Science and Global Security, 16:55–73, 2008

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929880802565131

Fissile Material Stockpiles and Production, 2008

Alexander Glaser and Zia Mian

Program on Science and Global Security, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, USA

This article presents estimates of global and national stockpiles of highly enriched uranium and separated plutonium based on the 2008 *Global Fissile Material Report* by the International Panel on Fissile Materials.[1] The global stockpile of highly enriched uranium (HEU) is estimated to be 1670 ± 300 tons. It is declining as Russia and the United States blend down about 40 tons per year of HEU for use in light-water power-reactor fuel. This rate of blend-down is far higher than the estimated rate of production of HEU, currently believed to be limited to production by Pakistan for weapons and by India for naval fuel. The global stockpile of separated plutonium, all of which can be used for weapons, is about 500 tons. About half of this stockpile is civilian and is currently growing at less than 5 tons a year. This rate will increase significantly once Japan's Rokkasho reprocessing plant begins commercial operation. Only India and Pakistan and perhaps Israel are believed to be producing plutonium for weapons, at a combined rate of less than 60 kg per year. The United States and Russia have declared as excess to weapons requirements or for all military purposes a significant fraction of their stocks of both highly enriched uranium and plutonium produced for weapons. The United States and Russia continue to blend down the 210 and 500 tons, respectively, of HEU that they have declared excess to produce low-enriched uranium to fuel light-water reactors. The United States and Russia have yet to put in place the infrastructure to eliminate the 34 tons of excess weapons plutonium each committed to dispose under the 2000 U.S.–Russian Plutonium Management and Disposition Agreement. The past two years have also seen plans for new civilian enrichment plants and progress on new reprocessing plants. During this time, some former production facilities have been shut down, others dismantled, and in some cases key components have been demolished.

INTRODUCTION

Fissile materials are materials that can sustain an explosive fission chain reaction. They are essential in all nuclear explosives, from first-generation fission weapons to advanced thermonuclear weapons. The most common fissile

Received 14 October 2008; accepted 21 October 2008.
Address correspondence to Alexander Glaser, Program on Science and Global Security, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544, USA. E-mail: aglaser@princeton.edu

materials in use are uranium highly enriched in the isotope uranium-235, and plutonium.

Uranium-235 makes up only 0.7% of natural uranium. The remainder is almost entirely non-chain-reacting uranium-238. Although an infinite mass of uranium with U-235 enrichment of 6% could, in principle, sustain a fast fission chain reaction, uranium enriched to above 20% U-235, defined as "highly enriched uranium," is generally taken to be required for a weapon of practical size. The IAEA therefore considers highly enriched uranium (HEU) a "direct use" weapon-material. Actual weapons use higher enrichment, however, as reflected by the definition of "weapon-grade" uranium as enriched to over 90% in U-235. The Hiroshima bomb contained about 60 kilograms of uranium with an average enrichment of 80%.

Plutonium is produced in a nuclear reactor when U-238 absorbs a neutron creating U-239, which subsequently decays to plutonium-239 (Pu-239) via the intermediate short-lived isotope neptunium-239. The longer an atom of Pu-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 Pu-240—or absorb a third or fourth neutron and become Pu-241 or Pu-242. Plutonium therefore comes in a variety of isotopic mixtures. According to the U.S. Department of Energy, "virtually any combination of plutonium isotope . . . can be used to make a nuclear weapon . . . reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states."[2] The IAEA considers as direct-use material all plutonium containing less than 80% plutonium-238. The weapon that destroyed Nagasaki contained 6 kg of plutonium.

The IAEA defines a "significant quantity" of fissile material to be the amount required to make a first-generation implosion bomb of the Nagasaki-type, including production losses. The significant quantities are 25 kg of U-235 contained in HEU and 8 kg for plutonium.

Nine states have nuclear weapons today. These are, in historical order: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan, and North Korea. Estimates of their current nuclear-weapon stockpiles are shown in Table 1. The U.S. and Russian stockpiles peaked at approximately 30,000 for the United States (around 1965) and 40,000 for Russia (around 1985). All nuclear weapon states except India, Pakistan, and perhaps Israel have stopped production of highly enriched uranium and plutonium for weapons.

This article summarizes the IPFM estimates for global and national stocks of HEU and plutonium. It reviews the status of enrichment and reprocessing plants currently operating, under construction, or planned and summarizes recent developments in the shutting down, dismantling, and demolition of former production facilities.

Table 1: Estimated nuclear-weapon stockpiles and fissile material production status, 2008.[i]

Country	Nuclear warheads
United States	about 10,000[a]
Russia	about 10,000[b]
France	fewer than 300
United Kingdom	185
China	about 240
Israel	100–200
Pakistan	about 60
India	60–70
North Korea	fewer than 5

Notes: [a]5000 deployed, plus 5000 awaiting dismantlement; [b]large uncertainty as to the number of warheads awaiting dismantlement.

[i]See R. S. Norris and H. M. Kristensen, "U.S. Nuclear Forces, 2008," *Bulletin of the Atomic Scientists* (March/April 2008): 50–58; R. S. Norris and H. M. Kristensen, "Nuclear Notebook: Russian Nuclear Forces, 2008," *Bulletin of Atomic Scientists* (May/June 2008): 54–57, 62; R. S. Norris and H. M. Kristensen, "Nuclear Notebook: Chinese Nuclear Forces, 2008," *Bulletin of Atomic Scientists* (July/August 2008): 42–44; R. S. Norris and H. M. Kristensen, "French Nuclear Forces, 2008," *Bulletin of Atomic Scientists* (September/October 2008): 56–58; R. S. Norris and H. M. Kristensen, "Pakistan's Nuclear Forces, 2007," *Bulletin of Atomic Scientists* (May/June 2007): 71–73; R. S. Norris and H. M. Kristensen, "India's Nuclear Forces, 2007," *Bulletin of Atomic Scientists* (July/August 2007): 74–78; S. N. Kile, V. Fedchenko, and H. M. Kristensen, "World Nuclear Forces, 2008," Appendix 8A in SIPRI Yearbook 2008, Oxford University Press on behalf of Stockholm International Peace Research Institute, 2008. The estimate for North Korea is based on its reported declaration of having produced 37 kg of weapons plutonium, sufficient for less than 10 weapons. Glenn Kessler, "Message to U.S. Preceded Nuclear Declaration by North Korea," *Washington Post*, 2 July 2008.

HIGHLY ENRICHED URANIUM

Only the United Kingdom and the United States have made public the total sizes of their stocks of HEU. Total U.S. production was 1,045 tons of HEU with an average enrichment of 82%.[3] The United Kingdom reported a stock of 21.86 tons as of March 2002.[4] Estimates of the remaining national holdings are generally quite uncertain. The estimated national stocks of highly enriched uranium as of mid-2008 are shown in Figure 1. According to these estimates, the global inventory totals 1,670 $\pm$ 300 tons. More than 99% of the global HEU stockpile is in the possession of the nuclear weapon states. There are about 10 tons of HEU in non-nuclear-weapon states under IAEA safeguards.

The main uncertainty in estimating the global total is due to a lack of information on the Russian stockpile. It is possible to estimate the growth of Russia's HEU stockpile using installed enrichment capacity offset by the gradual rise in the use of this capacity to produce low-enriched uranium (LEU) for power-reactor fuel. This suggests Russia's estimated HEU production peaked at around 50,000 kg/yr in the mid-1970s (Figure 2). Based on the notional scenario shown here, total Russian HEU production was on the order of 1,300–1,400 tons (90% enriched).[5]

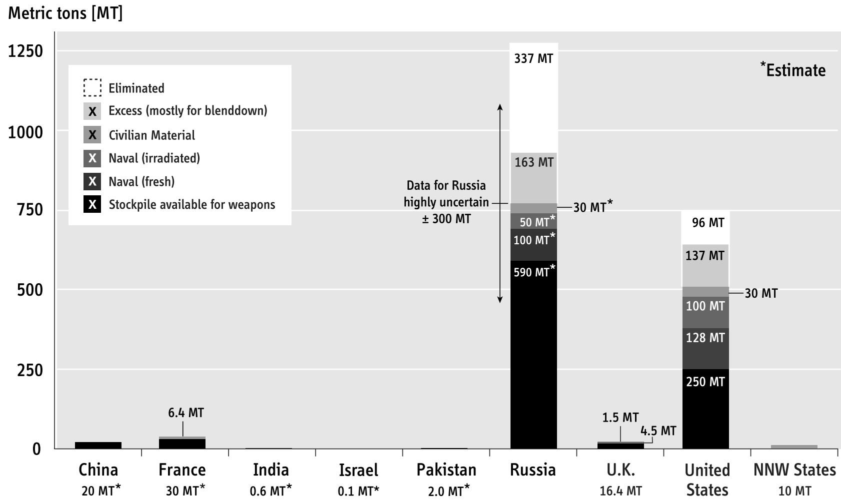

Figure 1: National stocks of highly enriched uranium as of mid-2008. The numbers for the United Kingdom and United States are based on official information. Numbers with asterisks are nongovernmental estimates, often with large uncertainties. Numbers for Russian and U.S. excess HEU are for June 2008. HEU in non-nuclear-weapon (NNW) states is under IAEA safeguards.

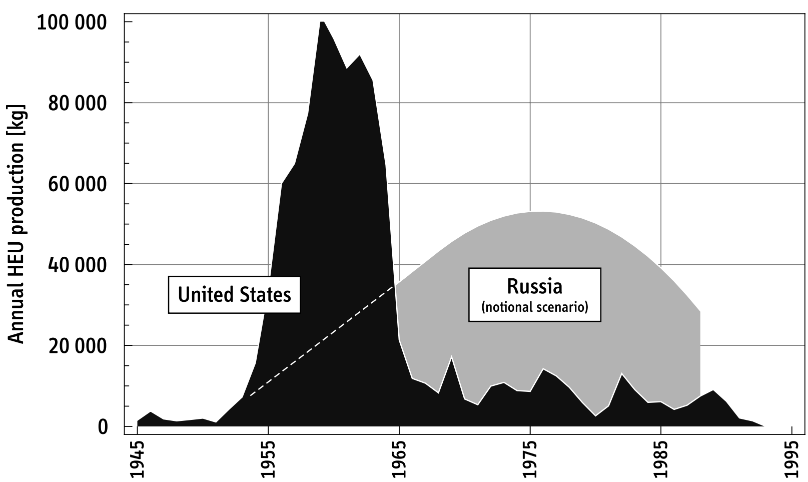

Figure 2: Historical production rates of HEU in the United States and Russia. The U.S. data is based on its 2001 declaration released in 2006 (*Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996,* U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf., Table 5-1).

Russia, the United Kingdom, and the United States each use HEU to fuel their submarine and (in the case of the United States) aircraft carrier propulsion reactors. France is shifting from HEU to LEU fuel for its nuclear submarines.

HEU is also used to fuel military and civilian research reactors and Russia's fleet of seven nuclear-powered icebreakers. The United States and the Soviet Union/Russia used and also supplied HEU to many countries for civilian research reactors and medical-isotope production as part of their Atoms for Peace programs.

In 1993, Russia contracted 500 tons of 90% enriched uranium in redundant Cold War warheads to be blended down to 4–5% U-235 to be sold to the United States for use as power-reactor fuel. As of June 2008, Russia had eliminated 337 tons of this weapon-grade HEU.[6] The deal is to be completed in 2013. In 1994, the United States similarly declared 174 tons of its weapon HEU excess and began to blend down most of it to low enrichment for use in U.S. power reactor fuel. In late 2005, the United States declared an additional 200 tons of HEU excess for weapons purposes. However, only 52 tons of this material will be blended down to low-enriched uranium. Of the remainder, 128 tons of weapon-grade uranium will be reserved for U.S. and U.K. naval-reactor fuel and 20 tons for space reactors and research reactors. As of mid-2008, the United States had eliminated about 96 tons out of a total of 210 tons of highly enriched uranium earmarked for blend-down.[7] Little if any of this material, however, was weapon-grade. Figure 3 shows the cumulative amounts of excess HEU blended down by Russia as part of the HEU deal and by the United States.

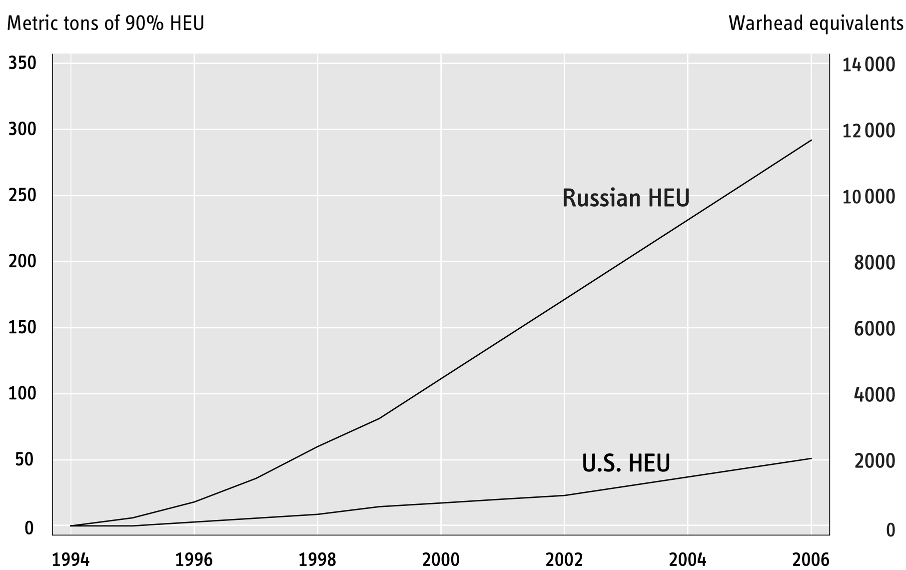

Figure 3: Cumulative HEU blended down by Russia and the United States, 1994–2006.

Israel may have acquired about 100 kg of weapon-grade HEU covertly in or before 1965 from the United States. There have been several classified investigations of this case. In October 2007, former Congressional staffer, Henry Myers wrote that "[s]enior officials in the U.S. government concluded in the late 1960s that weapon-size quantities of HEU had probably been diverted from NUMEC [Nuclear Materials and Equipment Corporation] to Israel."[8] Victor Gilinsky, a former U.S. Nuclear Regulatory Commissioner, has revealed that "the CIA believed that the nuclear explosives in Israel's first several bombs, about one hundred kilograms of bomb-grade uranium in all, came from material that was missing at a U.S. naval nuclear fuel plant."[9] In addition, Israel may have produced enriched uranium in limited quantities, but information on this program is very limited.[10]

Pakistan may be the only country producing HEU for weapons today. It is believed to have first achieved the capacity to produce a significant quantity of HEU in the early 1980s and to have built up its enrichment capacity, using its P-2 centrifuges, until 1990.[11] Pakistan continued to develop more powerful P-3 and P-4 centrifuges. These machines have estimated separative capacities two and four times that of the P-2, respectively.[12] Pakistan is estimated to have produced 1.6–2.8 tons of HEU by the beginning of 2008.[13] A value of 2 tons is used here as a central estimate for Pakistan's current stockpile of HEU.

Pakistan's annual HEU production capacity is constrained, however, by its limited domestic production of natural uranium (currently 40 tons per year) and the need to also fuel its Khushab plutonium production reactor, which requires about 13 tons per year. The natural uranium constraint will become more significant when the second and third production reactors at Khushab come on line. The three reactors will then require virtually all of the remaining natural uranium that Pakistan produces.

Naval HEU Use

France, Russia, the United Kingdom, and the United States use HEU to fuel submarine and ship propulsion reactors, and India is preparing to do so. France has almost completed a switch to LEU fuel for its nuclear navy. This assessment is based on the assumption that China uses low-enriched fuel only for its nuclear navy.

Toward the end of the Cold War, the Soviet Union and the United States each used annually about two tons of HEU for this purpose (Figure 4).[14] Today, Russia uses about one ton (not all weapon-grade) and the United States two tons of weapon-grade HEU per year. The Russian icebreaker fleet accounts for a significant fraction of Russia's HEU consumption. Russia also uses HEU for fueling plutonium- and tritium-production reactors.

Future levels of HEU use for naval propulsion purposes are highly uncertain. The demand could drop if Russia phases out the use of HEU for its nuclear icebreakers (as assumed for the projection in Figure 4).

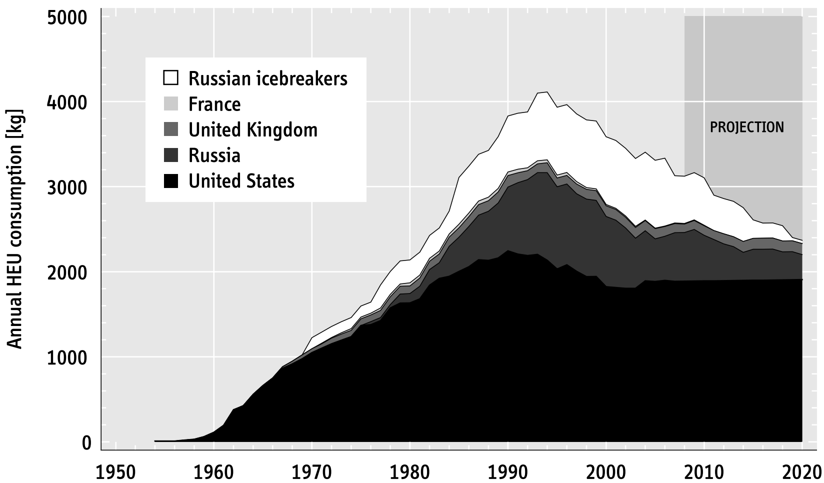

Figure 4: Estimated annual HEU consumption in naval vessels.[14]

The United States appears to be committed to maintaining its reliance on nuclear propulsion for its aircraft carriers and submarines, and possibly expanding it to include nuclear-powered cruisers. The 128 tons of HEU that the United States has set aside for military naval nuclear propulsion would be sufficient to fuel its surface ships and submarines for 40–60 years. In 2008, the U.S. Senate required the navy to study the possibility of LEU fuel for future nuclear powered ships.[15]

In 1998, the United Kingdom declared an inventory of 21.9 tons of military HEU.[16] According to a 2002 U.K. government report, this inventory included 3.9 tons of HEU in 51 spent submarine reactor cores in pool storage in the U.K.'s Sellafield reprocessing complex.[17] Based on this information, one can estimate that about 1,000 kg of U-235 has been fissioned since 1998 and that, as of 2008, the amount of HEU in spent submarine reactors cores was about 4.5 tons.

India has been producing HEU to fuel its planned nuclear-powered ballistic missile submarine, the Advanced Technology Vessel. Construction on the vessel is near completion, with the reactor integrated into a submarine hull at the end of 2007, and plans are to begin sea trials in early 2009.[18] As of the end of 2007, India would need to have produced at least 400 kg of HEU (enriched to 45% uranium 235), to supply fuel for the land-based prototype reactor and the first submarine core.[19] Reports suggest India intends to deploy three nuclear submarines, each armed with 12 missiles, by 2015.[20] This would require the production of an additional 400 kg of HEU over the next five to six years. To reach this goal, India will need a larger uranium enrichment capacity.[21] India has been purchasing material for building additional centrifuges.[22]

Table 2: Operational HEU-fueled research reactors (civilian and military) by power level in thermal megawatts (MWt) and type for selected countries and regions.[23]

Reactor	Russia	China	Europe	USA	Other	TOTAL
Steady State	16	3	12	11	17	59
< 0.25 MWt	1	3	5	1	12	22
0.25–2.0 MWt	1	—	—	4	2	7
2.1–10 MWt	7	—	—	2	3	12
> 10 MWt	7	—	7	4	—	18
Pulsed/Critical	54	1	7	8	2	72
Total	70	4	19	19	19	131

Civilian Use of HEU

HEU is used today as a research-reactor fuel in more than 130 civilian and military reactors worldwide (Table 2).[23] In addition, HEU remains at sites of many shut down, but not yet decommissioned reactors. Taken together, the global inventory of civilian HEU reactor fuel is very roughly 100 metric tons, widely distributed around the globe.[24] These reactors are a legacy from competing U.S. and Soviet Atoms for Peace programs of the 1950s and 1960s.

Since 1978, an international effort has been directed at converting HEU-fueled civilian research reactors to low-enriched fuel in the Reduced Enrichment for Research and Test Reactor (RERTR) program. Almost all new reactors designed since that time use LEU fuel.[25] By the end of 2007, the RERTR program had converted or partially converted 56 research reactors. The world's remaining research reactors consume about 800 kilograms of HEU per year—a significant reduction from more than 1,400 kg that were needed annually in the early 1980s (see Figure 5).[26] Most of this reduction is due, however, to the shutdown of about 110 no-longer-required HEU-fueled research reactors rather than reactor conversions to low-enriched fuel.

In 2004, the U.S. Department of Energy responded to Congressional concern about how slowly the HEU-cleanout programs were moving by establishing a Global Threat Reduction Initiative (GTRI) into which its reactor-conversion and spent HEU-fuel take back efforts were merged. Figure 5 shows how the annual HEU demand could drop to very low levels by 2020 if this program achieves its ambitious objectives.[27] Recently, Russia has agreed to study conversion of six of its own research reactors.[28] Critical assemblies and pulsed reactors containing huge quantities of barely irradiated uranium are not yet formally being targeted by any of these cleanout efforts, however.

SEPARATED PLUTONIUM

The global stockpile of separated plutonium is about 500 tons. It is divided almost equally between civilian stocks and military stocks, including material

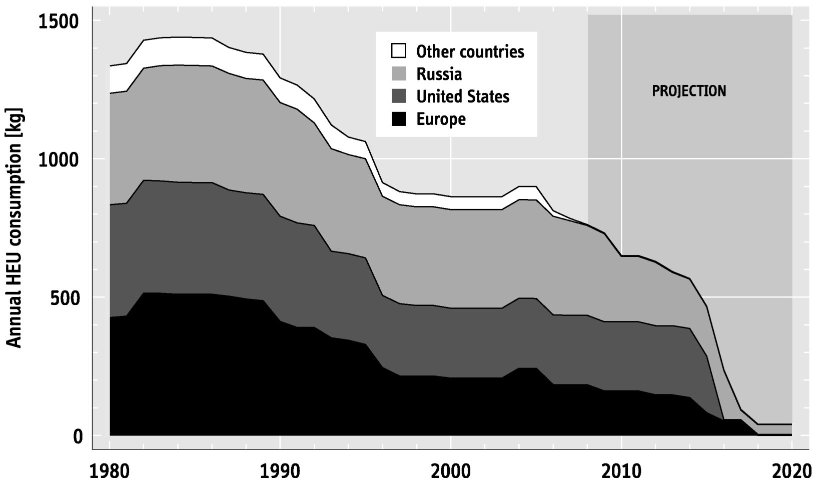

Figure 5: Estimated total annual HEU use in research reactors.

declared excess but not yet disposed. Separated plutonium exists mostly in nuclear weapon states, but Japan and Germany also have significant stocks. Figure 6 summarizes the data.

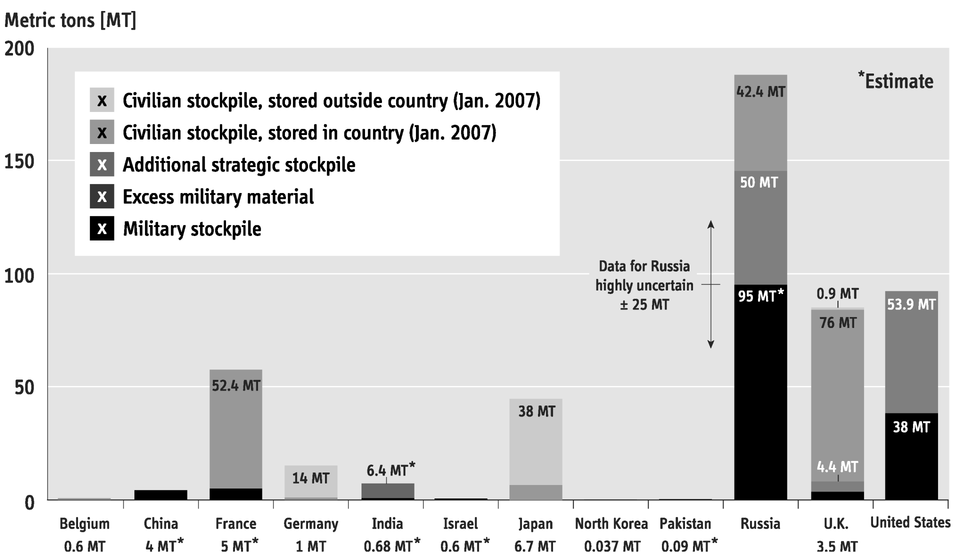

Figure 6: National stocks of separated plutonium. Civilian stocks are for January 2007 and based on the latest INFCIRC/549 declarations (when available and with the exception of Germany). Civilian stocks are listed by ownership, not by current location. India's plutonium separated from unsafeguarded spent PHWR fuel is categorized as an additional strategic stockpile.

Weapons Plutonium

Russia and the United States possess by far the largest stocks of military plutonium: 120–170 and 92 tons, respectively. Russia has declared 34 tons, and potentially up to 50 tons, of its weapon-grade plutonium excess for weapon purposes. The United States has declared excess 54 tons of separated government-owned plutonium, which includes 9 additional tons added to that category in September 2007.[29] The Russian and U.S. plutonium disposition projects have suffered many changes of plans and delays since they were launched in the mid-1990s.[30]

There is great uncertainty about Israel's plutonium production. Based on information from Mordechai Vanunu, Frank Barnaby estimated that Israel had produced 400–800 kg of plutonium in its Dimona reactor already by the mid-1980s.[31] But such a high estimate is based on the assumption that the thermal power of the reactor had been increased from its initial 26 megawatts (MWt) to 70 MWt, and eventually to 150–250 MWt.

If the power level of Dimona never exceeded 70 MWt, equivalent to a plutonium production rate of about 14–17 kg/yr,[32] by the mid-1980s, Israel's inventory of separated plutonium would have been in the range of 280–340 kg. By today, the reactor could have produced 560–680 kg. Assuming an average of 4 kilograms of plutonium per warhead, a stockpile of 600 kg of plutonium would be equivalent to an arsenal of 150 weapons. If the Dimona reactor is operated only for tritium production today, Israel could be reprocessing its spent fuel and separating the plutonium, but not using it to make weapons.

India continues to produce weapon-grade plutonium for weapons in its two production reactors, *Cirus* and *Dhruva*, at a rate of about 30 kilograms per year. It separates much more reactor-grade but weapon-usable plutonium from the spent fuel of its unsafeguarded pressurized heavy water power reactors (PHWRs). It may have separated about 6.4 tons of this power-reactor plutonium as of 2008.[33] A fraction of this plutonium is intended to fuel the Prototype Fast Breeder Reactor (PFBR), expected to be completed in 2010. The PFBR would consume reactor-grade plutonium but, in doing so, could produce over 140 kg a year of weapon-grade plutonium in the "blanket" of natural uranium surrounding the core.[34]

India's annual domestic uranium production has been falling short of the combined demand from its growing nuclear power and military programs (including both the naval-propulsion and plutonium-production reactors). The average capacity factor for India's PHWRs fell from about 75% in 2003–04 to 44% in 2007–08, suggesting that the needs of the military reactors have been given a higher priority.[35]

Pakistan continues to produce almost 12 kg per year of plutonium for weapons at its Khushab production reactor.[36] Work appears to have started on two additional production reactors at this site in 2001 and 2005, respectively. A new reprocessing plant is reportedly being built near Chashma.[37] Pakistan's first plutonium-production reactor took about a decade to build. If the second and third reactors take as long, then they may be expected to begin operating around 2011–14. As already noted, operating at full capacity, the three production reactors would require as fuel almost all the 40 tons/year of uranium that Pakistan currently produces.

In June 2008, North Korea is reported to have declared a plutonium inventory of 37 kg.[38] The U.S. government and independent analysts had previously estimated North Korea's plutonium stock as 30–50 kg.[39]

Civilian Plutonium

The global stockpile of separated civilian plutonium has been growing steadily for decades. From 1996, when all countries with civilian separated plutonium stocks— except India—agreed to publicly declare their civilian plutonium holdings annually to the IAEA, to 2007 the global stockpile rose from 160 tons to 240 tons, not including the plutonium declared excess for weapon-use by Russia and the United States.

More than 200 tons of the world's separated civilian plutonium, or 80% of the total, are stored at four sites in Europe and Russia. These are the French reprocessing and fuel-fabrication sites at La Hague and Marcoule, the British site at Sellafield, and Russia's Mayak facility.

Japan's Rokkasho reprocessing plant, which began active testing in 2006, continues to experience problems and is unlikely to begin commercial operation in 2008. Active testing was to have been completed in February 2008, but this was extended to July 2008 and then again to November 2008.[40] As a result of the testing, however, as of May 2008, the facility had separated about 2.7 tons of plutonium, which is stored mixed with an equal amount of uranium.[41]

The United Kingdom began reprocessing in 1952 to separate plutonium for weapons.[42] By the end of 2007, the United Kingdom also had separated a total of over 100 tons of civilian separated plutonium from domestic and foreign spent fuel. This amount separated will increase to 133 tons if existing contracts are fulfilled, with commercial operations expected to end by 2020. These activities have left a large environmental and cleanup problem at the Sellafield site, with estimates of cleanup costs now running at about $92 billion.[43] The plutonium from foreign spent fuel, or equivalent U.K. plutonium, will be returned to foreign clients as mixed oxide (plutonium–uranium, MOX) fuel, but the United Kingdom has not yet determined a strategy for disposition of the approximately 100 tons of plutonium that will have been separated from domestic spent fuel.[44]

In France, reprocessing for weapons started in 1958 and ended in 1993.[45] Since then, it has been a civilian program with both domestic and foreign customers. France has accumulated over 80 tons of separated plutonium, 30 tons of which is foreign-owned. Almost all of the foreign spent fuel under contract has been reprocessed, and only minor new contracts have been signed. The economic burden of reprocessing is increasingly a concern to France's national electric utility. As in the United Kingdom, reprocessing has left a large environmental and cleanup legacy.

China is developing a civilian plutonium complex. Its long-delayed pilot reprocessing plant at the Yumenzhen site, in Gansu Province with a design capacity of 50 tons/yr, is reported to have been completed and to be undergoing testing prior to start up.[46] China's National Nuclear Corporation has also agreed with the French company AREVA on feasibility studies for the construction of a large commercial reprocessing and MOX fuel fabrication facility complex in China.[47]

STATUS OF PRODUCTION FACILITIES WORLDWIDE

The first uranium-enrichment plants were built to produce HEU and the first reactors were built to produce plutonium—both for weapons. Today, the civilian nuclear sector vastly exceeds the nuclear-weapon sector in terms of the numbers of fuel cycle facilities and fissile-material production capabilities. There are currently 22 enrichment and 18 reprocessing plants located in 13 countries, excluding R&D and pilot-scale facilities. Seven enrichment or reprocessing facilities in nuclear weapon states are under international safeguards. There are currently 15 facilities that have not been offered for safeguards. Tables 3 and 4 show, respectively, the status of known uranium enrichment plants and reprocessing plants worldwide.

Aging and no-longer-operating fissile material production facilities in the nuclear weapon states continue to be closed down and in some cases dismantled.

In April and June 2008, Russia shut down its two remaining operating plutonium-production reactors at the Seversk/Tomsk-7 site.[48] The two reactors, ADE-4 and ADE-5, had been operating since 1965 and 1968, respectively, each producing about 0.5 tons of weapons plutonium per year, as well as electricity and steam for district heating.[49] Russia's last remaining plutonium production reactor (ADE-2), at the Zheleznogorsk/Krasnoyarsk-26 site, is expected to shut down 2010 when a replacement coal-fired plant is completed. The spent metal fuel used in the three reactors could not be safely stored for more than a few months without serious corrosion and was reprocessed.

Since 1994, the 18 tons of weapon-grade plutonium separated from the fuel of the three production reactors has been stored (10 tons in Seversk and 8 tons in Zheleznogorsk) under an agreement with the United States, and committed not to be used for weapon purposes. Rosatom plans to consolidate all this plutonium in underground storage in Zheleznogorsk.[50] Nine tons of the plutonium oxide is included in the 34 tons that Russia has committed to dispose of in MOX under the Russian–U.S. Plutonium Disposition Agreement.[51]

Table 3: Large enrichment facilities, operational, under construction, and planned. As listed by IAEA Nuclear Fuel Cycle Information System, unless otherwise indicated. The capacity is given in Separative Work Units per year. To produce one kilogram of weapon-grade uranium (90% U-235) from natural uranium requires about 200 SWU, at a tails assay of 0.3%.

Country	Name/Location	Type	Status	Process	Capacity 1000 SWU/year
Brazil	Resende Enrichment	Civilian	Under construction	GC	120
China	Lanzhou 2	Civilian	Under construction	GC	500
	Shaanxi Enrichment Plant	Civilian	In operation	GC	500
France	Eurodif (Georges Besse)	Civilian	In operation	GD	10800
	Georges Besse II	Civilian	Planned	GC	7500
Germany	Urenco Deutschland[a]	Civilian	In operation	GC	1800 (4500)
India	Rattehalli[b]	Military	In operation	GC	4–10
Iran	Natanz[c]	Civilian	Under construction	GC	100–250
Japan	Rokkasho Enrichment Plant	Civilian	In operation	GC	1050
Netherlands	Urenco Nederland[a]	Civilian	In operation	GC	2500 (3500)
Pakistan	Kahuta[b]	Military	In operation	GC	15–30
	Chak Jhumra, Faisalabad	Civilian	Planned	GC	150
Russia[d]	Angarsk	Civilian	In operation	GC	1600
	Novouralsk (Sverdlovsk-44)	Civilian	In operation	GC	9800
	Zelenogorsk (Krasnoyarsk-45)	Civilian	In operation	GC	5800
	Seversk (Tomsk-7)	Civilian	In operation	GC	2800
United Kingdom	Capenhurst	Civilian	In operation	GC	4000
United States	Paducah Gaseous Diffusion	Civilian	In operation	GD	11000
	Portsmouth	Civilian	Standby	GD	7400
	Piketon, Ohio (USEC/DOE)[e]	Civilian	Planned	GC	3500
	Eunice, NM (LES/Urenco)[e]	Civilian	Planned	GC	3000
	Eagle Rock, Idaho (AREVA)	Civilian	Planned	GC	3000
	Wilmington, NC (GLE)	Civilian	Planned	Laser	3500–6000

Notes: [a]Entries in parentheses for Urenco facilities are capacities after planned expansions are complete; [b]Estimates for India from: M. V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security,* 12 (2004); and for Pakistan from: David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996, SIPRI* (Oxford University Press, 1997); [c]Entry for Iran assumes 50,000 machines with a capacity of 2–5 SWU/yr each, from: Mark Hibbs, "Current Capacity at Natanz Plant about 2,500 SWU/yr, Data Suggest," *Nuclear Fuels* (31 January 2005); [d]Estimates for Russia are from: Oleg Bukharin, "Understanding Russia's Enrichment Complex," *Science & Global Security,* 12 (2004); [e]Information on planned U.S. centrifuge facilities from www.nrc.gov/materials/fuel-cycle-fac/gas-centrifuge.html.

In 2008, as a transparency measure, the French president invited international observers to witness the dismantlement of the Marcoule reprocessing plant and the Pierrelatte gaseous diffusion enrichment.[52] These military facilities had been in operation since 1958 and 1967 and were shut down in 1996.

Table 4: Reprocessing Plants worldwide, operational, under construction, and planned. As listed by the IAEA's Nuclear Fuel Cycle Information System, except where indicated. Actual throughput in reprocessing plants is often a small fraction of the design capacity. The capacity is given as the amount of spent fuel that can be processed per year, measured in tons of "heavy metal" (uranium in these cases) in the fuel.

Country	Name/Location	Type	Status	Capacity tHM/year
France	La Hague—UP2	Civilian	In operation	1000
	La Hague—UP3	Civilian	In operation	1000
China[a]	Yumenzhen	Civilian	In start-up	50
India[b]	Trombay	Military	In operation	50
	Tarapur	(Unclear)	In operation	100
	Kalpakkam	(Unclear)	In operation	100
Israel[c]	Dimona	Military	In operation	40–100
Japan	JNC Tokai Reprocessing Plant	Civilian	In operation	210
	Rokkasho Reprocessing Plant	Civilian	In start-up	800
North Korea[d]	Yongbyon	Military	Suspended	50–200
Pakistan[b]	Nilore	Military	In operation	10–20
	Chashma	Military	Under construction	50–100
Russia[e]	RT-1, Combined Mayak	Civilian	In operation	400
	RT-2, Krasnoyarsk, 1st Line	Civilian	Deferred	800
	Tomsk-7 (Seversk)	Civilian	In operation	6000
	Zheleznogorsk	Civilian	In operation	3500
United Kingdom	BNFL B205	Civilian	In operation	1500
	BNFL Thorp	Civilian	Suspended	900
United States	Savannah River—H Canyon	Civilian	In operation	15

Notes: [a]Mark Hibbs, "CNNC Favors Remote Site for Future Reprocessing Plant," *Nuclear Fuel* (7 April 2008); [b]Estimates for India and Pakistan are from Z. Mian and A.H. Nayyar, "An Initial Analysis of Kr-85 Production and Dispersion from Reprocessing in India and Pakistan." *Science and Global Security*, 10(3), (2002); [c]The estimate for Israel is inferred from David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996, SIPRI* (Oxford University Press, 1997): 259–261; [d]Estimates for North Korea from David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007," Institute for Science and International Security (20 February 2007); [e]Estimates for Seversk and Zheleznogorsk derived from annual plutonium production given by Thomas Cochran, Robert S. Norris, and Oleg A. Bukharin *Making the Russian Bomb: From Stalin to Yeltsin* (Westview, 1995): 280 and 291, and plutonium in spent fuel given by D. F. Newman, C. J. Gesh, E. F. Love, and S. L. Harms, *Summary of Near-term Options for Russian Plutonium Production Reactors* (Pacific Northwest National Laboratory, PNL-9982, July 1994): 9.

Decontamination and decommissioning of these facilities is expected to take several decades.

In 2007, the cooling towers of the eight dual-purpose British Calder Hall and Chapelcross reactors were demolished.[53] The reactors had been used for both electric-power production and off and on for military plutonium production, which ended in 1989.[54] The two groups of reactors were shut down in 2003 and 2004, respectively.

In October 2007, North Korea committed to end its nuclear weapon program, declare all its nuclear activities, and disable its Yongbyon plutonium-production reactor and the associated fuel-fabrication plant and reprocessing plants by the end of the 2007. The cooling tower of the Yongbyon reactor was demolished in June 2008.[55]

CONCLUSION

There are currently nine states with nuclear weapons. The largest arsenals are held by the United States and Russia, each of which has about 10 times as many weapons as the others combined.

The United States, United Kingdom, Russia, North Korea, France, and China have all stopped production of fissile materials for weapons. All but China have made official statements to that effect. Production is believed to be continuing in India and Pakistan, and possibly in Israel.

The global stockpile of highly enriched uranium (HEU) is estimated to be 1,670 $\pm$ 300 tons. It is declining, as the combined rate of blend-down by Russia and the United States of HEU to low-enriched uranium (LEU) for use in light water power reactor fuel is significantly greater than the combined annual production of HEU for weapons by Pakistan and for naval fuel by India. Both Pakistan and India may be trying to increase their rate of HEU production. There is growing evidence that Israel may have acquired up to 100 kg of HEU from the United States for its nuclear weapons program.

France, Russia, the United Kingdom, and the United States use HEU to fuel submarines and ships, and India is planning to begin sea trials of a nuclear-powered submarine. It is estimated that the United States uses two tons of weapon-grade HEU per year for naval propulsion whereas Russia uses about one ton (not all of which is weapon-grade). The United States has reserved 128 tons of HEU for naval fuel, but in 2008, the U.S. Senate required the navy to study the use of LEU fuel for future nuclear-powered ships. France has already been switching to LEU fuel for its nuclear navy.

HEU is also used as a research-reactor fuel in more than 130 civilian and military reactors, with almost 100 metric tons distributed worldwide in active and shut-down facilities. The annual consumption of HEU by research reactors has fallen to about 800 kilograms of HEU per year largely because of the shutdown of about 110 research reactors. Almost 60 additional reactors have been converted to low-enriched fuel.

The global stockpile of separated plutonium is about 500 tons, about half of which is civilian. Only India and Pakistan and perhaps Israel are believed to be producing plutonium for weapons, at a combined rate of less than 60 kg per year. This rate will increase substantially when Pakistan completes its two new production reactors at Khushab and if India uses its prototype fast breeder reactor, which is scheduled to come online in 2010, for the production of weapons plutonium. The civilian stockpile is, however, growing much faster, at almost 5 tons a year. This rate will increase once the U.K. Thorp facility resumes operation, Japan's Rokkasho reprocessing plant begins commercial operation and China begins to operate its new civilian reprocessing plant at Yumenzhen.

The Cold War arms race has left the United States and Russia with very large nuclear arsenals and fissile material stocks. Both have declared as excess to weapons requirements or for naval fuel some of the highly enriched uranium and plutonium they produced for weapons. The United States and Russia continue to blend down the 210 and 500 tons, respectively, of HEU that they have declared excess. The United States and Russia, however, have yet to begin eliminating the 34 tons of weapons plutonium each declared as excess.

Former production facilities continue to be taken out of service. In 2008, the two plutonium production reactors at Seversk, Russia, were finally shut down. The last remaining Russian production reactor is be shut down in 2010. France, meanwhile, has started to dismantle its military fissile material production facilities at Marcoule and Pierelatte, whereas the United Kingdom and North Korea have demolished key components of former production reactors.

New military facilities are under construction or planned in Pakistan and India. But the largest growth in capacity is in new civilian enrichment plants that are planned to be built in the United States and France. Despite their civilian status, many current and planned enrichment facilities in the United States may not be safeguarded by the International Atomic Energy Agency.

NOTES AND REFERENCES

1. *Global Fissile Material Report 2008,* International Panel on Fissile Material, Princeton, NJ, September 2008, www.ipfmlibrary.org/gfmr08.pdf

2. *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, U.S. Department of Energy, DOE/NN-0007, Washington, D.C., January 1997, pp. 37–39, www.ipfmlibrary.org/doe97.pdf

3. *Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996,* U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf

4. U.K. Ministry of Defence, *Historical Accounting for U.K. Defence Highly Enriched Uranium,* March 2006, www.ipfmlibrary.org/mod06.pdf

5. Note that total production does not include inventory removals due to nuclear weapon tests, fuel consumption, or other processes.

6. As of 30 June 2008, according to www.usec.com/megatonstomegawatts.htm

7. These 96 tons include: 14 tons (originally available as UF6) and 47 tons for USEC; 31.7 tons for TVA as part of the BLEU (Blended LEU) Program; 1 ton for the Reliable Fuel Supply (RFS) Project, and 2.5 tons for research reactor LEU fuel. Data from: R. George, "U.S. HEU Disposition Program," *INMM 49th Annual Meeting,* Nashville, TN, 13–17 July 2008.

8. H. Myers, "The Real Source of Israel's First Fissile Material," *Arms Control Today,* October 2007, 56. Henry Myers was on the staff of the House of Representatives Interior Committee, which had the responsibility for overseeing the NRC, when the Nuclear Regulatory Commission investigated the NUMEC matter in the late 1970s.

9. V. Gilinsky, "Israel's Bomb," *New York Review of Books* 51(8) (13 May 2004), www.nybooks.com/articles/17104. From the same author, see also "Time For More NUMEC Information," *Arms Control Today,* June 2008.

10. Frank Barnaby, *The Invisible Bomb: The Nuclear Arms Race in the Middle East* (I. B. Tauris, London, 1989), 40; and M. Vanunu, Interviews with Barnaby, September 1986. According to Vanunu's statements to Barnaby, the enrichment plant started production in 1979–1980.

11. Pakistan is estimated to have had an enrichment capacity of up to 15,000 kg SWU per year as of 1990 or, equivalently, 3000 P-2 centrifuges with an enrichment capacity of 5 SWU/yr, David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996*, *SIPRI* (Oxford University Press, 1997), 217–281.

12. M. Hibbs, "Pakistan Developed More Powerful Centrifuges," *Nuclear Fuel* 32(3), 29 January 2007; M. Hibbs, "P-4 Centrifuge Raised Intelligence Concerns about Post-1975 Data Theft," *Nucleonics Week* 48(7) (15 February 2007).

13. Pakistan may not have been able to take full advantage of its more powerful P-4 machines because of the limited supply of uranium that it has available, which must be shared with its Khushab production reactor. Once the other production reactors come online, requiring almost 40 tons/year of fuel if they are each the same size as the first Khushab reactor, Pakistan may have to resort to enrichment of its accumulated uranium tails or of reprocessed uranium from its production reactors. See Zia Mian, A. H. Nayyar, and R. Rajaraman, *forthcoming.*

14. O. Reistad and S. Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *The Nonproliferation Review* 15(2) (July 2008).

15. "The committee directs the Office of Naval Reactors to review carefully options for using low enriched uranium fuel in new or modified reactor plants for surface ships and submarines," Senate Committee on Armed Services Report, *National Defense Authorization Act for Fiscal Year 2009,* 12 May 2008, 515.

16. *The Strategic Defence Review*, July 1998. Cm 3999, www.ipfmlibrary.org/mod98.pdf

17. NIREX Technical Note. Document 375301, Implications of Declaring UK Uranium Stocks as Waste, 26 March 2002, www.ipfmlibrary.org/nir02.pdf

18. Sandeep Unithan, "The Secret Undersea Weapon," *India Today* (28 January 2008): 52–55.

19. It is estimated that each core contains 90 kg of uranium-235 in the form of 300 kg of 30-percent enriched HEU. M. V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security* 12 (2004): 115–124.

20. Unithan, *op. cit.*

21. India could not produce this much HEU by 2014 if it had simply maintained or even linearly increased its enrichment capacity from the estimated value of 3000 kg SWU/yr that it would have needed by 1999 to have produced the HEU for the land-based prototype core.

22. David Albright and Susan Basu, *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes,* Institute for Science and International Security, 18 January 2007.

23. Reistad and Hustveit, *op. cit.*

24. The United States holds about 45 tons of civilian HEU, which includes about 20 tons in storage at the Y-12 site for future use as HEU in research and space reactors, and about 13–15 tons in spent fuel. Ten tons of civilian HEU is in non-nuclear weapon states and 8 tons in the United Kingdom and France. Good estimates for China and Russia are not yet available, but all indications are that Russia's stock of civilian HEU is at least as large as that of the United States.

25. The most prominent and controversial exception is the research reactor FRM-II near Munich, Germany, which went into operation in 2004 and requires 35–40 kg of weapon-grade HEU per year. Enrichment reduction to 50% or less is planned, and should be completed by 31 December 2010 according to an agreement between the German Federal Government and Bavarian State Government.

26. Reistad and Hustveit, *op. cit.*

27. Only Germany's FRM-II would use HEU at that point.

28. Parish Staples, "An Overview of the Global Threat Reduction Initiative Program for Research Reactor Conversions," *49th INMM Annual Meeting*, 13–17 July 2008, Nashville, TN.

29. *U.S. Removes Nine Metric Tons of Plutonium From Nuclear Weapons Stockpile,* U.S. Department of Energy, Press Release, 17 September 2007, www.ipfmlibrary.org/bod07.pdf

30. See *Global Fissile Material Report 2007,* chapter 3.

31. Barnaby, *op. cit*., 25.

32. This production rate assumes 0.85 grams of plutonium produced per MWt-day, a reactor power of 70 MWt, and 250–300 effective full power days per year.

33. If the PHWR spent fuel is cooled on average of three years before discharge, then spent fuel discharged by the end of 2004 would be available for reprocessing by the end of 2007. This pre-2005 spent fuel contained an estimated 9.2 tons of plutonium. If the reprocessing plants operate with an average capacity factor of 70 percent, then about 6.4 tons of this plutonium could have been separated as of the beginning of 2008.

34. A. Glaser and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security* 15(2) (2007): 85–105.

35. M.R. Ramana, personal communication, August 2008, based on data from Nuclear Power Corporation of India Limited, www.npcil.nic.in/plantsoperation.asp

36. The natural uranium fueled reactor, which is based on the Canadian NRX reactor design (as is India's CIRUS reactor), is assumed to be 50 MWt and operating at 70% capacity, with a fuel burnup of 1000 MWd/t.

37. For details see chapter 1, *Global Fissile Material Report 2007*.

38. Glenn Kessler, "Message to U.S. Preceded Nuclear Declaration by North Korea," *Washington Post*, 2 July 2008.

39. The U.S. estimate was that North Korea produced 40–50 kg of plutonium, including the amount used in its test. Helene Cooper, "In Disclosure, North Korea Contradicts U.S. Intelligence on Its Plutonium Program," *New York Times*, 31 May, 2008. See also David Albright, Paul Brannan, and Jacqueline Shire, *North Korea's Plutonium Declaration: A Starting Point For An Initial Verification Process*, ISIS, 10 January 2008, www.isis-online.org

40. CNIC, *Rokkasho active tests*, cnic.jp/english/topics/cycle/rokkasho/activetests.html

41. Masa Takubo, personal communication, 10 August 2008, citing a report in the Japanese newspaper *Too Nippo*, 30 June 2008.

42. Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, IPFM Research Report No. 5, International Panel on Fissile Materials, July 2008, www.ipfmlibrary.org/rr05.pdf

43. *Ibid.*

44. *NDA Plutonium Options*, Nuclear Decommissioning Authority, August 2008, www.ipfmlibrary.org/nda08/pdf

45. Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France*, IPFM, April 2008.

46. Mark Hibbs, "CNNC Favors Remote Site for Future Reprocessing Plant," *Nuclear Fuel*, 7 April 2008.

47. Ann MacLachlan, "Areva, China Seal Long-Term Mining, Fuel Cycle Pact," *Nuclear Fuel,* 3 December 2007.

48. C. J. Chivers, "Russians to Shut Reactor That Produces Bomb Fuel," *New York Times,* 20 April 2008, www.nytimes.com/2008/04/20/world/europe/20russia.html, and updated at "Russia Ends Plutonium Production in Seversk," 5 June 2008, Russian Strategic Forces blog, www.russianforces.org/blog/2008/06/russia_ends_plutonium_producti.shtml

49. T. B. Cochran, R. S. Norris, and O. A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* (Westview Press, 1995), 138.

50. Pavel Podvig, "Plutonium from Last Russian Production Reactors," 16 July 2008, www.russianforces.org/nuclear/2008/07/plutonium_from_last_russian_pr.shtml

51. *Agreement between [the U.S. and Russia] concerning the management and disposition of plutonium designated as no longer required for defense purposes and related cooperation,* "Annex on Quantities, Forms, Locations and Methods of Disposition," 2000, www.ipfmlibrary.org/doe00.pdf

52. Speech by President Nicolas Sarkozy, *Presentation of Le Terrible in Cherbourg,* 21 March 2008, www.ipfmlibrary.org/sar08.pdf

53. "Chapelcross Cooling Towers," UK Nuclear Decommissioning Authority, 21 May 2007, www.nda.gov.uk/news/chapelcross-demolition.cfm; "Sellafield Towers are Demolished," *BBC*, 29 September 2007, news.bbc.co.uk/2/hi/uk_news/england/cumbria/7019414.stm

54. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996*, *SIPRI* (Oxford University Press, 1997), 63.

55. Blaine Harden and Stella Kim, "N. Korea Razes Cooling Tower In Show of Nuclear Accord," *Washington Post*, 28 June 2008.