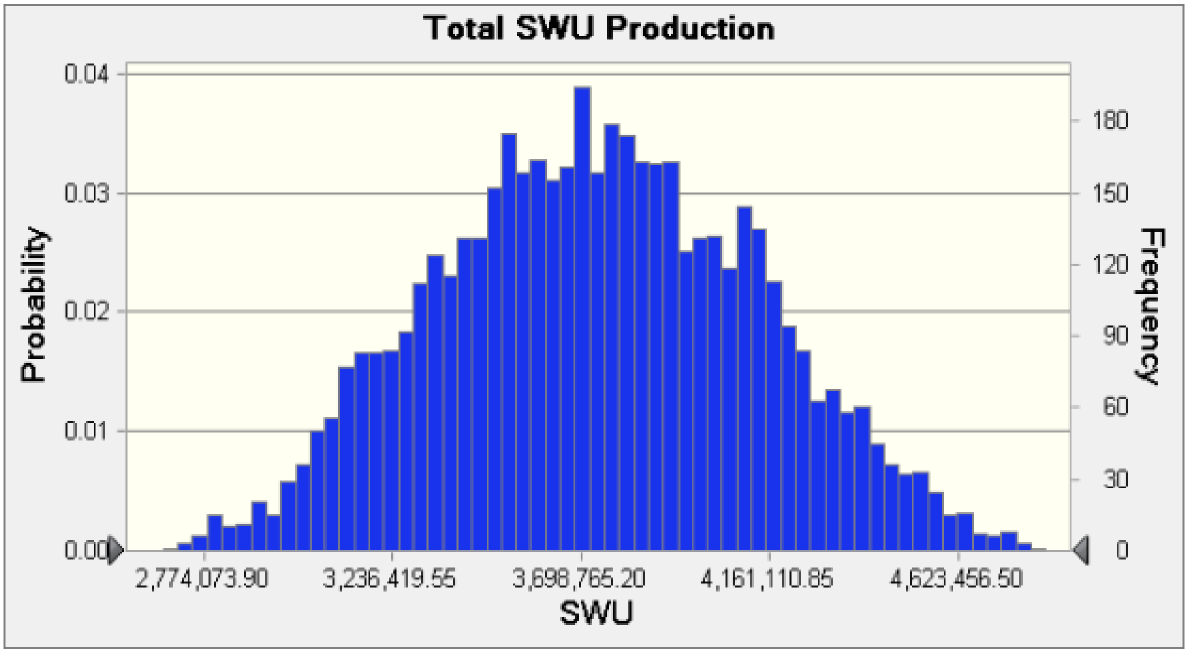
Another variable is the tails assay used in the plant. Here, the value in the first period is 0.4 percent and decreases to 0.3 percent in the second period, as the plant increases in separative power and uranium resources are conserved.

China has operated another gaseous diffusion plant to make weapon-grade uranium, namely the Heping Plant. The output of the second plant is highly uncertain. Based on information developed by Jeffrey Lewis, we assume that this plant started operating in 1970, albeit at a relatively low capacity and increased it later.

The relevant periods and values are:

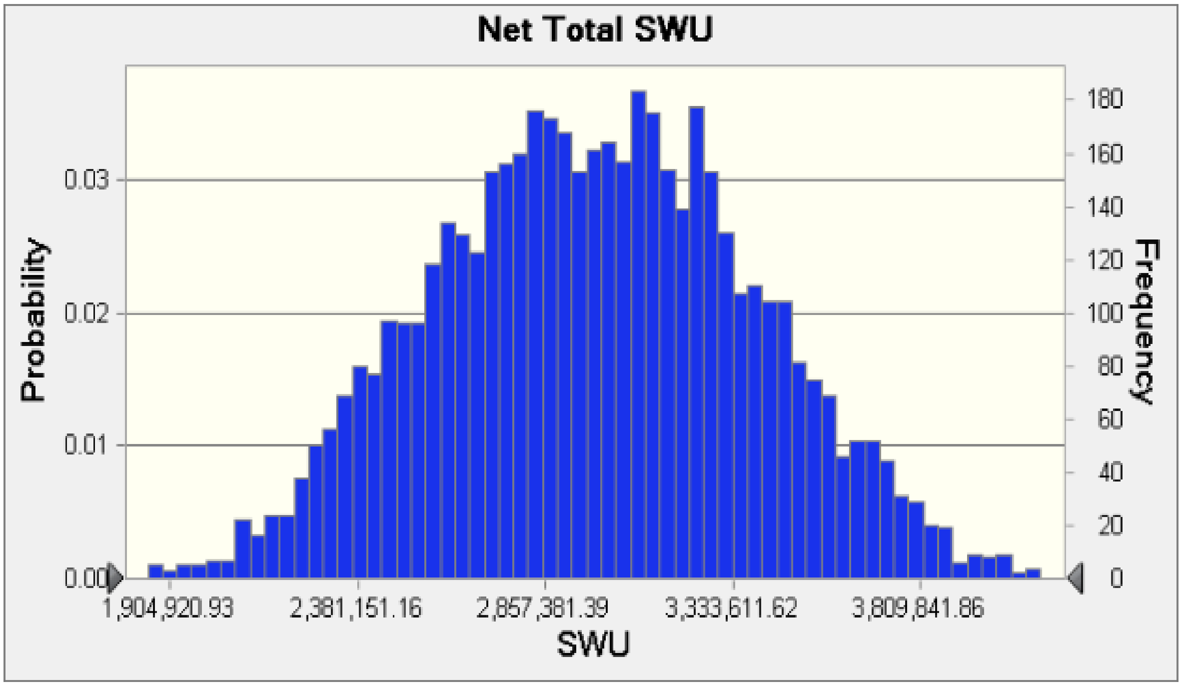
Period	Separative Work Output	Operation
1970-1974	50,000 to 150,000 swu/yr	3-4 years out of 5 years
1975-1985	150,000 to 250,000 swu/yr	9-11 years out of 11 years
1986-1987	250,000 to 350,000 swu/yr	1.75-2 years out of 2 years

The distribution below represents the total production of the two gaseous enrichment plants. It has a median of 3.74 million swu with full range of 2.6 to 5.0 million swu.

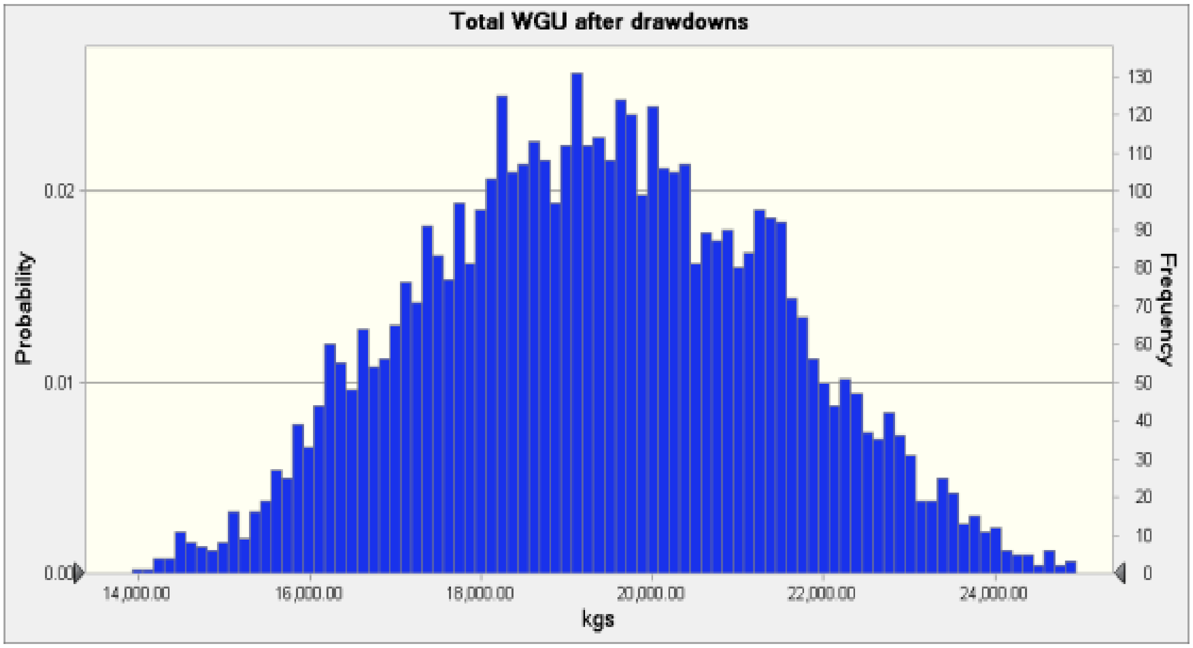


Not all the separative output would have gone to make WGU for nuclear weapons. The enrichment program is estimated to have supplied about 685,000 to 915,000 swu of enriched uranium for several non-weapon purposes, primarily fuel for research, production and naval reactors, and for nuclear weapon tests. See *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, op. cit.

Subtracting these requirements, the estimate of net production has a median of 2.98 million swu and a full range of 1.8 to 4.3 million swu (see distribution below).



The amount of WGU is derived by assuming an ideal cascade model. Although the latter is unrealistic, this method is used because of a lack of any data about the manner in which the plant was organized to enrich uranium up to weapon-grade and the greater uncertainties associated with the parameters described above. The resulting calculated WGU distribution has a median of 19.4 tonnes of weapon-grade uranium.



The range of this estimate, shown graphically above, has a standard deviation of about 2 tonnes of HEU. The full range is about 13-26 tonnes of HEU. Because of uncertainties in the estimate, the standard deviation is not used to set the range. Instead, a range of ± 5 tonnes is judged as adequate. This range is broader than that defined by the standard deviation but it excludes the extremes in the full range. Thus, the estimate is 19.4 ± 5 tonnes.

The values are similar to earlier ISIS estimates but, as discussed above, reflect newer information obtained by Jeffrey Lewis about the Chinese Heiping enrichment plants. In particular, he learned from Chinese publications that the Heiping enrichment plant started several years earlier than previously assessed. However, this shift in the timeline at Heiping combined with the Lanzhou enrichment plant ending HEU production earlier leads to an estimate that is similar to earlier ones. This new assessment contrasts with a few estimates that assess China as having several tonnes less HEU than what is estimated here. However, these lower estimates result mainly from having a later startup date for the Heiping enrichment plant.

In the mid-1980s, Chinese naval propulsion reactors were reported to use LEU fuel. The type of fuel used after this date is unknown.

(s) The French HEU estimate is from *Plutonium and Highly Enriched Uranium 1996*, op. cit., pp. 121-126. The value is the midpoint of the estimate, which is judged to have an uncertainty of 25 percent, slightly lower than the original source.

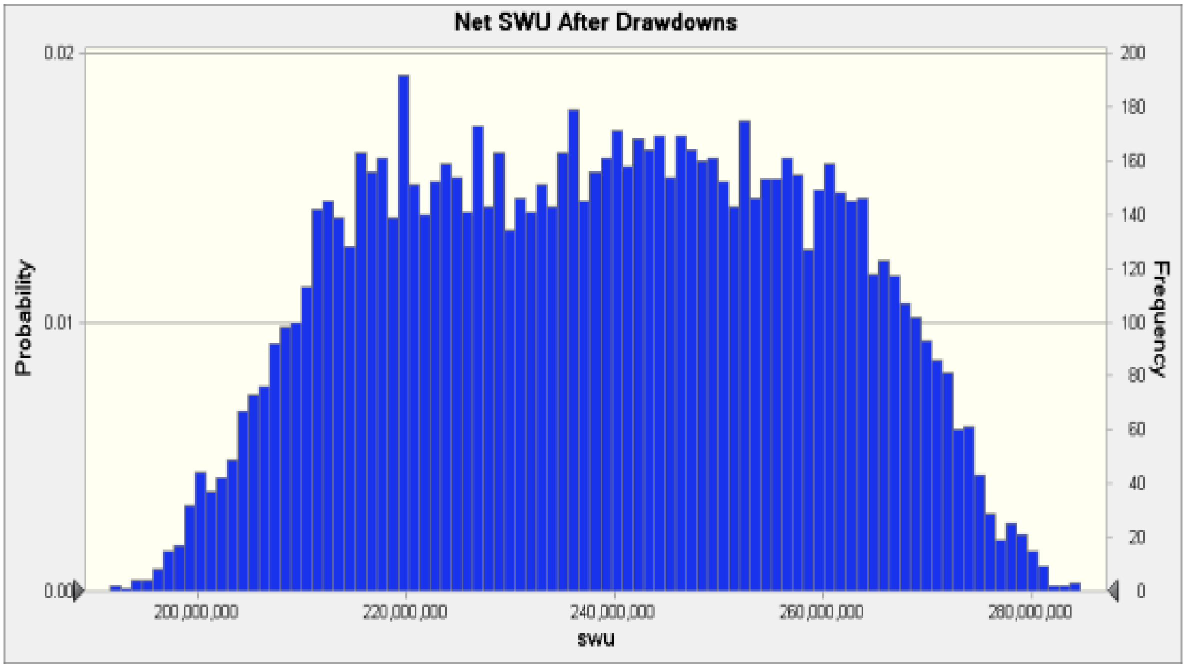
(t) The bulk of France's nuclear powered vessels have used LEU fuel. However, one or two of its strategic submarines reportedly used HEU fuel. These submarines were reportedly designed to require only one refueling during their lifetime. France may reprocess spent HEU fuel and recycle or blend down the recovered HEU. Any unreprocessed spent naval HEU fuel is included in this category.

(u) The Celestin military production reactors used weapon-grade uranium fuel. Through the end of their lifetime (shut down in 2009), these reactors are estimated to have required about 5.5 tonnes of weapon-grade uranium fuel. See *Plutonium and Highly Enriched Uranium 1996*, op. cit., p. 125; these data are used to extrapolate an estimate as to when the reactors shut down in 2009. This fuel may be disposed of or reprocessed. Without more information about the fate of this HEU, it is left in this category.

(v) Russia's HEU inventory remains difficult to estimate. The estimate here is based on earlier work done by one of the authors, based on recreating Russia's deployment of gaseous diffusion and centrifuge capacity until it ended HEU production in 1987/1988. See *Plutonium and Highly Enriched Uranium 1996*, op. cit., pp. 94-116. This earlier work is supplemented by more recent analysis by ISIS and the International Panel on Fissile Materials. Absent an official declaration, the WGU equivalent estimate (assuming all the HEU is 90 percent enriched) is derived by recreating total enrichment output (swu) and determining the drawdowns, including the use of HEU in nuclear testing and the production of enriched uranium for non-nuclear weapon purposes. Given the wide ranges of key variables, a frequency distribution of WGU stocks is derived. The first part of this calculation estimates total separative work produced until 1987/1988, when HEU production ended. The upper bound is taken from the 1996 reference and is 414 million swu. See *Plutonium and Highly Enriched Uranium 1996*, p. 110. The lower bound is taken as 350 million swu. It is derived by assuming a linear growth in enrichment capacity from 1952 to 1988, when the capacity reached almost 20 million swu per year. This lower bound is greater than an earlier one used by one the authors. See *Plutonium and Highly Enriched Uranium 1996*, op. cit. In summary, total production is estimated as 350-414 million swu.

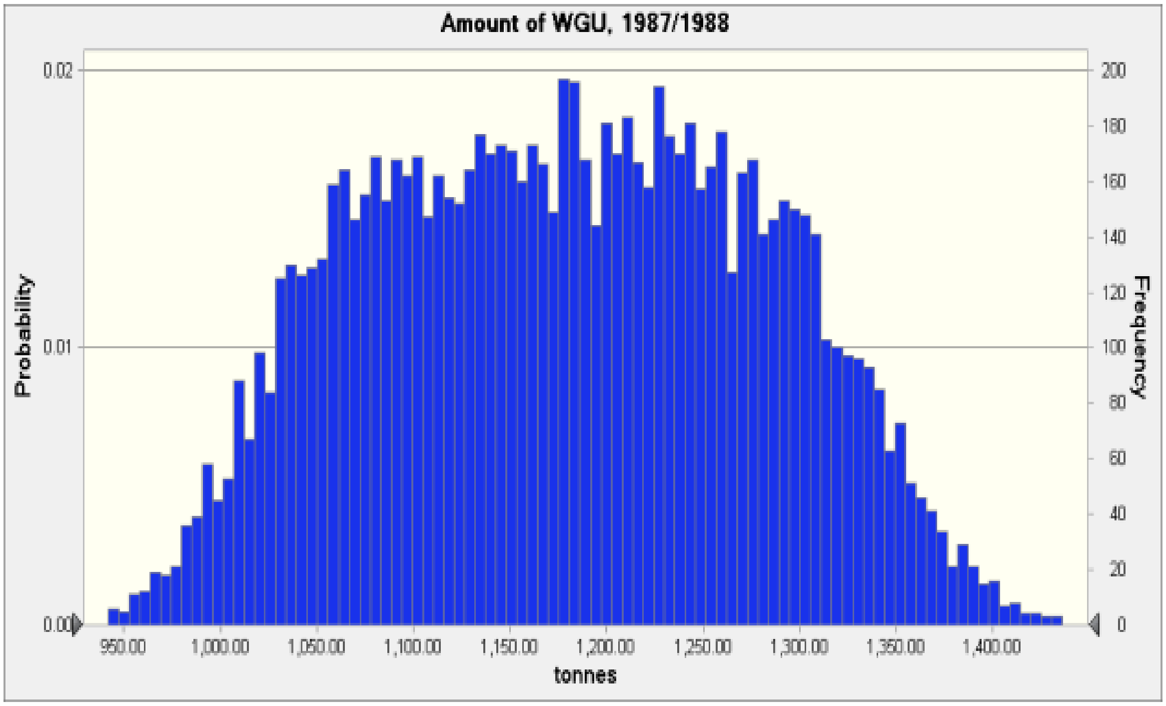
There were several non-weapon requirements for enriched uranium that are calculated as drawdowns in this total swu estimate. They include: (1) Domestic, East European, and Finish power reactors that required enriched uranium--about 50-67 million swu (where the upper bound is from *Global Fissile Material Report 2010*, op. cit., p. 61 and the lower bound is an ISIS estimate); (2) Western reactors received low enriched uranium in the amount of 40 million swu; (3) Naval reactors required about 22.5-34.5 million swu. See *Global Fissile Material Report 2010*, op. cit., p. 63; (4) plutonium and tritium production required about 9-12 million swu; (5) non-military research reactors used about 4-5 million swu; and (6) nuclear testing consumed about 1-2 million swu.

The distribution of net swu (reflecting drawdowns) has a median of about 238.8 million swu and a standard deviation of about 19.8 million swu. The distribution is:



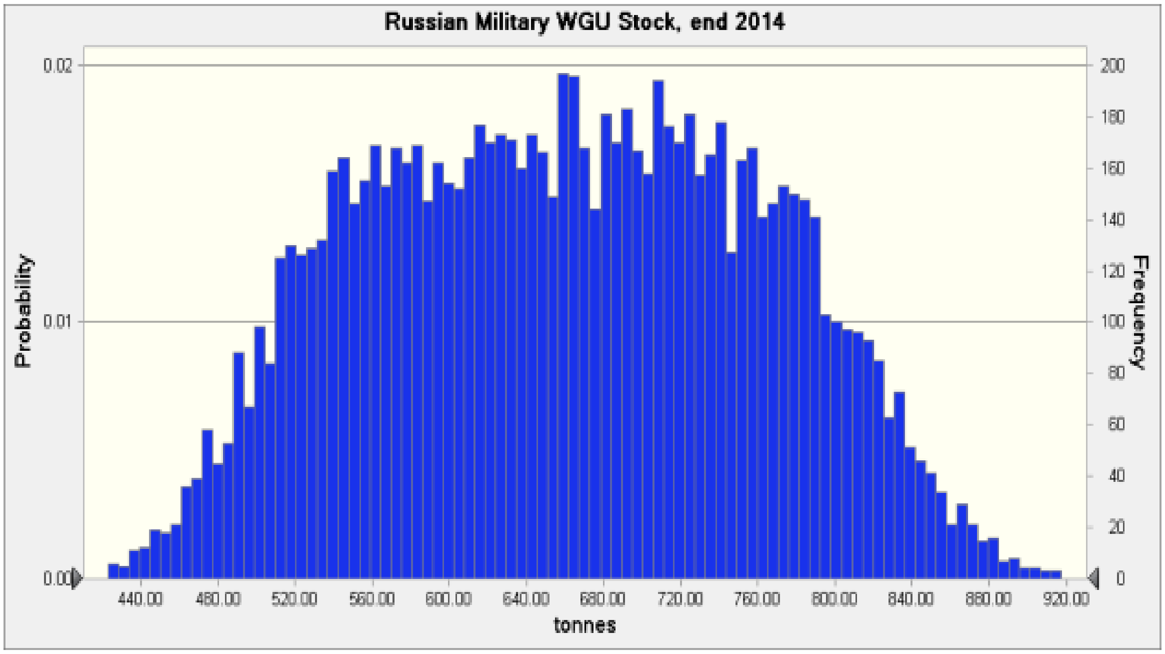
The production of enriched uranium is not 100 percent efficient, e.g. centrifuges break, cascades are not ideal, enrichment may happen in steps and not in long cascades, and the mixing of uranium streams leads to losses. However, this estimate does not factor in these inefficiencies. The reason is due to the large uncertainties in estimating the annual enrichment output in swu per year of the enrichment plants and the lack of information about Russia's experience in operating its enrichment plants. In addition, information is lacking on how Russia organized its cascades in its centrifuge plants to make weapon-grade uranium and how close these cascades approached an ideal cascade.

The amount of swu to produce one kilogram of WGU is derived assuming one long ideal cascade and a tails assay of 0.25-0.3 percent, or about 195-210 swu per kilogram of 90 percent enriched uranium. This is likely an underestimation of the true amount of swu needed to make one kilogram of WGU, but, as mentioned above, these inefficiencies are ignored here. Nonetheless, with these rates of WGU production, Russia is estimated to have produced about 1,180 tonnes of WGU through 1987/1988 with a standard deviation of about 100 tonnes. The full range is about 940-1,440 tonnes, although about 70 percent of the values fall within 100 tonnes of the median value. The distribution of values is:



After 1990, there were additional reductions in this stock. The additional HEU requirements for naval reactors were already included above. The "Megatons to Megawatts" program involved the blending down of 500 tonnes of WGU into low enriched uranium. The U.S.-sponsored Material Conversion and Consolidation (MCC) program buys and blends down into LEU excess non-weapons HEU from Russian facilities. The goal has been to eliminate 17 tonnes of HEU by the end of fiscal year 2015, and 15.2 tonnes had been blended down by the end of 2013. See IPFM, *Global Fissile Material Report 2013, Increasing Transparency of Nuclear Warhead and Fissile Material Stocks as a Step toward Disarmament, 2013*, citing personal communication from NNSA March 4, 2013. About two tonnes remains in HEU.

Factoring in these additional withdrawals leaves the following final distribution of WGU as of the end of 2014:



The median is about 660 tonnes and the standard deviation is about 100 tonnes. The full range is 420-920 tonnes. Here, the range is picked so that 80 percent of the values fall within this range, namely 660 ± 125 tonnes.

A potentially new development that may affect this estimate is that Russia apparently decided to resume making HEU for civil and possibly naval purposes. See Pavel Podvig, "Russia is set to produce new highly enriched uranium," *IPFM Blog*, June 1, 2012; and "Russia launches new HEU production line," *IPFM Blog*, October 29, 2012. It put into operation on November 23, 2012 an HEU production line at one of its enrichment plants. See *TVEL JSC Annual Report 2013*, p. 68; TVEL is the fuel company of Rosatom. Under a contract with China, Russia has supplied 240 kilograms of HEU (64.4% uranium 235) as part of the initial fuel loads of the Chinese fast reactor, the CEFR. This reactor is expected to switch to MOX fuel within a few years. However, the reason why Russia would not use its substantial stock of HEU to supply these requirements remains unknown.

(w) The amount of HEU dedicated to the Russian military naval program is difficult to estimate. The International Panel on Fissile Materials has estimated the amount of HEU used by Russian naval vessels. See *Global Fissile Material Report 2010*, table 4.2, p. 63 and pp. 60-63. This source provides information about the amount and enrichment level of HEU in generation 2, 3, and 4 submarine reactors and the one surface ship and the number of reactors of each type as of 2010. This information implies that about 13-15 tonnes of HEU are in the cores of the nuclear naval fleet. An estimated 5 tonnes are assumed to be in the naval fuel cycle to create reloads for these reactors. The total is 20 tonnes of HEU of enrichment levels of about 20 and 45 percent.

Russia reprocesses its naval spent fuel at the RT-1 plant at Mayak. The International Panel on Fissile Materials estimated in 2010 that about 10 tonnes of HEU (90 percent equivalent) were in naval spent fuel. See *Global Fissile Material Report 2010*, op. cit., p. 63. This value is converted into HEU of either about 20 or 45 percent enriched, since most Russian military naval reactors did not use 90 percent enriched uranium. With about 20 or 45 percent enriched HEU, the spent fuel would be expected to contain roughly 20-40 tonnes of HEU. This spent fuel is likely under the control of the Russian navy.

The total amount assigned to the naval program is 40-60 tonnes of HEU.

(x) Russia used HEU in its plutonium production reactors and its tritium production reactors. Although the practice prior to the demise of the Soviet Union was reportedly to recover the HEU from the irradiated fuel and recycle it in naval reactors, not all the HEU may have been recycled. But there is not enough information to make an estimate.

(y) The U.S. stock of military HEU draws upon data released officially by the U.S. Department of Energy. This stock includes HEU in nuclear weapons, the weapons production cycle, weapons reserves, and in reserves set aside for fueling naval reactors. The bulk of this material is likely over 90 percent enriched. The table at the end of this endnote summarizes the following estimates.

The amount of HEU in this category is calculated by starting with the HEU inventory declared by the DOE in 1996, or 741 tonnes. See Department of Energy, *Highly Enriched Uranium: Striking a Balance,* Revision 1, January 2001, see table 3-1, p. 38. As part of the Department of Defense HEU inventory, about 100 tonnes were in the naval propulsion program, which are in nuclear powered submarines, surface ships, and training platforms (see endnote (z)). These 100 tonnes are subtracted from this value, leaving 641 tonnes.

Another 239 tonnes are subtracted since this material is slated for disposition via downblending or disposal and not for use in nuclear weapons, leaving 402 tonnes. See Robert M. George, Office of Fissile Material Disposition, “U.S. HEU Disposition Program,” International Nuclear Materials Management Annual Meeting, July 2009, slide presentation, see slide 3; email to David Albright from DOE, April 9, 2015; see also columns 5 and 6 and endnote (z). It should be noted that included in this 239 tonnes is 22 tonnes of HEU in spent fuel and low equity discards, much of which was identified in the 1994 DOE declaration of HEU surplus to defense needs. According to DOE, this 22 tonnes contains about 7 tonnes of HEU in spent naval fuel stored at Idaho. It should also be noted that HEU in naval spent fuel that was recovered prior to 1992 was used in the Savannah River reactor fuel cycle resulting in the fissioning and transmutation of much of the contained uranium-235. The rest of this HEU is believed to be included in this 239 tonnes of HEU slated for disposition.

The HEU in naval spent fuel must also be subtracted from the inventory. However, this value is complicated to estimate because of the manner in which DOE has decided to keep certain information secret regarding HEU in the Naval Propulsion Program. For example, in *Striking a Balance*, the amount of uranium 235 that fissioned or was transmuted in naval reactor HEU was included. But in the update that brings the HEU declaration up to 2004 the amount of uranium fissioned or transmuted in naval fuel was not included. See DOE, *Highly Enriched Uranium Inventory*, January 2006. Thus, the subtraction of naval HEU must be done differently in each of the two time periods. So, up to 1996, the post-irradiation mass of the HEU in naval fuel needs to be removed, since the amount of uranium 235 consumed in naval reactors is already included in the DOE estimate. From 1996 through 2014, the initial mass needs to be subtracted, since the amount of uranium 235 consumed in naval reactors is not included. These values are estimated in endnote (z), and they are 9 tonnes (post-irradiation mass) and 27.4 tonnes (initial mass), respectively. Subtracting both values from 402 tonnes leaves 365.6 tonnes of HEU. However, some of this mass must be added back in, since as noted above, about 7 tonnes of HEU (post-irradiation mass) in naval reactor spent fuel are included in the 235 tonnes slated for disposition. After this correction, the value becomes 372.6 tonnes.

There were some additional reductions from 1996 through 2014 but these are believed to be relatively small. These drawdowns are transfers to foreign countries, and normal operating losses. See *Highly Enriched Uranium Inventory*, op. cit., p. 7. In this period, there were small additions to the inventory from receipts from foreign countries and miscellaneous receipts. From 1996 to 2004, these declared removals and additions were relatively small and almost equaled, meaning that their net effect on the inventory was very small. From 2004 to 2014, these values have not been declared or estimated but are not thought to affect the inventory significantly.

There could be other HEU deductions, reflecting HEU that does not meet specifications for use in nuclear weapons and is slated for disposal. This could include additional HEU in hard-to-recover scrap or other types of irradiated fuel not declared excess.

Another drawdown is the amount of HEU sent to the naval program from 1996 to the end of 2014. In endnote (z), this value is estimated crudely as 29-47 tonnes. After this drawdown, the military stock is at 325.6 to 343.6.

Not all of this stock of HEU is eligible for use in nuclear weapons. In 2005, the DOE announced that the military stock included about 160 tonnes of HEU reserved for naval propulsion programs. See DOE, *Highly Enriched Uranium Inventory,* January 2006, p. 3. This was later lowered to 128 tonnes because the rest of the HEU did not meet the specifications of the naval program (see endnote (z)). Whether additional HEU will be assigned to the naval propulsion program in future years is unclear. In any case, the off-spec HEU was assigned to the 2009 excess HEU stock of 235 tonnes See “U.S. HEU Disposition Program,” op. cit.

Since the 2005 announcement, some of this HEU was likely fabricated into naval fuel. Assuming that an average of 1.5-2.6 tonnes of HEU are needed each year for naval fuel (see endnote (z)), from 2005 to 2014 about 13.5-23.4 tonnes of HEU were sent to the naval program from this reserve of 128 tonnes. At the end of 2014, the reserve thus stood at about 104.5-114.5 tonnes of HEU.

Subtracting the remaining naval reserve of 104.5 to 114.5 tonnes from the military stock of 325.6 to 343.6 leaves a stock of 221.1-229.1 tonnes of HEU, which can be viewed as usable for nuclear weapons.

The same 2005 announcement stated that another 20 tonnes are reserved for space and research reactors that currently use HEU, pending development of fuels that would enable the conversion to LEU fuels. See *Highly Enriched Uranium Inventory*, op. cit., p. 3. It is assumed that this material is also included in the 235 tonnes of excess HEU in 2009. The DOE also set aside about 20 tonnes for downblending to LEU for research reactor fuel but this amount is believed to be included in the 2009 excess HEU stock.

In summary, and after rounding, the U.S. military stock is estimated as 325 to 345 tonnes at the end of 2014. Of this amount, about 220 to 230 tonnes are available for the nuclear weapons program. The following table summarizes the drawdowns and estimates. It should be emphasized that these values are estimates of the amount of HEU at the end of 2014. Several aspects of the U.S. HEU stock remain classified.

<table>
<tr><th colspan="3">U.S. HEU Military and Weapons Inventory, end of 2014</th></tr>
<tr><td>Declared inventory in 1996</td><td colspan="2">741 tonnes</td></tr>
<tr><td>In naval propulsion program in 1996</td><td colspan="2">-100 tonnes</td></tr>
<tr><td>Declared excess or slated for disposition</td><td colspan="2">-239 tonnes (7 t in naval spent fuel)</td></tr>
<tr><td rowspan="2">Removal of spent naval HEU fuel</td><td>To 1996</td><td>-9 tonnes
(post-irradiation mass)</td></tr>
<tr><td>From 1996 to 2014</td><td>-27.4 tonnes (initial mass)</td></tr>
<tr><td>Correction to account for 7 tonnes of spent naval HEU in amount of HEU declared excess</td><td colspan="2">+ 7 tonnes</td></tr>
<tr><td>Amount of HEU allocated to naval reactors
1996-2014</td><td colspan="2">-29 to 47 tonnes</td></tr>
<tr><td><i>Primary Military Stock</i></td><td colspan="2"><i>325.6 to 343.6 tonnes</i></td></tr>
<tr><td>HEU reserve assigned to naval reactors
2015-2055</td><td colspan="2">-104.5 to 114.5 tonnes</td></tr>
<tr><td><i>Nuclear Weapons Stock</i></td><td colspan="2"><i>221.1 to 229.1 tonnes</i>
<i>220 to 230 (rounded)</i></td></tr>
</table>

(z) This endnote discusses the HEU used in the naval propulsion program, and in particular it presents estimates of the total HEU production for the naval program, annual HEU requirements, spent fuel inventories, and the the amount of HEU in the naval program at the end of 2014. The starting point for these estimates is the DOE declaration. According to the U.S. Energy Department in 1996, as part of the Department of Defense inventory, the Naval Nuclear Propulsion Program included 100 metric tons of HEU in nuclear-powered submarines, surface ships, and training platforms. In addition, this category includes the BWX Technologies Naval Nuclear Fuel Division facility, the Knolls Atomic Power Laboratory, the Bettis Atomic Power Laboratory, and the Expended Core Facility at the Idaho National Engineering Environmental Laboratory. See Department of Energy, *Highly Enriched Uranium: Striking a Balance,* Revision 1, January 2001.

Total Production of HEU for Naval Propulsion by 1996

Much more HEU was produced for the naval program by the time enrichment of HEU for naval reactors stopped in 1992. This amount was not declassified by the DOE, but it can be roughly approximated based on information in official publications.

About 11-12 tonnes of uranium 235 were recovered from naval spent fuel through 1992, when reprocessing of naval fuel stopped. See *Plutonium and Highly Enriched Uranium 1996*, op. cit., p. 88. At an assumed 50 percent burnup, the original fuel contained about 22-24 tonnes of uranium 235. This corresponds to about 22.6-24.7 tonnes of fresh HEU (97% enriched).

As of 1996, the DOE stored 8.97 tonnes of HEU containing 7.44 tonnes of uranium 235 at its Idaho site (83% enriched), and by subtraction a total of 1.53 tonnes of this HEU was uranium 236 and uranium 238. See *Striking a Balance*, op cit. Table C-2, p. 139 (a footnote to this table says that this information does not include naval reactor spent fuel stored at the nearby Expended Core Facility run by the U.S. Navy.) If 50 percent burnup were achieved, the HEU fuel (initial mass) contained 14.88 tonnes of fresh uranium 235, or about 15.3 tonnes of fresh HEU (97% enriched). (For a calculation that shows that the burnup of this HEU was 49 percent, see *Global Fissile Material Report 2010*, op. cit., p.32, particularly endnote 129).

There were also HEU spent fuel stocks under the authority of the Naval program and likely included already in the 100 tonnes given above. Also located at the Idaho site in 1996 was 107.7 kilograms HEU (100.3 kg uranium 235 or 93.1%) in spent fuel from the Experimental Propulsion Reactor. In addition, another 3,018.8 kilograms (83% enriched) was in spent naval fuel at other sites that was in the possession of the U.S. Navy. See *Striking a Balance*, op. cit., tables C-2 and C-4. It should be noted that the latter value of 3,018.8 tonnes does not include HEU spent fuel stored at the Knolls Atomic Power Laboratory and the Betts Atomic Power Laboratory. Knolls Atomic Power Laboratory had as of December 31, 1993 1.6 tonnes of HEU with an unspecified but nonzero fraction in spent fuel. See March 8, 1995 letter to Kevin O'Neill, ISIS, from Roger Heusser, Deputy Director, DOE Office of Declassification, Office of Security Affairs. If the spent fuel with the 3,018 kilograms of HEU had an average burnup of 50 percent, its initial mass would have been about 5 tonnes of WGU. Adding in the essentially fresh 108 kilograms in the experimental propulsion reactor gives 5.2 tonnes. As stated above, these quantity of HEU should be included in the 100 tonnes assigned to the Naval program.

As of late 1996, the amount of HEU in naval spent fuel not under the control of the naval program, and thus not part of the 100 tonnes given above (and identified in *Striking a Balance)* totals about 9 tonnes of HEU (post-irradiation mass). Another source puts the total stock of spent naval HEU at DOE's Idaho facility at 14 tonnes in 1997. See Mr. Curtis, no title provided, "The United States Naval Nuclear Propulsion Program: Over 112 Million Miles Safely Steamed on Nuclear Power," undated. www.nwtrb.gov.meetings/1997/dec/crutis.pdf. The difference of five tonnes cannot be fully explained, although the 1997 number may reflect the receipt of additional shipments of spent naval fuel at DOE's Idaho site, HEU in spent fuel at sites not identified in *Striking a Balance*, or HEU under the control of the Navy.

Adding up the HEU initial masses associated with the recovered naval HEU and that stored at DOE sites in spent fuel as given in *Striking a Balance*, as of 1996, namely 22.6 to 24.7 tonnes and 15.3 tonnes, respectively, gives in total an additional 37.9 to 40 tonnes of HEU (initial mass) produced for use in naval reactors and not included in the 100 tonnes given above under the Naval Program. A significant fraction of the HEU in this additional stock, namely that recovered before 1992, entered the Savanah River reactor fuel cycle; another fraction was slated for geological disposal as spent fuel.

With 100 tonnes of HEU in naval reactors, the total amount of HEU produced for naval reactors by 1996 is estimated as 138-140 tonnes of HEU.

Naval HEU Spent Fuel Inventory by End 2014

As of early 2015, the inventory of HEU in spent naval reactor fuel had grown to about 28 tonnes of heavy metal (a unit typically reflecting that the material has been irradiated) and this inventory is expected to grow to about 65 tonnes in 2035. See email to David Albright from DOE, April 9, 2015 and DOE, *U.S. Radioactive Waste Inventory and Characteristics Related to Potential Future Nuclear Energy Systems*, May 2011, FCRD-USED-2011-000068, Rev 2, p. 8. Assuming that this 28 tonnes has the same post-irradiation enrichment as that listed in 1996 in *Striking a Balance*, namely 83 percent uranium 235, then 23.24 tonnes of it are uranium 235. If the fuel achieved 50 percent burnup, then the fresh fuel contained 46.48 tonnes of uranium 235, or about 47.9 tonnes of HEU (97% enriched), rounded to 48 tonnes.

With this data, a crude estimate can be derived of the average amount of HEU in spent fuel generated each year since 1996. First, the 12 tonnes of HEU (post-irradiation mass) that was known to be in spent fuel at Idaho and elsewhere in 1996 (see above) should be subtracted from the 28 tonnes (post-irradiation mass). This leaves 16 tonnes of HEU (post-irradiation mass) in spent fuel that was generated from 1996 to 2015, or about an average of 0.84 tonne of HEU per year (post-irradiation mass). In terms of initial mass, this value corresponds to an average of about 1.44 tonnes of HEU per year (initial mass), or a total mass of 27.4 tonnes (intial mass).

The naval spent fuel is slated for ultimate disposal in a geological repository. According to the DOE, the naval spent fuel is first sent to Idaho where it is examined in a water pool and packaged for permanent disposal, and about 60 percent of existing naval fuel has been packaged and placed in dry storage.

The post-irradiation mass of 28 tonnes is listed in columns 5 and 6.The value for HEU in naval reactor spent fuel in columns 5 and 6 overlaps with the value for HEU that is excess to national defense requirements (see endnote q), which also contains about 7 tonnes of HEU in naval spent fuel (see endnote (n)). As a result, these two values should not be totaled without removing 7 tonnes.

Future Growth of Naval Spent Fuel

From 2015 to 2035, the HEU in naval spent fuel is projected to grow by 37 tonnes, from 28 tonnes to 65 tonnes (post-irradiation mass). See *U.S. Radioactive Waste Inventory and Characteristics*, op. cit. This growth corresponds to an average of about 1.85 tonnes of HEU (post-irradiation mass) per year. In terms of initial mass and again assuming 50 percent burnup and 0.83 percent uranium 235, 37 tonnes (post-irradiation mass) would correspond to 66 tonnes of HEU (intial mass and a lower enrichment of 93% reflecting limited stocks of 97% enriched uranium). Thus, from 2015 to 2035, about 66 tonnes of HEU (initial mass) are expected to be discharged in spent fuel, or an average of about 3.3 tonnes per year.

This projection of the growth of HEU in spent naval fuel during the next 20 years is more than double the average rate of the previous 19 years. The explanation for this doubling is unclear.

HEU Used in Naval Fuel from 1996 to 2015
Since 1992, no new HEU has been produced for naval reactors. Any HEU had to come from existing inventories. How much has been allocated from 1996 to 2015? This value is not given in the official DOE HEU declarations.

An upper bound for this value can be extrapolated from the 2005, Secretary of Energy announcement that about 160 tonnes of the U.S. stock of HEU would be set aside for use by naval reactors, “postponing the need for construction of a new uranium high-enrichment facility for at least 50 years.” See DOE, *Highly Enriched Uranium Inventory* January 2006, p. 3. Later, the DOE estimated that only about 128 tonnes of this HEU could meet naval specifications for use in its fuel See “U.S.HEU Disposition”, op. cit. Using the 128 tonnes and dividing by 50 yields that an average of 2.6 tonnes of HEU are needed each year for naval propulsion during the next 50 years. Using a value of 2.6 tonnes of HEU per year as that assigned to the naval program since 1996, then the total amount would be 47 tonnes from the end of 1996 through 2014. However, the average HEU discharge in spent fuel during this period has been lower, at about 1.44 tonnes per year, rounded here to 1.5 tonnes per year. However, this average may not account for a large amount of HEU in lifetime cores during this period and not discharged. So, it is treated as a minimum, or about 28.5 tonnes of HEU were assigned to naval reactors from 1996 to 2015. Therefore, from the end of 1996 through 2014, the range assigned to naval reactors is 29-47 tonnes of fresh HEU.

End 2014 Inventory of HEU in Naval Program
As stated above, as of 1996, the naval program held about 100 tonnes of HEU. Given the cutbacks in U.S. naval forces since 1996, the total amount of HEU in Defense Department naval programs would be expected to be less than 100 tonnes as of the end of 2014. However, the above calculations suggest that the size of this inventory is smaller but not significantly lower than in 1996.

The DOE has not released the amount of uranium 235 lost to fission and transmutation in naval reactors. In the 1996 HEU declaration, the amount of fission and transmutation was included with losses in a combined figure of 31.9 tonnes of uranium 235 consumed in nuclear testing and naval reactors. See *Striking a Balance*, table 4-1. Earlier, our estimate was that 8-17 tonnes of HEU were consumed in US nuclear testing. See *Plutonium and Highly Enriched Uranium 1996, op. cit.*, p.85. Assuming that the HEU was mainly weapon-grade, then about 7.44-15.81 tonnes of uranium 235 were consumed in nuclear testing. Subtracting this range from the value in *Stricking a Balance* leaves 16.1-24.5 tonnes of uranium 235 lost to fission and transmutation in naval reactors as of 1996. The amount lost to fission from 1996 to 2015, cannot be estimated from available information but this loss should not be greater than in the period up to 1996, which included the Cold War. Here, a crude estimate is that the losses to fission (transmutated uranium 235, i.e. uranium 236, remains in the HEU) are 16-25 tonnes.

Table Quantity of HEU in Naval Programs, end of 2014	
As of 1996	100 tonnes
Addition of new HEU in fuel, 1996-2014	+29 to 47 tonnes (initial mass)
In spent fuel sent to DOE storage, 1996-2014	-27.4 tonnes (initial mass)
Fission of uranium 235, 1996-2014	-16 to 25? tonnes?
Total	85.6-94.6 tonnes

Because of the uncertainty of overestimating the transmutation and fission losses, the value is assigned 90 to 100 tonnes of HEU in the naval program in column 3.

(aa) The HEU in fresh and irradiated U.S. production reactor fuel is included in the excess value, see columns 5 and 6.

(bb) In late 1994, the United States declared as excess to military requirements about 174.3 tonnes of HEU (average enrichment is 60 percent). This stock is dynamic, in the sense that more HEU has been added to it and a significant amount has been blended down to low enriched uranium. As of 2009, the excess stock was 235 tonnes of HEU containing 217 tonnes of surplus, commercially-usable HEU and 18 tonnes of HEU in spent fuel and low equity discards. See "U.S. HEU Disposition Program," op. cit. According to the DOE, the amount in the category of spent fuel and low equity discards has increased by 4 tonnes since 2009, bringing the total to 22 tonnes, or a total of 239 tonnes declared excess. See email to David Albright, April 9, 2015. Of this total of 22 tonnes, about 7 tonnes is naval reactor spent fuel. About 186 tonnes of this HEU had been slated for downblending to LEU, although some of the HEU is not yet available. According to the DOE, as of early 2015, about 146 tonnes of this HEU has been downblended into LEU. See email to Albright, op. cit. That leaves 93 tonnes of excess HEU. The NNSA has described the downblending of 143 tonnes of HEU: about 47 tonnes were down blended by USEC for sale as power reactor fuel (completed June 2006), 45 tonnes were down blended for use in TVA commercial power reactors (completed in October 2011), 22 tonnes have been set aside for downblending to produce LEU research reactor fuel (over 4 tonnes has already been down blended), 17 tonnes were down blended to create the American Assured Fuel Supply (completed in December 2012), and 9 tonnes have been down blended for the MOX LEU Backup Inventory Project, and another 3 tonnes have been delivered. All down blending in these categories will be complete by mid FY 2015. To restate, as of early 2015, the excess is 230 tonnes – 146 tonnes = 93 tonnes. Some of this excess is in naval reactor spent fuel stored at DOE's Idaho facility, given as 7 tonnes by DOE (see endnote (y)). This 7 tonnes in the excess represent a double counting of the HEU in the other value in this column, namely 28 tonnes of HEU in naval reactor fuel slated for disposition (see endnote z). So, these two values should not be added without removing 7 tonnes from the total. The United States has accepted foreign HEU of U.S.-origin. This quantity of HEU was included in the 1996 and 2005 HEU declared inventories. The amount repatriated since 2005 may be included in the additional 4 tonnes of HEU in spent fuel and low equity discards. In any case, it a relatively small quantity. Similarly, for HEU from U.S. non-DOE research reactors. Spent fuel from DOE research reactors should be included in the above numbers.

(cc) The U.S. excess stock is considered a civil stock in summary tables and associated reports. The total includes the military, naval program, excess, and naval spent fuel stocks, or:

Military stock	325 to 345 tonnes
Naval programs	90 to 100 tonnes
Excess stock	93 tonnes
Naval spent fuel	28 tonnes
Correction (as above)	-7 tonnes
Total	529-559 tonnes
Mean	544 tonnes

It should be noted that this value is an estimate of the amount of HEU at the end of 2014. Several aspects of the U.S. HEU stock remain classified.