Preventing Nuclear Proliferation and Nuclear Terrorism

Essential steps to reduce the availability of nuclear-explosive materials

Center for International Security and Cooperation,
Stanford Institute for International Studies, Stanford University

and

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

Preventing Nuclear Proliferation and Nuclear Terrorism

Essential steps to reduce the availability of nuclear-explosive materials

Table of contents

Preface

This report originated in a five-day summer study held at Stanford University, 22-26 August 2003. The study was co-directed by Christopher Chyba, co-director of Stanford's Center for International Security and Cooperation (CISAC) at the Stanford Institute for International Studies, and Harold Feiveson and Frank von Hippel, co-directors of Princeton University's Program on Science and Global Security at the Woodrow Wilson School. Participants in the study are listed in Appendix C. A glossary of acronyms is included in Appendix D. The study was supported by a grant from the MacArthur Foundation to CISAC.

Prior to the August meeting, several participants produced draft papers, which provided starting points for five days of discussion. After the August meeting, the authors amended these papers, and the co-directors used these and other inputs from participants to produce this report.

Developments subsequent to the summer study cast new light on the issues examined here, stimulating further discussion and analysis. The conclusions and analysis presented therefore go beyond materials discussed at the August 2003 meeting. The report has been reviewed by the participants and is supported by an overall consensus. Nevertheless, not every participant or co-director subscribes to every one of the consensus report recommendations.

Since most of the study participants were trained in science or engineering, our focus was on technical issues underlying policy on fissile material policy. This unavoidably places an emphasis on supply-side measures to address nonproliferation and leaves largely unaddressed equally important demand-side measures that must be included in a comprehensive strategy. Nevertheless, our analyses lead to proposals for policy initiatives that must be important components of any effort to strengthen the nonproliferation regime.

Executive summary

This report proposes a set of initiatives aimed at stopping the spread of nuclear weapons to more countries and to non-state terrorist and criminal organizations. The most effective way to do this is to strictly limit access to the key nuclear-explosive materials required to make nuclear weapons: high-enriched uranium (HEU) and plutonium. These materials must be secured and, where possible, eliminated; and the number of locations where they can be found or produced drastically reduced.[1]

We propose measures to strengthen international security standards on the storage and transport of fissile materials; stop the spread of facilities capable of producing fissile materials (reprocessing and enrichment plants); end verifiably the production of fissile material for weapons; dispose of excess weapons and civilian fissile materials; and phase out the use of HEU as a reactor fuel.

Although the measures called for have been on the international agenda for decades, most are barely moving forward, if not completely stalled. These measures urgently need high-level attention.

Specifically, we call for the following initiatives:

- A finding by the U.N. Security Council that a country that withdraws from the Non-Proliferation Treaty (NPT) and seeks to use for weapons purposes materials and technology acquired while it was a member constitutes a threat to international security and that such country will be subject to a clearly articulated escalating set of sanctions imposed by the international community. Exporters and importers should negotiate bilateral safeguards as a backup to international safeguards to assure that, in addition to a country's obligations under the NPT, they have a bilateral agreement that any nuclear facilities, equipment, or material that is exported will not be converted to weapons use. Such backup safeguards are already mandated in some agreements for nuclear cooperation between supplier and receiver countries;

- The establishment of internationally verified minimum standards for the physical protection of fissile materials;

- An international agreement that countries will build new uranium enrichment plants only if they have been first reviewed and approved under agreed criteria by the International Atomic Energy Agency (IAEA) or a special committee under the U.N. Security Council and are subject to an additional level of multinational oversight;

[1] Nuclear-explosive material is fissionable material that can sustain an explosive chain reaction, notably plutonium of almost any isotopic composition and high-enriched uranium (HEU, uranium enriched to over 20 percent ^{235}U or 12 percent ^{233}U). In this report, we use this term interchangeably with "fissile material," although the standard definition of fissile material as material fissionable by thermal neutrons would not apply to all conceivable nuclear-explosive material.

- A moratorium on building new spent-fuel reprocessing plants until the existing plutonium stocks, including excess military stocks, are disposed of, and phase-out of plutonium separation at existing reprocessing plants if there is no compelling economic rationale to continue;

- A Fissile Material Cutoff Treaty (FMCT) to end further production of fissile materials for weapons or outside international safeguards;

- Actions by the United States and Russia to dispose of fissile materials recovered from excess weapons;

- A phaseout of the use of HEU in reactor fuel and critical assemblies.[2]

These measures could be considered by the NPT Parties at the 2005 NPT Review Conference as part of a package of proposals to strengthen the nonproliferation regime. A precedent for such strengthening and reinterpretation of the NPT occurred at the 1995 Review and Extension Conference where the NPT Parties reinterpreted Article V of the Treaty in a way that no longer supported provisions for the peaceful uses of nuclear explosives. Also, at that conference, the Parties strongly supported a cutoff treaty and continued disposal of recovered fissile materials.

The technical focus of this study led to an emphasis on supply-side improvements in the nonproliferation regime, that is, on measures that for the most part involve further restricting the availability of fissile material or its production technologies. Some of these measures would place requirements on nuclear weapons states and non-nuclear weapons states alike, some (like the fissile material cutoff treaty) would primarily affect nuclear weapons states, but for some (in particular, restrictions on the possession of enrichment and reprocessing plants) the restrictions would fall primarily on non-nuclear weapons states. Such added stringency on the conditions imposed on the NPT non-weapons states should be matched by more rapid progress by the NPT-recognized nuclear weapons states to meet their obligations under Article VI of that Treaty to reduce their nuclear weapons arsenals. These NPT-weapons-state obligations were given specific agreed interpretation at the 1995 NPT Review and Extension Conference. Given that the non-nuclear weapon states at the Conference agreed there to an indefinite extension of the NPT, these promises by the nuclear weapons states take on special significance.

Finally, supply-side measures to restrict the development of nuclear weapons will not succeed in perpetuity if countries continue to seek nuclear weapons as technological capacity diffuses to more and more countries. Any supply-side strategy to slow proliferation must therefore be mated with demand-side strategies that address the reasons that certain states choose to pursue nuclear weapons.

[2] A critical assembly contains enough fissile material to sustain a fission chain reaction at a low power level, for the purpose of investigating nuclear reactor core geometries and compositions.

1. Introduction

Despite a compelling security requirement to keep nuclear weapons out of the hands of terrorists and additional countries, not nearly enough is being done today to achieve this objective. In this report, we lay out a series of initiatives that the international community should now undertake.

All of our proposals focus on weapons-usable fissile materials—plutonium and high-enriched uranium (HEU). These are the essential materials for nuclear weapons. They and the technologies to produce them must be much more strictly controlled if further nuclear proliferation and nuclear terrorism are to be prevented.

Such strict control is still possible because, while plutonium and HEU are widely distributed in small quantities, the great preponderance of fissile material is stored at present in a limited number of locations in a limited number of countries. Similarly, the means of fissile material production—spent-fuel reprocessing and uranium enrichment plants—also are currently found in only a small number of countries.

A deteriorating situation. In spite of Libya's elimination of its nuclear weapons program, the most dramatic recent success of international nonproliferation policies, the situation is deteriorating. North Korea, which withdrew from the Non-Proliferation Treaty (NPT) in 2003, most likely has separated tens of kilograms of plutonium and may also have a program to produce HEU. Iran has begun a uranium enrichment program and has stated that it also plans to separate plutonium—activities that it claims unconvincingly are only for peaceful purposes. Brazil has built a small commercial gas-centrifuge uranium enrichment plant in addition to a similar plant that it had already built to enrich uranium for its naval-reactor program.

Recent revelations also have put a spotlight on a clandestine international commercial network established by Pakistan's A.Q. Khan and associates to sell centrifuge enrichment technology to at least Iran, Iraq, North Korea, and Libya, and in the case of the latter, nuclear-weapons blueprints as well.[3] The Pakistani experience is a warning that nuclear weapons-relevant material and technology are not necessarily well controlled and have a market in a number of countries. The potential future customers for fissile materials could include terrorist and criminal groups as well as governments. There is therefore reason for urgency to remove fissile material from as many locations as possible and slow the spread of the means of their production.

---

[3] See, e.g., Sharon Squassoni, "Closing Pandora's Box: Pakistan's Role in Nuclear Proliferation," *Arms Control Today* (April 2004); ISIS Issue Brief , 4 February 2004, Institute for Science and International Security, http://www.isis-online.org; Chaim Braun and Christopher F. Chyba, "Proliferation Rings: New Challenges to the Nuclear Nonproliferation Regime," *International Security* 29, no. 2 (2004): 5–49. The extent of the Khan network came to light in December 2003 when Libya's President Qaddafi disclosed and renounced his country's past proliferation activities.

Who has fissile material and the means to produce it? The situation today is roughly as follows:

- All the nuclear-weapons states (the United States, Russia, the United Kingdom, France, China, India, Israel, Pakistan, and North Korea) have or are developing both plutonium reprocessing and uranium enrichment plants.[4]

- The nuclear-weapon states also possess the vast quantity (more than 99 percent) of fissile material in the world. This includes plutonium and HEU in weapons or recovered from excess Cold War weapons (with more than 95 percent of this weapons material in Russia and the United States), HEU for use in naval reactors, research reactors, and Russian icebreakers (again virtually all in Russia and the United States), and plutonium separated from power-reactor spent fuel (mostly at reprocessing plants in France, Russia, and the United Kingdom).

  In total, very roughly 500 metric tons of separated plutonium (half weapons and half civilian) and 1,500-2,000 metric tons of HEU are held by the weapon states—enough to build more than 100,000 additional nuclear weapons.

- In most non-nuclear weapons states, there are no stockpiles of separated plutonium or HEU and no reprocessing plants or enrichment facilities. The exceptions are Japan and a few countries of Western Europe, which have some stocks of separated plutonium; Japan, which has reprocessing plants; Germany and the Netherlands, which have gas-centrifuge enrichment plants built and operated in concert with the United Kingdom; and a number of non-nuclear weapons states that have research reactors and critical assemblies fueled with HEU fuel—the total quantity of this fuel in non-weapons states being less than 10 metric tons.

- Far more plutonium than has been separated for weapons or civilian use exists in the accumulated stored spent fuel discharged by the world's nuclear power reactors (approximately 1400 metric tons at the end of 2003).[5] This plutonium too has to be guarded and monitored. However, because as spent fuel it is diluted by 100 times as much uranium and mixed with highly radioactive fission products, it appears well beyond the likely capabilities of terrorist groups to obtain and use for weapons.

- With respect to the terrorist threat, plutonium—even separated plutonium—is less of a concern than HEU, since the use of plutonium in a weapon would require the far more difficult implosion technology, while gun-type weapons that could employ HEU are within the technical reach of non-state groups.

---

[4] Little detailed public information is available on Israel's enrichment activities. However, Israel is reported to have some, possibly pilot-scale, enrichment programs at its Dimona reactor. See Joseph Cirincione with Jon B. Wolfsthal and Miriam Rajkumar, *Deadly Arsenals: Tracking Weapons of Mass Destruction* (Washington, D.C.), 234.

[5] David Albright and Kimberly Kramer, "Fissile Material: Stockpiles Still Growing," *Bulletin of the Atomic Scientists* (November/December 2004).

A to-do list for the international community. This distribution of fissile material defines the critical tasks facing the international community. It should

- reinforce the Non-Proliferation Treaty to make it far more difficult for countries to use the treaty as a cover for acquiring nuclear materials and technology that could later be diverted to the production of nuclear weapons;
- strengthen international physical-security standards;
- stop the uncontrolled spread of uranium enrichment plants, strengthen international safeguards at centrifuge enrichment plants, and subject all enrichment plants to an extra layer of multinational monitoring;
- establish a moratorium on building new spent-fuel reprocessing plants until existing stocks of separated civilian plutonium have been eliminated and there is a strong economic justification for such plants and encourage a phaseout of plutonium separation at existing reprocessing plants where there is no compelling economic rationale to continue;
- conclude a verified global treaty ending all further production of fissile materials for weapons;
- dispose of much more of the excess fissile materials recovered from dismantled Cold War weapons and the accumulated plutonium separated from spent civilian reactor fuel; and
- phase out the use of HEU as a reactor fuel.

In the remaining sections of this report, we provide the technical basis for each of these proposals.

2. Countries should not be allowed to use their nuclear materials and technology for weapons if they leave the NPT

> “Each Party shall in exercising its national sovereignty have the right to withdraw from the Treaty if it decides that extraordinary events related to the subject matter of this Treaty, have jeopardized the supreme interests of its country. It shall give notice of such withdrawal to all other Parties to the Treaty and to the United Nations Security Council three months in advance. Such notice shall include a statement of the extraordinary events it regards as having jeopardized its supreme interests.
>
> —*Treaty on the Non-Proliferation of Nuclear Weapons* (1970), Article X
>
> “The proliferation of all weapons of mass destruction constitutes a threat to international peace and security.”
>
> —*U.N. Security Council* meeting at the level of heads of state and government, 31 January 1992, http://projects.sipri.se/cbw/docs/cbw-unsc23500.html

Article IV of the nuclear Non-Proliferation Treaty (NPT) promises non-nuclear parties to the treaty full cooperation by other parties in the development of civilian uses of nuclear energy, as long as these uses are under international safeguards as appropriate. However, this should not allow a party to withdraw from the treaty and then use fissile materials or production facilities acquired while they were parties to the treaty to make nuclear weapons.

For example, consider the case of North Korea. North Korea joined the NPT in 1985. On 10 January 2003, North Korea announced its withdrawal from the NPT. Subsequently it began to recover plutonium from spent fuel in a reprocessing plant and to produce more plutonium in its small power reactor. It appears to intend to use all this plutonium to make weapons. The spent fuel, the reprocessing plant, and the reactor had all been under IAEA safeguards. It also appears that North Korea was clandestinely acquiring uranium enrichment capacity while it was a party to the NPT.

The situation in Iran presents the potential for a similar cautionary tale. Although still under the umbrella of the NPT, Iran appears to be gathering a formidable capacity to produce fissile materials, a substantial part of which seems unrelated to plausible near-term civil purposes.

To address these cases and other similar cases in the future, the parties to the NPT should affirm that the NPT does not allow a country to withdraw from the treaty in a manner that frees it from safeguards obligations.

To enforce this interpretation, the Security Council should state that the withdrawal of a country from the NPT in this fashion would constitute “a threat to the peace" under Chapter VII of the U.N. Charter and it should be prepared to authorize an escalating series of measures against any country that does so. Such a declaration by the Security Council would reinforce and build upon a statement made by the Security Council at the level of heads of state and government in 1992: "The proliferation of all weapons of mass destruction constitutes a threat to international peace and security." In this manner, the Council could make clear that all nuclear materials, facilities, and related equipment in a country's possession at the time it leaves the NPT must remain under IAEA safeguards.

As this report was being put into final shape, the U.N. published a study done by its High-Level Panel on Threats, Challenges, and Change.[6] The study addressed the issue of withdrawal in a slightly different way than discussed above:

> A State's notice of withdrawal from the Treaty on the Non-Proliferation of Nuclear Weapons should prompt immediate verification of its compliance with the Treaty, if necessary mandated by the Security Council. The IAEA Board of Governors should resolve that, in the event of violations, all assistance provided by the IAEA should be withdrawn.[7]

However the procedures are framed, there must be developed an international understanding that states cannot turn nuclear materials and facilities acquired while they were members of the NPT to the production of nuclear weapons simply by withdrawing from the Treaty.

In addition to the recommended Security Council actions, the Nuclear Suppliers Group (NSG) should also be enlisted to ensure against such a result. The NSG, a group consisting of most major nuclear exporters, has developed voluntary guidelines for nuclear transfers that have been revised regularly since the group's founding in 1977 (initially as the London Club). These NSG guidelines should be amended to require that NSG exporters insist on *bilateral* inspection rights as well as IAEA safeguards on exported enriched uranium, reactors, and other major nuclear items as a backup to IAEA inspection rights should a country withdraw from the NPT. The NSG guidelines should also require recipients not to export any nuclear material or equipment or any fissile material made with it, unless the original exporter has the same rights to bilateral inspections in the country or countries of final destination.

It will also be critical for members of the NSG, possibly through the Security Council, to work to ensure that countries now outside of the NSG adopt and enforce export restrictions as strong as those imposed by the NSG.[8] These countries include states such as Malaysia, one of whose factories was implicated in the A.Q. Khan network, and the three nuclear states that have so far stayed outside the NPT—India, Israel, and Pakistan.

---

[6] United Nations, *A More Secure World: Our Shared Responsibility*, Report of the High-Level Panel on Threats, Challenges, and Change (December 2004).
[7] Ibid., para. 134.
[8] See the discussion of U.N. Security Council Resolution 1540 in chap. 3.

3. International minimum standards for the physical security of fissile materials should be established and verified

> "The conference notes the paramount importance of effective physical protection of all nuclear material and calls on all States to maintain the highest possible standards of security and physical protection of nuclear materials. The Conference notes the need for strengthened international cooperation in physical protection."
> —*Final Document of the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons,* discussions of Articles III & IV, para. 42.

More than a score of countries have stocks of fissile materials far greater than what the IAEA denotes as significant.[9]

Despite the fact that the theft of such material *anywhere* is a threat to countries *everywhere*, it is remarkable that there are no international minimum standards on the physical security of nuclear materials. The existing Convention on the Physical Protection of Nuclear Material[10] is applicable to the protection of nuclear materials in transit *between* IAEA member countries but not *within* them. These IAEA guidelines are not mandatory, so they cannot be verified or enforced. Efforts to get a consensus among the members of the IAEA to strengthen the guidelines or make them mandatory have not gotten far. But such international minimum standards for the physical security of fissile materials should be established and verified. Such standards should include, for example, the development of design-base threats, the establishment and use of red-team exercises, and requirements for peer review of such exercises.

The U.N. Security Council took an impressive step in this direction in April 2004. Based on a draft resolution that the United States and United Kingdom presented to the Council members, the Security Council adopted Resolution 1540.[11] This is an initiative that we support and to which we wish to draw special attention.

There are 12 points listed in Resolution 1540. Of these, points 1 through 3 represent Security Council lawmaking, a remarkable new approach to global enforcement of nonproliferation requirements.[12]

Point 2 requires states to adopt internal legislation, announcing that the Security Council

---

[9] The IAEA defines as a "significant quantity" of fissile material the amount required to make a first-generation (Nagasaki-type) implosion bomb, including production losses: 8 kg of plutonium or 25 kg of U-235 in HEU.
[10] IAEA information Circular (INFCIRC) 225/Rev. 4;
http://www.unodc.org/unodc/en/terrorism_convention_nuclear_material.html
[11] S/RES/1540 (2004) at http://www.un.org/Docs/sc/unsc_resolutions04.html.
[12] See Braun and Chyba, "Proliferation Rings."

decides also that all States . . . shall adopt and enforce appropriate effective laws which prohibit any non-State actor to manufacture, acquire, possess, develop, transport, transfer or use nuclear, chemical or biological weapons and their means of delivery.

Point 3 states that the Security Council "decides" that states shall

"a. Develop and maintain appropriate effective measures to account for and secure" nuclear, chemical, or biological weapons and materials;

"b. Develop and maintain appropriate effective physical protection measures;

"c. Develop and maintain appropriate effective border controls and law enforcement efforts" to prevent illicit trafficking in these materials;

"d. Establish, develop, review and maintain appropriate effective national export and trans-shipment controls over such items, including appropriate laws and regulations to control export, transit, trans-shipment and re-export" of such items, along with appropriate penalties for violations.

Of these requirements, points 3a and 3b relate to physical security. Point 3d comes into play in international attempts to prevent the proliferation of enrichment and reprocessing technologies, which we discuss in the following two sections.

4. International controls on centrifuge-enrichment plants should be strengthened

> "In light of the increasing threat of proliferation, both by States and by terrorists, one idea that may now be worth serious consideration is the advisability of limiting the processing of weapon-usable material (separated plutonium and high enriched uranium) in civilian nuclear programmes—as well as the *production* of new material through reprocessing and enrichment—by agreeing to restrict these operations exclusively to facilities under multinational control. These limitations would naturally need to be accompanied by appropriate rules of assurance of supply for would-be users."
>
> —*Statement by the IAEA Director General Dr. Mohamed ElBaradei* to the 58th Regular Session of the U.N. General Assembly, 3 Nov. 2003

The spread of uranium enrichment capacity to an increasing number of non-weapons states poses a serious nuclear proliferation challenge. Even if a country with such facilities remains in full compliance with the NPT, including subjecting these facilities to IAEA safeguards, the possession of enrichment capacity would put it very close to a nuclear weapons capability.

The predominant nuclear reactor in use worldwide today is the light water reactor (LWR), which requires low-enriched uranium as fuel (LEU—typically about 4 percent ^{235}U). Therefore, a country depending upon light water reactors needs either its own uranium enrichment plant or an assured source of LEU from another country. Possession of enrichment capacity can raise a serious proliferation concern, since an enrichment plant configured to produce LEU can be reconfigured or operated so as to produce high-enriched uranium (HEU). HEU, defined as uranium containing 20 percent or more ^{235}U, is weapon-usable, although the weapon-grade uranium actually used in nuclear weapons is generally taken to contain 90 percent or more ^{235}U.

Although possession of any kind of enrichment plant would give a country the capability to produce high-enriched uranium, modern gas-centrifuge enrichment plants pose the most significant current challenge to the nonproliferation regime. Their inherent energy efficiency and modularity make the construction of small clandestine enrichment facilities a special concern. Also, their low inventory of uranium would allow a rapid shift from the production of low-enriched to high-enriched uranium in declared facilities. Finally, the myriad of piping connections in the centrifuge cascade (a number of centrifuges linked together) makes the diversion of materials from within the cascade a concern.

Due to their superior economics, centrifuges account for about half of world enrichment capacity today. The technology will become nearly universal among those states enriching uranium when plans to replace the gaseous diffusion plants in France and the United States with centrifuge enrichment plants are implemented. It is unlikely that any other technology with more favorable nonproliferation characteristics will be able to compete economically against the modern gas centrifuge.

Today, about a dozen countries have the capacity to produce centrifuges and operate centrifuge enrichment plants (see Table 4.1). There are currently seven large centrifuge enrichment plants whose low-enriched uranium (LEU) product is exported: four in Russia and one each in Germany, the Netherlands and United Kingdom. There are five more centrifuge plants that provide only domestic civilian enrichment services: two in China, two in Japan, and one in Brazil.[13] Finally, as has recently been revealed, Iran is constructing centrifuge plants, and Libya was in the initial stage of a centrifuge program.

Table 4.1. Centrifuge facilities in the world, operational and planned

Country	Name/Location	Status	Start-up	Capacity tSWU/yr	Safeguards[a]
Brazil	Aramor (Navy) Resende (civilian)	Operational Under constr.	1988 2005?	20? 100	IAEA/ABACC IAEA/ABACC
China	(2 sites)	Operational	1998/2000	1,000	IAEA
France	Tricastin	Planned	?	?	IAEA/Euratom
Germany	Gronau	Operational	1985	1,300	IAEA/Euratom
India	Mysore	Operational	late 1980s	low	No
Iran	Natanz	Under constr.	?	?	IAEA
Iraq	Al Furat	Destroyed (1991)	—	—	(No)
Israel	Dimona	Operational		Pilot-scale?	No
Japan	Rokkasho	Operational	1992	1,050	IAEA
Netherlands	Almelo	Operational	1976–1980	1,950	IAEA/Euratom
North Korea	?	Under constr.?		?	(No)
Pakistan	Kahuta	Operational	mid-1980s	9–15	No
Russia	(4 Sites)	Operational	1960–1980	15,000	No
United Kingdom	Capenhurst	Operational	1976–1980	2,000	IAEA/Euratom
United States	?	Planned	?	?	IAEA

Centrifuge: total capacity operational in 2003	22,200 tSWU/yr	
All processes: Total enrichment capacity available in 2003	53,500 tSWU/yr	
Total enrichment capacity required in 2003	35,000 tSWU/yr	
[a] IAEA refers to safeguards applied by the International Atomic Energy Agency, Euratom to safeguards applied by Euratom, and ABAAC to safeguards applied by the Argentine-Brazilian Agency for Accounting and Control of Nuclear Material.		

[13] See http://www.antenna.nl/wise/uranium/efac.html for lists of all of these plants except for those of Brazil and Iran.

While world demand for enrichment work is currently reduced by LEU originating from down-blended Russian HEU,[14] various additional centrifuge projects are in the advanced planning stages. As a result, even if the worldwide installed reactor capacity does not grow, the total centrifuge capacity will probably double by the time the two remaining large gaseous diffusion plants are shut down. Since centrifuge facilities can be operated economically in relatively small modular units,[15] the total *number* of facilities could increase substantially.

A small gas-centrifuge plant capable of producing a significant, i.e., weapons quantity (defined by the IAEA to be uranium containing 25 kg ^{235}U) of weapon-grade uranium per year could be hidden relatively easily in a small, anonymous building or even in a cave. The floor area required would be on the order of 1000 square meters.[16] A plant of this capacity would consume only about 100 kilowatts of electrical power.[17] Remote sensing techniques or wide-area environmental monitoring to detect gaseous releases would likely not be effective in detecting such a small centrifuge facility.[18]

A single cascade within a large centrifuge plant designed to produce 4–5 percent LEU could quickly produce weapon-grade uranium if the output were passed twice more through the cascade. Alternatively, three such cascades could be arranged in series.[19]

---

[14] The 500 metric tonnes of the original 20-year HEU deal, when diluted with natural uranium down to LEU and used as fuel in light water reactors, will have fueled the equivalent to 500 GWe-years. (Note that, in practice, the HEU is not diluted with natural uranium, but with 1.5 percent–enriched feed-stock produced from uranium tails assays). The world's fleet of light water power reactors generates about this much power in two years. Therefore, although significant, this quantity, and even potential additional stocks of military HEU that could become available in the mid-term future, both combined are not sufficient for a long-term structural impact on the LEU market. Down-blended military stocks could defer, but ultimately not prevent construction of additional enrichment plants for a given total reactor capacity.

[15] Capacities of centrifuge plants are typically 10 times smaller than those of large gaseous diffusion plants.

[16] Taking 200 kilogram separative work units (SWU) as the amount of enrichment work required to produce a kg of 90 percent enriched uranium and assuming 5 SWUs/machine-year, approximately 1000 machines would be required. One source gives the outside diameter of the Urenco G-2 casing as 0.22 m and the outside diameter of the rotor as about 0.15 m; see Mark Hibbs, "Customs Intelligence Data Suggest DPRK Aimed at G-2 Type Centrifuge," *Nuclear Fuel* 28 (26 May 2003): 3. Assuming that a single centrifuge occupies on average an area of $(0.5\ m)^2 = 0.25\ m^2$, the equipment could be fit into a square area less than 20 meters on a side. Including support equipment, the area of an entire facility could be about 40x40 meters.

[17] Based on 50–240 kwh/SWU for centrifuge plants. Maurice Lenders, "Uranium Enrichment by Gaseous Centrifuge" (presentation to Deutsches Atomforum, Dresden, May 2001), http://www.urenco.com/pdf/atomforum_May_2001.pdf.

[18] Centrifuge plants operate at very low pressures. Leakage therefore ordinarily would be *into* rather than *out of* the system resulting in very low leakage rates of materials that could be detected off-site. This is not to say that a country undertaking uranium enrichment would be free of risk of discovery. Aside from the centrifuges themselves, the enterprise would include uranium hexafluoride production and possibly dedicated electrical power systems capable of being detected. Also accidents, such as an exploding centrifuge (which happens) could give away the game.

[19] In one sample configuration, a cascade for the production of 3.8 kg/day of 4.4 percent enriched uranium would involve 1,628 centrifuges with 11 stages, including both enrichment and depletion sides, with 17 centrifuges at the top of the cascade. Alexander Glaser, "The Gas Centrifuge and Nuclear Weapons Proliferation" (presentation at the Stanford summer study, 18 August 2003). If such a cascade were fed

A common measure of enrichment capacity is the kilogram separative work unit, or SWU. It would require about 200 SWUs to produce 1 kilogram of weapon-grade uranium, starting with natural uranium as feed, and therefore 5,000 SWUs to produce one significant quantity (or critical mass). Compared with this, the capacity of a large commercial enrichment plant (on the order of 1 million SWU per year) is immense. It would require only about 1 percent of the centrifuges of such a plant to produce 200 kilograms of 90 percent enriched uranium annually—enough for 8 nuclear weapons.[20]

Current IAEA safeguards standards for centrifuge enrichment plants do not include independent verification of the actual installed enrichment capacity. As a consequence, there is the possibility of covert production of HEU in declared facilities or the covert production of additional undeclared LEU that could be enriched to HEU in a small covert facility.[21] Environmental (swipe) sampling techniques, which were developed and implemented in the 1990s, would provide an effective tool to detect undeclared HEU production if they were used inside the facility. Measurements of minor uranium isotopes in the tails, which are easy to do and non-intrusive, could also indicate the production of HEU. Verifying that no undeclared LEU production has taken place would require independent verification of a plant's enrichment capacity and of the plant's material balance.

We recommend that the IAEA and member countries agree to

- limit the number of enrichment plants,
- strengthen the international safeguards at centrifuge enrichment plants, and
- subject them to an extra layer of multinational safeguards.

More detail providing backup for these recommendations is given below.

---

with 4.4 percent enriched uranium, it could produce 26.4 percent enriched uranium. Fed 26.4 percent enriched uranium, it could produce 86 percent enriched uranium. The mass of feed for the second and third cycles would be 1/8 and 1/56 that of the first. The enrichment times would be shorter in the approximately the same ratio.

[20] Assume that the 4.4 percent LEU is enriched in two stages: 1) to 26.4 percent enrichment with 0.711 percent tails and 2) to 90 percent enrichment with 4.4 percent tails so that no new feed ports are required to dispose of the tails. The ratio of feed to product is $F/P = (e_p - e_t)/(e_f - e_t) = 6.95$ for the first stage and 3.89 for the second stage, where e_p, e_f, and e_t are respectively the fractional enrichments of the product, feed, and tails. The formula for SWUs per kg. of product is $V(e_p) - V(e_t) - F/P[V(e_f) - V(e_t)]$, where $V(x) = (2x-1)\ln[x/(1-x)]$, $V(0.00711) = 4.87$, $V(0.044) = 2.81$, $V(0.264) = 0.484$, $V(.9) = 1.76$. Therefore, 12 SWUs are required to produce 1 kg of 26.4 percent enriched uranium from 4.4 percent enriched uranium and 8 SWUs to produce 1 kg of 90 percent enriched uranium from 26.4 percent enriched uranium. To produce 1 kg of 90 percent therefore requires 27 kg of 4.4 percent enriched uranium and 54.7 SWUs. To produce 222 kg of 90 percent enriched uranium containing 200 kg of U-235 from 600 kg of 4.4 percent enriched LEU requires 12,000 SWUs or 1.2 percent of the capacity of a million SWU/yr plant.

[21] It should be noted that number of SWUs required to produce a given amount of weapon-grade uranium would be significantly reduced if the feed to the covert facility is LEU rather than natural uranium; and the feed could be further reduced if the tails assay is increased.

Limit the number of centrifuge plants. Article IV of the NPT currently is interpreted to give countries the right to obtain enrichment technology, because it is an essential part of the fuel cycle of most reactors. However, Articles I and II of the NPT can be interpreted as requiring that the risk of nuclear proliferation be minimized as long as all states can fully enjoy the civilian benefits of nuclear technology. We believe that balancing these two interests requires the international community to minimize the number of locations where enrichment facilities are built, subject to the requirement that there are enough producers so that any NPT party in good standing has an assurance of supply at competitive prices. The current number of plants and the diversity of their locations and ownerships does provide a reasonable level of such assurance, which could be strengthened still more through explicit guarantees by the nuclear suppliers.

In his talk at the National Defense University on 11 February 2004, President Bush called upon the Nuclear Suppliers Group (NSG) of countries to deny enrichment and reprocessing technologies "to any state that does not already possess full-scale, functioning enrichment and reprocessing plants," and, at the same time, to ensure that states that do not have enrichment plants have reliable access to civilian reactor fuel.[22]

A problem with the Bush proposal is that it creates a new discrimination within the NPT regime in addition to the fundamental one between nuclear and non-nuclear weapons states. In addition, if the Bush conditions are applied rigorously, some countries such as Australia and Canada—to take two countries among others with impeccable nonproliferation credentials who may wish to develop enrichment capabilities—would be denied the facilities, while Argentina and Brazil for example might not be if their small existing enrichment plants are seen as entitling them to remain members of the uranium-enrichment club. For these reasons, the Bush proposal appears unlikely to be accepted for the long term.[23] In their June 2004 summit meeting, the G-8 states were only willing to agree to a one-year moratorium on exports of enrichment and reprocessing plants despite the fact that no member of the NSG has contracted to export either type of plant to a non-weapons state since the 1970s.[24]

We propose that no new enrichment facilities be built anywhere without a persuasive economic rationale based on projected market demand and taking into account the existing capacity of other facilities. Nations and firms that propose new centrifuge-enrichment plants should be challenged by other countries (as well as within the country proposing the new plant) and the IAEA and be asked to provide a detailed justification explaining why the enrichment services that the new enrichment plant is expected to provide could not be provided more economically by an existing enrichment plant. A

---

[22] The White House, "Fact Sheet: Strengthening International Efforts Against WMD Proliferation" (11 February 2004), www.whitehouse.gov/news/releases/2004/02/20040211-5.html.

[23] See, e.g., Jon Wolfsthal, "The Nuclear Third Rail: Can Fuel Cycle Capabilities Be Limited?" *Arms Control Today* (December 2004).

[24] The G-8 governments agreed that "it would be prudent not to inaugurate new initiatives involving transfer of enrichment and reprocessing equipment and technologies to additional states" and called upon all states to adopt this strategy of prudence. "G-8 Action Plan on Nonproliferation," G-8 Summit 2004, Sea Island (10 June 2004), http://www.g8usa.gov.

formal international licensing process could be organized under the auspices of the IAEA or possibly a special committee set up under the Security Council.

The U.N. High-Level Panel put forward a similar proposal that "States should … voluntarily institute a time-limited moratorium on the construction of any further enrichment or reprocessing facilities, with a commitment to the moratorium matched by a guarantee of the supply of fissile materials by the current suppliers at market rates."[25]

Whether a moratorium is framed as voluntary or not, France and the United States, both of which propose to build large new centrifuge plants to replace their aging gaseous diffusion plants, should set positive examples by offering formal justifications for their proposed new facilities and preparing "proliferation-impact statements." So should any other country in the future wishing to undertake uranium enrichment.

Countries that forgo their own enrichment facilities will rightly demand strong guarantees of fuel supply. As noted, the diversity and capacity of existing facilities already provides assurance of supply of low-enriched uranium at competitive prices. But it would also be helpful, as part of a comprehensive approach to this problem, for the nuclear suppliers to issue new explicit guarantees of uninterrupted fuel supply to any country with civilian nuclear power unless that country were found in noncompliance with the NPT by the IAEA and then the Security Council.

Strengthen international safeguards. The first enrichment facilities were built in the nuclear-weapons states to produce HEU for weapons and then converted in Russia and the United States and supplemented in China, France, and the United Kingdom to produce LEU for nuclear power plants. Because of this history, for two decades, the supply of enrichment services of LEU for commercial purposes was monopolized by these nuclear weapon states. Their enrichment facilities were unsafeguarded when constructed and, in Russia and the United States, remain so today.

In the mid-1970s, three non-weapons parties to the NPT, Germany, Japan, and the Netherlands, decided to build centrifuge enrichment plants. The NPT required that these facilities be placed under IAEA safeguards. Studies carried out under the auspices of the IAEA in the 1970s revealed that no simple safeguards concept existed that would be acceptable for centrifuge enrichment facilities.[26] Because centrifuge facilities show a high degree of operational flexibility, the natural safeguards approach would be to require intrusive monitoring. However, centrifuge technology holders were concerned that their design secrets might be compromised if the inspectors had access to their machines. As a result, the question of whether or not inspectors would have access to the cascade halls at all was the subject of considerable debate.

---

[25] U.N., *More Secure World*, para. 131.

[26] A. von Baeckmann, "Implementation of IAEA Safeguards in Centrifuge Enrichment Plants," *Proceedings of the Fourth International Conference on Facility Operations-Safeguards Interface*, Albuquerque, N. Mex. (29 September – 4 October 1991), 185–190.

The current safeguards arrangements for centrifuge enrichment plants were worked out in the Hexapartite Safeguards Project (HSP) that met under IAEA auspices from 1980 to 1983.[27]

In essence, the HSP approach allows carefully delimited access of the inspectors to the cascade areas. The main purpose of this access is to verify that no material has been enriched beyond the declared enrichment level and in particular that no HEU is being produced—a fact that was considered too difficult to assure with safeguards methods applied outside the cascade halls.[28]

Monitoring activities outside the cascade halls are focused mainly on material accountancy. The main objective of these procedures is to verify that all of the declared natural uranium fed into the facility is accounted for in the form of enriched and depleted product material and to attempt to detect evidence of any undeclared feed and withdrawals.

Technological advances made since the 1980s make possible the development of tighter safeguards that provide for reliable verification of plant capacity via SWU metering and therefore assurance that no undeclared feedstock is being used. The use of swipe sampling and continuous air sampling allows real-time monitoring of the isotopic composition of uranium particles in the air and thereby verification that no HEU is being produced.[29] These approaches are included in the IAEA safeguards recently proposed for the Chinese centrifuge facility at Shaanxi.[30] More work is required, however, to integrate these techniques with the HSP safeguards approach and to persuade states to cooperate with the IAEA in their implementation. This new standard should ultimately be applied to all currently operating facilities. New plants should be required to have safeguard-friendly designs from the ground up.

Here again, France and the United States can set a good example with their proposed large new centrifuge plants by cooperating with the IAEA in advancing the

---

[27] The members of the HSP are the IAEA, Euratom, Australia (which was considering constructing a centrifuge enrichment plant at the time), Japan, the United States, and the parties to the 1970 Treaty of Almelo under which the United Kingdom, Germany, and Netherlands cooperate on centrifuge enrichment. For an early discussion of the HSP, see J. H. Menzel, ed., "Safeguards Approach for Gas Centrifuge Type Enrichment Plants," *Nuclear Materials Management* 12, no. 4 (Winter 1983): 30–37.

[28] A maximum access delay of two hours is permissible in order to allow the operator to protect exposed visible information (for instance, to conceal open centrifuges or centrifuge components), which otherwise might be compromised. Four to 12 unannounced annual visits take place in facilities with up to one million SWU/yr capacity.

[29] J. Cooley et al. (IAEA) and P. Friend et al. (Urenco), "Experience with Environmental Swipe Sampling in a Newly Built Gas Centrifuge Enrichment Plant," *Proceedings of the 40th Annual Meeting of the Institute of Nuclear Materials Management* (1999); W. Bush et al. (IAEA), "IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union" *Proceedings of the Symposium on International Safeguards,* IAEA (2001).

[30] A. Panasyuk, A. Vlasov and S. Koshelev (Russian Ministry of Atomic Energy); T. Shea and D. Perricos (IAEA); and D. Yang and S. Chen (China Atomic Energy Authority), "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," *Proceedings of the Symposium on International Safeguards,* IAEA (2001).

state-of-the-art in international safeguards. This would strengthen their ability to insist that all countries be subject to such strict procedures. In addition, all countries operating or hosting enrichment facilities should accept the Additional Protocol (INFCIRC/540).

Multinational involvement. On 3 November 2003, in a speech at the United Nations Mohamed ElBaradei, director general of the IAEA, proposed that enrichment and reprocessing be restricted "exclusively to facilities under multinational control."[31]

Multinationalization of the fuel cycle has been considered off and on since at least the 1970s. Indeed, NSG guidelines already state that suppliers should "encourage" recipients to "accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities."[32]

The merits and drawbacks of a layer of multinational involvement would depend, however, on the details of how it is accomplished. Multinational control could involve multinational ownership of critical facilities, multinational management, or multinational oversight of various kinds; and it might or might not grandfather existing facilities that are not now under multinational auspices.[33]

Multinational involvement also must be designed so that it does not contribute to the proliferation of centrifuge technology. We note in this connection that the existing multinational enrichment arrangements at Urenco and Eurodif were designed mainly to minimize and share economic risks involved in developing enrichment capacities able to compete with existing U.S. supplies. Nonproliferation criteria were not given high priority and experience has shown that the Urenco arrangements, at least, were not robust with respect to nonproliferation.[34] Nevertheless, even those poorly designed arrangements do have indisputable virtues if they serve as an alternative to a proliferation of small national enrichment plants.

---

[31] Mohamed ElBaradei, IAEA director general (statement to 58th Regular Session of the U.N. General Assembly, 3 November 2003). ElBaradei's statement was ambiguous in that it referred to facilities producing *high-enriched uranium*, not enrichment facilities per se; however in other statements, ElBaradei appears to mean the latter: for example, Mohamed ElBaradei, "Saving Ourselves from Destruction," op-ed, *New York Times*, 12 February 2004, A37.

[32] Sec. 6 of the NSG Part I guidelines, published in IAEA INFCIRC/254/Rev.5/Part 1 (Corrected), "Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment, and Technology," http://www.nsg-online.org/guide.htm.

[33] Lawrence Scheinman, "The Nuclear Fuel Cycle: A Challenge for Nonproliferation," *Disarmament Diplomacy* (March/April 2004). See also Tariq Rauf and Fiona Simpson, "The Nuclear Fuel Cycle: Is It Time for a Multilateral Approach?" *Arms Control Today* (December 2004).

[34] Urenco involuntarily became a source of centrifuge technology for Iraq and Pakistan, and indirectly (via Pakistan) to Iran, Libya, and North Korea. In Urenco, each participating country operates its own enrichment facility, pursues national R&D on centrifuge technology, and withdrawal from the Urenco founding agreement (the Almelo Treaty of 1970) is not precluded. For a more detailed discussion of nonproliferation criteria for multinational enrichment arrangements, see A. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation*, Stockholm International Peace Research Institute (SIPRI), (London and New York: Taylor & Francis Ltd, 1983).

Therefore, in cases when construction of an enrichment facility is justified by regional needs, regional arrangements that provide an extra degree of control should be encouraged as an important confidence-building measure. Arrangements for regional transparency, such as Euratom and the Argentine-Brazilian Agency for Accounting and Control of Nuclear Material (ABACC), should be strongly encouraged.

Here again, to set a good example, France and the United States should explore different forms of multinational transparency for their proposed new centrifuge enrichment plants.

5. There should be a moratorium on new spent-fuel reprocessing

Reprocessing of spent fuel to separate plutonium is one of the two routes (along with uranium enrichment) to the acquisition of nuclear-weapons material. This is the reason that President Bush, IAEA Director ElBaradei, and others have looked for ways to prevent the proliferation of reprocessing technologies. The dangers of such proliferation are especially evident in the case of the current reprocessing technology being employed—the so-called PUREX process—which is designed to produce a stream of plutonium unmixed with fission products or other transuranic elements that could complicate the extraction of the plutonium in a form where it could be readily converted into plutonium metal or oxide.

Unlike enrichment, reprocessing is an unnecessary technology for the current generation of nuclear power plants. These reactors operate on a once-through fuel cycle, with the spent reactor fuel stored at the reactor site for several years, with the expectation that the fuel will eventually be sent to a geological repository. Spent fuel can be stored at low cost and risk for many decades, either at reactors or in centralized storage facilities, pending permanent geological disposal or an agreement on some other disposal approach.

Huge stockpiles of separated plutonium have accumulated already as a result of civilian reprocessing. The amount of plutonium in these civilian stockpiles approximately equals all of the weapons plutonium produced for the world's nuclear weapons. This plutonium has accumulated in large part because Russia and the United Kingdom have not sought to recycle the plutonium recovered from the reprocessing into fresh fuel.[35] Also, the Japanese nuclear industry, which has planned to recycle its approximately 40 tons of separated plutonium, has been stymied for a decade by the opposition of local populations around the reactor sites. The result has been an accumulation worldwide of more than 200 tons of separated civilian plutonium—enough to make 25,000 Nagasaki-type warheads. It is difficult to justify further plutonium separation at a time when the international community has been unable to find enough funding to help Russia dispose of the 34 tons of plutonium that it has recovered from dismantled weapons and declared excess.

Furthermore, reprocessing with the subsequent recycling of plutonium in the fresh fuel for the current generation of reactors is not economic at current prices for uranium and other fuel-cycle services.[36] Although separation and recycling of plutonium could

---

[35] The United Kingdom has only one light water reactor to handle recycling and has not seriously considered recycling in its gas-cooled reactors. Russia has long thought of its plutonium as startup fuel for a breeder program sometime in the future. As already noted, at current uranium prices, plutonium recycling is uneconomic—even if the plutonium input to a mixed-oxide facility is considered free.

[36] The most recent survey of nuclear-fuel-cycle economics may be found in Matthew Bunn, Steve Fetter, John Holdren and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Managing the Atom Project, Harvard University, 2003). For natural uranium costing $50/KgU, and the central cost estimates used in this report for conversion, enrichment, and uranium fuel fabrication pf $6/kgU, $100/kgSWU, and $250/kgU respectively, 1 kilogram of 4.4 percent enriched LEU fuel would cost $1200/kgU. The central estimate of the authors for the cost of fabricated MOX fuel is $1500/kgHM (HM = heavy metal, i.e. total uranium plus plutonium in the MOX). Thus, even when the

become economic in case of much higher uranium prices and/or at sharply reduced reprocessing costs, such conditions seem unlikely to be achieved in the coming decades, even with a substantial expansion of nuclear power. This is discussed in more detail in Appendix A.

Since reprocessing is unnecessary to a nuclear power program and expensive, one might expect that there would be little demand for reprocessing plants in countries that do not now have them, even if the countries are planning to deploy nuclear reactors. This is today largely the case. But for countries that may in the future wish to assert a right to reprocessing, the case against this is complicated by the ongoing reprocessing programs in a few countries—notably France, India, Japan, Russia, and the United Kingdom.

The reprocessing activities of France, Russia, and the United Kingdom grew out of their weapons programs, which gave them a strong foundation to develop the capability to handle spent fuel from civilian nuclear reactors. These activities also have been financed in part by payments from Germany, Japan, and a few other countries in Eastern and Western Europe to handle their spent fuel. The United Kingdom is reprocessing its own spent fuel partly because much of this fuel cannot long be stored in water, and it is not recycling the separated plutonium. Russia also is not recycling. Therefore, in Russia and the United Kingdom, the separated plutonium is accumulating in storage. Of the three main reprocessors, only France is recycling the plutonium separated from its own spent fuel into its LWRs. Japan has had plans to recycle its separated plutonium but has not done so yet on a commercial scale, but is nearing completion of a large new reprocessing plant at Rokkasho.[37] India also has not been recycling.

The initial impetus for the reprocessing was the expected advent of plutonium breeder reactors that would use plutonium extracted from LWR spent fuel in startup cores. In India, Russia, and perhaps Japan, interest in a future breeder program still is a motive for reprocessing. But the economics of breeder reactors is as poor as that for recycling plutonium in LWRs, and the introduction of truly competitive breeder reactors appears decades away.[38] Furthermore, the foreign countries that have sent spent fuel to France and the United Kingdom for reprocessing are not renewing contracts, so that the reprocessing enterprises there are shrinking. As discussed further in Appendix A, the U.K. reprocessing enterprise is expected to shut down around the end of the decade, and

---

plutonium is taken to be free, each kilogram of MOX fuel would cost considerably more than an equivalent kilogram of uranium fuel. The high cost of MOX fuel fabrication is due in large part to the high cost of building a MOX-fuel-fabrication plant (construction cost of $0.5-1 billion for a plant with a capacity of 120 tons HM/yr) and the high cost of operating it (about $600/kgHM). A memorandum by the Nuclear Energy Division of the French CEA points out that the cost penalty of reprocessing and recycling is small compared with the total cost of electricity and that the long-term waste disposal advantages of the reprocessing could justify the added costs. Jacques Bouchard, "Comments on the MIT Report on the Future of Nuclear Power—an Interdisciplinary MIT Study," presented in a letter to Ronald Lehman, Lawrence Livermore National Laboratory, 17 September 2003—hereinafter referred to as the *Bouchard Memorandum*.

[37] The Federation of Electric Power Companies of Japan calls the closed fuel cycle part of the "vital goal of ensuring energy security" for Japan. See *Power Line* 25 (July 2004), http://www.fepc.or.jp/english/powerline/25/.

[38] Bunn et al., *Economics of Reprocessing*.

one of the reprocessing plants at La Hague in France is scheduled soon to stop operation. Japan's reprocessing plant at Rokkasho is heavily subsidized and its startup has been delayed.

Advocates of reprocessing believe it could mitigate the nuclear waste-disposal problem.[39] It could help some in certain circumstances. But to have a significant long-term impact on waste disposal, reprocessing would have to be accompanied by a large deployment of fast-neutron reactors to help fission the recycled plutonium and other transuranics. Although each recycle could reduce the *net* quantities of these materials, the plutonium and other transuranics would have to be recycled through several generations before they were reduced to very low levels.[40] At present levels of technology, such repeated recycling would make nuclear power much more costly, and it would also produce new and accompanying streams of radioactive wastes, including the waste from decommissioning the reprocessing and transuranic fuel fabrication facilities. The potential use of reprocessing to rationalize waste disposal is addressed in further detail in Appendix A.

A second argument recently put forward by advocates of reprocessing is that advanced separation techniques could be developed to make reprocessing more proliferation resistant (and possibly also more economic). In particular, the United States has under way an advanced fuel cycle initiative focused on pyroprocessing, which would keep the separated plutonium always mixed with other transuranic elements and possibly also some radioactive fission products. While the proliferation resistance of such advanced reprocessing would be superior to the current PUREX process, in which undiluted plutonium is produced at the reprocessing plant, it nevertheless appears inferior from a nonproliferation perspective to the once-through fuel cycle in which the spent fuel is not reprocessed at all. This is because the advanced separation schemes create difficult measurement challenges, thus complicating safeguards, and also because they appear vulnerable to simple modifications that would allow the separation of pure plutonium. This is discussed further in Appendix A.

For reasons discussed above, we believe that the IAEA and member countries should agree on the following:

- There should be a moratorium on constructing new reprocessing facilities as long as the world has not solved the problem of the existing huge stockpiles of separated plutonium and until there is a strong economic justification for reprocessing.[41]

- Research and development on advanced reprocessing and recycle technologies should be confined to countries already operating reprocessing plants. In particular,

---

[39] See, e.g., *Bouchard Memorandum.*
[40] To our knowledge, the requirement of repeated recycling was first made clear by Thomas Pigford, "Actinide Burning and Waste Disposal: Questions and Commentary," *MIT International Conference on the Next Generation of Nuclear Power Technology* (5 October 1990).
[41] As noted above, the U.N. High-Level Panel suggested that a moratorium be voluntary; *More Secure World*, para. 131.

cooperation with other countries in the U.S. Advanced Fuel Cycle Initiative should be structured so that the cooperation does not lead to the spread of sensitive technologies, such as hot cells with remote manipulators, to non-reprocessing states.

- Nations should place their spent fuel in interim dry storage after it has cooled for a few years and groups of nations should jointly develop safe and secure storage in regional repositories. Such regional repositories would make strong economic sense for countries with small nuclear power programs. Until there is some political consensus, however, on what to do with spent fuel in the long term, most such storage facilities will have to be considered interim facilities.

6. A verified ban should be concluded on new production of fissile material for weapons

"The Conference agrees on the following practical steps for the systematic and progressive efforts to implement . . . the 1995 Decision on 'Principles and Objectives of Nuclear Non-Proliferation and Disarmament: . . . including the necessity of negotiations at the Conference on Disarmament on a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other explosive devices . . . with a view to their conclusion within five years."
—*Final Document of the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons,* discussions of Article VI, para. 15.

Article VI of the NPT requires nuclear-weapon states to

> pursue negotiations in good faith on effective measures relating to a cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control.

One of the central measures relating to fissile material that is being urged upon the weapon states is a verifiable ban on the production of additional fissile material for weapons. This measure would also help reduce the risks of nuclear terrorism since material that is not produced cannot be stolen.

With the end of the Cold War, the five NPT weapons states all announced (China informally) that they had either ended or suspended their production of fissile material for weapons (see Table 6.1). A Fissile Material Cutoff Treaty (FMCT) would make these commitments permanent and legally binding and should be done verifiably. That would in turn make reductions in warhead stockpiles irreversible to the extent those reductions included disposition of the fissile materials recovered from dismantled warheads. If the treaty were joined by India, Israel, and Pakistan, it would also limit the buildup of their warhead stockpiles and begin to integrate the three non-NPT nuclear weapons states into the global fissile-material-control regime.

In 1993, the U.N. General Assembly voted without opposition to launch negotiations on a "non-discriminatory, multilateral and international and effectively verifiable treaty banning the production of fissile material for nuclear weapons and other explosive devices."[42] The U.N.'s forum for such negotiations is the Conference on Disarmament in Geneva, which operates by consensus.

[42] UNGA 48/75L Consensus Resolution (16 December 1993), http://www.acronym.org.uk/fissban/unga93.htm

Unfortunately, more than a decade after the U.N. resolution, negotiations on a FMCT have not made progress. Launch of the negotiations was stalled by the insistence of various countries on linkages to other negotiations—most recently linkage by China and Russia to talks on a treaty to prevent the weaponization of outer space. However, in 2003 countries dropped all requirements for strong linkage and the way appeared open for negotiations. [43]

Table 6.1. Status of fissile material production

	HEU[44]	**Military Pu**[45]	**Civilian Pu**[46]
China	Halted (1987/8)	Halted (1991)	Separating?
DPRK	Active program	Producing	------
France	Ended (by 1996)	Ended (1994)	Separating
Israel	?	Producing	------
Japan	------	------	Resumption planned
Pakistan	Producing	Producing	------
India	Producing	Producing	Separating
U.K.	Ended (1963)	Ended (1996)[47]	Separating
U.S.	Ended (1992)	Ended (1988)	Ended (1972)
USSR/Russia	Ended (1987/8)	Separating[48]	Separating

An FMCT would constitute an agreement by the weapons states to match a central NPT commitment of the non-nuclear weapons states: not to produce fissile

[43] In early August 2003, China and Russia accepted a weakening of their linkage requirements to the establishment of a group dealing with nuclear disarmament (i.e., no requirement of negotiations) and discussions of PAROS (Prevention of an Arms Race in Outer Space) "including the *possibility* of negotiating a legally binding instrument" [emphasis added]. Hu Xiaodi, Ambassador for Disarmament Affairs of China, Plenary of the 2003 Session of the Conference on Disarmament (7 August 2003), http://www.china-un.ch/eng/53991.html.

[44] David Albright, Frans Berkhout and William Walker, *Plutonium and High-Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (Oxford: Stockholm International Peace Research Institute [SIPRI] and Oxford University Press, 1997), table 4.1; 83.

[45] Ibid., 40, 68, 76.

[46] Ibid., 156.

[47] *A Summary Report by the Ministry of Defence on the Role of Historical Accounting for Fissile Material in the Nuclear Disarmament Process, and on Plutonium for the United Kingdom's Defence Nuclear Programme*, http://www.mod.uk/publications/nuclear_weapons/accounting.htm.

[48] Russia is still operating three plutonium-production reactors because they provide heat for local populations, but it agreed in September 1997, in exchange for U.S. assistance in converting these reactors, that "The plutonium produced after entry into force of this Agreement in the reactors . . . shall not be used in nuclear weapons" and would be subject to U.S. monitoring; *Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors,* articles IV, V. In March 2003, the United States and Russia agreed instead to shut down the reactors and replace them with fossil-fueled plants, but the estimated cost of doing so has increased to more than $1 billion; *DOE's Effort to Close Russia's Plutonium Production Reactors Faces Challenges, and Final Shutdown Is Uncertain* (U.S. Government Accountability Office, GAO-04-662, June 2004).

material for weapons. The verification arrangements could be similar to those accepted by the non-nuclear-weapons states under the NPT—although significantly more bounded in that HEU and plutonium produced before the treaty came into force would not be subject to IAEA inspection.

The United States has been a leading proponent of an FMCT. In July 2004, however, the Bush Administration announced a major shift in the U.S. position, declaring that it now opposes provisions for inspections and verification as part of the treaty. The State Department released a statement that inspections "would have to be so extensive that it could compromise key signatories' core national security interests and so costly that many countries will be hesitant to accept it." It argued further that "even with extensive verification measures, we will not have high confidence in our ability to monitor compliance with an FMCT."[49]

Even without on-site inspections and other agreed inspection procedures, some monitoring of an FMCT would be possible. For example, satellite images could verify that large plutonium-production reactors and gaseous-diffusion enrichment plants are not operating.[50] However, it is impossible to determine remotely whether an operating enrichment plant is producing low- or high-enriched uranium—or whether civilian plutonium or high-enriched uranium is being diverted to weapons use. Similarly, India and Pakistan could not monitor a shutdown of each other's reprocessing plants without at least being able to emplace instruments on each other's territories to detect the krypton-85 that is released to the atmosphere by reprocessing.[51] Given such uncertainties, on-site inspection procedures will be needed and, despite the U.S. Administration's pessimism, we believe they could be effective, as evidenced by the recent record of the IAEA in helping to ferret out the clandestine fissile-material-production programs of Iran and North Korea. It is also valuable for the nuclear weapon states to accept similar verification arrangements to those now accepted by the non-weapons-state parties to the NPT.

This is not to say that it will be an easy matter to work out detailed and effective verification arrangements. Particular attention will have to be given to whether to allow production of HEU for naval production reactors and, if it is allowed, how to verify that the HEU is not diverted to weapons.[52] Since Russia and the United States have such huge

---

[49] Dafna Linzer, "U.S. Shifts Stance on Nuclear Treaty," *Washington Post,* 31 July 2004.

[50] Hui Zhang and Frank von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *Science & Global Security* 8 (2000): 261; Idem, "Building Confidence in a Fissile Materials Production Moratorium Using Commercial Satellites," *Disarmament Forum* 3 (2000): 71; Idem, "Eyes in the Sky: Watching for Weapons Work," *Bulletin of the Atomic Scientists* 57 (July/August 2001): 61. China's mothballed production reactors and enrichment plants have not been dismantled because China keeps open the option of resuming production if the United States appears to be deploying a missile defense that brings China's deterrent into question.

[51] Z. Mian and A. H. Nayyar, "An Initial Analysis of ^{85}Kr Production and Dispersion from Reprocessing in India and Pakistan," *Science & Global Security* 10 (2002): 151.

[52] The FMCT would bring newly produced fissile material in the weapons states under IAEA safeguards, except for fissile material produced to fuel military reactors—in practice, naval propulsion reactors. This loophole stems from a similar loophole in the NPT, which bans the diversion of fissile material "to nuclear weapons or other nuclear explosive devices" but requires safeguards only on fissile materials being used for

quantities of excess weapons HEU—on the order of 100 times more than the one or two tons a year or so that each requires for its naval reactors—the issue of their producing new HEU for that purpose need not arise for many decades. The United Kingdom is in the same position by virtue of its access to U.S. HEU.[53] The issue might therefore first arise for India, which is developing a reactor for a nuclear submarine that reportedly would use HEU fuel.[54] Brazil also has a prototype reactor for a nuclear submarine, but currently is expected to use low-enriched uranium (LEU).[55]

Similarly, for the weapons states, attention will have to be given to how to verify that reactors used to produce tritium for boosted nuclear weapons are not also being used to produce unsafeguarded plutonium.

In some respects, verification of an FMCT could be simpler than the safeguards in place in non-weapons states. For instance, spent fuel and LEU fresh fuel are subject to safeguards in the non-weapons states, since the spent fuel could be diverted and reprocessed and the LEU used as feed in an enrichment plant to produce HEU. But it may be less important to monitor the spent fuel and LEU as closely in the weapons states under a cutoff—at least in the near term—since these states already possess large stockpiles of fissile materials.

A cutoff could also be the core of a larger treaty that would require verifiable agreements on minimal standards for the physical security of fissile materials and provide a framework for irreversible reductions of fissile stockpiles by the nuclear weapons states. A candidate draft of such a larger treaty on fissile materials has been developed by Thomas Shea, a participant in the summer study. We include it as Appendix B to this report.

"peaceful purposes." The IAEA's model safeguards agreement with non-nuclear-weapons-state parties to the NPT therefore includes provisions for the termination of safeguards on fissile materials that a non-weapons state declares is required for "a non-proscribed military activity." Since this provision has never been utilized, it has not yet been determined how a non-weapons state could convince the IAEA that none of its unsafeguarded fissile material was being diverted to weapons use.

53 Chunyan Ma and Frank von Hippel, "Ending the Production of High-enriched Uranium for Naval Reactors," *Nonproliferation Review* 8 (2001): 86, http://cns.miis.edu/pubs/npr/vol08/81/81mahip.pdf.

54 Mark Hibbs, "India to Equip Centrifuge Plant with Improved Rotor Assemblies," *Nuclear Fuel* 22 (1 December 1997): 7.

55 Mark Hibbs, "Brazil May Enrich to HEU for Submarine Reactor Fuel," by *Nuclear Fuel* 25 (24 July 2000): 7.

7. Much more fissile material from excess weapons should be declared excess and eliminated

Table 7.1 Weapon-usable fissile materials end of 2003 (in metric tons)[56]

	Military HEU[57] [excess] (93% equiv.)	**Civilian HEU**[58]	**Weapon-grade Pu** [excess]	**Separated civilian Pu**[59] (in country)
Belgium	--	?	--	3.5
China	20 ± 5	?	4.8 ± 2	0
France	30 ± 7	6.4	5 ± 1.5	78
Germany		0.8	--	11
India	?		0.3-0.47	2-3[60]
Israel	--		0.5-0.65	
Japan	--	?	--	5.4
North Korea	?		0.015-0.038	
Pakistan	1-1.25		0.02-0.06	--
South Africa		0.4-0.6		
U.K.	~21	1.6	7.6 [4.4][61]	96
U.S.	700 ± 50 [123][62]	?	85 [38][63]	14.5
USSR/Russia	1070 ± 300 [300]	?	145 ± 25 [50][64]	38
Total	**1840 ± 360** [423]	**≈50**[65]	**248 ± 30** [92]	**≈ 252**

[56] Unless otherwise noted, based on David Albright and Kimberly Kramer, "Plutonium Watch: Tracking Plutonium Inventories," *Global Fissile Material Inventories* (June 2004), http://www.isis-online.org/global_stocks/plutonium_watch2004.html; "Military and Excess Stocks of Highly Enriched Uranium in the Acknowledged Nuclear Weapon States," *Global Fissile Material Inventories* (June 2004), http://www.isis-online.org/global_stocks/military_excess_heu.html; Albright and Kramer, "Stockpiles Still Growing."

[57]Excess refers to Russian, U.K., and U.S. declarations of quantities of weapons HEU and plutonium that they planned or agreed to dispose of. HEU that contains less than 90 percent U-235 has been equated to an amount of 93 percent enriched uranium that contains an equal amount of U-235. Since the declarations, the United States has down-blended approximately 50 tons of the HEU and Russia approximately 200 tons.

[58] Including in stored spent fuel.

[59] Based on national declarations to the IAEA concerning policies regarding the management of plutonium, InfCirc/549, http://www.iaea.org/pubications/documents/Infcircs. About 52 tons of the plutonium stored at French and U.K. reprocessing plants belonged to other countries, mostly sent by Japan and Germany, and smaller amounts sent by Switzerland, Spain, Sweden, and the Netherlands. The data for Germany, Russia, and the United States are for the end of 2002. Data for other countries are for end of 2003.

[60] M.V. Ramana, private communication, 5 January 2005. See appendix A, table A-1.

[61] *Role of Historical Accounting for Fissile Material in the Nuclear Disarmament Process.*

[62] Assuming that the entire 174.7 tons initially declared excess has an average enrichment of 62 percent.

[63] In its Infcirc/549 declaration (24 October 2003), the United States reported 52.5 tons of plutonium excess. This included 4.6 tons in unirradiated MOX fuel or other fabricated products, 7.5 tons contained in spent fuel, and 40.4 tons unirradiated plutonium held elsewhere. Table assumes the 52.5 tons includes 38 tons of weapons plutonium declared excess plus 14.5 tons of civilian and other plutonium.

[64] The total and excess include about 13 metric tons of plutonium produced in plutonium production reactors since 1994, which Russia has committed not to use in nuclear weapons.

[65] Albright and Kramer, "Stockpiles Still Growing," 14.

Russia and the United States have declared a portion of their military stocks, most of it recovered from dismantled nuclear warheads, as "excess," and have launched programs to dispose of some of this material (see Table 7.1).

The most important of these undertakings is the 1993 U.S.-Russian agreement under which the United States committed to buy, over a 20-year period, 500 tons of 90 percent enriched excess Russian high-enriched uranium (HEU) after the uranium had been blended down to the enrichment of 4 to 5 percent used in light water power reactors. The agreement has yielded an income for Russia's Atomic Energy Agency of about half a billion dollars per year, which has helped stabilize Russia's nuclear complex. This stabilization is an important security objective in its own right.

Russia and the United States each also agreed in 2000 to dispose of 34 tons of weapon grade plutonium. Implementation of this agreement is not progressing, however. Unlike HEU disposal, plutonium disposal will have to be subsidized. The current estimate of the subsidy required for disposing of the 34 tons of weapons plutonium that Russia has declared excess is about $2 billion. The G-7 countries[66] have agreed in principle to provide this subsidy but have not made sufficient firm commitments for the effort to be launched. U.S-Russian disagreements over liability for accidents would currently block progress even if financing were available.

From a security perspective, the most crucial near-term objective is that the plutonium be put into secure storage. In Russia, the plutonium could be put into the high-security storage facility that has been built for this specific purpose, with $500 million of U.S. Cooperative Threat Reduction program funds, near Russia's Mayak plutonium complex. With both the Russian and U.S. plutonium in secure storage, Russia and the United States could then investigate improvements or alternatives to the current disposal program.

Declarations of excess fissile material. Altogether, 734 tons of fissile materials recovered from Russian and U.S. weapons have been committed for disposition:

- Russia has declared excess 500 metric tons of 90 percent enriched uranium and 34 tons of weapon-grade plutonium (of which 25 tons will be from weapons[67]); and

[66] The G-7 were originally seven leading industrialized states: Britain, Canada, France, Germany, Italy, Japan, and the United States, which have been meeting annually since 1976 on global economic and political issues. The European Community (EC) has been participating since 1977 and Russia since 1994. The summit is now referred to as the G-8 counting the countries involved but not the European Community. The G-7 governments and the EC are the key donors in helping Russia with its Cold War legacy of nuclear, biological, and chemical weapons.

[67] Nine tons are to come from weapon-grade plutonium stored at the production reactors that originally produced it. "Mayak Fissile Materials Storage Facility," *Controlling Nuclear Warheads and Materials* (Nuclear Threat Initiative, 2004), http://www.nti.org/e_research/cnwm/securing/mayak.asp.

- The United States has declared excess 174.7 tons of HEU (130.7 tons of which has an average enrichment of 62 percent)[68] and 34.5 tons of weapon-grade plutonium (of which up to 27.6 tons will come from weapons[69]).

Assuming 3–4 kg of plutonium per warhead, 25 tons of plutonium is equivalent to about 7,000 warheads.[70] Similarly, assuming 25 kg of weapon-grade uranium per warhead, Russia's 500 tons of HEU corresponds to about 20,000 warheads and the approximately 100 tons of weapon-grade equivalent HEU declared excess by the United States corresponds to about 4,000 warheads.[71] (Since the plutonium and HEU are recovered from the same warheads, the warhead equivalents for the plutonium and the HEU should not be added.[72])

Comparing the numbers in Table 7.1 with the quantities of plutonium and HEU declared excess, it would appear that the United States has about 47 tons of weapon-grade plutonium and the equivalent of 525 ± 70 tons of weapon-grade uranium that have

---

[68] "U.S. High-Enriched Uranium: Another Piece of the Puzzle," *RWE Nukem Online* (August 2004), 4. Of the remaining 44 tons, 16 are in spent fuel from U.S. production reactors and 28 tons are currently simply described as "assorted."

[69] Attachment to letter from Linton Brooks, then DOE deputy administrator for Defense Nuclear Nonproliferation, announcing a revised strategy for U.S. plutonium disposition (fax, 23 January 2002). The United States actually declared 38.2 tons excess but 3.7 tons were in the form of dilute residues and in spent fuel and were rejected by Russia as no match for its clean plutonium metal.

[70] Four kg per weapon was used as a planning figure in *Managing and Disposition of Excess Weapons Plutonium* (U.S. National Academy of Sciences, 1994), 19, http://www.nap.edu/books/0309050421/html/index.html. Another estimate may be obtained from the fact that 3.4 tons of plutonium was consumed in 1,125 U.S. nuclear tests; *Plutonium: The First 50 Years* (U.S. Department of Energy, DOE/DP-0137, 1996), 3 and http://www.thebulletin.org/issues/nukenotes/so03nukenote.html.

[71] The U.S. Enrichment Corporation, the U.S. agent for purchasing the blended-down Russian weapons uranium, assumes an average of 25 kg per warhead (the quantity also designated by the IAEA as significant); http://www.usec.com/v2001_02/HTML/Megatons_status.asp.

[72] The plutonium is in the fission trigger of the warhead and the HEU is typically in the secondary fusion-fission stage. It appears, therefore, that Russia has declared excess the HEU equivalent to many more warheads than would be accounted for by its declaration of excess weapons plutonium. Similarly, the U.S. appears to have declared excess the plutonium recovered from more warheads than we have attributed to its declaration of excess HEU. These discrepancies can be explained: (1) The United States has declared excess proportionately less of its weapons HEU than plutonium because it is transferring most of the weapon-grade uranium recovered from its excess weapons to a stockpile reserved for future naval-reactor use; and (2) Russia has declared excess proportionately more weapon-grade uranium than weapons plutonium because it made a commercial deal with the United States to blend down the uranium and sell the resulting LEU to the United States for power-reactor fuel. Its declaration of excess weapons plutonium was simply a match to what the United States was willing to declare excess—although Russia is believed to have produced quite a bit more than the United States The United States has declared a total inventory of weapon-grade plutonium of 85 tons. This total includes 38 tons declared excess, only 34 tons of which was accepted by Russia as being concentrated enough to be weapon-usable); Albright et al., *Plutonium and High-Enriched Uranium 1996*, 49. Russia's inventory of weapon-grade plutonium as of the end of 1993 has been estimated at 131 ± 25 tons; Ibid., 58. Since that time, Russia has continued to operate three plutonium-production reactors because their heat is required during the winter. These reactors produce together on the order of one ton of plutonium per year.

not been declared excess.[73] Nongovernmental estimates of Russia's remaining HEU stocks are 220-895 metric tons, and of Russia's remaining weapon-grade plutonium stocks are 110 ± 20 tons.[74]

Most of the excess fissile material has been recovered from dismantled non-strategic warheads, which were retired as a result of the U.S.-Soviet reciprocal unilateral initiatives of late 1991. According to nongovernmental estimates, Russia retired 11,000-18,000 and the United States about 6,000 non-strategic warheads between 1991 and 2002.[75]

Today, Russia and the United States have each approximately 10,000 nuclear weapons (Russia possibly more). Under the 2002 Strategic Offensive Reductions Treaty, the United States and Russia agreed to downsize their stockpiles of operationally deployed strategic warheads to less than 2200 by 2012. Even granting each side an additional 1,000–2,000 non-strategic warheads and substantial reserves of non-deployed warheads and components,[76] both Russia and the United States would appear to have room and reason to undertake substantial further dismantling of warheads that would allow the release of more excess material. Indeed, in June 2004, the Bush Administration announced a "significant [but classified] reduction in the nation's total nuclear weapons stockpile by 2012."[77] According to nongovernmental estimates, the result will be to reduce the U.S. stockpile from about 10,000 to about 6000 warheads.[78]

The United States will likely be unwilling to declare additional fissile materials excess, however, until Russia provides more information about the quantities of fissile materials in its stockpile and makes parallel commitments. One critical step that Russia and the United States could take in parallel, therefore, is to make their fissile stockpiles more transparent.

Nongovernmental estimates of the total stockpiles of military fissile material held by other countries amount to about 50 tons of weapon-grade equivalent HEU and about 13 tons of weapon-grade plutonium. France, Russia, and the United Kingdom also have

---

[73] Albright, et al., *Plutonium and High-Enriched Uranium 1996,* 91. This source estimates U.S. stocks of HEU at 645 tons ± 10% (93% ^{235}U equivalent). Subtraction of the approximately 120 tons (weapon-grade equivalent) that the United States has declared excess reduces this to the equivalent of 525 tons ± 13% of weapon-grade HEU.

[74] Albright et al., *Plutonium and High-Enriched Uranium 1996,* 58, 113. We have assumed that Russia's three still-operating production reactors will have produced 20 tons of plutonium between 1994 till they shutdown.

[75] Joshua Handler, "The 1991-1992 [U.S. and Soviet Presidential Nuclear Initiatives] and the Elimination, Storage, and Security of Tactical Nuclear Weapons," *Tactical Nuclear Weapons,* eds. Brian Alexander and Alistair Millar (Brasseys, Inc., 2003), 20.

[76] The United States currently has a reserve of plutonium pits and HEU-containing secondaries sufficient to assemble about 5,000 warheads, "U.S. Nuclear Stockpile," *Bulletin of the Atomic Scientists* (July 1997), http://www.thebulletin.org/issues/nukenotes/ja97nukenote.html.

[77] "Administration Plans Significant Reduction in Nuclear Weapons Stockpile," National Nuclear Security Administration press release (3 June 2004).

[78] "NRDC Nuclear Notebook," *Bulletin of the Atomic Scientists* (September/October 2004).

well over 100 tons of plutonium separated from civilian spent fuel. Although this plutonium is not weapon-grade, it is weapon-usable.

At least one more cycle of reductions of weapons fissile-materials could be carried out on a bilateral Russian-U.S. basis before the stocks of other countries became significant on a relative scale (see Table 7.1).

Declarations of total stocks. The United States has published the total amount of plutonium in its stockpile[79] and has prepared but not yet released an unclassified report on the history of its production of HEU.[80] The estimates of U.S. plutonium in Table 7.1 are based on the former. The estimates of Russian fissile materials are murkier, since Russia has released no information about the size of its stocks of fissile materials beyond the much-debated 1993 statement by then Russian Minister of Atomic Energy Victor Mikhailov that Russia possessed two and one half times the 500 tons of weapon-grade uranium that it had agreed to sell to the United States.[81]

As the United States has demonstrated with its declaration of its plutonium stockpile, such declarations do not require a country to reveal sensitive information such as the amounts of fissile materials in specific types of nuclear weapons or in particular locations. What the declarations do require, if they are to be verifiable, however, is information about the history of fissile-material production and disposition. Information in the U.S. DOE report, *Plutonium: The First 50 Years,* includes the following accounts:

- Annual plutonium production at each of the two U.S. production sites; plutonium acquired from the fuel of other government reactors and civilian reprocessing; and the net from imports from and exports to individual foreign countries;

- Plutonium expended in nuclear explosions (3.4 tons in 1125 explosions); and

- Estimated losses to waste (3.4 tons), fission and transmutation in reactors (1.2 tons), and decay (0.4 tons, primarily 14-year half-life ^{241}Pu).

---

[79] *Plutonium: The First 50 Years* (U.S. Department of Energy, DOE/DP-0137, 1996).

[80] The report was scheduled for release in 1997 (http://www.osti.gov/html/osti/opennet/document/jan97/prcfacts.html#I11) but not then released. In response to a Freedom of Information Request from Roger Heusser, the former director of the DOE's Office of Nuclear and National Security Information, the Bush Administration agreed to release the report—but only after it has been revised, because it "contains unclassified but sensitive security information that terrorists could use as a road map to the locations of DOE fissile nuclear materials" (Joseph S. Mahaley of the DOE Office of Security, 9 June 2003, quoted in the Federation of American Scientists, *Secrecy in Government Report,* http://www.fas.org/sgp/news/2003/06/doe060903.html). The DOE did release some information in 1994, showing that total production of HEU (of unspecified enrichments) between 1945-1992 at Oak Ridge and Portsmouth was 994 metric tons; http://www.osti.gov/html/osti/opennet/document.

[81] E. Martin, "A View from the Top: Russia's Minister N. Mikhailov," *NUKEM Market Report* 3 (1993).

There is considerable physical evidence of both the production and use of plutonium and HEU.[82] This physical and available documentary evidence should be preserved to facilitate verification of future declarations.

HEU stockpiled for naval reactor use. The situation with the HEU stocks is complicated by the U.S. determination to reserve large quantities of weapon-grade uranium for future use in naval reactor fuel. One simple estimate suggests that the United States has sequestered for this purpose about 200 tons of weapon-grade uranium[83]—about 100 years of current U.K. and U.S. use.[84]

Disposition of excess weapons HEU. Russia's agreement to blend down and sell to the United States 500 tons of excess Russian weapon-grade uranium is a great success story of post-Cold War fissile-material policy. The 30 tons of weapon-grade uranium that Russia blends down each year as a result of this agreement fuels the equivalent of almost one half of the U.S. light water power-reactor capacity or about one-seventh of the world's nuclear-power capacity.[85]

There have been a number of proposals to accelerate this deal, which, at its currently agreed rate of 30 tons of 90 percent enriched uranium blended down per year, will be completed in 2013. Largely as a result of the blend-down agreement, the U.S. Enrichment Corporation (USEC), the broker for the Russian-U.S. deal, has already shut down one of the two U.S. enrichment plants and is operating the second at about 50 percent of nominal capacity. Neither USEC or any foreign enrichment supplier is willing to shut down additional enrichment capacity in order to make available a still larger share of the global uranium-enrichment market for blended-down Russia weapons uranium. And the Russian government has not yet shown interest in proposals that it partially blend

[82] Physical evidence of plutonium production includes transmutation products in the permanent components of plutonium-production reactors. Quantitative evidence of HEU production could be extracted from quantities, age, and isotopic makeup of depleted uranium at uranium-enrichment plants. See Steve Fetter, "Nuclear Archeology: Verifying Declarations of Fissile-Material Production," *Science & Global Security* 3 (1993), 237.

[83] The United States has declared 45 percent of its weapon-grade plutonium excess. If it had declared a similar fraction of its weapons uranium excess, it would have declared excess about 300 tons of weapon-grade-equivalent HEU. It has actually declared only the equivalent of about 100 tons. This suggests that the United States has sequestered for future naval-reactor use the equivalent of about 200 tons of weapon-grade uranium.

[84] Ma and von Hippel, "Ending the Production of High-Enriched Uranium for Naval Reactors," 86.

[85] The global enrichment market (excluding the reenrichment of depleted uranium) is 35-39 million SWUs/yr. Lenders, "Uranium Enrichment by Gaseous Centrifuge." Thirty tons of 90 percent enriched uranium, blended down with 1.5 percent enriched uranium can produce 886 tons of 4.4 percent enriched uranium. U.S. LEU requirements are the equivalent of approximately 2000 tons of 4.4 percent enriched uranium per year. Enriching natural uranium to produce a kg of 4.4 percent enriched uranium leaving 0.3 percent depleted uranium "tails" requires 9.8 kg of uranium and 6.0 SWUs. Therefore, the Russian weapons uranium is displacing almost 9,000 metric tons of natural uranium and about 5 million SWUs per year.

down additional weapon-grade uranium to create a stockpile of 20 percent enriched uranium that could be further blended down and sold at a later time.[86]

Disposition of excess weapons plutonium. In September 2000, the United States and Russia signed an agreement in which each committed to dispose of 34 metric tons (MT) of excess weapon-grade plutonium, at a rate of at least 2 metric tons per year, beginning no later than 31 December 2007.[87] The currently proposed method for disposal of excess weapons plutonium is in mixed-oxide (MOX) fuel, where plutonium would be mixed with depleted uranium. In this mix, the principal isotope of weapon-grade plutonium, ^{239}Pu, would substitute for the 4–5 percent ^{235}U that sustains the chain reaction in low-enriched uranium (LEU).

Because of the extreme inhalation hazard represented by plutonium oxide, the manufacture of MOX fuel costs more than the LEU that it would replace, even if the plutonium input is considered to be free.[88] As a result, plutonium disposition, unlike HEU disposition, is not self-financing. The forward cost of disposing of 34 tons of excess U.S. weapons plutonium in MOX has been estimated at $2.8 billion, of which only $0.7 billion would be recovered from the sale of the MOX fuel.[89]

As of the end of 2003, the U.S. program was at least a year behind its 2002 schedule with regard to its goal of starting construction of a U.S. MOX-fuel fabrication plant in 2004.[90] The situation is further complicated by the fact that the U.S. Congress requires that the U.S. and Russian plutonium-disposition programs proceed in parallel and the Russian program is facing a number of fundamental obstacles, including lack of funding, lack of U.S.-Russian agreement on the division of responsibility for liability for any damages, inadequate attention to security arrangements, inadequate reactor capacity to burn the MOX, and a vision of a plutonium fuel cycle in Russia that undercuts the rationale for the plutonium-disposition program. We describe each of these problems briefly below.

---

[86] The Nuclear Threat Initiative has launched a joint study with the Russian Atomic Energy Agency of possible accelerated blend-down initiatives. Daniel Horner, "NTI Blend-Down Study of Russian HEU to Examine Many Options for Speed-Up," *Nuclear Fuel* 28 (17 March 2003), 12. See also Robert Civiak, *Closing the Gaps: Securing High-Enriched Uranium in the Former Soviet Union and Eastern Europe,* Federation of American Scientists (2002), http://www.fas.org/ssp/docs/020500-heu/.

[87] The total amount of plutonium that Russia committed to dispose of under the Plutonium Management and Disposition Agreement is actually 38 MT, because Russia wants to conceal the isotopic composition of its warhead plutonium by blending it with about four tons of reactor-grade plutonium.

[88] See Bunn et al., *Economics of Reprocessing*.

[89] *Report to Congress: Disposition of Surplus Defense Plutonium at Savannah River Site* (National Nuclear Security Administration, February 2002), http://www.nci.org/pdf/doe-pu-2152002.pdf. It was estimated that the capital cost of the U.S. MOX fuel fabrication facility would be $1.1 billion, that operations over 13 years would cost $1.2 billion and that the MOX fuel would be sold for $0.7 billion. A pit disassembly and conversion facility for conversion of the plutonium to oxide suitable for a MOX plant would cost an additional $1.7 billion.

[90] *Report to Congress: Surplus Defense Plutonium at Savannah River*, Ttable ES-4. According to a July 2004 briefing to the Nuclear Regulatory Commission by the proposed licensees, construction of the facility was scheduled to start in May 2005; briefing by Duke, Cogema, and Stone & Webster, "Mixed Oxide Fuel Fabrication Facility Construction Authorization Request (CAR) Revision Summary, 14 July 2004, 29, http://www.nrc.gov/materials/fuel-cycle-fac/mox/meetings.html.

Financing. The estimated cost for disposing of Russia's excess weapons plutonium in Russian light water reactor (LWR) fuel over a period of 15 years is $2.1 billion (not including the cost to turn the metal into oxide) of which about $1 billion would be for capital costs, including modifying Russian LWRs to take MOX fuel. Only $0.3 billion would be recovered from the sale of the MOX fuel.[91] Russia has made clear that the full net costs of its effort will have to be underwritten by other countries in the G-8 group of countries. Thus far, commitments totaling about $0.8 billion (half from the United States) have been obtained.[92]

Liability. The United States and Russia are at an impasse over liability language in their negotiations of cooperation agreements on plutonium disposition. The Bush Administration insists that the language in the agreement exempt the U.S. government and its contractors from liability for any accidents, including events due to allegedly malicious acts.[93]

Security. It is almost unavoidable that plutonium would be more vulnerable to theft during transport and fabrication than it would be in secure storage. These risks must be minimized if the project is to do more good than harm. Unfortunately, the evidence available at this point indicates that other considerations have been given a higher priority than security in the design of both the Russian and U.S. plutonium disposition programs.

For example, despite the extra risks of theft in transport, Russia's Atomic Energy Agency has chosen to site the MOX fuel fabrication plant in the middle of Siberia at a second plutonium center at Seversk near Tomsk 2,000 kilometers from the plutonium conversion facility at the Mayak plutonium processing center in the Urals.[94]

In the United States, the Nuclear Regulatory Commission is not planning to require a materials protection, control, and accounting (MPC&A) plan for the U.S. MOX plant before authorizing its construction.[95] (The NRC could stipulate further

---

[91] *Scenarios and Costs in the Disposition of Weapon-Grade Plutonium Withdrawn from Russia's Nuclear Military Programs* (Joint U.S.-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition, Department of Energy, 2003). The reduced value of the MOX fuel in Russia would be in part due to lower LEU fuel prices there and in part due to the fact that, in order to increase the plutonium throughput through a limited number of reactors, the MOX fuel would be discharged when it had only achieved 63 or 75 percent of the burnup of the equivalent LEU fuel. A plutonium conversion (from metal to oxide) facility would cost an additional $0.3 billion.

[92] "Disposition of United States and Russia Federation Weapon-Grade Plutonium" (White House Fact Sheet, 21 July 2000), http://usinfo.state.gov/topical/econ/group8/summit00/wwwhplutonium.html; "Russian MOX Cost Estimates Refined For G8, But Large Unknowns Remain," *Nuclear Fuel* (26 May 2003), 6.

[93] Daniel Horner, Ann MacLachlan, and Alexei Breus, "Plutonium S&T Agreement Lapses; Impact on Disposition Effort Unclear," *Nuclear Fuel* 28, (4 August 2003), 3. For an analysis and proposals for how to deal with the issue, see D. Brubaker and L.S. Spector, "Liability and Western Nonproliferation Assistance to Russia: Time for a Fresh Look?" *Nonproliferation Review* (Spring 2003).

[94] " Russian MOX Cost Estimates Refined For G8, But Large Unknowns Remain, *Nuclear Fuel* (26 May 2003), 6.

[95] The NRC has permitted the proposed licensee to submit its license in two parts, a Construction Authorization Request and an Operating License Application. According to this scheme, detailed

requirements at a later stage of construction.) Since Russia has agreed to accept the U.S. design for its own MOX fuel fabrication plant, any design flaws that could impede MPC&A in the U.S. plant would be replicated in the Russian plant.

Inadequate reactor capacity. Russia barely has adequate reactor capacity to deal with the 34 tons of weapons plutonium it has declared excess.[96] It certainly does not have enough for the approximately 100 tons that it would have to declare excess to get down to the U.S. post-reduction level or the additional 37 tons of civilian plutonium that it has accumulated.

The Russian Atomic Energy Agency's proposal for how to deal with this problem is construction of a fast-neutron reactor that could irradiate plutonium at a rate 5 times higher than an LWR of equivalent capacity.[97] Russia has one aging 0.6 GWe fast-neutron reactor that could irradiate 17 tons of Russia's excess plutonium if its life can be extended until 2025.[98] A joint U.S.-Russian working group has examined the possibility of building a new 0.8-GWe reactor but it seems likely that Russia would have to finance it.[99] An alternative approach that has been explored would be the fabrication of Russian MOX for use in LWRs in other countries. Thus far, however, no country has been willing to irradiate more than its own separated plutonium.

Russia's continuing interest in a plutonium economy. By helping to finance the construction of a MOX fuel-fabrication facility, the G-7 would be helping Russia's Atomic Energy Agency achieve a goal of providing international reprocessing and MOX fuel fabrication services. The result in the longer term could be the separation of much more plutonium, undercutting the project's rationale.

One argument made for the consistency of pursuing a disposition program for weapons plutonium while separating plutonium from power-reactor spent fuel is that the power-reactor plutonium is not weapon-grade. Plutonium recovered from high-burnup fuel could be significantly harder to handle for relatively unsophisticated proliferators, including terrorists, than weapon-grade plutonium—just as HEU would be easier to

---

information about materials accounting and control and physical protection at the facility needs to be submitted only in the second part.

[96] This is why the latest U.S.-Russian study has the MOX only partially burned up in the reactors.

[97] *Scenarios and Costs in the Disposition of Weapon-Grade Plutonium,* table 18. This ratio stems primarily from the fact that the percentage of plutonium in fast-reactor fuel is much higher than that in LWR fuel (about 20 percent versus 4 percent) but the amount of energy extracted per kilogram of the fuel would not be nearly in that high a ratio. It also is based on the assumptions that LWR control systems cannot handle a core containing more than one third MOX fuel but that the cores of fast-neutron reactor can be designed to safely accommodate 100 percent MOX fuel.

[98] *Scenarios and Costs in the Disposition of Weapon-Grade Plutonium,* Table 18.

[99] *Cost Implications of Fast Reactor Options in the Disposition of Russian Weapon-Grade Plutonium Withdrawn from Nuclear Military Programs* (Joint U.S.-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition, July 2002).

handle than plutonium. However, numerous expert studies have concluded that plutonium recovered from high-burnup fuel is weapon-usable. [100]

The immobilization alternative. If Russia were willing to consider plutonium disposal via immobilization with high-level waste, that would remove the bottleneck of Russia's inadequate reactor capacity for MOX irradiation. During the Clinton Administration, the United States tried to satisfy both Russia and its own anti-reprocessing policy by proposing to follow both routes. (The Bush Administration has dropped immobilization.[101]) Germany, which now has an anti-reprocessing policy, has indicated that it will not contribute to the disposition of Russian plutonium in MOX but would contribute to its disposition via immobilization.[102] Russia insists, however, that its excess weapon plutonium be used as fuel.[103]

Secure interim storage for the excess plutonium. The stalled progress of the plutonium disposition projects provides an opportunity to review the current programs and possible alternatives. In the meantime, Russia's excess weapons plutonium should be moved into the new high-security storage facility that has been built for it with approximately $500 million of U.S. funding near the Mayak plutonium center in the Urals.[104] Shipments of plutonium to the Mayak facility should be subject to stringent security.

Bilateral and international monitoring of excess weapon plutonium. Subjecting the stored plutonium to both bilateral and IAEA monitoring would provide additional assurance of its security. Reciprocal transparency with an overlay of IAEA monitoring was, in fact, proposed in 1993 by the then Minister of Atomic Energy Victor Mikhailov of Russia and then Secretary of Energy Hazel O'Leary of the United States. Concluding both a bilateral agreement to allow U.S. monitoring of the Russian plutonium in the Mayak facility and a trilateral agreement among the IAEA, Russia, and the United States to allow IAEA monitoring of excess Russian and U.S. plutonium have been complicated,

---

[100] See, e.g., J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security* 4 (1993: 111; and *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (U.S. Department of Energy, DoE/NN-0007, 1997), 37-39.

[101] The Bush Administration justified canceling plutonium immobilization with the argument that pursuing two plutonium disposition paths would incur unnecessary cost. The United States has also been concerned that Russia would refuse to go down the MOX path alone, if the United States took only the immobilization route; *Disposition of Surplus Defense Plutonium.*

[102] One option for immobilization would be to make storage MOX, which could be disposed of directly with spent LWR fuel. J. Kang, F.N. von Hippel, A. MacFarlane and R. Nelson, "Storage MOX: A Third Way for Plutonium Disposition?" *Science & Global Security* 10 (2002): 85; A. MacFarlane, J. Kang, R. Nelson and F. von Hippel, "Plutonium Disposal: The Third Way," *Bulletin of the Atomic Scientists* 57 (May/June 2001), 53-57.

[103] A decade ago, in a paper co-authored by Russia's then minister of atomic energy, Russia's plutonium was assigned the same value per gram as Russia's weapon-grade uranium and it was argued that, "[t]here is no urgency in [its] elimination. The involvement of weapon-grade plutonium in power industry should become a natural process" when BN-800 fast-neutron breeder reactors are commercialized. The paper argued that the plutonium should be kept in secure storage till that time. V.N. Mikhailov et al., "Plutonium in nuclear power industry" (probably 1993); Thomas Lippman, "Russia Thinks Plutonium from Arms Has Commercial Value, Congress Told" *Washington Post,* 10 March 1993, A-24.

[104] http://www.nti.org/e_research/cnwm/securing/mayak.asp#budget.

however, by the fact that the plutonium will be in classified form for many years until it is processed into plutonium oxide for feeding into a MOX fuel fabrication or immobilization facility.

Russia has been so concerned about revealing sensitive design information that it is converting the 25 metric tons of plutonium that are to be stored in the Mayak facility into solid 2-kilogram plutonium spheres first. Even then, however, Russia considers the isotopic makeup of the plutonium in the spheres classified. U.S. plutonium will remain in pit form until the U.S. pit conversion and MOX fuel-fabrication facilities are built.

At the expert level, the United States, Russia, and IAEA have worked together to establish arrangements where unclassified attributes of U.S. plutonium warhead pits or Russian plutonium metal storage forms can be determined from their gamma and neutron emissions as measured outside their sealed containers with an information barrier filtering out classified information before it is shared with the inspecting party.[105] However, political agreement to go ahead has not been achieved.

The bilateral Russian-U.S. transparency agreement has also been impeded by Russia's desire for reciprocal transparency. The position of the U.S. Department of Defense has been that U.S. verification of the presence of Russia's weapons plutonium in the Mayak storage facility is required as part of the agreement for U.S. financing of the construction of the facility.

Continued delay in resolving these issues postpones realizing the security benefits from the Mayak storage facility, which is essentially complete.[106]

---

[105] Thomas E. Shea, "IAEA Verification of Weapon-Origin Material in the Russian Federation & the United States" *IAEA Bulletin* 43.4 (2001), 49; Thomas E. Shea, "Potential Roles for the IAEA in a Warhead Dismantlement and Fissile Materials Transparency Regime," ed. Nicholas Zarimpas, *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions* (SIPRI/Oxford University Press, 2003), 229.

[106] Matthew Bunn, Anthony Wier and John Holdren, "Mayak Storage Facility," *Controlling Nuclear Warheads and Materials,* http://www.nti.org/e_research/cnwm/monitoring/mayak.asp.

8. The use of high-enriched uranium in reactor fuel should be phased out

High-enriched uranium (HEU) poses the most serious nuclear-terrorism risk since it can be used to make simple gun-type nuclear weapons with explosive yields greater than one kiloton. The Soviet Union and United States exported research reactors fueled with weapon-grade uranium to about 40 other countries. Worldwide, there are still over 140 operating HEU-fueled research reactors and a comparable number of shut-down but not decommissioned reactors—so that their HEU remains on site. Many of these are in insecure locations. The U.S. Department of Energy has identified 128 locations associated with research reactors worldwide where there is at least 20 kilograms of high-enriched uranium.[107]

The Soviet Union and United States recognized in the mid-1970s the danger that this HEU might fuel nuclear-weapons proliferation and launched programs to develop substitute low-enriched uranium (LEU) fuels for foreign research reactors that the United States and USSR were supplying with fuel. As of the end of 2003, 38 reactors in 19 countries had been converted to LEU fuel out of 105 HEU-fueled research reactors on the U.S. target list for conversion.

However, the U.S. conversion program is currently funded at less than $10 million per year, and its focus is too narrow. For example, it does not target critical assemblies, which are used to mock up fast-neutron and other reactors, or pulsed reactors, which are standard equipment at nuclear weapon design institutes in Russia and the United States. These reactors do not require refueling but can have very large inventories of HEU.

Also, although the IAEA has estimated that only about 15 percent of the 275 research reactors operating worldwide will be required in the future,[108] there is no international program for helping countries shut down and decommission their excess research reactor capacity.

Finally, there has been virtually no official discussion yet about the possibility of converting to LEU the more than 200 HEU-fueled reactors powering French, Russian, U.K., and U.S. navy submarines and ships.[109]

We therefore recommend that

---

[107] *DOE Needs to Take Action to Further Reduce the Use of Weapons-Usable Uranium in Civilian Research Reactors* (U.S. Government Accountability Office, GAO-04-807, July 2004), 28.
[108] "New Life for Research Reactors? Bright Future But Far Fewer Projected," IAEA press release (8 March 2004), http://www.iaea.org/NewsCenter/Features/ResearchReactors/reactors20020308.html.
[109] Ma and von Hippel, "Ending the Production of High-Enriched Uranium for Naval Reactors," 86. However, the Nuclear Threat Initiative foundation recently decided to fund the development of low-enriched uranium replacement fuel for Russia's nuclear-powered icebreakers; Laura Holgate, NTI, personal communication, 12 October 2004.

- funding be provided for decommissioning research reactors that are no longer needed, to include the removal of the core and all spent fuel, site decontamination, and programs to help facility personnel transition to new occupations or compete as users groups for irradiation time at other reactors;

- conversion of research reactors that are not to be decommissioned be accelerated and broadened to include critical assemblies and pulsed reactors;

- no new HEU-fueled civilian reactors be constructed and the production of high-density fuels developed to convert research reactors from HEU to LEU be licensed only for use with LEU;[110] and

- countries that use HEU-fueled reactors for naval propulsion purposes (Russia, the United Kingdom, and the United States) convert these reactors when practicable and design future propulsion reactors to use LEU.

A detailed analysis of a comprehensive approach to eliminate high-enriched uranium from all nuclear-reactor fuel cycles has been provided in an article[111] by Frank von Hippel, one of the co-directors of the summer study.

---

[110] The new German FRM-2 reactor uses early high-density fuel developed for reactor conversion to make possible a more compact core. This makes it perhaps the most difficult research reactor to convert to LEU, even with the highest-density fuels theoretically possible.

[111] Frank von Hippel, "A Comprehensive Approach to Elimination of Highly-Enriched-Uranium from All Nuclear-Reactor Fuel cycles," *Science and Global Security* 12 (2004): 137-165, http://www.princeton.edu/~globsec/people/fvhippel.html.

Appendix A. A moratorium on new reprocessing plants

Spent fuel reprocessing, along with uranium enrichment, is one of two routes to the production of weapons-usable material. And, unlike civilian enrichment, civilian reprocessing produces directly weapons-usable material.

Status of civilian reprocessing worldwide

Civilian spent-fuel reprocessing is now under way or planned in six countries, China, France, India, Japan, Russia, and the United Kingdom (see Box A-1). The operating plants together are today separating about 20 metric tons of plutonium annually. About one-third of this plutonium is being recycled in light water reactors, mostly in France and Germany, though Japan has ambitious plans for recycling, which have so far been delayed by public opposition.

The French, Russian, and U.K. and reprocessing plants were built based on experiences derived from the weapons programs of these countries. In addition, France's UP-3 reprocessing plant at La Hague and the U.K. THORP plant at Sellafield were largely subsidized by Belgian, German, Japanese, and Swiss utilities. By shipping their spent fuel to be reprocessed abroad, the German and Japanese utilities were able to satisfy governmental and environmentalist demands that they had acceptable plans for disposal of their radioactive wastes.

However, the utilities in Belgium, Germany, and Switzerland are now turning to domestic spent-fuel storage at their reactors pending the availability of a geological repository and are not renewing contracts with the French and U.K. reprocessing plants. Japan, which has constructed—but has not yet put into operation—its own large reprocessing facility also will no longer be sending fuel to France and the United Kingdom.[112] As a consequence, the Sellafield and La Hague plants will soon have few or no foreign customers. That is why the United Kingdom has now decided to shut down

[112] Germany and Japan have been the dominant foreign customers of the British (80 percent of first 10-year baseload contracts) and French (83 percent) reprocessing companies. German utilities have committed to end spent-fuel shipments to foreign reprocessing plants by 1 July 2005. Japan is reorienting itself toward domestic reprocessing, and the other smaller foreign reprocessing customers (Belgium, Italy, Netherlands, Spain, Sweden, Switzerland) have all opted for storage. "Swiss Government Moves to Ban Future Reprocessing by Utilities, *Nuclear Fuel* (14 June 1999), 3; "Belgium Cancels 1991 Reprocessing Contract, Postpones Debate on MOX," *Nuclear Fuel* (14 December 1998), 16; "Sweden Rejects BNFL Reprocessing Following Sellafield Disclosures," *Nuclear Fuel* (6 March 2000), 9; "Spanish Waste Plan Puts Off Long-Term Decisions until At Least 2010," *Nuclear Fuel* (6 September 1999), 3; "Italy's ENEL Evaluating Bids for Spent Fuel Dry Storage System," *Nuclear Fuel* (30 November 1998), 10; "Dutch Utility EPZ No Longer Sees MOX Use as an Option at Borssele," *Nuclear Fuel* (10 June 2002), 6. As of the end of 1999, France's 800-ton/yr capacity UP-3 reprocessing plant, at which foreign spent fuel was being reprocessed, had less than 1600 tons of contracted fuel to reprocess. "Reprocessing: Managing the End of the Contracts," Wise-Paris, http://www.wise-paris.org.

THORP by 2010.[113] Britain's older B-205 reprocessing plant that reprocesses the less easily stored metal fuel from Britain's first-generation gas-cooled Magnox reactors will operate until 2012, after which time all those reactors will have been shut down.

Box A1. Existing reprocessing plants[a]

FRANCE—La Hague. The reprocessing plant at La Hague, operated by the government-owned company, Cogema, contains two facilities, **UP-2** and **UP-3**, each with a capacity of 800 tHM/y [tonnes heavy metal (i.e. uranium plus transuranics) per year]. La Hague has reprocessed comparable amounts of domestic and foreign fuel. The foreign fuel has been mainly from Japan, Germany, and Switzerland. Future reprocessing is expected to be of French spent fuel only.

UNITED KINGDOM – Sellafield. Two reprocessing plants, operated by the government-owned company, British Nuclear Fuels Limited (BNFL) are currently in operation at Sellafield: **B205,** which processes uranium-metal fuel from Britain's first generation of gas-cooled, graphite-moderated "Magnox" reactors, began operating in 1964. In May 2000, BNFL announced that given the planned schedule of shut-downs of the Magnox reactors, B205 will shutdown in 2012. **THORP** (thermal oxide reprocessing plant) reprocesses primarily foreign light-water reactor spent fuel but also some uranium oxide fuel from Britain's second-generation Advanced Gas-Cooled Reactors. It commenced operations in 1994 with an order book of 7000 tHM to be reprocessed in first 10 years of operation. Two-thirds of these startup orders were from overseas customers – Germany, Japan, the UK, and a few others. By the end of 2004, the 10-year baseload total of spent fuel reprocessed will be about 5000 tHM. Post baseload contracts appear to have been signed with two customers only – Germany for 950 tHM and UK for 2500 tHM. No new post-baseload contracts are expected. THORP is expected to shutdown by 2010.

RUSSIA—Ozersk. The **RT-1** plant in the Mayak complex in the Urals, which began operations in 1976, is Russia's only commercial reprocessing facility. It reprocesses the fuel of first-generation Soviet light-water VVER-440 reactors in Russia and Eastern Europe, and HEU fuel from naval reactors, research reactors, and plutonium and isotope production reactors. Its average throughput has been about 100 tHM/y.

JAPAN. Japan has contracted with BNFL and Cogema to reprocess Japanese spent fuel. About 27 tonnes of separated Japanese plutonium are now stored in these countries. A relatively small reprocessing plant at **Tokai** has been operating since 1977. Through 2000, it had reprocessed about 1000 tHM, yielding approximately 5.5 t of separated plutonium. A much larger plant with a capacity of 800 tHM/y, completed but not yet operating at **Rokkasho**, was built from blueprints supplied by Cogema.

INDIA. India has used a reprocessing plant at Trombay to extract plutonium for weapons. Two other plants, PREFRE and Kalpakkam, are used for civilian reprocessing. The **Trombay** plant, which reprocesses natural uranium metal fuels, had a original capacity of 30 tHM/y between 1964 and 1972. When it was re-commissioned in 1985 its capacity was increased to 50 tHM/y. The plant may have separated 500-750 kg of weapon-grade plutonium. **The Power Reactor Fuel Reprocessing (PREFRE)** facility, located in Tarapur, began operating in 1978 reprocessing uranium oxide fuel from pressurized heavy water reactors. Its initial nominal capacity was100 tHM/y, which was upgraded to 150 tHM/y in 1991. However, the volume of spent fuel reprocessed has been reported as being substantially less than the plant's design throughput. **Kalpakkam**, a second civilian reprocessing plant, which began operation in 1998, has two reprocessing lines each with a design capacity of 100 tHM/y which may be upgraded to 125 tHM/y. The plan is to run the first for seven to eight years and then run the second line.

CHINA. China has constructed a pilot reprocessing plant at Lanzhou, with a nominal capacity of about 50 tHM/y. China is considering whether to build a large commercial reprocessing plant of capacity 800 t/y by 2020.

[a] Source: D. Albright, F. Berkhout and W. Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford University Press, 1997).

---

[113] Paul Brown, "Sellafield Shutdown Ends the Nuclear Dream: £1.8bn Thorp Plant that Promised Limitless Electricity to Close by 2010," *The Guardian*, 26 August 2003, http://www.guardian.co.uk/nuclear/article/0,2763,1029361,00.html.

A high-level French government commission concluded in 2000 that if France were to stop reprocessing in 2010, it would save 28 to 39 billion francs ($4–5 billion) over the remaining lifetime of its current fleet of power reactors.[114] Nevertheless, there are no plans to end reprocessing at La Hague soon.

Reprocessing in Japan is still much more costly than in France. Japan's nuclear utilities have asked the central government to pick up 9.1 trillion yen ($76 billion) in projected costs associated with operating the Rokkasho reprocessing plant over 40 years.[115] As of the time of this writing, the Japanese government had not yet authorized commencement of operations at the plant.

Chinese, Indian, and Russian reprocessing plans appear still to be tied to hopes in those countries for the commercialization of plutonium breeder reactors, or in the case of India, of a so-called thorium breeder, which would convert the source material, ^{232}Th, into chain-reacting ^{233}U. But with the price of uranium likely to stay low for the foreseeable future, economic justification for a breeder appears unlikely for at least several decades.

New reprocessing

For countries with fledgling nuclear power programs, such as Iran, or even for countries, such as South Korea, which have substantial nuclear power but no reprocessing plants, plausible civilian rationales to embark on reprocessing are hard to find.

A potential near-term reason for reprocessing is to allow a country to recycle separated plutonium into light water reactors. But this rationale for reprocessing faces several objections. First, it would allow only a modest reduction in uranium requirements—about 16 percent assuming the current practices of recycling the

---

[114] *Economic Forecast Study of the Nuclear Option* (Planning Commission, Government of France, 2000), http://www.plan.gouv.fr/organisation/seeat/nucleaire/accueilnucleaire.html, sect. 3.4.

[115] This includes an estimated $22 billion for decommissioning the plant and $54 billion for management of the transuranic wastes, storage of the high-level waste returned from overseas reprocessing, interim spent-fuel storage, and MOX fabrication costs during the period 2005-45. (Apparently no discounting has been done, since the quoted costs for the period 2005-25 is about the same as for the period 2025-45.) The utilities are only willing to pay for the costs of operating the plant, which they estimate at $57 billion for that 40-year period. Operating at full capacity (800 tU/yr) that corresponds to $1,800/kgHM for operations plus $1,700/kgHM for waste management plus $700/kgHM for decommissioning ("METI Preparing Panel to Consider Fuel Cycle Cost-Sharing Measures," *Nuclear Fuel* 28, no. 146 [7,July 2003]). In a recent paper (*Platts Nuclear Fuel*, [16 August 2004]), it is reported that the Japanese government and industry estimate the total costs of operating the back end of the closed fuel cycle over 40 years (reprocessing and complete waste management) 18.8 trillion Yen ($156 billion). The costs of reprocessing alone were estimated at 8 trillion Yen ($66 billion). Given a capacity of Rokkasho of 800 metric tons per year, the total back-end and reprocessing operation costs come to about $5,000/kgHM and $2,000/kgHM respectively. Calculation by Chaim Braun, personal communication, 21 August 2004.

plutonium only once and the uranium not at all.[116] For a country dependent on outside uranium supply, such reduction would not significantly enhance its energy independence.

More important, the economics of such recycling are poor. In a recent study by Matthew Bunn, Steve Fetter, John Holdren, and Bob van der Zwaan, the authors conclude that recycling could not be competitive with the once-through fuel cycle, in which the spent fuel is disposed of directly without reprocessing, until natural-uranium prices reached $360/kgU.[117] This estimate assumes a nominal reprocessing cost of $1,000/kgHM. For a new country embarking upon reprocessing, the costs would likely be much higher. But because the costs of fabrication of mixed-oxide fuel (MOX) are so much higher than those of LEU, even if the plutonium from reprocessing were considered free, a kilogram of MOX today would still cost more than an equivalent kilogram of LEU.[118]

Finally, reprocessing is not needed to rationalize radioactive waste disposal. Many of the countries with relatively large nuclear power programs, such as Canada, Germany, South Korea, and the United States, are planning on keeping their spent fuel stored at the reactor sites (or possibly at away-from-reactor storage facilities) until such time the fuel will be sent to a geological repository. For countries with small nuclear power programs and those starting up, such as Iran, the spent fuel could be stored for long periods at the reactor sites in dry storage, or potentially sent out of country. For example, Russia has indicated that it would take back spent fuel from the Bushehr reactor in Iran, which is now nearing completion with Russian assistance.

One further possible rationale for reprocessing is to fuel breeder reactors, which could in principle over time make a country independent of uranium fuel from abroad. As discussed further below, the promise of breeders provided the initial rationale for reprocessing. Fast-neutron reactors fueled by plutonium were seen as the answer to expected scarcities of uranium because they are able to breed plutonium from ^{238}U, which comprises 99.3 percent of natural uranium. Breeder reactors would thus be fueled by ^{238}U instead of ^{235}U, potentially increasing the amount of fission energy that could be extracted from a kilogram of uranium 100-fold. In a breeder economy, the spent fuel from LWRs or other conventional reactors would be reprocessed to provide plutonium for the startup of the breeders, and then the spent fuel from the breeder reactors themselves would be continuously reprocessed to separate plutonium.

---

[116] John Deutch, Ernest Moniz et al., *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge: MIT Press, 2003), chap. 4.
[117] Matthew Bunn, Steve Fetter, John Holdren and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Harvard, Project on Managing the Atom, 2003), exec. summary.
[118] Bunn et al., *Economics of Reprocessing vs. Direct Disposal,* exec. summary and table 2.1., 19. The key values used by the authors were $100/SWU for uranium enrichment, $1,000/kgHM for reprocessing, and $250/kgHM for LEU fuel fabrication. The range for the cost of MOX fabrication was $700–2300. At the central value for MOX fabrication of $1500 and uranium at $50/kg, one kilogram of LEU would cost $1,235. The comparable kilogram of MOX fuel would cost $1,500, even granting no cost for the plutonium or uranium in the MOX fuel. See ibid., 15.

However, the commercialization of fast breeders appears decades away for economic reasons. In the Bunn et al. study referred to above, using central estimates for the costs of reprocessing, plutonium fuel fabrication, and uranium processing and enrichment, and a breeder reactor capital cost penalty compared with a new light water reactor (LWR) of $200/kW, the authors conclude that the breeder would not be competitive with an LWR until the price of uranium reached $340/kgU—almost ten times the price today. Even if the capital costs of a breeder could be reduced to that of an LWR, the breakeven price of uranium would be $140/kgU, more than three times the current price.[119]

For all these reasons, it should be possible for the international community to agree to a moratorium on the construction of any new reprocessing plant or at a minimum to demand of any country contemplating reprocessing that it produce a comprehensive economic rationale for such activity.

Historical justifications for reprocessing

The initial justification for reprocessing was that with nuclear power expected to rise sharply and world uranium resources thought to be very limited, the uranium-efficient breeder reactors would be essential to keep nuclear power going and, furthermore, that for countries dependent upon imported uranium fuel, breeder reactors would protect against disruptions in supplies of uranium.

These rationales no longer hold. First of all, nuclear power worldwide, which was officially projected in the 1970s to grow to thousands of gigawatts of installed capacity by the year 2000, has grown far more slowly. It is now an order of magnitude below what was then projected. Nuclear power ended its exponential growth in the early 1980s and is now relatively flat – and installed capacity may actually decline in the next two decades (see Figure A-1) if the current moratorium on new reactor construction in Germany, the United States, and a few other countries continues, although net capacity is very likely to grow in Asia.

Second, additional rich deposits of uranium have been found in Australia and Canada, and overall, experts now believe uranium resources to be far greater than initially supposed.[120] Global reserves of natural uranium recoverable at costs of up to

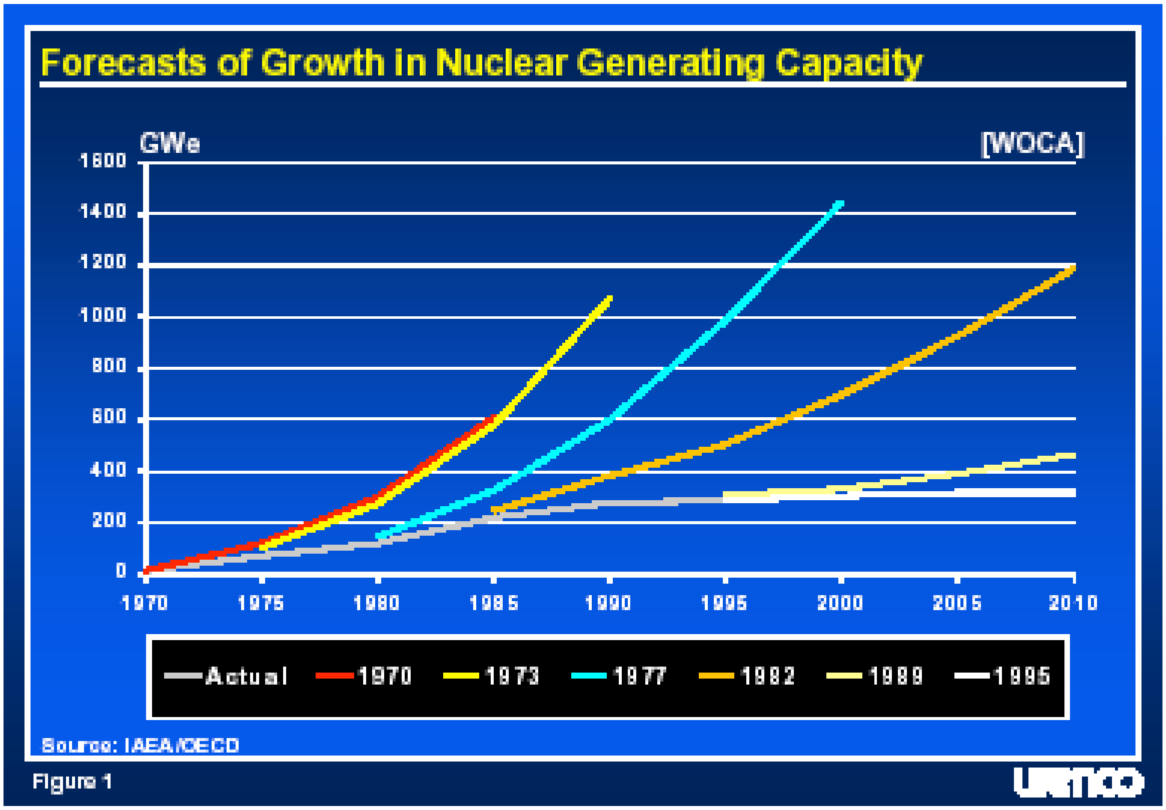
[119] Bunn et al., *Economics of Reprocessing vs. Direct Disposal,* exec. summary and table 3.1, 71. The key central values adopted by the authors are $1,000/kgHM for reprocessing and $100/SWU for enrichment. The capital cost penalty for a breeder compared with an equivalent LWR ranged in the analysis from $0 to $400 and led to a breakeven uranium price between $134/kgU to $560/kgU. Though not countering these economic arguments, a memorandum by the Nuclear Energy Division of the French CEA points out that the cost penalty of reprocessing and recycling is small compared with the total cost of electricity and that the long-term waste disposal advantages of the reprocessing could justify the added costs. Jacques Bouchard, "Comments on the MIT Report on the Future of Nuclear Power—an Interdisciplinary MIT Study," presented in a letter to Ronald Lehman, Lawrence Livermore National Laboratory, 17 September 2003—hereinafter referred to as the *Bouchard Memorandum*.

[120] Deutch et al., *Future of Nuclear Power*, 57-59.

$130/kgU (far less than the breakeven uranium price for breeders discussed above) would last 200-1500 years at current rates of consumption.[121]

[121] There are an estimated 16-105 million tons of uranium in reasonably assured resources recoverable at $130/kgU. *Uranium 2001: Resources, Production and Demand* (OECD Nuclear Energy Agency and the International Atomic Energy Agency, Paris, 2002); Bunn et al., *Economics of Reprocessing vs. Direct Disposal,* app. B. We assume that 0.2 out of 0.7 % ^{235}U would be left in the depleted uranium at future higher uranium prices. The world demand for natural uranium in 2002 was approximately 63,000 tons and is projected to rise to about 75,000 tons in 2010. "World Contracted [Natural Uranium] Supply and Demand for the Year 2002 and Beyond," *Nukem Market Report Data Feature*, January 2003, http://www.nukemonline.com.

Figure A-1. **World nuclear capacity a) as projected,[122] b) actual1960-2001[123]**



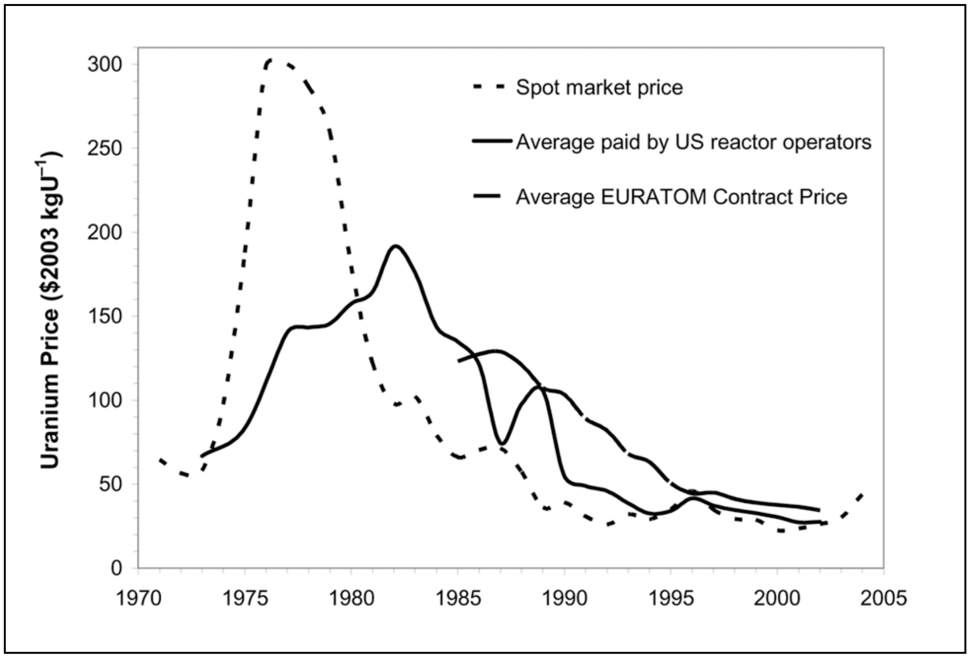
As a result of the great slowing of nuclear power growth and the increase in uranium availability, after a steep run up in the 1970s when the commitments to reprocessing were being made, the price of uranium has since declined by an order of magnitude in constant dollars.[124] (The uranium price in current dollars is shown in Figure A-2.) The current price of uranium is roughly $40/kg, and this may be compared with the breakeven price for breeder reactors, discussed above, of well over $300/kg. In addition, the costs of reprocessing have escalated sharply from the optimistic days of the 1970s. Estimated costs in constant 1992 U.S. dollars for reprocessing in a newly constructed

---

[122] M. Lenders (Urenco), "Uranium Enrichment by Faseous Centrifuge" (presentation to Deutsches Atomforum Annual Meeting on Nuclear Technology, Dresden, 16 May 2001). Figure courtesy of M. Lenders.
[123] "Nuclear Power Nears Peak," World Watch Institute Press Release, 04 March 1999, http://www.worldwatch.org/press/news/1999/03/04/. Updated to 2001 using Energy Annual Review 2002 (U.S. Energy Information Administration, 2003), sec. 11, http://www.eia.doe.gov/emeu/aer/aerpdf.html.
[124] Bunn et al., *Economics of Reprocessing vs. Direct Disposal,* fig. 2-4. The value of a dollar decreased by a factor of 0.53 between 1980 and 2000 (GDP deflator, *Statistical Abstracts of the United States: 2001* [U.S. Census Bureau], table 640). Between January 1978 and May 2001, the unrestricted spot price of natural uranium declined from about $261 to $19 per kg in constant U.S. GDP-deflated May 2001 dollars. By July 2004, the price had increased again to $42/kg. *RWE Nukem Market Report* (August 2004), 17.

plant increased from about $100 per kilogram of heavy metal in the early 1970s to $2000 in the1990s.[125]

Figure A-2. Uranium prices through time.



The price of uranium has declined greatly even in current dollars since the decisions were made in the 1970s by France and the United Kingdom to build commercial reprocessing plants.[126]

The principal impetus to breeder reactors therefore has gone, bringing the demise of breeder development programs in France, Germany, and elsewhere. Some work on breeders does continue in India, Japan, and Russia. The U.S. demonstration breeder reactor program was canceled in the early 1980s.

As the breeder dream faded, those countries engaged in the reprocessing sought ways to use the separated plutonium other than simply to store it and wait for the breeder. By the mid-1980s, these countries, notably France, Germany, and Japan, began to recycle plutonium in light water reactors using mixed-oxide fuels (MOX). However, as already noted, such recycling cuts the requirements for natural uranium only by about 16 percent, and even if the plutonium were considered to be free—that is, with the costs of reprocessing ignored altogether—with today's uranium prices, a kilogram of MOX fuel costs more than an equivalent kilogram of LEU.

---

[125] *Nuclear Wastes: Technologies for Separations and Transmutation* (Washington, D.C.: National Academy Press, 1996), 117.
[126] Bunn et al., *Economics of Reprocessing vs. Direct Disposal,* fig. 5. Figure courtesy of the authors.

Stockpiling uranium provides less costly protection against uranium-supply cutoffs than deploying breeder reactors.

Some countries, notably Japan in the past and China and India today, have justified their reprocessing and breeder reactor development programs because of their small national uranium resource bases. In the cases of China and Japan, this concern is mitigated by the fact that uranium is cheap, available from many potential suppliers, and easily stored. Uranium costs about the same amount per kilogram as oil does per barrel but releases more than 600 times as much energy in a light water reactor.[127] A 10-year supply of uranium for a one million kilowatt-electric (1 GWe) power plant at a price of \$40/kgU would cost less than \$100 million—which is modest in comparison with the estimated \$2-4 billion capital cost for constructing a new light water reactor of that capacity.[128]

India has a special argument for its continuing breeder-reactor program. It *is* being subjected a uranium embargo because it has not joined the Non-Proliferation Treaty as a non-weapons state, although Russia is supplying it LEU at present (see below). In 1992, the Nuclear Suppliers Group, which includes the world's major uranium exporters, agreed not to export nuclear materials or technologies to countries that were not parties to the NPT unless they accepted equivalent full-scope safeguards on all their nuclear activities. Because of its nuclear-weapons program, India will not accept full-scope safeguards. India also believes that its uranium resources are only sufficient to support about 10 GWe of nuclear capacity for a 30-year reactor lifetime.[129] It currently has approximately 2.8 GWe of nuclear capacity but hopes to have 20 GWe of capacity by 2020.[130] It therefore has just launched construction of a 0.5 GWe demonstration breeder reactor with a projected capital cost of about \$0.75 billion.[131] Russia, which is now exporting LEU to India, will supply India with fuel for two light water reactors that it is building under an agreement that predates the NSG guidelines. However, Russia has evidently decided not to supply any further reactors at the site of the two under

---

[127] Producing 1 kg of 4.4% enriched uranium requires about 10 kg of natural uranium (assuming 0.3% uranium tails). The enriched uranium will produce 50 MWt-days = 40×10^{12} joules of heat in a reactor or 4×10^{12} joules/kgU. For comparison, one barrel of oil will produce about 6×10^{9} joules. See Paul Leventhal and Steven Dolley, "A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium," *Science and Global Security* 5, no. 1 (1994).

[128] Providing the fuel for a 1 GWe light water reactor requires about 200 tons of natural uranium per year. Capital costs from Deutch et al., *Future of Nuclear Power,* chap. 5.

[129] India has reported about 52,000 tons of uranium in-place in proven economical reserves. *Uranium 1995: Resources, Production and Demand* (OECD/IAEA, 1996, 191). India's indigenous power reactor is the pressurized heavy-water reactor (PHWR), which requires about 140 tons of U per GWe-year at 80 percent capacity, about 20 percent less than a pressurized water reactor for a fuel burnup of 50 MWd/kgU and an enrichment tails assay of 0.3 percent. *International Nuclear Fuel Cycle Evaluation, Advanced Fuel Cycles, and Reactor Concepts* (IAEA, INFCE/PC/2/8, 1980, 60, 72).

[130] R. Chidambaram, "Nuclear Energy Needs and Proliferation Misconceptions," *Current Science* 81, no. 1 (10 July 2001): 17-21.

[131] The estimated cost is about \$0.75 billion (Rs. 3,492 crores). T. S. Subramanian, "A Prototype of Promise: The Construction of the Prototype Fast Breeder Reactor, a Milestone on the Road to Energy Security, Begins in Kalpaakam in Tamil Nadu," *Frontline,* 11-24 October 2003, http://www.flonnet.com/fl2021/stories/20031024001904600.htm.

construction and has indicated that it will not supply LEU for the Tarapur reactor initially constructed by the United States.[132]

A case could be made for changing the policies of the Nuclear Suppliers Group (NSG) to allow India to import natural uranium and low-enriched uranium in exchange for India's agreeing to give up its civilian reprocessing and breeder reactor programs and accepting international safeguards on its civilian nuclear-power program. India's nuclear establishment, however, is likely to oppose such a proposition.

Impact on the radioactive waste problem

Reprocessing and recycling as practiced today, in which the spent MOX fuel (after just one round of recycling) is designated for a waste repository, would have limited impact on radioactive waste disposal. However, advanced reprocessing and transmutation schemes that separate plutonium and other long-lived transuranic elements from the spent fuel and then fission (transmute) them could in principle simplify the radioactive waste problem created by nuclear power.[133] (We discuss one advanced concept, pyroprocessing, further below.) The transmutation could do so by keeping out of a geological repository most of the long-lived radioactive isotopes. In addition, for a repository whose capacity is limited by the accumulated long-term heat load of the buried wastes, removal of the transuranics (especially ^{241}Am and ^{238}Pu) could in principle greatly expand the quantity of wastes that could be emplaced. Mainly for this reason, the United States is now investigating such advanced reprocessing and transmutation technologies.[134]

To reprocessing proponents, the heat-load argument appears particularly cogent in the case of Yucca Mountain, the prospective repository for U.S. commercial radioactive wastes. The Department of Energy argues that if plutonium and other transuranics are removed and recycled, Yucca Mountain will have the physical capacity to hold the associated reprocessing wastes from U.S. nuclear power plants almost indefinitely.[135] If so, this could make it possible to delay a bruising political battle over the siting of a second repository in the United States.

At present, there is a statutory limit of 63,000 tons of commercial spent fuel that could be sent to Yucca Mountain, and a theoretical limit of 120,000 tons, which appears to be based on limits of 2,000 acres for the site and a heat-load limit of 60 tons per acre.[136] In the absence of the transuranic elements, the radioactive decay heat of the remaining reprocessing waste will decline for a few hundred years with the 30-year half-

---

[132] M.V. Ramana, private communication, 5 January 2005. This may signal that Russia is now reluctant to go against the NSG guidelines.

[133] This argument is made cogently by the French Nuclear Energy Division of the CEA. *Bouchard Memorandum.*

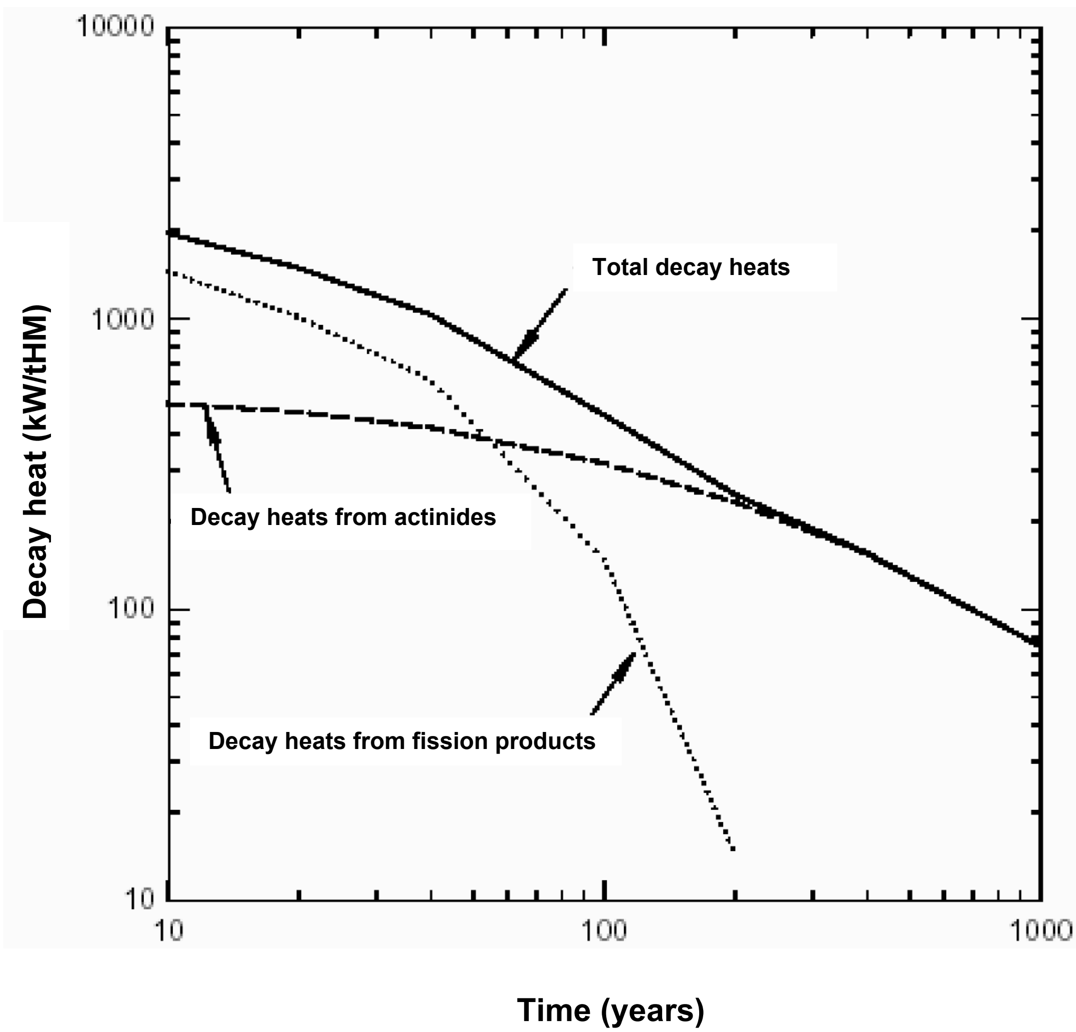
[134] *National Energy Policy* (The White House, May 2001), 5-17, http://www.whitehouse.gov/energy; *Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research* (Department of Energy, Office of Nuclear Energy Science and Technology, Report to Congress, 2003), www.ne.doe.gov/reports/AFCI_CongRpt2003.pdf

[135] *Advanced Fuel Cycle Initiative,* figs. I-1 and II-2.

[136] Ibid., 4; Per Peterson, private communication, 7 August 2002.

life of the fission products ^{137}Cs and ^{90}Sr.   If the current statutory limit were increased to the theoretical capacity of 120,000 tons, then after 30 years the heat load would have declined by half and an additional 60,000 tons could be added.   This process could continue for 100–200 years until the repository is closed, resulting in an increase in the repository's capacity by an order of magnitude. It just so happens that the U.S. nuclear-power plant fleet currently discharges spent fuel at a rate of approximately 60,000 tons in 30 years.

Figure A-3. Decay heat of spent LEU fuel over time.



Decay heat of a ton of 53 MWd/kgHM spent LEU fuel as a function of cooling time. After removal of plutonium and other transuranics, the decay heat of the remaining high-level waste declines with a roughly 30-year half-life for hundreds of years.[137]

[137] Calculation by Jungmin Kang.

The potential benefits of the reprocessing and transmutation, however, are offset by several considerations. First, with respect to the long-term radioactivity, in addition to the transuranics, there are long-lived fission products, ^{99}Tc and ^{129}I, which would remain in the radioactive wastes, and, worse, these isotopes are highly water soluble—creating, for example, at Yucca Mountain the most serious water contamination potential.[138]

More important, the reprocessing and constant recycling required to draw down to very low levels all the transuranics would involve a tremendous enterprise. The recycling and transmutation of transuranics would result in huge quantities of dilute transuranic waste, including the decommissioning waste from the reprocessing and transuranic-fuel-fabrication facilities. Dealing with this waste would result in substantial occupational radiation doses and additional opportunities for accidental dispersal of radioactivity into the environment.

Finally, the capacity of repositories under study in other countries, unlike Yucca Mountain, may not be so geographically limited in area—and so, in this sense, Yucca Mountain represents a unique case. And even for Yucca Mountain, as long as the repository remains open and under active ventilation, it would not be significantly heat-load constrained.[139]

The proliferation risks of reprocessing and recycling compared with those of the once-through fuel cycle

A country with a closed fuel cycle in which the plutonium in the spent fuel discharged from power reactors is separated for recycling into either light water reactor or breeder reactor fuel is producing enough plutonium for scores to hundreds of nuclear weapons a year from each GWe of nuclear-power capacity.[140] This simple fact suggests that a once-through fuel cycle, in which the spent fuel is stored with the plutonium diluted in a ceramic matrix by 100 times as much uranium mixed with intensely radioactive fission products, is markedly more proliferation resistant.

Reprocessing advocates have challenged this conclusion with three arguments:

1. A country could always construct a simple, quick, and dirty reprocessing operation to extract plutonium from spent fuel for weapons regardless of whether commercial reprocessing facilities existed.

---

[138] Thomas Pigford, "Actinide Burning and Waste Disposal: Questions and Commentary" (MIT International Conference on the Next Generation of Nuclear Power Technology, 5 October 1990). See also "Waterborne Radiological Results," *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye Country, Nevada* 1, sec. 5.4.2 (DOE/EIS-0250, February 2002), http://www.ymp.gov/documents/feis_2. ^{99}Tc has a half-life of 213,000 years; ^{129}I, 17 million years; and ^{14}C, 5,600 years.

[139] Per Peterson, private communication, H.A. Feiveson, 7 August 2002.

[140] A pressurized water reactor produces about 320 and 250 kg/GWe-yr of plutonium at fuel burnups of 33 and 53 MWd/kgU respectively, *Plutonium Fuel: An Assessment* (OECD, 1989), table 9. A breeder reactor would discharge 3,000 kg/GWe-yr.

2. Placing spent fuel in a repository without separating out the plutonium will over time create a plutonium mine as the radioactive fission products in the spent fuel decay.

3. Advanced reprocessing techniques can be developed that recycle the plutonium always mixed with other transuranic elements and some radioactive fission products and so render the plutonium unusable for weapons unless further separated.

We address these three arguments in turn below.

Simple, quick, and dirty reprocessing.[141] In 1977, Floyd Culler, then the associate director of Oak Ridge National Laboratory (ORNL), distributed a memorandum providing the design of a crude plant that allegedly could recover daily five kilograms of plutonium from half a ton of spent power-reactor fuel.[142] The memorandum claimed that a small- or medium-size country could construct this facility in about six months.

The Office of Technology Assessment and Congressional Research Service undertook their own studies on the question at about the same time. They agreed that a crude reprocessing plant could be built by a relatively unsophisticated country—but not as quickly or as invisibly as the ORNL study claimed. A review of the ORNL memo commissioned by the Controller General of the General Accounting Office came to the same conclusion. It also concluded that "the possibility of quick construction of secret reprocessing plants is not a significant factor in a decision on whether to allow reprocessing of spent fuel."[143]

Plutonium mines. Direct disposal of spent fuel underground would create potential plutonium mines from which future governments or sub-national groups could acquire plutonium for weapons centuries or millennia hence.

The current practice in countries engaged in plutonium recycling of undertaking only one recycle, however, would not eliminate this problem. The mixed-oxide (MOX) fuel still contains about 60 percent as much fissile plutonium when it is spent as when it was fresh.[144] To keep most of the plutonium out of the repository would require indefinitely repeated recycling and the construction of a large number of fast-neutron reactors to burn the plutonium.[145] Such activity would sharply increase the flows of

[141] A comprehensive analysis of this issue may be found in Marvin Miller, "The Feasibility of Clandestine Reprocessing of LWR Spent Fuel," app. 2, Victor Gilinsky, Marvin Miller, and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors* (Washington, D.C.: The Nonproliferation Policy Education Center, September 2004).
[142] D.E. Ferguson, memorandum to F.L. Culler, 30 August 1977.
[143] Controller General of the United States, EMD-78-104, 1978.
[144] For MOX fuel made with plutonium recovered from 10-year-old spent LEU fuel with a burnup of 43 MWd/kgHM irradiated to that same burnup. The fissile isotopes are ^{239}Pu and ^{241}Pu, *Plutonium Fuel: An Assessment* (OECD, 1989), table 12B.
[145] For example, for the United States, a project to fission the 600 tons of transuranics in the 62,000 tons of spent fuel programmed to be stored in Yucca Mountain would require a first generation of 30 GWe of liquid-metal-cooled reactor capacity. These reactors could transmute 53 percent of the transuranics in 32

plutonium for the foreseeable future, the risks of which would have to be weighed against the more distant future risks of plutonium mines.

This issue can be debated for at least 50 years before any spent fuel will be irreversibly buried. In the meantime, spent fuel can be stored at low cost and risk for many decades at reactors or in centralized storage facilities. Priority should be given to the disposition of the huge stockpiles of separated plutonium that have been separated in past reprocessing but simply stored instead of being recycled.

Proliferation-resistant reprocessing. There are alternative reprocessing technologies that are more proliferation resistant than the current PUREX reprocessing process—especially with regard to diversion of plutonium by sub-national groups. [146]

The alternative reprocessing technologies would recycle plutonium mixed with minor transuranics (neptunium, americium, and curium) and, in some cases, some minor fission products. Such contaminated plutonium would be much less attractive as a nuclear-weapons material. However, it would be much easier to recover pure plutonium from this concentrated and mildly radioactive material than from ceramic spent fuel, in which it is diluted by 100 times as much uranium and mixed with intensely radioactive fission products, notably 30-year half-life ^{137}Cs.

Pyroprocessing is the alternative reprocessing technique that is currently receiving the most attention. It was originally proposed by Argonne National Laboratory in the mid-1980s for an on-site reprocessing plant for Argonne's candidate design for the fast plutonium breeder reactor, the Integral Fast Reactor (IFR).[147] It became a centerpiece of the Department of Energy's Advanced Fuel Cycle Initiative[148] after it was endorsed in 2001 by the Bush Administration's cabinet-level National Energy Policy Development (NEPD) Group, chaired by Vice President Cheney:[149]

The NEPD group recommends that, in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods such as

---

years. A second generation of 9 GWe of capacity would then transmute 53 percent or the remaining inventory in the following 32 years, and so on. *Nuclear Wastes: Technologies*, 79-80. See also Deutch et al., *Future of Nuclear Power*, 59-60.

[146] PUREX is a process in which the spent fuel is first chopped up and dissolved in nitric acid. The uranium and plutonium are extracted in an organic solvent, tributyl phosphate, which is bubbled through the acid. The plutonium and uranium are then separately extracted from the solvent. M. Benedict, T. Pigford and H.W. Levi, *Nuclear Chemical Engineering* (McGraw-Hill, 1981), 21.

[147] See "IFR," http://www.anlw.anl.gov:80/anlw_history/reactors/ifr.html. Although funding for the IFR by the U.S. Department of Energy was terminated in 1993, support for the development of pyroprocessing continued when it was approved for the disposition of the sodium-bonded spent fuel from Argonne's Experimental Breeder Reactor II. Proponents of the IFR are also optimistic about the prospects for renewed funding, based on support for nuclear power in general and this technology in particular by members of the Bush administration.

[148] *Advanced Fuel Cycle Initiative*.

[149] *National Energy Policy*. This recommendation is repeated three times: 5-17, 5-22, and app. 1.

pyroprocessing that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium worldwide.

The key step in pyroprocessing is an electro-refining process originally developed by the minerals industry to purify metals: An impure metal is made into an anode that dissolves in a salt and is deposited in a condition of greater purity at a cathode after electro-transport through the salt.[150]

Even if it could be done effectively, which has not yet been established, pyroprocessing of spent nuclear fuel has two serious drawbacks with respect to proliferation resistance, as was pointed out in a study in 1992 done for the Department of Energy by Wymer et al.:[151] (1) Inherent difficulties in measuring the plutonium in-process inventory and (2) Possibilities for further purifying the product. We describe these in more detail below.

Plutonium measurement problems. It is difficult to measure accurately the very large quantity of plutonium in process in electro-refining because, unlike the plutonium in the PUREX acids and organic solvents, it would not be distributed uniformly in the molten salt.[152] Wymer et al. therefore concluded that a safeguards approach for pyroprocessing would have to rely primarily on containment and surveillance. The problem with this approach, however, is that, should there be breakdown of the system, it would not be possible to determine afterwards how much, if any, material had been diverted. This is why materials accounting and control are fundamental to current IAEA safeguards, with containment and surveillance playing a supplementary role.[153] Argonne and Los Alamos National Laboratories are therefore trying to develop an accurate materials-accounting system for a pyroprocessing plant.[154]

Purification of product. Wymer et al. also pointed out that the operator of a pyroprocessing plant could modify the operation of the electrorefiner to produce a plutonium product that is significantly less contaminated by the minor transuranics and

---

[150] W.H. Hannum, et al., "Nonproliferation and Safeguards Aspects of the IFR," *Progress in Nuclear Energy* 31, nos. 1–2 (1997): 203–217.

[151] *Nonproliferation Risks and Benefits of the Integral Fast Reactor,* International Energy Associates Limited, Washington, D.C., Report IEAL-R/86-100, 1986; R.G. Wymer et al., *An Assessment of the Proliferation Potential and International Implications of the Integral Fast Reactor*, Martin Marietta Energy Systems Inc. Report K/ITP-511, 1992.

[152] Because of the approximately 1 percent measurement uncertainties, it is difficult to meet the IAEA's goals for timely detection of diversion of significant quantities of nuclear material from a large PUREX reprocessing plant. For example, in a plant which reprocesses 800 tons of LWR spent fuel containing about 1% of plutonium while operating for about 300 days per year, the uncertainty in closing the material balance in the process material balance area (MBA) of the plant would be about 8 kg of plutonium per month, assuming that the measurement error is ~ 1% of the throughput. This implies that the minimum detectable loss that meets the IAEA's goal of a 95% detection probability and a 5% false alarm probability is 3.3 X 8 or about 25 kg per month. For more details, see M. Miller, *Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?* (Washington, D.C.: Nuclear Control Institute, August 1990).

[153] *NPT Model Safeguards Agreement*, INFCIRC/153, para. 29.

[154] See, e.g., J. Roglans-Ribas et al., *Technology Demonstration of Proliferation Resistance for an Advanced Fuel Cycle Facility,* International Atomic Energy Agency, Report IAEA-CN-108-44, 1993.

rare-earth fission products than the design product. They estimated that the time required to make such changes would range from days to months, depending on which parameters were changed. Alternatively, because of the high plutonium concentration and smaller radiation barrier of the pyroprocessing product, plutonium could be extracted with a PUREX facility much smaller and less heavily shielded than would have been required to recover the plutonium from the original spent fuel.

Thus the proliferation resistance of the pyroprocessing product is superior to that of the pure plutonium recovered using the PUREX process but markedly inferior to the original LWR spent fuel. It therefore fails the National Academy of Science's proposed spent fuel standard as a measure of proliferation resistance in that the contained plutonium is much more physically susceptible to extraction and use for nuclear weapons than is the plutonium in LWR spent fuel.[155]

The need to deal with the legacy of huge civilian stockpiles of separated plutonium

A final important argument for a reprocessing moratorium is the huge stockpile of separated civilian plutonium that has accumulated as a result of past reprocessing. More than 200 tons of plutonium have accumulated at commercial reprocessing plants in France, Japan, Russia, the United Kingdom, and elsewhere. The last thing the world needs is an increase in these stockpiles.

---

[155] The spent fuel standard refers to the goal of making any product containing plutonium "roughly as inaccessible for weapons use as … the quantity of plutonium in spent fuel from commercial nuclear-power reactors." National Academy of Sciences, *Management and Disposition of Excess Weapons: Reactor-Related Options* (National Academy Press, 1995), 2. The plutonium concentration in the pyro product is much greater than in LWR spent fuel—about 15 percent versus about 1 percent. The gamma radiation barrier of an Integrated Fast Reactor fuel assembly is dominated by the rare-earth fission product cerium-144 and is reported as approximately 1000 rem/hr initially if the fuel is fabricated from IFR fuel with only 100 days between IFR fuel discharge and fabrication. W. H. Hannum, D.C. Wade, H.F. MacFarlane, and R.N. Hill, "Nonproliferation and Safeguards Aspects of the IFR," *Progress in Nuclear Energy* 31 (1997): 203. For comparison, the minimum IAEA standard for self-protection is 100 rem/hr. *The Physical Protection of Nuclear Material and Nuclear Facilities,* International Atomic Energy Agency, INFCIRC/225/Rev.4. However, the half-life of ^{144}Ce is only 0.78 years. Its concentration in spent fuel would therefore decline as a result of decay by a factor of one hundred in five years. This makes the proliferation-resistance of pyroprocessing irrelevant for most existing U.S. spent fuel, which, on average is already over a decade old. In contrast, the radiation barrier for an LWR spent fuel assembly at 1 meter after 10 years cooling is well over 1000 rem/hr and decaying with the 30-year half-life of ^{137}Cs, so that it would be self-protecting for 100 years. W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air*, Lawrence Livermore National Laboratory, UCRL-ID-115199, 1994. See Jungmin Kang and Frank von Hippel, "Lack of Self-Protection Benefits from Recycling Minor Transuranics and Rare-Earth Fission Products with Plutonium Aged from Spent Fuel," 21 December 2004, Program on Science & Global Security, Princeton University, to be published in *Science & Global Security*.

Table A-1. Stocks of un-irradiated civilian plutonium (end of 2002) [156]

	Civilian plutonium in country (metric tons)		Abroad
	Total	**Foreign owned**	
Belgium	3.4	2	0.4
China	0	0	0
France	80	32	0
Germany	11	0	~14.5
India	2-3[157]	0	0
Italy	0	0	2.4
Japan	5.3	0	33
Netherlands	0	0	2
Russia	37	0	0
Spain	0	0	0-1
Sweden	0	0	1
Switzerland	1	0	0-2
U.K.	91	21	0
U.S.	4.6[158]	0	0
Total	**≈ 238**	**55**	**≈55**

As has been noted above, in the absence of breeder reactors to use this plutonium, some countries are recycling their separated plutonium back into the light water reactors from whose spent fuel the plutonium was originally separated. France, although it has a large stockpile of 47 tons of separated plutonium—about seven years' production from its domestic UP2 reprocessing plant—is carrying out such a program reasonably successfully.[159] Recycling of plutonium is proceeding relatively smoothly in Germany as well—especially since an agreement was reached with the domestic anti-nuclear

[156] Except where otherwise indicated, based on David Albright, "Separated Civil Plutonium Inventories: Current Status and Future Directions," revised 10 June 2004, http://www.isis-online.org, table 1; this table itself is largely based on national declarations to the IAEA concerning "policies regarding the management of plutonium," InfCirc/549, http://www.iaea.org/Infcircs.html. About 50 tons of the plutonium stored at French and U.K. reprocessing plants belonged to other countries.

[157] This assumes that about 50 percent of India's heavy-water power reactor spent fuel has been reprocessed; and it appears that less than 1 ton has been burned: M.V. Ramana, private communication, 5 January 2005.

[158] In its Infcirc/549 declaration (24 October 2003), the United States reported 52.5 tons of plutonium excess. This included 4.6 tons in unirradiated MOX fuel or other fabricated products, 7.5 tons contained in spent fuel, and 40.4 tons unirradiated plutonium held elsewhere. This table includes only the 4.6 tons. Table 7.1, in order to better show the excess plutonium declared by the United States, included 14.5 tons in the non-weapons category.

[159] David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford: SIPRI/Oxford University Press, 1997),169.

movement to end the shipment of spent fuel abroad for reprocessing and gradually phase out nuclear power in Germany.[160]

Political opposition from local governments has thus far stalled the launch of Japan's plutonium recycling program.

Russia and the United Kingdom do not have adequate LWR capacity to irradiate their stocks of separated plutonium and therefore are simply storing it. Their plutonium either will be stored indefinitely until reactors are built to irradiate it or will be made less accessible by some other means.

A 1998 Royal Society report expressed concern about the lack of any solid plan to deal with United Kingdom's very large (70 tons at the end of 2002) stockpile of separated civilian but weapons-usable plutonium. It warned that, even in stable Britain, "the chance that the stocks of plutonium might, at some stage, be accessed for illicit weapons production is of extreme concern."[161] Reactor-grade plutonium recovered from light water reactor spent fuel will typically have a relatively high concentration (about 25 percent) of ^{240}Pu, compared to less than 6 percent in weapon-grade plutonium. Plutonium recovered from high-burnup fuel would be significantly harder to handle for relatively unsophisticated proliferators, including terrorists, than weapon-grade plutonium. However, numerous expert studies have concluded that it is weapons-usable.[162]

As of the end of 2002, the amount of separated civilian plutonium stored at Russia's Mayak reprocessing plant had risen to 36 tons, up by 2 tons since the end of 2001. The U.S. Department of Energy's Materials Protection, Control, and Accounting (MPC&A) program has helped Russia upgrade security in the warehouses in which this plutonium is stored in roughly 15,000 coffee-pot–size cans by installing intrusion sensors and radiation monitors and laying heavy concrete blocks over the concrete trenches in which the cans are stored.

Summary and conclusions

Unlike uranium enrichment, spent-fuel reprocessing is not required to support the current generation of nuclear power plants. It is also much more costly than spent fuel storage and provides direct access to nuclear-weapon materials.

France and the United Kingdom, the countries that have had large merchant reprocessing operations, have lost their foreign customers. The United Kingdom is therefore abandoning reprocessing. Russia, which has a much smaller commercial

---

[160] German utilities have committed to end spent-fuel shipments to foreign reprocessing plants by 1 July 2005. "Phase-Out Deal Doesn't Solve Utility Concerns About Fuel Logistics," *Nuclear Fuel* (26 June 2000), 3.

[161] *Management of Separated Plutonium,* (London, The Royal Society, 1998) Summary.

[162] See, e.g., J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security* 4 (1993): 111; *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives,* U.S. Department of Energy, DOE/NN-0007, 1997, 37-39.

reprocessing plant, has lost some of its foreign customers but may retain a few because, unlike France and the United Kingdom, it is willing to keep the plutonium and radioactive waste.

Japan may begin to operate its large new reprocessing plant at Rokkasho especially since local governments have blocked long-term interim spent-fuel storage everywhere else, including at nuclear power plants, although it remains unclear how much fuel will be processed. India continues to justify its reprocessing by its ongoing breeder-reactor development program. The industrialized countries have abandoned breeder reactors as uneconomic for the foreseeable future. China is beginning its own small reprocessing and breeder-reactor development program.

Given this situation, we believe that the IAEA and member countries could agree on the following:

- Any country proposing to build a new reprocessing facility should be required to provide a detailed justification (economic or otherwise) for its construction, together with a proliferation impact statement. No new reprocessing facility should be built unless it is determined by the IAEA Board of Governors or a special committee of the U.N. Security Council that it is necessary (e.g., for R&D or to deal with old, unstable spent fuel), that the problem cannot be dealt with at an existing reprocessing facility, and that arrangements are in place to assure that any separated fissile material will be disposed of promptly (within less than a year).

- Reprocessing of stable fuel at existing facilities should only be conducted to the extent that arrangements are already in place for the prompt recycling of the separated plutonium.

- Countries should be encouraged to collaborate on establishing regional interim storage facilities and geological repositories for spent fuel. Any decision by a host country such as Russia[163] to reprocess stored fuel should be subject to prior consent by the countries owning the spent fuel, and by any other country with prior consent rights over the reprocessing of the fuel.[164] Once again, the process should require environmental, economic, and proliferation analysis and international review before it is approved.

- R&D on reprocessing and recycling technologies should be confined to countries already operating reprocessing plants. In particular, the U.S. Advanced Fuel Cycle

[163] As of this writing, only Russia has expressed an interest in interim storage of foreign spent fuel. Russia has been accepting for more than a decade spent fuel from Ukraine and other East European countries for storage at its Zelezhnogorsk nuclear complex outside Krasnoyarsk. However, the storage is in a water pool rather than in safer dry-storage casks—and with the ultimate intention of reprocessing it. "U.S.-Russian Talks May Table Swapping Iran Reactors for Reprocessing Consent," *Nuclear Fuel* (30 September 2002), 3.

[164] The United States in particular has reserved consent rights over the reprocessing of any foreign spent fuel that has been produced with material (e.g. uranium enriched in the United States) or technology (e.g., a reactor design) exported by the United States. *Nuclear Nonproliferation Act of 1978* (Public Law 95-242).

Initiative should be structured so that it does not lead to the spread of sensitive technologies, such as remote manipulators and hot cells, to states not currently engaged in reprocessing.

Appendix B. Candidate draft of a treaty on fissile materials

Treaty Banning the Production of Fissile Material for Use in Nuclear Weapons or Other Nuclear Explosive Devices

The States concluding this Treaty, hereinafter referred to as the "Parties to the Treaty,"
Certain that weapons of mass destruction pose unparalleled dangers to humankind, and of the consequent need to strive toward the elimination of existing nuclear arsenals, the prevention of further proliferation of nuclear weapons, and the prevention of nuclear terrorism,
Convinced that controls on fissile and fissionable materials would limit the manufacture of nuclear weapons and provide a mechanism for international verification related to nuclear disarmament and non-proliferation,

Concerned that the peaceful use of nuclear energy should not contribute to the manufacture of nuclear weapons, that fissile and fissionable material used for peaceful purposes should be protected from diversion or theft for use in the manufacture of nuclear weapons or other nuclear explosive devices, that hazardous radioactive material should not find use in radiological dispersal devices, and that nuclear installations or transport systems are protected against sabotage,
Confident that the participation of all States in a treaty banning the production of fissile and fissionable material for use in nuclear weapons and other nuclear explosives, on an equitable, non-discriminatory basis will serve to ensure peace, security, and prosperity, and recalling United Nations General Assembly Resolution 48/75L of 16 December 1993 and subsequent Resolutions calling for a non-discriminatory multilateral and internationally and effectively verifiable treaty banning the production of fissile and fissionable material for nuclear weapons or other nuclear explosive devices,

Recognizing that banning production includes

- *Ceasing plutonium and high-enriched uranium production activities carried out for nuclear weapons manufacture prior to the entry into force of the treaty;*
- *Prohibiting the future production of weapons-usable fissile and fissionable material for nuclear weapons or other nuclear explosives;*
- *Submitting to verification under the treaty, fissile or fissionable material that could be used in nuclear weapons or other nuclear explosive devices that was produced prior to the entry into force of the treaty, including civil stocks and material that has been declared by a State Party to be excess to its military program requirements;*
- *Submitting to verification under the treaty, fissile or fissionable material that could be used in nuclear weapons or other nuclear explosive devices produced in peaceful nuclear applications prior to the entry into force of the treaty;*
- *Conducting all future production of fissile or fissionable material that could be used in nuclear weapons or other nuclear explosive devices for peaceful applications and non-explosive military applications under approved conditions and subject to verification; and*
- *Assuring that fissile material permitted under the treaty for peaceful use or for non-explosive military applications does not become available – intentionally or unintentionally – for use in the manufacture of nuclear weapons or other nuclear explosive devices by other States or sub-national entities,*

Noting that States party to comprehensive Safeguards Agreements with the International Atomic Energy Agency (hereinafter referred to as IAEA) are subject to de jure prohibitions on the production or acquisition of nuclear material except for peaceful use and that, in accordance with the terms of IAEA agreements, safeguards apply to all source or special fissionable material in all peaceful nuclear activities within the territory of each State, under its jurisdiction or carried out under its control anywhere, to verify that such material is not diverted to nuclear weapons or other nuclear explosive devices,

Acknowledging the ability of the IAEA to undertake the verification responsibilities of the Treaty and thereby coordinate the verification required under the Treaty with IAEA non-proliferation safeguards implemented under existing IAEA safeguards agreements, to provide for the convergence of those measures as progress towards nuclear disarmament occurs, and to assure that the verification of this Treaty will be carried out in a non-discriminatory manner with minimum cost and intrusion into *legitimate activities of the Parties,*

Have agreed as follows:

A. OPERATION

Article I
Basic Undertakings

1. Each Party to the Treaty undertakes not to produce, import, or otherwise acquire from any source whatsoever fissile or fissionable material meeting the definition of material subject to this Treaty for use in nuclear weapons or in any other nuclear explosive device.
2. Each Party to the Treaty undertakes not to redirect the use of any stocks of fissile or fissionable material under its possession or control for use in nuclear weapons or in any other nuclear explosive device.
3. Each Party to the Treaty undertakes not to develop, manufacture, receive, or otherwise obtain from any source whatsoever any facility, equipment, material or technology suitable for the production of material subject to this Treaty, except when such facility, equipment, material, or technology has been approved for peaceful use by the Conference of States Parties.
4. Each Party to the Treaty undertakes not to transfer to any recipient whatsoever fissile or fissionable material meeting the definition of material subject to this Treaty for use in nuclear weapons or other nuclear explosive devices.
5. Each Party to the Treaty undertakes not to transfer to any recipient whatsoever any facility, equipment, material, or technology suitable for the production or use of material subject to this Treaty, except for transfers to States when such facility, equipment, material or technology is approved for peaceful or non-explosive military use by the Conference of States Parties, and provided said material subject to this Treaty or facility, equipment, material, or technology is subject to verification under the Treaty.
6. Each Party to the Treaty undertakes to prevent the theft or unauthorized use of any material subject to this Treaty or of any facility, equipment, material or technology suitable for the production or use of material subject to this Treaty and to take all appropriate domestic and international measures, as relevant, to prevent the transport or use of any such material subject to this Treaty or of any facility, equipment, material, or technology suitable for the production or use of material subject to this Treaty should these preventive measures fail.

Article II

Cessation of Production for Nuclear Weapons
and Verification of Production Facilities and Excess Military Stocks

Cessation of Production

7. Within 90 days of entry into force of the Treaty, each State Party shall submit a declaration to the Director General providing information on all production facilities that were constructed in each State, including the name of each production facility, its address and geographical coordinates, its purpose, the date of its construction, the date(s) of operation, its operational status, and plans for reconfiguring the production facility for non-proscribed purposes or decommissioning. This information shall include facilities that were constructed but were never put into operation.
8. Upon entry into force of the Treaty, all facilities used for, or intended for use for, or capable of the production of fissile material or fissionable material for the manufacture nuclear weapons shall either cease operations permanently or shall be maintained on standby pending approval by a Conference of States Parties for the modification and operation of said facilities for legitimate and prudent peaceful use.

Verification of Production Facilities

9. All production facilities shall be subject to inspection by the IAEA to confirm that production remains stopped, or if subsequent operations are approved by the Conference of States Parties, to confirm that the operations remain in accordance with the approval, and that all fissile material or fissionable material that should be subject to the Treaty is submitted to verification under the Treaty.

Excess Materials Released from Military Use

10. Within 90 days of entry into force of the Treaty, each State shall declare to the IAEA its existing stocks of fissile material and fissionable material meeting the definition of material subject to the Treaty, which each State has determined to be excess to its military needs.
11. In conjunction with nuclear arms reductions after entry into force of the Treaty, each State shall identify proportionate amounts of fissile material or fissionable material meeting the definition of material subject to the Treaty to be declared as excess to its military needs. The implementation of these provisions shall be subject to review by the Conference of States Parties prior to implementation and the results attained shall be reported to the Conference.

Verification of Excess Materials

12. Within 18 months of entry into force of the Treaty, each State and the IAEA shall present for adoption by the Conference of States Parties a proposed plan to verify said excess material as material subject to the Treaty. The verification provisions shall ensure that no information classified by the State relevant to the design or manufacture of nuclear weapons shall be divulged through or as a result of the verification activities carried out.

Article III
Peaceful Use

Peaceful Use Program Approval

13. Each State Party to the Treaty shall have the right to pursue peaceful applications of nuclear energy, provided that the activities a State selects comprise a rational and coherent nuclear energy program and are introduced in a time frame that is consistent with the aims of this Treaty.
14. Within 90 days of entry into force, each State Party shall provide a description of its Peaceful Use Program for nuclear energy. That information shall include the role of each facility within that program and the future plans for each existing facility and for each new facility in planning or construction, including decommissioning plans.
15. Within three years of entry into force, a Committee of the Conference of States Parties shall review each State's peaceful nuclear energy program. As appropriate, consistent with the spirit of the Treaty, the Committee of the Conference of States Parties may recommend modifications, and it may, as deemed necessary, order the cessation of operations in whole or in part.
16. Subsequent to the initial review, the State shall submit any plans for the construction of any new facility or physical modification or change in operation of any existing facility intended to or capable of production, processing, storage, utilization, or disposition of material subject to the Treaty. Where such construction or modifications involve importing material subject to the Treaty or a facility, material, equipment, or technology specified on the Nuclear Suppliers Group Guidelines, the exporting State and the importing State shall make representations to the Committee of the Conference of States Parties to assist in the determination. The IAEA shall present its analysis to the Committee of the Conference in those proceedings.

17. In the event that the findings of the Committee are not acceptable to the State, the State may appeal to the Conference of States Parties.

Facility Design Information

18. Within 90 days of entry into force of the Treaty, each State Party shall submit to the Director General design information on all existing and new facilities described in the Peaceful Use Program of the State that produce, process, store, utilize, and dispose of the fissile or fissionable material defined as material subject to the Treaty, or could carry out such functions on said material. Facility design information should be provided in preliminary form for new facilities and for modifications of existing facilities as early as possible, before the commencement of any construction, and should be revised as the facility is built or modified.

Facility Design Information Verification

19. Each facility shall be subject to verification over its entire life cycle, including during construction, commissioning, operation, modification, upgrade, and decommissioning. The objectives of facility design information verification are to establish the verification approach for material subject to the Treaty and to provide assurance that all fissile and fissionable material stored, processed, or used in that facility is and remains subject to verification. Facility design information verification shall confirm that the physical features and technical capabilities of the facilities conform to the design information provided by the State, confirm the performance of facility systems and equipment for use in the control of and accounting for material subject to the Treaty, confirm that all operations carried out conform to information declared by the facility operator and the State and remain in accordance with the approval granted by the Conference of States Parties, and confirm that all fissile material or fissionable material that should be subject to the Treaty is submitted to verification under the Treaty.

Specified Equipment Design Information

20. Within 90 days of entry into force of the Treaty, each State Party shall submit to the Director General design information on all existing specified equipment. The Conference of States Parties shall determine which design information on proliferation-sensitive equipment may be withheld for security reasons. A registry shall be established by the State for each type and item of such equipment, indicating their design features, date, and place of manufacture, location, use and status. The registry shall be maintained for each such item from manufacture to destruction.

Specified Equipment Design Information Verification

21. Each item of specified equipment shall be subject to verification over its entire life cycle, including during its development, manufacturing, testing, operation, modification, upgrade and decommissioning. The objectives of specified equipment design information verification are to establish the verification methods and procedures relevant to each item of specified equipment, to track each item of equipment over its life cycle, and to confirm that that equipment is used exclusively in accordance with approvals granted by the Conference of States Parties.

Initial Inventory of Material Subject to the Treaty and Inventory Changes

22. Within 90 days of entry into force of the Treaty, each State Party shall submit to the Director General a declaration of all material subject to the Treaty on the territory of the State or under its control anywhere. The declaration shall be listed by location, type and characteristics of said material and shall include the amount, isotopic composition, physical and chemical form, the dates and methods used to establish the declared amounts and composition, and the combined uncertainty of all measurements and calculations used to determine the amounts and composition declared.

23. Each State Party shall submit inventory change reports on a monthly basis for each type of material subject to the Treaty, for each facility and for the State as a whole, showing the book inventory at the end of the previous reporting period, additions, and removals during that period, and the resulting ending book inventory. The removals shall include radioactive decay of plutonium 238 and 241, where the amounts of these materials are sufficient to affect their accountancy. The estimates of book inventory, additions, and removals shall include estimates of the random and systematic uncertainty of all measurements and calculations used to determine the amounts and compositions declared.
24. Each State Party shall ensure that all material subject to the Treaty is maintained at all times under effective control and accounting arrangements, that the locations and amounts are known at all times, that the amounts are determined by measurement and supporting computations, and that the information is acquired, processed, reported, and archived in such a manner as to facilitate verification.

Spent Fuel Registry

25. Within 90 days of entry into force of the Treaty, each State Party shall provide a declaration to the Director General providing information on all irradiated fuel assemblies discharged from nuclear power and research reactors within the State, including the identification of each fuel assembly, the date of last discharge, the initial and final composition of fissile material and fissionable material, the disposition of that fuel assembly and its present location. Thereafter, the State shall provide periodic updates on the relocation and disposition of the fuel assemblies already declared and information on irradiated fuel assemblies discharged after the entry into force of the Treaty.

Verification of Material Subject to the Treaty
Arising From Peaceful Use

26. Within 180 days of entry into force of the Treaty, inspections shall commence in each State Party of all material subject to the Treaty to verify that said material remains properly accounted for and is not diverted or misused for the undeclared production of fissile or fissionable material or for purposes unknown.
27. Upon entry into force of the Treaty, the IAEA together with each State Party to the Treaty shall establish agreed arrangements to assure that all fissile material or fissionable material meeting the definition of material subject to the Treaty produced or imported subsequent to the entry into force of the Treaty is declared by the State Party to the Treaty to the Director General and is subject to verification thereafter.
28. Upon entry into force, the IAEA and each State Party to the Treaty shall agree upon additional measures to provide assurance of the absence of undeclared production or imports of fissile material or fissionable material meeting the definition of material subject to the Treaty. The registry of irradiated fuel assemblies declared under Section 25 shall be used, inter alia, in planning such additional measures.
29. The Conference of States parties shall approve of prioritization and phased implementation as may be practically necessary during the initial period of implementation of the Treaty.
30. The Director General shall prepare guidelines for such arrangements for approval by the Conference of States Parties and shall report on the arrangements agreed.
31. The Director General shall report to the Conference of States Parties on an annual basis on the implementation of the verification provisions and the findings obtained, separately for each State Party to the Treaty.

Proliferation Resistance

32. States Party to the Treaty shall pursue peaceful applications of nuclear energy in a manner intended to prevent or inhibit the misuse of such applications for the development or production of nuclear weapons or other nuclear explosive devices. States intending to

develop nuclear capabilities shall proceed in measured steps that are clearly consistent with prudent and legitimate peaceful use.

33. Nuclear reactors and associated fuel cycles shall be selected, designed, deployed, and operated so as to achieve robust proliferation resistance:
    a. Nuclear energy systems shall be designed to the extent practicable to avoid the use or production of separated fissile or fissionable material meeting the definition of material subject to this Treaty. Recognizing the special risks associated with highly enriched uranium, the enrichment of uranium used in nuclear power reactors and research reactors shall be below the values stipulated for fissile material meeting the definition of material subject to this Treaty. Future naval propulsion reactors should be designed using lower enrichment uranium to the extent possible.
    b. Intrinsic features shall be incorporated into each nuclear energy application to physically inhibit the diversion of nuclear material; to inhibit undeclared production of fissile or fissionable material meeting the definition of fissile or fissionable material meeting the definition of material subject to this Treaty; and to incorporate physical structures, instruments, monitoring systems, and data collection systems to facilitate verification as required under the Treaty.
    c. Nuclear energy systems shall be deployed under institutional and commercial arrangements that include extrinsic proliferation resistance measures to inhibit their misuse as a means to acquire fissile or fissionable material for use in nuclear weapons or other nuclear explosive devices. Transfers of isotopic enrichment technology and reprocessing or other technologies for separating and purifying fissile or fissionable material meeting the definition of material subject to this Treaty should be discouraged and deferred. Other States or Groups of States under proliferation-resistant arrangements should meet the needs of States for fresh fuel and for the management of radioactive wastes arising from nuclear energy applications, wherever possible.
    d. Nuclear energy systems shall be operated in such a manner as to avoid the accumulation of material subject to this Treaty in excess of specific requirements and approved schedules.
34. The Conference of States Parties shall determine the adequacy of proliferation resistance in new projects and modifications to existing projects in each State Party to the Treaty, taking into account the national energy demand, the existing nuclear capability, the incremental change in the State's proliferation capability that would result from the proposed project, the technical, legal, and financial infrastructure, and proliferation risk.

Article IV
Non-Explosive Military Use

35. Each Party to the Treaty shall have the right to produce and employ material subject to the Treaty for non-explosive military applications, noting the requirements of Section 33.a, according to these provisions:
    a. Within 90 days of the entry into force of this provision of the Treaty, existing stocks of fissile material or fissionable material intended for non-explosive military applications shall be declared to the IAEA and shall be subject to IAEA verification thereafter.
    b. At least two years prior to actual need, each State shall request the approval of the Conference of States Parties for the release of a specified amount of material subject to the Treaty for a specified non-explosive military application. The amount specified shall be indicated in terms of the specific intended use, including, as appropriate, the name and model of any vessel or spacecraft to be powered by the use of such material. The amount requested shall include reasonable amounts for the process requirements corresponding to a maximum of 18 months of fuel manufacturing operations, including anticipated scrap and waste.
    c. At least two years prior to the commencement of production, each State shall request the approval of the Conference for the production of material subject to the Treaty for use in specified non-explosive military applications. The fissile or fissionable material

to be produced shall be subject to IAEA verification and shall be released in accordance with the provisions above. The amounts of fissile material or fissionable material to be produced for non-explosive military use shall not exceed the amounts necessary for more than five years of processing and use.

36. Upon completion of a process campaign, the remaining unused material (feed, intermediate products, and any scrap material) shall be resubmitted to IAEA verification.
37. The IAEA shall carry out managed access inspections of all processing and storage facilities used in conjunction with non-explosive applications of material subject to the Treaty, using appropriate inspection methods to confirm, to the extent possible taking into account the classification of information for such military programs, that the material subject to the Treaty has not been diverted for use in nuclear weapons or other nuclear explosive devices or for purposes unknown.
38. The IAEA shall carry out managed access visits to vessels or other locations where the military applications are carried out, or to install monitoring systems intended to limit inspector access, for the purposes of confirming that such applications are in fact carried out.

Article V
Prevention of Theft or Unauthorized Use of Material Subject to the Treaty

39. States Parties to the Treaty shall remain accountable for establishing measures within their territory or anywhere under their control to conduct any operations defined within the Treaty in such a manner as to minimize opportunities for nuclear terrorism, to protect all installations and transport systems associated with the operation of the Treaty, to implement measures to detect acts of terrorism in time to prevent their effect, to respond with appropriate means to prevent their success, and to bring to justice those responsible for the planning, support, and execution of such acts.
40. States Parties to the Treaty shall, under the auspices of the Treaty, cooperate and collaborate in exchanging information on threats of nuclear terrorism and on the mechanisms intended to prevent such acts. States Parties to the Treaty shall remain responsible for the countermeasures implemented within their respective territories and under their control.
41. States Parties to the Treaty shall accede to the Convention on the Physical Protection of Nuclear Material and shall implement the provisions of INFCIRC/225, "Recommendations for the Physical Protection of Nuclear Materials."
42. States Parties to the Treaty shall adopt and implement physical protection intrinsic features and extrinsic measures to
    a. minimize and control access to weapon-usable and other nuclear material, hazardous radioactive material, facilities and transport systems (e.g., through the use of personnel authorization systems, physical barriers, detection equipment, and other appropriate measures);
    b. minimize the vulnerability of nuclear reactor plant systems to cyber attack;
    c. provide immediate response, including use of force, if an act of nuclear terrorism is suspected or if unauthorized access to weapons-usable and other nuclear material, hazardous radioactive material, facilities, and transport systems is anticipated or attempted;
    d. take immediate action to recover any stolen material and minimize the consequences of any act of nuclear terrorism; and
    e. protect vital equipment required to maintain radioactive materials in a safe state, in particular, for reactors, the safety systems which provide reactivity control, decay heat removal, and radionuclide confinement.
43. There shall be created within the International Atomic Energy Agency a physical protection inspection service, which shall be staffed with qualified experts who shall carry out their duties in accordance with the strictest standards of confidentiality.

States Parties to the Treaty may undertake this inspection service on a voluntary basis or as may be specified in legal arrangements concerning nuclear commerce.

B. VERIFICATION AGREEMENTS

Article VI

44. Within 180 days of the entry into force of the Treaty, the following verification agreements shall enter into force between each State and the IAEA:
    a. A comprehensive safeguards agreement incorporating all articles of INFCIRC/153, without diminution, together with a Protocol Additional to the safeguards agreement incorporating all articles of INFCIRC/540, without diminution; and
    b. A complementary verification agreement specific to the Treaty, setting out the obligations and responsibilities of each State and the IAEA for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty. This verification agreement shall address separately the obligations arising from Articles I through IV of the Treaty.
45. For Parties to the Treaty having nuclear material at the time of entry into force of the Treaty that is not subject to IAEA safeguards, the complementary verification agreement specific to the Treaty shall have the effect of suspending relevant parts of the comprehensive safeguards agreement and Additional Protocol as necessary to prevent classified information relevant to the design or manufacture of nuclear weapons from being divulged through or as a result of the implementation of IAEA verification.
46. The Conference of States Parties shall consider steps appropriate to bring about the convergence over time of the verification requirements to a single, non-discriminatory system, with the ultimate goal of removing the suspensions noted in Section 45, at intervals not to exceed 10 years, and upon the entry into force of any arms reductions or nuclear arms control measures.

C. CONFIDENCE BUILDING MEASURES

Article VII
Transparency

47. States Parties to this Treaty are expected to conduct all nuclear operations within their territory or anywhere under their control in an open manner, intended to maintain the support of their citizens and to assure neighboring States and the international community that the activities they carry out are consistent with the spirit of this Treaty and its provisions.

Article VIII
Participation in Complementary Treaty Regimes

48. The provisions of this Treaty are intended to complement and extend the scope and provisions of the Treaty for the Non-Proliferation of Nuclear Weapons. States Parties to this Treaty are encouraged to conclude regional treaties in order to assure the total absence of nuclear weapons in their respective territories.

Article IX
Cooperative Threat Reduction

49. In furtherance of the aims of this Treaty, States Parties are encouraged to resolve potential threats to the security of States under the auspices of the Treaty.
50. States Parties to the Treaty are encouraged to cooperate to address the security and safety of existing and future nuclear installations, systems, and equipment, and including, where appropriate, the security and safety of nuclear weapons.

D. ADMINISTRATION

Article X
Conference of States Parties

51. The Conference of States Parties shall determine the manner in which the Treaty is implemented, in accordance with the Articles below. Three years after the entry into force of this Treaty, the first Conference of States Parties to the Treaty shall be held in Vienna, Austria, to establish its rules and procedures to review the operation of this Treaty with a view to assuring that the purposes of the Preamble and the provisions of the Treaty are being realized. Thereafter, the Conference of States Parties to the Treaty shall convene at regular intervals to be established by the Conference to review implementation of the Treaty and the timing of transitional implementation measures. The Conference of States Parties to the Treaty may be convened on an urgent and essential basis upon the request of any Party, or upon the request of the Board of Governors of the IAEA (hereinafter referred to as the "Board of Governors").
52. The Conference of States Parties shall review and approve of the collection and disbursement of funds for the purposes of verification of the Treaty, for support to States Parties to the Treaty to facilitate, as necessary, the implementation of the Treaty, and for other purposes as may be approved by the Conference, which are consistent with the aims of this Treaty.
53. The Conference of States Parties shall establish a mechanism to provide incentives to individuals and groups to come forward with information pertaining to noncompliance or the threat of nuclear terrorism. Such incentives shall include rewards to be paid for information that is deemed to be reliable and relocation of individuals and their families who might suffer as a result of making such information known.

Article XI
Responsibilities of the IAEA

54. The Depository for the Treaty shall be the Director General of the IAEA (hereinafter referred to as the "Director General"). This Treaty, the Arabic, Chinese, English, French, Russian, and Spanish texts of which are equally authentic, shall be deposited in the archives of the Director General. The Director General to the Governments of the signatory and acceding States shall transmit duly certified copies of this Treaty to all States Parties.
55. The verification and confidence building measures set forth in the Articles above shall be implemented by and through the Director General and the Secretariat of IAEA. Parties to the Treaty shall conclude verification agreements with the IAEA as specified in Article VII of the Treaty.
56. At periodic intervals to be established by the Conference of States Parties, the Director General shall report to the Conference of States Parties on the implementation of the Treaty separately for each State Party, in respect of the nuclear energy program agreed by the Conference of States Parties, information received from the State, the verification activities carried out and the conclusions drawn from those verification activities. The Board of Governors shall review such reports prior to their submission to the Conference of States Parties and shall take appropriate steps to implement any actions specified by the Conference arising from its consideration of such reports.
57. The Director General shall establish and maintain a special fund to be created for the purpose of collecting and disbursing funds for the implementation of this Treaty, under the supervision of the Conference of States Parties, as established in Article XI, Section 45 above.

58. The Board of Governors shall recommend to the Conference of States Parties the budget for implementation of the Treaty, together with the organizational structure and staffing of the Secretariat of the IAEA for this purpose. The budget shall include the costs to the IAEA Secretariat for the implementation of the Treaty in all aspects, together with the costs of projects in States Parties meeting the provisions of Article XI, Section 45 as necessary for the implementation of the Treaty.

Article XII
Entry into Force

59. The Treaty shall enter into force in two steps. Upon ratification by 35 States, except for Article II, Sections 10–11 and Article IV, the Treaty shall enter into force. Article II, Sections 10–11 and Article IV shall enter into force when a minimum of five States, which possess material subject to the Treaty that is not subject to IAEA safeguards, deposit their instruments of ratification. Any State possessing such material may waive this provision and bring the remaining Articles into force before the minimum condition is met.
60. Any State that does not sign the Treaty before its entry into force may accede to it at any time thereafter.
61. This Treaty shall be subject to ratification by signatory States. Instruments of ratification and instruments of accession shall be deposited with the Director General. The Director General shall promptly inform all signatory and acceding States of the date of each signature, the date of deposit of each instrument of ratification or of accession, the date of the entry into force of this Treaty, and the date of receipt of any requests for convening a conference or other notices.
62. For States whose instruments of ratification or accession are deposited subsequent to the entry into force of this Treaty, it shall enter into force on the date of the deposit of their instruments of ratification or accession.
63. This Treaty shall be registered by the Director General pursuant to Article 102 of the Charter of the United Nations.
64. The Treaty shall remain in force indefinitely.

Article XIII
Provisional Arrangements

65. In the period from the opening of the Treaty for signing and entry into force under the provisions of Article XII, the States signing the Treaty shall comprise an interim body to advise on the preparations for implementation. This Preparatory Conference of States Parties shall be empowered to review ongoing nuclear construction projects and to determine whether or not they meet the relevant considerations of Article III, Section 15.

Article XIV
Implementation by States Parties

66. Each party to the Treaty shall enact and enforce laws and regulations governing the implementation of the Treaty, including criminal proceedings against organizations and individuals found in violation of the provisions of Articles I through V of the Treaty.

Article XV
Amendments

67. Any Party to the Treaty may propose amendments to this Treaty. The text of any proposed amendment shall be submitted to the Director General who shall circulate it to all Parties to the Treaty. Thereupon, if requested to do so by one-third or more of the Parties to the Treaty, the Director General shall convene a Conference of States Parties, to which they shall invite all the Parties to the Treaty, to consider such an amendment.

68. Any amendment to this Treaty shall be approved by a majority of the votes of all the Parties to the Treaty. The amendment shall enter into force, for each Party that deposits its instrument of ratification of the amendment, upon the deposit of such instruments of ratification by a majority of all the Parties. Thereafter, it shall enter into force for any other Party upon the deposit of its instrument of ratification of the amendment.

Article XV
Finance

69. Upon entry into force, each State Party to the Treaty shall commence the collection of a 1 percent surcharge on all electricity or other energy products produced within each State through the use of nuclear energy. The funds collected by each State shall be deposited at quarterly intervals in the special account established for this purpose under the provisions of Article XI, Section 56 above.
70. If for any reason the funding provided through Section 68 is deemed to be insufficient to allow the Treaty to be implemented as intended, the Conference of States Parties shall determine whether to increase the rate from 1 percent, or to include the shortfalls in the regular budget of the IAEA, to be secured according to the procedures specified in the IAEA Statute.

Article XVI
Noncompliance

71. Any State Party to the Treaty, or the Director General, may convene a special meeting of the Conference of States Parties to raise a question of noncompliance by a State Party to the Treaty with any of the Treaty's provisions. Such a meeting would commence not less than 24 hours nor more than 48 hours following the notification to the States Parties, and to the Director General, as appropriate. In such cases, the States Parties participating in the special meeting shall constitute a quorum.
72. The special meeting of the Conference of States Parties shall hear the allegations and the response of the State Party or States Parties for which noncompliance is raised. This hearing shall be of a preliminary nature and shall not extend beyond 72 hours of the commencement of the special meeting.
73. The special meeting of the Conference of States Parties may decide to refer the allegation to the United Nations Security Council, or the special meeting of the Conference of States Parties may establish a judiciary panel for the purposes of determining the merit of the allegations and the remedies to be effected.
74. Such a panel would be comprised of nine senior justices or diplomats of ambassadorial rank or above. Three of the panel members shall be named by the State Party or States Parties or by the Director General, as appropriate, alleging the noncompliance. The State Party or States Parties alleged to be in noncompliance shall name three of the panel members. The final three panel members shall be chosen to be mutually acceptable to the State Party or States Parties or by the Director General, as appropriate, alleging the noncompliance, and to the State Party or States Parties alleged to be in noncompliance. In the event that the Parties are unable to agree upon the panel within 72 hours of the request, the Secretary General of the United Nations shall provide appropriate panelists.
75. One panel member of the latter group shall be selected to be the President of the Special Panel. Should the selection not be made within 48 hours, the Secretary General shall name the President of the Panel.
76. The Panel shall have the right to call witnesses and to receive any and all information supporting the allegation and the response, with the exception of information deemed to be sensitive in relation to the design or manufacture of nuclear weapons.

77. The Panel shall conclude its investigation as soon as possible. Its findings shall address the validity of the charges alleged and the remedies to be pursued.

Article XVII
Withdrawal from the Treaty

78. Until such time as the total number of States Parties is 170 or less, each Party shall in exercising its national sovereignty have the right to withdraw from the Treaty if it decides that extraordinary events, related to the subject matter of this Treaty, have jeopardized the supreme interests of its country. It shall give notice of such withdrawal to all other Parties to the Treaty and to the United Nations Security Council three months in advance. Such notice shall include a statement of the extraordinary events it regards as having jeopardized its supreme interests.
79. Upon the entry into force of the 171st Party to the Treaty, the provisions of Section 78 shall no longer apply. Thereafter, each party to the Treaty shall remain a Party to the Treaty for as long as the Treaty remains in force.
80. In the event that a Party to the Treaty believes that it is compelled to consider withdrawing from the Treaty or suspending its observance its undertakings under the Treaty, due to threats to its integrity by another State or group of States, the Party shall request the Conference of States Parties to address the situation with the intention of maintaining the spirit of the Treaty and the integrity of the regime it creates.

In witness whereof the undersigned, duly authorized, have signed this Treaty.

Done in duplicate, in Vienna, the < date>nth day of <Month>, two thousand and <year>.

Annex: Definitions

81. Fissile material shall mean any nuclear species that will fission when struck by a neutron of any kinetic energy; fissionable material shall mean any nuclear species that will fission when struck by a neutron of kinetic energy in excess of a threshold value.
82. Material subject to the Treaty shall mean fissile and fissionable materials which each State Party is required to include under its obligations to report and which the IAEA is required to verify, comprising all fissile and fissionable material separated from fission products which is not contained in deployed nuclear weapons or strategic reserves:

a. plutonium containing any combination of isotopes, except for plutonium containing 80% or more of the isotope ^{238}Pu;
b. uranium containing any mixture of the isotopes ^{235}U and ^{233}U such that $(\%^{235}U + {}^{5}/_{3}(\%^{233}U)) \geq 20\%U$;
c. neptunium; and
d. americium.

83. Additional fissile or fissionable materials suitable for the manufacture of nuclear weapons or other nuclear explosive devices, or changes in these parametric values, may be modified by a simple majority of the Conference of States Parties.
84. Physical Protection shall mean the use of technical, administrative and operational measures to prevent the theft of material subject to the Treaty, theft of hazardous radioactive material for use in a radiological dispersal device, or sabotage of a nuclear installation or transport system.
85. Production (of material subject to the Treaty) shall mean:
    a. Enrichment of isotopes to produce uranium or plutonium with enhanced fission properties;
    b. Separation of any fissile or fissionable material from fission products through reprocessing or any other process, provided that the fissile or fissionable material separated qualifies as material subject to the Treaty under Section 70;
    c. Separation of americium from plutonium, except from plutonium produced prior to entry into force that has not been submitted to verification under the Treaty.
86. A production facility shall mean any facility in which any production activity is carried out or could be carried out.
87. Proliferation resistance shall mean the ability of a nuclear reactor and its associated fuel cycle to impede the diversion or undeclared production of fissile or fissionable material meeting the definition of material subject to the Treaty. Proliferation resistance shall include:
    - Intrinsic features such as physical properties or characteristics of nuclear energy systems that are intended to reduce the usability of the nuclear material for nuclear weapons or nuclear explosive devices, restrict physical possibilities for diversion, prevent or inhibit undeclared production of fissile material or fissionable material, and facilitate verification; and
    - Extrinsic measures resulting from States' undertakings to strengthen international norms against proliferation, reduce the incentives of States to acquire enrichment or reprocessing technologies, restrict access to sensitive nuclear materials and facilities, implement verification at the local, State, regional and international level, and provide for prompt and effective resolution of anomalies and violations.
88. Specified equipment shall mean equipment identified in Annex II of INFCIRC/540, as may be amended.

Draft prepared by: Thomas E. Shea, PhD

Appendix C. Participants in the 2003 Stanford summer study*

Chaim Braun – *CISAC, Stanford Institute for International Studies*
Oleg Bukharin – *U.S. Nuclear Regulatory Commission*
George Bunn – *CISAC, Stanford Institute for International Studies*
Christopher Chyba – *CISAC, Stanford Institute for International Studies*
Jean du Preez – *Monterey Institute for International Studies*
David Elliott – *CISAC, Stanford Institute for International Studies*
Harold Feiveson – *Program on Science & Global Security, Princeton University*
Steve Fetter – *School of Public Policy, University of Maryland*
Victor Gilinsky – *Energy Consultant, formerly Commissioner, Nuclear Regulatory Commission*
Alexander Glaser – *Program on Science & Global Security, Princeton University*
Michael Levi – *King's College London*
Edwin Lyman – *Union of Concerned Scientists*
Michael M. May – *CISAC, Stanford Institute for International Studies*
Zia Mian – *Program on Science & Global Security, Princeton University*
Marvin Miller – *Massachusetts Institute of Technology*
Robert Nelson – *Union of Concerned Scientists*
Pavel Podvig – *CISAC, Stanford Institute for International Studies*
Thomas Shea – *Pacific Northwest Laboratory, formerly of the International Atomic Energy Agency*
Henry Sokolski – *Nonproliferation Policy Education Center*
Fritz Steinhausler – *University of Salzburg, Salzburg, Austria*
Benn Tannenbaum – *American Association for the Advancement of Science*
Frank von Hippel – *Program on Science & Global Security, Princeton University*
Dean Wilkening – *CISAC, Stanford Institute for International Studies*

*with current (March 2005) affiliation

Appendix D. Glossary of acronyms

ABAAC: Argentine-Brazilian Agency for Accounting and Control of Nuclear Material

CISAC: Center for International Security and Cooperation

DPRK: Democratic Peoples Republic of Korea

FMCT: Fissile Material Cutoff Treaty

G-7: Group of Seven industrialized countries

G-8: Group of Eight industrialized countries

GWe: gigawatt-electric

HEU: high-enriched uranium

IAEA: International Atomic Energy Agency

LEU: low-enriched uranium

LWR: light water reactor

MOX: mixed-oxide

MPC&A: Material Protection, Control, and Accounting

NPT: Nuclear Non-Proliferation Treaty

NRC: Nuclear Regulatory Commission

NSG: Nuclear Suppliers Group

Pu: plutonium

SWU: separative work unit

^{235}U: uranium-235

USEC: United States Enrichment Corporation