Appendix 13C. Multilateral control of the nuclear fuel cycle

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I. Introduction

The international community recognized at an early stage that nuclear technology was inherently 'dual-use'; that is, it could be used for both civil and military applications. In 2005 the issue of how to reconcile the development of nuclear energy with the goal of nuclear weapon non-proliferation featured prominently on the international agenda. This was highlighted in October, when it was announced that the Nobel Peace Prize for 2005 would be awarded jointly to the International Atomic Energy Agency (IAEA) and its Director General, Mohammed ElBaradei, 'for their efforts to prevent nuclear energy from being used for military purposes and to ensure that nuclear energy for peaceful purposes is used in the safest possible way'.[1]

Since the early 1940s, three types of proposal have been put forward for ways to control the spread of sensitive nuclear technology and materials.[2] One type is multilateral arrangements for the joint use, development or ownership of sensitive nuclear fuel cycle facilities.[3] Under such arrangements no individual participant would have sole control over any nuclear facilities and thus could not covertly divert them to military purposes. This type of multinational arrangement may prove to be both politically and commercially viable.

The second type of proposal has involved legal and regulatory barriers to the transfer of sensitive technologies and materials. This approach shaped the non-proliferation regime that is in place today: although nuclear facilities are owned and operated nationally, most of them are subject to certain restrictions, regulations and safeguards imposed by international treaties and agreements. The legal and political foundation of this regime was laid in the 1968 Treaty on the Non-Proliferation of Nuclear Weapons (Non-Proliferation Treaty, NPT).[4] The NPT relies on the Inter-

[1] Norwegian Nobel Committee, 'The Nobel Peace Prize for 2005', Press release, Oslo, 7 Oct. 2005, URL <http://nobelprize.org/peace/laureates/2005/press.html>.

[2] Scheinman, L., 'Control of proliferation and the challenge of sensitive nuclear technology', *Journal of Nuclear Materials Management*, vol. 33, no. 4 (summer 2005), pp. 34–35; and Rauf, T., 'Background & report of the Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle', Address to the International Conference on Multilateral, Technical and Organizational Approaches for the Nuclear Fuel Cycle Aimed at Strengthening the Non-Proliferation Regime, Moscow, 13–15 July 2005, URL <http://www.iaea.org/NewsCenter/News/PDF/rauf_report220605.pdf>.

[3] 'Nuclear fuel cycle' is defined by the IAEA as 'a system of nuclear installations and activities interconnected by streams of nuclear material'. It represents the totality of all nuclear installations and activities involved in the production of nuclear power or nuclear materials. International Atomic Energy Agency (IAEA), *IAEA Safeguards Glossary: 2001 Edition*, International Nuclear Verification Series no. 3 (2001), URL <http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf>, p. 37. See also section V of this appendix.

[4] On the NPT see chapter 13 and annex A in this volume. For the text of the treaty see URL <http://www.un.org/Depts/dda/WMD/treaty/>.

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national Atomic Energy Agency (IAEA) and its safeguards system for verification of the parties' fulfilment of their treaty obligations. The IAEA has improved its verification mechanisms over the years.[5] In addition, controls on the transfer of sensitive materials and technologies between states have been agreed by various export control regimes, including the Nuclear Suppliers Group (NSG).[6] The 2003 Proliferation Security Initiative (PSI) was launched by the United States and a group of other states to intercept illicit transfers of weapons of mass destruction (WMD), missiles and their components, including nuclear weapons and materials.[7] UN Security Council Resolution 1540 linked the nuclear non-proliferation regime and international criminal law in order to curb the access of non-state actors to sensitive materials and technologies.[8] In June 2004 the Group of Eight (G8) leading industrialized nations adopted the Action Plan on Nonproliferation, which, in particular, endorsed the work of the NSG, called for universal adherence to IAEA safeguards and reiterated the G8's commitment to the PSI.[9]

The third approach is a technical one. The known types of nuclear fuel cycle entail certain proliferation risks because they all involve the use of nuclear explosive isotopes: uranium-235, plutonium-239 or uranium-233. Many experts claim that new technologies can reduce those risks. Innovative processes are being developed that are claimed to be inherently proliferation-resistant, economically attractive and environmentally safe.

Section II examines the NPT regime and new developments in nuclear power. Section III describes the history of studies and negotiations on multilateral cooperative arrangements for the use of sensitive nuclear fuel cycle facilities. This approach was developed considerably in 2005, as described in section IV. Section V reviews proposals for the development of proliferation-resistant technologies, and section VI offers the conclusions.

II. The NPT and nuclear energy

A number of developments since 2003 have given rise to concerns about perceived weaknesses in the NPT regime. First, in early 2003 IAEA inspectors discovered that Iran had for many years failed to declare important nuclear activities, in contravention of its NPT-mandated safeguards agreement with the Agency. This led some outside observers to conclude that Iran was seeking to put into place, under the cover of a civilian nuclear power programme, the infrastructure needed to produce

[5] For a discussion of the development of IAEA safeguards see Zarimpas, N., 'Nuclear verification: the IAEA strengthened safeguards system', *SIPRI Yearbook 2000: Armaments, Disarmament and International Security* (Oxford University Press: Oxford, 2000), pp. 496–508. For the list of states with IAEA safeguards agreements in force see annex A in this volume.

[6] On the export control regimes and their participating states see the glossary and chapter 16 in this volume. On the NSG see also appendix 13B.

[7] On the PSI see Ahlström, C., 'The Proliferation Security Initiative: international law aspects of the Statement of Interdiction Principles', *SIPRI Yearbook 2005: Armaments, Disarmament and International Security* (Oxford University Press: Oxford, 2005), pp. 741–65; and the glossary in this volume.

[8] United Nations Security Council Resolution 1540, 28 Apr. 2005, available at URL <http://www.un.org/documents/scres.htm>; and Anthony, I., 'Arms control and non-proliferation: the role of international organizations', *SIPRI Yearbook 2005* (note 7), pp. 542–47.

[9] Group of Eight (G8), G8 Action Plan on Nonproliferation, Sea Island, Georgia, 9 June 2004, URL <http://www.g8.utoronto.ca/summit/2004seaisland/nonproliferation.html>.

nuclear weapons.[10] Second, also in 2003, North Korea became the first state party to withdraw from the NPT. It subsequently announced that it had built nuclear weapons using the infrastructure it had acquired, in compliance with the treaty, for peaceful purposes.[11] Evidence of the existence of an illicit international nuclear technology transfer network began to emerge publicly in October of that year, when Iran admitted to the IAEA that it had covertly imported sensitive components from Pakistan. Libya's decision in December to abandon its WMD capabilities and most of its advanced missile programmes resulted in the official disclosure of this network, led by Pakistan's most prominent nuclear scientist, Abdul Qadeer Khan.[12]

In October 2003 IAEA Director General ElBaradei noted that the performance of the NPT was 'less than optimal' and pointed out that controlling access to sensitive technologies has become increasingly difficult because technical barriers to proliferation have gradually eroded, because much of the hardware on the market is of a dual-use nature, and because the diversity of the technology makes it difficult to control procurement and sales.[13] In addition, some observers conclude that there is an inherent structural weakness in the NPT, because, in accordance with Article IV, a state has the right to develop sensitive nuclear fuel cycle capacities 'to develop research, production and use of nuclear energy for peaceful purposes', but it can then withdraw from the treaty without legal consequences, for example, in order to pursue a nuclear weapons option.[14] At the June 2004 meeting of the IAEA Board of Governors, ElBaradei announced that he had appointed an international Expert Group to explore innovative multilateral approaches to the secure development of nuclear energy.[15] The group published its recommendations in February 2005, and in May its findings and proposals were presented at the NPT Review Conference.[16] Implementation of some of the recommendations began in September 2005 (see section IV below).

Against the background of a 'battered' nuclear non-proliferation regime, in 2005 signals of a renewed interest in nuclear power on the part of various states became especially visible. Three factors were cited as influencing states' interest. First, soaring fossil fuel prices in 2005 prompted energy consumers to investigate alternative options for the production of electricity. Second, many states paid increased attention to the 1997 Kyoto Protocol and emissions of greenhouse gases. Fossil fuels are believed to be contributing to global warming by producing greenhouse gases, while emissions from nuclear energy are lower by two orders of magni-

[10] Kile, S. N., 'Nuclear arms control and non-proliferation', *SIPRI Yearbook 2004: Armaments, Disarmament and International Security* (Oxford University Press: Oxford, 2004), pp. 604–11.

[11] Kile, S. N., 'Nuclear arms control, non-proliferation and ballistic missile defence', *SIPRI Yearbook 2003: Armaments, Disarmament and International Security* (Oxford University Press: Oxford, 2003), pp. 578–91.

[12] Kile, S. N., 'Nuclear arms control and non-proliferation', and Hart, J. and Kile, S. N., 'Libya's renunciation of nuclear, biological and chemical weapons and ballistic missiles', *SIPRI Yearbook 2005* (note 7), pp. 551–55 and 629–48, respectively. On developments in 2005 see chapter 13.

[13] ElBaradei, M., 'Towards a safer world', *The Economist*, 18 Oct. 2003, p. 43.

[14] Kile (note 12), p. 573.

[15] IAEA, Introductory statement to the Board of Governors by IAEA Director General Dr Mohamed ElBaradei, DG/14062004, Vienna, 14 June 2004, URL <http://www.iaea.org/NewsCenter/Statements/2004/ebsp2004n003.html>.

[16] IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report to the Director General of the International Atomic Energy Agency* (IAEA: Vienna, 2005), URL <http://www-pub.iaea.org/MTCD/publications/PDF/mna-2005_web.pdf>. On the 2005 NPT Review Conference see chapter 13 in this volume.

tude.[17] Finally, some governments regarded nuclear power as a way to enhance their energy independence and security of supply. As stated by ElBaradei, owing to the 'diverse global roster of stable uranium producers and the small storage space required for a long term nuclear fuel supply', nuclear power is considered to be the source of electricity that is relatively independent of the international political situation.[18] The importance of this consideration was emphasized by the dispute between Russia and Ukraine over gas prices, which resulted in the temporary curtailing of supplies of Russian natural gas to Europe in January 2006.[19] In the same month there were reports of temporary cuts in the supply to Europe of Russian gas piped via Ukraine caused by extremely cold weather conditions, and there were explosions on pipelines delivering natural gas to Georgia.[20] These incidents reinforced the arguments of advocates of nuclear power that this is the most dependable source of energy.

Analysis of data on the numbers and output of future nuclear power reactors around the world shows that Asia is, and is likely to remain, the main growth area for the nuclear industry, with China, India, Japan and South Korea leading in the number of planned and proposed reactor projects (see table 13C.1). The second largest projected area of growth is Europe, where Russia has the most ambitious construction plans. In January 2006 the head of the Russian Federal Atomic Energy Agency (Rosatom), Sergey Kirienko, put forward a plan to build 40 new nuclear power reactors within the next 25 years.[21] The USA may become the third largest area of growth in the future: the 2005 Energy Policy Act includes a considerable package of incentives to encourage the construction of new nuclear power plants in the USA.[22] President George W. Bush vowed to 'start building nuclear plants again by the end of this decade'.[23] There were also signs in 2005 of a possible change of policy in favour of nuclear power in Western Europe.[24]

As shown in table 13C.1, the combined electricity generation capacity of the 168 reactors that are now under construction or planned to be built is about

[17] Organisation for Economic Co-operation and Development (OECD), 'Nuclear energy today', OECD Policy Brief, Feb. 2005, URL <http://www.oecd.org/dataoecd/32/62/34537360.pdf>, pp. 1–3. The Kyoto Protocol to the 1992 United Nations Framework Convention on Climate Change is available at URL <http://unfccc.int/resource/docs/convkp/kpeng.html>.

[18] ElBaradei, M., 'Nuclear power: a look at the future', International Conference on Fifty Years of Nuclear Power: The Next Fifty Years, 27 June 2004, URL <http://www.iaea.org/NewsCenter/Statements/2004/ebsp2004n005.html>.

[19] White, A., 'Europe seeks home-grown power solutions', Business Week Online, 5 Jan. 2006, URL <http://www.businessweek.com/ap/financialnews/D8EUKIRG4.htm>.

[20] Warner, T., 'Gazprom accuses Ukraine of restricting supplies', *Financial Times*, 23 Jan. 2006, URL <http://news.ft.com/cms/s/d5800b62-8b52-11da-91a1-0000779e2340.html>; and Chivers, C. J., 'Explosions in southern Russia sever gas lines to Georgia', *New York Times*, 23 Jan. 2006, URL <http://www.nytimes.com/2006/01/23/international/Europe/23georgia.html>.

[21] Nikol'skii, A., '$60 mlrd na AES' [$60 billion for nuclear power plants], *Vedomosti*, 23 Jan. 2006.

[22] 'US energy bill favours new build reactors, new technology', *Nuclear Engineering International*, 12 Aug. 2005, URL <http://www.neimagazine.com/storyprint.asp?sc=2030325>.

[23] The White House, Office of the Press Secretary, 'President signs Energy Policy Act', 8 Aug. 2005, URL <http://www.whitehouse.gov/news/releases/2005/08/20050808-6.html>.

[24] MacLachlan, A., 'France's common EU energy policy would include nuclear power', *Nucleonics Week*, 26 Jan. 2006; Shaikh, T., 'Blair to give his blessing to nuclear reactors as only way to cut emissions', *The Independent*, 22 Nov. 2005, URL <http://news.independent.co.uk/uk/politics/article328586.ece>; and Krägenow, T., 'Union und SPD wollen Atomausstieg verschleppen' [Union and SPD want to delay the halt to nuclear power], *Financial Times Deutschland*, 20 Oct. 2005, URL <http://www.ftd.de/pw/de/26975.html>.

Table 13C.1. Number and capacity of nuclear power reactors in the world, as of January 2006[a]

	Operating		Under construction		Planned		Proposed	
Region/state	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)
Asia	*108*	*79 590*	*16*	*11 318*	*28*	*31 932*	*47*	*32 160*
China	9	6 572	3	3 000	7	7 000	19	15 000
Taiwan	6	4 904	2	2 600	–	–	–	–
India	15	3 040	8	3 602	–	–	24	13 160
Indonesia	0	–	–	–	–	–	2	2 000
Japan	56	47 839	1	866	12	14 782	–	–
Korea, North	–	–	1	950	1	950	–	–
Korea, South	20	16 810	–	–	8	9 200	–	–
Pakistan	2	425	1	300	–	–	–	–
Viet Nam	–	–	–	–	–	–	2	2 000
Europe	*205*	*172 215*	*8*	*7 930*	*1*	*925*	*20*	*21 210*
Armenia	1	376	–	–	–	–	–	–
Belgium	7	5 801	–	–	–	–	–	–
Bulgaria	4	2 722	–	–	–	–	1	1 000
Czech Republic	6	3 368	–	–	–	–	2	1 900
Finland	4	2 676	1	1 600	–	–	–	–
France	59	63 363	–	–	–	–	1	1 600
Germany	17	20 339	–	–	–	–	–	–
Hungary	4	1 755	–	–	–	–	–	–
Lithuania	1	1 185	–	–	–	–	–	–
Netherlands	1	449	–	–	–	–	–	–
Romania	1	655	1	655	–	–	3	1 995
Russia	31	2 1743	4	3 775	1	925	8	9 375
Slovakia	6	2 442	–	–	–	–	2	840
Slovenia	1	656	–	–	–	–	–	–
Spain	9	7 588	–	–	–	–	–	–
Sweden	10	8 918	–	–	–	–	–	–
Switzerland	5	3 220	–	–	–	–	–	–
Turkey	–	–	–	–	–	–	3	4 500
UK	23	11 852	–	–	–	–	–	–
Ukraine	15	13 107	2	1 900	–	–	–	–
Middle East	–	–	*1*	*915*	*2*	*1 900*	*5*	*4 650*
Egypt	–	–	–	–	–	–	1	600
Iran	–	–	1	915	2	1 900	3	2 850
Israel	–	–	–	–	–	–	1	1 200
North America	*124*	*113 119*	–	–	*2*	*1 540*	*11*	*14 000*
Canada	18	12 599	–	–	2	1 540	–	–
Mexico	2	1 310	–	–	–	–	–	–
USA	104	99 210	–	–	–	–	11	14 000
South America	*4*	*2 836*	*1*	*692*	*1*	*1 245*	–	–
Argentina	2	935	1	692	–	–	–	–
Brazil	2	1 901	–	–	1	1 245	–	–
Africa: S. Africa	*2*	*1 800*	–	–	*1*	*165*	*24*	*4 000*
World total	**443**	**369 560**	**26**	**20 855**	**35**	**37 625**	**107**	**76 020**

[a] 'Operating' indicates that the reactor is connected to the grid; 'Under construction' means 'first concrete for reactor poured, or major refurbishment under way'; 'Planned' means 'approvals and funding in place, or construction well advanced but suspended indefinitely'; and 'Proposed' means that there is a 'clear intention but still without funding and/or approvals'.

Sources: World Nuclear Association, 'World nuclear power reactors 2004–06 and uranium requirements', 4 Jan. 2006, URL <http://www.world-nuclear.org/info/reactors.htm>; IAEA Power Reactor Information System (PRIS), 2 Mar. 2006, URL <http://www.iaea.org/programmes/a2/index.html>; and World Nuclear Association, 'Nuclear power in China', Information and Issue Brief, Dec. 2005, URL <http://www.world-nuclear.org/info/inf63.htm>.

135 gigawatts-electric (GW(e)). The construction of additional reactors will probably be announced in the near future. The total electricity generation capacity of the 443 currently operated reactors is about 370 GW(e). The fleet of operating reactors is ageing, and older reactors are being decommissioned. It remains an open question whether the future pace of construction of new reactors would be sufficient to keep up with the retirement of older plants.

III. Multilateral cooperative strategies

The idea of international control of nuclear power was first put forward in 1946, in a formal US proposal known as the Baruch Plan. The plan envisaged 'the creation of an International Atomic Development Authority, to which should be entrusted all phases of the development and use of atomic energy', including ownership or managerial control over nuclear fuel cycle activities judged to be potentially dangerous for world security, and the right to control, inspect and license all other nuclear activities.[25] This plan was dismissed, primarily by the Soviet Union, as being too far-reaching and intrusive.

The centrepiece of the Atoms for Peace plan, presented by US President Dwight D. Eisenhower at the UN General Assembly in 1953, was the creation of an international atomic energy agency 'to which the governments principally involved would make joint contributions' from their stockpiles of fissile material and natural uranium.[26] The 1956 IAEA Statute provides for the creation of an international nuclear fuel bank that could guarantee the supply of fuel to those states that need it, thus relieving them of the need to have their own facilities.[27] Article XII.A.5 of the IAEA Statute gives the Agency the right to require temporary 'deposit with the Agency of any excess of any special fissionable materials' produced for peaceful uses 'in order to prevent stockpiling of these materials'. This clause provides for the creation of an IAEA bank of plutonium or spent fuel where it could be placed under international inspection and control until it was required for use in civil nuclear power applications. Variations of these two ideas have been discussed since then.

Simultaneously with the establishment of the IAEA in 1956, the Council of Ministers of the Organisation for European Economic Co-operation approved the creation of a European reprocessing plant—Eurochemic—as a joint undertaking.[28] In the late 1950s, during the initial stages of the development of nuclear energy in European countries, international cooperation seemed to be the least risky way for the NNWS

[25] 'The Baruch Plan, Presented to the United Nations Atomic Energy Commission, June 14, 1946', NuclearFiles.org, URL <http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/arms-control-disarmament/baruch-plan_1946-06-14.htm>.

[26] Fischer, D., 'History of the International Atomic Energy Agency: the first forty years', IAEA, Vienna, 1997, URL <http://www-pub.iaea.org/MTCD/publications/PDF/Pub1032_web.pdf>, p. 9.

[27] IAEA, Statute of the IAEA, URL <http://www.iaea.org/About/statute_text.html>, Articles III.A.2 and B.3, IX, XI, XII, XIII, XIV.B.2 and E–G.

[28] Fischer (note 26), pp. 61–62.

to obtain cutting-edge reactor technology. The USA was also likely to support such solutions pending the establishment of the nuclear non-proliferation regime.[29] Eurochemic was set up by 13 member states of the European Nuclear Energy Agency (which became the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development in 1972) as an international shareholding company open for business participation with an objective to serve as the nucleus of a European reprocessing industry. It carried out an innovative research programme, trained a large number of specialists and operated an industrial pilot reprocessing plant in Mol, Belgium, commissioned in 1966.[30] Because of its small size and its situation in a competitive market, the plant was closed down in 1975. The Eurochemic company operated until 1990, with the Belgian Government progressively taking over its installations.

The Treaty establishing the European Atomic Energy Community (Euratom Treaty) was signed in 1957. A fundamental objective of Euratom is to encourage progress in the field of nuclear energy in the EU: the Euratom Supply Agency (ESA), established in the Euratom Treaty and operative since 1960, is to ensure the supply of ores, source materials and special fissile materials by means of a common supply policy based on the principle of equal access to sources of supply. No contract in the EU on nuclear supply, including purchases, sales, exchanges and enrichment, can be concluded without the consent of the ESA. It also has 'a right of option' on those materials produced in the territories of EU member states. Another fundamental objective of Euratom is to prevent the diversion of nuclear materials from peaceful to military use on EU territory by applying the system of Euratom safeguards.[31]

In 1970 the Treaty of Almelo was signed by the Federal Republic of Germany, the Netherlands and the United Kingdom, creating the Uranium Enrichment Company (Urenco).[32] The treaty formed the basis for cooperation between these three countries for the development and industrial exploitation of centrifuge uranium enrichment technology. Until September 1993 each party had a national company operating its own enrichment plant, which were all then brought together into a centrally managed international group of companies. In 2004 Urenco covered 19 per cent of world enrichment needs and had a turnover of €707 million.[33] However, multilateral arrangements of this kind can be misused: for example, A. Q. Khan diverted Urenco centrifuge technology to the Pakistani nuclear weapon programme.[34]

In 1973 France, Belgium, Spain and Sweden formed the joint stock company EURODIF. In 1974 EURODIF decided to build a large gaseous diffusion enrichment plant on the Tricastin nuclear site at Pierrelatte in France's Rhône valley. Sweden withdrew from the project in 1974. In 1975 Sweden's 10 per cent share in EURODIF

[29] Berkhout, F., *Radioactive Waste: Politics and Technology* (Routledge: London, 1991), p. 55.

[30] Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency, *History of the EUROCHEMIC Company 1956–1990* (OECD: Paris, 1996), reviewed in OECD, Nuclear Energy Agency, Press communiqué, Paris, 26 Nov. 1996, URL <http://www.nea.fr/html/general/press/1996/1996-17.html>.

[31] The Treaty establishing the European Atomic Energy Community (Euratom Treaty) entered into force on 25 Mar. 1957; see URL <http://europa.eu.int/scadplus/treaties/euratom_en.htm>, Articles 1, 2, 52–76, 80, 86–91, 171, 195 and 197.

[32] Krass, A. S. et al., SIPRI, *Uranium Enrichment and Nuclear Weapon Proliferation* (Taylor & Francis: London, 1983), p. 31, available in full text on SIPRI's website at URL <http://www.sipri.org>.

[33] Urenco, *Urenco Annual Report and Accounts, 2004*, URL <http://www.urenco.com/im/uploaded/1125054354.pdf>.

[34] Smith, C. and Bhatia, S., 'How Dr. Khan stole the bomb for Islam', *The Observer*, 9 Dec. 1979.

went to Iran as a result of an arrangement between France and Iran. The French government subsidiary company Cogema and the Iranian Government established the Sofidif (Société franco–iranienne pour l'enrichissement de l'uranium par diffusion gazeuse) enterprise with 60 per cent and 40 per cent shares, respectively. In turn, Sofidif acquired a 25 per cent share in EURODIF, which gave Iran its 10 per cent share of EURODIF.[35] Iran's agreement with EURODIF was cancelled after the 1979 Islamic Revolution. Currently, EURODIF Production is a subsidiary of the Areva Group. In 2004 the uranium enrichment market share of EURODIF was about 25 per cent.[36]

The 1974 IAEA General Conference, prompted by India's test of a nuclear explosive device in May of that year, discussed the possibility of establishing international facilities to handle spent nuclear fuel from nuclear power plants as an alternative to the development of plutonium reprocessing technologies in individual states.[37] In the same year the IAEA started the Regional Nuclear Fuel Cycle Center (RNFC) study project to assess the feasibility and advantages of such facilities.[38] It led to the discussion of RNFCs at the 1975 NPT Review Conference, which encouraged the IAEA to continue the study and secured support for it from individual states.[39] The RNFC study, completed in 1977, provided a review of the regional cooperative projects covering the entire back-end of the fuel cycle. The study was based on the assumption that world nuclear power would soon be based largely on fast reactors, but this did not happen.[40] Partially for this reason, and because of a general lack of political will, no follow-up action was taken.

On 7 April 1977 the USA proposed an International Nuclear Fuel Cycle Evaluation (INFCE) to investigate ways of strengthening the technological base of the nuclear non-proliferation regime. The INFCE Conference opened on 19 October, with the participation of 40 state representatives. INFCE touched upon all three approaches to the problem of the dual-use nature of nuclear energy (see section I).[41] It was agreed that multinationalization has the potential to limit the number of sensitive facilities, which should have a positive impact on both non-proliferation and the economical operation of the plants. However, considerable drawbacks such as the risk of leak of sensitive know-how were highlighted. By the time of its conclusion in 1980, INFCE had failed to reach consensus on important questions, including the distribution of responsibilities between the host country and foreign shareholders and assurance of supply for foreign investors. No concrete steps stemmed from this comprehensive study, but its findings have considerably influenced the debate.

[35] Krass et al. (note 32), pp. 200, 215.

[36] Areva Group, *Annual Report 2004* (Areva: Paris, Apr. 2005), p. 44.

[37] Scheinman (note 2), p. 34.

[38] Lee, B. W., 'Viable scheme for regional fuel cycle center: issues and strategies', Nuclear Cooperation Meeting on Spent Fuel and High Level Waste Storage and Disposal, Las Vegas, Nev., 7–9 Mar. 2000, URL <http://eed.llnl.gov/ncm/session4/Lee_Byong_Whi.pdf>.

[39] 'Final Declaration of NPT Review Conference', *SIPRI Yearbook 1976: World Armaments and Disarmament* (Taylor & Francis: London, 1976), p. 408.

[40] A fast reactor is one that operates mainly with neutrons in the energy range above 0.1 MeV (fast neutrons) and does not need a moderator. Fast reactors are generally designed to use plutonium fuel and can produce, through the transmutation of uranium-238, more plutonium than they consume. IAEA (note 3). On the back- and front-end of the nuclear fuel cycle, see section V of this appendix.

[41] 'Nuclear fuel cycle and nuclear proliferation', *SIPRI Yearbook 1978: World Armaments and Disarmament* (Taylor & Francis: London, 1978), p. 26; and Stein, M. et al., 'Multi- or internationalization of the nuclear fuel cycle: revisiting the issue', *Journal of Nuclear Materials Management*, vol. 32, no. 4 (summer 2004), p. 54.

Among many other concepts discussed in the INFCE framework was one that envisaged an international plutonium storage facility. To continue the examination of the issue, in 1978 the IAEA established the Committee on International Plutonium Storage (IPS) to explore possibilities for implementing the INFCE concept under Article XII.A.5 of the IAEA Statute. This is different from the RNFC approach, in which control of materials and technologies was to remain with a group of states, not the IAEA. The Committee looked into the issue until 1982, when it outlined the basis for an IPS scheme in its Final Report, but disagreements over the definition of 'excess plutonium', the nature and location of storage facility, and the mechanisms determining the release of plutonium by the IAEA led to no outcome.[42] An Expert Group on Spent Fuel Storage was convened in parallel, also with no results.

The 1978 US Nuclear Non-Proliferation Act (NNPA) provided for negotiations on the establishment of an International Nuclear Fuel Authority (INFA) with responsibility for ensuring fuel supply on reasonable terms, which could have led to the creation of the backup fuel bank. However, this initiative was not pursued.[43]

In June 1980 the IAEA established the Committee on Assurances of Supply (CAS) to explore measures to ensure a guaranteed supply of nuclear material, equipment and technology to states committed to non-proliferation and to determine the IAEA's role in this context.[44] CAS discussed various emergency and backup supply mechanisms, including the idea of multinational fuel cycle centres, but was unable to reach consensus before it was disbanded in 1987.

On 5 December 1980 the UN General Assembly established the United Nations Conference for the Promotion of International Cooperation in the Peaceful Use of Nuclear Energy (UNCPICPUNE).[45] It discussed, in particular, the concerns of developing states related to nuclear safety issues, security measures to prevent diversion, and the link between non-proliferation and assurances of supply. UNPICPUNE reaffirmed the need for international cooperation on the peaceful uses of nuclear energy but failed to result in any substantive product.

The IAEA held the International Symposium on Nuclear Fuel Cycle and Reactor Strategies on 3–6 June 1997 as another follow-up to the 1980 INFCE study. IAEA Director General Hans Blix stated there that installed nuclear capacity in 2000 had turned out to be much lower than was predicted in 1980, that fast breeder technology was not commercialized and that the closed nuclear fuel cycle had not taken hold.[46] Nonetheless, the symposium concluded that the creation of a global nuclear system in which sensitive fuel cycle activities are centralized in a few locations is still feasible; that such multilateral centres can provide both economic and non-proliferation benefits; and that international cooperation in the back-end of the nuclear fuel cycle,

[42] Rauf, T., 'Perspectives on multilateral approaches to the nuclear fuel cycle', Address to the 2004 Carnegie Nonproliferation Conference, Washington, DC, 2004, URL <http://www.ceip.org/files/projects/npp/resources/2004conference/speeches/rauf.ppt>.

[43] The NNPA also sought to limit the transfer of reprocessing technology and to curb the reprocessing of US-origin fuel abroad. Nuclear Non-Proliferation Act of 1978, URL <http://www.nti.org/db/china/engdocs/nnpa1978.htm>.

[44] Bailey, E. et al., *PPNN Briefing Book*, vol. 1, 'The peaceful uses of nuclear energy', *The Evolution of the Nuclear Non-Proliferation Regime*, 6th edn (Mountbatten Centre for International Studies, Program for Promoting Nuclear Non-Proliferation (PPNN): Southampton, 2000), URL <http://www.mcis.soton.ac.uk/Bb1Chap8.pdf>, p. 48.

[45] Bailey et al. (note 44), p. 48.

[46] IAEA, 'Nuclear fuel cycle and reactor strategies: adjusting to new realities, Contributed papers, IAEA International Symposium, Vienna, 3–6 June 1997', IAEA-TECDOC-990, 18 Dec. 1997, URL <http://www-pub.iaea.org/MTCD/publications/PDF/te_990_prn.pdf>.

including centralized disposal of the spent nuclear fuel, should be encouraged. In 2003 and 2005 the IAEA again confirmed that regional spent-fuel storage facilities are technically feasible, potentially viable economically, and advantageous in terms of non-proliferation and nuclear security, and that the real challenges to their development lay in the areas of political, social and public acceptance.[47] In 2001 and 2002 the IAEA broadened its focus on multilateralization of the fuel cycle beyond reprocessing and enrichment to include repositories for spent fuel and nuclear waste. In 2004 the Agency published its conclusions on developing multinational radioactive waste repositories.[48]

IV. Multilateral approaches to the nuclear fuel cycle

In 2003 and 2004 IAEA Director General ElBaradei gave a new impetus to studies on security in the development of nuclear energy. This was first done in his statement to the IAEA General Conference in September 2003 and developed further in October 2003, when he proposed a new approach to the problem, consisting of three parts: (*a*) the restriction of operations with highly enriched uranium (HEU) and plutonium exclusively to facilities under multinational control; (*b*) a transition to new nuclear-energy systems that by design avoid the use of materials directly usable for weapons; and (*c*) the introduction of multinational approaches to the management and disposal of spent fuel and radioactive waste.[49]

The Expert Group that was established by ElBaradei in June 2004 had a threefold mandate: (*a*) to analyse issues and options relevant for multilateral nuclear approaches (MNAs) to the nuclear fuel cycle; (*b*) to provide an overview of the incentives and disincentives for cooperation in multilateral arrangements; and (*c*) to provide a brief review of the historical and current experiences and analyses relevant to the study. The group was to set out options for a solution, but not to choose or indicate any preference for one option. Any solution that was proposed was to be concrete, inclusive and without reference to the status of specific states under the NPT.

The Expert Group concluded that past initiatives for multilateral nuclear cooperation had not produced any tangible results, for several reasons. First, proliferation concerns were not strong enough in the past. Second, most of the past initiatives lacked sufficient economic incentives. Third, concerns about assurances of supply were paramount. Finally, factors such as national pride and expectations of technological and economic spin-offs played a role in negotiations on MNAs. The Expert Group agreed that 'the case to be made in favour of MNAs is not entirely straightforward', but it tried to contribute to the development of MNAs by identifying five specific options that would be possible to introduce gradually and noted a number of pros and cons for each. All these options aim at a simultaneous increase in non-proliferation assurances and assurances of supply and services relevant to the nuclear fuel cycle.[50]

[47] Rauf (note 42); and IAEA, 'Technical, economic and institutional aspects of regional spent fuel storage facilities', IAEA-TECDOC-1482, Nov. 2005, URL <http://www-pub.iaea.org/MTCD/publications/PDF/te_1482_web.pdf>.

[48] IAEA, 'Developing multinational radioactive waste repositories: infrastructural framework and scenarios of cooperation', IAEA-TECDOC-1413, 15 Oct. 2004, URL <http://www-pub.iaea.org/MTCD/publications/PDF/te_1413_web.pdf>.

[49] ElBaradei (note 13), pp. 43–44.

[50] IAEA (note 16).

1. The first option is to reinforce existing commercial market mechanisms using assurances provided by suppliers through long-term contracts and transparent arrangements, possibly with government backing. For the front-end of the fuel cycle this could mean, for example, that a state which decided not to pursue nuclear fuel production would be offered an arrangement whereby it could lease nuclear fuel and then give it back or one in which it would be guaranteed the provision of enrichment capacities. Commercial or intergovernmental 'fuel banks' could be envisaged. At the back-end of the fuel cycle, commercial offers to store and dispose of spent fuel are possible. The major advantages of this arrangement are that it is easy to implement, does not require new facilities or further dissemination of know-how and does not imply an extra financial burden on the IAEA. The disadvantages of this approach may come from its market nature, because the costs of required idle reserve capacities may be high. In addition, the credibility of assurances provided by private firms or even by consortia of states may not seem sufficient for some.

2. The second option is to introduce international supply guarantees with IAEA participation. This is a variation of the previous option, with the IAEA acting as a guarantor of the supply. For the front-end of the fuel cycle, for example, the IAEA either could hold title to the stock of nuclear material or may have in place the mechanism to ensure that one supplier would replace another should the first fail to perform. For the back-end of the fuel cycle this could mean essentially the revival of the old idea of International Plutonium Storage (IPS), exploiting the provisions of Article XII.A.5 of the IAEA Statute. The Expert Group noted that the failure of previous ideas of this kind was due to the reluctance of states to renounce national sovereignty over separated plutonium. The international storage of spent fuel, however, could generate more interest because it is less immediately valuable, more difficult to store and less sensitive than separated plutonium. International storage of mixed oxide (MOX) fuel is also conceivable in this framework. The advantages and disadvantages of this option are similar to those of the previous option; in addition, the participation of the IAEA gives more credibility and flexibility to the whole exercise. In the case of IPS, other difficulties apply, related to the complex setup and demanding management requirements, with attending financial implications.

3. In this option, national facilities would be put under multinational control, with the participation of all states, regardless of their relationship to the NPT. This would mean the creation of new players on the market. For the front-end of the fuel cycle, EURODIF would be the most likely model for such conversion. For the back-end there are the existing examples of Eurochemic and the reprocessing of Japanese nuclear fuel in the UK. The advantages of such an arrangement include the fact that no new construction of facilities or dissemination of know-how are required, additional safeguards may be introduced where they do not exist, and the expertise of various states may be pooled. The disadvantages, especially regarding the back-end of the fuel cycle, include the difficulties of international management, low political and public acceptance, increased transportation requirements and the fact that several multinational facilities would have to be built, in more than one country, in order to provide credible assurance of supply. However, arguments for internationalization of the efforts of the nuclear industry are visible in the adjacent area of nuclear science, with its trend to consolidate future research in a few 'centres of excellence'.[51]

[51] IAEA, 'New life for research reactors? Bright future but far fewer projected', IAEA Staff Report, 8 Mar. 2004, URL <http://www.iaea.org/NewsCenter/Features/ResearchReactors/reactors20040308.html>.

4. A fourth option is to create, through voluntary agreements and contracts, multinational or regional MNAs for new facilities based on joint ownership, drawing rights or co-management. Different models have been used to operate a multinational enrichment facility at the front-end of the nuclear fuel cycle. The original arrangement of Urenco entailed the sharing of technology between the partners involved. Later, Urenco evolved into the complex 'black-box' model, in which design and assembly of centrifuges are done in the Netherlands and completed centrifuges are exported to enrichment plants in partner states. Another model is used by EURODIF: the level of investment of each partner corresponds to its percentage share of the product, but the enrichment facility is operated by only one partner—France. Joint construction of a new facility for the back-end of the fuel cycle was investigated in the IAEA's RNFC study. The example of a multinational reprocessing facility is Eurochemic. There is also the conceivable option of 'fuel cycle centres', combining in one location several segments of the fuel cycle. It is believed that regional fuel cycle centres offer most of the benefits of other MNAs, in particular with regard to material security and transport. The existence of precedents and the results of studies suggest that this fourth option is feasible, although the creation of a new facility from scratch would require large human and financial resources, and additional non-proliferation and commercial issues would have to be addressed. Issues of political and public acceptance would also arise under this approach.

5. The fifth option is more remote. In the case of a further expansion of nuclear energy around the world, there may be scope for the development of a nuclear fuel cycle with stronger multilateral arrangements and broader cooperation, involving the IAEA and the international community. For example, a worldwide network of regional fuel cycle centres would minimize transport and give customers a degree of flexibility.

The Expert Group's report prompted both debate and official action. At the September 2005 IAEA General Conference, the USA officially declared that the US Department of Energy (DOE) would reserve up to 17 tonnes of HEU from materials previously declared excess to US national security needs for 'an IAEA verifiable assured supply arrangement' for states renouncing enrichment,[52] and Russia has made a similar proposal.[53] In October 2005 the Nuclear Threat Initiative (NTI) endorsed the idea of a uranium stockpile being used as 'a backstop guarantee of nuclear fuel supply' under IAEA control and assessed that the optimum size of a fully developed stockpile should be 10 per cent of annual civilian demand. The NTI announced its intention to contribute to such a stockpile low-enriched uranium (LEU) of sufficient volume to yield fuel for one standard 1000-megawatts-electric (MW(e) power reactor for three years. The NTI offered to give a $50 million grant to the IAEA to cover the cost of buying the HEU declared excessive for military purposes, its downblending to LEU, transport and storage.[54] In November 2005 Russia tried to resolve the international controversy over the scope and nature of Iran's nuclear programme by offering to establish a joint venture to produce nuclear fuel on Russian territory,

[52] IAEA, 'Communication dated 28 September 2005 from the Permanent Mission of the United States of America to the Agency', IAEA Information Circular INFCIRC/659, 29 Sep. 2005, URL <http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc659.pdf>.

[53] 'Russia proposes creating reserve stock of nuclear fuel under IAEA control', RIA Novosti, 13 July 2005.

[54] 'Catalyzing an IAEA nuclear material stockpile', Material from the NTI Governing Board Meeting, Moscow, Oct. 2005, provided by Rolf Ekéus.

effectively outsourcing the Iranian enrichment programme to Russia.[55] In January 2006 Russian President Vladimir Putin generalized this proposal and essentially endorsed the findings of the IAEA Expert Group by calling for the 'creation of a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA'.[56] In February 2006 the US DOE announced its Global Nuclear Energy Partnership (GNEP) programme, part of which is a proposal to establish 'a fuel services program that would allow developing nations to acquire and use nuclear energy economically while minimizing the risk of nuclear proliferation'.[57]

The idea of multilateral supply guarantees is thus beginning to materialize under the umbrella of the IAEA, although many practical arrangements remain to be settled. Some states are less than enthusiastic, however, because in their view such guarantees can be successful only if all parties are confident in the availability of fuel and services, regardless of political developments. An IAEA fuel bank is not acceptable to some to a large extent because they do not see sufficiently credible assurances that the IAEA would not stop supplies for reasons other than those related to the compliance of individual states with the NPT: for example, for fear that the necessary export licences would not be granted for political reasons. Various models for providing such assurances were put forward in 2005.[58]

V. Proliferation-resistant nuclear fuel cycle technologies

The nuclear fuel cycle consists of two distinctive parts. The first part, or 'front-end', is a set of stages that lead to the preparation of fuel for reactor operation. Although enrichment is not needed for some reactors and it is conceivable to use thorium instead of uranium, in most cases the front-end consists of uranium ore exploration, mining, milling, uranium conversion, enrichment and fuel fabrication.[59] After fuel has been irradiated and unloaded from the reactor, the second part of the nuclear fuel cycle, the 'back-end', begins. It may consist of three stages: intermediate fuel storage; fuel reprocessing in order to separate useful isotopes such as plutonium-239 and uranium-235 from waste; and nuclear waste disposal.[60] Fuel reprocessing may be omitted, in which case all the spent fuel is ultimately disposed as waste. It is widely recognized that two steps of the nuclear fuel cycle—enrichment and reprocessing—are especially proliferation-prone. It is relatively easy to build a crude nuclear

[55] See chapter 13.

[56] Official Web Portal of the President of Russia, 'Statement on the Peaceful Use of Nuclear Energy', 25 Jan. 2006, URL <http://president.kremlin.ru/eng/text/speeches/2006/01/25/1741_type82912type82914_100665.shtml>.

[57] US Department of Energy, Office of Public Affairs, 'Department of Energy announces new nuclear initiative', Press release, Washington, DC, 6 Feb. 2006, URL <http://www.gnep.energy.gov/pdfs/gnepPressRelease020606.pdf>.

[58] Goldschmidt, P., 'Mechanisms to increase nuclear fuel supply guarantees', Carnegie International Non-Proliferation Conference, Washington, DC, 7–8 Nov. 2005, URL <http://www.carnegieendowment.org/static/npp/2005conference/presentations/Goldschmidt_fuel_supply.pdf>; Gottemoeller, R., 'One model for a fuel supply agreement', Presentation at the Workshop on International Fuel Services, Nuclear Power and Nonproliferation, Stockholm, 12 Dec. 2005; and chapter 13 in this volume.

[59] 'Enrichment' is 'an isotope separation process by which the abundance of a specified isotope in an element is increased', e.g., production of HEU or heavy water. IAEA (note 3), pp. 33, 41.

[60] Nuclear fuel 'reprocessing' is 'a chemical separation of nuclear material from fission products'. IAEA (note 3), pp. 33, 41.

explosive device once a sufficient amount of direct-use material is obtained. Enrichment and reprocessing can lead to the production of such material in the eminently suitable form of HEU or plutonium.

Uranium enrichment facilities under IAEA safeguards currently exist in Argentina, Brazil, China, Germany, Iran, Japan, the Netherlands and the UK. Furthermore, enrichment facilities that are not under safeguards exist in France, India, Pakistan, Russia and the USA. Australia, Israel and South Africa have developed technologies and processes to the point where they can be said to have a working understanding of uranium enrichment.[61] Industrial-scale uranium enrichment facilities are listed in table 13C.2.

None of the nuclear weapon states is believed to be currently reprocessing spent nuclear fuel for military purposes, although this may be under way in India, Israel, North Korea and Pakistan. Large commercial plutonium separation plants are operated in France, Russia and the UK. India operates three smaller plutonium separation facilities and one for thorium separation. Japan operates one such facility and is planning to begin commercial operation of another in the near future.[62] Details on world civilian reprocessing plants are given in table 13C.3. A significant number of other countries that pursued but subsequently abandoned military nuclear programmes have also conducted research on or developed reprocessing technologies and processes.

Many of the technologies employed in the contemporary nuclear fuel cycle were originally developed for use in military applications. For instance, gaseous diffusion technology for uranium enrichment 'was developed in an atmosphere of intense urgency and with virtually none of the normal constraints on costs, efficiency and profitability', let alone environmental, non-proliferation or sustainability considerations.[63] This has resulted in a highly distorted subsequent development of the enrichment industry and nuclear fuel cycle technologies in general. With the huge investments already made in military applications, governments around the world have been more inclined to adapt developed technologies and processes than to search for new ones that could be more suitable for the safe development of civil nuclear power. A different approach to dealing with the dual nature of nuclear energy is based on the idea of introducing new, proliferation-resistant technologies. Although they cannot make nuclear facilities absolutely proliferation-proof, new technologies could make illicit use very difficult.[64] This approach may be applied on two levels.

At one level, proposals have been made to replace individual sensitive technologies with proliferation-resistant technologies. The most successful proposal today is to replace the HEU fuel of research and isotope-producing reactors with high-density LEU fuel. The Reduced Enrichment for Research and Test Reactors (RERTR) Program was initiated by the US DOE in 1978 and is still operating successfully, with

[61] IAEA (note 16), pp. 133–36; and Makhijani, A., Chalmers, L. and Smith, B., 'Uranium enrichment', Institute for Energy and Environmental Research, Takoma Park, Md., 15 Oct. 2004, URL <http://www.ieer.org/reports/uranium/enrichment.pdf>.

[62] 'Summary table: production and status of military stocks of fissile material, end of 2003', URL <http://www.isis-online.org/mapproject/supplements.html>; World Nuclear Association, 'Processing of used nuclear fuel' Information and Issue Brief, London, Mar. 2005, URL <http://www.world-nuclear.org/info/inf69.htm>; and IAEA (note 16), pp. 79–81.

[63] Krass et al. (note 32), pp. 14–16.

[64] A good review of the notion of 'proliferation resistance' is given in Feiveson, H. A., 'Proliferation resistant nuclear fuel cycles', *Annual Review of Energy*, vol. 3 (Nov. 1978), pp. 357–94.

Table 13C.2. Estimated world industrial-scale uranium enrichment capacity, as of April 2005

Operator	Technology	Nominal capacity (million kgSWU per year)[a]
China		
Heping Uranium Enrichment Plant	Gaseous diffusion	0.2–0.3[b]
Lanzhou Nuclear Fuel Complex	Centrifuge	0.5
Shaanxi Uranium Enrichment Plant[c]	Centrifuge	0.5
France		
EURODIF Production	Gaseous diffusion	10.8
Germany		
Urenco Deutschland GmbH	Centrifuge	1.8
Japan		
Japan Nuclear Fuel Limited	Centrifuge	1.05
Netherlands		
Urenco Nederland BV	Centrifuge	2.6
Russia		
Angarsk Electrolysis Chemical Complex	Centrifuge	1.6
Urals Electrochemical Integrated Plant	Centrifuge	9.8
Zelenogorsk Electrochemical Plant	Centrifuge	5.8
Siberian Chemical Combine	Centrifuge	2.8
United Kingdom		
Urenco (Capenhurst) Ltd	Centrifuge	3.0
United States		
United States Enrichment Corporation	Gaseous diffusion	11.3

[a] Separative work unit (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. The unit of separative work is the kilogram separative work unit (kgSWU, or SWU).

[b] Unofficial estimates. Cirincione, J., Wolfsthal, J. B. and Rajkumar M., 'China', *Deadly Arsenals: Nuclear, Biological, and Chemical Threats* (Carnegie Endowment for International Peace: Washington, DC, 2005), p. 162. Some experts believe that this facility was shut down.

[c] There are 2 facilities at this plant.

Sources: IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report to the Director General of the International Atomic Energy Agency* (IAEA: Vienna, 2005), pp. 62–66; Bukharin, O., 'Understanding Russia's uranium enrichment complex', *Science and Global Security*, no. 12 (2004), p. 195; *Urenco Annual Report and Accounts, 2004*, URL <http://www.urenco.com/im/uploaded/1125054354>, p. 8; Harding, P. J. C., Urenco, 'The role of UK business in providing security of energy supply from nuclear power: BEA Workshop, London, 14 April 2005', URL <http://www.worldenergy.org/wec-geis/global/downloads/bea/BEA_WS_0405Harding.pdf>, p. 9; Nuclear Engineering International, *World Nuclear Industry Handbook 2005* (Wilmington Publishing: Sidcup, 2005), p. 216; and World Nuclear Association, 'Nuclear power in China', Information and Issue Brief, Dec. 2005, URL <http://www.world-nuclear.org/info/inf63.htm>.

a parallel programme in Russia. Proposals along these lines exist for other types of reactor using HEU, in particular for naval propulsion.[65]

Another suggestion has been to introduce the proliferation-resistant technology of chemical enrichment of uranium, which would be economically competitive with other processes while producing LEU, but would make it technically infeasible to reach a level of enrichment that is suitable for a nuclear explosive device. Variations of such technologies have been developed independently by France and Japan. On the one hand, slow kinetics and criticality limitations, the two main intrinsic features of both processes, do not allow the attainment of high uranium-235 assays and thus make them proliferation-resistant.[66] On the other hand, French chemical enrichment technology was pursued in the Iraqi clandestine nuclear programme and might have produced LEU for further enrichment in another process if more effort had been put into it.[67] The chemical enrichment process is reportedly economically competitive, relatively simple and fairly similar to processes in the petrochemistry industry, and adaptable to small- or medium-scale applications. It also involves a low level of energy consumption.[68] The technology for gaseous diffusion enrichment can also be proliferation-resistant if the plant using this technology is designed specifically to produce LEU.[69]

Proposals have also been put forward to introduce proliferation-resistant technologies to the back-end of the fuel cycle. The idea here is to develop processes for spent fuel reprocessing that would operate with mixtures of plutonium and other selected elements for preparing proliferation-resistant fuel. For example, in November 2005 the US Secretary of Energy, Samuel W. Bodman, set the goal to develop 'recycling technologies that do not produce separated plutonium'.[70] This idea was incorporated in the US DOE's Global Nuclear Energy Partnership (GNEP) programme.[71] Some experts question the value of such recycling technologies in terms of their proliferation resistance.[72]

At the second level, several more ambitious proposals have been put forward for the development of new, innovative nuclear energy systems that would be safe, sustainable, economically attractive and proliferation-resistant.

[65] von Hippel, F., 'A comprehensive approach to elimination of highly-enriched-uranium from all nuclear-reactor fuel cycles', *Science and Global Security*, no. 12 (2004), p. 147. Russia also proposed building floating nuclear power plants that would use an LEU-based fuel and would be available for leasing. Samoilov, O. B., 'Russian reactor development: ploughing the waves', *Nuclear Engineering International*, Jan. 2006.

[66] Krass et al. (note 32), pp. 17–21. 'Assay' refers to the level of enrichment; see, e.g., IAEA, 'Management of high enriched uranium for peaceful purposes: status and trends', IAEA-TECDOC-1452, June 2005, p. 1.

[67] Cordesman, A. H., *Iraq and the War of Sanctions: Conventional Threats and Weapons of Mass Destruction* (Praeger: Westport, Conn., 1999), p. 614.

[68] Coates, J. H. and Barré, B., 'Practical suggestions for the improvement of proliferation resistance within the enriched uranium fuel cycle', eds F. Barnaby et al., SIPRI, *Nuclear Energy and Nuclear Weapon Proliferation* (Taylor & Francis: London, 1979), pp. 49–53; and Kokoski, R., SIPRI, *Technology and the Proliferation of Nuclear Weapons* (Oxford University Press: Oxford, 1995), p. 64.

[69] Kokoski (note 68), pp. 65–66.

[70] '2005 Carnegie Non-proliferation Conference: Remarks prepared for Energy Secretary Sam Bodman', Washington, DC, 7 Nov. 2005, URL <http://www.doe.gov/engine/content.do?PUBLIC_ID=19141&TT_CODE=PRESSSPEECH>.

[71] US Department of Energy (note 57).

[72] Kang, J. and von Hippel, F., 'Limited proliferation-resistance benefits from recycling unseparated transuranics and lanthanides from light-water reactor spent fuel', *Science and Global Security*, no. 13 (2005), pp. 169–81.

Table 13C.3. World civilian spent fuel reprocessing capacity, as of April 2005

Operator (Plant)	Nominal capacity (MTHM/yr)	Reprocessing fuel type
France		
COGEMA (La Hague UP2 800)	1 000[a]	Light-water reactors
COGEMA (La Hague UP3)	1 000[a]	Light-water reactors
India		
Indira Gandhi Centre for Atomic Research (Kalpakkam Atomic Reprocessing Plant)	125	Pressurized heavy-water reactors
Nuclear Power Corporation of India, Ltd (Tarapur Power Reactor Fuel Reprocessing Plant)	100	Pressurized heavy-water reactors
Bhabha Atomic Research Centre (Trombay Plutonium Reprocessing Plant)	50	Pressurized heavy-water reactors
Japan		
Japan Nuclear Fuel Cycle Development Institute (Tokaimura Reprocessing Plant)	200	Light-water reactors
Russia		
Mayak Production Association (RT-1 Reprocessing Plant)	400	VVER-440 and RBMK power reactors; research, naval, fast, isotope-producing reactors
United Kingdom		
British Nuclear Group (Sellafield Mixed Oxide Plant)	1 500	Magnox reactors
British Nuclear Group (Thermal Oxide Reprocessing Plant)	900	Advanced gas-cooled and light-water reactors

MTHM = Metric tonnes of heavy metal.

[a] The actual maximum combined production level of all the La Hague plants does not exceed 1700 MTHM/year. Extra capacity is kept in order to maintain ‘industrial flexibility to spread the workload more evenly between the 2 units, and not to increase total production’. COGEMA, ‘Press release: Review of the public inquiry concerning the La Hague plant’, 7 June 2000, URL <http://www.cogemalahague.fr/servlet/ContentServer?pagename=cogema_en/communique/communiqué_full_template&c=communique&cid=1039473237061&p=1039482707003>.

Sources: IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report to the Director General of the International Atomic Energy Agency* (IAEA: Vienna, 2005), pp. 79–81; Korotkevich, V. and Kudryavtsev, E., ‘Spent nuclear fuel management in the Russian Federation: technology and safety’, *Bulletin on Atomic Energy* (Moscow), no. 12 (Dec. 2002), p. 26, URL <http://www.minatom.ru/filereader?id=18150>; ‘Processing of used nuclear fuel for recycle’, World Nuclear Association Issue Brief, Dec. 2005, URL <http://www.world-nuclear.org/info/inf69.htm>; Nuclear Engineering International, *World Nuclear Industry Handbook 2005* (Wilmington Publishing: Sidcup, 2005), p. 218; and IAEA Nuclear Fuel Cycle Information System (NFCIS), URL <http://www-nfcis.iaea.org/NFCIS/NFCISMain.asp>.

Some studies claim that it may be conceivable to develop a sustainable and proliferation-resistant (because of the specific qualities of the isotopes involved) thorium fuel cycle, although significant technical problems need to be resolved.[73] The thorium fuel cycle concept is not expected to be completely proliferation-proof, but its realization would employ technologies that would make the diversion of fissile material extremely difficult.[74] Development of the thorium nuclear fuel cycle is led by India, and studies are being carried out in Canada, Germany, Russia, the USA and other states. Indian uranium reserves are modest but India's thorium reserves are the world's second largest.[75] In 1958 the Indian Government formally adopted a long-term plan for a future closed thorium fuel cycle and for providing India with an unlimited supply of thorium–uranium-233 fuel.[76] It stipulated that India would build three distinct types of nuclear reactor in consecutive stages. Currently, India is entering the second stage of that plan and is continuing to implement it, but it is still uncertain how proliferation-resistant India's thorium fuel cycle will be.

In January 2000 the US DOE began discussions with other states on international cooperative development of so-called 'Generation IV' nuclear energy systems that comprise the entire nuclear power plant as well as facilities for the entire fuel cycle. This group, representing states with significant nuclear expertise, was formally chartered into the Generation IV International Forum (GIF) in 2001. The goal of the GIF is the research and development of innovative reactor and fuel cycle technologies that represent advances in sustainability, economics, safety, reliability and proliferation-resistance; and they should become commercially viable before 2030. To this end, GIF members selected the six most promising reactor technologies.[77] In February 2005 the USA, Canada, France, Japan and the UK signed an agreement on the joint development of such technologies,[78] with Switzerland and South Korea joining later in the year. The DOE also runs the Advanced Fuel Cycle Initiative, in

[73] Thorium is assessed to be about 3 times more abundant than uranium and about as common as lead. The only natural isotope of thorium, thorium-232, is fertile (it can be converted into a special fissionable material) like uranium-238 and can absorb slow neutrons in the reactor to produce uranium-233, which is fissile (capable of undergoing fission by neutrons of all energies) like uranium-235. Uranium-233 can be separated from the spent fuel and fed back into the reactor as part of a closed fuel cycle. Los Alamos National Laboratory, Chemical Division, 'Thorium', 15 Dec. 2003, URL <http://periodic.lanl.gov/elements/90.html>.

[74] Galperin, A., Reichert, P. and Radkowsky, A., 'Thorium fuel for light water reactors: reducing proliferation potential of nuclear power fuel cycle', *Science and Global Security*, vol. 6 (1997), pp. 265–90.

[75] World Nuclear Association, 'Thorium', Information and Issue Brief, Nov. 2004, URL <http://www.world-nuclear.org/info/inf62.htm>; and 'Thorium: statistics and information', US Department of the Interior, US Geological Survey, Minerals Information, June 2005, URL <http://minerals.usgs.gov/minerals/pubs/commodity/thorium/index.html>.

[76] Perkovich, G., *India's Nuclear Bomb: The Impact on Global Proliferation* (University of California Press: Berkeley, Calif., 1999), pp. 26–27.

[77] The members of the GIF are Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland, the UK, the USA and the EU. US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 'A technology roadmap for Generation IV nuclear energy systems', Dec. 2002, URL <http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf>; and World Nuclear Association, 'Generation IV nuclear reactors', Information and Issue Brief, Apr. 2005, URL <http://www.world-nuclear.org/info/inf77.htm>.

[78] The Framework Agreement for International Collaboration on Research and Development of Generation IV Nuclear Energy Systems is available on the Generation IV International Forum website at URL <http://www.gen-4.org/PDFs/Framework-agreement.pdf>.

particular 'to develop reactor fuel and fuel cycle technologies to support Generation IV nuclear energy systems'.[79]

In 2001 the IAEA launched the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). The aim of the project is for IAEA member states to jointly develop innovative nuclear reactor and fuel cycle technology with certain basic features, including effectively unlimited fuel resources, nuclear and environmental safety, proliferation resistance and economic competitiveness.[80] As of the end of 2005 INPRO had developed and validated the methodology for the assessment of innovative nuclear energy systems and is conducting assessments of individual systems under development in IAEA member states in order to pursue their construction in the future. INPRO assessments include a review of the options for multilateral nuclear fuel cycles.[81] In particular, Russia's proposal for a closed nuclear fuel cycle with fast reactors is being evaluated.[82] In September 2005, at the IAEA General Conference, the USA announced that it will join INPRO.[83] This step improved cooperation between INPRO and GIF, which do very similar work.

VI. Conclusions

The only certain way to diminish the risk of the diversion of civil nuclear materials to military programmes would be to cease the use of nuclear power. Nuclear technologies for energy generation are predominantly used for the production of electricity. The sources currently discussed as possible substitutes for nuclear fission in electricity production are fossil fuels, renewable sources and nuclear fusion.[84] If restrictions on the emission of greenhouse gases or price considerations come to impose limitations on the development of fossil fuel power plants, then renewable sources would step in. The prospects for such sources to become reliable replacements for nuclear power within the next few decades are questionable, however. The

[79] US Department of Energy, Office of Nuclear Energy, Science and Technology, 'Advanced Fuel Cycle Initiative', Washington, DC, Nov. 2005, URL <http://www.ne.doe.gov/infosheets/afci.pdf>; and 'Advanced fuel cycle program: addressing national priorities and needs', Advanced Fuel Cycle Initiative website, URL <http://afci.lanl.gov/aboutaaa.html>.

[80] International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), INPRO Brochure, Sep. 2004, IAEA website, URL <http://www.iaea.org/img/assets/3836/inpro_2004.pdf>, pp. 1–2.

[81] IAEA, 'Draft terms of reference for Phase-1B (second part) and Phase II International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)', URL <http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS/Downloads/INPRO/tor_phase_1b_2_rev_ys_final.pdf>.

[82] Perrera, J., 'Innovation for tomorrow', *Nuclear Engineering International*, 29 Sep. 2005, URL <http://www.neimagazine.com/story.asp?sectioncode=76&storyCode=2031487>.

[83] IAEA Information Circular INFCIRC/659 (note 52).

[84] Fusion power is useful energy generated in nuclear fusion reactions where 2 light atomic nuclei fuse together to form a heavier nucleus and release energy. The most feasible reaction is between 2 isotopes of hydrogen—deuterium and tritium. Deuterium occurs naturally in sea water (30 grams per cubic metre), which means that fusion energy, if and when it is developed, would provide a practically unlimited energy resource. Contemporary fusion research is led by the EU, Japan, Russia and the USA, with substantial programmes also under way in Brazil, Canada, China, India and South Korea. There are a number of ongoing experimental attempts to build fusion power generators, but none of them continuously generates more energy than it uses. As announced in June 2005, the first experimental reactor intended to achieve this goal, ITER, will be built at Cadarache, France, at a cost of €10 billion. Current plans for the development of fusion power show that this technology is not planned to be ready for commercial production of electricity until 2050 or even later. 'France gets nuclear fusion plant', BBC News, 28 June 2005, URL <http://news.bbc.co.uk/1/4629239.stm>; and ITER, 'Fast track to fusion', 21 Oct. 2004, URL <http://www.iter.org/fast_track.htm>.

future share of nuclear power in electricity production may vary, but it is likely that in the foreseeable future all three sources will be used, at least until (or unless) there is a breakthrough in nuclear fusion technology. This means that the goal of ensuring the security and development of nuclear power will remain important for years to come. Even though all three approaches discussed in this appendix may serve this goal well, none of them is sufficient alone. Multilateral arrangements may be misused, as can proliferation-resistant technologies. In addition, international control may be rejected because the NPT does not provide for any consequences for non-nuclear weapon states parties that withdraw from it after having acquired nuclear material and fuel cycle technologies for peaceful purposes.

It is the combination of the three approaches that seems most promising: carried out together, they may reinforce the strengths and cancel the flaws of each other. The IAEA is already combining all three approaches in its work, simultaneously conducting studies on internationalization of the nuclear fuel cycle, developing INPRO and strengthening the safeguards regime. In 2005 Russia and the USA showed that they are also pursuing all three routes simultaneously. However, the exact, optimal combination of measures in the three approaches was not defined in 2005.