Appendix 12C. Fissile materials: global stocks, production and elimination

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I. Introduction: fissile materials and nuclear weapons

Fissile materials can sustain an explosive fission chain reaction. They are essential for all types of nuclear explosives, from first-generation fission weapons to advanced thermonuclear weapons. The most common fissile materials are uranium enriched to more than 20 per cent in the chain-reacting isotope uranium-235 (U-235) and plutonium of almost any isotopic composition. The fission of 1 kilogram of fissile material—the approximate amount that fissioned in both the Hiroshima and Nagasaki bombs—releases energy equivalent to the explosion of about 18 kilotons of chemical high explosive.

Lack of access to fissile materials represents the main technical barrier to the acquisition of nuclear weapons. International monitoring of the production, use and disposition (i.e. management and disposal) of both military and civilian fissile materials is crucial for nuclear disarmament, for halting the proliferation of nuclear weapons and for ensuring that terrorists do not acquire them.

This section reviews some basic background information on fissile materials and their use in nuclear weapons. Section II discusses the need for better information on military and civilian holdings of highly enriched uranium (HEU) and separated plutonium and provides estimates for current global holdings of these materials. Section III describes the production of HEU by gas centrifuge, the creation of plutonium in nuclear reactors and its subsequent separation, and the current approaches to disposition of these materials. Section IV presents some conclusions.

Only 0.7 per cent of naturally occurring uranium is U-235. The remainder is almost entirely the non-chain-reacting isotope U-238. Although in principle uranium with an enrichment of U-235 as low as 6 per cent could sustain an explosive chain reaction, the critical mass of material required would be infinitely large. Enrichment to 20 per cent U-235 is generally taken to be the lowest concentration practicable for use in weapons. Uranium enriched to 20 per cent or higher is defined as HEU. The International Atomic Energy Agency (IAEA) considers such HEU a direct-use weapon material. In practice, however, in order to minimize the mass of the nuclear explosive, weapon-grade uranium is usually enriched to over 90 per cent in U-235.

Increasing the fraction of U-235 in uranium requires sophisticated isotope separation technology. Isotope separation on the scale required to produce nuclear weapons is not considered to be within the reach of terrorist groups.

Plutonium is produced in a nuclear reactor when U-238 absorbs a neutron and becomes U-239, which subsequently decays to plutonium-239 (Pu-239) via the inter-

* This appendix is based primarily on chapters 1, 2, 3 and 6 of International Panel on Fissile Materials (IPFM), Global Fissile Material Report 2006 (IPFM: Princeton, N.J., 2006), URL <http://www.fissilematerials.org/>. Many of the documents referred to in that book and in this appendix are archived on the IPFM website at URL <http://www.ipfmlibrary.org/>.

mediate, 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 become Pu-240—or a third or fourth neutron and become Pu-241 or Pu-242. Plutonium therefore comes in a variety of isotopic mixtures. Weapon designers prefer to work with a mixture that is predominantly Pu-239 because of its relatively low rate of spontaneous emission of neutrons and gamma rays and low generation of radioactive heat. Weapon-grade plutonium contains more than 90 per cent of the isotope Pu-239. The plutonium in typical spent fuel from power reactors (reactor-grade plutonium) contains 50–60 per cent Pu-239 and about 25 per cent Pu-240.

For a time, many in the nuclear industry believed that the plutonium generated in power reactors could not be used for weapons. One reason was the belief (or hope) that the spontaneous emission of neutrons by Pu-240, which is typically four times more abundant in power-reactor spent fuel than in weapon-grade plutonium, would start the explosive chain reaction prematurely during the implosion of the plutonium core and sharply reduce the weapon's explosive yield. However, it is now understood that virtually any combination of plutonium isotopes can be used to make a nuclear weapon with a reliable yield of at least 1 kiloton, using technologies no more sophisticated than those used in the Nagasaki bomb.[1]

The amount of fissile material in a nuclear warhead depends on design details, including whether it is a pure fission weapon, such as the Hiroshima and Nagasaki bombs, or a two-stage, thermonuclear weapon. The Hiroshima bomb contained about 60 kg of uranium enriched to about 80 per cent in chain-reacting U-235. In this 'gun-type' weapon, one piece of HEU of less than a critical mass was fired into another to make a supercritical mass able to sustain an exponentially growing fission chain reaction. The Nagasaki bomb was an implosion device operated on a principle that has been incorporated into most modern weapons. Chemical explosives imploded a 6-kg mass of plutonium to a higher density. While 6 kg is normally less than critical mass, this implosion reduced the spaces between the atomic nuclei and resulted in less leakage of neutrons out of the mass, with the result that it became supercritical. In both designs, the chain reaction was initiated by releasing neutrons at the moment when the fissile material was most supercritical.

Gun-type weapons are simpler than implosion devices (although they can only be constructed using HEU, not plutonium, and require at least twice as much HEU as an implosion weapon), and those with the intent to make them do not need a high level of technical sophistication. Indeed, the US Department of Energy (DOE) has warned that it may be possible for intruders in a fissile-material storage facility to use nuclear materials for on-site assembly of an improvised nuclear device in the short time before guards could intervene.[2]

The IAEA defines a significant quantity of fissile material as 'the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded'. This estimate is for a first-generation implosion

[1] Mark, J. C., 'Explosive properties of reactor-grade plutonium', *Science & Global Security*, vol. 4 (1993), p. 111; and US Department of Energy (DOE), *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, DOE/NN-0007 (DOE: Washington, DC, Jan. 1997), URL <http://www.ipfmlibrary.org/doe97.pdf>, pp. 37–39.

[2] US Department of Energy (DOE), Office of Security Affairs, Office of Safeguards and Security, 'Protection and control planning', *Manual for Protection and Control of Safeguards and Security Interests*, DOE M 5632.1C-1 (DOE: Washington, DC, 15 July 1994).

bomb and includes production losses. The agency assumes a significant quantity to be 8 kg of plutonium or HEU containing 25 kg of U-235.[3]

In more advanced, modern fission weapons, the yield is typically boosted by an order of magnitude by introducing a mixture of deuterium and tritium, heavy isotopes of hydrogen, into the hollow shell of fissile material (the 'pit' of the weapon) just before it is imploded.[4] When the temperature of the fissioning material inside the pit reaches 100 million degrees Celsius, it can ignite the fusion of tritium with deuterium, which produces a burst of neutrons that increase the fraction of fissile material fissioned and thereby the power of the explosion.

Advanced fission weapons may contain significantly less material than the 6 kg of plutonium in the Nagasaki bomb. For example, the US Government has declassified the fact that 4 kg of plutonium is sufficient to make a nuclear explosive device.[5] Based on the critical mass ratios, it is plausible to assume that three times that amount of weapon-grade uranium (about 12 kg) would be sufficient if HEU were used in a similarly advanced design of a fission weapon.

In a modern thermonuclear weapon, a fission nuclear explosive generates X-rays that compress and ignite a second nuclear explosive, a 'secondary', containing both uranium and thermonuclear fuel. The energy released by the secondary is generated by both the fission of HEU and the fusion of deuterium and tritium. In the secondary, the tritium is produced during the explosion by neutron absorption in lithium-6. Modern warheads therefore typically contain both plutonium and HEU. It is assumed that the average modern nuclear warhead contains the equivalent of about 25 kg of HEU enriched to 90 per cent in the isotope U-235.[6]

II. Military and civilian fissile material stocks

During the cold war, the Soviet Union and the USA produced almost the entire current global stockpile of HEU for nuclear weapons and naval propulsion reactors and about half the global stockpile of separated plutonium for nuclear weapons. The other half of the plutonium stockpile derives from the reprocessing of civilian spent power-reactor fuel. The main contributors to military stockpiles of HEU and plutonium have ceased production, but the civilian stockpile of plutonium continues to grow at a significant rate.

[3] This can be plutonium of any composition, but less than 80% Pu-238. Plutonium containing more than 80% Pu-238 is considered unusable for nuclear weapons because of the large amount of heat generated by the relatively short (88-year) half-life of the isotope. The IAEA figure for HEU presumably corresponds to the amount required for 90% enriched uranium. For lower enrichments, more material would be required. International Atomic Energy Agency (IAEA), *Safeguards Glossary 2001 Edition*, International Nuclear Verification Series no. 3 (IAEA: Vienna, June 2002), URL <http://www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubid=6570>, pp. 23, 24.

[4] Deuterium, a stable isotope of hydrogen with 1 neutron and 1 proton in the nucleus, occurs naturally. Tritium, which has 2 neutrons and 1 proton, has a half-life of 12 years and is made in nuclear reactors. The natural abundance of tritium is negligible.

[5] 'Hypothetically, a mass of 4 kilograms of plutonium or uranium-233 is sufficient for one nuclear explosive device.' US Department of Energy (DOE), Office of Declassification, 'Restricted data declassification decisions 1946 to the present', RDD-7, Washington, DC, 1 Jan. 2001, p. 26.

[6] E.g. the US Enrichment Corporation (USEC) uses this figure. The corporation purchases low-enriched uranium produced by blending down Russia's excess 90% enriched HEU as part of a Russia–USA agreement. The 25 kg figure is used to calculate the number of warheads equivalent to the quantity of HEU blended down. See the USEC US–Russian Megatons to Megawatts Program, URL <http://www.usec.com/v2001_02/html/megatons_fact.asp>.

Availability of information

Non-nuclear weapon states that are parties to the 1968 Treaty on the Non-proliferation of Nuclear Weapons (Non-Proliferation Treaty, NPT)[7] are required to declare to the IAEA, and update regularly, information on the locations and quantities of all nuclear materials on their territories. In the European Union (EU) the European Atomic Energy Community (Euratom), which shares monitoring responsiblities with the IAEA, provides such reports on behalf of the EU member states. The IAEA does not make this information available to other governments or the public; it publishes only the total quantities of fissile materials under its safeguards in all the non-nuclear weapon states. The NPT does not require any disclosure of fissile material stocks by the five nuclear weapon states—China, France, Russia, the United Kingdom and the USA—that are parties to the NPT.[8] Despite this, all five states have made public some information on their production and holdings of fissile material. Since 1998 these five states (plus Belgium, Germany, Japan and Switzerland) have each year publicly declared to the IAEA their holdings of civilian plutonium, and in some cases of civilian HEU.[9] The UK and the USA have each published details of their total stocks of military plutonium and HEU. All but China (which has made unofficial indications) have officially declared that they have ended or suspended their production of fissile materials for weapons.[10]

In 1994 the US Department of Energy made public the total quantity of HEU that it had produced, and in 1996 published a history of US plutonium production and use.[11] A much fuller history of US HEU production and disposition was completed in January 2001 but was only released five years later as a result of a series of appeals under the US Freedom of Information Act by the Federation of American Scientists.[12] In 1998 the UK made public its entire stocks of HEU and civilian and military plutonium.[13]

A 1993 United Nations General Assembly resolution proposed a fissile material cut-off treaty (FMCT), and a negotiating mandate was agreed in 1995 at the Conference

[7] For a description of the main provisions of the NPT and a list of the parties see annex A in this volume. The full text of the NPT is available at URL <http://disarmament.un.org/wmd/npt/npttext.html>.

[8] There are 3 confirmed nuclear weapon states (those that have openly tested nuclear weapons) that are not party to the NPT: India, North Korea and Pakistan. Israel is an unconfirmed but de facto nuclear weapon state not party to the NPT. On the nuclear forces of all 9 nuclear weapon states see appendix 12A.

[9] These declarations are published by the International Atomic Energy Agency (IAEA) as additions to INFCIRC/549. See IAEA, URL <http://www.iaea.org/Publications/Documents/Infcircs/>.

[10] Albright, D., Berkhout, F. and Walker, W., SIPRI, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (Oxford University Press: Oxford, 1997), pp. 38, 68, 76, 80.

[11] US Department of Energy, 'Declassification of the United States total production of highly enriched uranium', Fact sheet, Washington, DC, 27 June 1994; and US Department of Energy, 'Declassification of today's highly enriched uranium inventories at Department of Energy laboratories', Fact sheet, Washington, DC, 27 June 1994—both available at URL <http://www.osti.gov/opennet/forms.jsp?formurl=document/press/pcconten.html>; and US Department of Energy (DOE), *Plutonium—The First 50 Years: United States Plutonium Production, Acquisition, and Utilization from 1944 through 1994*, DOE/DP-0127 (DOE: Washington, DC, 1996).

[12] US Department of Energy (DOE), *Uranium—Striking a Balance: A Historical Report on the United States HEU Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996* (DOE: Washington, DC, 2001).

[13] British Ministry of Defence, *Strategic Defence Review*, Cm 3999 (Stationery Office: London, 1998), URL <http://www.mod.uk/DefenceInternet/AboutDefence/CorporatePublications/PolicyStrategyandPlanning/StrategicDefenceReview.htm>, para. 72.

Table 12C.1. Global stocks of highly enriched uranium[a]

Country	National stockpiles (93% enriched equivalent, tonnes)	Production status	Comments
China	22 ± 5.5	Stopped 1987–89	
France	33 ± 6.6	Stopped early 1996	
India	0.2 ± 0.1	Continuing	
Pakistan[b]	1.3 ± 0.2	Continuing	
Russia[c]	770 ± 300	Stopped 1987 or 1988	Includes 100 tonnes assumed to be reserved for naval and other reactor fuel; does not include 215 tonnes to be blended down
UK[d]	23.4 (declared in 2002)	Stopped 1963	
USA[e]	495 (declared)	Stopped 1992	Includes 128 tonnes reserved for naval and other reactor fuel; Does not include 139 for blend-down, or for disposition as waste
Non-nuclear weapon states[f]	~10		
Total	**~1325 ± 310**		**Not including 354 tonnes to be blended down**

[a] Estimates are for the end of 2003 but the blending down of excess Russian and US weapon HEU up to late 2006 has been taken into account. Totals are rounded to nearest 5 tonnes.

[b] This figure assumes production at a rate of 0.1 tonnes per year between 2003 and 2006.

[c] As of 1 Oct. 2006, 285 tonnes of Russia's weapon-grade HEU had been blended down. The estimate shown for the Russian reserve for naval reactors is not based on any public information.

[d] This figure includes 21.9 tonnes of HEU as of 31 Mar. 2002, the average enrichments of which were not given. The UK declared 1.5 tonnes of civilian HEU to the IAEA as of the end of 2005.

[e] The amount of US HEU is given in actual tonnes, not 93% enriched equivalent. As of 30 Sep. 1996 the USA had an inventory of 740.7 tonnes of HEU containing 620.3 tonnes of U-235 and had declared 174 tonnes with approximately 70-per cent average enrichment to be excess. An additional 20 tonnes were declared excess in 2005, an amount that was increased to 52 tonnes in 2006. As of the end of 2006, the USA had blended down 87 tonnes of HEU.

[f] This figure does not include HEU originally enriched to 20–26% in spent fast-reactor fuel in Kazakhstan.

Sources: Institute for Science and International Security, 'Global stocks of nuclear explosive materials', Dec. 2003, URL <http://www.isisonline.org/global_stocks/end2003/tableofcontents.html>; Albright, D., Berkhout, F. and Walker, W., SIPRI, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford University Press: Oxford, 1997), p. 80, table 4.1; **Russia**: United States Enrichment Corporation, 'Megatons to megawatts', URL <http://www.usec.com>; **UK**: British Ministry of Defence, 'Historical accounting for UK defence highly enriched uranium', London, Mar. 2006, URL <http://www.mod.uk/DefenceInternet/AboutDefence/CorporatePublications/HealthandSafetyPublications/Uranium>; International Atomic Energy Agency (IAEA), INFCIRC/549/Add.8/9,

15 Sep. 2006, URL <http://www.iaea.org/Publications/Documents/Infcircs/>; **USA**: US Department of Energy (DOE), *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* (DOE: Washington, DC, 2001); Presentation by Robert George and Dean Tousley, US Department of Energy, 'US Highly Enriched Uranium Disposition', to the Nuclear Energy Institute Fuel Supply Forum, 24 Jan. 2006—available at URL <http://www.pogo.org/m/hsp/Y12/appendix-F.pdf>; Statement by William Tobey, Deputy Administrator for Defence Nuclear Nonproliferation, National Nuclear Security Administration, US Department of Energy, before the House Government Reform Committee Subcommittee on National Security, Emerging Threats, and International Relations, 26 Sep. 2006—available at URL <http://www.gsinstitute.org/docs/SNS_Congressional_Transcript.pdf>; **Non-nuclear weapon states**: International Atomic Energy Agency (IAEA), *Annual Report 2005* (IAEA: Vienna, 2006), table A20.

on Disarmament.[14] One of the 13 steps agreed to by the NPT nuclear weapon states at the 2000 NPT Review Conference was to begin talks on a 'non-discriminatory, multilateral and international effectively verifiable treaty banning the production of fissile material for nuclear weapons' and reach agreement within five years.[15] If nuclear disarmament is ever to be carried towards completion, all states with nuclear weapons will eventually have to declare to the IAEA or some similar international institution their entire stocks of fissile material by amount, form and location. There are obvious benefits for a country to prepare such a declaration as soon as possible, not least for itself, because reconstruction of the history of its fissile-material production may be based on ephemeral and inadequate records, the interpretation of which will require the assistance of production workers who will become less available with time. A 2006 report on Britain's HEU stocks describes the problems that its authors encountered with original records:

> This review has been conducted from an audit of annual accounts and the delivery/receipt records at sites. A major problem encountered in examining the records was that a considerable number had been destroyed for the early years of the programme. . . . Even where records have survived, other problems have been encountered, including: . . . [distinguishing] between new make and recycled HEU . . . some early records make no specific mention of waste and effluent disposals . . . [and for] some records . . . assessments had to be made to establish units. Other records do not identify quantities to decimal places and may have been rounded. . . . [and] in some cases no indication of enrichment value was available. Average figures were used, or knowledge of the process used to assure that the material was indeed HEU.[16]

The British and US precedents show that it is possible to make substantial declarations about fissile stocks without serious negative consequences. To date, however, none of the other nuclear weapon states has made comparable declarations. Published estimates of their stocks of fissile materials produced for weapons are made by independent non-governmental analysts and have substantial levels of uncertainty. The most complete compilation of publicly available data and estimates of global pro-

[14] On the FMCT see chapter 12.

[15] 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, Final document, New York, 19 May 2000, URL <http://disarmament2.un.org/wmd/npt/final doc.html>.

[16] British Ministry of Defence, 'Historical accounting for UK defence highly enriched uranium', London, Mar. 2006, URL <http://www.mod.uk/DefenceInternet/AboutDefence/CorporatePublications/HealthandSafetyPublications/Uranium>, p 5.

duction and consumption of fissile materials can be found in the 1996 SIPRI study by David Albright, Frans Berkhout and William Walker.[17] Albright and his colleagues at the Institute for Science and International Security have regularly updated this information.[18] The figures below are based largely on this work.

Highly enriched uranium

As of mid-2006, the global stockpiles of HEU totalled roughly 1025–1625 tonnes (see table 12C.1) plus about 350 tonnes of HEU excess to weapon requirements that will be blended down to low-enriched uranium (LEU).[19] More than 99 per cent of this material is in the possession of the five NPT-signatory nuclear weapon states. The only states believed to be currently producing HEU are Pakistan (for weapons) and India (for naval-reactor fuel). Their estimated production rates are approximately 100 kg per year each.[20] France, Russia, the UK and the USA use HEU to fuel submarine and ship- propulsion reactors, although France is transferring to LEU fuel for this purpose.[21] During the cold war, the Soviet Union and the USA each used more than 2 tonnes of HEU per year for this purpose,[22] and today, Russia and the USA annually use about 1 tonne and 2 tonnes of weapon-grade-equivalent HEU, respectively.[23] The Soviet Union and the USA have also used—and Russia still uses—HEU for other military purposes, including to fuel plutonium and tritium production reactors.

HEU is also used to fuel civilian research reactors as well as Russia's fleet of nine nuclear-powered civilian vessels—eight icebreakers and one transporter ship—that ply the country's northern seaways.[24] As part of the Atoms for Peace programme, the Soviet Union/Russia and the USA have been supplying HEU to many countries for civilian research reactors and medical-isotope production since the 1950s. Most civilian HEU is in the NPT-signatory nuclear weapon states, but more than 10 tonnes is in non-nuclear weapon states.[25] Roughly 50 tonnes of the HEU shown in table 12C.1 is

[17] Albright, Berkhout and Walker (note 10).

[18] Institute for Science and International Security (ISIS), 'Global stocks of nuclear explosive materials', Dec. 2003, URL <http://www.isis-online.org/global_stocks/end2003/tableofcontents.html>.

[19] LEU is uranium enriched in U-235 to less than 20%.

[20] Mian, Z. et al., *Fissile Materials in South Asia and the Implications of the US–India Nuclear Deal*, (Princeton University: Princeton, N.J., Sep. 2006), URL <http://www.fissilematerials.org/southasia.pdf>. Israel may also have been producing HEU using centrifuge technology since 1979 or 1980 and a laser-isotope enrichment process since 1981. Barnaby, F., *The Invisible Bomb: The Nuclear Arms Race in the Middle East* (IB Tauris: London, 1989), p. 40.

[21] Ma, C. Y. and von Hippel, F., 'Ending the production of HEU for naval reactors', *Nonproliferation Review*, vol. 8 no. 1 (spring 2001), pp. 86–107.

[22] Albright, Berkhout and Walker (note 10), pp. 88, 112.

[23] Most of Russia's nuclear submarines are believed to be fuelled by uranium enriched to 21–45%. Ma and von Hippel (note 20).

[24] See International Atomic Energy Agency, The National Report of the Russian Federation on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, Moscow, 2006, URL <http://www-ns.iaea.org/conventions/waste-jointconvention.htm>, p. 14. Sea trials of the newest Russian icebreaker, the *50 Let Pobedy* [50 Years of Victory], took place in Jan. 2007. See Novosti, 'Russia tests nuclear icebreaker on open sea', 23 Feb. 2007, URL <http://en.rian.ru/russia/20070131/59989100.html>.

[25] International Atomic Energy Agency (IAEA), *Annual Report 2005* (IAEA: Vienna, 2006). Table A20 shows that 19.4 tonnes of HEU are under IAEA safeguards in the non-nuclear weapon states. An unofficial breakdown by the Institute for Science and International Security shows that about 11 tonnes of this material was in Kazakhstan—mostly in fresh and spent fuel associated with the shut-down

in the fuel cycles of civilian research reactors worldwide and of Russia's nuclear-powered civilian vessels.[26] Even though this material currently represents only a small percentage of the global total, it would be sufficient for about 1000 gun-type nuclear weapons and more than twice as many implosion-type weapons. Also, this HEU is located at more than 100 sites, many of which are inherently difficult to secure. This civilian HEU is currently the object of a global clean-out campaign in which research reactors are being converted to LEU and excess civilian HEU is being blended down. This programme is, however, far from comprehensive.[27]

The global stock of HEU is shrinking. In 1993 Russia contracted for 500 tonnes of 90 per cent enriched uranium in redundant warheads to be blended down to LEU with 4–5 per cent U-235 to be sold to the USA for use as power-reactor fuel.[28] As of 31 December 2006, 292 tonnes had been blended down, the equivalent of almost 11 700 nuclear bombs.[29] In 1994 the USA similarly declared 174 tonnes of its weapon-grade HEU to be excess[30] and began to blend down most of it to LEU for use as fuel in US power reactors. As of July 2006, about 87 tonnes had been blended down.[31]

In late 2005 the USA declared an additional 200 tonnes of HEU to be excess. However, only 52 tonnes of this material will be blended down to LEU. Of the remainder, 128 tonnes of weapon-grade uranium will be reserved for British and US naval-reactor fuel, and 20 tonnes for space reactors and research reactors.[32] If Russia has similarly reserved the equivalent of 100 tonnes of weapon-grade uranium for future naval-reactor use, this would leave 370–970 tonnes of HEU in Russia's weapon stockpile and 320 tonnes in the US weapon stockpile.

If Russia and the USA reduced their stocks of nuclear warheads to 1000 each—as many analysts believe they could before expecting other countries to join them in similar disarmament measures[33]—then they would each only require about 30 tonnes

BN-350 fast-neutron power and desalination reactor whose fresh fuel was enriched to up to 26%. URL <http://www.isis-online.org/global_stocks/end2003/civil_heu_watch2005.pdf>; In 2005, the Nuclear Threat Initiative announced that the unused BN-350 fresh fuel (containing 2.9 tonnes of HEU) had been blended down. Nuclear Threat Initiative (NTI), 'Government of Kazakhstan and NTI mark success of HEU blend-down project', Press release, 8 Oct. 2005. The U-235 in the spent BN-350 fuel is probably mostly fissioned down to less than 20% enrichment.

[26] Glaser, A. and von Hippel, F., 'Global cleanout: reducing the threat of HEU-fueled nuclear terrorism', *Arms Control Today*, Jan./Feb. 2006, pp. 18–23.

[27] Glaser and von Hippel (note 25).

[28] Russian–US Agreement Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons, signed on 18 Feb. 1993 at Washington, DC.

[29] US Enrichment Corporation, 'Progress report: US–Russian megatons to megawatts program', 31 Dec. 2006, URL <http://www.usec.com/v2001_02/HTML/Megatons_status.asp>.

[30] In 2001 this number was revised to 178 tonnes, but more recent statements by the US Department of Energy (DOE) quote the earlier quantity of 174 tonnes. US DOE (note 12), p. 2.

[31] Tobey, W., Deputy Administrator for Defense Nuclear Nonproliferation, US National Nuclear Security Administration, testimony before the US House Government Reform Committee Subcommittee on National Security, Emerging Threats, and International Relations, 26 Sep. 2006.

[32] Presentation by Samuel Bodman, US Secretary of Energy, to the 2005 Carnegie International Non-proliferation Conference, 7–8 Nov. 2005, URL <http://www.carnegieendowment.org/static/npp/2005 conference/2005_conference.htm#Bodman/>. Bodman originally announced that 160 of the 200 tonnes would be reserved for naval-reactor fuel. However, 40 of the 160 tonnes was later found to be unsuitable for that use. Presentation by Robert George and Dean Tousley, US Department of Energy, 'US Highly Enriched Uranium Disposition', to the Nuclear Energy Institute Fuel Supply Forum, 24 Jan. 2006—available at URL <http://www.pogo.org/m/hsp/Y12/appendix-F.pdf>.

[33] Feiveson, H. (ed.), *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-alerting of Nuclear Weapons* (Brookings: Washington, DC, 1999), pp. 136–37.

Table 12C.2. Global stocks of separated plutonium

Country	Military stocks, as of December 2005 (tonnes)	Military production status	Civilian stocks as of December 2005, unless indicated (tonnes)
Belgium	0		3.3 in Belgium + 0.4 abroad (end of 2004)
China	4 ± 2	Stopped in 1991	0
France	5 ± 1.25	Stopped in 1994	81.2 (includes 30 foreign owned)
Germany	0		20–25 in France, Germany and the UK
India[a]	0.52	Continuing	5.4
Israel	0.45 ± 0.11	Continuing	0
Japan	0		5.9 in Japan + a total of 38 in France and the UK
North Korea	0.035 ± 0.018	Continuing	0
Pakistan	0.064	Continuing	0
Russia[b]	145 ± 25 (34–50 declared excess)	Effectively stopped in 1997	41.2
Switzerland	0		Up to a total of 2 in France and the UK
UK	7.6 (4.4 declared excess)	Stopped in 1989	104.9 (includes 27 foreign owned and 1 abroad)
USA[c]	92 (45 declared excess)	Stopped in 1988	0
Totals	**~255 ± 28 (up to 100 declared excess)**		**~245**

[a] In 2005 US President George W. Bush and India's Prime Minister Mohanman Singh proposed that India separate its military and civilian nuclear activities and submit its civilian nuclear activities to IAEA monitoring in exchange for access to materials and technology in the international market to support its civilian nuclear programme. Consequently, India has proposed to include in the military sector much of the plutonium separated from India's spent power-reactor fuel that is labelled civilian here.

[b] The military plutonium holdings of the NPT-signatory nuclear weapon states were unchanged between 2003 and 2005, except for Russia, which is producing about 1.2 tonnes of weapon-grade plutonium annually in 3 production reactors that continue to operate because they also produce heat and electricity for nearby communities. Russia has committed not to use this material for weapons.

[c] In its IAEA INFCIRC/549 statement of 4 Nov. 2005, the USA declared as civilian stocks a total of 45 tonnes of material described as plutonium contained in unirradiated MOX fuel or other forms, and unirradiated separated plutonium held elsewhere.

Sources: Institute for Science and International Security (ISIS), 'Global stocks of nuclear explosive materials', Dec. 2003, URL <http://www.isis-online.org/global_stocks/end2003/tableofcontents.html>; Military production status: Albright, D., Berkhout, F. and Walker, W., SIPRI, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (Oxford University Press: Oxford, 1997); Civilian stocks (except for India): declarations by country to the International Atomic Energy Agency (IAEA) under INFCIRC/549, 31 Mar 1998, URL <http://www.iaea.org/Publications/Documents/Infcircs/index.html>; **India:** Estimate based on assuming 50% of India's accumulated heavy-water reactor spent fuel has been reprocessed. Mian, Z. et al., *Fissile Materials in South Asia and*

the Implications of the US–India Nuclear Deal (Princeton University: Princeton, N.J., Sep. 2006), URL <http://www.fissilematerials.org/ipfm/site_down/ipfmresearchreport.pdf>; **North Korea**: Albright, D. and Brannan P., *The North Korean Plutonium Stock mid-2006* (Institute for Science and International Security: Washington, DC, 26 June 2006). **Russia**: US–Russian Plutonium Management and Disposition Agreement, signed at Moscow, 4 June 2000.

of HEU for weapons, including material used for research and development (R&D) and in working inventories. On this scale, the 250 or so tonnes of HEU that the USA and Russia have so far kept in reserve for naval-propulsion and other reactors is a huge amount. This suggests that the question of HEU-fuelled reactors will have to be dealt with before it can become politically feasible to make such deep cuts in the stockpiles of weapon-grade HEU.

Separated plutonium

The global stockpile of separated plutonium is a little over 500 tonnes. It is divided almost equally between weapon and civilian stocks, but it is all weapon-usable. It is held mostly in nuclear weapon states, but Japan and a few non-nuclear weapon states in Europe also have significant stocks (see table 12C.2).

France, the UK and the USA have officially announced that they have stopped producing and separating plutonium for use in weapons, and China has given unofficial indications to that effect. Russia continues to produce about 1.2 tonnes of separated weapon-grade plutonium per year as an unwanted by-product of the continued operation of three plutonium-production reactors, which supply heat and power to local populations. Russia and the USA are cooperating on a project to refurbish and build coal-fired district heating plants to make it possible to shut down these reactors.[34] To the best of the authors' knowledge, India, Israel, North Korea and Pakistan have not stopped their production of plutonium for weapons.

Russia and the USA own virtually all of the world's stock of military plutonium: 120–170 and 92 tonnes, respectively. Russia has declared 34–50 tonnes of weapon plutonium as excess, and the USA has declared as excess 45 tonnes of government-owned plutonium.[35] However, they could declare considerably more. Assuming that in the average Russian or US warhead there is 4 kg of plutonium, each country would require about 30 tonnes of weapon-grade plutonium to support the roughly 6000 warheads that they are each expected to retain up to 2012, including R&D and process inventories. Thus, Russia and the USA could declare as excess over half and about one-third, respectively, of their remaining stockpiles. If they reduced the number of

[34] Nuclear Threat Initiative (NTI), 'Plutonium production reactor shutdown,' URL <http://www.nti.org/e_research/cnwm/ending/plutonium.asp/>.

[35] At their 2 Sep. 1998 summit, US President Bill Clinton and Russian President Boris Yeltsin declared the intentions of the USA and Russia to 'remove by stages approximately 50 tonnes of plutonium from their nuclear weapons programs, and to convert this material so that it can never be used in nuclear weapons'. However, because only 34 tonnes of the US material declared excess was from its weapon programme, the US–Russian Plutonium Management and Disposition Agreement, signed at Moscow on 1 Sep. 2000, covered only 34 tonnes each. In its Nov. 2005 INFCIRC/549 statement to the International Atomic Energy Agency the USA declared as civilian stocks a total of 45 tonnes, described as 'plutonium contained in unirradiated MOX fuel or other forms' and 'unirradiated separated plutonium held elsewhere'. It also declared excess 7.5 tonnes of plutonium in government-owned spent fuel.

their nuclear weapons to 1000 each, Russia and the USA would require perhaps only 5 tonnes of weapon-grade plutonium each.[36]

Large quantities of plutonium have been separated from civilian spent fuel in reprocessing plants in a few countries. Some of this plutonium has been mixed with uranium and then fabricated into mixed-oxide (MOX) fuel and used in light-water reactors (LWRs).[37] However, most of it remains stockpiled in reprocessing plants at La Hague in France, Sellafield in the UK and at the Mayak plant in Ozersk, Russia. A similarly large stockpile is expected to build up at Japan's new Rokkasho Reprocessing Plant. The global total of separated civilian plutonium is about 250 tonnes, about as much as has been produced for weapons, and is still growing.

The fact that the amount of civilian separated plutonium already exceeds the amount of weapon plutonium that has not been declared excess could complicate future negotiations on nuclear arms reductions if the issue of eliminating additional excess weapon plutonium is confronted.

III. The production and disposition of fissile materials

The production of HEU and plutonium both start with natural uranium. HEU is produced by enriching natural uranium to increase the percentage of U-235. Plutonium is produced in nuclear reactors through the exposure of U-238 to neutron radiation and is subsequently separated in a reprocessing operation. The five nuclear weapon states party to the NPT have produced both weapon-grade uranium and plutonium. India, Israel and North Korea have produced mainly plutonium, and Pakistan mainly HEU. The potential for production of HEU and plutonium is also inherent in the civilian nuclear fuel cycle.

Highly enriched uranium production

Since natural uranium contains only about 0.7 per cent of the chain-reacting U-235 and about 99.3 per cent of the non-chain-reacting U-238, it has to be enriched in U-235 to be usable in nuclear weapons. Natural uranium must also be enriched in order to fuel LWRs, but only to 3–5 per cent U-235, which is not weapon-usable.

The isotopes U-235 and U-238 are chemically almost identical, differing in weight by only about 1 per cent, which means that they are very difficult to separate either chemically or physically. Only a small number of states possess the enrichment capacity to separate these isotopes from LWR fuel on a scale sufficient to make nuclear weapons. However, even a small enrichment plant such as the one that Iran proposes to build at Natanz, which is designed to fuel only a single 1000 megawatts-electric (MW(e)) power reactor, could make enough HEU for tens of nuclear bombs a year.[38]

[36] This estimate assumes 4 kg of plutonium per warhead and a working inventory and R&D stock of about 20%.

[37] LWRs use ordinary water to slow the neutrons in the nuclear reaction and to cool the reactor core.

[38] In any enrichment facility, the feed (e.g. natural uranium) is split into 2 streams: the product stream enriched in U-235, and the waste (or 'tails') stream depleted in U-235. The work required is measured in separative work units (SWU). Similarly, the capacity of enrichment facilities is commonly measured in SWU per year (SWU/yr). Thus, for example, if 0.2% of the U-235 is left in the depleted uranium, it takes about 150 tonnes of natural uranium feed and 130 000 SWU to produce 20 tonnes per year of uranium enriched to 4 % U-235, a typical annual fuel requirement for a 1000 MW(e) LWR reactor. For 0.3% U-235 in the depleted uranium, a plant with a separative capacity of 130 000 SWU/yr could use the

Thus, the uranium feed and the enrichment capacity required to sustain even a small civil nuclear power programme based on LWRs would offer a platform for a significant weapon programme.

There are several demonstrated methods for enriching uranium, but today the two main techniques that are used on a commercial scale are gaseous diffusion and gas centrifuges. France and the USA still operate gaseous diffusion plants but both countries plan to switch to more economical gas centrifuge enrichment technology. Table 12C.3 shows the current operational status of enrichment facilities worldwide.

In a modern gas centrifuge, uranium is fed into a rotor in gaseous form (uranium hexafluoride, UF_6) and is rotated at enormous speeds so that the UF_6 is pressed against the wall of the rotor with more than 100 000 times the force of gravity. The centrifugal force pushes the heavier U-238 closer to the wall than the lighter U-235. The gas closer to the wall becomes depleted in U-235, whereas the gas closer to the axis of the rotor is enriched in U-235. This effect is exploited to separate the two isotopes.

Both the throughput of material and the enrichment achieved by a single machine are very small, so the process is repeated tens of times in a system of hundreds or thousands of interconnected centrifuges (a 'cascade') to produce uranium enriched to the 3–5 per cent level used in most LWRs (the most common type of reactor). If the cascade is extended to three times as many stages, or the uranium is recycled through the cascade three or four times, then weapon-grade uranium can be produced.

From a non-proliferation perspective, centrifuge technology has two major disadvantages relative to gaseous diffusion technology. First, the inventory in a centrifuge plant is only tens of kilograms, while it is more than 1000 tonnes in a large gaseous diffusion plant. This means that it could take only days to reconfigure and refill a centrifuge cascade for HEU production, while it would take months in the case of a gaseous diffusion plant. This makes centrifuge plants more susceptible to a 'breakout' scenario, in which peaceful technology is quickly converted to weapon use.

Second, clandestine centrifuge facilities are virtually impossible to detect with remote sensing techniques. A centrifuge plant with a capacity to make enough HEU for a bomb or two per year could be small and indistinguishable from many other industrial facilities. Furthermore, unlike gaseous diffusion enrichment plants, which require huge amounts of electric power to operate, centrifuge plants have low power consumption and therefore no unusual thermal signatures compared to other types of factories with comparable floor areas. Leakage of UF_6 to the atmosphere from centrifuge facilities is also minimal (and therefore difficult to detect) because the gas in the pipes is below atmospheric pressure. Air therefore leaks into the centrifuges rather than the UF_6 leaking out.[39]

From a technical perspective, the disposal of HEU is simple and straightforward. The material can be blended down to LEU by mixing it with depleted, natural or slightly enriched uranium. As noted above, both Russia and the USA are blending down some of their excess weapon-grade uranium. This process cannot be reversed

same amount of natural uranium feed to produce about 650 kg/year of weapon-grade uranium (93% U-235). For an extensive technical overview of uranium enrichment and proliferation risks see Krass, A. S. et al., SIPRI, *Uranium Enrichment and Nuclear Weapon Proliferation* (Taylor & Francis: London, 1983), URL <http://www.sipri.org/contents/publications/Krass83.html>.

[39] A small amount of UF_6 does leak out when the containers are connected to and disconnected from the cascade.

Table 12C.3. Significant uranium enrichment facilities and capacity worldwide, as of December 2005

Country	Facility name/ location	Type	Status	Enrichment process[a]	Capacity (thousands SWU/yr)[b]
Brazil	Resende Enrichment	Civilian	Under construction	GC	120
China	Lanzhou 2	Civilian	Operational	GC	500
	Shaanxi Enrichment Plant	Civilian	Operational	GC	500
France	Eurodif (Georges Besse)	Civilian	Operational	GD	10 800
	Georges Besse II	Civilian	Planned	GC	7 500
Germany	Urenco[c] Deutschland	Civilian	Operational	GC	1 800/4 500
India	Rattehali	Military	Operational	GC	4–10
Iran	Natanz	Civilian	Under construction	GC	100–250
Japan	Rokkasho Enrichment Plant	Civilian	Operational	GC	1050
Netherlands	Urenco Nederland	Civilian	Operational	GC	2 500/3 500
Pakistan	Kahuta	Military	Operational	GC	15–20
Russia	Angarsk	Civilian	Operational	GC	2 350
	Novouralsk	Civilian	Operational	GC	12 160
	Seversk	Civilian	Operational	GC	3 550
	Zelenogorsk	Civilian	Operational	GC	7 210
UK	Capenhurst	Civilian	Operational	GC	4 000
USA	Paducah	Civilian	Operational	GD	11 300
	Piketon, Ohio	Civilian	Planned	GC	3 500
	Portsmouth	Civilian	Standby	GD	7 400
	Eunice, NM (LES/Urenco)	Civilian	Planned	GC	3 000

[a] GC = gas centrifuge; GD = gaseous diffusion. Apart from some laboratory facilities, all enrichment facilities today use the GD or GC process.

[b] SWU/yr = Separative work units per year: a SWU is a measure of the effort required in an enrichment facility to separate uranium of a given content of uranium-235 into 2 components, 1 with a higher and 1 with a lower percentage of uranium-235.

[c] Capacities for Urenco facilities also show scheduled expansions.

Sources: Except where indicated below, enrichment capacity data are based on International Atomic Energy Agency (IAEA), Nuclear Fuel Cycle Information System (NFCIS), Feb. 2006, URL <http://www-nfcis.iaea.org/Default.asp>; **China**: IAEA, *Country Nuclear Fuel Cycle Profiles*, 2nd edn, (IAEA: Vienna 2005); **India**: Ramana, M. V., 'An estimate of India's uranium enrichment capacity', *Science & Global Security*, vol. 12 (2004); **Iran**: Estimates for the Natanz facility assumes 50 000 machines with a capacity of 2–5 SWU/yr each. Hibbs, M., 'Current capacity at Natanz Plant about 2500 SWU/year, data suggest,' *Nuclear Fuel*, 31 Jan. 2005; **Pakistan**: Albright, D., Berkhout, F. and Walker, W., SIPRI, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford University Press: Oxford, 1997); **Russia**: International Business Relations Corporation, *Russian Enrichment Industry, State & Prospects. Annual Report 2004* (Department of Nuclear Power & Nuclear Fuel Cycle: Moscow, 2005), Fig. 5.1 (data for 2000–10); **USA**: Estimates for planned facilities based on Nuclear Regulatory Commission, 'Gas centrifuge enrichment facility licensing', 25 Aug. 2006, URL <http://www.nrc.gov/materials/fuel-cycle-fac/gas-centrifuge.html>.

without re-enrichment. It is economically attractive since the product (LEU) can be sold for use as commercial reactor fuel at a price several times higher than the cost of the blending-down process.

Plutonium production

Plutonium is produced in nuclear reactors. Almost all reactors dedicated to the production of plutonium for weapons use natural uranium as fuel. In such reactors, about 0.9 grams of plutonium are produced per gram of U-235 fissioned or, almost equivalently, per megawatt-day. For example, India's CIRUS research reactor, which generates 40 MW(t), would—at 70 per cent capacity—produce about 9.2 kg of weapon-grade plutonium annually.[40]

Plutonium is also produced in civilian power reactors. In LWRs the net plutonium production is only 0.2–0.3 g of plutonium per megawatt-day, because most of the plutonium is fissioned *in situ* during its long residence in the reactor core. A 1000-MW(e) (3000-MW(t)) LWR, operating at 90 per cent of its capacity, produces about 250 kg of plutonium per year. Because the burn-up of the fuel is much higher than in production reactors, more than 40 per cent of the plutonium produced consists of heavier plutonium isotopes.

In heavy-water reactors (HWRs), which use water enriched in deuterium and are fuelled with natural uranium, production of plutonium per megawatt-day is about twice as high as in LWRs and the fraction of heavier isotopes in the plutonium is smaller—about 25 per cent. CANDU (Canadian Deuterium–Uranium) reactors, the dominant HWR type, are refuelled continuously, instead of every 18–24 months as in the case of LWRs. This means that international monitoring of the fuel is more costly.

Global civil nuclear capacity grew rapidly during the 1970s and 1980s. Later, public opposition, high costs, unresolved waste issues and the 1979 Three Mile Island and 1986 Chernobyl accidents led to a sharp decline in new orders for nuclear power plants worldwide. As of the end of 2006, the world nuclear capacity stood at about 370 gigawatts-electric (GW(e)), almost 90 per cent of which was in LWRs.[41]

The total spent fuel generated annually by the world's reactors is approximately 10 000 tonnes, containing about 75 tonnes of plutonium. Less than one-quarter of the spent fuel generated each year is reprocessed. The remainder is stored at reactor sites.

Several countries have produced prototype sodium-cooled reactors that, when fuelled by plutonium, can produce more fissile plutonium than they consume. When they are configured in this way, they are known as breeder reactors. The cores of such reactors are surrounded by natural or depleted uranium blankets. The plutonium that builds up in these blankets is weapon-grade, typically with a Pu-239 fraction of more than 95 per cent. Although the uranium-based spent fuel of all reactors contains substantial amounts of plutonium, as long as the plutonium remains embedded in the spent fuel along with the highly radioactive fission products, it is dilute and difficult to access. The fuel elements containing the spent fuel can only be handled remotely

[40] MW(t) refers to the total power that a reactor generates, while MW(e) refers to the electrical power that a reactor generates. Megawatt-day (MW-day) denotes the total energy that would be produced in a 24-hour period by a reactor producing power at a constant rate of 1 MW(t). The fission of 1 g of uranium or plutonium releases about 1 MW-day of energy.

[41] International Atomic Energy Agency (IAEA), IAEA Power Reactor Information System (PRIS), 19 Jan. 2007, URL <http://www.iaea.org/programmes/a2>.

Table 12C.4. Significant reprocessing facilities worldwide, as of December 2005
All facilities process light-water reactor (LWR) fuel, except where indicated.

Country	Facility name /location	Type	Status	Design capacity (tHM/yr)[a]
France	La Hague UP2	Civilian	Operational	1000
	La Hague UP3	Civilian	Operational	1000
India[b]	Trombay (HWR fuel)[c]	Military	Operational	50
	Tarapur (HWR fuel)	Unclear	Operational	100
	Kalpakkam (HWR fuel)	Unclear	Operational	100
Israel	Dimona (HWR fuel)	Military	Operational	40–100
Japan	JNC Tokai	Civilian	Operational	210
	Rokkasho	Civilian	Operational	800
Pakistan	Nilore (HWR fuel)	Military	Operational	10–20
Russia	Mayak RT-1, Ozersk (formerly Chelyabinsk-65)	Civilian	Operational	400
	Seversk (formerly Tomsk 7)	Military	Operational	6000
	Zheleznogorsk (formerly Krasnoyarsk-26)	Military	Operational	3500
UK	BNFL B205 Magnox, Sellafield (graphite-moderated reactor fuel)	Civilian	Operational	1500
	BNFL Thorp, Sellafield	Civilian	Shut down, future uncertain	900

HWR = Heavy water reactor.

[a] Design capacity refers to the highest amount of spent fuel the plant is designed to process and is measured in tonnes of heavy metal per year (tHM/yr), tHM being a measure of the amount of heavy metal—uranium in these cases—that is in the spent fuel. Actual throughput is often a small fraction of the design capacity. E.g. Russia's RT-1 plant has never reprocessed more than 130 tHM/yr and France, because of the non-renewal of its foreign contracts will soon only reprocess 850 tHM/yr. LWR spent fuel contains about 1% plutonium, and heavy-water- and graphite-moderated reactor fuel about 0.4%.

[b] As part of the 2005 Indian–US nuclear deal, India has decided that none of its reprocessing plants will be opened for IAEA safeguards inspections.

Sources: Except where indicated below, data on design capacity are based on International Atomic Energy Agency (IAEA), Nuclear Fuel Cycle Information System (NFCIS), Feb. 2006, URL <http://www-nfcis.iaea.org/>; **India**: Mian, Z. and Nayyar, A. H., 'An initial analysis of Kr-85 production and dispersion from reprocessing in India and Pakistan', *Science and Global Security*, vol. 10, no. 3 (2002) pp. 151–79; **Israel**: Estimate inferred from Albright, D., Berkhout, F. and Walker, W., SIPRI, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford University Press: Oxford, 1997); **Pakistan**: Mian and Nayyar (above); **Russia**: Estimates for Seversk and Zheleznogorsk facilities are based on Bukharin, O. A., Cochran, T. and Norris R. S., *Making the Russian Bomb: From Stalin to Yeltsin* (Westview: Boulder, Colo., 1995), pp. 280, 291; Data for plutonium concentration in spent fuel are based on Gesh, C. J. et al., 'Summary of near-term options for Russian plutonium production reactors', Pacific Northwest National Laboratory, PNL-9982, July 1994, p. 9.

owing to the very intense radiation field generated by the fission products, which makes their theft a rather unrealistic scenario.[42] Separated plutonium emits very little penetrating radiation, however, and is directly weapon usable.

Reprocessing

Separation of plutonium is carried out in a reprocessing facility. With the method that is currently used—plutonium and uranium recovery by extraction (PUREX)—spent fuel is chopped into small pieces and dissolved in hot nitric acid. The plutonium is then extracted into an organic solvent, which is mixed with the nitric acid using blenders and pulse columns and then separated with centrifugal extractors. Because all of this has to be done behind heavy shielding and with remote handling, reprocessing requires both resources and expertise. However, detailed descriptions of the process have been available in the technical literature since the 1950s.

At present, France, India, Japan, Russia and the UK are carrying out large-scale reprocessing and recovery of plutonium from civilian spent fuel (see table 12C.4). This civilian separation of plutonium stemmed originally from the interest of the industrialized countries in commercializing plutonium breeder reactors. Interest peaked in the 1970s, driven by an expectation that the world's nuclear generating capacity would grow to thousands of gigawatts by the year 2000 and approach 10 000 GW(e) in 2020.[43] Such a huge capacity could not have been supported by known reserves of high-grade uranium ore.

Efforts to commercialize plutonium breeder reactors have failed, however, because of their high cost and technical difficulties.[44] A few countries in Western Europe are therefore using their separated plutonium mixed with uranium to make MOX fuel for conventional LWRs as a substitute for standard LEU fuel. This is not a particularly economically attractive strategy because MOX fuel fabrication is costly. Furthermore, one recycle reduces the amount of plutonium by only about one-third. The spent MOX is being stored. Reprocessing continues in France and Japan largely because of local resistance to both indefinite storage of spent fuel on reactor sites and to the siting of centralized interim or long-term storage facilities.[45] However, all the

[42] E.g. consider the dose rate from a pressurized water reactor (PWR) fuel assembly to an unshielded person. A typical PWR assembly contains about 500 kg of uranium. The fuel has a burn-up of up to 50 000 MW-days per tonne and contains about 6 kg of plutonium. Even after 15 years of cooling, a person 1 metre from such a fuel assembly would receive a lethal dose of radiation in a few minutes. A person 5 m away would receive a lethal dose in a couple of hours. Lloyd, W. R., Sheaffer, M. K. and Sutcliffe, W. G., 'Dose rate estimates from irradiated light-water-reactor fuel assemblies in air', Lawrence Livermore National Laboratory, 1994, URL <http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=10137382>, p. 3. After the first decade from discharge, the dose rate declines by roughly a factor of 2 every 30 years.

[43] See e.g. US Atomic Energy Commission, 'Proposed final environmental statement on the liquid metal fast breeder reactor program', Washington, DC, 1974.

[44] A list of 11 shutdown and 8 operational fast-neutron reactors as of 1995 is given in Albright, Berkhout and Walker (note 10), p. 196. Since that time, 2 more reactors (Kazakhstan's BN-350 and France's Superphénix) have been shut down permanently, 1 (Japan's Monju) was shut down for more than a decade by a sodium fire, and France's Phénix is scheduled to be shut down. Russia's BN-600 has operated at an average of 74% of its capacity since 1980 but has been plagued with 15 sodium fires in 23 years. Bakanov, M. V., Oshkanov, N. N. and Potapov, O. A., 'Experience in operating the BN-600 unit at the Belyiyar nuclear power plant', *Atomic Energy 96*, no. 5 (2004), p. 315.

[45] See e.g. Katsuta, T. and Suzuki, T., *Japan's Spent Fuel and Plutonium Management Challenge* (International Panel on Fissile Materials: Princeton, N.J., Sep. 2006), URL <http://www.fissilematerials.org/ipfm/site_down/ipfmresearchreport02.pdf>.

foreign customers of the French, Russian and British reprocessing companies appear to be shifting to interim domestic spent fuel storage because of the high costs of reprocessing and the fact that interim storage must be found for the repatriated reprocessing waste in any case.

Russia and the UK are simply storing their separated plutonium, and Japan has delayed its plutonium-recycling programme by a decade because of local opposition, provoked in part by reports of accident cover-ups and falsified quality control information. As a result, 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 2005, the global stockpile rose from 160 tonnes to 250 tonnes, not including the plutonium declared excess for weapons use by Russia and the USA.

Japan's new reprocessing plant began operation in 2006, meaning that the growth of the global stockpile of separated civilian plutonium will continue for some time even if the UK ends its reprocessing operations by 2012, as currently planned. The USA abandoned reprocessing in the late 1970s for economic and non-proliferation reasons. The US Administration of President George W. Bush has recently embraced reprocessing, however, as part of its proposed Global Nuclear Energy Partnership.[46] This initiative—like Japan's reprocessing—is also driven principally by pressures to begin removing spent fuel from power reactor sites.[47]

Plutonium disposition

The debate on the management and irreversible disposal of separated plutonium inventories has focused primarily on the weapon plutonium declared excess by both Russia and the USA. The options were laid out in the 1990s when the US National Academy of Sciences published two extensive studies on the subject.[48] Most of the considerations are equally applicable, however, to the disposition of civilian stocks of separated plutonium that are accumulating in Europe, Russia and—soon—Japan.

One option is to store excess inventories of separated plutonium indefinitely in high-security facilities, such as that built with US assistance near the Mayak reprocessing facility in Russia,[49] and the UK's Sellafield reprocessing plant. This approach is only as effective, however, as the institution responsible for security. In 1998, a report by the Royal Society of London expressed deep concern over the fact that at some stage the UK's very large stockpile of separated civilian (but weapon-usable)

[46] See the website of the US DOE's Global Nuclear Energy Partnership at URL <http://www.gnep.energy.gov/>.

[47] See e.g. von Hippel, F., *Management of Spent Fuel in the United States: The Illogic of Reprocessing* (International Panel on Fissile Materials: Princeton, N.J., Jan. 2007), URL <http://www.ipfmlibrary.org/ipfmresearchreport03.pdf>.

[48] National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* (National Academy Press: Washington, DC, 1994); and National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (National Academy Press: Washington, DC, 1995). These studies built on analyses in an earlier article. See Berkhout, F. et al., 'Disposition of separated plutonium', *Science and Global Security*, vol. 3 (1993), pp. 161–213.

[49] See the discussion of the history of this facility, the construction of which was subsidized by the USA, in Bunn, M. and Weir, A., 'Securing nuclear warheads and materials', Nuclear Threat Initiative, Washington, DC, July 2006, URL <http://www.nti.org/e_research/cnwm/securing/mayak.asp>.

plutonium might be accessed for illicit weapon production.[50] If this is a concern in the UK, it should be a concern in any country with significant quantities of separated plutonium.

Aside from storage, all options under consideration for disposing of separated plutonium involve mixing it with fission products, either produced by neutron irradiation after fabrication into reactor fuel or through mixing with fission-product waste from reprocessing. The effectiveness of this approach is often measured by the spent-fuel standard, which was defined by the US National Academy of Sciences as the objective of making excess plutonium as inaccessible for weapon use as the much larger and growing stock of plutonium in spent fuel.[51]

One way to do this is by mixing the plutonium with uranium to make MOX fuel and then irradiating the fuel in power reactors. MOX fuel containing about 4–8 per cent plutonium mixed with depleted uranium can be used as an alternative to LEU fuel in a LWR.[52] In a second approach, the plutonium would be mixed with existing fission products in highly radioactive reprocessing waste, or with spent fuel, to create a radiological barrier.[53]

In the long term (after a century or so of cooling), the gamma-radiation field around spent fuel will die down to levels that are no longer dangerous enough to deter handling, and additional protective barriers such as deep underground storage would be required.

Russia and the USA each agreed in 2000 to eliminate 34 tonnes of weapon plutonium.[54] However, Russia agreed only on the conditions that its plutonium and most of the US plutonium be disposed of in MOX fuel and that the governments of the other members of the Group of Eight (G8) industrialized nations fund the building and operation of the necessary infrastructure in Russia to fabricate MOX fuel.[55] Implementation of the agreement was stalled for years by disputes between Russia and the USA with regard to immunity from liability of US contractors in Russia.[56] The governments of the G8 states have committed $800 million, but that is not enough to cover both the construction and operation of a MOX-fuel fabrication plant. The estimated cost of constructing the US MOX facility increased from less than $1 billion to $4.9 billion between 2002 and 2006.[57] In 2006 the US Congress began to reassess this

[50] Royal Society of London, *Management of Separated Plutonium* (Royal Society: London, 1 Feb. 1998), URL <http://www.royalsoc.ac.uk/document.asp?tip=1&id=1915>.

[51] National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* (note 47), p. 34. The US Department of Energy put the standard in different but essentially equivalent words: 'A concept to make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors'. US Department of Energy (DOE), Office of Fissile Material Disposition, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, DOE/MD-0003 Rev. 1 (DOE: Washington, DC, 1996), URL <http://www.fas.org/nuke/control/fmd/docs/PUD71996.htm>.

[52] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency, *Plutonium Fuel: An Assessment* (OECD: Paris, 1989), pp. 50–51.

[53] On the options for disposition with spent fuel see von Hippel, F. et al., 'Storage MOX: a third way for plutonium disposal?', *Science and Global Security*, vol. 10 (2002), p. 85.

[54] The US–Russian Plutonium Management and Disposition Agreement was signed at Moscow on 1 Sep. 2000.

[55] The members of the G8 are listed in the glossary in this volume.

[56] The issue was finally resolved in 2006—see chapter 12 in this volume; and US Department of Energy, Office of Public Affairs, 'US and Russia sign liability protocol', 15 Sep. 2006, URL <http://www.energy.gov/print/4160.htm>.

[57] US Department of Energy (DOE), Office of the Inspector General, Office of Audit Services, 'Status of the mixed oxide fuel fabrication facility', DOE/IG-173, Washington, DC, 21 Dec. 2005.

programme and considered the idea of decoupling the Russian and US plutonium disposition programmes and shifting the focus of the US programme to the option of immobilizing the plutonium with fission products.[58]

IV. Conclusions

At present, there are roughly 1700 tonnes of HEU and 500 tonnes of separated plutonium in the world, enough for more than 100 000 nuclear weapons. Virtually all the HEU and about half the plutonium are a legacy of the nuclear arms race of the cold war. Russia and the USA could reduce their stockpiles of weapon materials by about 90 per cent and still each have enough for 1000 nuclear warheads—roughly as many as the rest of the nuclear weapon states combined.

About 250 tonnes of plutonium has been separated from civilian spent nuclear power-reactor fuel, mostly in France, Russia and the UK. The growing stock of civilian separated plutonium will soon be significantly larger than the amount of weapon plutonium. This could complicate future negotiations on nuclear arms reductions if the issue of eliminating excess weapon plutonium is confronted.

Russia, the UK and the USA have reserved very large stocks of weapon-usable HEU for future use in their naval reactors. The USA alone has declared a naval reserve of weapon-grade uranium that is large enough to make approximately 5000 nuclear warheads. This suggests that the question of HEU-fuelled reactors will have to be dealt with before deep cuts in the stockpiles of weapon HEU become politically feasible.

There remain large uncertainties about the size of fissile material stockpiles held by various countries. Declarations of fissile material stocks and greater transparency about production histories and disposition would build confidence for further reductions in the stockpiles of weapon fissile materials and will be necessary if nuclear disarmament is to be achieved.

[58] 'House appropriators deliver blow to DOE's GNEP, MOX programs', *Nuclear Fuel*, 22 May 2006.