IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2007

Second report of the International Panel on Fissile Materials

Developing the technical basis for policy initiatives to secure and
irreversibly reduce stocks of nuclear weapons and fissile materials

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Developing the Technical Basis for Policy Initiatives to Secure and Irreversibly Reduce Stocks of Nuclear Weapons and Fissile Materials

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On the cover: the map shows existing and planned uranium enrichment and plutonium separation (reprocessing) facilities around the world. *See Figure 6.1 of this report for more details.*

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from sixteen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in more than one hundred locations. The total amount used for this purpose is sufficient to make about one thousand Hiroshima-type bombs, a design well within the potential capabilities of terrorist groups.

The Panel is co-chaired by Professor R. Rajaraman of Jawaharlal Nehru University in New Delhi and Professor Frank von Hippel of Princeton University. Its members include nuclear experts from Brazil, China, France, Germany, India, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom and the United States. Professor José Goldemberg of Brazil stepped down as co-chair of IPFM on July 1, 2007. He will continue as a member of IPFM. Short biographies of the panel members can be found at the end of this report.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. It has full panel meetings twice a year in capitals around the world in addition to specialist workshops. These meetings and workshops are often in conjunction with international conferences at which IPFM panels and experts are invited to make presentations.

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Summary

Almost two decades since the end of the Cold War, the United States and Russia still retain stockpiles of about 10,000 nuclear weapons each and have committed only to reduce to about half that number by the end of 2012, when the Strategic Offensive Reductions Treaty comes into force.

There are now seven other nuclear weapon states, including North Korea, which carried out its first nuclear test on October 9, 2006. Their arsenals range from a few simple warheads to several hundred high-yield thermonuclear weapons.

There are growing concerns about a loss of momentum in the nuclear disarmament process, additional states acquiring nuclear weapons, and the possibility of nuclear terrorism.

Fissile materials, ordinarily plutonium and highly enriched uranium (HEU), are the essential ingredients in all nuclear weapons. Securing, consolidating, and eliminating fissile material stocks worldwide are the common imperatives in the overlapping efforts to eliminate nuclear weapons in the countries where they exist, halt their spread to still more countries, and prevent terrorists from obtaining them.

This is the second report by International Panel on Fissile Materials on the global situation with regard to efforts to secure and eliminate fissile materials. In this year's report:

- Chapter 1 provides an overview of the status of fissile-material stocks and their production and disposition worldwide;

- Chapters 2 through 5 describe progress in reducing and consolidating global stocks of nuclear weapons and fissile materials; and

- Chapters 6 through 9 discuss initiatives aimed at strengthening international controls over fissile materials and the means of their production.

A short Appendix provides an introduction to fissile materials and their use in nuclear weapons.

Below we summarize briefly some of our key findings and conclusions.

Highly enriched uranium (*Chapters 1 and 2*). As of early 2007, the global stockpiles of HEU totaled between 1400 and 2000 metric tons.* The uncertainty reflects mostly the fact that Russia has not revealed how much HEU it has made.

During 2006, Russia blended down 30 metric tons of weapon-grade uranium to low-enriched uranium (LEU) and shipped it to the United States. This met about half the fuel requirement of U.S. nuclear power plants. Thus far, almost 300 tons of Russian weapon-grade uranium have been disposed of in this way. This program is expected to continue until 2013, by which time 500 tons of HEU, enough for 20,000 weapons, will have been blended down.

In the United States, a total of 87 tons of excess HEU had been blended down as of mid-2007. None of this HEU was weapon-grade. The United States plans to blend down or otherwise dispose of 147 additional tons of HEU, some from weapons, over the next few decades.

Russia and the United States retain for weapons a combined total of 600 to 1200 tons of HEU—sufficient for 25,000 to 50,000 nuclear warheads.

The United States has set aside almost all its excess weapon-grade uranium for use as naval-reactor fuel—enough for 5,000 more nuclear warheads. Russia and the United Kingdom also have large reserves of HEU for naval fuel. These naval HEU stockpiles, and their vulnerable processing and transport links, would be eliminated if the three countries followed France's example and moved to naval reactors fueled with LEU.

HEU also has been used as a fuel for research reactors worldwide since the 1960s. The United States is leading a global effort to clean out often insecure civilian HEU. Thus far, HEU in both fresh and spent fuel has been completely removed from sixteen countries. Twenty-eight, however, still have enough civilian HEU to make at least one nuclear weapon. Russia, which has half of the world's 140 HEU-fueled research reactors, has no policy with regard to HEU cleanout at home.

Separated plutonium (*Chapters 1 and 3*). The current global stockpile of *separated* plutonium is about 500 tons.

During 2006, Russia and the United States made no progress toward implementing their agreement to each dispose of a minimum of 34 tons of excess weapon-grade plutonium. These programs, launched in 2000, have experienced slipping schedules and rising cost estimates. Russia's intention to use its excess plutonium to fuel a breeder reactor indicates that it expects eventually to separate the plutonium again.

India, Pakistan and probably Israel continue to produce more plutonium for weapons. Both India and Pakistan are expanding their production capabilities but, on 14 July 2007, North Korea shut down its plutonium production reactor—hopefully permanently.

As of 2007, the global stock of *civilian* plutonium is approximately 250 metric tons—our central estimate of the amount of plutonium that was made for weapons in the Cold War. Stocks of separated plutonium continue to build up at reprocessing plants in India, Japan, Russia and the United Kingdom. About 8 kg of this "reactor-grade" plutonium is sufficient to make a simple nuclear weapon.

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* In this report, the term "tons" denotes metric tons.

The United Kingdom has decided to abandon spent-fuel reprocessing. Like France and Russia, it has lost its foreign reprocessing customers. It now is faced with the challenge of disposing of one third of the world's separated civilian plutonium and cleaning up the legacy of radioactive contamination from reprocessing, at a cost currently estimated at $75 billion.

Japan has shifted from reprocessing abroad to reprocessing at home. In 2006, it began to operate a new $20 billion domestic spent-fuel reprocessing plant. Operating at design capacity, this plant will separate more than 20 kg of plutonium per day. Japan has not yet been able to begin recycling any of its 40 tons of already separated plutonium into light-water power reactor fuel.

In the United States, the Bush Administration has proposed to reverse a three-decade-old moratorium on domestic reprocessing. This so-called Global Nuclear Energy Partnership initiative is encountering strong opposition in the U.S. Congress, however, and its future is uncertain.

Consolidation of fissile materials in the U.S. nuclear complex (*Chapter 4*). Following the attacks of 11 September 2001, the U.S. Department of Energy (DOE) raised the security requirements for the hundreds of tons of fissile materials spread over its huge nuclear complex. In fiscal year 2006, it spent over $1 billion on this effort.

To further strengthen security and reduce costs, DOE is beginning to consolidate its fissile materials into a smaller number of sites and buildings. When this effort is complete, four of the DOE's ten main sites will no longer have weapon quantities of fissile materials. At three others, fissile materials will be consolidated into one or two high-security buildings. Progress is being slowed in some cases by opposition at sites that stand to lose fissile materials and fear for their current missions and budgets.

Consolidation has not yet touched the naval-reactor fuel cycle. Naval-reactor fuel is fabricated in the United States at two private lower-security facilities using HEU shipped from the DOE's Y-12 Site in Tennessee. All U.S. HEU processing and storage could be consolidated at the Y-12 site, where work is underway on new high-security HEU storage and processing buildings.

Progress toward nuclear disarmament (*Chapter 5*). Nothing would reduce the nuclear threat to civilization and increase the credibility of the nonproliferation regime more than the United States and Russia cutting their weapons and associated fissile-materials stockpiles much more deeply.

There are well-developed proposals for how the United States and Russia could quickly reduce the number of warheads in their nuclear stockpiles to 1000 each. Deeper cuts to about 200 weapons each could be made if other nuclear weapon states joined the arms limitation process. Such deep cuts would make it possible to eliminate most of the global stockpile of weapons HEU and plutonium.

International monitoring in the nuclear-weapon states (*Chapter 6*). In the 1990s, the United States, Russia, France and the United Kingdom officially ended their production of plutonium and HEU for weapons and China communicated unofficially that it had joined the moratorium. All enrichment and reprocessing activities in these countries therefore could be subject to international monitoring, as in the non-weapon states.

All five of these NPT nuclear weapon states have made “voluntary offers” of nuclear facilities for International Atomic Energy Agency (IAEA) safeguarding. The United Kingdom and the United States have offered all of their civilian nuclear facilities. France, Russia and China have made more limited offers. Budget constraints have prevented the IAEA from putting more than a few of these nuclear facilities under safeguards.

In France and the United Kingdom, all civilian nuclear facilities, including enrichment and reprocessing plants, are subject to Euratom safeguards. This has established an invaluable precedent for the extension of international safeguards into the civilian sectors of the other weapon states.

If the IAEA mandate were extended to include safeguarding enrichment plants, reprocessing plants, and all civilian fissile materials in the nuclear weapon states, much of the infrastructure for a verified ban on the production of fissile material for weapons (a Fissile Material Cutoff Treaty) would have been established.

The future of nuclear power (*Chapter 7*). Over the past two decades, there has been little growth in installed nuclear energy capacity in most of the world, with the exception of some limited construction in Asia. Nevertheless, given the cost increases in oil and natural gas, and rising concerns about climate change, many in the nuclear industry hope for a three to four-fold increase in global nuclear capacity by 2050. Nuclear power continues to have very high capital costs, however, and there is a lack of public support for a major expansion.

Whatever the future of nuclear power, it is important to limit the spread of national gas-centrifuge uranium enrichment plants, because they can easily be converted to the production of HEU for weapons. One alternative is to have uranium enrichment take place only in facilities that are multinationally owned and operated.

There is no need for spent-fuel reprocessing plants, national or multinational. Reprocessing and storage or recycling of the recovered plutonium persist only where governments do not allow much less costly and more secure dry-cask storage of spent fuel.

Russia’s role in the international nuclear fuel cycle (*Chapter 8*). Russia is seeking to consolidate its civilian nuclear activities into a single state-owned company that can compete in the global nuclear market as a supplier of nuclear fuel cycle services and reactors.

Russia owns about half of the world’s uranium enrichment capacity. It is becoming a major international supplier of uranium-enrichment services and recently proposed to build a multinational enrichment plant at Angarsk that will be open to IAEA safeguards. Russia also fabricates fuel for all Soviet and Russian designed nuclear power reactors, as well as for some Western reactors, and is constructing power reactors in the developing world.

Russia’s commercial spent nuclear fuel reprocessing industry, like those of France and the United Kingdom, is losing its foreign customers. Because of domestic opposition to taking other countries’ radioactive waste, Russia now requires that radioactive waste from foreign spent fuel be returned to the countries of origin. As a result, those countries are switching to domestic dry-cask storage of their spent fuel.

Environmental monitoring to detect clandestine fissile material production (*Chapter 9*). As part of the Additional Protocol to their NPT safeguards agreements, non-weapon states agree to allow the IAEA to conduct wide-area environmental monitoring to detect clandestine reprocessing or uranium enrichment. Thus far, however, the IAEA Board has not authorized such monitoring.

Field tests have shown that krypton-85, a gaseous fission product that is released when spent fuel is dissolved, can be detected reliably at distances on the order of one hundred kilometers downwind from small reprocessing plants. It could therefore be feasible to install detectors outside military complexes to confirm non-intrusively that a country is not separating plutonium inside.

It has proven more difficult so far to detect clandestine uranium enrichment programs. It is widely believed that any uranium that might leak from a facility would be quickly diluted in the atmosphere to the point where it could no longer be detected against the background of naturally occurring uranium. Uranium is used in centrifuge enrichment plants in the form of gaseous uranium hexafluoride (UF_6), however, and it appears likely that it will remain tagged by fluorine long after its release. It could therefore be distinguishable from natural uranium quite far downwind.

1

Nuclear Weapon and Fissile Material Stockpiles and Production

In the *Global Fissile Material Report 2006* we emphasized that:

- The production of fissile materials for nuclear weapons had stopped in the United States, the United Kingdom, Russia, France and China, but was continuing in India, Pakistan, and North Korea, and possibly Israel;

- A significant fraction of the highly enriched uranium (HEU) and plutonium produced for weapons in the United States and Russia had been declared excess in the mid-1990s, but much more could be, given the subsequent further downsizing of their nuclear-weapon stockpiles;

- The United States is maintaining a large stock of weapon-grade HEU—enough to make more than 5,000 warheads—for future use as fuel in nuclear-powered submarines and other ships. Russia probably has a similar naval HEU stockpile. At some point, the size of these stockpiles will become an impediment to further disarmament;

- Tens of tons of HEU reactor fuel, much of it under inadequate security, is distributed at civilian reactor sites around the world; and

- The global stockpile of civilian but weapon-usable separated plutonium is comparable to that of plutonium produced for weapons and, despite efforts in some countries to recycle it, is growing at an average rate of about ten tons per year.

During 2006, the international community continued to make steady, if slow, progress in reducing excess HEU stocks, but made virtually no progress in disposing of excess weapons plutonium or slowing the buildup of separated civilian plutonium. Sometime in the coming year, the global stock of civilian plutonium will exceed our estimate of the amount of plutonium made for weapons during the Cold War.

Highly enriched uranium (HEU). Russia and the United States continued to blend down their excess weapon HEU to low-enriched uranium (LEU) for light water reactor (LWR) fuel. In 2006, Russia blended down 30 tons of excess weapon HEU and at least 1.5 tons of excess civilian HEU and the United States blended down approximately ten tons of HEU. This is a huge amount of material, but it corresponds to only about ten percent of the remaining HEU assigned for blend-down and three percent of the global HEU stockpile. Some of the HEU declared excess by the United States remains in weapons today, and will be in weapon components for decades.

International efforts directed at converting HEU-fueled research reactors to LEU fuel and to clean out spent HEU fuel from research reactors have accelerated. So far, 16 out of 56 countries that have hosted HEU-fueled reactors have had their civilian HEU removed. But there are still approximately 140 HEU-fueled reactors in the world (not counting naval-propulsion reactors), half of which are in Russia. Russia still does not have a policy on converting its HEU-fueled reactors or cleaning HEU out of those reactor-facilities it no longer needs.

Separated plutonium. As part of the U.S.-India nuclear deal, India has refused to place under international safeguards its stock of spent fuel from indigenous power reactors, separated plutonium, reprocessing plants, fast breeder reactor program, and several CANDU-type reactors needed to provide the initial fuel for the breeder reactors. India is building a 500 MWe fast breeder reactor that could increase India's weapon-grade plutonium production by a factor of five. Pakistan is building its second and third plutonium production reactors, which could at least triple its annual rate of weapon-grade plutonium production.

One of the United Kingdom's two civilian reprocessing plants remained shut down during 2006 because of a pipe failure and major spill of dissolved spent fuel in April 2005. But Japan began operating its new reprocessing plant in Rokkasho. The Bush Administration initiated a program that aims to lead within a decade to the United States separating up to 30 tons of plutonium per year.

The following discussion updates our estimates of national nuclear weapon arsenals and global fissile material stocks and discusses the above developments in more detail.

Nuclear Weapon Arsenals

Nine states have nuclear weapons. These are, in historical order: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan and North Korea. The first five are parties to the Nonproliferation Treaty (NPT). Estimates of their current nuclear-weapon stockpiles are shown in Table 1.1. The U.S. and Russian stockpiles peaked at approximately 30,000 for the United States (around 1965) and 40,000 for Russia (around 1985). They have been dropping since then, albeit, at a slower pace since the late 1990s.[1]

Country	Nuclear Warheads
United States	about 10,000 5000 deployed + 5000 in reserve
Russia	about 10,000 Large uncertainty as to the number of warheads awaiting dismantlement
France	348
United Kingdom	185
China	about 130
Israel	about 100
Pakistan	about 60
India	about 50
North Korea	less than 10

Table 1.1. Estimated total nuclear-weapon stockpiles, 2007.[2]

The United States and Russia are reducing their deployed nuclear weapons as part of the June 2003 Strategic Offensive Reduction Treaty (SORT). This agreement requires that by December 31, 2012, each country's total number of deployed strategic nuclear warheads should not exceed 2200.[3] SORT does not require that warheads taken off deployment be eliminated, and the agreement expires on the day that its limits are to be met. However, Congressional pressure forced the Bush Administration in 2004 to reduce by almost half (to about 5000) the number of warheads the U.S. expects to retain in its active stockpile in 2012.[4]

The Natural Resources Defense Council (NRDC) estimates of the nuclear-weapon stockpiles of China, France, and the United Kingdom are shown in Figure 1.1. Estimates of the size and composition of China's nuclear arsenal have recently been significantly revised. The NRDC assessment of China's stockpile is largely based on information from the U.S. Department of Defense, which in 2006 abandoned its long-standing assumption that China had a large number of tactical nuclear weapons.[5] There are no official sources to confirm this re-evaluation, but China's Foreign Ministry declared in April 2004 that China "possesses the smallest nuclear arsenal" among the nuclear-weapon states of the NPT.[6] This statement suggests less than 200 deployed Chinese nuclear weapons.[7]

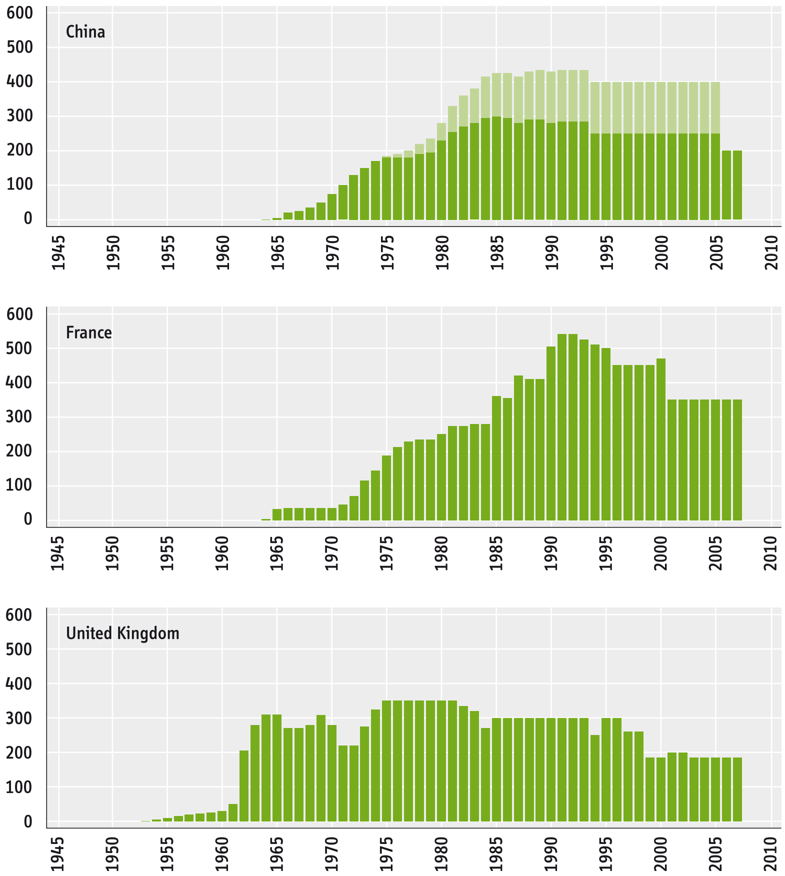

Figure 1.1. Estimated total stockpiles of nuclear weapons in China, France and the United Kingdom. In 2006, the Natural Resources Defense Council revised its estimates for China. Among other changes, it concluded that China may not have the tactical nuclear weapons previously ascribed to it (light green in graph).

In December 2006, the United Kingdom announced that it will further reduce the number of deployed nuclear weapons, from fewer than 200 to “fewer than 160,” and carry out an equivalent 20-percent reduction in size of its “overall warhead stockpile, which includes a small margin to sustain the operationally available warheads.”[8]

Highly Enriched Uranium (HEU)

More than 99 percent of the global HEU stockpile is in the possession of the nuclear weapon states. Only the United Kingdom and the United States have made public the total sizes of their stocks of HEU.[9] Estimates of the remaining national holdings are generally highly uncertain.

As of early 2007, we estimate that the global stockpiles of HEU totaled more than 1700 tons.* This number carries a large uncertainty, about ±300 tons, primarily due to a lack of more detailed official data on Russia’s HEU inventory. The total includes about 360 tons of HEU that has been declared excess to weapon requirements and is to be blended down to low enriched uranium (LEU) or in spent fuel that is to be disposed of directly as waste. These HEU disposition programs are discussed in detail in Chapter 2. Figure 1.2 shows the inventories by country and category.

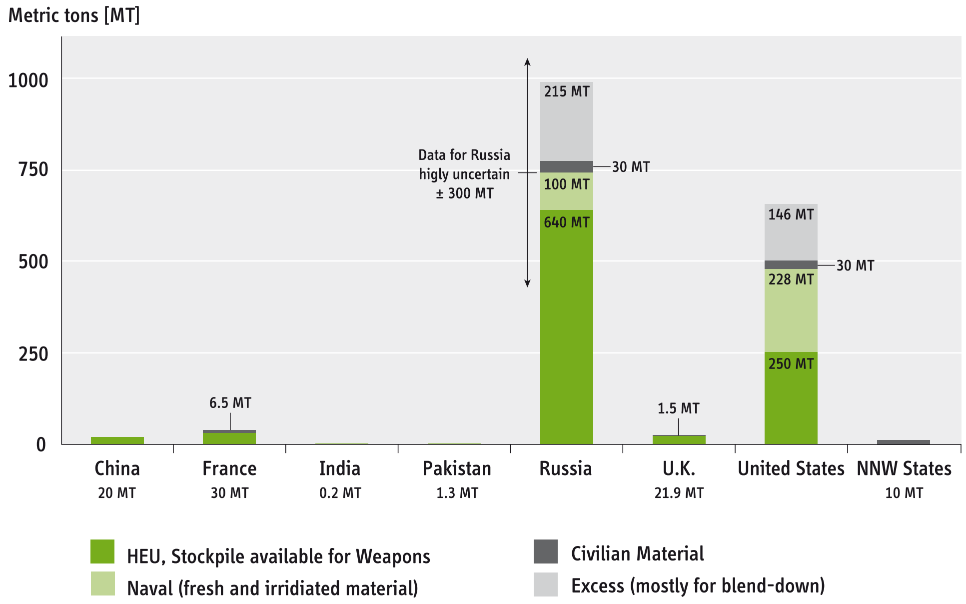

Figure 1.2. National stocks of highly enriched uranium as of mid-2007. Only the numbers for the United Kingdom and United States are based on official information. Other numbers are non-governmental estimates, often with large uncertainties.[10]

The United States has almost 480 tons of HEU in its military stockpile today, including 128 tons of fresh HEU reserved for naval propulsion and about 100 tons in spent naval fuel. It declared a total inventory of 741 tons as of September 30, 1996.[11] The breakdown of the U.S. stockpile is discussed in more detail in Appendix 1A to this chapter. In the case of Russia, we assume that a naval stockpile of 100 tons and a civilian stockpile of 30 tons exist today. These values are very rough estimates.

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* Throughout this report, tons refer t metric tons. One metric ton corresponds to 1000 kg or about 2205 lb.

HEU production. None of the five nuclear weapon states of the NPT are thought to be producing highly enriched uranium.[12] The only states believed to be doing so are Pakistan for weapons, and India for naval-reactor fuel. Their production rates have been estimated to be on the order of 100 kg per year each.[13] A recent report suggests, however, that Pakistan has developed more advanced centrifuge technology (P-3 and P-4).[14] If these machines have gradually replaced the earlier designs (P-1 and P-2), then Pakistan's production rate and inventory of weapon-grade uranium could be significantly higher than previously estimated. India also appears to be expanding its centrifuge program, moving to a larger number of machines with increased separative power.[15] This could allow it to produce highly enriched uranium for both naval fuel and, at higher enrichments, for weapons.

HEU used to fuel naval and other military reactors. France, Russia, the United Kingdom and the United States use HEU to fuel submarine and ship propulsion reactors, although France is switching to LEU fuel.[16] During the Cold War, the Soviet Union and the United States each used more than two tons of HEU per year for this purpose.[17] Today, Russia uses about one ton and the United States, two tons of weapon-grade-equivalent HEU per year. Russia also uses HEU for fueling plutonium and tritium production reactors.[18]

The 128 tons of HEU that the United States has set aside for military naval nuclear propulsion would be sufficient to fuel its existing fleet of aircraft carriers and submarines for 40-60 years.[19] The United States appears to be committed to maintaining its reliance on a nuclear navy, and possibly expanding it to include nuclear-powered cruisers.[20] The U.S. Navy is developing a Next Generation Core (NGR-93), which will use 93-per cent enriched HEU recovered from excess Cold War weapons, instead of the specially produced 97-per cent enriched material that has been used up to present.[21]

Civilian HEU inventory and sites. HEU is used to fuel civilian research reactors as well as Russia's fleet of nine nuclear-powered civilian vessels (eight icebreakers and one transporter ship) that ply the country's northern seaways.[22] As part of the Atoms for Peace program, the Soviet Union/Russia and the United States have supplied HEU to many countries for civilian research-reactor fuel and medical-isotope production targets since the 1950s.

Very roughly, one hundred tons of the HEU are in the fuel cycles of civilian research reactors worldwide and in Russia's nuclear-powered civilian vessels.[23] Most civilian HEU is in the NPT nuclear weapon states. About ten tons are in non-nuclear weapon states.[24]

In connection with a voluntary agreement with the IAEA, nine countries make information about their civilian stocks of plutonium publicly available. France, Germany, and the United Kingdom have begun also to declare their civilian HEU-inventories.[25] The inventories for these three countries are shown in Table 1.2. The other six countries in the plutonium management regime, Belgium, China, Japan, Russia, Switzerland and the United States, all have HEU stocks and could join in making such declarations.

	Fresh	Irradiated
France	4900 kg	1580 kg
Germany	330 kg	730 kg
United Kingdom	1350 kg	140 kg
Declared total	6580 kg	2450 kg

Table 1.2. Civilian HEU inventories declared by three European Union members for December 2005. This information is provided as a voluntary transparency measure in their annual INFCIRC/549-communications to the IAEA.

Even though civilian HEU currently represents only a small percentage of the total global HEU, it would be sufficient for more than 1,000 gun-type nuclear weapons and more than twice as many implosion-type weapons. This HEU is located at about 100 sites, in 40 countries worldwide. Figure 1.3 shows countries categorized by the size of their current holdings of civilian HEU.

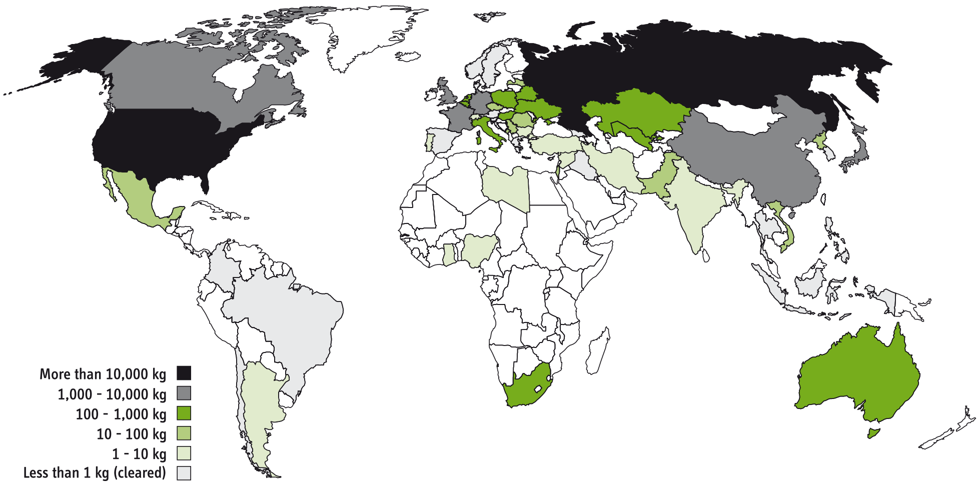


Figure 1.3. Civilian HEU is still distributed around the globe in large quantities. International efforts to convert HEU-fueled research reactors to LEU have reduced the annual demand of the material by about 250 kg of HEU per year. Yet, there are still about 100 sites in 40 countries where the material can be found in significant quantities, at operational or shut down, but not yet decommissioned HEU-fueled reactors.

Civilian HEU is currently the object of a global cleanout campaign in which research reactors are being converted to LEU, with spent HEU fuel taken back to its country of origin, and excess civilian HEU being blended down. As of May 2007, we consider 16 countries that previously had HEU to be cleaned out, i.e., previously existing HEU-fueled reactors have been converted or shut down, and the remaining fresh and spent fuel has been shipped back to the country of origin.[26]

However, this program is far from comprehensive. It largely excludes, for instance, critical assemblies and pulsed-power reactors that can contain huge quantities of barely-irradiated HEU.[27] Table 1.3 gives a break-down of the remaining HEU-fueled research reactors as of 2007.

Reactor	Russia	China	Europe	United States	Other	TOTAL
Steady state	20	3	12	11	23	69
< 0.25 MWt	1	3	5	1	12	22
0.25-2.0 MWt	1	-	0	4	4	9
2.1-10 MWt	6	-	2	3	6	17
> 10 MWt	12*	-	5	3	1	21
Pulsed/Critical	48 + 3**	1	6	8***	5	71
Total	71	4	18	19	28	140
Civilian	54	4	15	12	27	111
Military	17	-	3	7	1	29

Table 1.3. Operational HEU-fueled research reactors by power level in thermal megawatts (MWt) and type for selected countries and regions.[31] Approximately half are in Russia. *Includes 5 production and 2 breeder reactors. **Includes 3 military reactors of unknown mode of operation. ***Includes 4 critical assemblies moved to the Device Assembly Facility in Nevada that are either operational or soon will be.

Separated Plutonium

Plutonium is produced in the uranium fuel of all nuclear reactors—primarily by the absorption of neutrons in U-238. The total spent fuel generated annually by the world's reactors is approximately 10,000 tons, containing about 75 tons of plutonium. Once the U.K.'s B-205 Magnox fuel reprocessing plant and THORP light-water reactor fuel reprocessing plants are shut down, (currently scheduled for 2012) less than one-quarter of the spent fuel generated each year will be reprocessed, even if Japan is operating its new Rokkasho plant at its full 800 tons/year capacity. Unreprocessed spent fuel, which in the case of the dominant light-water reactors contains about one percent plutonium, is stored at reactor or central interim-storage sites.

The global stockpile of *separated* plutonium is about 500 tons. It is divided almost equally between weapon and civilian stocks, but it is virtually all weapon-usable. Separated plutonium exists mostly in nuclear weapon states, but Japan and a few non-nuclear weapon states in Europe also have significant stocks. Figure 1.4 summarizes the data.

Russia and the United States possess by far the largest stocks of military plutonium: 120-170 and 92 tons, respectively. Russia has declared 34 tons, and potentially up to 50 tons, of its weapon-grade plutonium excess for weapon purposes.[28] The United States has declared excess 45 tons of separated government-owned plutonium.[29] Their respective plutonium disposition projects have not made much progress since they were launched in the mid-1990s (see Chapter 3 of this report).

The civilian plutonium stockpile is still growing worldwide. In 2007, we estimate this civilian stockpile will likely exceed the global military stock. Japan, which recently began operation of a large reprocessing facility in Rokkasho, will be a major contributor to this growth until it is able to recycle plutonium into mixed-oxide fuel (MOX) as rapidly as it separates it from spent fuel. In contrast, Germany's stockpile of separated plutonium is now shrinking as a consequence of Germany's decision in the early 2000s to stop spent-fuel shipments to the United Kingdom and France for reprocessing. Its last shipment of spent fuel occurred in April 2005. Germany's utilities expect that its final batch of separated plutonium will be converted into MOX fuel in 2013.[30]

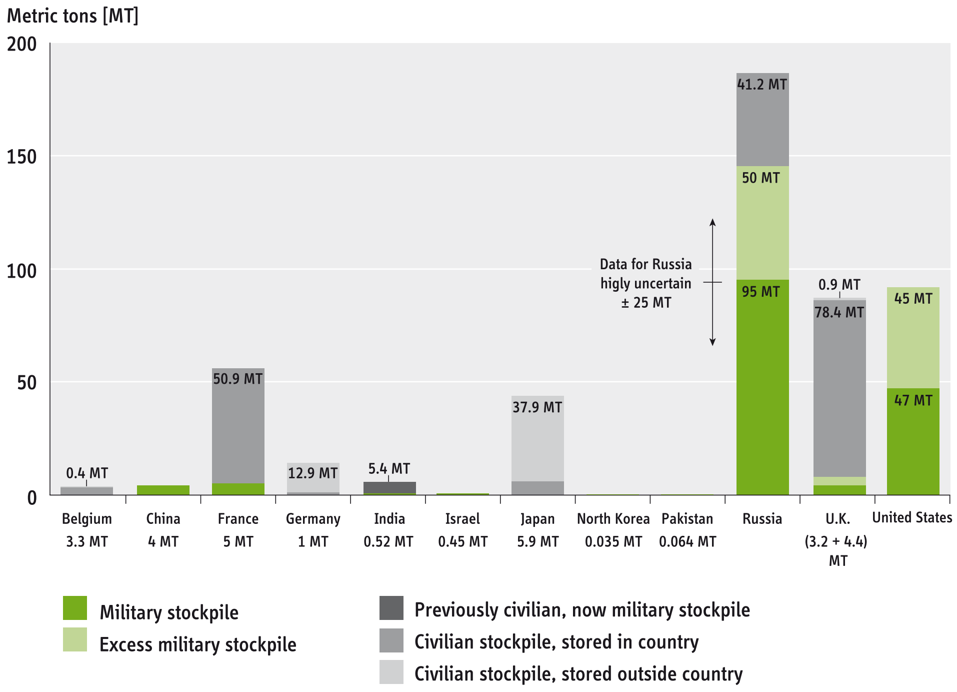


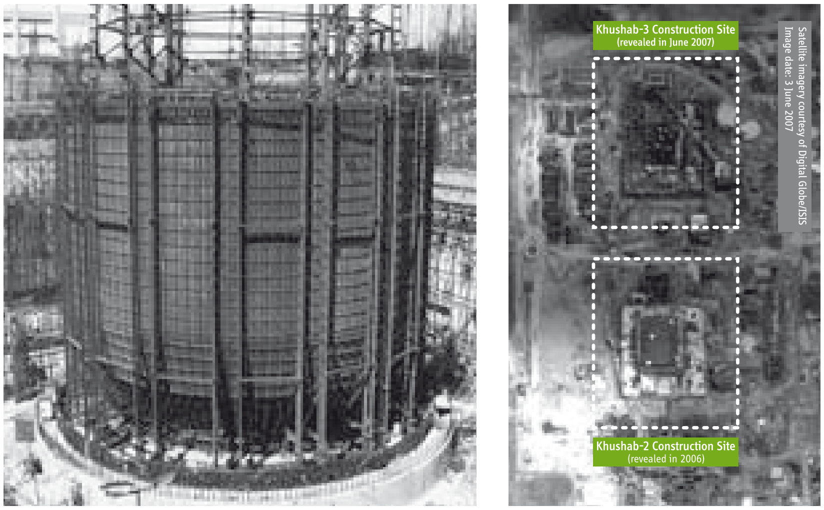
Figure 1.4. National stocks of separated plutonium.[32] Civilian stocks are for December 2005 and based on the latest INFCIRC/549 declarations (when available and with the exception of Germany, see also Appendix 1B to this chapter). Civilian stocks are listed by ownership, not by current location. Weapon stocks are based on non-governmental estimates except for the United Kingdom and the United States, whose governments have made declarations. India's plutonium separated from unsafeguarded spent PHWR fuel is assigned to its military stockpile.

Military production. The French, U.K. and U.S. Governments have announced publicly that they have stopped producing and separating plutonium for use in weapons, and China has given unofficial indications to that effect.[33] Russia continues to produce about 1.2 tons of separated weapon-grade plutonium per year as an unwanted by-product of the continued operation of three plutonium-production reactors, which supply heat and power to nearby populations. Russia and the United States are cooperating on a project to refurbish and build coal-fired district-heating plants to make it possible to shut down these reactors.

India and Pakistan have not stopped production of plutonium for weapons. Israel may also still be producing plutonium for weapons with its reactor at Dimona.[34] In addition, both India and Pakistan are building new unsafeguarded reactors (Figure 1.5) that would increase their rate of production of military plutonium within the next decade.

India plans to complete construction of its first high-power plutonium breeder reactor, the 500 MWe Prototype Fast Breeder Reactor (PFBR), by 2010. This reactor would not be safeguarded under the U.S.-India nuclear agreement and would use unsafeguarded plutonium extracted from India's spent heavy-water-reactor (PHWR) fuel for its initial core and reloads.

India's Department of Atomic Energy has emphasized the military significance of its fast breeder program in the debate on the U.S.-India Deal[35] and independent analyses have shown that more than 140 kg of weapon-grade plutonium could be produced annually in a "blanket" of natural uranium around the breeder core.[36] For comparison, the Indian reactors *Cirus* and *Dhruva* produce together an estimated 30 kg of plutonium per year, for India's nuclear arsenal. India is also building another two new reprocessing plants, at Tarapur and Kalpakkam, which are planned to start operating within a few years.[37] It currently has three plants, with a combined capacity of about 250 tons/year.



Satellite imagery courtesy of Digital Globe/ISIS
Image date: 3 June 2007

Figure 1.5. New reactors under construction in India and Pakistan. Construction of the containment vessel of India's Prototype Fast Breeder Reactor (PFBR) as of 2006, seen on the left. India has insisted that this reactor is part of its national-security infrastructure and will not be offered for international safeguards. It could produce up to 140 kilograms of weapon-grade plutonium per year. Pakistan is building a second and third plutonium production reactor at its Khushab site (right). These two reactors would at least triple Pakistan's production rate of weapon plutonium.[38]

In 2006, commercial satellite imagery revealed the existence of a second plutonium production reactor under construction at the site near Khushab where Pakistan's first plutonium-production reactor is located. Not much is known about its design power level and some estimates have been very high.[39] At the bottom end of the range, its production capacity would be comparable to that of the existing Khushab-1 reactor—about 13 kilograms per year if it operated 300 days per year. More recently, in June 2007, early signs of construction activity for a third production reactor were discovered just north of the site of the second reactor.[40] Once operational, these new reactors could at least triple Pakistan's capacity for producing plutonium for weapons.

Pakistan seems also to have resumed construction of a second reprocessing plant at its Chashma power-reactor site.[41] This emphasis on plutonium production may indicate that Pakistan's nuclear weapon program, which has relied on HEU, is now shifting to more compact plutonium-based weapons. (The critical mass of plutonium is one third or less than that of weapon-grade uranium, depending upon the surrounding material.) Pakistan's reported level of mining of natural uranium is very limited.[42] The demands of its military HEU and plutonium-production reactor programs could move it to conserve uranium by first using it to fuel the plutonium production reactors—which consume less than 20 percent of the U-235 when producing weapon-grade plutonium—and then enriching the resulting slightly depleted uranium to weapon-grade. Both Russia and the United States did this early in their nuclear weapon programs when their demand for natural uranium exceeded the supply.

North Korea resumed production of plutonium in its 20 MWt reactor in Yongbyon in early 2003. In a February 2007 agreement, North Korea committed to end its plutonium production—and, in mid-July 2007, the IAEA confirmed that it had done so.[43]

Civilian stocks and production. At present, France, India, Japan, Russia and the United Kingdom are carrying out large-scale reprocessing and recovery of plutonium from power-reactor spent fuel. This stemmed originally from an interest in commercializing liquid-sodium-cooled plutonium breeder reactors. So far, efforts to commercialize breeder reactors have failed because of their high cost and the operational and safety complications associated with using the sodium coolant, which burns on contact with water or air.

Despite the unfavorable economics of plutonium recycle in light-water reactors, reprocessing continues in France and in Japan.[44] France recycles its plutonium in light-water reactors and Japan hopes to do so, while Russia and the United Kingdom store their separated plutonium. India plans to use its separated heavy-water-reactor plutonium to fuel unsafeguarded plutonium-breeder reactors.

Aside from Japan, virtually all the countries that have been sending their spent fuel to France, the United Kingdom and Russia to be reprocessed have decided to stop and store their spent fuel domestically. Germany, which has already been mentioned in this connection, was the largest reprocessing customer of France and the United Kingdom, after Japan. But Belgium, Spain, Sweden and Switzerland have also not renewed their reprocessing contracts with France and the United Kingdom. Armenia, Bulgaria, the Czech Republic, Finland, Hungary, the Slovak Republic and the Ukraine have not renewed their spent-fuel reprocessing contracts with Russia. Russia has been reprocessing spent fuel from only 15 percent of its nuclear generating capacity.

With the demise of its foreign reprocessing business, the United Kingdom has decided to end its reprocessing program altogether and close its facilities. In the near term, France and Japan will dominate the global reprocessing picture. China plans to open a pilot civilian reprocessing plant. India proposes to build internationally monitored reprocessing plants for the fuel from light-water reactors it seeks to import under the U.S.-India deal.

Overall, the global stockpile of separated civilian plutonium has been growing steadily for decades. From 1996, when all countries with civilian separated plutonium stocks—except India—agreed to publicly declare their civilian plutonium holdings annually to the IAEA, to 2005, the global stockpile rose from 160 tons to 250 tons, not including the plutonium declared excess for weapon use by Russia and the United States (see Appendix 1B).

Unlike France, Japan does not yet have a plutonium recycling program in place. Therefore, the most significant impact on the future trend of the global stockpile of civilian plutonium will be due to Japan's new reprocessing plant, which began initial operations in August 2006. By December 2006, 50 tons of PWR fuel (109 assemblies) and 10 tons of BWR fuel (57 assemblies) had been reprocessed and some of the plutonium was recovered in a 50-50 mixture of plutonium and uranium oxides.[45] Full-scale operation of the facility is currently expected to begin in November 2007, but completion of the local MOX-fuel fabrication plant is not expected earlier than 2012. Japan's plutonium stockpile, therefore, is likely to grow from 40 tons today to more than 70 tons by 2020.[46]

The United Kingdom, which started large scale reprocessing in the 1950s, is planning to end this program by 2011-2012, when existing contracts at the British Nuclear Fuels' THORP facility were to have been fulfilled.[47] It is not clear that THORP will be able to fill its contracts by that date.[48] The plant was closed in 2005 following a leak—permission was given in early 2007 to restart it and work may resume later in 2007.[49] But the U.K.'s Nuclear Decommissioning Authority has raised the possibility of shipping already separated British plutonium and high-level waste to the foreign reprocessing customers, which give the United Kingdom the option of not restarting.[50] The United Kingdom has not been recycling its separated plutonium in power reactors.

The United States abandoned reprocessing in the late 1970s for economic and nonproliferation reasons, but the Bush Administration has recently embraced reprocessing as part of its proposed Global Nuclear Energy Partnership (GNEP). This proposal—like Japan's reprocessing—is driven principally by pressures to begin removing spent fuel from power reactor sites.[51] In the United States, unlike Japan, however, local governments are almost all allowing their nuclear utilities to build additional on-site dry-cask spent-fuel storage.

Plutonium transport. More than 200 tons of the worlds's separated civilian plutonium, or 80 percent of the total, are stored at four sites in Europe and Russia. These are the French reprocessing and fuel-fabrication sites at La Hague and Marcoule (together 64.2 tons, as of December 2005), the British site at Sellafield (102.3 tons) and Russia's Mayak facility (40 tons).

From a security perspective, the concentration of the separated plutonium at a few sites is favorable. Due to the recycle of a large fraction of plutonium that is separated in France, however, there are frequent transports of large quantities of separated plutonium over long distances in Western Europe. In the future, there will also be frequent transports from Western Europe to Japan. Even though Japan has now begun to operate its own reprocessing facility, there are still more than 30 tons of Japanese separated plutonium stored in France and the United Kingdom awaiting shipment to Japan over the next years or decades. And although Germany stopped shipping spent fuel for reprocessing in April 2005, shipments of MOX fuel to Germany will continue until its existing stockpiles of separated plutonium in France and the United Kingdom have been consumed (circa 2013 in the case of France).

Fissile materials are most vulnerable to theft or dispersal when in transit.[52] An average of about 100 commercial shipments containing an average of about 300 kilograms of civilian plutonium will take place annually worldwide over the next 15 years.[53] Centralizing reprocessing centers would *not* significantly reduce transport vulnerability since the plutonium is recycled in many dispersed nuclear power plants. However, co-locating the fabrication of MOX fuel with reprocessing plants reduces the danger of theft of pure separated plutonium oxide.

Examples of transports. The 12-15,000 kilograms per year of plutonium separated at La Hague reprocessing facility are sent in the form of plutonium oxide to the fuel-fabrication plant at Marcoule (Melox plant), a distance of more than 1000 kilometers. From the fuel-fabrication plant in Southern France, the MOX fuel is shipped to 6 sites in France, where 20 reactors are licensed to use MOX-fuel, and to reactors in Germany, Switzerland, Belgium and Japan. Figure 1.6 illustrates some of the transport paths.

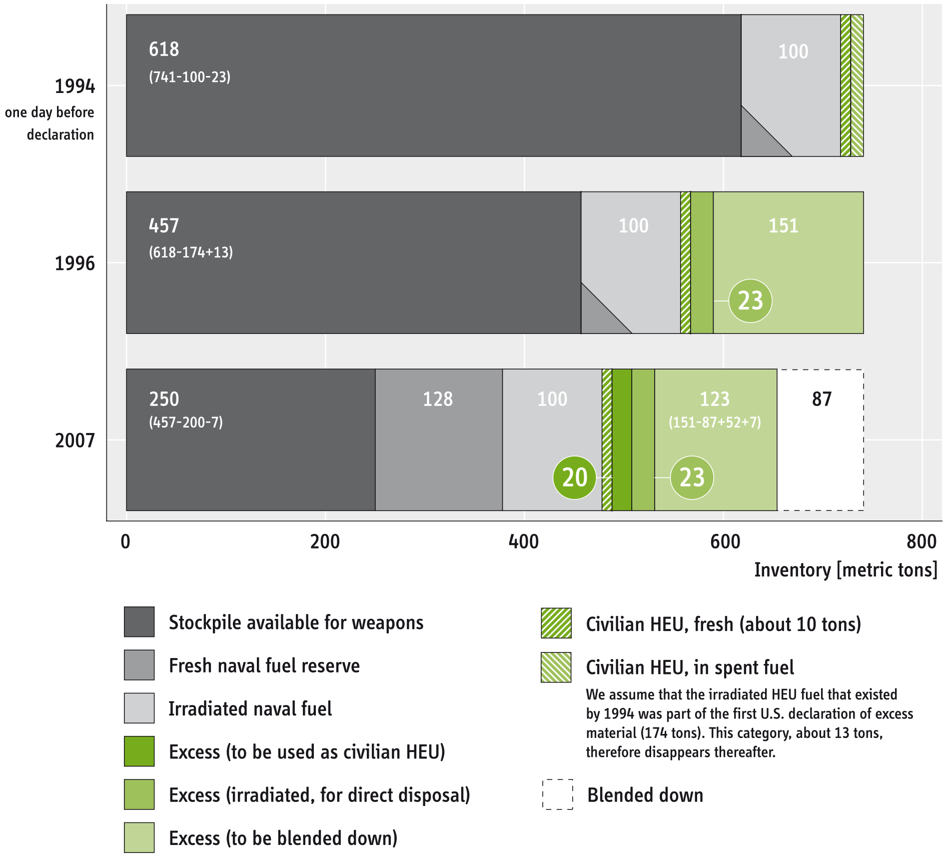
Figure 1.6. Sites and transport-routes of separated plutonium in Europe. Separated plutonium oxide is shipped regularly from the French reprocessing facilities for fuel-fabrication at Marcoule and from there to reactor sites in France, Germany, and elsewhere. Right: In October 2004, Greenpeace activists were able to intercept a truck carrying 140 kilograms of U.S. weapon-grade plutonium across France at a public gas station.[54] [Photo courtesy of Greenpeace/Clements]

MOX fuel containing 12–15,000 kilograms of separated plutonium is transported each year over distances on the order of 1000 kilometers to supply German and French reactors.[55] Reportedly, 270-300 kg of plutonium are transported per shipment from La Hague to Marcoule for fuel fabrication.[56] MOX-fueled reactors need between 400–500 kg of plutonium per year, which may be delivered in one or two shipments. Thus shipments of a few hundred kilograms of plutonium—enough to make 30-60 Nagasaki bombs—are on the roads during an average week in France and Germany.

The reprocessing and MOX programs in Western Europe, especially France, show the scale and problems associated with the large-scale transport of plutonium for use in the nuclear fuel cycle. Even in a relatively localized MOX-program involving two neighboring countries, huge quantities of plutonium may be on the roads a large fraction of the time. This problem will become more acute if there is a broader reliance on plutonium-recycling worldwide.

Appendix 1A. The U.S. HEU Inventory

In 2006, the U.S. Government released a detailed report on U.S. "production, acquisition, and utilization" of HEU through September 1996. The report had been completed at the end of the Clinton Administration in 2001.[57] This report and more recent declarations and official briefings make it possible to discuss the evolution of the U.S. HEU-inventory in greater detail. Figure A1.1 shows how excess weapon HEU has been shifted to other purposes or eliminated since 1993.



We assume that the irradiated HEU fuel that existed by 1994 was part of the first U.S. declaration of excess material (174 tons). This category, about 13 tons, therefore disappears thereafter.

Figure 1A.1. Evolution of the U.S. Stockpile of HEU since new production ended in 1992. Prior to the first excess-declaration in 1994, the inventory was 741 tons. As of mid-2007, 87 tons had been blended down. The average enrichment of the blended down material was about 53%. The 87 tons therefore are equivalent to 51 tons of 90%-enriched uranium (see Table 2.1 in Chapter 2 for details). Today, about 250 tons of U.S. HEU remain available for use in weapons—enough for 10,000 warheads. A significant fraction of the HEU that has been declared excess and assigned for blend-down, however, is still in assembled nuclear weapons.

The 2001 report gave the U.S. HEU inventory as 741 metric tons as of September 30, 1996 (all numbers are rounded to the nearest ton.) This number is used as the baseline for the present discussion, even though some material (on the order of one ton) has been returned from foreign countries in the meantime, mostly in the form of U.S. origin irradiated research-reactor fuel. Another ten tons of HEU may be returned over the next several years.[58]

1994 Inventory. Prior to a first stockpile-declaration in December 1994, there were about 23 tons of HEU in the civilian nuclear complex: about 10 tons as fresh HEU and 13 tons in irradiated fuel.[59] The 2001 report suggests that the 13 tons of irradiated HEU that existed at that time are now part of the 23 tons earmarked for direct disposal. The civilian stockpile of 10 tons of HEU, which is also needed to supply the remaining U.S. research reactors, is carried along in the following.

1996 Inventory. In 1994, the United States declared 174 tons of its HEU inventory to be excess.[60] About 150 tons of this was in unirradiated form and to be blended-down for use as fuel in U.S. power reactors.[61]

2007 Inventory. In late 2005, the United States declared an additional 200 tons of HEU to be excess. However, only 52 tons of this material will be blended down to LEU. Of the remainder, 128 tons of weapon-grade uranium will be reserved for naval-reactor fuel and 20 tons for space and research reactors.[62] An additional 8 tons of HEU in spent research-reactor fuel were subsequently added to the excess material for blend-down. About 1 ton of this is in returned fuel from foreign reactors.

As of mid-2007, 87 tons of the total amount of HEU earmarked for blend down had been processed.[63] None of this HEU was weapon-grade (see Chapter 2).

Taken together, almost 480 tons of HEU remain in the U.S. military stockpile today, including the 128 tons of fresh HEU reserved for naval propulsion. This total, however, includes about 100 tons of HEU in spent naval reactor fuel, which is to be disposed of as radioactive waste.[64] This reduces the amount of unirradiated HEU in the U.S. military stockpiles to about 380 tons. The approximately 250 tons that are currently assigned for weapon purposes are roughly consistent with the estimated 10,000 warheads in the U.S. active and reserve stockpiles, if one assumes an average of 25 kg of HEU per warhead.[65] If the United States dismantled most of its nuclear warheads over the 2200-deployed strategic-warhead limit agreed to for the end of 2012 under the Russian-U.S. Strategic Offensive Reductions Treaty, it could declare excess almost another 200 tons of its stockpile of weapon HEU.

Appendix 1B. Civilian Plutonium Stockpile Declarations

The global stockpile of separated civilian plutonium has been growing steadily for decades. In 1997, as part of an initiative aimed at "increasing the transparency and public understanding of the management of plutonium" nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and United States) began to declare publicly their stocks of civilian plutonium annually to the IAEA. These declarations (INFCIRC/549) are publicly available at the IAEA website. Some countries now add civilian HEU to their declarations. All the INFCIRC/549 declarations give the fissile material stocks at reprocessing plants, fuel-fabrication plants, reactors, and elsewhere, divided into non-irradiated forms and irradiated fuel.

Between 1996, the first year covered by the declarations, and the end of 2005 the global civilian plutonium stockpile rose from 160 tons to 250 tons, not including the plutonium declared excess for weapons use by Russia and the USA. Russia does not include in its declaration excess weapons plutonium, whereas the United States does.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Belgium (Addendum 3)	2.7	2.8	3.8	3.9	2.7	2.9	3.4	3.5	3.3	
	not disclosed									
	?	0.8	1.0	0.9	0.6	1.0	0.4	0.4	0.4	
France (Addendum 5)	65.4	72.3	75.9	81.2	82.7	80.5	79.9	78.6	78.5	81.2
	30.0	33.6	35.6	37.7	38.5	33.5	32.0	30.5	29.7	30.3
	0.2	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Germany (Addendum 2)	Germany's INFCIRC/549 declarations cannot be used to reconstruct the evolution of the German plutonium stockpile (see note below for details) The inventory is on the order of 15 tons today									
Japan (Addendum 1)	5.0	5.0	4.9	5.2	5.3	5.6	5.3	5.4	5.6	5.9
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	15.1	19.1	24.4	27.6	32.1	32.4	33.3	35.2	37.1	37.9
Russia (Addendum 9)	28.2	29.2	30.3	32.0	33.4	35.2	37.2	38.2	39.7	41.2
	0.0									
	0.0									
U.K. (Addendum 8)	54.8	60.1	69.1	72.5	78.1	82.4	90.8	96.2	102.6	104.9
	6.1	6.1	10.2	11.8	16.6	17.1	20.9	22.5	25.9	26.5
	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
United States (Addendum 6)	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	44.9	45.0
	0.0								0.0	0.0
	0.0								0.1	0.0

Table 1B.1. Annual inventories (as of December 31, 2005) of civilian separated plutonium in metric tons as declared through IAEA INFCIRC/549-communcations. Russia's declaration does not include its stockpile of weapon plutonium declared excess to military needs, whereas the U.S. declaration does include this material. White background: inventory held in country; light-grey: foreign-owned; dark-grey: stored outside the country (i.e., not included in local inventory). China and Switzerland also make INFCIRC/549 declarations, but China's have all been zero and Switzerland has only been declaring the amount of plutonium that is in fresh MOX fuel in the country and not yet loaded into its reactors as of the end of the year.

The INFCIRC/549 declarations of Germany are difficult to interpret. Most recently, Germany declared a stockpile of more than 10 tons of plutonium. The German declarations note that "[d]ata on material outside Germany [...] are not available." This suggests that the declared inventory of 10 tons is held within the country. However, the statement on the lack of data on German plutonium outside the country only applies to separated plutonium at reprocessing facilities, i.e., mainly at La Hague. Virtually the entire plutonium-stockpile may be stored as MOX-fuel at the French fabrication site MELOX.

Since important legacy stocks of plutonium have been removed from Germany—notably the core of the German breeder reactor SNR-300, which was stored in Hanau for many years—we do not expect other major stocks to be present at any given time. To account for the delivery and storage of MOX-fuel before a scheduled reload takes place, we assume a typical stockpile of plutonium in Germany on the order of one ton at any given time (Figure 1.4).

Cleaning up After the Cold War

2 Disposition of Excess Highly Enriched Uranium

Russia and the United States have declared excess significant portions of the huge stockpiles of highly enriched uranium (HEU) they produced for weapons during the Cold War and have initiated programs to dispose of these materials. They also are co-operating to reduce civilian use of HEU in other countries and retrieve the HEU that they exported as part of their Atoms for Peace programs.

Russia has declared 500 metric tons of HEU excess to its military needs. The United States originally declared 174.3 tons of HEU excess to military requirements and, in 2005, an additional 200 tons excess to *weapon* requirements (most of the latter material will be used as naval reactor fuel). Much more HEU will have to be declared excess, however, if the stockpiles in each country are to be reduced irreversibly below 10,000 warheads (see Chapter 1).

Most of the HEU declared excess for all military requirements will be converted to low-enriched uranium (LEU) containing 4-5 percent U-235. This is relatively easily done by dilution with depleted, natural or slightly enriched uranium. LEU cannot sustain an explosive nuclear chain reaction but is used to fuel most of the world's nuclear-power reactors and is therefore of commercial value.

This chapter describes the progress of the Russian and U.S. HEU disposition programs and how they could be expanded and accelerated. It also provides a brief update on the progress of the international programs to clean out and dispose of civilian HEU. The quantities of HEU involved are much smaller than those in the weapons programs but civilian sites are typically much less secure than military ones. Cleaning them out may therefore contribute more to reducing the overall danger of nuclear theft.

HEU to LEU

HEU contains 20 percent or more of the chain-reacting isotope U-235. Natural uranium contains only 0.7 percent. (The process of HEU production is described in the Appendix to this volume.)

In Russia, virtually all excess HEU comes from weapons and contains 90-percent U-235. The process of elimination in Russia therefore begins with the conversion of HEU weapon components into metal shavings and then the metal to oxide. The oxide is put through a solvent extraction process to remove chemical impurities and then converted to UF_6 gas, which is blended with a stream of UF_6 gas enriched to 1.5-percent U-235. The 1.5-percent enriched blend-stock is made by stripping more U-235 out of already depleted “tails” from past enrichment operations.[66] About 30 tons of this blend-stock are required to dilute one ton of HEU (see Figure 2.1).

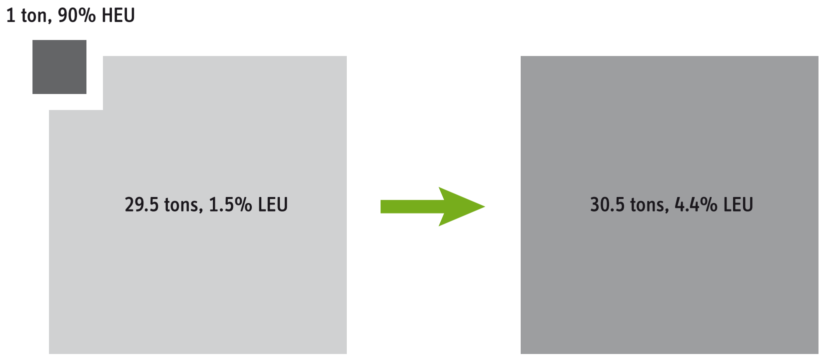


Figure 2.1. Schematic showing amount of 1.5-percent enriched blend-stock required to blend down one ton of excess 90-percent enriched Russian weapon uranium LEU for use as power-reactor fuel. Thirty tons of this LEU is sufficient to fuel a typical one-gigawatt reactor for 1.5 years.

In the United States, the excess HEU being blended down to LEU is from production scrap and reactor fuel as well as from weapons and comes in a variety of forms and enrichments. There is therefore no single U.S. blend-down process. A significant fraction of U.S. HEU is being blended down by mixing acid solutions of HEU and blend-stock together to produce LEU.

Disposition of Excess Russian HEU

Currently, Russia is carrying out two HEU disposition programs in cooperation with the United States:

- The HEU Purchase Agreement, aimed at converting excess Russian weapon HEU to LEU for export to the United States; and
- A much smaller U.S.-financed Material Consolidation and Conversion (MCC) Program, designed to remove excess HEU that is primarily civilian from Russian research institutes and blend it to LEU, to be left in Russia.

In addition to these two programs, Russia’s Federal Atomic Energy Agency (Rosatom) is also using enriched uranium, which may be HEU, for blending with Western European reprocessed uranium to be recycled in light water reactor (LWR) fuel.[67] Each of these efforts is described below.

The HEU Purchase Agreement. In 1993, the United States and Russia reached an agreement under which Russia committed to blend down to an enrichment of 4 to 5 % over a 20-year period 500 tons of 90 percent enriched uranium recovered from dismantled warheads. The United States committed to buy the blended-down uranium for use in LWR fuel.[68] Approximately 30 tons of HEU are being blended each year and the 500-ton agreement is to be completed in 2013. As of the end of 2006, Russia had delivered to the United States LEU blended down from about 292 tons of HEU—the equivalent of almost 12,000 warheads. Figure 2.2 shows the progress of the Russian and also the U.S. blend-down program.

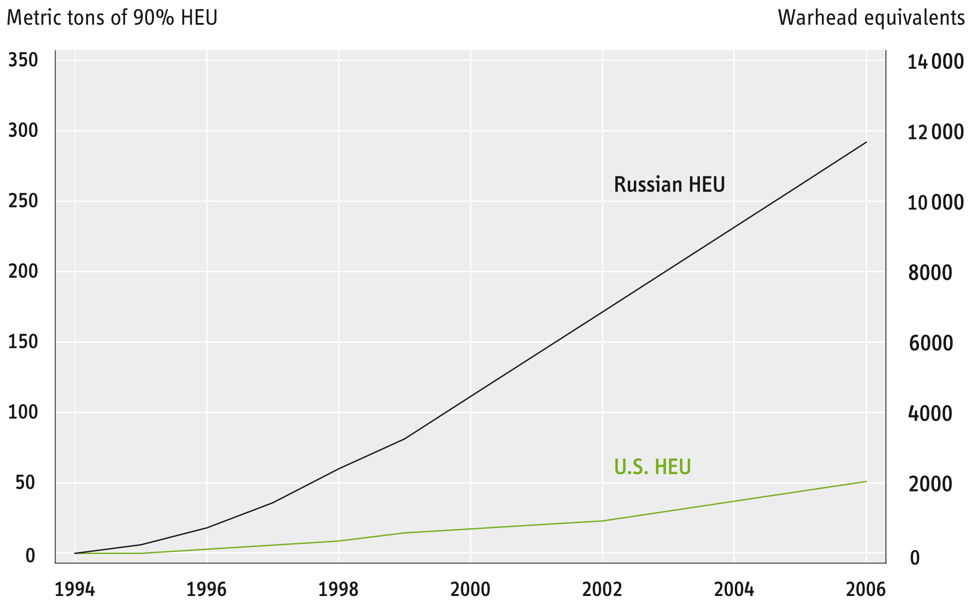


Figure 2.2. Cumulative amounts of excess HEU blended down by Russia for sale to the United States and by the United States. The Russian HEU is 90-percent enriched. The U.S. HEU is of various enrichments but represented here by tons of 90-percent HEU containing the same amount of U-235. Shown on the right-hand side are the number of warheads that could be made from this material, assuming 25 kg of HEU per warhead. The U.S. quantities are relatively small, in part because almost all U.S. excess weapon-grade uranium is being set aside for future use as naval-reactor fuel.[69]

As part of their agreement, the United States and Russia established transparency measures to be used by the United States at the Russian HEU blend-down facilities and by Russia at U.S. facilities receiving the Russian LEU for further processing. The sites involved and the material flows between them are shown in Figure 2.3.[70] U.S. inspectors make several visits each year to the facilities where the HEU metal shavings are converted to oxide. There, they can observe the whole oxidation procedure from the beginning and use gamma-ray spectrometry to confirm that the uranium is weapon-grade. The inspectors then attach tags and seals to the containers of oxide before it is shipped to the blend-down facilities.

When the containers of oxide arrive at the blend-down sites, the U.S. inspectors check the tags and seals. They can also request nondestructive analysis of the chemical composition and enrichment of containers of HEU oxide, observe the feeding of oxide into a process that chemically converts the HEU to a hexafluoride form, and perform an assay of the HEU hexafluoride withdrawn from the conversion process. The United States also has equipment continuously monitoring the enrichments and flows of UF_6 gas at the blending point. There, the 90-percent enriched HEU in one pipe and the 1.5 percent enriched blend-stock in another mix to form the LEU that flows out through a third pipe.

Russian inspectors similarly have the right to regularly visit the U.S. fuel fabrication facilities where the LEU is fabricated into reactor fuel.

In aggregate, these measures give the U.S. Government confidence that the LEU arriving in the United States was in fact derived from weapon-grade metal and Russia confidence that the LEU is used for fuel.

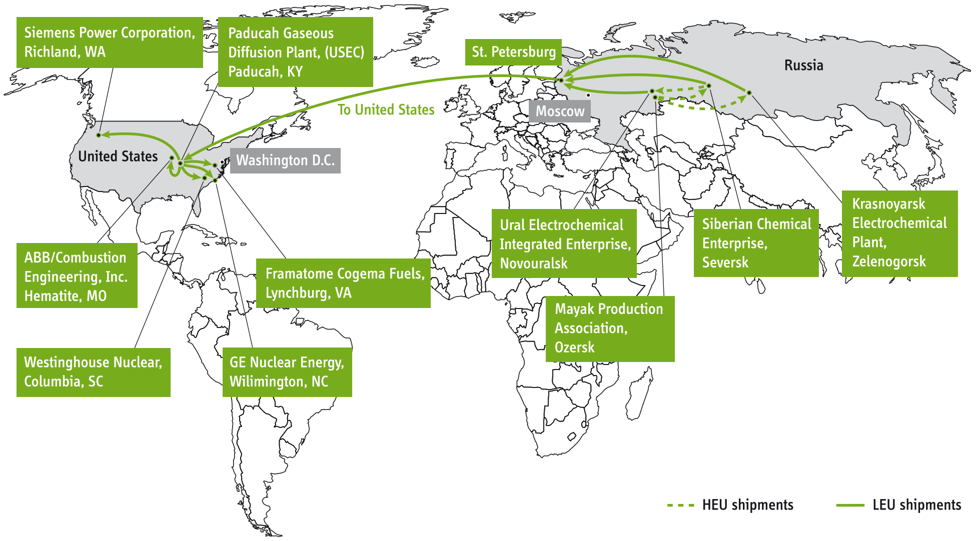


Figure 2.3. Geography of the U.S.-Russian HEU deal. Russian HEU metal from excess weapons is chopped up and oxidized at the Ozersk and Seversk facilities. It is then converted into UF_6 and blended down to LEU at Novouralsk, Seversk and Zelenogorsk. It is shipped to USEC's Paducah, Kentucky site for final adjustment of enrichment before being shipped to one of five U.S. fuel-fabrication plants. (Adapted from Status of Transparency Measures for U.S. Purchase of Russian Highly Enriched Uranium, U.S. General Accounting Office Report GAO/RCED-99-194, 1999, p. 9.)

Russia has been annually supplying the United States through the HEU deal with the equivalent of about 5.5 million SWUs of enrichment work—about 44 percent of U.S. nuclear-utility requirements.[71] The United States is currently negotiating with Russia over what access to the U.S. market Russia will have after the HEU deal ends in 2013. Rosatom hopes to have 20-25% of the U.S. enrichment market in the post-2013 period. The United States has not yet agreed, but is likely to need at least that much enrichment work from Russia.

No definite decisions have yet been announced regarding what will happen to Russia's large remaining quantities of excess weapon HEU when the 500-ton HEU Purchase Agreement is completed in 2013. Sergei Kirienko, the head of Russia's Federal Atomic Agency (Rosatom), has repeatedly made clear, however, that Russia will not continue to dispose of its HEU through USEC after 2013. The way in which the HEU Purchase Agreement is currently implemented by USEC makes it less profitable for Russia than simply selling the blended-down LEU directly on the open market.

There are many alternatives to continuing the HEU deal in its current form. For example, if Russia could get trade barriers removed, it could sell blended down excess HEU on the open market.[72] Alternatively, Rosatom may wish to use blended down HEU to fuel some of the reactors it plans to build in Russia and abroad. This LEU would not need to meet Western commercial specifications and could be produced simply by blending the HEU with natural or depleted uranium. Russia is believed to be spending as much enrichment work stripping tails to produce the blend-stock used in the Russia-U.S. deal as would have been required to produce the LEU from natural uranium.[73]

Not needing to enrich blend-stock would free more Russian enrichment capacity for foreign business. It also would make it much easier for Russia to blend excess HEU at a rate greater than 30 tons per year. Studies by Russian experts sponsored by the Nuclear Threat Initiative (NTI) indicate that the largest constraint on Russia's blend-down rate is its capacity to make the 1.5-percent enriched blend-stock.[74]

With the end of the HEU Puchase Agreement only six years away, accelerating the HEU blend-down rate would only make sense, however, if Russia increased the amount to be blended down beyond the 500 tons already committed. The United States could encourage Russia to do so by offering to let it compete for a larger share of the U.S. enrichment market if it does so.[75] The United States also could offer to ship some of its depleted uranium to Russia on condition that some agreed amount of HEU would be blended down. Although considered waste until recently, at current high uranium prices, U.S. depleted uranium could profitably be enriched by Russia's centrifuge plants. For example, if the relatively rich U.S. depleted uranium were used to produce 1.5-percent enriched blend-stock for the HEU Purchase Agreement, it would save Russia a great deal of enrichment work.[76]

Acceleration of Russia's blend-down rate could raise concerns about the potential disruption of the world enrichment market. If this became a problem—which appears unlikely, given the currently tight market—it could be mitigated if Russia stored some material it blended down until the market was ready to absorb it. The United States could encourage this by paying Russia, as a security investment, for the cost of blending to 19-percent LEU, with Russia gaining the full commercial value when the 19-percent stockpile was eventually blended down to 4-5 percent LEU and sold for power reactor fuel.

Material Consolidation and Conversion (MCC) Program. The second Russian-U.S. cooperative HEU blend-down effort is focused on excess civilian HEU in Russia's nuclear research institutes and the facilities that fabricate Russia's research-reactor fuel. Many of these facilities have large quantities of HEU (see, for example, Figure 2.4). Under this program, the Research Institute of Atomic Reactors in Dmitrovgrad (RIAR) and the Scientific Production Association Luch in Podolsk are funded by the U.S. DOE to buy excess civilian HEU and blend it down to LEU. The MCC Program is interested primarily in material enriched to more than 80-percent and containing more than 50-percent uranium by weight.

MCC Program plans call for blending 17 tons of Russian civilian HEU to LEU by the end of 2015. As of the end of fiscal year 2006, some 8.4 tons of HEU had been blended down.[77] The down-blended material is shipped to the Machine Building Plant (Russian acronym MSZ) in Elektrostal for fabrication into reactor fuel.

Blending-up west European reprocessed uranium. Nuclear utilities in Germany, Sweden, Switzerland, and the Netherlands have been sending reprocessed uranium to Russia to be mixed with Russian enriched uranium to produce LEU. This is part of an agreement in which the fuel-fabrication company, MSZ of Elektrostal, uses hardware supplied by the French company AREVA, to produce fuel containing an equivalent amount of LEU for the European utilities.[78] MSZ has already produced more than 1000 fuel assemblies containing about 500 tons of low-enriched uranium.[79]

Figure 2.4. The BFS-2 Critical Assembly at the Institute of Physics and Power Engineering (IPPE), Obninsk, Russia, has huge inventories of HEU and plutonium. These include about 700 kg of weapon-grade uranium fuel in thousands of disks that are stacked up in columns mixed with similar disks of 36-percent enriched HEU, depleted uranium and plutonium to simulate large fast-reactor cores. Since the maximum enrichment in a fast reactor core is less than 36-percent, the weapon-grade uranium is not required and could be declared excess and blended down by the MCC Program.[80]

Some sources indicate that the reprocessed uranium is being blended with HEU, originally destined for submarine and icebreaker fuel, or even ex-weapon HEU.[81] If the blending were done with 90-percent enriched HEU, roughly 35 kilograms of HEU would be required to produce each ton of LEU. For 500 tons, some 17.5 tons of HEU could have been consumed. But a responsible Russian official reports that the material comes from reprocessed naval and icebreaker spent fuel with an enrichment of 16-17%.[82] In that case, this program would not, strictly speaking, count as additional blending of HEU, which is defined as containing at least 20 percent U-235.

Disposition of Excess U.S. HEU

The U.S. HEU disposition program is not as far advanced as Russia's. This is in part because the pace of dismantlement of U.S. nuclear weapons and weapon components has been so slow. According to DOE, some of the HEU declared excess will not be available for down-blending until 2050.[83] Most of the material being blended down is less than weapon-grade because the U.S. Navy has requisitioned virtually all excess weapon-grade uranium for use as naval fuel (see Chapter 1). The proposed disposition paths for the various batches of excess U.S. HEU are shown in Table 2.1.

The blend-down of two batches of HEU to LEU for USEC to sell for power-reactor fuel has been completed.[84] HEU also is being blended down to 19.75-percent enriched LEU for research reactor fuel. As of the end of 2006, some 2.6 metric tons of HEU had been down-blended for this purpose. These campaigns account for more than 70 percent of the U.S. HEU that had been blended down.

Because of contamination with artificial uranium isotopes, a substantial fraction of the remaining U.S. excess HEU cannot easily be processed into LEU that meets U.S. commercial specifications.[85] DOE therefore negotiated an agreement with the government-owned Tennessee Valley Authority (TVA) to use in its reactors off-specification LEU blended from some 40.3 tons of HEU. This HEU is in a wide range of forms: solutions, oxides, fabricated fuel, uranium fluorides, uranium-aluminum ingots, and metal disks. It is being dissolved and down-blended at the H-Canyon reprocessing facility at the Savannah River Site (SRS) in South Carolina and at Nuclear Fuel Services (NFS) in Erwin, Tennessee. As of late 2006, 23 tons of this "off-spec" HEU had been blended down.[86]

Destination	Quantity [tons U]	Average Enrichment	Disposition Period	Completed as of end 2006
Blend-down to LEU for USEC	14	75%	1995–1998	14
	47	43.7%	1998–2006	47
Blend-down to off-spec. LEU for TVA	40	60.7 %	2002-2016	23
Blend-down to LEU for research reactor fuel	10	33.4 %	2002-2016	2.6
Blend-down to LEU for reliable fuel supply	17	71.4 %	2007–2010	0
Blend-down to LEU, unallocated	23	Not available	2010–2020	0
	20	77%	2007–2030	0
	32	93%	2007–2050	0
	8	Not available	2010–2019	0
HEU fuel for research and space reactors	20	93%	n.a.	0
Disposition as waste or blend-down to be decided	23	Not available	TBD	0
Total	**254**			**87**

Table 2.1. Disposition plans and accomplishments for U.S. HEU declared excess to military needs.[87]

In total, as of mid-2007, 87 tons of U.S. excess HEU containing 45.8 tons of U-235 had been blended to LEU (see Table 2.1).[88]

In July 2007 DOE issued a contract for blending down 17.4 tons of excess HEU that the United States had pledged to use to establish a U.S.-controlled reserve of LEU for foreign countries that do not enrich their own LEU if their suppliers fail to deliver.[89] The plan is to complete blending down 9.3 tons by March 2009.[90]

For the remaining excess U.S. HEU, 75 tons is designated for down-blending to LEU for commercial use.[91] The pace of blending of this material is expected to be slow. For fiscal year 2010 and beyond, DOE only plans to blend about 3 tons of HEU per year.[92] At 25 kg average per warhead, this corresponds to the equivalent of about 120 warheads per year, which is close to the estimated rate of dismantlement of excess U.S. warheads in recent years. Given the planned increase in this dismantlement rate to perhaps 300 warheads per year (see Chapter 5), the blend-down rate also could increase.

The United States has invited the IAEA to monitor a portion of the U.S. HEU disposition effort. In a “verification experiment,” the IAEA confirmed the down-blending of 3.5 tons of HEU at a USEC facility in Portsmouth, Ohio, and monitored blend-down of 46.6 tons of HEU at BWX Technologies. There does not appear to be any international monitoring in place at Nuclear Fuel Services or at the DOE’s Savannah River or Y-12 sites, however, where the remainder of the U.S. HEU blend-down is being carried out. There is also no bilateral monitoring with Russia comparable to that associated with the HEU Purchase Agreement.

Disposition of Civilian HEU in other Countries

There are about 20 tons of civilian HEU in countries other than the United States and Russia, of which about half is in non-weapon states.[93] Much of it is excess to any current or likely future fuel needs. All but a few percent of this material was supplied by either the United States or Russia, and both the United States and Russia are now engaged in active programs to take some of this material back or otherwise arrange appropriate disposition for it.[94] The U.S. program is managed by the DOE's Global Threat Reduction Initiative (GTRI).

As part of the Bush-Putin nuclear security initiative launched at the Bratislava summit in early 2005, Russia and the United States hope to remove or otherwise dispose of all of the estimated 2.2 tons of Russian-origin HEU outside of Russia. As of the end of 2006, some 0.5 tons of HEU, including 60 kilograms in irradiated fuel, had been returned to Russia under this program. Under current plans, all of the HEU currently outside of reactor cores is to be removed or blended down by the end of 2010. The remainder is to be removed by the end of 2015, after it has been discharged from reactors and cooled enough for transport.[95] Once in Russia, the fresh HEU is blended down to LEU at the Luch and Dmitrovgrad facilities. The irradiated fuel is reprocessed and its HEU blended down to LEU in the Mayak facility.

Some Russian-origin material in Kazakhstan, the Ukraine, and Belarus is likely to be blended down in those countries. In a program largely financed by the private Nuclear Threat Initiative, Kazakhstan has already blended down 2.9 tons of unused HEU fuel (enriched to 22-26%) that had been destined for the BN-350 fast-neutron reactor.[96]

An estimated 17.5 tons of U.S.-origin HEU that was shipped abroad had not been returned as of the beginning of the U.S. take-back program in 1996.[97] Of this, some 5.2 tons—roughly one-third—was in fuel eligible for take-back (currently aluminum-based and TRIGA reactor fuels and target material from isotope production). DOE estimates that, after irradiation, this eligible material now contains 3.6 tons of HEU.[98]

Several countries are not planning to take advantage of the take-back offer, however. As of mid-2007, 1.14 tons HEU had been returned and DOE expected the return of only an additional 110 kg by the end of the program.[99]

When returned to the United States, aluminum-based fuel is sent to the DOE's Savannah River Site where DOE currently plans to reprocess it in the H-Canyon.[100] TRIGA fuels are being shipped to the Idaho National Laboratory and will probably be placed in a geological radioactive waste repository.

The remaining 12.3 tons of the original HEU not currently eligible for the U.S. take-back program is mostly in Europe, Canada, or Japan. Small but significant quantities are in many other countries, however. A modest fraction of this material has already been reprocessed abroad, and more is slated for reprocessing in the future. For much of the rest, however, no definite disposition path has been identified.

GTRI therefore has launched an effort known as the "Emerging Threats and Gap Materials" program designed to dispose of potentially vulnerable material not covered by other efforts. This material includes HEU that is neither of U.S. or Russian origin. The new program removed its first 83 kilograms of HEU during fiscal year 2006, (fresh, unirradiated HEU from Belgium, Canada and the Netherlands).[101]

The GTRI hopes to remove a total of 1.4 tons of material in this program by the end of 2013. Several disposition paths are being pursued. Unirradiated HEU is to be added to the stocks of excess U.S. HEU at the DOE's Y-12 facility in Tennessee, from where it is to be sent to Nuclear Fuel Services or Savannah River for blending. Some spent HEU fuel is to be reprocessed at La Hague, France. In addition, DOE is currently considering whether additional HEU and plutonium can be imported into the United States.[102]

Even if successful, however, all these programs will leave many tons of HEU at research reactors and associated sites outside the United States and Russia.

Conclusion

HEU is being eliminated on a large scale by blending down to LEU for commercial use. The primary Russian HEU down-blending program will end in 2013, however. The scale of the U.S. effort has been limited by the U.S. Navy's requisition of almost all excess weapon-grade uranium for its fuel stockpile. And the rate of the U.S. blend down now appears to be limited—at least in part—by the leisurely pace of U.S. warhead dismantlement. The efforts in both countries need to be expanded and accelerated.

Russia and the United States therefore should immediately begin discussions on blending large additional quantities of excess weapon HEU to LEU. Given the current high price of natural uranium—which is anticipated to last at least a decade—both countries could realize billions of dollars.

This approach would contribute to deep and irreversible nuclear arms reductions, strengthen international political support for the nonproliferation regime, and reduce the costs and risks of guarding HEU.

Reductions in excess stocks of civilian HEU should be pursued with equal urgency. If the United States, Russia, and other countries work together to ensure that unneeded civilian HEU is consolidated in secure locations and blended down, the number of civilian sites with enough HEU to make a bomb could be reduced dramatically within a few years. In the longer term the goal should be to eliminate the use and presence of HEU at all civilian facilities.

3 Disposition of Excess Plutonium

During the Cold War, the Soviet Union and United States produced huge quantities of plutonium for weapons. In the early 1990s, following substantial cuts in their nuclear arsenals, Russia and the United States began discussing what to do with their excess weapon materials and, in 2000, concluded a Plutonium Management and Disposition Agreement (PMDA), committing each to eliminate 34 tons of excess weapon plutonium.[103]

The most urgent steps to be taken with this excess plutonium—and with all other separated plutonium worldwide—are to ensure that it is secure and under international monitoring to increase confidence that these stocks will not be used in weapons. In the longer term, however, these excess stocks should be physically transformed into forms from which it would be expensive and difficult to recover for use in weapons.

Applying disposition only to the 34 tons of plutonium in each country currently covered by the U.S.-Russian agreements would have little benefit for international security, however, unless it was a first step toward disposition of much larger quantities of excess plutonium. For Russia, 34 tons of plutonium represents about a quarter of its total stockpile of 120-170 tons of weapon-grade plutonium. For the United States, it is just over a third of its *total* stockpile of 92 tons of separated plutonium—including plutonium that is not weapon-grade (see Chapter 1). If the United States and Russia disposed of larger fractions of their plutonium stockpiles, it would make deep nuclear arms reductions more difficult to reverse and constitute a step toward fulfilling their Nonproliferation Treaty commitments. This would help build political support for strengthening the nonproliferation regime.

Disposition also could facilitate consolidation of excess plutonium into smaller numbers of secure sites.[104] It is not likely, however, that disposition of the 34 tons of excess weapon plutonium by each country will substantially reduce the risk of nuclear theft. This plutonium is some of the most secure in either country and some of the buildings where it resides are likely to still contain tons of plutonium when its disposition is complete. If the highest practicable standards of security and accounting are not maintained during processing and transport, in terms of the danger of theft, the disposition cure could be worse than the disease of excess stockpiles.

Unfortunately, disposition of the U.S. and Russian excess weapon plutonium has yet to begin. The original schedules on both sides have slipped by more than seven years and the estimated costs have more than doubled.

This chapter describes disposition options and assesses the Russian and U.S. programs. The discussion is also relevant to the problem of disposing of the world's growing stocks of separated civil plutonium—especially in the United Kingdom, which currently has no disposition plan.

Plutonium Disposition Options

Unlike highly enriched uranium (HEU), weapon-grade plutonium cannot simply be eliminated as a potential weapon material by dilution with a non-fissile isotope. All plutonium isotopes can support an explosive chain reaction and only plutonium-238, which is available in only relatively small quantities, is considered unusable for weapons. Nuclear weapon designers prefer to use weapon-grade plutonium, containing typically more than 90 percent Pu-239 because other isotopes generate far more heat and spontaneous neutrons. Nevertheless, even a simple Nagasaki-type design made from power reactor plutonium, which contains only 50-60 percent Pu-239, would have an assured yield in the kiloton range. Advanced nuclear weapon states can make nuclear weapons with reactor-grade plutonium that have yield, reliability, and weight comparable to those made from weapon-grade plutonium.[105] Table 3.1 lists the isotopics of typical plutonium compositions. Additional properties of plutonium are summarized in the Appendix to this report.

	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Super-grade	–	98.0%	2.0%	–	–	–
Weapon-grade	0.01%	93.8%	5.8%	0.13%	0.02%	0.22%
Fuel-grade	1.2%	70.9%	15.4%	6.4%	1.9%	4.2%
Reactor-grade (33 GWd/t)	1.3%	60.3%	24.3%	5.6%	5.0%	3.5%
Reactor-grade (50 GWd/t)	2.7%	47.0%	26.0%	9.0%	9.0%	6.0%
MOX-grade	1.9%	40.4%	32.1%	10.7%	7.8%	7.1%
Fast breeder reactor blanket	–	96.0%	4.0%	–	–	–

Table 3.1. Isotopic contents of different plutonium grades.[106]

An extensive two-volume study from the U.S. National Academy of Sciences (NAS), published in the mid-1990s, laid out potential plutonium-disposition options.[107]

One option would be to store excess inventories of separated plutonium indefinitely in high-security facilities, such as that built with U.S. assistance near the Mayak reprocessing facility in Russia[108] and its U.S. counterparts such as the Device Assembly Facility in Nevada (see Figure 4.2). The security of the plutonium would depend on the ceaseless vigilance of the responsible institutions, however, and it would remain available for remanufacture into nuclear weapons quickly and at low cost.

Beyond storage, the NAS, U.S.-Russian and G-8 studies all concluded that the two least problematic approaches would be:

- Mixing the plutonium with uranium, fabricating it into mixed oxide (MOX) fuel and irradiating the material in existing reactors, or

- Immobilizing the plutonium with high-level wastes (HLW).[109]

Both of these approaches would result in most of the plutonium being embedded in large, intensely radioactive waste forms from which it would be difficult and costly to recover. The NAS judged that, in these forms, the plutonium could be made roughly as inaccessible for weapon use as the much larger and growing quantity of plutonium in spent nuclear fuel, an objective they called the “spent fuel standard.”[110]

Disposition begins with the weapon components that contain plutonium metal being cut up and the plutonium being separated from other materials and converted to an oxide (see Figure 3.1). A variety of mechanical or chemical processes can be used for doing this.

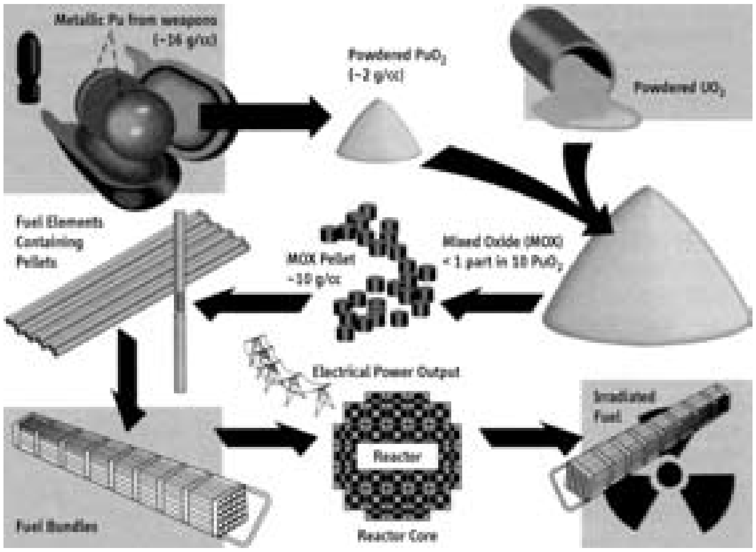


Figure 3.1. Diagram of plutonium pit being cut up, the plutonium made into MOX fuel and the fuel being irradiated in a nuclear-power reactor.[111]

The U.S. DOE is planning to build a large and expensive Pit Disassembly and Conversion Facility (PDCF) for this purpose at its Savannah River Site. It appears likely that Russia will do this work at existing facilities that have been used for manufacturing plutonium weapon components, primarily at the Mayak plutonium facility in the Urals. Plutonium from excess Russian pits is currently being moved into the Mayak storage facility after conversion into 2-kg metal balls. It would be turned into oxide just before fabrication into MOX.[112]

The plutonium declared excess by the United States also includes a variety of non-metallic forms ranging from oxide powders to fabricated fuel elements. Some may be too contaminated to be used as MOX fuel, and could be immobilized with radioactive waste.[113]

MOX fuel. In the MOX fuel approach, the plutonium oxide would be mixed with uranium oxide, pressed, baked and ground into cylindrical ceramic pellets, and loaded into long metal tubes to make fuel rods. The fresh MOX fuel would contain 4-5 percent plutonium. After irradiation in a reactor, the spent MOX fuel would still contain about two thirds as much plutonium, but in large, intensely radioactive fuel assemblies that would require remotely-handled chemical processing to recover the plutonium.

MOX fuels are much more hazardous and expensive to fabricate than standard uranium. Also, handling a weapon-usable material like plutonium requires much more stringent safeguards and security than are required at a facility fabricating low-enriched uranium-fuel.[114]

How many reactors might be required for plutonium disposition? For a one-GWe light-water reactor (LWR) able to take a full core of MOX fuel, roughly one ton of plutonium would be loaded every year.[115] For safety reasons, however, almost all LWRs are limited to using MOX for only one-third of their cores, which reduces the amount of plutonium loaded per GWe-year by a factor of three. Fast-neutron reactors designed for full MOX cores can use fuel with much higher plutonium concentrations. They also fission a smaller fraction of the plutonium. As a result, Russia's demonstration 0.8 GWe BN-800 fast-neutron reactor, currently under construction, is expected to be able to irradiate some 1.6 tons of plutonium in MOX each year—as much as five 1-GWe LWRs operating with one-third cores.

Immobilization. In the immobilization approach, the plutonium would be immobilized in either a glass (often called "vitrification") or a ceramic form.[116] The glass form would typically contain less than 10 percent plutonium by weight. Some ceramics might hold more. In most variants of the immobilization approach, fission products would also be included in the immobilized form.

Mixing plutonium and high-level waste (HLW) together into a homogeneous glass or ceramic poses challenges ranging from the need to avoid criticality to the difficulty of finding waste forms and production processes that can handle substantial concentrations of *both* plutonium and fission products. In recent years, the U.S. DOE therefore has focused on a "can-in-canister" approach, in which the plutonium is immobilized in cylinders of glass or ceramic. These cylinders fit into metal cans that are placed on a rack inside a large canister into which molten HLW glass is poured (see Figure 3.2). Thus, the immobilized plutonium would end up embedded in a large, intensely radioactive waste form that would be stored pending ultimate disposal in a geologic repository.

Another immobilization approach that has been proposed is referred to as "storage-MOX." In this option, MOX plants would fabricate MOX pellets without the stringent quality requirements required for reactor fuel, and tubes containing these pellets would be interspersed with spent fuel rods in disposal casks for storage and eventual disposal. The spent fuel would provide a radiation barrier that would make it more difficult to access the storage MOX.[117]

Disposition of Russia's Excess Weapon Plutonium

Russia's nuclear-energy establishment has always seen its excess plutonium as an asset that should be used to produce energy. It has taken the view that, if other countries want Russia to burn weapon plutonium before it becomes an economic fuel for future fast-neutron reactors, then they should pay the full costs of doing so, including the design, construction and operation of facilities to produce MOX fuel, and the reactor modifications required to adapt existing Russian reactors to use it. The Russian-U.S. plutonium-disposition agreement of 2000 therefore committed the parties to seek international funding for Russia's disposition program. It was also agreed that each country could blend the 34 tons of weapon-grade plutonium with up to four tons of reactor-grade plutonium, for a total of 38 tons of plutonium. This provision was inserted at Russian insistence to keep the isotopics of the weapon-grade plutonium secret.

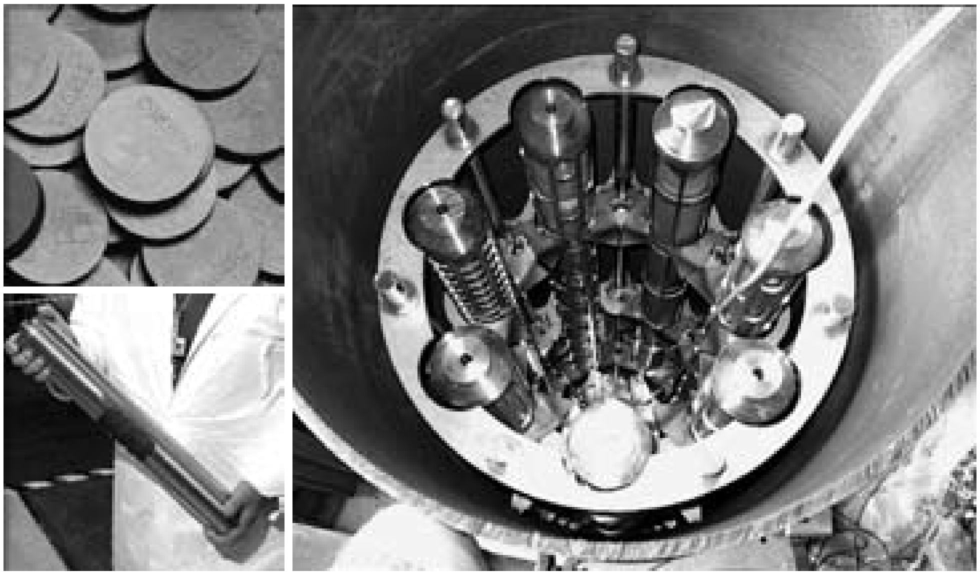


Figure 3.2. Plutonium immobilization with the can-in-canister approach. Left top: plutonium immobilized in ceramic pucks. Left bottom: pucks stacked in a can. Right: cans emplaced in a canister before molten glass containing radioactive waste is poured around them to provide the radiation barrier. [Source: U.S. DOE]

In 2001, a joint U.S.-Russian study envisioned that 14.5 tons of Russia's excess plutonium would be used in the BN-600 fast-neutron reactor and the rest in VVER-1000 LWRs.[118]

It also has been suggested that Russian plutonium could be disposed of in West European reactors that have already been licensed for MOX fuel.[119] Reactors in Canada and the Ukraine have also been proposed. None of these proposals have, however, found constituencies in Russia, the United States, or the proposed third countries.

Although it was originally envisioned that a full-scale MOX plant would be operating in Russia by 2007, a December 2006 joint U.S.-Russian report projected that this facility would not begin operations until 2017 or 2018, a delay of at least ten years.[120] One reason for the delay was an extended dispute over the liability of U.S. contractors for any damages due to their contributions to Russia's plutonium disposition program. The Bush administration demanded for a time that Russia should accept liability even in the event of intentional sabotage by U.S. personnel. This was only resolved, without such a provision, in a U.S.-Russian protocol signed on September 15, 2006.[121]

Funding also has been a problem. To date, Western contributors have only pledged about $850 million (including $400 million from the U.S. Government).[122] The estimated cost for the Russian disposition program increased from about $1.8 billion in 2000 ($2.1 billion in 2006 dollars) to $4.1 billion, with roughly half of the total being for up-front capital and licensing costs, and the other half for operations costs over the program lifetime.[123] These cost estimates are substantially higher than international experience would suggest and the differences have not been publicly explained.[124]

Another complication stemmed from the fact that, while the year-2000 Russian-U.S. plutonium disposition agreement called for using most of the excess plutonium as MOX in Russian LWRs, there continued to be a strong faction within the Russian nuclear establishment that believed that the plutonium should be saved for starting up a fleet of fast-neutron breeder reactors. The position of this group has been strengthened by the Bush Administration's recent Global Nuclear Energy Partnership (GNEP) initiative, which proposes international cooperation on fast-neutron reactors.[125] Another group in the Russian nuclear establishment has favored the use of high-temperature gas reactors, such as the gas-turbine modular helium reactor, which is being developed in a joint Russian-U.S. program.

By early 2007, it appeared that the fast-neutron-reactor advocates had won and the Russian Government had decided to use most of the excess plutonium covered by the year-2000 agreement to fuel the BN-800 fast-neutron reactor, now under construction at Beloyarsk.[126] Russian officials have publicly indicated that Russia will pay the cost of building the BN-800 itself.[127] The U.S. Government has reported that it has told the Russian Government that "it does not plan to provide assistance beyond the $400 million already pledged, and does not expect any significant increase in any other donors' pledges."[128] Nevertheless, the international funds already pledged may well be sufficient to pay the costs of converting the weapon plutonium metal into oxide and of storing the resulting spent fuel to assure that it is not reprocessed until after the disposition program is complete.

Some argue that proceeding with disposition in the BN-800 may be worse than not proceeding with disposition at all, as the BN-800 is designed to produce more plutonium than it consumes, and the spent fuel will be reprocessed and the plutonium recycled. DOE is seeking a commitment from the Russian Government that it will modify the BN-800 to operate as a net burner of plutonium (although likely changes would only change the breeding ratio from slightly above to slightly below 1.0). It is also seeking a commitment that any future reprocessing of the spent fuel would be done in a way that does not separate pure, weapon-grade plutonium. Russia always planned to reprocess the spent MOX fuel in any case but the Plutonium Management and Disposition Agreement prohibits it from recovering the plutonium until all the original plutonium has been irradiated. The plutonium therefore would stay in the spent fuel for a period of some decades at least.[129]

Disposition of U.S. Excess Weapon Plutonium

The U.S. program for disposition of its own excess weapon plutonium has also suffered years of delay and rapidly escalating costs. Today, its future, like that of the Russian disposition program, is very much in question.

In the mid-1990s, the U.S. Government conducted extensive studies of the technical feasibility, cost, safety, environmental impacts, and nonproliferation implications of a wide range of different plutonium disposition options.[130] In January 1997, it was decided to pursue a "dual-track" strategy to convert relatively uncontaminated plutonium metal and oxide into MOX and immobilize materials too difficult to clean up for MOX use—though the option of immobilizing the entire excess stock remained open. At that time, implementing such a hybrid strategy was estimated to cost $3.1 billion ($3.8 billion in 2006 dollars).[131] The U.S. DOE envisioned that an immobilization plant would begin operating by the end of 2003 and a MOX plant by the end of 2006.[132]

Today, DOE does not expect its MOX plant to open until 2016.[133] It hopes that an immobilization plant might open by 2013.[134] The capital and operating costs for disposition of U.S. excess plutonium using these facilities are now estimated at more than $10 billion (in 2006 dollars).[135] The delays and cost over-runs have been attributed, in part, to lax DOE oversight of the contractors, along with delays and limits on funds projected to be available, which have stretched out the planned construction period and increased costs.[136] The liability dispute also delayed the U.S. program, as Congress had linked U.S. disposition to progress on Russian disposition.

As in the Russian case, current cost estimates are dramatically higher than those for comparable European facilities, for reasons that have not been publicly explained.[137] Congress, observing the delays and mounting costs, has become increasingly skeptical, and several key members have sought to cut the program's budget or redirect its course.[138]

As of mid-2007, DOE's "baseline" approach was to dispose of at least 34 tons of U.S. excess weapon-grade plutonium in MOX fuel. If less than 34 tons usable in MOX is available from the plutonium stocks already declared excess, DOE expects to make up the difference from additional declarations of excess plutonium in the future. This would leave up to 13 tons of contaminated separated plutonium, which is not covered by the Russian-U.S. deal to be disposed of (see Figure 3.3).[139]

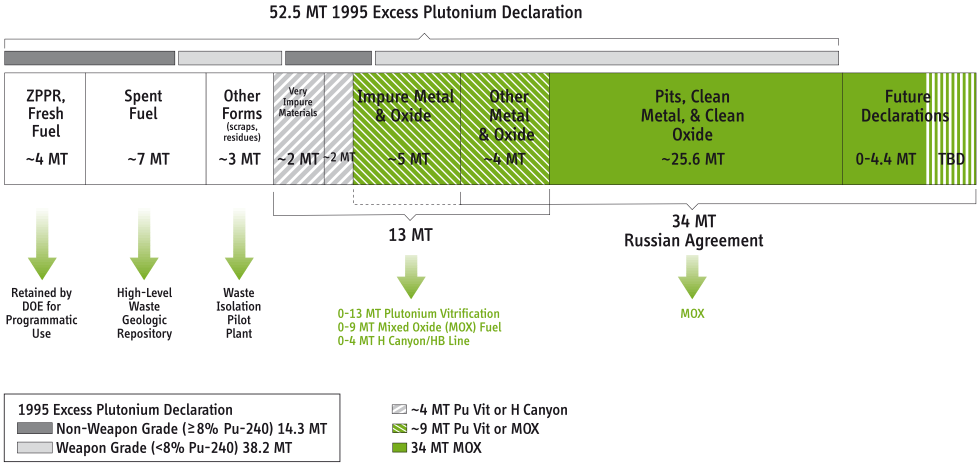


Figure 3.3. Planned disposition pathways for different categories of U.S. excess plutonium. The 52.5 tons of plutonium the United States declared excess in 1995 contains many different categories of material. Seven tons are already in spent fuel and, according to current plans, will be disposed of in a geologic repository. Three tons are in various low-concentration scraps and residues and are being disposed of in the deep underground transuranic waste repository known as the Waste Isolation Pilot Plant. Four tons are in the form of fresh fuel for a fast critical assembly that DOE decided to decommission in 2007 but may be used elsewhere. That leaves 38.5 tons requiring some form of further processing for disposition. [Source: DOE, April 2007]

In addition to the MOX plant, DOE's baseline approach therefore includes a small-scale plutonium vitrification plant to prepare up to 13 tons of impure plutonium for can-in-canister disposition with U.S. high-level waste. If any of the plutonium is too contaminated for immobilization, it would be dissolved in the H-canyon at the Savannah River Site, which was formerly used for reprocessing HEU fuel from plutonium and tritium production reactors. The plutonium solution would then be mixed directly with high-level waste being vitrified in a large melter at the Savannah River Site.[140]

MOX or not? The fundamental question being debated in the U.S. Government in 2007 is whether to go ahead and build the extraordinarily expensive proposed MOX plant or not. Construction began on August 1, 2007 but the fate of the facility is by no means assured.

One option would be to abandon the effort and continue to store the U.S. excess plutonium indefinitely. This would mean abandoning the Russian-U.S. year-2000 agreement, which would presumably lead to no disposition of Russian excess weapon plutonium. In addition, DOE argues that this approach would be very expensive, continuing the costs of storage effectively forever.[141]

Alternatively all the plutonium could be immobilized. This too, however, might result in no Russian plutonium disposition. Russian negotiators have objected to the immobilization of U.S. plutonium on the grounds that, unlike the MOX approach, the plutonium isotopics would remain weapon-grade. It appears unlikely that Russia would give up this objection except perhaps in the context of a larger bargain on nuclear trade.

The passion of the internal U.S. debate on MOX versus immobilization reflects, in part, the concern on the part of the critics that pursuing the MOX route will make easier and more likely the establishment of a closed fuel cycle in the U.S. With the DOE's recent embrace of reprocessing, this concern has become more plausible. Unless the design of the proposed MOX plant were substantially changed, however, it would not be capable of handling reactor-grade plutonium without unacceptable radiation doses to the workers. In any case, having a MOX plant already paid would mitigate only slightly the poor economics of plutonium recycling.

DOE has brought forward a constellation of technical and economic arguments against immobilization of all of its excess plutonium, arguing that plutonium immobilization is not as technically mature as MOX, which has been used commercially in Western Europe for years;[142] that the cost for immobilization would be almost as high as for MOX;[143] and that the radioactive waste at Savannah River will be disposed of before immobilization could be completed, leaving no source of a radiation barrier for the plutonium-bearing waste forms.[144]

Immobilization advocates point to DOE's baseline plan to design, build, and begin operating a plutonium vitrification plant at Savannah River by 2013 as evidence that the technical challenges with immobilization are manageable. There are serious technical concerns, however, over the viability of DOE's current plans for this plant.[145] With regard to costs, immobilization advocates argue that much of the $4.8 billion capital cost of the projected MOX plant could be saved by canceling it and using DOE's proposed small immobilization plant and operating it at a somewhat higher throughput for a longer time. DOE's belief, however, is that a larger facility using ceramic rather than glass would have to be built, requiring years of additional research and development. Finally, it seems unlikely that the high-level waste at Savannah River would be all disposed of before immobilization could be carried out.[146] If this were to happen, however—or if more plutonium were declared excess, canisters containing immobilized plutonium could be shipped from Savannah River to Hanford, where vitrification of HLW will last much longer.

There is a real possibility that an all-immobilization approach could be implemented relatively quickly at a lower cost than the MOX approach. Too little is known at present, however, to be confident of this—partly because of DOE's refusal to pursue immobilization seriously. An independent review of the issues would be valuable.

For any approach, the year-2000 Russian-U.S. plutonium-disposition agreement specifies that disposition covered by the agreement cannot proceed until the two sides have agreed on bilateral monitoring provisions. No such agreement is yet in sight. Moreover, the year-2000 agreement calls for consultations with the IAEA "at an early date" on IAEA monitoring of the plutonium disposition process starting by the time the material arrived at a fuel fabrication or immobilization facility. Although construction on the U.S. MOX plant has begun, no consultations have yet occurred with the IAEA on the design features that would affect its ability to monitor the process.[147]

Disposition of Civil Plutonium

In addition to the stockpiles of excess weapon plutonium, there are also over 250 tons of separated plutonium in civilian stores—mostly in France, Russia and the United Kingdom—but increasingly in Japan as well. This plutonium is also weapon-usable.

Most countries with separated civil plutonium plan eventually to use this material as fuel—either in LWRs or in future fast-neutron reactors. Currently, however, the use of plutonium as fuel is not keeping up with its continued separation, leading to ever-growing stockpiles (see Chapter 1).

Russia has some 40 tons of civilian separated plutonium. Its current plan appears to be to continue to store this material for fast-neutron reactors that the leaders of its nuclear-energy establishment believe will become economic around 2030 (see Chapter 8).

While Japan has an official policy not to build up stockpiles of separated plutonium, it is in the process of doing so, starting up its Rokkasho reprocessing plant while use of its plutonium as MOX fuel continues to be delayed.[148]

The United Kingdom, which has no plutonium recycle program in place, has the world's largest civil stock of separated plutonium, with over 100 tons of separated plutonium on its soil, of which it owns over 75 tons. The U.K. Government has examined both immobilization and MOX options, but has not yet made a disposition decision, and its plutonium will continue to build up in storage until the United Kingdom ends its reprocessing program in 2012. A number of analysts have proposed options for immobilizing this plutonium for disposal.[149]

Conclusion

Disposition of excess separated plutonium has proven to be difficult for both Russia and the United States. Schedules on both sides have slipped by a decade over the past seven years, and estimated costs have more than doubled. Neither country has the technical infrastructure for carrying out plutonium disposition today. The implementation of their commitments to reduce their stockpiles of plutonium therefore remains very much in question.

Pending physical disposition, the United States and Russia should move aggressively to consolidate their stocks of excess plutonium in a smaller number of highly secure locations and open this material to international monitoring, including monitoring from outside its containers while it is still in classified form.[150] The United States and Russia also should agree on and implement bilateral and international monitoring measures on their eventual plutonium disposition, as called for in their agreement of 2000.

Given the decisions that they have made to further reduce their weapon stockpiles since 2000, the United States and Russia should also each substantially increase the amounts that they have declared excess. They should declare excess and available for disposition all of their separated plutonium except for that needed to maintain a small remaining nuclear warhead stockpile, pending nuclear disarmament.

States that have excess stocks of separated civilian plutonium also should reduce these stockpiles to the minimum required to support ongoing nuclear energy programs. If they cannot use these materials expeditiously as fuel, they should consider the option of immobilization for disposal with radioactive waste.

4

Fissile Material Consolidation in the U.S. Nuclear Complex

In May 2003, twenty months after the September 11, 2001 attacks on the United States, the U.S. Department of Energy (DOE) upgraded the security requirements for its nuclear sites—and then again in 2004. DOE reduced these requirements somewhat in 2005 and gave postponements to some sites. Nevertheless, the DOE physical security budget in fiscal year 2006 was $1.3 billion.[151] To reduce these costs and to increase security overall, DOE has begun to consolidate weapon quantities of fissile materials to a smaller number of sites and to build higher-security facilities at those sites.

In this chapter, we describe the DOE nuclear complex and the status of efforts to assure the security of the hundreds of tons of fissile materials distributed among the various facilities.[152] We assess the various consolidation initiatives, which, if carried to completion, would clean out four of the sites and consolidate the materials in fewer facilities in most of the others.

Nevertheless, the effort needs to be both more urgent and more comprehensive. We point in particular to two privately owned facilities that produce HEU fuel for the U.S. nuclear navy. These sites could be closed and the HEU fuel fabrication moved to DOE's Y-12 facility in Tennessee, where weapon components containing HEU are stored and dismantled.

The DOE Nuclear Complex

Hundreds of tons of HEU and plutonium, and other directly weapon-usable fissile materials, are stored at sites that are owned by DOE or produce reactor fuel for the U.S. Navy's nuclear-powered ships and submarines.

Figure 4.1 shows the locations of the twelve sites in the DOE nuclear complex. Table 4.1 provides information about their activities and fissile-material inventories, based on information released by DOE in a period of unparalleled openness in the mid-1990s.

Six of the twelve sites are weapon-design and production centers, two are naval-reactor fuel production facilities, one does nuclear energy R&D, and one does nuclear science. The final two, the Hanford and Savannah River sites, are the foci of efforts costing tens of billions of dollars to clean up the environmental contamination caused by U.S. plutonium production for weapons during the Cold War. Savannah River is also the designated site for the disposition of some of the plutonium that has been declared excess.

In the 1990s, DOE made public that eleven of the 12 sites—plus the Rocky Flats plutonium-component production site outside Denver—had ton quantities of fissile materials—much larger than the kilogram quantities that are considered significant on a weapons scale. These quantities of material are defined by DOE as Category I or II quantities of "special nuclear materials," as shown in Table 4.2.

The shutdown Rocky Flats Plutonium Plant outside Denver was cleaned out in 2003.[153] But, twelve sites still host ton quantities of fissile material because the Nevada Test Site has become the site of a high-security fissile material storage facility.

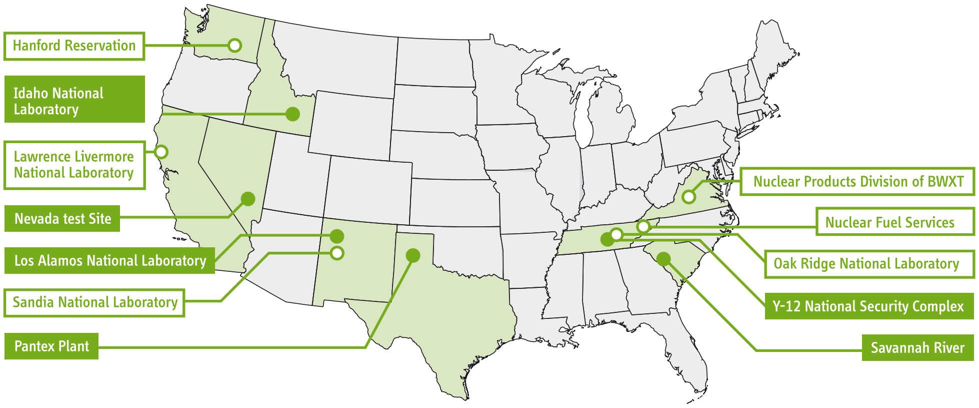


Figure 4.1. DOE sites with weapon quantities of special nuclear materials. The consolidation discussed in this chapter would reduce the number of sites from 12 to the 6 shown with solid circles. The sites shown with hollow circles would be cleaned out.

Site	Primary Mission	Fissile Material Inventories (metric tons)	
		Separated Plutonium[a]	Unirradiated HEU[b]
Nuclear Weapon Sites			
Lawrence Livermore National Laboratory, California	Nuclear weapon R&D, to be cleaned out	0.3	0.2
Los Alamos National Laboratory, New Mexico	Nuclear weapon R&D	2.7	3.5
Nevada Test Site, Nevada	Nuclear weapon R&D	–	–
Pantex, Texas	Nuclear weapon assembly/ disassembly; plutonium component storage	Not reported separately	Not reported separately
Sandia National Laboratory, New Mexico	Nuclear weapon R&D, to be cleaned out	–	0.7
Y-12, Oak Ridge, Tennessee	Nuclear-weapon HEU component production, disassembly, storage	–	169 (in 1994)[c]
HEU Reactor Fuel-Production Sites			
BWXT Nuclear Products Division, Lynchburg, Virginia	Naval reactor fuel production	–	Not reported separately
Nuclear Fuel Services, Erwin, Tennessee	Naval reactor fuel production	–	Not reported separately
Nuclear Energy R&D			
Idaho National Laboratory, Idaho[d]	Nuclear energy R&D, to be partially cleaned out	4.5	8.1 tons HEU 0.3 tons Np-237[e] 0.35 tons U-233[f]
Nuclear Science			
Oak Ridge National Laboratory, Tennessee	Nuclear science, formerly reactor development, to be cleaned out	–	0.9 tons HEU 0.5-1.5 tons U-233[f]
Nuclear-Cleanup Sites			
Hanford Site, Washington	Former plutonium-production site, to be cleaned out	4.5[g]	0.3
Savannah River Site, South Carolina	HEU spent-fuel and plutonium storage/ disposition	2.0[h]	14

Table 4.1. U.S. sites with weapon quantities of fissile material.

Table 4.1. Notes:

[a] As of September 1994. *Plutonium: The First 50 Years*, Department of Energy, DOE/DP-0137, p. 20.

[b] As of September 1996 except where noted. *Highly Enriched Uranium: Striking a Balance; A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, DOE, 2001, Rev. 1, www.ipfmlibrary.org/doe01.pdf, pp. 37, 38, 138.

[c] Openness Press Conference, DOE, 27 June 1994.

[d] Formed in 2005 by a merger of Argonne National Laboratory-West with the Idaho National Engineering Laboratory.

[e] Proposed, *Draft Environmental Impact Statement for the Proposed Consolidation of Nuclear Operations Related to Production of Radioisotope Power*, DOE/EIS-0373D, 2005, Table 2.1.

[f] See discussion under Oak Ridge National Laboratory below.

[g] Four tons of separated plutonium from the Plutonium Finishing Plant and 55 unirradiated FFTF fuel assemblies in 1993 containing approximately 10 kg of plutonium each (see section on Hanford for references. The remaining 6.5 tons of plutonium at Hanford was in spent fuel.

[h] Some in spent fuel. Subsequently received some of the 12.7 tons removed from the Rocky Flats Site.

Material	Category I	Category II
Plutonium or ^{233}U	Mass Range	
Metal	2 kg or more	0.4–2 kg
In "high-grade" material (carbide, oxide, nitride) in concentrated solutions (≥ 25 grams/liter), etc.	6 kg or more	2–6 kg
In "low-grade" material, dilute solutions (1–25 g/l), process residues, "moderately irradiated," etc.	Not applicable	16 kg or more
HEU, neptunium-237, or americium-241 or -243		
Metal	5 kg or more of contained ^{235}U or other isotope	1–5 kg ^{235}U or other isotope
In "high-grade" material (carbide, oxide, nitride, UF_4 or UF_6 enriched to more than 50%)	20 kg or more of contained ^{235}U or other isotope	6–20 kg ^{235}U or other isotope
In "low-grade" material and 20–50% enriched HEU	Not applicable	≥ 50 kg ^{235}U or other isotope

Table 4.2. U.S. Department of Energy categorization of fissile materials.[154] Category I material requires the same security as nuclear weapons; Category II material has to be in a storage vault in a protected area.

Changes in the Design Basis Threat

In May 2003, twenty months after the September 11, 2001 attacks, which involved 19 hijackers, DOE ordered a significant increase in the Design Basis Threat (DBT) at all its nuclear sites. The DBT establishes the number and capabilities of potential adversaries that a facility must be prepared to defend against. The number of assumed attackers in the pre-9/11 DBT was about one quarter the number involved in the 9/11 attacks.

On September 14, 2004, DOE further increased the DBT. Although the details are classified, the 2004 DBT specified that site security forces should be prepared to repel more than three times the number of attackers assumed prior to 9/11—but still fewer than the number of attackers directly involved in 9/11. Furthermore, the sites were advised that they should assume that the attackers could possess far more lethal weapons and much larger truck bombs than had previously been considered.[155]

Finally, the new guidance advised that, if the attackers succeeded in penetrating a facility storing certain types of fissile material, they might be able to manufacture and detonate an Improvised Nuclear [explosive] Device (IND) on the spot.[156] Preventing their escape with fissile materials would therefore be insufficient. Any access would have to be prevented.

All DOE sites were expected to be able to deal with the 2003 DBT by October 2006—and the 2004 DBT by October 2008.[157] The number of assumed attackers in the 2004 DBT was down-sized by about 25 percent in late 2005. On January 19, 2006, the Administrator of the National Nuclear Security Administration (NNSA), the organization within DOE which is responsible for the six nuclear-weapon sites, concluded that even the 2005 DBT could not be achieved because of White House imposed budget caps: "We need to be clear that we won't meet the requirements."[158]

Additional expenditures are required for guards, high-security storage facilities, fences, intrusion sensors and cameras, and delaying devices for storage facilities entered without authorization codes. At its four non-NNSA sites (i.e., the nuclear-energy, nuclear-science and nuclear-cleanup sites listed in Table 4.1) DOE employed about 1000 security officers and requested $300 million for security in fiscal year 2006.[159]

NNSA reports that in fiscal year 2006 its sites were able to meet the 2003 DBT.[160] None met the 2005 DBT, however (see Table 4.3). Livermore, Pantex and Savannah River should be able to meet the deadline in 2008. Idaho National Lab has received a waiver until 2009, and Los Alamos and Y-12 until 2011. Hanford and Oak Ridge have received indefinite waivers until their inventories of special nuclear materials can be removed (see the discussions of these sites below).

Site	Deadline for Protection Against 2005 DBT (fiscal year)
National Nuclear Security Administration Sites	
Lawrence Livermore National Laboratory, California	2008
Los Alamos National Laboratory, New Mexico	Waived till 2011
Nevada Test Site, Nevada	Waived till 2009
Pantex, Texas	2008
Sandia National Laboratory, New Mexico	Cleanout expected in 2008
Y-12, Oak Ridge, Tennessee	Waived till 2011
Other DOE Sites	
Idaho National Laboratory	Waived till 2009
Oak Ridge National Laboratory	Indefinite waiver pending cleanout
Savannah River Site	2008
Hanford Site	Indefinite waiver pending cleanout

Table 4.3. Deadlines for protection of DOE facilities against the 2005 Design Basis Threat.[161]

Two non-DOE facilities annually process tons of weapon-grade uranium into fuel for U.S. Navy propulsion reactors and research reactors worldwide, and blend down additional tons of excess weapon HEU to LEU: Nuclear Fuel Services, located in Erwin, Tennessee; and the Nuclear Products Division of BWXT in Lynchburg, Virginia. Because these sites are privately owned, their physical security requirements are set by the U.S. Nuclear Regulatory Commission (NRC). The NRC DBT for protection of the HEU at these sites is about half of the DOE 2005 DBT.[162] The GAO recently issued a classified report that is highly critical of the security of these facilities.[163]

The Consolidation Alternative

Faced with the huge anticipated costs of the new security requirements, in May 2004, DOE endorsed consolidation of nuclear materials at fewer sites, and in fewer and more secure buildings within existing sites, as a way to both reduce DOE security costs and increase security.

Consolidation is not a new idea. In 1999, a classified report strongly urged construction of consolidated underground storage facilities for HEU at the Y-12 site in Tennessee, and for plutonium at the Savannah River site in South Carolina.[164] A 2001-2002 study of the security of DOE and Defense Department nuclear sites, chaired by former National Security Advisor Brent Scowcroft, also recommended consolidation.[165]

The Secretary of Energy's Advisory Board (SEAB) Task Force on the Nuclear Weapons Complex of the Future recommended in 2005 that all of the weapon complex's Category I and II quantities of special nuclear materials be removed to a single Consolidated Nuclear Production Center (CNPC) at a remote location—with "as small a total physical footprint as possible."[166] The task force recommended underground facilities to simplify the security problem.

In 2006, NNSA published its own "vision" for a modernized nuclear weapon complex in 2030 which included much more modest consolidation. HEU-component production and storage would still be carried out at the Y-12 site, but in two new high-security buildings. Warhead assembly and disassembly would continue to take place at Pantex. Plutonium R&D and production of pits would be carried out at a site still to be determined. But Category I/II quantities of fissile materials would be removed from the national laboratories. The deadlines were 2008 for Sandia, 2014 for Lawrence Livermore, and 2022 for Los Alamos, unless Los Alamos was selected as the national site for plutonium R&D and pit production.[167]

Subsequently, as part of the National Defense Authorization Act for 2007, Congress mandated that all Category I/II special nuclear materials should be removed from both Livermore and Los Alamos by 2012.[168]

Experience with implementing consolidation efforts, however, shows that it can be a slow and troubled process. Since the 2004 decision to begin consolidation, the only facility to be actually cleaned-out was Los Alamos Technical Area 18, a facility with 2.8 metric tons of fissile materials, located at the bottom of a canyon, where nuclear criticality experiments were carried out.[169] It had been proven to be very insecure. Reportedly, in an October 2000 force-on-force test, several "mock terrorists" penetrated the facility while large plates of HEU were outside the vault. The protective force was unable to drive the intruders out, and as a result, the attackers had time to create an IND—and potentially a nuclear explosion.

Following this failed security test, DOE ordered TA-18 to be cleaned out by the end of 2004. It took till 2005, and tremendous efforts by top DOE officials (and by non-governmental organizations to keep DOE focused on the issue) to finally overcome the resistance of laboratory officials and remove the fissile material from TA-18 to the Device Assembly Facility at the Nevada Test Site (shown in Figure 4.2), and the TA-55 facility at Los Alamos (shown in Figure 4.5).[170]

Below we discuss the sites listed in Table 4.1 as follows:

- Four sites where the decision to clean out has been made, but where implementation issues remain;

- Three sites where consolidation is taking place on-site; and

- Four sites where plans for consolidation have not yet been developed.

At the 12th site, the Nevada Test Site, aside from a deep-underground tunnel in which explosive subcritical experiments with plutonium are carried out, the high-security Device Assembly Facility (DAF) is the only facility that contains special nuclear materials.

Figure 4.2. The Device Assembly Facility on the Nevada Test Site. A 10,000 m^2 facility, the DAF is designed for security. It is mostly underground, behind the one visible wall with its two guard towers. It was built in the early 1990s for assembly of nuclear explosives before nuclear tests. Recently, DOE moved to the DAF a portion of the 2.8 tons of fissile materials removed from Los Alamos Technical Area 18.[171]

Four Sites Where the Clean-Out Decision Has Been Made

DOE appears to have decided to remove fissile materials from four of its sites: Sandia National Laboratory, New Mexico; Lawrence Livermore National Laboratory, California; Oak Ridge National Laboratory, Tennessee; and the Hanford Reservation in Washington State. For the last three, however, implementation issues remain. The plan for Livermore is confused and uncertain, reflecting an ongoing struggle. The plan for Oak Ridge is costly and could be delayed by inadequate funding. And the plan for Hanford cannot currently be implemented, because its plutonium cannot be shipped to the destination site.

Sandia National Laboratory, New Mexico. SNL is a nuclear weapon engineering laboratory located on Kirtland Air Force Base within the built-up area of Albuquerque, New Mexico. The laboratory does not do research on weapon components that contain fissile materials, but hosts the HEU-fueled Sandia Pulsed Reactor and Annular Core Research Reactor (ACRR).

The Sandia Pulsed Reactor has been of special concern because its fuel plates contain weapon quantities of barely irradiated HEU. In May 2004, the Secretary of Energy announced that the reactor was no longer required, and that Sandia would cease operating it by 2007, because computer simulation now made possible “an intelligent substitution of advanced technology for brute force.”[172] NNSA has delayed removal of the HEU to the end of fiscal year 2008.[173]

The HEU in Sandia’s ACRR is more heavily irradiated.[174] DOE therefore does not consider it to be Category I or II special nuclear material. It is not clear if ACRR has a mission any more, and it may be decommissioned.[175] If it is not, the DOE Global Threat Initiative (GTRI) has the ACRR on its list for conversion to LEU fuel.[176]

Lawrence Livermore National Laboratory, California. LLNL, east of the San Francisco Bay, has hundreds of kilograms of plutonium and HEU within its “Superblock.”[177] Figure 4.3 shows a view of the laboratory from the air. Guarding the Superblock accounts for much of Livermore’s $100 million per year safeguards and security budget.[178]

The need for weapon quantities of fissile materials at Livermore has been questioned since the end of the Cold War. In 1995, a DOE task force on “Alternative Futures for the Department of Energy National Laboratories” recommended that the site be cleaned out by 2000.[179]

There has been resistance to this proposal within both Livermore and NNSA, however. In 2005, NNSA declared that removal of the fissile materials would threaten the "viability" of Livermore, and doubled the limit on the amount of plutonium that could be kept there from 700 to 1400 kilograms.[180] In 2006, Congress mandated that all Category I/II special nuclear material be removed from Livermore by 2012.[181] NNSA pushed back again, however, committing only to "evaluate relocating Category I/II inventories by 2014."[182]

All DOE R&D activities involving Category I/II quantities of plutonium and HEU that are conducted at Livermore could be consolidated at other sites. The NNSA plan is apparently to move them to Los Alamos. The destination at Los Alamos, however, would be the controversial Chemistry and Metallurgy Research Replacement building which may not be built (see section on Los Alamos below).[183]

Figure 4.3. Lawrence Livermore National Laboratory. A one-mile (1.6 km) square site, originally located in the middle of a desert. Since that time, a residential neighborhood has been built across the street from the west side of the laboratory. "Superblock," where the plutonium and HEU are located, is approximately half a mile from the nearest houses. To secure the site, DOE has authorized the installation of Gatling guns that fire up to 4000 rounds a minute and can kill at up to 2 miles.[184]

Oak Ridge National Laboratory, Tennessee. ORNL stores 0.45-1.5 tons of unirradiated uranium-233, a legacy of its 1960s molten-salt breeder reactor program.[185] This material has a much smaller critical mass than HEU and is just as usable for making a gun-type improvised nuclear device.[186]

It is, therefore, extraordinary that ORNL does not have the security systems required for housing weapon-grade materials. In September 2005, one of the authors of this chapter walked unescorted for 15 minutes around the outside of the building that houses the U-233 before there was a response from the guard force. Since then, DOE has sent three teams to ORNL to determine how it might meet the 2003 DBT requirement. In 2006, Oak Ridge spent $12 million to secure this single building.[187]

As a result of instructions from Congress in 2005, DOE proposes to dilute the U-233 with depleted uranium to less than one percent U-233 enrichment—far below the level where it would be weapon-usable.[188] In its budget request for fiscal year 2008, the DOE Office of Environmental Management states that down-blending will not begin until 2012 and estimates that it will cost $355 million.[189] There is no obvious reason for the large cost and long timeline.[190]

ORNL is also the home of the 85-Megawatt (thermal) High Flux Isotope Reactor, which uses weapon-grade uranium fuel at a rate of about 100 kilograms per year (see Figure 4.4).[191] The DOE Global Threat Reduction Initiative is currently developing high-density, low-enriched replacement fuel for this type of reactor with the objective of completing the conversion of it and all other U.S. civilian high-powered HEU-fueled reactors by 2014.[192]

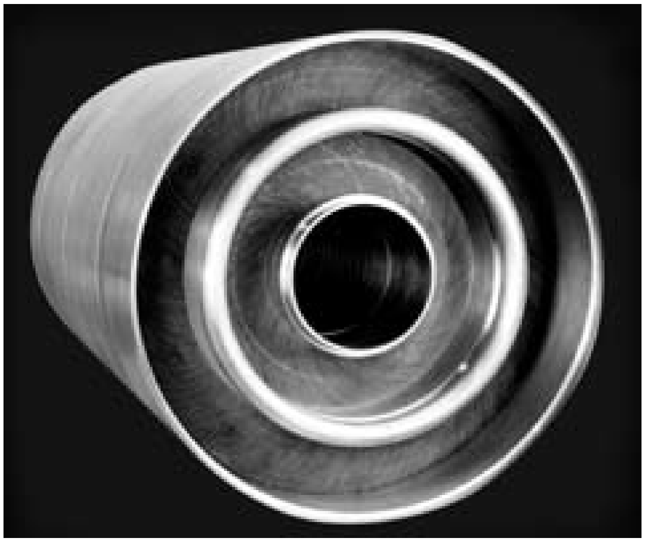


Figure 4.4. Core of the Oak Ridge High-Flux Isotope Reactor (HFIR). This compact core, which has a volume of only about 0.08 cubic meters (3 cubic feet), contains 10 kilograms of weapon-grade uranium. The HFIR uses about ten such cores each year. [Photo courtesy of BWXT Nuclear Operations Division]

Hanford Reservation, Washington State. Hanford is where the United States first produced plutonium for nuclear weapons. In 1989, after producing 67 tons of plutonium, its production facilities were shut down and it has become a major environmental remediation site.[193] The remaining 4 tons of separated plutonium at the Hanford's Plutonium Finishing Plant have been packaged and put in on-site storage along with about 0.5 tons of plutonium in unused Fast Flux Test Reactor Fuel.[194] On-site consolidation, therefore, has been completed.

Nevertheless, the annual cost of guarding this plutonium would increase by $85 million if the security standards at the Plutonium Finishing Plant were brought up to the level required by the 2005 DBT.[195] DOE proposes instead to move the plutonium to secure storage at its Savannah River Site (SRS), but Congress has forbidden DOE from shipping additional plutonium to the SRS until there are disposition plans for all of the plutonium there.[196]

In 2002, DOE cancelled plans for construction of a plutonium immobilization plant at SRS that would have mixed plutonium not pure enough to be used directly for reactor fuel with high-level radioactive waste and glass. DOE is now once again considering building a plutonium immobilization plant for Savannah River to be completed in fiscal year 2013.[197] This is discussed in Chapter 3 on plutonium disposition.

If a DOE recommitment to a plutonium immobilization plant at Savannah River is sufficient to satisfy the congressional requirement for a disposition path for all plutonium shipped there, it should be possible to begin cleaning out Hanford within a year or two. Otherwise, an interim option would be to move the plutonium from Hanford to the more secure Device Assembly Facility at the Nevada Test Site.

Three Sites Where On-Site Consolidation is Taking Place

Three DOE sites are consolidating their fissile material stocks at fewer on-site locations in an effort to reduce vulnerabilities and security costs. These are the Idaho National Laboratory, the Savannah River Site, and the Y-12 Site in Oak Ridge, Tennessee

Idaho National Laboratory. INL was created in 2005 by merging Argonne National Laboratory's nuclear-reactor site (Argonne West) with the Idaho National Engineering and Environmental Laboratory. It hosts more than nine tons of separated HEU and plutonium.[198] This material is a legacy of the U.S. plutonium-breeder reactor program and other reactor development programs.

Four tons of the separated plutonium at INL is associated with the Zero Power Physics Reactor (ZPPR), which was built in the 1960s to mock up fast-neutron reactor cores. When the predecessor critical assemblies at DOE's Argonne National Laboratory outside of Chicago were decommissioned, their plutonium fuel also was shipped to INL.[199] ZPPR was shutdown in 1997. The decision to decommission was finally made in 2007.[200] Today, the criticality of proposed core designs is mostly tested with computer simulations benchmarked against past criticality experiments.

INL is responding to the increased costs of security by reducing the number of locations on its 890 square mile site where weapon quantities of fissile materials are stored. Excess HEU is being shipped off site to be blended down to LEU.[201] As at Hanford, however, excess plutonium cannot be shipped to the Savannah River Site until DOE commits to a comprehensive plutonium disposal program there. Congress is, therefore, supporting the preparation of INL's Buildings 651 and 691 as secure storage facilities.[202]

The DOE budget justification for fiscal year 2008, INL has reduced "Category I facilities at INL to two co-located Category I facilities protected by a single Perimeter Intrusion Detection and Assessment System (PIDAS)."[203] We assume that the area being referred to is the "Materials and Fuels Complex," formerly, Argonne West. This complex was also proposed in 2005 to be the site for preparing plutonium-238 radioisotope heat sources for space missions to the outer planets. This will involve the transport of 300 kilograms of neptunium-237 from the Savannah River Site to the INL Materials Fuel Complex to be fabricated into targets for irradiation in the Advanced Test Reactor (ATR) located 25 km away. The targets then would return to the Materials Fuel Complex for processing to recover the plutonium-238.[204]

The ATR is a 250-Megawatt (thermal) reactor that each year uses more than 100 kilograms of weapon-grade uranium in its fuel.[205] It has an associated critical facility with tens of kilograms of unirradiated HEU fuel. As with the Oak Ridge HFIR reactor discussed above, the DOE Global Threat Reduction Initiative is developing high-density, low-enriched replacement fuel that, under the current schedule, would make conversion of the ATR possible by 2014.

Savannah River Site, South Carolina. SRS, located about 20 miles south of Aiken, South Carolina, spreads across a 315 square mile site. During the Cold War, its primary mission was to produce plutonium and tritium for the U.S. nuclear weapon program, but the production reactors were shut down in the early 1990s. Now, its major new mission is the disposition of the 45 tons of separated plutonium that DOE has declared excess to military needs (see Chapter 3).

Excess plutonium, including some shipped from the decommissioned Rocky Flats Plutonium Pit Production Facility, is stored in three SRS buildings. In order to save more than $120 million in security upgrade costs, DOE plans to move all this plutonium to the building that formerly housed the K-reactor.[206]

Y-12 Site, Tennessee. The Y-12 Site is a huge complex of buildings covering an area of more than a square mile in a valley 5 miles north of Oak Ridge National Laboratory. Since the World War II Manhattan Project, this facility has manufactured and dismantled the HEU components in U.S. nuclear weapons. Hundreds of tons of HEU in weapon components, metal HEU storage disks ("pucks"), and accumulated HEU production wastes are stored in four buildings.[207] The main HEU-storage building is constructed of wood. The other buildings perform processing as well as storage functions. NNSA considers it impractical to protect these buildings against the 2005 DBT.[208]

DOE plans to replace these facilities with two new high-security buildings:

- The HEU Uranium Materials Facility, which will replace the wooden HEU storage building, is scheduled to be completed in 2009 for a cost of about a half billion dollars,[209] and

- A billion-dollar Uranium Processing Facility, that is still being designed, will replace the other buildings.

There are two important issues that should be considered in going forward with the design of the new HEU-processing facility. First, it should be possible to integrate it with the new HEU storage facility in a way that eliminates the vulnerability of having to transport HEU back and forth between the two buildings. Second, as discussed below, consideration should be given to building into the Uranium Processing Facility capabilities to fabricate naval and other HEU reactor fuel as well as nuclear-weapon components.

Four Sites that Require Further Study

For the remaining four sites, planning for consolidation either has not happened or is incomplete. These are: Los Alamos National Laboratory, the Pantex warhead assembly/disassembly plant, and the BWXT and Nuclear Fuel Services HEU processing facilities.

Los Alamos National Laboratory. As noted, the critical facilities at Los Alamos (Technical Area 18) have been moved to the National Test Site's Device Assembly Facility. Additional consolidation is underway.[210]

LANL's work with Category I quantities of fissile materials is increasingly associated with its production of warhead plutonium "pits." The Rocky Flats Plant in Colorado ended its production of pits in 1989. LANL therefore established a pilot pit-production line in its TA-55 facility (see Figure 4.5).[211] This line has begun to produce about ten plutonium pits per year for the U.S. warhead stockpile, a rate that is to increase to 30-40 pits per year.[212] Expansion of production to up to 80 pits per year has been discussed.[213]

The future of plutonium-related activities at LANL is uncertain, however. As mentioned above, in 2006 NNSA published a "vision" in which all Category I/II quantities of special nuclear materials would be removed from LANL by 2022. NNSA also considers LANL a possible site for its proposed centralized plutonium operations, however, and has requested funding for a new billion-dollar [Plutonium] Chemistry and Metallurgy Research Replacement Facility there, which would be completed sometime between 2014 and 2018.[214] In 2006, the House Appropriations Committee observed that it "finds this type of planning by the NNSA simply irrational."[215] In 2007, the committee voted to stop funding for the project.[216]

Given the recent finding that most of the plutonium pits that are to remain in the U.S. weapon stockpile "have credible minimum lifetimes in excess of 100 years as regards aging of plutonium,"[217] there would appear to be little reason to do pit production for several decades, if ever.[218]

Figure 4.5. TA-55 Facility at Los Alamos National Laboratory. It is currently the only facility in the United States where the plutonium "pits" of nuclear warheads are manufactured. Note the double fence around the facility. This is the so-called Perimeter Intrusion Detection and Assessment System (PIDAS) that is standard around DOE high-security facilities. The bare area between the fences is monitored with intrusion sensors. [Photo courtesy of the Los Alamos Study Group]

In any case, as long as LANL remains the lead DOE site doing plutonium R&D and pilot-plant activities, security will be maximized if all activities involving weapon-quantities of plutonium are consolidated into a single facility.

Pantex. DOE's nuclear weapon assembly/disassembly facility is located outside of Amarillo, Texas. It stores more than 14,000 plutonium pits, some in WWII-era bunkers in an area called, "Zone 4." Reportedly, the plutonium in about 7000 of those pits has been declared excess and is to be shipped to the Savannah River Site for disposal.[219] Much more plutonium could and should be declared excess in the future.

Warhead assembly and disassembly actually takes place in a second security area at Pantex, Zone 12. We do not know whether DOE has examined the feasibility of consolidating all activities involving weapon quantities of fissile materials into Zone 12.

This might be feasible if the number of reserve pits is reduced and the excess pits have been shipped to the Savannah River Site for disposal. DOE has also considered storing up to 8000 excess pits in the Device Assembly Facility on the Nevada Test Site.[220]

Nuclear Fuel Services and BWXT's Nuclear Products Division. NFS is located in Erwin, Tennessee, and BWXT Nuclear Products Division in Lynchburg, Virginia. They are private facilities that annually process tons of HEU for the production of naval and research reactor fuel and for down-blending to LEU for power reactors.[221] The security standards required by the Nuclear Regulatory Commission (NRC) at these two sites are, however, much lower than those required by DOE at Y-12, which handles similar quantities of HEU.

If the NFS and BWXT HEU-processing activities were relocated to Y-12, this would consolidate all U.S. HEU-processing activities at a single site. It would also eliminate HEU transport between the three sites. Such a move might be facilitated by the fact that BWXT manages the Y-12 site for DOE.

Research reactors are shifting from HEU to LEU fuel. Fabrication of LEU fuel for research reactors could continue at the Erwin and Lynchburg sites. In the longer-term, the use of HEU in naval reactors should be phased out in the United States as is being done in France.[222]

Conclusion

Securing fissile materials has become so costly that the U.S. Department of Energy has decided to consolidate its activities involving weapon-quantities of fissile materials to a few high-security buildings on a small number of sites. Opposition from some sites that stand to lose their fissile materials and missions, and poor management by DOE have slowed the effort.

But the sprawling R&D and production base that was built for frequent remanufacture of a Cold War stockpile of tens of thousands of weapons makes no sense for today's static stockpile of thousands of warheads—much less for the stockpile of hundreds to which the United States could reduce.

The other U.S. nuclear activity that involves huge quantities of fissile materials, the U.S. nuclear navy's fuel cycle, thus far has been untouched by consolidation. It has two fuel production facilities and its HEU stockpile is stored at DOE's Y-12 site, creating vulnerable transport links between three sites. Given that naval fuel production too has been greatly reduced, as a result of the shrinkage of the U.S. nuclear navy and its shift to lifetime nuclear cores, consideration should be given to consolidating all U.S. HEU activities on a single site. The obvious candidate is Y-12, where high-security buildings are being built that are probably far larger than will be needed to support a future much smaller and relatively static U.S. nuclear arsenal.

Of course, if the U.S. nuclear navy shifted to LEU fuel, it would eliminate both the danger that HEU could be stolen from its fuel cycle and the potential obstacle that its huge reserve of weapon-grade uranium poses to the possibility of truly deep cuts in other countries' fissile material stockpiles.

5 Progress Toward Nuclear Disarmament

There were about 60,000 nuclear weapons worldwide at the end of the Cold War. It is estimated that more than 30,000 nuclear weapons remain, including weapons that have been partially dismantled into components. Of these, more than 10,000 are believed to be operational in the arsenals of the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan, and perhaps North Korea. The United States and Russia have over 90 percent of all deployed nuclear weapons. The other seven nuclear weapon states are estimated to possess a combined total of less than 1000 operational warheads. The unexpectedly slow pace of nuclear reductions has led many to question the commitment of the nuclear armed states to the goal of eliminating these weapons.

This chapter looks at the current arsenals of the United States and Russia and their plans for reducing them. It describes proposals for cutting these arsenals to 1000 warheads or fewer, as a next step in arms reduction—and then for deep cuts which would bring them down to 200 warheads or fewer. Such reductions would permit very large quantities of fissile materials to be declared excess to military requirements and made available for disposition under international safeguards.

A key constraint on the pace of irreversible nuclear disarmament is the slow rate of warhead dismantlement, currently running at a fraction of the rate that prevailed during the 1990s. This rate could be significantly increased in the United States by focusing resources on warhead dismantlement at the Pantex warhead assembly and disassembly plant in Texas.

Nuclear Disarmament

International support. The international community recognized very early on the need for eliminating nuclear weapons. The very first U.N. General Assembly Resolution called for "the elimination from national armaments of atomic weapons and of all other major weapons adaptable to mass destruction."[223] The United States was the only country with nuclear weapons at that time. The Soviet Union tested its first weapons in 1949, however, and the arms race ensued. Simple fission weapons with yields of 10-20 kilotons gave way to thermonuclear weapons, with megaton yields. Within two decades, Britain, France and China had also acquired and tested nuclear weapons (see Table 5.1).

Country	Date of First Nuclear Test	Date of First Thermonuclear Test
United States	July 16, 1945	November 1, 1952
Russia	August 29, 1949	August 12, 1953
United Kingdom	October 3, 1952	November 8, 1957
France	February 13, 1960	August 24, 1968
China	October 16, 1964	June 17, 1967
India	May 18, 1974	May 11, 1998
Pakistan	May 28, 1998	
North Korea	October 9, 2006	

Table 5.1. First nuclear and thermonuclear tests, 1945–2006.[224]

The goals of nuclear disarmament and non-proliferation were formally linked in the 1970 Nuclear Non-proliferation Treaty (NPT). The intent of the Treaty is laid out in the preamble, which states that the signatories are:

> "Desiring to further the easing of international tension and the strengthening of trust between States in order to facilitate the cessation of the manufacture of nuclear weapons, the liquidation of all their existing stockpiles, and the elimination from national arsenals of nuclear weapons and the means of their delivery".[225]

Article VI of the NPT specifically calls on nuclear-weapon states party to the treaty "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament." The United States, Russia and the United Kingdom joined the NPT at its inception, but China did not become a party to the treaty till 1991 and France till 1992.

In 1996, the International Court of Justice, ruling on a case brought by the United Nations General Assembly, gave a unanimous advisory opinion interpreting Article VI as "an obligation to pursue in good faith *and bring to a conclusion* negotiations leading to nuclear disarmament in all its aspects" [emphasis added].[226] Subsequently, at the April 2000 NPT Review Conference, the nuclear weapon states that are parties to the NPT (the United States, Russia, the United Kingdom, France, and China) offered an "unequivocal undertaking … to accomplish the total elimination of their nuclear arsenals."[227]

Israel, India, Pakistan and North Korea, the countries outside the NPT that possess nuclear weapons, also have committed to the goal of nuclear disarmament. Israel has supported a U.N. resolution calling for a Nuclear Weapons Free Zone in the Middle East, on the condition that "the Middle East … should also be free of Chemical [and] Biological weapons as well as ballistic missiles."[228] The Prime Ministers of India and Pakistan, in their 1999 Lahore Declaration, announced that both countries were "committed to the objective of universal nuclear disarmament and non-proliferation."[229] Similarly, in the September 2005 six-party talks, North Korea agreed that it was "committed to abandoning all nuclear weapons and existing nuclear programs and returning, at an early date, to the Treaty on the Non-Proliferation of Nuclear Weapons and to IAEA safeguards."[230]

U.S.-Soviet/Russian nuclear-warhead reduction agreements. Starting in 1969 with the Strategic Arms Limitation talks, the focus of nuclear limits and reductions negotiated by the United States and the Soviet Union and then Russia has been on *deployed* warheads and delivery vehicles—with the decision on elimination of warheads removed from deployment left to the owning country.[231] The 1987 Intermediate Nuclear Forces (INF) Treaty eliminated all Soviet and U.S. ground-launched ballistic and cruise missiles with ranges between 500 km and 5500 km, along with their launchers and support and training equipment. A total of almost 2700 missile systems were eliminated. The 1991 START treaty limited the United States and Russia to 1600 strategic nuclear weapon delivery systems (i.e., long-range missiles and bombers) each and capped the number of warheads that they could carry.

The 1991 U.S. and Soviet Presidential Nuclear Initiatives for the first time effected the destruction of entire classes of U.S. and Soviet nuclear battlefield warheads as well as removal of other classes of weapons from deployment.[232] President G. H. W. Bush announced first that the United States would destroy all nuclear artillery and nuclear warheads for short-range ballistic missiles and also no longer deploy nuclear weapons on surface ships or land-based naval planes. The Soviet Union reciprocated by announcing it would eliminate its nuclear artillery, nuclear mines, and land-based tactical nuclear warheads. Tactical naval nuclear weapons would be placed in storage in Russia, and some would be destroyed.

These were reciprocal unilateral initiatives and, in contrast to the treaties limiting strategic and intermediate-range forces, involved no verification. Independent analysts estimate that Russia has 2000-3000 operational tactical nuclear warheads today.[233] The United States may possess a total of about 1300.[234] The U.S. total includes an estimated 350 nuclear bombs stored in Belgium, Germany, Italy, the Netherlands, Turkey, and the United Kingdom.[235] While the United States has formal control of all of these weapons, an estimated 140 are earmarked for use by the air forces of Belgium, Germany, the Netherlands, Italy and Turkey.[236] These are currently the only land-based nuclear weapons that are stationed outside of their owning country (Figure 5.1).

The most recent U.S.-Russia strategic arms control treaty, the Strategic Offensive Reduction Treaty (SORT) entered into force in June 2003. Under SORT, the United States and Russia agreed that by December 31, 2012 each will not deploy more than 2200 strategic nuclear warheads.[237] SORT does not have its own verification arrangements and depends on the verification system established by the START Treaty. The START Treaty will expire in 2009, however. SORT also is easily *reversible,* in that it does not require the elimination of either delivery vehicles or warheads, and it expires at the end of 2012, at the end of the day on which its limits come into force.

President Putin, in 2006, called for a “renewed dialogue on the main disarmament issues.”[238] In March 2007, the U.S. ambassador to Moscow announced, “It is also important today to look ahead to the challenges and possibilities that lie beyond the expiration of the START Treaty in 2009 and the Moscow Treaty in 2012. At the direction of our Presidents, we have begun a strategic security dialogue to consider what we want in place when the START Treaty expires, what further steps to pursue, and what sort of transparency and confidence-building regime makes the most sense.”[239]

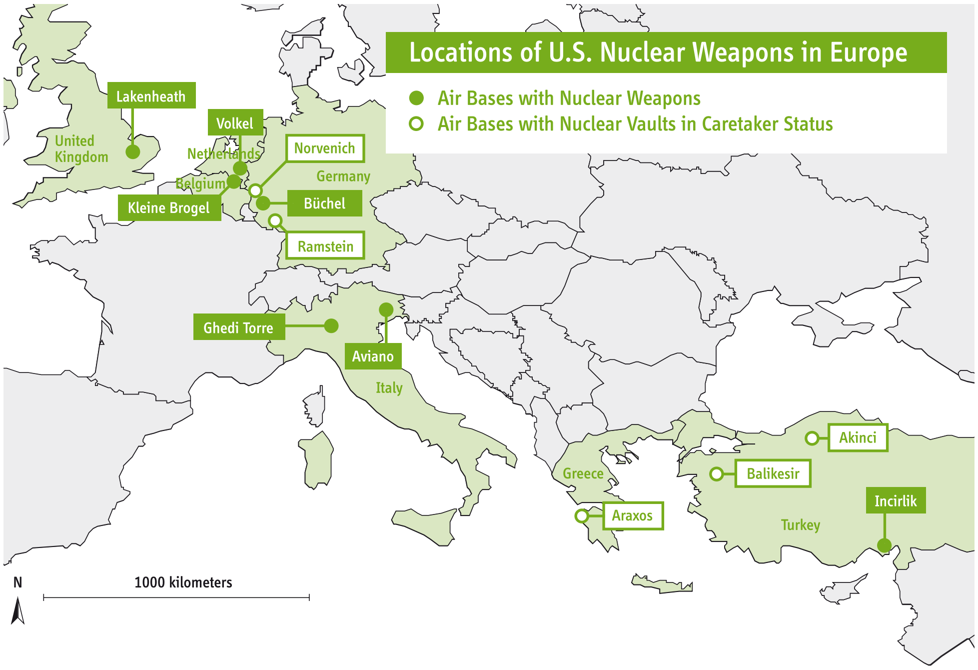


Figure 5.1. U.S. nuclear weapons and storage vaults in Europe.[240] The United States maintains about 350 nuclear weapons at military bases in Western Europe, and a number of nuclear weapon storage vaults from which the weapons have been removed, but that could be brought back into use.

Current U.S. and Russian Nuclear Arsenals and Planned Reductions

Despite four decades of nuclear arms control negotiations and agreements, the United States and Russia continue to retain very large nuclear arsenals. They each have about 15,000 nuclear warheads and equivalent sets of reserve components, about one-third of which are currently deployed as shown in Table 5.2.

	ICBMs	SLBMs	Long-Range Bombers	Nonstrategic	Total
United States	900	1728	1917	500	5045
Russia	1788	636	872	2330	5614

Table 5.2. Estimates of U.S. and Russian deployed nuclear warheads, 2007.[241]

Among the nine nuclear weapon states, only the United States and Russia maintain thousands of warheads on hair-trigger alert—ready to be launched within 15-30 minutes.[242] Only these states plus the United Kingdom, France and China keep nuclear weapons routinely deployed with their armed forces. Although Israel, India, Pakistan and North Korea do not currently have any of their warheads permanently deployed, they probably can deploy them at short notice.

Table 5.3 provides estimates of the quantities of fissile material in the operational warheads of the NPT weapon states and the differences between those quantities and their estimated total military stocks. It will be seen that the operational warheads probably contain only a small fraction of their military fissile-material stocks.

	Estimated Fissile Material Available for Weapons [tons]		Deployed Weapons	Fissile Material in Deployed Weapons [tons]		Estimated Excess [beyond existing deployed arsenals, tons]	
	HEU	Plutonium		HEU	Plutonium	HEU	Plutonium
China	20 ± 5	4 ± 2	130	3.2	0.5	12–22	1–5
France	30 ± 6	5 ± 1	348	8.7	1.4	15–27	2–5
Russia	640 ± 300	95 ± 25	5614	140	22.4	200–800	50–100
U.K.	22 (declared)	3.2 (declared)	185	4.6	0.7	17.4	2.5
U.S.	250 (declared) 350 (inc. naval)	47 (declared)	5045	126	20.2	124–224	27

Table 5.3. Estimated fissile material inventory in deployed nuclear arsenals and potentially excess stocks of HEU and plutonium. These estimates assume 4 kg of plutonium and 25 kg of HEU per warhead. Totals may not add up because of rounding.

As part of its SORT reductions, the United States plans by 2012 to reduce the number of warheads carried by its Intercontinental Ballistic Missiles (ICBMs) to 500 warheads on 450 missiles, with perhaps 300 additional warheads in reserve for possible upload.[243] The U.S. Navy will retain 14 out of its 18 ballistic-missile submarines, each equipped with 24 Trident II missiles, but the missiles probably will be downloaded from an average of six today, to four warheads each by 2012.[244] The Air Force plans to retire its 400 Advanced Cruise Missiles but will retain many older dual-capable (armed with either nuclear or conventional warheads) Air Launched Cruise Missiles for its long-range bombers.[245]

In addition to its almost 5000 deployed nuclear weapons, the United States had, as of the end of 2006, a "responsive" force of about 2000 warheads, and another 3000 awaiting dismantlement—for a total stockpile of about 10,000 intact warheads. Five thousand pits are designated as a strategic reserve.[246] (See Figure 5.2)

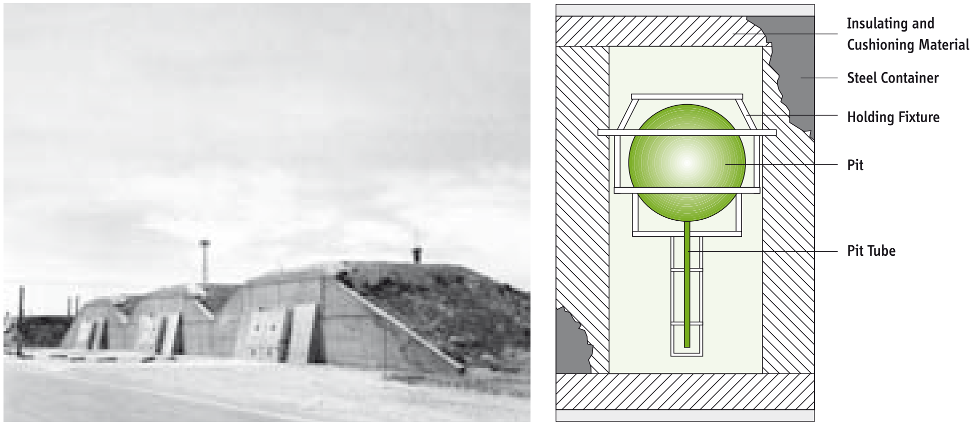


Figure 5.2. Nuclear weapons storage bunkers, Pantex Plant, Amarillo, Texas.[247] Some staging bunkers, or "igloos," contain nuclear weapons to be dismantled, or which have just been assembled and await shipment. Others contain plutonium pits from dismantled warheads. There are 60 of these earth-mounded bunkers in an area designated Zone 4.[248] In these bunkers, the plutonium pits from disassembled nuclear weapons are stored in sealed steel containers (illustrated on the right).[249] As of June 2007, 14,000 plutonium pits were stored at Pantex.

There is greater uncertainty about the Russian arsenal. It is estimated to have over 5000 operational weapons with perhaps 10,000 additional intact warheads in reserve or awaiting dismantlement.[250]

Although the SORT treaty does not require the elimination of warheads removed from deployment, the United States is substantially reducing its stockpiles. In mid-2004, the U.S. Government announced that it would shift almost half of the current U.S. nuclear-warhead stockpile into the dismantlement queue by 2012. Non-governmental estimates project a reduction to about 5000 total warheads.[251] Assuming that there are 4 kg of plutonium in the average Russian or U.S. warhead, each country would require about 25 tons of weapon-grade plutonium and 150 tons of weapon-grade uranium to support 5000 warheads, assuming roughly 20 percent for R&D and process inventories. A comparison of this number to the estimated plutonium inventories in Table 5.3 shows that Russia and the United States could *today* declare excess, over half, and about one third, respectively, of their stockpiles of plutonium reserved for weapons.

Down to 1000 or Less

A 1999 study, *The Nuclear Turning Point: A Blue Print for Deep Cuts and De-Alerting of Nuclear Weapons*, proposed that the United States and Russia reduce their operational warheads to 2000 each by the end of 2007, and to a ceiling of 1000 weapons each by 2012.[252] All of the remaining weapons would be dismantled as part of a bilaterally verified process, with the fissile materials placed in internationally monitored storage pending final disposal. The United States and Russia would also insist that all the nuclear-armed states, including those outside the NPT, end their production of fissile materials for nuclear weapons.

As an illustration of a 1000-warhead arsenal, it was suggested that the United States could eliminate its ICBMs and move to a force that relied on 640 warheads on ten ballistic-missile submarines and 320 air-launched cruise missiles. At any time, at least four submarines carrying about 250 warheads could be survivably deployed at sea. Similarly, Russia could reduce to a force of 160 single-warhead ICBMs in silos and on mobile launchers; 432 warheads on submarines; and 404 air-launched cruise missiles. From these, about 150 warheads could be survivably deployed on submarines at sea and mobile missiles in the field.[253] A more recent proposal for a possible U.S. 1000-warhead nuclear force envisages 500 operationally deployed nuclear warheads and another 500 in a responsive force.[254]

The fissile material inventory required to sustain a 1000-warhead arsenal would be about 5 tons of weapon-grade plutonium and 30 tons of HEU, including material for nuclear-weapon R&D and in working inventories.

Deeper Cuts in Nuclear Forces

Before the United States and Russia reduce below 1000 total weapons each, the other weapon states will probably have to join the nuclear disarmament process. At the 1995 NPT Review and Extension Conference, Britain indicated its willingness to join the disarmament process once "U.S. and Russian stockpiles were in the hundreds."[255] France and China also have indicated a willingness to join such negotiations, once the United States and Russia have reduced to much smaller warhead stockpiles.[256]

The *Nuclear Turning Point* proposed that the United States and Russia each reduce their nuclear arsenals to 200 warheads by 2020, that China cap at this level, and that the United Kingdom and France reduce to a combined 200-warhead force. The 200-warhead forces would be fully de-alerted, i.e., not ready to launch at short notice, but would have a fraction of the warheads survivably deployed (see Table 5.4).

For an arsenal of about 200 warheads, the fissile material requirement—including material for R&D and a working inventory—would be 1 ton of plutonium and 5 tons of HEU.

	Launchers	Warheads
United States		
Submarines	8 boats x 3 missiles x 4 warheads	96
Bombers		100
Russia		
Mobile ICBMs	80	80
Submarines	8 boats x 3 missiles x 4 warheads	96
Bombers		24
Europe		
Submarines	8 boats x 4 missiles x 4 warheads	128
Bombers		72
China		
Mobile ICBMs	130	130
Submarines	4 boats x 12 missiles x 1 warhead	48
Bombers		20

Table 5.4. Nuclear Turning Point proposal for notional 200 warhead forces.[257]

The United Kingdom, in a 2006 Defense White Paper announced that it intended to reduce its warhead stockpile to less than 160 operationally available nuclear warheads, with only one submarine armed with 48 warheads on patrol at any time and at "several days notice to fire."[258] The United Kingdom has 22 tons of HEU and 3.2 tons of weapon-grade plutonium in its military stockpile, far more than is required for the arsenal it now has. The U.K. military HEU stockpile—like that of Russia and the United States—is for naval reactor fuel as well as for weapons. But it has not declared excess the plutonium from its recent warhead reductions.

Israel, India and Pakistan would also have to join the disarmament process, and the reductions would have to be accompanied by parallel actions, including entry into force of the Comprehensive Test Ban Treaty and a Fissile Material Cut-Off Treaty.

Warhead Dismantlement

A key element in deep cuts in the nuclear arsenals will be to ensure that they are irreversible. Excess warheads that are removed from deployment will need to be dismantled rather than simply stored, and their fissile materials will have to be eliminated. The rates of warhead dismantlement have slowed dramatically in recent years, in both the United States and Russia, however, leaving a large stock of weapons that potentially could be returned to service.

In the early 1990s, warhead dismantlement rates in Russia were estimated at about 2000 per year.[259] One independent estimate of the current dismantlement rate in Russia is 400-500 warheads a year, with about 200 dismantled warheads being replaced with remanufactured warheads. The net reduction rate in the Russian stockpile therefore would be 200-300 per year.[260] Russia currently has two operating nuclear weapon assembly/disassembly plants: one in Lesnoy (formerly Sverdlovsk-45) and the other in Trekhgorny (Zlatoust-36).[261]

Assuming an average of 25 kg of HEU per warhead, Russia's current dismantlement rate would yield much less HEU than the 30 tons per year that it is blending down to LEU for sale to the United States. Russia would have to be making up the difference from a large stock of HEU components from earlier dismantlements.

In the United States, between 1980 and 1992, a total of 13,223 warheads were retired and dismantled at DOE's Pantex warhead assembly and disassembly plant in Texas (see Figure 5.3).[262] For the period of fiscal years 1990-98, over 11,500 warheads were dismantled at an average rate of about 1300 per year.[263] More recent dismantlement rates have been classified. It has been reported, however, that the U.S. warhead dismantlement rate may have fallen to about 130 weapons per year in 2003, and continued at about the same rate through 2006 (see Figure 5.4).[264]

Figure 5.3. Warhead dismantlement cells, Pantex plant, Amarillo, Texas.[265] The circular concrete structures, "gravel gerties," cover cells where warhead components containing conventional high explosives are assembled and disassembled. Pantex has 13 such disassembly cells and 60 bays that can be used for assembly/disassembly operations involving insensitive high explosives. 31 of these 73 cells and bays are not currently in operational use.[266]

As of June 2007, 14,000 plutonium pits from dismantled warheads were stored at the Pantex plant.[267] Thermonuclear components, which contain HEU, are stored and dismantled at the Y-12 Plant in Oak Ridge, Tennessee.

The Natural Resources Defense Council and Federation of American Scientists estimate that the U.S. stockpile of "active" warheads will decline from almost 10,000 warheads today, to approximately 5,000 warheads by the end of 2012. The DOE estimates that dismantlement of previously retired warheads, and those that are added to the queue because of the 2004 decision, will not be completed until 2023.[268] Dismantling 5000 warheads between 2006 and 2023 would require the average dismantlement rate to increase to about 300 warheads per year.

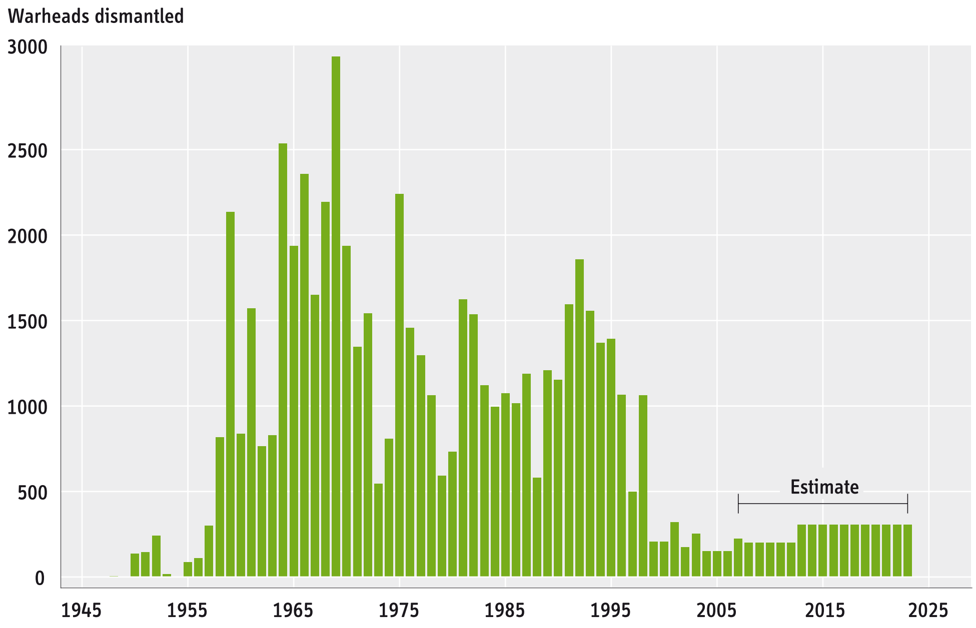


Figure 5.4. NRDC/FAS estimate of the rate of U.S. nuclear weapons dismantlement, 1945-2023.[269]

In its proposed National Defense Authorization Act for fiscal year 2008, the U.S. House of Representatives included a requirement that the Department of Energy's National Nuclear Security Administration submit, by February 1, 2008, a report that includes "the current plan and schedule for retirement and dismantlement of those warheads that have not yet been retired and dismantled but are not part of the nation's enduring stockpile;" and an assessment of the capacity of the Pantex and Y-12 plants to respectively accommodate accelerated warhead and HEU component dismantlement schedules.[270]

One way to increase the U.S. warhead dismantlement rate would be to reduce the rate at which warheads are going through the Life Extension Program at Pantex. This program refurbishes and modernizes warheads in order to extend their operational lives and capabilities. Much of the U.S. stockpile is currently going through this process. Approximately 550 W-87 ICBM warheads went through this program between 1994 and 2004.[271] Refurbishment of about 480 B-61 mod-7 and mod-11 gravity bombs is to be completed by 2009.[272] Life extension of the W-80 cruise-missile warheads was deferred in 2006.[273] The Life Extension Program for the W-76 Trident missile warheads is expected to produce its first refurbished warhead in 2007-8 and is to be completed by 2022 at an estimated cost of almost $3 billion.[274] There are currently about 3000 W-76 warheads in the stockpile.[275] It is expected that in the first phase about one-quarter of them will be refurbished by 2012.[276] This alone would require processing about 125 warheads per year at Pantex, which is about the estimated current total dismantlement rate.

Reducing this high rate of remanufacture could allow a higher rate of warhead dismantlement. Such a reduced rate should be considered. A 1999 Jason report remarked that:

> "We have seen on many bar charts the "design life" of a nuclear weapon stated as 20 years, or perhaps 25 years, and one still

> sees a peak in planned remanufacture at precisely 20 years or 25 years after a weapon was manufactured. However, there is no such thing as a “design life”. The designers were not asked or permitted to design a nuclear weapon that would go bad after 20 years.”[277]

The study concluded that “there is certainly no reason to expect all of the nuclear weapons of a given type to become unusable after 20 or 25 years.”[278] A subsequent Jason study concluded that rather than 20-25 years, “the primaries of most weapons systems types in the stockpile have credible minimum lifetimes in excess of 100 years.”[279]

The problems of safe storage and disposition of the large number of plutonium pits and HEU secondaries that have already been produced by warhead dismantlement to date, and of disposition of the plutonium and HEU that they contain, are addressed in other chapters of this report.

Conclusion

De-alerting and deep cuts in U.S. and Russian nuclear arsenals to 200 nuclear weapons each, with the other nuclear weapon states cutting to similar levels, would mark a big step towards the elimination of nuclear weapons. To be irreversible, these reductions in deployed weapons and the subsequent warhead dismantlement process would need to be transparent and verifiable with the excess fissile materials placed under international monitoring and disposed of as quickly as possible. After such reductions it should be easier to take the final steps toward the elimination of nuclear weapons.

Strengthening International Controls

6

International Safeguards in the Nuclear Weapon States

The international safeguards system has evolved over the past 50 years to give suppliers confidence that nuclear materials and technologies delivered to foreign countries would not be used for military purposes. Since the NPT came into force, it has also been used to verify that non-nuclear weapon states that are parties to the Treaty are complying with their obligation not to divert nuclear materials to weapon purposes. The development and function of this system is discussed more fully in *Global Fissile Material Report 2006*.

Accounting and inspection of nuclear materials, therefore, became the Treaty's primary instrument of verification. The task was given to the International Atomic Energy Agency (IAEA) in Vienna. Although IAEA safeguards have been more rigorously applied and expanded beyond material accounting since the negotiation of the Additional Protocol in the 1990s, the monitoring of fissile materials remains an essential instrument of Treaty verification.

In the late 1950s a regional safeguards system was founded within the European Communities—now the European Union—to facilitate free trade in nuclear materials within Community boundaries. Under the Euratom Treaty, all civilian materials in member states, including in the nuclear-armed states (France and the United Kingdom), have to be submitted to Euratom safeguards and inspected accordingly.

Under NPT rules, however, the nuclear weapon state parties to the NPT were exempt from IAEA safeguards. The exemption was justified mainly on the grounds that there was no point in verifying the non-diversion of civilian materials to weapon programs, when it was lawful for the nuclear weapon states to produce unlimited quantities of fissile materials for weapons outside safeguards.

This exemption of nuclear weapon states from NPT safeguards broadened the Treaty's discrimination between the nuclear weapon and non-nuclear weapon states to their civilian sectors, and was controversial from the outset. To help assuage the non-weapon states' concerns that they would be placed at a commercial disadvantage, the United Kingdom, United States and France, in the 1970s, followed by the Soviet Union and China in the 1980s, concluded "voluntary offer" safeguards agreements with the IAEA. According to these agreements, at the Agency's discretion, certain civilian facilities and/or materials could be brought under IAEA safeguards. Due to constraints on the IAEA safeguards budget, and the priority that the Agency has given to safeguards in the non-weapon states, however, only a small proportion of the facilities and stocks offered by the weapon states have been inspected by the IAEA.

After the Cold War, the nuclear weapon states ended their production of fissile material for weapons and some began to declare materials to be excess to their military needs. It was widely expected that, in this context, the IAEA would be drawn into verifying that fissile materials removed from dismantled warheads would not be returned to military programs. In addition, it was anticipated that the Fissile Material Cut-Off Treaty (FMCT) proposed by the U.N. General Assembly in 1993, would require verification that the weapon states were not producing fissile materials for weapon purposes. Therefore, when the NPT safeguards system was reformed later in the 1990s through negotiation of the Additional Protocol, its application in the nuclear-weapon states also became an issue.

However, as illustrated in Figure 6.1 below, IAEA safeguards and verifications have not expanded as rapidly into the nuclear weapon states as was hoped in the mid-1990s. In particular, failure to negotiate the FMCT, together with the U.S. government's withdrawal in 2004 of support for a verified Treaty, has deprived the application of IAEA safeguards in nuclear-armed states of much of its momentum. Failure to conclude the Trilateral Initiative, which would have enabled the IAEA to verify that excess weapon-origin fissile materials in Russia and the United States were not being returned to military programs, has also hindered progress.[280]

Nevertheless, the extension of safeguards into the nuclear weapon states remains an important issue—not least because the largest enrichment and reprocessing capacities and the bulk of HEU and separated plutonium are located in nuclear weapon states. New enrichment and reprocessing facilities, some of which may process foreign fuels and be placed under multinational governance, are also being proposed there. In addition, the extension of safeguards in the nuclear weapon states could facilitate the widening of IAEA safeguards in India, Israel and Pakistan, which have stayed out of the NPT and armed themselves with nuclear weapons.

Finally, to be consistent with the NPT and the decisions of the 1995 and 2000 NPT Review Conferences, the regulation of fissile materials in all states should be approached *as if the world is preparing for complete nuclear disarmament*, however distant that prospect may be.[281] Adherence to this principle implies a commitment to an FMCT and to the extension of international safeguards, step-by-step, to all nuclear facilities and materials in the nuclear weapon states. It also encourages attainment of the highest standards of material accounting and management in all states, and satisfies concerns for greater equity.

This chapter reviews the current application of international safeguards in the nuclear weapon states and proposes a step-by-step approach to expansion of these safeguards.

Voluntary-Offer Agreements between NPT Nuclear-Weapon States and the IAEA

In 1967, President Johnson declared that the United States would permit the IAEA to apply safeguards to all nuclear activities in the United States, excluding only those with direct national security significance. He was responding to concerns in some non-weapon states that IAEA safeguards would place them at a commercial and industrial disadvantage in developing nuclear energy for peaceful purposes. The United Kingdom followed immediately with a similar declaration.[282] These statements broke a potential impasse in concluding the NPT and were the foundation for the voluntary safeguards offers to the IAEA, ultimately made by all five nuclear-weapon states.

The key elements of the Agreements are summarized in the appendix (Table 6A.1). All five contain the same basic commitments that:

- Safeguards can be applied to facilities, or parts thereof, on a list provided by each government to the IAEA; and

- Source or special fissionable material[283] submitted to safeguards in these facilities may be withdrawn from safeguards, but only "as provided for in the agreement" in question.

Under the Agreements, the states have the authority to decide which facilities or materials are eligible for safeguards, while the IAEA has the authority to decide which eligible facilities will, in fact, be selected, and for how long. Subject to these limitations on scope in each agreement, the safeguards techniques and procedures follow closely the NPT model safeguard document for the non-weapon states (INFCIRC/153) with some adjustment for France and the United Kingdom to take into account Euratom's necessary involvement.

There are also significant *differences* between the five voluntary offer agreements. In particular:

- Their scopes vary dramatically: the United Kingdom and the United States Agreements allow the IAEA to safeguard all of their nuclear activities that lack security significance. France emphasizes its right to designate the materials, within facilities, that may be safeguarded. China commits itself only to make "some of its civilian nuclear facilities" available to Agency safeguarding. Most significantly, Russia limits IAEA safeguards to "several nuclear power stations and nuclear research reactors," thereby placing Russia's extensive fuel cycle outside the scope of its voluntary offer agreement. Recently, however, it has offered the Angarsk enrichment facility to the IAEA for safeguarding;

- The United Kingdom alone, explicitly commits itself to withdraw materials from safeguards only "for national security reasons." The United Kingdom has taken the further step of regularly publishing information on its withdrawals from safeguards on a government website;

- The French and British voluntary offer agreements envisage joint safeguarding by the IAEA and Euratom, and adopt safeguards practices laid down in the NPT model document for the European Union (INFCIRC/193).

There is, therefore, considerable variation across the nuclear weapon states voluntary offer agreements. This contrasts with the uniform scope and practice of safeguards applied to non-nuclear weapon states parties to the NPT. In the post-Cold War context, the nuclear weapon states should consider harmonizing some or all aspects of the agreements.

IAEA Safeguards in the United States, Russia and China. In the United States, nearly all civilian facilities licensed by the Nuclear Regulatory Commission (214 in 1998) are on the list of facilities eligible for IAEA safeguards. In addition, the United States has placed 36 DOE facilities, which are exempt from the NRC's licensing process, on the list eligible for IAEA safeguards. The United States informs the Agency as sites are added to, or removed from, the facilities list, leaving it to the Agency to select the sites at which safeguards, including inspections, are to be applied.

Enrichment and reprocessing facilities worldwide

◘ Enrichment Facility
● Reprocessing Facility

* Under safeguards in non-nuclear weapon state
** Under safeguards in nuclear weapon state
▲ Offered for safeguards (in nuclear weapon state)
▲▲ Not offered for safeguards (in nuclear weapon state)
▼ Shutting down in foreseeable future

Operational
Under Construction
Planned
Future uncertain

tSWU: A separative work unit (1000 kilograms SWU) measures the capacity of machines and plants to enrich uranium.

tHM: Metric tons of heavy metal (tHM) measures the quantity of spent nuclear fuel reprocessed.

IPFM graphics redrawn from *Bulletin of the Atomic Scientists*

Figure 6.1. Safeguards status of enrichment and reprocessing facilities worldwide that are operational, under construction, or planned. There are a total of 36 known facilities (20 enrichment and 16 reprocessing plants) located in 13 countries, not counting R&D and pilot scale facilities. Only five non-nuclear weapon states operate such plants (Brazil, Germany, Iran, Japan, and the Netherlands), all under IAEA safeguards. Seven enrichment or reprocessing facilities in nuclear weapon states are under international safeguards. In the European Union, all reprocessing and enrichment facilities are under EURATOM safeguards. In weapon states outside of the European Union, six more have been offered for IAEA safeguards. There are currently 15 facilities—some of them military—that have not been offered for safeguards. Some of the reprocessing and enrichment facilities in the nuclear weapon states are to be shut down within the next five years.


Seversk▲▲
3,550 tSWU/YR
Seversk▲▲▼
6,000 tHM/YR
Novouralsk▲▲
12,160 tSWU/YR
Zelenogorsk▲▲
7,210 tSWU/YR
Zheleznogorsk▲▲▼
3,500 tHM/YR
Angarsk▲
2,350 tSWU/YR
BNFL Magnox**▼
1,500 tHM/YR
BNFL Thorp**▼
900 tHM/YR
Urenco Nederland*
2,500 tSWU/YR
Rokkasho*
800 tHM/YR
Rokkasho*
1,050 tSWU/YR
Yongbyon▲▲▼
50–200 tHM/YR
Mayak RT-1▲▲
400 tHM/YR
Urenco Capenhurst**
4,000 tSWU/YR
Urenco Deutschland*
1,800 tSWU/YR
La Hague UP2**
1,000 tHM/YR
La Hague UP3**
1,000 tHM/YR
JNC Tokai*
210 tHM/YR
Georges Besse II▲
7,500 tSWU/YR
Eurodif/Georges Besse**▼
10,800 tSWU/YR
Lanzhou 2▲
500 tSWU/YR
Shaanxi**
500 tSWU/YR
Kahuta▲▲
15–20 tSWU/YR
Nilore▲▲
10–20 tHM/YR
Natanz*
100–250 tSWU/YR
Dimona▲▲
40–100 tHM/YR
Tarapur▲▲
100 tHM/YR
Trombay▲▲
50 tHM/YR
Kalpakkam▲▲
100 tHM/YR
Rattehalli▲▲
4–10 tSWU/YR

Initially, the IAEA selected in the United States two operating commercial power reactors and one active commercial fuel fabrication plant, with rotations to different similar facilities in two-year intervals. Between 1990 and 1993 no inspections were carried out at U.S. facilities, due to IAEA budgetary constraints, but they were resumed in 1994 for the purpose of verifying that former defense materials were not returned to weapons. The United States reimbursed the IAEA for the cost of these inspections in order not to reduce the IAEA's ability to achieve its safeguards objectives in non-nuclear-weapon states.

Beginning in 1993, the United States made available for IAEA safeguards 12 tons out of the more than 200 tons of fissile material that it had declared excess to national defense needs. Since 1994, the IAEA has conducted almost 500 inspections at six U.S. facilities containing these excess weapon materials (see Table 6.1). A storeroom within the Y-12 facility at Oak Ridge, where the weapon components containing HEU are fabricated, dismantled and stored, contained 10 tons of weapon-grade uranium that were offered for IAEA safeguards. These inspections gave the agency experience with the constraints on inspectors inside a defense facility. Two tons of plutonium at the former Hanford military plutonium-production site and the shutdown Rocky Flats plutonium weapon component production facilities were also put under Agency safeguards. The Rocky Flats material was subsequently transferred to the former Savannah River plutonium production site.

Also in the United States, at the BWXT naval and research-reactor fuel-fabrication facility, and the former Portsmouth gaseous-diffusion enrichment plant, the Agency was given the opportunity to monitor the down-blending of HEU to LEU. As of the end of 2005, three U.S. facilities had materials under IAEA safeguards: Y-12, Savannah River, and BWX Technologies. Verification activity at these sites has created opportunities to assess new technologies including remote monitoring, independently verify declared enrichment of HEU being down-blended, and explore the utility and applicability of advanced inspection technologies.

Facility	Inspection dates
Oak Ridge Y-12 Plant Vault	1994 –
Hanford Vault	1994 – 2005*
Rocky Flats Vault	1995 – 2003
BWXT U.S. HEU down-blending and, during 1996-2000, down-blending Kazakhstan HEU (Project Sapphire)	1996 –
Portsmouth Gaseous Diffusion Plant	1997 – 1998**
Savannah River Site K-Area Materials Storage Facility (KAMS)	2003 –

Table 6.1. U.S. facilities containing excess weapon materials subject to IAEA inspection since 1994.[284]
*In March 2005, DOE placed an additional ton of plutonium under IAEA safeguards at KAMS, and in April 2005 the IAEA removed the seals from the plutonium under safeguards at Hanford, except for several reference standards. Since then, IAEA inspections at Hanford have been periodic. **DOE and the IAEA conducted a verification experiment.

In Russia, according to the 2005 IAEA Annual Report, no facilities were being inspected. Our understanding is that a storage facility, containing uranium, removed from Iraq pursuant to U.N. Security Council Resolution 687 was safeguarded by the IAEA under the Russian voluntary-offer agreement. This appears to have been the only occasion in which a Russian facility was subject to IAEA inspection since the voluntary offer was concluded in 1985. Otherwise, safeguards activities in the Russian Federation have been limited to the evaluation of accounting reports on the export and import of nuclear materials.

It should nevertheless be noted that in 2007 Russia and Kazakhstan established an international uranium enrichment center at Angarsk, Russia, where uranium enrichment has been carried out since the 1960s. The center is open to other countries to join through intergovernmental agreements. Partners would have access to LEU but not to enrichment technology. The concept is predicated on IAEA involvement including safeguards and a seat on the facility's supervisory commission. At the time of this writing, however, no decision had been taken by the IAEA on whether to apply safeguards at Angarsk, or on the scope of the safeguards that might be applied.

In China, three facilities were being safeguarded by the IAEA in 2005, according to its Annual Report of that year: the Shaanxi centrifuge enrichment plant; the QSNPP power reactor; and an HTGR research reactor. The enrichment plant and power reactor are being safeguarded in accordance with China's contracts with their suppliers, France and Russia respectively.

In summary, the almost negligible IAEA inspection activity in the United States, Russia and China have provided little on which to build an international monitoring system in these countries. In contrast, the United Kingdom and France have had extensive experience with international safeguarding, including in all their active enrichment and reprocessing plants.

Euratom and IAEA Safeguards in France and the United Kingdom. The European Union's safeguards system was established by the Euratom Treaty of 1957. Originally involving the six founding members of the Communities, it now covers the Union's 27 member states. The Euratom Treaty is not strictly a non-proliferation instrument, as it takes no view on the legitimacy or legality of military activities.[285] It does, however, provide support for the non-proliferation objectives of the European Union, the NPT, and other institutions. "The task of Euratom safeguards is to ensure that within the European Union nuclear material is not diverted from its intended use."[286] This entails ensuring that nuclear materials will not be used in military programs once they have been labelled "civil."

The United Kingdom and France concluded voluntary offer agreements with the IAEA and Euratom in 1976 and 1978 respectively. However, the extensive experience of international safeguards in these states has been driven more by their membership of the Euratom Treaty, by their commercial reprocessing of foreign spent fuels, and by the U.K.'s involvement in centrifuge enrichment with Germany and Holland, than by their obligations under these voluntary offer agreements.

Following the 1995 declarations by the United Kingdom and France of their moratoria on further production of fissile materials for explosive purposes, their entire nuclear fuel-cycles (other than those facilities in the United Kingdom serving naval requirements) were brought in stages under Euratom safeguards.[287] The French government has closed all of its military fuel-cycle facilities. The present coverage of international safeguards in France and the United Kingdom is summarized in Table 6.2 and also illustrated in Figure 6.1.

Euratom now safeguards all plutonium, domestic or foreign, in the four British and French reprocessing facilities, and in their two MOX fuel-fabrication facilities:

- UP2-800 at La Hague, France and B205 at Sellafield, United Kingdom, which reprocess domestic light-water reactor (LWR) and Magnox gas-cooled reactor fuels respectively;
- UP3 at La Hague, which has processed foreign LWR fuels, and THORP at Sellafield, which has processed foreign LWR and domestic Advanced Gas-Cooled Reactor fuels; and
- The MELOX MOX-fuel fabrication facility at Marcoule, France and the Sellafield MOX Plant (SMP).

	Under Euratom Safeguards	Designated for Safeguarding by the IAEA	Unsafeguarded
France	All civilian materials	• Spent fuel ponds at La Hague UP2 and UP3 reprocessing plants • MOX storage and loading areas at La Hague • MOX destined for NNWS at MELOX fuel-fabrication plant, Marcoule	• Materials in weapon cycle • Facilities and materials in naval-reactor fuel cycle
United Kingdom	All civilian materials	• Two plutonium stores at Sellafield reprocessing plant • Capenhurst centrifuge enrichment plant	• Materials in weapon cycle • Facilities and materials in naval-reactor fuel cycle

Table 6.2. International safeguards coverage in France and the United Kingdom.

The European Union carries the main financial burden of safeguarding the British and French nuclear fuel cycle facilities. Euratom transmits safeguards information about the nuclear materials in these facilities to the IAEA in accordance with the voluntary offer agreements.

In 2002, Euratom's mission and processes were reviewed by a High-level Expert Group.[288] The group's report was accompanied by a proposal from within the Commission to shift the emphasis in Euratom safeguarding from traditional material accountancy, to the auditing of operators. One intention was to free financial resources for reallocation to transport and other fields of activity.[289] In the face of strong opposition from member states from within Euratom and the Commission and from the IAEA, however, these proposals were dropped. Euratom safeguarding, and its partnership with the IAEA have, therefore, continued uninterrupted although some issues have still to be resolved.

IAEA Safeguards at the French and United Kingdom reprocessing plants. Under intergovernmental agreements, including the France-Japan, U.K.-Japan and E.U.-Japan Agreements, the French and British governments, and facility operators, are required also to facilitate IAEA safeguards on all Japanese plutonium in Europe.[290] (IAEA safeguards have not been required, however, for non-weapon states within the European Union and in Switzerland when they shipped their spent fuel to La Hague and Sellafield.)[291]

To minimize costs and complications, French- and U.K.-origin plutonium are substituted for Japanese plutonium. The manner in which this substitution is carried out differs in the two countries. In France, when Japanese spent fuel enters the reprocessing plant, an equivalent quantity of plutonium in French spent fuel in the spent-fuel storage ponds at La Hague, is placed under IAEA safeguards. Inventories, specifically of Japanese plutonium, are inspected by the IAEA again, after they emerge from the reprocessing plant and are processed into MOX fuel for return to Japan.

In the United Kingdom, when Japanese spent fuel enters the THORP reprocessing plant, equivalence is maintained by placing under IAEA safeguards U.K. separated plutonium in two stores at Sellafield that contain both domestic and foreign material.[292] The resubmission of Japanese plutonium to IAEA inspection will happen again at the MOX-fuel stage.

As a result of these substitutions, the entire UP2/UP3 spent fuel ponds and the two major Sellafield plutonium stores are safeguarded by the IAEA. Parts of the MELOX MOX-fuel fabrication facility are safeguarded as well. Together, these arrangements account for the bulk of the plutonium held under IAEA safeguards in the nuclear weapon states (see below).[293]

IAEA Safeguards at centrifuge-enrichment plants. The United Kingdom is a member of the 1980s Hexapartite Safeguards Project, which developed techniques for safeguarding centrifuge enrichment plants, and committed the participating states, including the weapon states, to accepting IAEA safeguards on their operating facilities.[294] The IAEA has since placed Urenco's plants, in the United Kingdom, Germany and the Netherlands, under safeguards carried out jointly with Euratom (see Figure 6.1).

France's Eurodif enrichment plant uses the gaseous diffusion method and is safeguarded by Euratom, but not the IAEA. A replacement plant is to be constructed using Urenco-designed centrifuges. France is not a part of the Hexapartite agreement, but the Treaty of Cardiff requires that any French centrifuge plant involving Urenco will be safeguarded by the IAEA.[295] The United States is a part of the Hexapartite agreement. Although this agreement is not legally binding, it is expected that the two new centrifuge plants will also be safeguarded by the IAEA. How, precisely, safeguards will be applied at the French and U.S. plants, remains subject to negotiation. The IAEA has three objectives when safeguarding a centrifuge enrichment plant: to detect diversion of a declared product; to detect undeclared excess production of LEU; and to detect clandestine HEU production. How the safeguards approach would be customized for each plant, and whether the new facilities' location in the nuclear weapon states would be taken into account, remain to be seen.

Quantities of Fissile Material under IAEA Safeguards in the nuclear weapon states. The quantities of plutonium and enriched uranium under IAEA safeguards in the nuclear weapon states at the end of 2005 are shown in Table 6.3. As the information provided by states to the IAEA is confidential, the inventories in the five countries are aggregated by the IAEA. Nevertheless, because so few facilities in the nuclear weapon states have been brought under Agency safeguards, it is possible to back out the national contributions to these totals with reasonable accuracy.

Most of the plutonium under IAEA safeguards is that in the French spent-fuel pools and the U.K. plutonium stores discussed above. The 103.5 tons of "plutonium contained in irradiated fuel" is close to the estimated 105.9 tons of "plutonium contained in spent fuel at reprocessing plants" as of 31 December 2005, reported by France under the Guidelines for the Management of Plutonium.[296]

	Quantity in Tons
Plutonium contained in irradiated fuel	104
Separated plutonium outside reactor cores	79
Separated plutonium in fuel elements in reactor cores	0
HEU (equal to or greater than 20% U235)	10
LEU (less than 20% U235)	4972

Table 6.3. Quantities of fissile material in the nuclear weapon states under IAEA safeguards, end of 2005.[297]

Likewise, a majority of the inventory of 78.7 tons of "separated plutonium outside reactor cores" is comprised of foreign and U.K.-origin plutonium stored at Sellafield. The U.K. Government has reported under the Guidelines that 101.1 tons of separated plutonium, of which 26.5 tons were foreign-owned, were held there on 31 December 2005.[298] Two tons of plutonium declared by the United States to be excess to its military requirements were also held under safeguards at Savannah River on that date (see above). We therefore surmise that the separated plutonium held under IAEA safeguards in the nuclear weapon states at the end of 2005 must include in addition, 76.7 tons of plutonium in the United Kingdom, of which 26.5 tons belong to Japan and the European non-nuclear weapon states whose spent fuel had been reprocessed at Sellafield.

Regarding HEU, the 10 tons reported as safeguarded by the IAEA in Table 6.3, was presumably the excess weapon-grade uranium that the Clinton administration asked the IAEA to safeguard at the Y-12 plant at Oak Ridge. The Bush administration has since proposed exchanging this for 17.4 tons of less than weapon-grade HEU, which will be blended down to LEU. The 10 tons of weapon-grade material will be transferred to the naval reserve.[299]

Regarding LEU, most of the 4972 tons reported as safeguarded by the IAEA as of the end of 2005 was likely located at the Capenhurst centrifuge enrichment facility due to the U.K.'s involvement in the Hexapartite Project. The remainder presumably was at China's centrifuge enrichment plant at Shaanxi, which is under IAEA safeguards by agreement between China and Russia, which supplied the centrifuges.

The quantities of fissile material that are available for IAEA safeguarding in the nuclear weapon states as a result of their voluntary offers are much larger, however, than the quantities actually under safeguards.

The Additional Protocol in the NPT Nuclear-Weapon States

The 1997 Additional Protocol to the standard NPT safeguards agreement with the non-weapon states (INFCIRC/153) was negotiated following the discovery that Iraq had developed a secret nuclear program, in parallel with the one that the IAEA was inspecting. The Additional Protocol requires that the non-nuclear-weapon states that are parties to the NPT provide information about all of their nuclear-related activities, even if they do not involve nuclear materials—centrifuge development and production, for example. It also gives the IAEA the authority to ask for access to, and to take environmental samples at, sites that have not been declared as nuclear sites.[300] Since these requirements go well beyond the previously understood requirements of the NPT, the Additional Protocol must be ratified by a State Party before it comes into force in that country. As of 13 June 2007, the Additional Protocol was in force for 79 non-weapon states and had been signed by an additional 28.[301]

The Additional Protocol is targeted primarily at the non-weapon states but all five NPT nuclear-weapon states have, in addition to their voluntary safeguards offers, taken steps to conclude Additional Protocol agreements with the IAEA. Three of these agreements (with China, France and the United Kingdom) have entered into force.[302] Preparation of Russia's Additional Protocol with the IAEA was under way in 2004, but is still not completed. The United States signed an Additional Protocol with the IAEA in 1998 and submitted it to the Senate in May 2002 for advice and consent on ratification, which was given in March 2004. Implementing legislation was passed by Congress in December 2006 as part of the U.S.-India Peaceful Atomic Energy Act.[303] The U.S. Additional Protocol will not enter into force, however, until the United States notifies the IAEA that the statutory and constitutional requirements have been met, and deposits the instrument of ratification. As of this writing, the Bush Administration had not yet done this.

The motivation of the nuclear-weapon states for adhering to the Additional Protocol is the same as that which led them earlier to enter into voluntary safeguards agreements with the IAEA—to increase the credibility of their efforts to encourage the non-weapon states to ratify the Additional Protocol. During the negotiation of the Protocol in the mid-1990s, non-nuclear weapon states contended that verification would be costly and intrusive and could therefore potentially put them at increased commercial disadvantage, relative to nuclear weapon states in the civil nuclear market. The weapon states have sought to respond to these arguments by accepting additional obligations for their own civilian nuclear programs.

The five weapon-state Additional Protocols all draw upon the Model Additional Protocol developed for the non-weapon states. Primarily, they widen the range of information reported to the IAEA under the voluntary offer agreements. The main limitations in the published nuclear-weapon-states Protocols (the Russian Additional Protocol is not yet available) are as follows:

- The United States will not provide the IAEA with access to any information that it considers of "direct national security significance." Furthermore, no access by the IAEA to any location in the United States may take place without authorization of the U.S. Government, and all locations, sites and facilities owned by the U.S. Departments of Defense and Energy are exempted. For private sites, the owner or operator of a location may withhold consent, but the U.S. government also may seek an administrative search warrant to secure access. The United States also will not permit environmental sampling at any location unless the President "has determined and reported to the appropriate congressional committees with respect to the proposed use of environmental sampling." Finally, restrictions are placed on the nationalities of IAEA inspectors.

- The scope of the British and French Additional Protocols is narrower than that of their American counterpart, being restricted to providing the IAEA with information arising from civil industrial trade or R&D activities carried out in cooperation with NPT non-nuclear weapon states. The purpose is to help the IAEA detect undeclared nuclear materials and activities in the non-weapon states. The IAEA has broad rights of access, however, within these Protocols' more specific frameworks. Most information gathered by France, the United Kingdom and the European non-weapon states for the IAEA under their Additional Protocols, is transmitted directly to the IAEA, rather than via Euratom, whose role is limited to the verification of their declarations of civilian nuclear materials.[304]

- The Chinese Additional Protocol is a considerably more restricted version of the British and French Additional Protocols. In particular, it does not allow the IAEA any access to sites and facilities in China for verification purposes.

Conclusions and Recommendations

There is a striking contrast between the mandatory, highly rule-bound application of IAEA safeguards in the non-weapon states, and their very limited and discretionary application to civilian nuclear activities in the nuclear-weapon states.

There is also a striking difference between Euratom's extensive, mandatory safeguarding of civil nuclear materials in France and the United Kingdom, and the IAEA's limited and voluntary safeguarding of such materials in China, Russia and the United States.

It is also notable that nearly all of the separated plutonium and HEU that is safeguarded by the IAEA in the weapon states is monitored for idiosyncratic reasons. Over 95 percent of the plutonium is safeguarded because of the requirements of Japan's agreements with France, the United Kingdom and the EU. One hundred percent of the relatively small quantity of HEU safeguarded by the IAEA in the nuclear-weapon states is the result of a gesture made by the Clinton administration. Similarly, LEU is safeguarded by the IAEA in the nuclear weapon states mainly due to the Hexapartite Agreement, which brought under IAEA safeguards the U.K. centrifuge enrichment plants at Capenhurst.

Nevertheless, the substantial fraction of the global civil nuclear-weapon state fuel-cycle facilities in Europe is under international safeguards. And an even more substantial part of the global fuel-cycle could be brought under safeguards if the IAEA had the resources required to take full advantage of the voluntary offer agreements. If the IAEA were required to do so, however, its budget would have to be increased if safeguarding in the non-weapons states were not to suffer.

In 1970, the IAEA's Board of Governors approved the Timbs Criteria, which suggested that the IAEA should invest its resources in safeguards in the nuclear weapon states in only two circumstances:

1. When the facility was of advanced design and the IAEA could use the experience to prepare itself for safeguarding such facilities when they were built in the non-weapon states; and

2. When the absence of safeguards on fuel-cycle-service providers in the nuclear weapon states gave them an unfair advantage in competition with fuel-cycle providers in the non-weapon states.[305]

In the 1990s, after the end of the Cold War, there was an additional reason: to place under IAEA safeguards materials that the nuclear weapon states were declaring excess to military requirements.

Today, the arguments for the IAEA to take fuller advantage of the nuclear weapon states' voluntary offers to accept more extensive safeguards are that:

- Inequalities between the weapon and non-weapon states would be lessened;

- Safeguards on fuel-cycle activities across the weapon and non-weapon states could be more integrated. This is becoming increasingly important as civilian nuclear industries are globalized;

- International safeguards would encourage the highest standards of nuclear-material accounting and regulation in the weapon as well as non-weapon states;

- An infrastructure of monitoring would be established in the weapon states that would lay the basis for verification of an FMCT and the disarmament goals agreed to in the NPT's Article VI, and at the 1995 and 2000 NPT Review Conferences; and

- The NPT states' bargaining position on expanding IAEA safeguards in India and the other non-NPT states would be strengthened.

On the other hand, there are also arguments against extending IAEA safeguarding in the nuclear weapon states:

- Diversion of civilian nuclear materials to weapon purposes would have relatively little security significance in a nuclear-weapon state;

- There would be relatively little benefit in expanding the IAEA's expertise;

- Unwelcome strains would be placed on the IAEA budget, which is already strained, and is unlikely to be increased to meet this purpose;

- It would require more trained inspectors at a time when retirements of senior experts is becoming a serious problem for the Agency; and

- It might be resisted by at least some of the nuclear weapon states.

We find the "case for" much more compelling. We therefore propose that IAEA safeguards in the nuclear weapon states be expanded in the following three stages:

1. Those nuclear weapon states that have not already done so, should expand their voluntary offers for IAEA accounting and inspection to include all their civilian nuclear facilities and the materials contained therein;

2. All new civilian enrichment and reprocessing facilities in the nuclear-weapon states should be placed under permanent IAEA safeguards. This is particularly important given current pressures to establish new enrichment plants—and perhaps also reprocessing plants—and the desirability of applying common safeguards design standards and practices to them;

3. All separated plutonium and HEU that are excess to military requirements should be placed under IAEA safeguards.

A still more comprehensive application of IAEA safeguards in the nuclear weapon states could come with the conclusion of a verified FMCT.

If IAEA safeguards are to be applied more widely in the nuclear weapon states, questions about their financing will have to be addressed vigorously. In a statement to the Board of Governors on 9 July 2007, the IAEA's Director General, Dr. Elbaradei, observed that "the Agency remains under-funded in many critical areas, a situation which, if it remains unaddressed, will lead to a steady erosion of our ability to perform key functions, including in the verification and safety fields." He announced that a study was being initiated to "examine the programmatic and budgetary requirements of the Agency over the next decade or so" which would be reviewed by a high level panel of experts.

Given the IAEA's need to protect its ability to carry out effectively its expanding safeguards responsibilities in the non-weapon states (and in India and North Korea) and pressures on it to expand its activities on various fronts, the Agency may be inclined to give safeguarding in the weapon states a relatively low priority. Should the nuclear weapon states themselves contribute extra funds for IAEA safeguarding on their territories? Could they agree on how this might be done equitably? Given their individual and collective wealth, resource scarcity seems a weak reason for not proceeding. Exploring the options, including a possible small charge on nuclear generated electricity to support IAEA safeguards, should form part of the Director General's study.[306]

The political climate for reaching agreement on a substantial extension of international safeguarding in the nuclear weapon states may seem unfavourable today. However, the desirable trend is surely in that direction. We encourage the nuclear weapon states and the IAEA to review the situation and come forward with proposals in the run-up to the NPT Review Conference in 2010.

Appendix 6A

	INFCIRC/263	INFCIRC/288	INFCIRC/290	INFCIRC/327	INFCIRC/369
Country	**U.K./Euratom 1976**	**United States 1977**	**France/Euratom 1978**	**USSR/Russia 1985**	**China 1988**
Preamble	"the U.K. has stated that at such time as international safeguards are put into effect in non-nuclear weapon states in implementation of the provisions of the [NPT], it would be prepared to offer an opportunity for the application of similar safeguards in the United Kingdom subject to exclusions for national security reasons only."	"the U.S ... has indicated that at such time as safeguards are being generally applied [under] Article III of the [NPT], the U.S. will permit the Agency to apply its safeguards to all nuclear activities in the U.S., excluding only those with direct national security significance"	"with a view to encouraging the acceptance of ... safeguards by an ever greater number of states, France is prepared to afford the Agency the opportunity to apply its safeguards on French territory by concluding an agreement for that purpose." "Whereas the purpose of such an agreement is of necessity different from the aims pursued by safeguards agreements between Agency and non-nuclear-weapon States."	"the Soviet Union, ... as an act of good will, has expressed its willingness to place under Agency safeguards some of its peaceful nuclear facilities, namely several nuclear power stations and nuclear research reactors."	"China has decided to voluntarily place some of its civilian nuclear facilities under Agency safeguards by concluding a safeguards Agreement," "the purpose of a safeguards agreement giving effect to this offer by China would thus necessarily differ from the purpose of safeguards agreements between the Agency and the non-nuclear weapon states."
Basic Undertaking	"The U.K. shall accept the application of safeguards" ... "on all source and special fissionable material in facilities or parts thereof within the United Kingdom, subject to exclusions for national security reasons only, with a view to enabling the Agency to verify that such material is not, except as provided in this Agreement, withdrawn from civil activities"	"The U.S. undertakes to permit the Agency to apply safeguards ... on all source or special fissionable material in all facilities in the U.S., excluding only those facilities associated with activities of direct national security significance to the U.S., [to enable] the Agency to verify that such material ... is not withdrawn ... from activities in facilities while such material is being safeguarded"	"France shall accept the application of safeguards ... on source and special fissionable material to be designated by France, in facilities or parts thereof in France, to verify that such material is not withdrawn from civil activities, except as provided for in this Agreement."	Russia "shall accept the application of safeguards ... on all source or special fissionable material in peaceful nuclear facilities to be designated by [Russia] within its territory" to verify that "such material is not withdrawn, except as provided for in this Agreement, from those facilities while such material is subject to safeguards under this Agreement."	"China shall accept the application of safeguards" to verify that "all source and special fissionable material in peaceful nuclear facilities to be designated by China within its territory ... is not withdrawn, except as provided for in this Agreement, from those facilities while such material is subject to safeguards under this Agreement"

Table 6A.1 Voluntary offer safeguards agreements.

7 Managing the Civilian Nuclear Fuel Cycle

Over the past twenty years, there has been little construction of new nuclear-power plants, with the exception of in Asia, where there has been some limited building. There is now, however, an active debate about the possibility of a dramatic nuclear "renaissance," driven in part by concerns over climate change. This chapter examines the potential implications of an expansion in nuclear power for fissile-material controls. The main concerns relate to the proliferation of national enrichment and reprocessing capabilities, which give states the capability to produce fissile materials for weapons. Overall, we emphasize that:

- Nuclear power worldwide would have to expand five-fold or more to make a significant contribution to greenhouse-gas reductions. Such an expansion is far from certain, however, and even industry optimists do not see it being achieved before 2050.

- Even if nuclear power expands substantially, there is no economic rationale for reprocessing, for the recycling of plutonium in light water reactors (LWRs), or for the adoption of closed fuel cycles of any type. Furthermore, there are compelling security reasons to avoid reprocessing and recycling.

- Concern that some countries could use gas-centrifuge uranium-enrichment plants to make material for nuclear weapons has led to calls for dividing the world permanently into fuel-supplier states—basically, the NPT weapon states plus Europe and Japan—and fuel-recipient states. Such a division is in all likelihood unworkable. Using multinational ownership to protect against proliferation may be politically more feasible and is already happening to some degree.

Nuclear Power Today

At the end of July 2007, 438 nuclear-power plants, with a generating capacity of 371 gigawatts-electric (GWe) were in operation in 31 countries (see Table 7.1). These units provide about 16 percent of electrical energy worldwide.[307] Eight countries accounted for 80 percent of global nuclear capacity: the United States, France, Japan, Germany, Russia, South Korea, Ukraine, and Canada.

Country	No. of Units	Total GW(e)	Country	No. of Units	Total GW(e)
Argentina	2	0.9	Mexico	2	1.4
Armenia	1	0.4	Netherlands	1	0.5
Belgium	7	5.8	Pakistan	2	0.4
Brazil	2	1.8	Romania	1	0.7
Bulgaria	2	1.9	Russian Federation	31	21.7
Canada	18	12.6	Slovak Republic	5	2.0
China	11	8.6	Slovenia	1	0.7
Czech Republic	6	3.5	South Africa	2	1.8
Finland	4	2.7	Spain	8	7.5
France	59	63.3	Sweden	10	9.0
Germany	17	20.3	Switzerland	5	3.2
Hungary	4	1.8	Taiwan, China	6	4.9
India	17	3.8	Ukraine	15	13.1
Japan	55	47.6	United Kingdom	19	10.2
Korea, Republic of	20	17.4	United States	104	100.3
Lithuania, Republic of	1	1.2	Total	438	371.0

Table 7.1. Operating reactors and nuclear capacities by country, 2007.[308]

Nuclear Capacity Growth Projections

Short-term projections to 2030. Out to 2030, projections can to some extent be based on actual plans. Such projections vary somewhat, but tend to fall into the range of 400–600 GWe installed nuclear capacity in 2030. Table 7.2 shows two scenarios offered by the OECD's International Energy Agency (IEA), which projects worldwide capacity at 416 or 519 GWe in 2030, depending on policies. Light-water reactors account for about 88 percent of the world's nuclear capacity, and an even greater fraction of current plant construction.[309]

The lower projection is for the International Energy Agency's reference scenario, which assumes that current government policies remain broadly unchanged. The higher projection represents what the agency judges could be achieved if government policies promoted nuclear power as part of the solution to climate change. The International Atomic Energy Agency (IAEA), envisioning greater potential for expansion, projects a global nuclear capacity ranging from 414 to 679 GWe in 2030.[310] The U.S. Energy Information Administration estimates 438 GWe, near the lower end of the IEA and IAEA ranges.[311] The uranium-fuel trading company NUKEM projects a capacity of 535 GWe in 2030.[312]

Projections to 2050 and Beyond. For those advocating or expecting a serious nuclear renaissance, the period after 2030 is of greatest interest. The 2003 MIT interdisciplinary study on the future of nuclear power presented one high scenario, in which nuclear power capacity reaches 1500 GWe in 2050 (see Figure 7.1).

Region	Nuclear Capacity [GW]			Share of nuclear in electricity generation		
	2005	2030 Reference Scenario	2030 Alternative Policy	2005	2030 Reference Scenario	2030 Alternative Policy
OECD	**308**	**296**	**362**	**22%**	**16%**	**22%**
OECD North America	112	128	144	18%	15%	18%
OECD Europe	131	74	110	28%	12%	20%
OECD Pacific	65	94	108	25%	32%	41%
Transition economies	**40**	**54**	**64**	**17%**	**18%**	**23%**
Developing countries	**19**	**66**	**93**	**2%**	**3%**	**5%**
China	6	31	50	2%	3%	6%
India	3	19	25	2%	6%	9%
Other Asia	5	10	10	4%	3%	4%
Latin America	3	4	6	2%	2%	3%
Middle East and Africa	2	3	3	1%	1%	1%
World	**368**	**416**	**519**	**15%**	**10%**	**14%**

Table 7.2. International Energy Agency (IEA) nuclear capacity projections for 2030.[313]

The MIT study estimated the distribution of this nuclear capacity by dividing the countries of the world into different groups based on their level of economic development. For the developed countries and Russia, the study then assumed that nuclear power would provide on average 51 percent of total electric power in 2050. In the large or advanced developing countries that already have nuclear power (including Argentina, Brazil, China, India, Mexico and South Africa) it was assumed to provide 30 percent of total electric energy in 2050.

Among the most populous, less-advanced developing countries, India was assumed to have 175 and Indonesia 39 equivalent GWe of nuclear power capacity in 2050. None of the least developed countries were assumed to have any nuclear power in 2050. How-

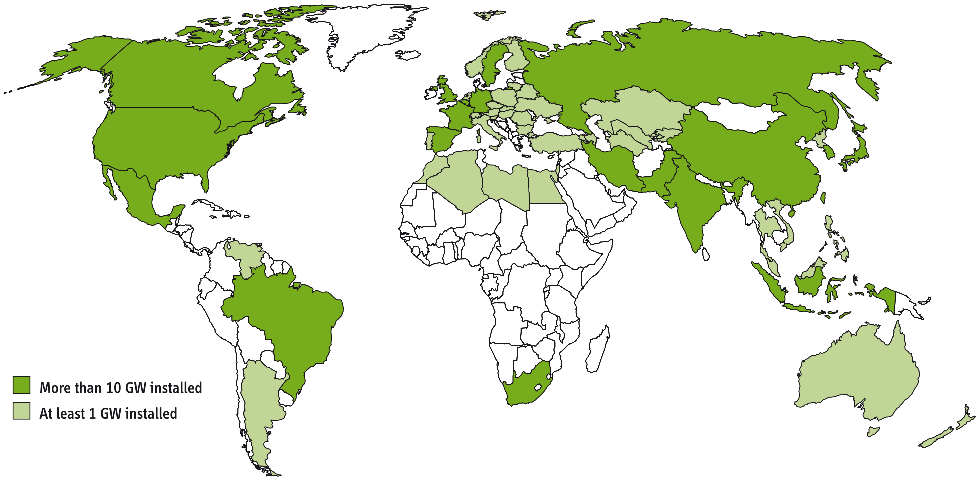


Figure 7.1. MIT's 1500 GWe high-growth nuclear scenario predicts reactors in 58 countries.[314]

ever, several developing countries that have no or negligible nuclear power today—including Algeria, Armenia, Azerbaijan, Belarus, Georgia, Indonesia, Iran, North Korea, Malaysia, Pakistan, the Philippines, Poland, Thailand, Turkey, Turkmenistan, Uzbekistan, Venezuela, and Vietnam—were assumed to acquire nuclear-power plants by 2050. In fact, some of these countries are already expressing an interest in nuclear power.[315]

Constraints on Nuclear Growth

Throughout most of the nuclear era, projections of future nuclear growth have been consistently too optimistic. Figure 7.2 shows the history of IAEA nuclear-power projections for OECD countries.

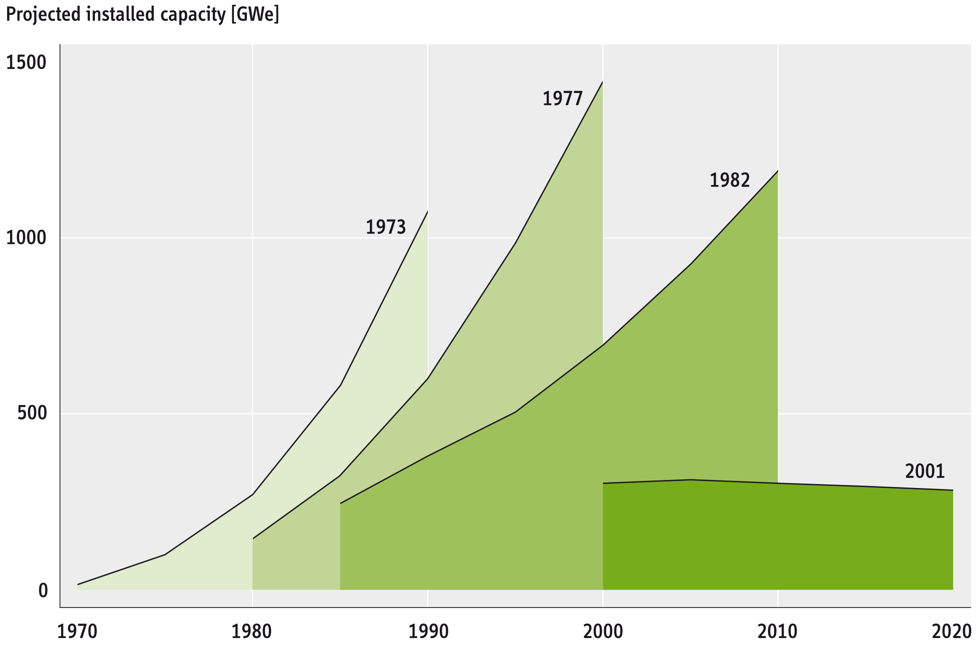


Figure 7.2. IAEA forecasts made in 1973, 1977, 1982, and 2001 for nuclear capacity growth in OECD countries.[316]

Projections for nuclear-power growth outside of the OECD have been overoptimistic as well. For example, in 1985, the Chinese government projected a nuclear capacity of 20 GWe by the year 2000.[317] At the end of 2005, China had only 6.4 GWe in operation. Similarly, in 1962, the Indian Atomic Energy Commission projected a capacity of 20–25 GWe in 1987.[318] As of May 2007, India's nuclear capacity was only 4.1 GWe.

Many of the factors that constrained nuclear power in the past—high capital costs, slower-than-projected growth in demand for electricity, scarcity of capital in developing countries, and problems with public acceptability—are likely to continue to dampen its growth. We find it unlikely that nuclear capacity will reach even the 1000 GWe of MIT's low-growth scenario by 2050.

High capital costs. Figure 7.3 compares the International Energy Agency's estimates of the cost of nuclear power with the costs of power generated by gas, coal, and wind. The cost estimates for gas and coal do not include the extra cost of capturing and sequestering carbon dioxide, which may become part of a future climate-change mitigation strategy. For the integrated gasification combined cycle (IGCC) system, carbon-capture costs are estimated to add about 1.5 cents per kWh.[319]

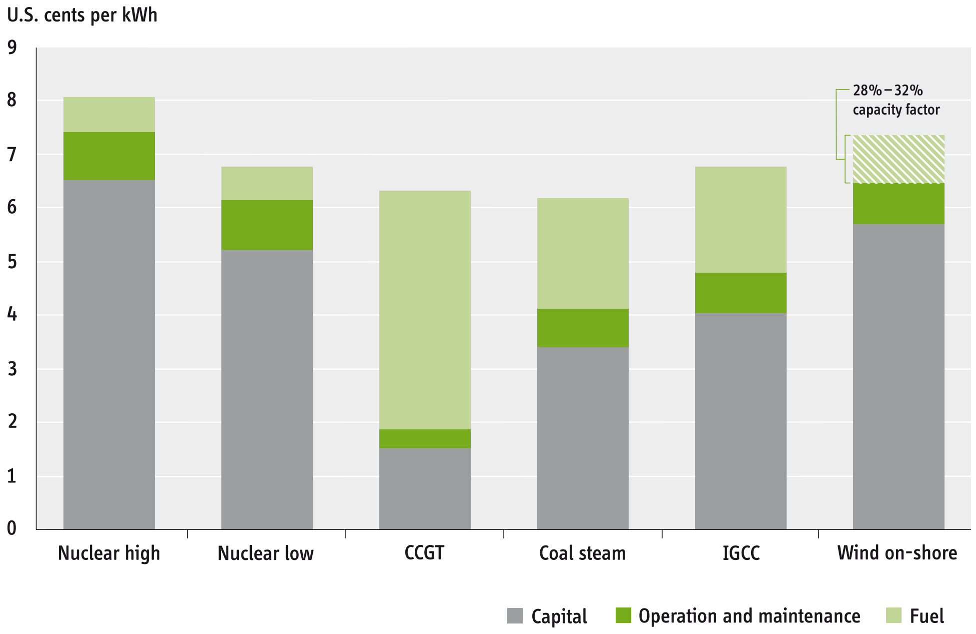


Figure 7.3. Electricity generating costs for low and high-cost nuclear plants and some alternatives. The alternatives considered were combined cycle gas turbine (CCGT), coal steam, integrated gasification combined cycle coal (IGCC), and on-shore wind.[320]

The "overnight" capital costs assumed for nuclear power in Figure 7.3 (i.e., costs excluding interest charged during construction) were $2000/kWe (in 2006 dollars) for the low case and $2500/kWe for the high case. Nuclear power would be in the same cost range as coal and wind for the $2000/kWe case.[321] The MIT study found, somewhat less optimistically, that nuclear power would be roughly competitive with coal if nuclear power's overnight costs could be kept to $2000/kWe *and* countries enacted a substantial tax on carbon dioxide emissions to the atmosphere.[322]

The capital charge for the plant is the most important cost element for nuclear power and is affected by the economic conditions of each country. For developing countries, in which investors require high real interest rates and returns on capital, every additional $500 per kWe capacity in the "overnight" capital costs adds about 1.5 cents per kWh to the cost of electricity. Other costs are less, but can still be significant. Since 9/11, concerns about terrorist attacks have driven up insurance and security costs.[323] The interest charged during construction also adds significantly to costs—especially if there are delays.

A recent estimate for the cost of building the first nuclear unit at a new U.S. site was $2400–3500 per kilowatt (in 2006 dollars).[324] The uncertainties are large because no new plants have been built in the United States in recent decades, and only a few elsewhere. In Asia, the overnight costs for recent plants (in 2002 dollars) ranged from $1800/kWe to $2800/kWe. In Europe, the Olkiluoto-3 reactor now under construction in Finland has an estimated overnight cost of $2500–3000/kWe.[325] Construction of this reactor is already behind schedule by a year and a half.[326]

The U.S. Energy Policy Act of 2005 sought to reduce investor risks for the first six new nuclear power plants built in the United States through two billion dollars of government guarantees and incentives.[327] Nevertheless, Standard and Poor's, which sets corporate credit ratings, stated in January 2006 that, "from a credit perspective, [the] provisions may not be substantial enough to sustain credit quality and make [nuclear generation] a practical strategy."[328]

Slower-than-projected growth in electricity demand. The 2006 IAEA nuclear projection of 414–679 GWe in 2030 was based on an assumed growth rate of total global electricity consumption of between 2 and 3 percent per year.[329] This is the range in which consumption grew during the 1990s. However, as analyzed by Goldemberg and Lucon, growth rates in both OECD and non-OECD countries declined between 1971 and 2003 owing to increased efficiency in electricity use and the saturation of electrification.[330] If this second-order trend continues, the lower end of the IAEA's range for electricity demand in 2030 is more likely to be realized[331] and global electric consumption in 2050 would be roughly two thirds that assumed in the MIT scenarios.[332]

Lack of capital for nuclear-power investments in developing countries. Unlike dams and other infrastructure, nuclear power plants are not underwritten by the World Bank or most other international lending organizations. Nuclear energy is also not included in the Kyoto protocol mechanisms, under which the industrialized (Annex 1) states can obtain credits against their own greenhouse-gas emissions for investments that reduce emissions in developing countries.[333] The large investments required for nuclear power would therefore compete in developing-country budgets with investments for health, education, and poverty reduction.

Public acceptability. Simply to replace retiring nuclear capacity will require building a large number of new plants in the coming decades. Given continuing public skepticism about nuclear power, this may be challenging. An IAEA-sponsored opinion poll of 18 countries in 2005 found that about two-thirds of those expressing an opinion opposed shutting down nuclear power, but about the same fraction opposed building additional reactors. When asked specifically about the possible use of nuclear energy to combat climate change, only 38 percent expressed support for an expanded reliance on nuclear power.[334]

Nuclear Power and Climate Change

Nuclear power's environmental appeal is that it emits less carbon dioxide to the atmosphere than does coal or natural gas. When compared to an equivalent modern coal plant, 1 GWe of nuclear capacity operating at an average capacity factor of 90% reduces the amount of carbon released to the atmosphere by about 1.5 million metric tons annually.[335]

Total global carbon emissions to the atmosphere in 2006 from fossil fuels were approximately 7 billion metric tons per year. Assuming business as usual, emissions are projected to approximately double in 50 years (a 1.6 percent average annual growth rate). The deployment of an additional 700 GWe nuclear capacity by 2050—in place of building 700 GWe of modern coal-electric plants—would lessen projected emissions by one billion tons of carbon per year. If the rate of carbon emissions is to be stabilized and then reduced, other technologies will have to be deployed as well. These technologies will both complement and compete with nuclear power.

Energy efficiency is likely to be the most important. In the International Energy Agency's "Alternative Scenario"—in which governments adopt an array of policies to reduce greenhouse gas emissions—energy efficiency accounted for two-thirds of the potential emissions reduction by 2030.[336] Other studies of opportunities to reduce greenhouse gas emissions have reached similar conclusions.[337]

On the supply side, wind power and integrated gasification combined cycle (IGCC) plants burning coal with carbon capture and storage currently appear to be the most economically promising among the non-nuclear technologies that could reduce carbon emissions from electricity production.

Efficiency improvements in the power sector could also have a substantial impact.[338] In its business-as-usual scenario, the IEA estimated that coal-based electricity production would roughly double by 2030, with an average efficiency reaching about 40%. Today, the worldwide average efficiency of coal-based plants is below 30%, but newer coal plants have efficiencies up to 46%.[339] By 2030, efficiencies could reach 50% or higher.[340] Using technologies to shift the average efficiency of the world's coal-based plants from 40% to 45% in 2030 would save roughly the same amount of carbon emissions as would replacing 266 GWe of 50%-efficient coal plants with nuclear power, assuming both operated at a 90% capacity factor.[341]

At a national level, the average efficiency of China's 307 GWe of coal-fired plants was only 23 percent in 2004.[342] The IEA predicts an efficiency of about 37% in 2030. If this could be raised to 42% for the 1040 GWe of coal-fired capacity that China is expected to have online by 2030, that would save 3.5 times as much carbon as would the 31 GWe of nuclear capacity that the IEA expects China to deploy by then.[343]

Minimizing Proliferation Dangers from the Growth of Nuclear Power

The proliferation implications of an expansion in nuclear power depend primarily on what happens at the front and back ends of the nuclear fuel cycle. At the front end, where nuclear fuel is produced, the primary concern is the proliferation of national uranium enrichment plants. At the back end, the concern is the management of plutonium in the spent fuel.

The spread of national uranium enrichment plants. In 2006, global demand for uranium enrichment was 44 million SWU/yr. This enrichment demand was met almost entirely from enrichment plants in Russia, Western Europe, and the United States.[344] For the MIT scenario of 1500 GWe in 2050, in which virtually all new reactors would be light-water reactors, the annual enrichment demand would climb to 225 million SWU.

A five-fold increase in uranium enrichment capacity need not result in a corresponding increase in the risk of proliferation. The large enrichment enterprises in Russia, the United States, and Western Europe could increase their output to supply enough LEU to satisfy global demand. It is likely, however, that some countries—for reasons of energy security, technological pride, or interest in a nuclear-weapon option—would want to construct their own national enrichment facilities. Brazil and Iran are current examples. Future enrichment plants, like those being built today, would probably be based on gas centrifuges.

In some cases, a national centrifuge-enrichment capability may be justified on economic grounds. In industrialized nations, a modern centrifuge plant could be economically competitive at around 1.5 million SWU/yr capacity—enough to service about 10 GWe of light-water-reactor capacity.[345] In the MIT 1500-GWe scenario, approximately 20 countries are forecasted to have at least 10 GWe of nuclear capacity by 2050, including Indonesia, Iran, and Pakistan.

Economics are not likely to be a barrier, even in countries where a national capability would not be economically competitive, however, because the cost of nuclear power is relatively insensitive to the cost of enrichment. A doubling of enrichment costs raises the cost of nuclear electricity by only a few percent.[346] This could be acceptable to a country interested in acquiring a national capability to avoid fuel-supply disruptions, or for other non-economic reasons.

In 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 to ensure that states which do not already have enrichment plants have reliable access to civilian reactor fuel.[347] Other NSG member states, which had not sold either technology since India's nuclear test of 1974, agreed to continue their moratorium on exports on a year-to-year basis—but did not embrace the proposal of a permanent ban.

Indeed, President Bush's proposal may have triggered an unprecedented burst of interest in uranium enrichment capabilities. Concerned that the United States was trying to foreclose their future enrichment options, half a dozen non-weapon states announced an interest in building national enrichment plants in the near future.[348]

Mohammed El-Baradei, Director General of the IAEA, put forward an alternative proposal: to put fuel-cycle facilities under multi-national control and give fuel-supply assurances to countries foregoing national enrichment plants.

These and other proposals were discussed in a study commissioned by the IAEA,[349] and at an IAEA workshop in Vienna in September 2006.[350] In both venues, representatives of many countries made clear that they viewed any plan that created, or appeared to create, a permanent two-tier system of fuel-producer and fuel-purchasing states as unacceptable. One prominent ambassador participating in the expert study apparently spoke for many when he said:

> "Any system that is not perceived to be fair and aimed at universal rights is bound to fail and risks unraveling the whole structure of nonproliferation. … Limitations on technological development will need to be universal, not just for some and not for others."[351]

This suggests that, unless a generally accepted and non-discriminatory framework for the supply of fuel-cycle services through a small number of multinational enterprises can be developed, the spread of nuclear power is likely to stimulate more countries to acquire a national enrichment capability—and with it the option to produce weapon-grade uranium on short notice.

There is already a significant multinational presence in the global uranium enrichment market. The two largest suppliers of enrichment are Urenco and Tenex. Urenco is already multinational, co-owned by the Netherlands, the United Kingdom, and Germany.[352] The French Government owned conglomerate Areva now co-owns with Urenco the Enrichment Technology Company (ETC), which has been producing centrifuges for Urenco and now will do so for enrichment plants to be built in the United States and France.

Tenex markets Russia's national enrichment services. In 2006, President Putin proposed the creation of an international uranium-enrichment center in Russia to provide nuclear enrichment services on a non-discriminatory basis and under the supervision of the IAEA. More specifically, he offered to other countries the opportunity to become co-owners of a uranium enrichment plant at Angarsk.[353] Chapter 8 describes this initiative in more detail.

The problem of plutonium in spent fuel. At the back end of the fuel cycle, worldwide, about 10,000 metric tons of spent fuel containing approximately 75 tons of plutonium are discharged from reactors each year. To manage this material, two spent-fuel strategies are being used:

- Reprocessing of the spent fuel, with the separated plutonium either recycled in mixed-oxide fuel (MOX) for LWRs, or stored indefinitely for possible future use in fast breeder or burner reactors.

- Interim storage of the spent fuel with the object of either direct disposal in a geological repository, or of making a later decision between reprocessing or direct disposal.

France and Japan both plan to reprocess most of their spent fuel. France recycles its plutonium once and then stores the resulting spent MOX fuel to be reprocessed when fast-neutron reactors are commercialized. Japan plans to do the same. The United Kingdom has been reprocessing most of its spent fuel and storing the plutonium but plans to stop reprocessing around 2012 and not to reprocess the spent fuel from any future reactors.[354] Russia reprocesses a small percentage of its spent fuel and is storing the separated plutonium for future use in plutonium-breeder reactors.

A dozen countries that previously sent spent fuel to France, the United Kingdom, or Russia for reprocessing, have now switched or are switching to interim storage.[355] The United States adopted an interim-storage strategy in the late 1970s but is once again debating reprocessing owing to delays in the opening of its spent-fuel repository.[356]

In recent years, an average of approximately 2000 metric tons of spent fuel have been reprocessed annually. The total plutonium separated is about 20 metric tons per year. Approximately one-half of the separated plutonium has been recycled in MOX fuel in Europe.[357] This resulted in a savings of about 1300 tons of natural uranium per year—about 2 percent of world uranium demand.[358] Most of the remaining separated plutonium is being added to the stockpiles at reprocessing plants in the United Kingdom, Russia, and Japan.

The alternative to reprocessing is dry-cask storage.[359] The U.S. Nuclear Regulatory Commission has concluded that such storage would be safe and secure for at least 100 years and has licensed casks for 60 years.[360] Virtually every operating reactor in the United States either already has dry-cask storage, or has such storage under construction or planned.[361] The same is true in an increasing number of other countries with nuclear-power programs.

In comparing the costs of the two management options, two flows of material should be kept in mind:

- In the non-reprocessing alternative, all of the spent uranium fuel is put into dry-cask storage within about 20 years of discharge from the reactors; and

- With reprocessing and MOX recycling, the separated high-level waste (HLW) *and the spent MOX fuel* are stored indefinitely at the reprocessing plant.[362]

The MIT study estimated that the costs of storing and disposing of unreprocessed spent fuel to be about the same as storing and disposing of high-level wastes and MOX spent fuel.[363] This seems reasonable since the high-level wastes contain all the fission products and all the transuranics other than plutonium, and the spent MOX fuel still contains about 70 percent as much plutonium as fresh MOX fuel.[364] The French Government similarly estimated the "end of cycle" costs for the two fuel cycles as virtually the same.[365]

If the storage and disposal costs are assumed to be roughly equal, the economic comparison between the two alternatives is dominated by the reprocessing and MOX fuel fabrication costs less the saving of the cost of the LEU fuel that is replaced by the MOX fuel. In this comparison, the reprocessing costs far exceed the uranium and enrichment savings made possible by the use of MOX fuel. If, for example, uranium costs $130/kg, reprocessing costs $1000/kg, and MOX fabrication costs $1500/kg, then electricity generated with MOX fuel will cost roughly 2 cents per kilowatt-hour more than electricity generated with LEU fuel.[366]

In the longer run, advocates of reprocessing believe that a growing nuclear economy, rising uranium prices and limited waste repository space should persuade countries to move to closed fuel cycles based on a mix of light-water and fast-neutron reactors.[367] In the 1970s, this transition was projected for the 1990s. Today, however, even the advocates project it to be about 50 years away. Nevertheless, some countries persist in their reprocessing and fast-reactor programs despite the economic penalties associated with them. This is partly because of institutional inertia and local resistance to storing spent fuel at nuclear reactor sites.

The MIT study calculates the fissile-material flows for a 1500-GWe scenario with a mixture of LWRs and fast reactors. The plutonium and other transuranic elements fueling the fast reactors are obtained by reprocessing the spent fuel from all the reactors. In this scenario, about one thousand tons of plutonium are separated each year.[368] This plutonium would not be self-protecting, even if it were mixed with the transuranics.[369]

The once-through fuel cycle has the advantage that there is no nuclear-explosive material in the fresh fuel, and the plutonium in the spent fuel is left mixed with intensely radioactive fissile products. This provides a nearly intractable barrier to sub-national groups seeking to acquire fissile material from the civilian fuel cycle. Reprocessing, by contrast, puts huge quantities of separated weapon-usable plutonium into the civilian fuel cycle.

Conclusion

If nuclear power grew approximately three-fold to about 1000 GWe in 2050, the increase in global greenhouse-gas emissions projected in business-as-usual scenarios could be reduced by about 10 to 20 percent.

Even a modest expansion of nuclear power would be accompanied by a substantial increase in the number of countries with nuclear reactors. Some of these countries would likely seek gas-centrifuge uranium-enrichment plants as well. Centrifuge-enrichment plants can be quickly converted to the production of highly enriched uranium for weapons. It is therefore critical to find multinational alternatives to the proliferation of national enrichment plants.

If a large-scale expansion of nuclear power were accompanied by a shift to reprocessing and plutonium recycle in light-water or fast reactors, it would involve annual flows of separated plutonium on the scale of a thousand metric tons per year—enough for 100,000 nuclear bombs. Fortunately, while there are strong security reasons to avoid plutonium recycling, there appears to be no economic rationale for such recycling for at least 50 years.

8 Russia’s Nuclear-Energy Complex and its Roles as an International Fuel-Cycle-Services Provider

This chapter provides an overview of Russia’s nuclear energy complex as well as its roles as an international provider of nuclear fuel cycle services. Russia has a highly-developed nuclear-energy infrastructure, including a complete fuel cycle. Its excess enrichment capacity has allowed it to become a major international supplier of enrichment services, and President Putin has initiated the internationalization of one of Russia’s uranium enrichment centers. Russia has scaled back its interest in taking back foreign power-reactor spent fuel, however. Currently, it is willing to take back only fuel that it has supplied for Russian or Soviet-design reactors. Even there, as Russia increases its reprocessing charges and adopts the practice of shipping back, to the country of origin, the high-level radioactive waste from reprocessing, it is losing all of its foreign customers.

Russia’s Nuclear-Energy Complex

Nuclear power capacity. Russia has 31 commercial power reactors at 10 sites, with a total generating capacity of 21.8 GWe, (billion Watts) that provided about 16-17 percent of Russia’s electric power in 2006 (see Table 8.1). Four nuclear power units are under construction and projected to start operation between 2009 and 2012.[370]

The operating reactors are on average 60 percent through their currently licensed lives of 30 years. Russia’s nuclear power operator, “Rosenergoatom,” however, has developed a special program to extend the operation of Russia’s first and second generation pressurized water (VVER-440s) and graphite-moderated reactors (RBMKs) by up to 15 years.[371]

Nuclear Power Plant	Number Units & Reactor Type*	Generating Capacity [GWe]	Start of Commercial Operation**	Spent Fuel on Site as of 1 Jan. 2006 [metric tons]
Balakovo	4 VVER-1000	3.80	1986 – 1993	407
Beloyarsk	2 AMB***			192
	1 BN-600	0.56	1981	47
Bilibino	4 EGP-6	0.48	1974 – 1976	136
Kalinin	3 VVER-1000	2.85	1985 – 2006	189
Kola	4 VVER-440	1.64	1973 – 1984	116
Kursk	4 RBMK-1000	3.70	1977 – 1985	3808
Novovoronezh	2 VVER-440	1.77	1972 – 1973	745
	1 VVER-1000		1981	133
Rostov (Volgodonsk)	1 VVER-1000	0.95	2001	84
Smolensk	3 RBMK-1000	2.78	1983 – 1990	2240
Sosnovy Bor (Leningrad)	4 RBMK-1000	3.70	1974 – 1981	4240
Total	**31**	**21.8**		**12337**

Table 8.1. Russia's nuclear-power plants and their spent fuel.[372] *VVERs are pressurized-water reactors. RBMK, AMB and EGP are graphite-moderated, water-cooled reactors. BNs are sodium-cooled reactors. **Ranges are given for multiple unit power plants whose units started up over a span of years. ***Two AMB units at the Beloyarsk plant have been shut down and are now under decommissioning.

To expand and replace Russia's aging nuclear generating capacity, the Russian government and its nuclear agency, Rosatom, developed a program to build 42 new nuclear reactors by 2030 (see Figure 8.1).[373] On July 15, 2006, the Russian government formally approved funding for this construction program through 2015.[374] The central government has allocated 674.8 billion rubles ($24 billion), and Rosenergoatom, the agency in charge of the nation's nuclear plants, allocated another 796.6 billion rubles ($26 billion) through 2015.[375] Three new units are to be initiated in 2007[376] and, starting in 2009, construction on two new VVER-1200 units is to be initiated each year. Thus, the current plan is that, by 2015, ten new nuclear power units will be put into operation and construction will be initiated on an additional ten. The expansion program beyond 2015 must be considered uncertain, however, because Rosatom is supposed to find its own funding. This will be quite a challenge[377] and continuing government construction subsidies may be required—perhaps from the regional governments—if the plan is to come to fruition.

In the near-term, nuclear power in Russia is to be based primarily on light-water reactors (VVERs). Russia's confirmed uranium reserves could support about 100 GWe of LWR reactors through their 45-year lifetimes.[378]

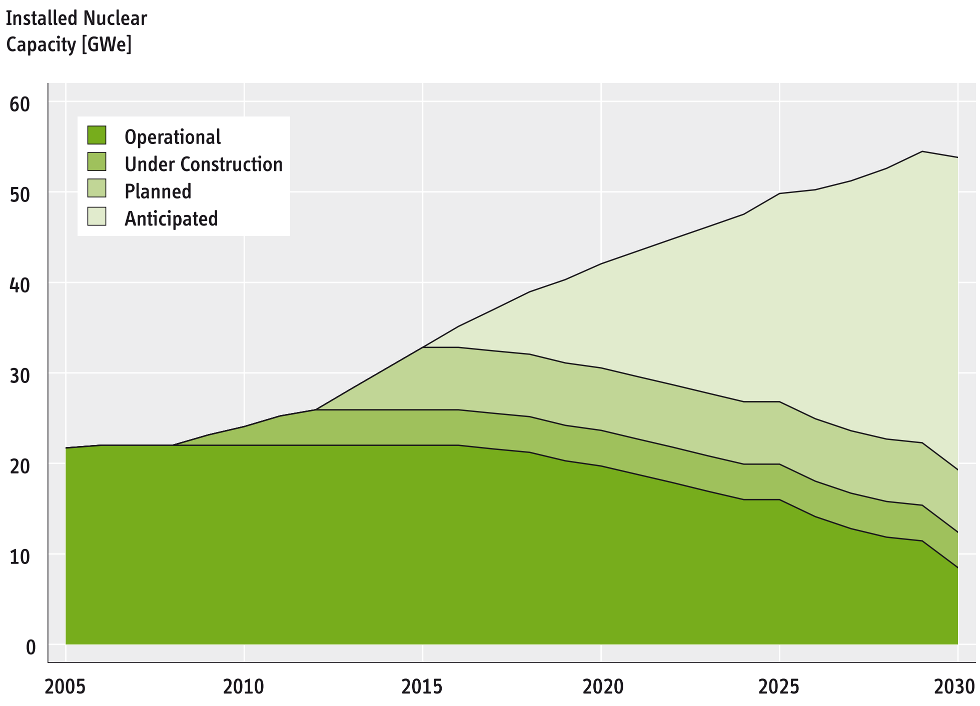


Figure 8.1. Current plans for Russian nuclear capacity growth.[379]

In the longer term, however, Russia's nuclear planners believe that the country's limited uranium supplies require the development of fast neutron plutonium-breeder reactors, operating on a closed fuel cycle. According to this strategy, large-scale construction of breeder reactors would start in 2030, preceded by construction sometime between 2020 and 2025 of a large VVER spent-fuel reprocessing plant that would provide plutonium to start up the breeder reactors. Rosatom is currently working to complete a 0.8-GWe semi-commercial breeder reactor (the BN-800), a Soviet project that began construction in 1984. Rosatom is also doing R&D on breeder-reactor fuel reprocessing and fabrication.[380]

Previous attempts elsewhere to commercialize breeder reactors have failed because of their high capital costs and maintenance problems associated with their liquid sodium coolants. Russia's 0.56 GWe capacity BN-600 has operated relatively successfully since 1981, however, despite many sodium leaks and fires.[381] The year 2030 is still far enough in the future so that there is not significant discussion among Russian nuclear planners about how high the cost of domestic uranium would have to climb to justify shifting to breeder reactors—or about the costs and benefits of having Russia's nuclear power plants fueled by less costly foreign uranium.[382]

In addition to building land-based nuclear power plants, Rosatom is building a prototype floating nuclear power plant with a capacity of 0.07 GWe to supply power to Russia's Artic Region and also for export. The floating power plant is equipped with two KLT-40S ice-breaker reactors. Rosatom proposes to complete seven floating nuclear power plants by 2015.[383]

Uranium enrichment complex. Russia has four gas-centrifuge enrichment plants. An interior view is shown in Figure 8.2. As shown in Table 8.2, the estimated total enrichment capacity of these plants at the end of 2006 was 26 million SWU/yr. Each generation of centrifuges has a somewhat increased enrichment capacity. All plants now operate using generation 5 to generation 8 gas centrifuges (see Figure 8.2) and are to be equipped with generation 7 and 8 centrifuges by 2010, when the installed separation capacity will have increased to a level of 28.2 M SWU/yr.[384]

Plant	Location	Capacity [million SWU/yr]	Enrichment limits [%]
Urals Electrochemical Combine	Novouralsk, Sverdlovsk region	12.45	up to 30
Electrochemical Plant	Zelenogorsk, Krasnoyarsk region	7.39	5
Angarsk Electrolyzing Chemical Combine	Angarsk, Irkutsk region	2.5	5
Siberian Chemical Combine	Seversk, Tomsk region	3.65	5
Total Capacity		25.99	

Table 8.2. Russian uranium enrichment plants and their approximate capacities as of the end of 2006.[385]

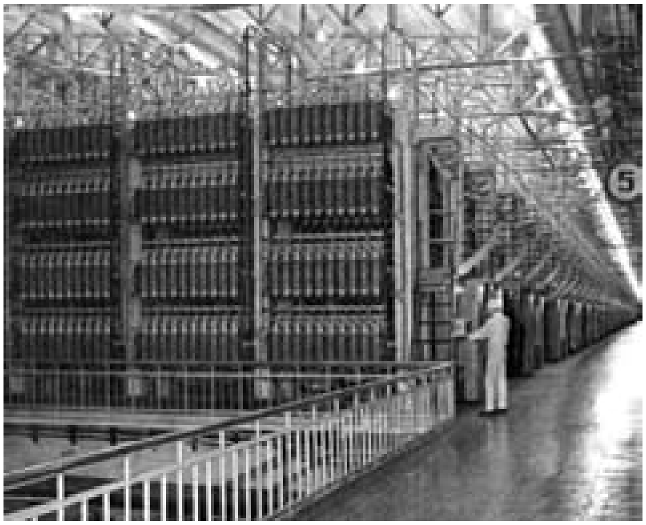


Figure 8.2. Centrifuge cascade in the Novoularsk centrifuge enrichment plant. Russian centrifuges are short and stacked on top of each other.[386]

Less than 40 percent of Russia's installed uranium-enrichment capacity is currently used to provide LEU for existing reactors of Russian design, in Russia and abroad. Another 20-25 percent (5.5 million SWUs/yr) is used to produce 1.5-percent enriched uranium for down-blending of excess weapon-grade uranium to 4–5 percent U-235 for use as power-reactor fuel in the United States. This capacity will become available for the production of LEU upon the completion of HEU blenddown program in 2013.[387] The remaining 40 percent or so of Russia's enrichment capacity is used to enrich natural uranium and re-enrich reprocessed uranium for European customers, and to extract the equivalent of additional "natural" uranium from depleted uranium (see Figure 8.3).[388]

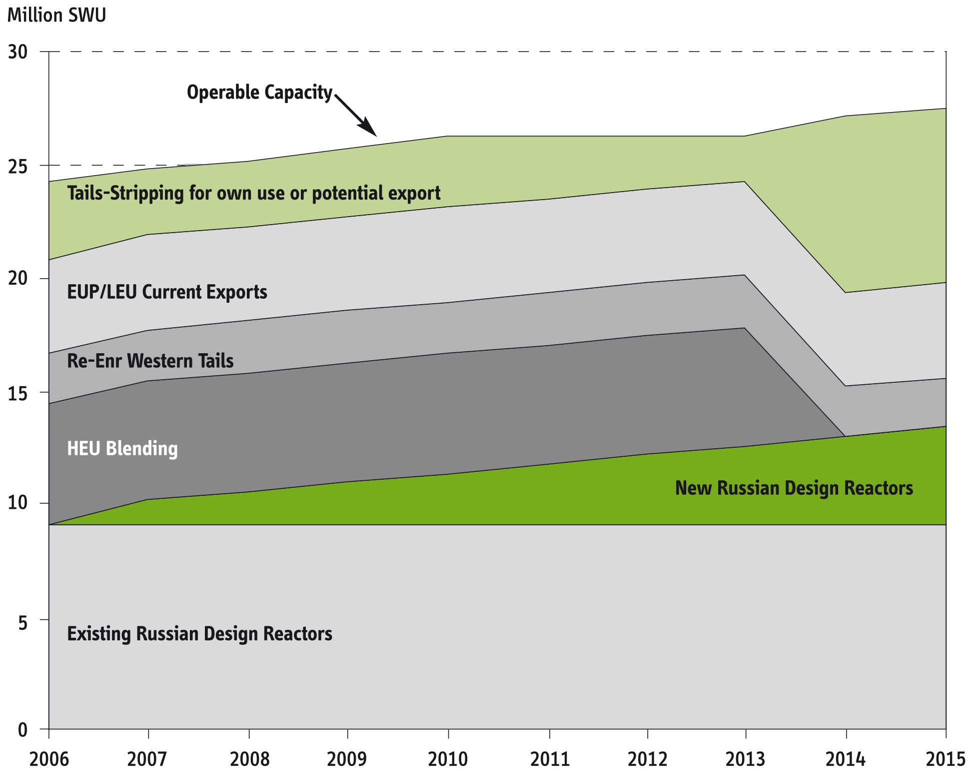


Figure 8.3. Russia's SWU capacity and its estimated allocation. [Data courtesy of Nukem Market Report, April 2006]

Fuel fabrication services. Russia's fuel-fabrication provider TVEL is a conglomerate of four companies that produces fuel for 76 reactors and also mines uranium. TVEL produces about 1000 tons of fuel per year but has a fabrication capacity of about 2000 tons per year.

Spent fuel management services. Russia reprocesses the fuel discharged from its remaining VVER-440s and the prototype, sodium-cooled BN-600 reactor (together totaling about 15 percent of its power-reactor capacity) plus the HEU fuel discharged by its naval and research reactors. This fuel is reprocessed in the Urals, at the Mayak Production Association RT-1 facility. Spent fuel from VVER-1000 reactors—which constitute 35-percent of Russia's nuclear-generating capacity—is shipped to a large storage pool at the Siberian Mining-Chemical Combine near Krasnoyarsk, which was originally supposed to be a part of a second, much larger, but never completed reprocessing plant, RT-2. Spent fuel from Chernobyl-type RBMK power reactors—50 percent of Russia's nuclear capacity—is stored in pools at the nuclear power plants.

In recent years, the RT-1 plant has reprocessed no more than 150 metric tons of spent fuel per year.[389] With the installation of storage racks, in which the spent fuel assemblies are stored with less space between them, the RT-2 pool capacity has been increased from 13,416 VVER-1000 fuel assemblies (about 6000 metric tons) to 8600 metric tons. At the end of 2006, the pool was approximately 50-percent full.

The pools at the RBMK nuclear power plants are almost full. In 2003, the Federal Atomic Energy Agency, therefore, started to build a huge dry-cask spent fuel storage facility for RBMK fuel at the RT-2 site. Its design capacity is 37,785 metric tons: 26,510 tons for RBMK-1000 fuel and 11,275 tons for VVER-1000 spent fuel. It is expected that the first storage unit (for 5082 metric tons of RBMK-1000 fuel) will be put into operation during 2009.[390]

Reconsolidation of Russia's civilian nuclear complex. In April 2007, President Vladimir Putin signed a decree consolidating Russia's civilian nuclear activities into one state-owned company, Atomenergoprom.[391] Atomenergoprom will be a giant company with the mission of competing in the global nuclear market with other industry giants such as France's AREVA. It will also try to attract investments to help expand Russia's domestic nuclear power production capacity.[392]

Atomenergoprom will own the nuclear fuel fabricator, TVEL; Russia's enrichment plants; its nuclear power plants (Rosenergoatom); the state-owned uranium trader, Tekhsnabexport (Tenex);[393] the companies that build nuclear power plants at home and abroad (Atomenergomash and Atomstroiexport); and a number of nuclear-energy R&D institutes.

On October 12, 2006, Russia and Kazakhstan signed an agreement to join their efforts in the nuclear-energy sector.[394] Kazakhstan, whose known uranium resources are larger than those of Russia,[395] will dominate the collaboration in the areas of uranium mining, milling and processing. Uranium enrichment will continue to be done only in Russia, and fuel fabrication, in both countries. In June 2007, Sergei Kiriyenko, head of Rosatom, announced that 5 million SWUs/yr of enrichment capacity would be added at Angarsk to enrich uranium from Kazakhstan.[396]

Russia as an International Supplier of Fuel Cycle Services

Enrichment. Russia is a major international supplier of enrichment services, see Figure 8.4.

Russia has also been quite active in the international effort to stem the spread of national uranium enrichment plants, which has recently focused on trying to persuade Iran to suspend the construction of its Natanz enrichment plant. In this context, in 2006, President Putin proposed to offer other countries the opportunity to become co-owners of one of Russia's uranium enrichment plants, which is to operate under IAEA monitoring[397] and provide non-discriminatory access to LEU for civilian fuel.[398]

The Angarsk enrichment plant, which has never produced HEU, was selected by Rosatom as the site for this international enrichment center. It currently has the smallest capacity of Russia's enrichment plants with a capacity of only 2.6 million SWU/yr, but, including the new capacity associated with the Russian-Kazakh joint venture and additional proposed expansion, it could reach 10 million SWU/yr by 2015.[399] Foreign shareholders will have a right to participate in the center's management, including access to all information about prices and contract provisions. They will also be able to contract for deliveries of enriched uranium or enrichment services, and receive a share of the profits. They will not, however, have access to enrichment technology.[400] In order to ease foreign access to the center, the Russian government has removed the Angarsk plant from its list of restricted areas.[401]

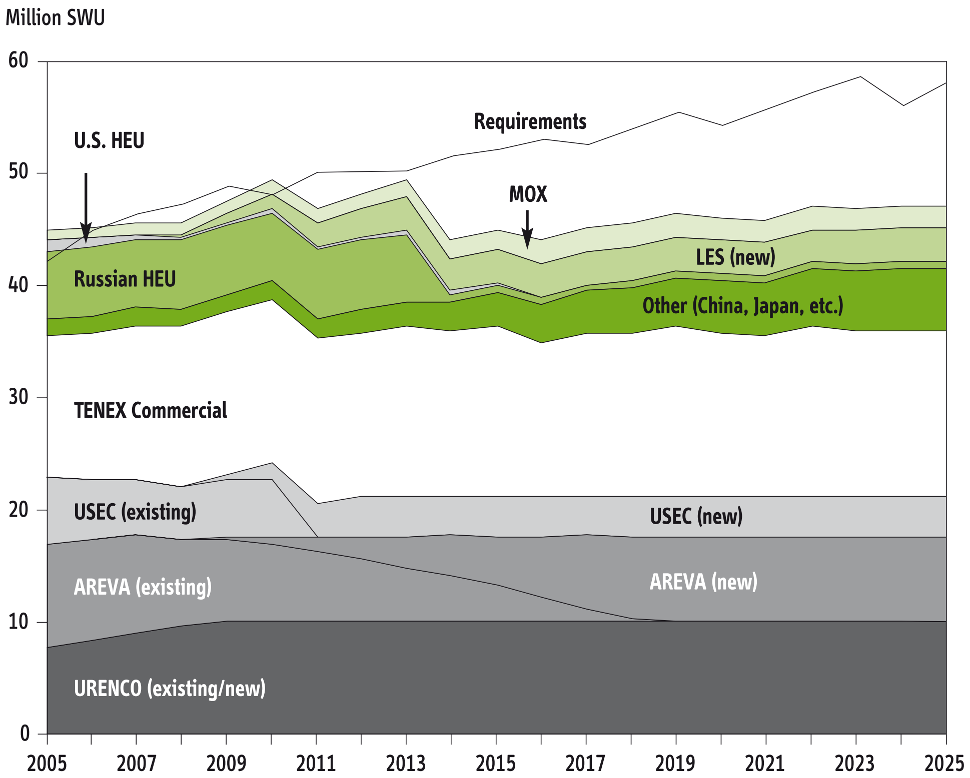


Figure 8.4. Projected global enrichment demand and supply. TENEX markets Russia's uranium-enrichment services and the LEU produced by blending down its excess weapon-grade HEU. Russia has the capacity to fill most of the gap shown here between projected supply and demand. URENCO is co-owned by Britain, Germany and the Netherlands. AREVA is France's nuclear conglomerate. USEC is the U.S. Enrichment Corporation. LES is a commercial plant with URENCO technology being built in the United States. MOX shows the modest projected savings of enrichment work as a result of plutonium recycle.[402]

Fuel fabrication. As of the end of 2006, MSZ, in Elektrostal, had produced more than 1000 fuel assemblies, containing about 500 tons of re-enriched reprocessed uranium for European utilities in Germany, Sweden, Switzerland, and the Netherlands, using equipment supplied by the French company AREVA.[403] TVEL has also restored its monopoly in supplying fuel for Russian-designed reactors by signing contracts to supply fuel for the two Czech VVER-1000s at Temelin and for the two Finnish VVER-440s at Loviisa.[404]

Spent fuel take-back policy. Russia, and previously the Soviet Union, have long had a policy of taking spent fuel back if it is of Russian origin and irradiated in Soviet and Russian-designed reactors. During Soviet times, spent fuel from VVER-440 reactors in Bulgaria, the Czech Republic, Finland, East Germany, Hungary and the Slovak Republic was shipped back to the Soviet Union for reprocessing. Today, however, only the Ukraine and Bulgaria ship spent fuel to Russia, about 220 tons and 40 tons a year respectively.[405] VVER-440 reactor fuel is reprocessed at RT-1, while VVER-1000 fuel is stored in the RT-2 storage pool.

Because of the rising price of Russia's spent-fuel services, however, and Russia's requirements under new reprocessing contracts to ship back the vitrified high-level waste from reprocessing, the Ukraine, and Bulgaria too, are making other plans.[406] In 2001, the Ukraine brought into operation its first dry-cask spent-fuel storage facility at the Zaporozhskaya nuclear-power plant, and, in 2005, the Ukraine's nuclear utility, Energoatom, announced a tender for construction of a second common dry storage facility for the South-Ukrainian, Rivnenskaya and Khmelnitskaya nuclear-power plants.[407] Bulgaria is building a dry storage facility near its Kozloduy nuclear power plant.[408]

In the late 1990s, when Russia's Ministry of Atomic Energy (MinAtom) was struggling financially, its Minister, Eugene Adamov, seized on the idea of taking non-Russian origin spent fuel for storage in Russia. It was estimated that the import of 10,000 tons of spent fuel could bring in $20 billion worth of foreign exchange. Public opinion in Russia was very strongly against the import of spent fuel from other countries, but, in 2001, as a result of Minatom's lobbying, Russia's Duma passed federal laws that allowed the import of spent fuel into Russia "for temporary technological storage and (or) reprocessing." The laws require that the agency reserve the "right to return radioactive wastes resulting from reprocessing to the country of origin of the spent fuel." They also require that some of the income from the reprocessing of foreign spent fuel be spent on the environmental rehabilitation of areas in Russia that have been radioactively contaminated by military and civilian reprocessing.[409] Subsequently, a number of regulations for the operation of storage facilities and reprocessing plants for the transport of spent fuel and for managing the radioactive wastes created as a result of reprocessing, were put into effect.

Despite the enabling legislation and regulations, however, Minatom's successor agency, the Federal Atomic Energy Agency (Rosatom) has not contracted with any new customers to import spent nuclear fuel. The potential customers that had been mentioned most frequently by Minatom were Taiwan and South Korea. Both countries have large quantities of spent fuel that they would like to get rid of. But the United States has "consent rights" on transfer to any third country of all Taiwanese and most South Korean spent fuel, and requires assurance that the spent fuel will not be reprocessed without its permission. Since Russian law requires eventual reprocessing or return of any imported spent fuel, and Rosatom is not interested in providing interim storage of foreign spent fuel, U.S. prior consent would be required. It is conceivable that the United States might eventually give such consent if Russia promised that it would not return the separated plutonium to Taiwan and South Korea, but, based on the history of U.S. prior consent agreements for reprocessing in Europe and Japan, many years of negotiation would be required. Canada, which supplied South Korea with four CANDU reactors, has similar consent rights on transfers of their spent fuel.

A second reason for Rosatom's reconsideration of the idea of importing foreign spent fuel was that it could saddle Rosatom with potentially huge financial liabilities. Arrangements have been discussed, under which Russia would have the right to return spent fuel to its foreign owners after providing interim storage, but their execution could excite the same concerns in the population of the owning country that motivated the arrangements for export of the fuel to Russia in the first place. Such arrangements are therefore unattractive to both sides.

Finally, the idea of importing foreign spent fuel has excited opposition from a large spectrum of Russia's social and local constituencies. Rosatom's current management, unlike that of Minatom, is reluctant to initiate nuclear projects against public opinion.[410] Therefore, on July 11, 2006, Rosatom's head, Sergei Kirienko, announced in Russia's reprocessing center, Ozersk, that "Russia has not imported foreign spent fuel, is not importing and will not import it in the future."[411]

Nevertheless, Russia will continue to be willing—indeed eager—to take back Russian-origin spent fuel. The Russian-Iran contract assumes that all spent fuel from the Bushehr nuclear power plant will be returned to Russia. Russia is willing to negotiate the same arrangement with India, for the spent fuel from the two reactors being constructed by Rosatom at the Kudankulam power station. In theory, Russia could expand that program to include Russian-origin fuel irradiated in non-Russian-design reactors. The legislation that was approved in 2001 allows Rosatom to lease fresh fuel to foreign customers, and keep title to it, thereby changing its status from "foreign" to "domestic." For the moment, however, Russian spent-fuel take back is limited to spent fuel from Russian or Soviet exported reactors—and, even that is becoming more the exception than the rule.

Conclusion

Russia operates only about 6 percent of the world's nuclear generating capacity—but owns about half of the world's uranium-enrichment capacity. It has therefore, become a major international provider of enrichment services. Russia also fabricates fuel for all Soviet and Russian designed power reactors, as well as for some Western PWR and BWR reactors, and has become a fierce competitor for the construction of power reactors in the developing world.

In the late 1990's, it was anticipated that Russia might also become a major international supplier of spent-fuel services by taking other countries' spent fuel for eventual reprocessing. The lack of new foreign customers; public opposition and other complications resulted in Russia reconsidering its plans. It has decided not to expand its customer base for spent fuel storage and reprocessing services beyond the Soviet/Russian design reactors for which it supplies fuel. Also, as Russia's reprocessing fees have increased, and it begins to ship back high-level waste to its existing foreign reprocessing customers, most of them have decided to shift to domestic spent-fuel storage. Russia, therefore, will soon be importing very little foreign spent fuel for either storage or reprocessing.

9 Detection of Clandestine Fissile Material Production

One of the greatest challenges in the verification of the current nuclear nonproliferation regime is to detect clandestine production of significant quantities of fissile materials. The Additional Protocol, introduced in 1997 by the International Atomic Energy Agency (IAEA), was developed to meet this challenge. It sought to do so mainly by increasing the quantity and quality of data voluntarily reported by states, and by giving the agency extra investigative rights.

The Additional Protocol provided the agency with two specific tools to facilitate detection of covert fissile material production, wide-area environmental sampling (WAES), and location-specific environmental sampling.[412] These allow the IAEA to collect samples of air, water, vegetation, soil, and surface residues (swipes) to search for indicators of clandestine activity. While the agency currently uses location-specific sampling, wide-area environmental sampling has not been used and would require the prior consent of the IAEA Board of Governors.[413] Procedural arrangements also would have to be developed.

This chapter examines some of the technical methods and constraints on using environmental sampling for the detection of undeclared facilities in a large region, and to detect undeclared production at known facilities. For example, the latter could be implemented outside of military facilities into which the owning government was reluctant to allow international inspectors. We call this "stand-off verification" (SOV). Such techniques could also be used to verify a future Fissile Material Cutoff Treaty (FMCT).

Current Capabilities

The IAEA currently uses a number of techniques to detect clandestine activities. We review them briefly here and give a summary in Table 9.1.

Surface swipes are the only kind of environmental samples currently taken by the IAEA. Over the past ten years, these have become a key tool for the detection of undeclared HEU and plutonium production. Approximately 800 to 1000 surface-swipe samples are taken per year and analyzed by the IAEA for residues from such activities.[414] In some cases, it is even possible to determine the age of uranium or plutonium particles.[415] Particles can also reveal the existence of undeclared activities elsewhere, if they come from workers or equipment that was transferred from another site.

Satellite imagery is another well-established method for identifying nuclear activity.[416] Visible-light imagery can monitor facility construction and demolition activities at known sites, as well as monitor the operation of nuclear reactors equipped with vapor-emitting cooling towers. Satellites capable of thermal-infrared imaging also can be used to detect hot water flowing into rivers, or the ocean, from nuclear reactors.[417] Satellite technology cannot, however, discover uranium enrichment when performed by gas centrifuges, or reprocessing. This capability gap could be filled if there were an environmental sampling method capable of detecting such activities.

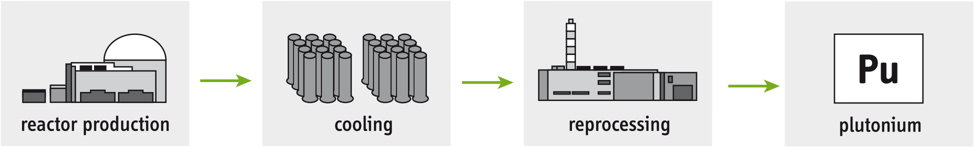


Figure 9.1. Plutonium production and separation. Reactors are readily detected, making undeclared plutonium production difficult when appropriate safeguards are applied to monitor the inventory of spent fuel in cooling ponds.

Detectability (Selected Technologies)					
		Satellite Imaging		Environmental Sampling	
		Visible Imagery	Thermal Imagery	SOV	WAES
Plutonium Production	Reactor	Yes	Yes	Yes	Yes
	Reprocessing	No	No	Yes	Large scale only
HEU Production	Conversion	No	No	Yes	Large scale only*
	Calutron/EMIS	No	Yes	Yes	No
	Gaseous Diffusion	Yes	Yes	Likely*	No
	Centrifuge	No	No	Unlikely	No

Table 9.1. Current ability to detect remotely various stages in the production of weapon-usable fissile materials. Note that the plutonium route is subject to detection by at least one established technology, whereas the production of HEU with centrifuges can escape detection entirely. An asterisk indicates that the conclusion is based on models.

Wide-Area Environmental Sampling

The most promising implementation of WAES is to detect in the atmosphere, far downwind, substances emitted from facilities engaged in the production of fissile materials. Once detected, attempts can be made to trace the effluent back to its approximate origin using meteorological data.

One implementation of WAES is to create a network of detectors that is permanently deployed over a large region to detect the presence of any undeclared activity. A second is to deploy a smaller, ad-hoc network in a region where undeclared activity is suspected on the basis of other indicators. A third approach would be to take samples at random locations and at random times in such a way that the probability of detection is low but perhaps sufficient to create a deterrent effect.

The limitation on these methods is that, as emissions travel through the atmosphere, they become more and more dilute with distance, and at some distance become too dilute to detect with confidence. This maximum detection distance establishes the density of detectors required to cover any given area and thus the cost. Figure 9.2 shows the impact of maximum detection distance on detector density. It also illustrates the substantial infrastructure requirements for large area coverage with detection ranges of 100 and even 300 km.

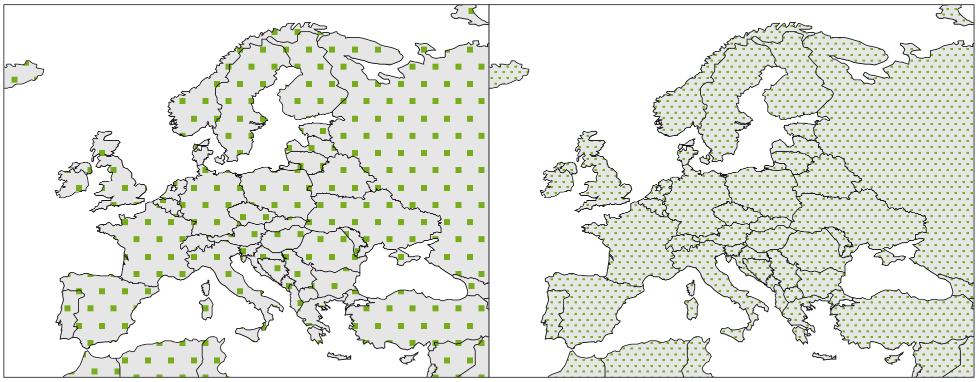


Figure 9.2. Maps showing hypothetical detector networks for a maximum detection distance on the order of 300 km (left) and 100 km (right). A three times increase in detection distance would reduce the cost of the network nine-fold while keeping the probability of detection approximately constant.

For a large network of fully automatic stations, the costs would be on the order of one million U.S. dollars capital cost, and $0.1–0.5 million operating cost per station per year. A more affordable implementation for the near term would be small ad-hoc networks or SOV installations in regions where clandestine activities are suspected.

Once detected, it is necessary to try to trace a detected plume backwards to discover its possible origin by calculating the "retro-plumes" for the detecting stations and stopping the simulation at an appropriate time. Various approaches have been used to derive a probable source region and source time from multi-station detection and non-detection data.[418]

Krypton-85 as an Indicator of Undeclared Plutonium Separation

The fission product krypton-85 is generated along with plutonium in reactor fuel. It has a half-life of 11 years and is released during reprocessing. Because it is a chemically inert "noble" gas, it is difficult for a plant operator to filter krypton out from the plant's emissions.[419] Because of krypton-85's relatively long half-life, a global background has accumulated in the atmosphere from past reprocessing. Figure 9.3 shows the calculated global krypton-85 distribution in July 1987, based on an atmospheric-transport model using actual and estimated emissions from the large-scale reprocessing facilities that were operating at that time.

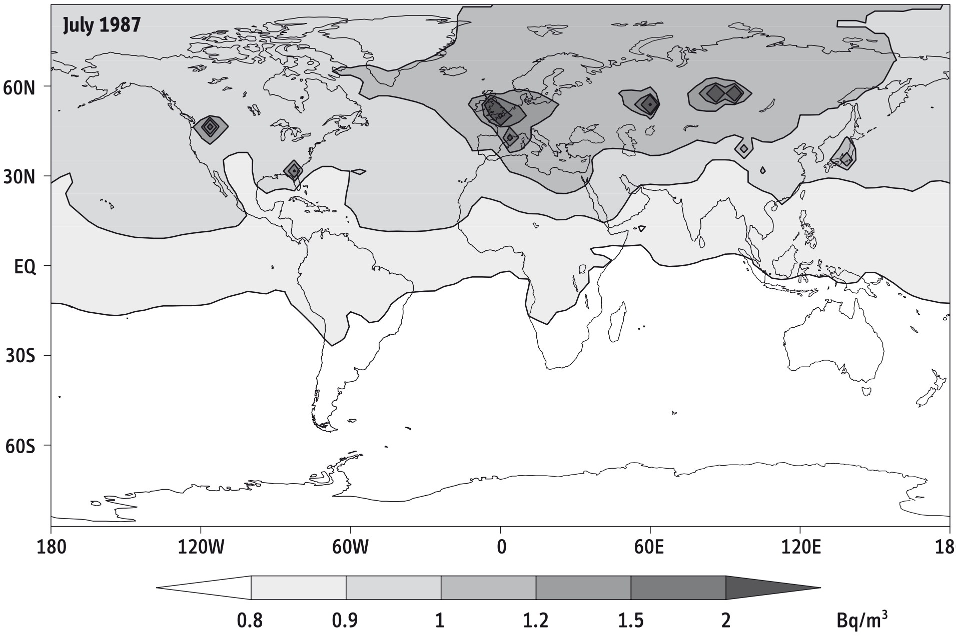


Figure 9.3. Calculated surface concentrations of krypton-85 in July 1987. These values are based on a global atmospheric-transport model, with source information based on actual and estimated emissions from the several large reprocessing facilities that were operating at the time.[420]

The krypton-85 background is of critical importance because it will determine the threshold at which a plume from a small reprocessing plant could be detected. Although krypton-85 is removed from the atmosphere by radioactive decay at a rate of 6.6 percent per year, the background is slowly increasing because the global release rate from commercial reprocessing outpaces the decay rate, as shown in Figure 9.4. Moreover, if a large overt reprocessing plant is present in the region, its plume will create variations in the background that are difficult to predict. Five major reprocessing plants contributing plumes shown in Figure 9.3 have since shut down or will do so soon.[421]

Detectability of krypton-85 plumes. We describe here two experiments—one in Japan and one in Germany—in which krypton-85 samples were collected over a period of years near a small reprocessing plant.

Tokai Pilot Reprocessing Plant, Japan. Krypton-85 releases were monitored at the Tokai Reprocessing Plant in Japan between 1995 and 2001. At the same time, the Meteorological Research Institute in Tsukuba, located 60 km to the southwest, measured week-long averages of the krypton-85 concentration in the air. Figure 9.5, which shows both the release (above the axis) and detection data (inverted below the axis), clearly demonstrates the strong correlation of the larger peaks.

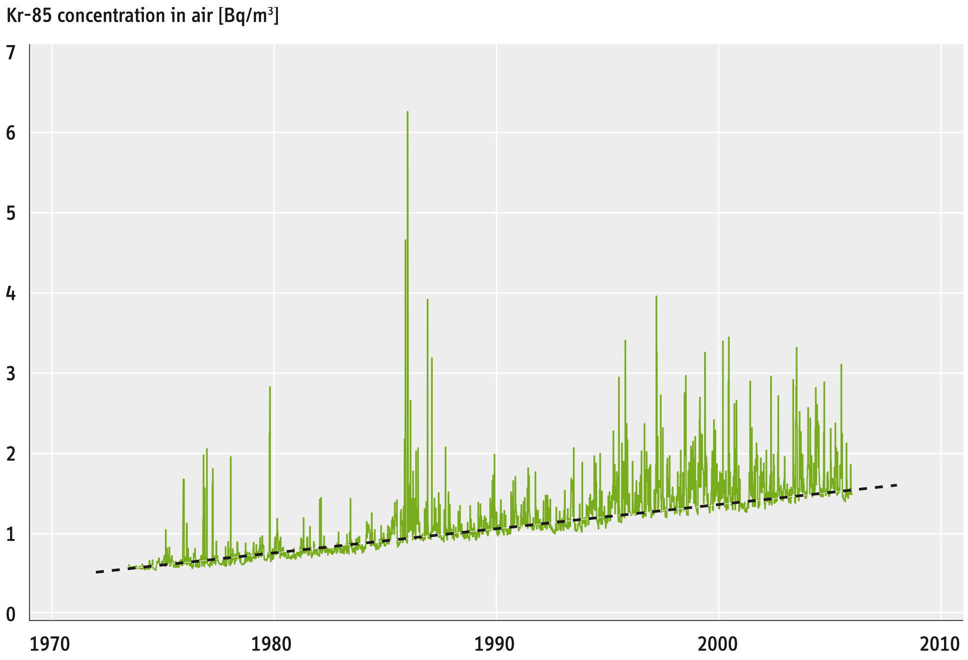


Figure 9.4. Krypton-85 plumes from regional reprocessing and from the Chernobyl accident on top of a rising global background at a European site. The figure shows data for a sampling site in Freiburg, Germany, which is 735 and 1,065 kilometers from the major reprocessing plants at La Hague, France and Sellafield, United Kingdom respectively. The plumes from these plants would make it more difficult to identify a small plume of krypton-85 from covert plutonium separation in Western Europe. The strongest peak in the plot is due to the release of krypton-85 caused by disruption of the reactor core of Chernobyl unit #4 at the end of April 1986. Over the four decades shown, the concentration of krypton-85 increased at a rate about 0.35 Bq/m^3 per decade. [Data courtesy of the German Federal Office for Radiation Protection (BfS)]

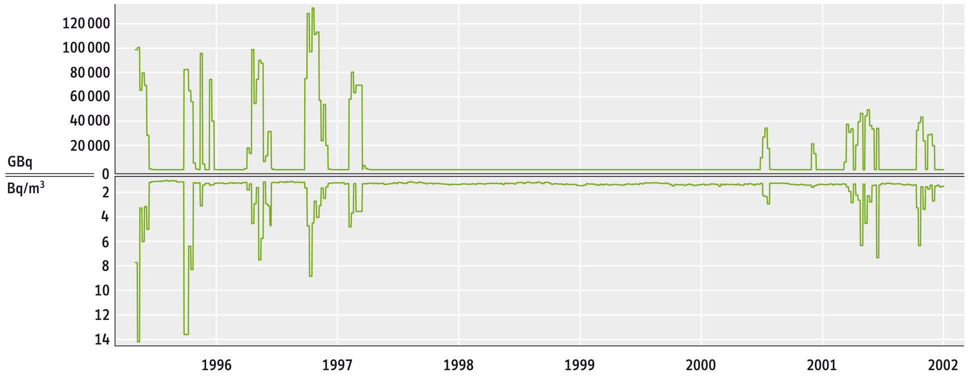


Figure 9.5. One-week average atmospheric Kr-85 concentrations measured at Tsukuba, Japan, 1995–2001. The spikes above the axis show krypton-85 releases from Japan's Tokai Reprocessing Plant. The inverted spikes, below the axis, show the results of measurements of Kr-85 concentrations in the atmosphere at Tsukuba, 60 km away. No spikes were detected in Tsukuba between April 1997 and July 2000 when the Tokai plant was closed down. [Data courtesy of C. Schlosser and H. Sartorius, German Federal Office for Radiation Protection (BfS)]

A statistical analysis of the data indicates that the hypothetical separation of one significant quantity (8 kg) of weapon-grade plutonium over a period ranging between 1 and 190 days at the Tokai Reprocessing Plant could be detected with a high probability at Tsukuba, 60 km away. For a longer separation period (i.e., slower separation rate), the krypton concentrations drop below the detection threshold (see Figure 9.6).[422]

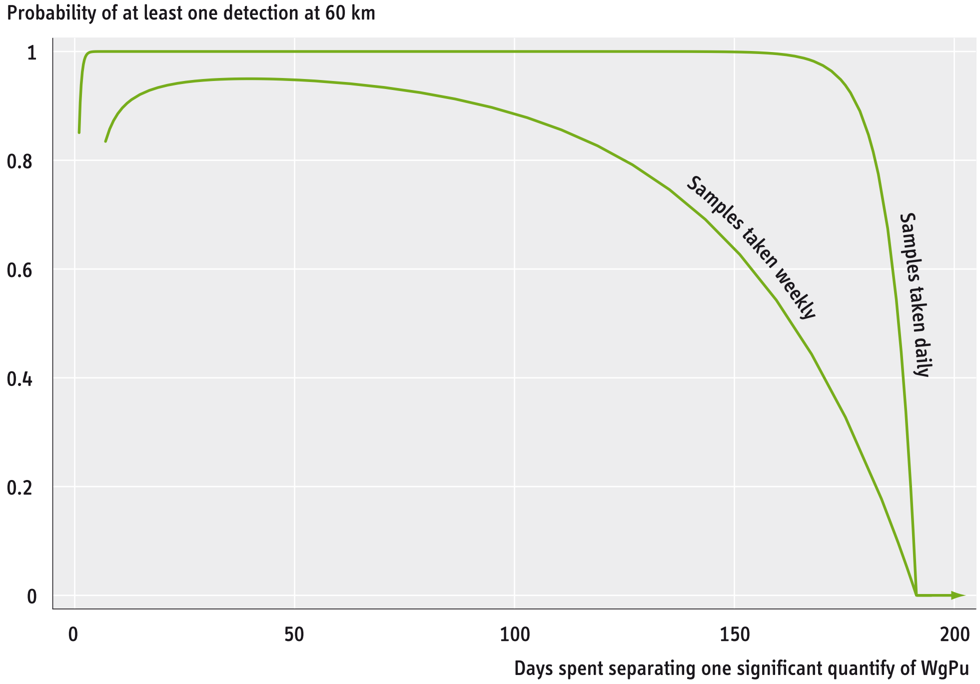


Figure 9.6. Estimated cumulative probability of detecting plutonium separation at the Tokai plant with detectors located 60 km away in Tsukuba during the period of 1995–2001, when there was no large reprocessing plant operating in the region. The curves give the overall probability that a single station detects the separation of 8 kg of weapon-grade plutonium at least once, as a function of the days spent on the effort, assuming the krypton is evenly released over the duration of the campaign. The curve falls off toward the right, because as the time over which the krypton-85 is released grows longer, its concentration in the plume becomes smaller and less detectable. The curve also falls off toward the left, because as the time spent releasing krypton becomes very short, there is an increased chance that the winds blow away from the detector. The upper curve represents the probability of detection for daily samples, and the lower curve for weekly samples. The detection threshold was set to practically eliminate false alarms (4 standard deviations above the mean background variation).

The sensitivity of wide-area environmental sampling is strongly affected, however, by the variability of the local krypton-85 background. The measurement conditions in Japan were particularly favorable during 1995 to 2001 because no other reprocessing plants were operating in the region at that time, and as a result, the krypton-85 background was fairly smooth. In 2006, the large Rokkasho Reprocessing Plant began operating in northern Japan.

Karlsruhe Pilot Reprocessing Plant, Germany. Even though the background concentration of krypton-85 is more variable in areas where large commercial reprocessing plants are operating, a German case study, which was within the area affected by the large krypton-85 plumes from the reprocessing plants in France and the United Kingdom, demonstrated that the detection of a small reprocessing facility is still possible under these conditions. For a period of two and a half years during 1985 to 1988, weekly air samples were taken at various distances downwind in the prevailing wind direction along the Rhine Valley from the pilot reprocessing facility in Karlsruhe (Wiederaufarbeitungsanlage Karlsruhe, WAK).[423]

Plutonium separation at a rate of about 4 kg per week was detected, with a probability of 70% in weekly air samples taken at a distance of 5 km; 40% at a distance of 39 km; and 15% at 130 km distance in the opposite wind direction (up the valley). The derived detection limits were the production of 40 g/week of weapon-grade plutonium for a detector placed at 5 km distance; 200 g/week at 39 km; and 1000 g/week at 130 km. These results were obtained, however, for a high false-alarm rate. Up to five percent of the detections occurred when there was no release from the Karlsruhe plant. These were most likely due to the background plumes from the French or U.K. reprocessing plants.

Location-specific environmental sampling (stand-off verification). The above-mentioned experiments show that krypton-85 emissions could be used in a stand-off-verification mode to determine, non-intrusively, whether reprocessing was ongoing at a known facility. For the WAK reprocessing plant, the detection rate for the separation of 4 kg of plutonium per week was found to be as high as 80–90% at a distance of less than 1 km outside the fence of the facility. The minimum krypton-85 concentration that could have been detected at this distance was the equivalent of 2 grams of weapon-grade plutonium per week. Care has to be taken in choosing a suitable distance from the stack in order to assure that the plume touches the ground before traveling past the sampling site even with stable atmospheric conditions.

Figure 9.7 shows a small reprocessing facility, at the Dimona site in Israel, and the size of the secure area outside of which krypton detectors might be installed, given a stand-off-verification agreement.

IKONOS satellite imagery courtesy of Space Imaging Middle East/GeoEye
Image date: 26 Jan 2002

Figure 9.7. The Dimona nuclear complex in Israel. The on-site reprocessing plant has an estimated capacity of about 40–100 tons of spent fuel per year. The stack (revealed by its shadow) out of which krypton-85 would most likely be released, is marked by the white ellipse. The area enclosed by the dashed boundary, about 1000 meters at its widest point, indicates the fence of the secure area outside of which stand-off verification detectors could be placed. Based on the findings of the WAK case study, a few detectors located beyond the fence could make it virtually impossible for undeclared plutonium separation to evade detection over time.

Detection of Undeclared Uranium Enrichment

The large size and energy demand of uranium enrichment by gaseous diffusion makes it very amenable to detection using satellite imagery.[424] However, gas centrifuges are now the most modern, economical, and widespread enrichment technology in operation, and are expected to remain dominant into the foreseeable future.

In contrast to plutonium production, none of the steps leading up to and including centrifuge enrichment are reliably detected by satellite imagery (see Figure 9.8).[425] Wide-area environmental sampling, therefore, would be particularly valuable if it could detect undeclared HEU production.

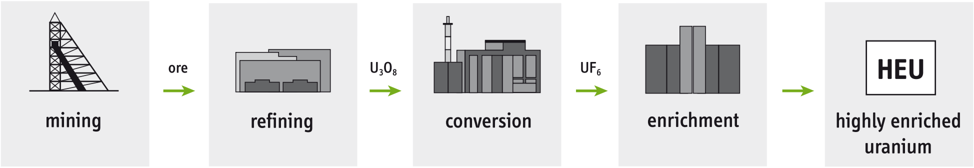


Figure 9.8. HEU production pathway. Unlike plutonium production, the steps involved in the production of HEU do not lend themselves to established methods of detection, thereby making it particularly important to determine the possibility of detecting HEU production with location-specific or wide-area environmental sampling.

Uranium source terms. From Urenco data, it appears that the emissions from a large-scale centrifuge plant can be kept very low. The alpha activity in the exhaust air of Urenco's enrichment plant at Gronau, Germany is equivalent to the release of 2.0 grams of natural uranium per year. The Gronau environmental report states that this release primarily represents material that is already present in the local atmosphere and was sucked in and "re-emitted" by the plant. Further contributions are associated with the tails-storage area. At the fence of the site, however, the uranium concentration in the air is down to the background level in the region.[426]

Therefore, it is not surprising that an IAEA-sponsored study concluded that, if one used traditional methods that are insensitive to the chemical form of uranium, the plume from a small clandestine enrichment plant would be lost in the background noise at significant distances.[427]

An alternative approach, however, would be to look instead, for molecules containing both uranium and fluorine, specifically, molecules of uranyl-fluoride (UO_2F_2), which are produced when UF_6 gas that has leaked from a plant reacts with moisture in air.[428] This would distinguish uranium released from an enrichment program from the ubiquitous background of natural uranium.

Clandestine UF_6 production plants, also called "conversion" plants, would be easier to detect than uranium-enrichment plants. Little UF_6 leaks out of a centrifuge enrichment plant because the gas in the centrifuges is at less than atmospheric pressure. Conversion plants operate at high pressures, however, and typically release more—although still not very much—UF_6 to the atmosphere, per unit of throughput. A modern conversion plant is estimated to release about 20 grams of the 6 tons or so of natural uranium in UF_6 feed that would be required to produce enough weapon-grade uranium for a nuclear explosive (roughly 25 kg).[429]

The range at which effluents from conversion plants might be detected depends critically on the sensitivity of the detectors. Since no technology has been developed for the purpose of detecting UO_2F_2 or other UF_6 degradation products, the range of possible sensitivities remains unknown. Typical detection sensitivity limits for chemicals in airborne particles range from the sub to single part per billion levels. Figure 9.9 shows a sample plot for the theoretical ranges at which a plant releasing one gram per day would be detectable, assuming different sensitivities, and a total suspended solids level typical of cities.[430]

Figure 9.9. Equal concentration contours of UO_2F_2 associated with average daily releases from a uranium conversion facility. The simulation assumes a continuous release of 1 gram of UF_6 per day from the plant. The UF_6 reacts in the atmosphere to form UO_2F_2. The contours show a 12-hour average snapshot of the UO_2F_2 concentration as a fraction of the total suspended particles in typical city air 16 days after the start of the release. A concentration of 1 ppb of total suspended particles in typical city air is equivalent to 1×10^{-7} micrograms per cubic meter of UO_2F_2.[431]

One countermeasure to detection would be to locate a clandestine plant near an overt leaky plant. In such a situation, however, stand-off verification techniques applied around the declared plant should be able to verify whether nearby buildings were also releasing UF_6.

Conclusions

Because the waste heat from nuclear reactors can be detected by satellites, there is already considerable protection against undeclared plutonium production and separation in countries where spent fuel is subject to international monitoring. Wide-area environmental monitoring for krypton-85 emissions could provide an additional safeguard, by making it more difficult to conceal reprocessing. With current technology, however, the cost for a wide-area monitoring network would be high. It is considerably more feasible to deploy a few detectors around known reprocessing plants, to determine whether reprocessing is taking place in a facility to which access was being denied. This may be of particular interest for checking sensitive locations under a future FMCT.

At present, centrifuge enrichment plants are virtually undetectable, by both satellite, and wide-area environmental sampling. If sensitive detection techniques for UO_2F_2 can be developed, it may be possible to detect at least UF_6 production for a clandestine enrichment program. This suggests that it would be worthwhile to consider strengthening international material controls at existing conversion plants to assure that they could not be used as an alternative source of supply for a clandestine enrichment program.

Appendix

Fissile Materials and Nuclear Weapons

Fissile materials are essential in all nuclear weapons, from simple first-generation bombs, such as those that destroyed Hiroshima and Nagasaki sixty years ago, to the lighter, smaller, and much more powerful thermonuclear weapons in arsenals today. The most common fissile materials in use are uranium highly enriched in the isotope uranium-235 (HEU) and plutonium. This Appendix draws on material from the *Global Fissile Material Report 2006* to describe briefly the key properties of these fissile materials, how they are used in nuclear weapons, and how they are produced.

Explosive Fission Chain Reaction

Fissile materials can sustain an explosive fission chain reaction. When the nucleus of a fissile atom absorbs a neutron, it will usually split into two smaller nuclei. In addition to these "fission products," each fission releases two to three neutrons that can cause additional fissions, leading to a chain reaction (see Figure A.1). The fission of a single nucleus releases one hundred million times more energy per atom than a typical chemical reaction. A large number of such fissions occurring over a short period of time, in a small volume, results in an explosion. About one kilogram of fissile material—the amount fissioned in both the Hiroshima and Nagasaki bombs—releases an energy equivalent to the explosion of about 18 thousand tons (18 kilotons) of chemical high explosives.

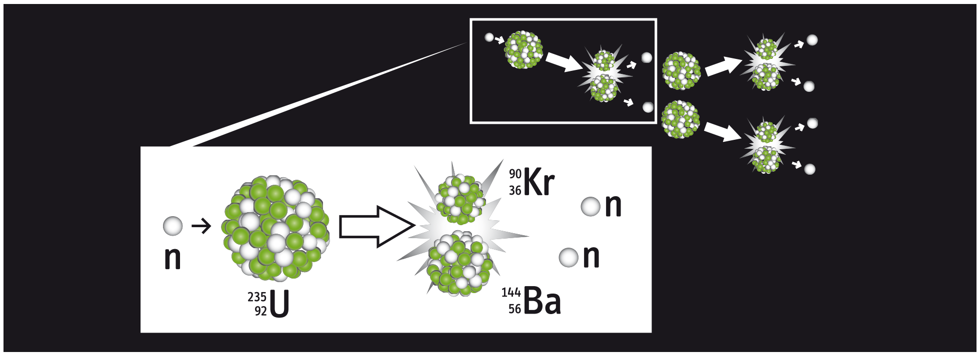


Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission products, which separate at high velocities. Additional neutrons are released in the process, which can set off a chain reaction in a critical mass of fissile materials. The chain reaction proceeds extremely fast; there can be 80 doublings of the neutron population in a millionth of a second, fissioning one kilogram of material and releasing an energy equivalent to 18,000 tons of high explosive (TNT).

The minimum amount of material needed for a chain reaction is defined as the critical mass of the fissile material. A "subcritical" mass will not sustain a chain reaction, because too large a fraction of the neutrons escape from the surface rather than being absorbed by fissile nuclei. The amount of material required to constitute a critical mass can vary widely—depending on the fissile material, its chemical form, and the characteristics of the surrounding materials that can reflect neutrons back into the core.

Along with the most common fissile materials, uranium-235 and plutonium-239, the isotopes uranium-233, neptunium-237, and americium-241 are able to sustain a chain reaction. The bare critical masses of these fissile materials are shown in Figure A.2.

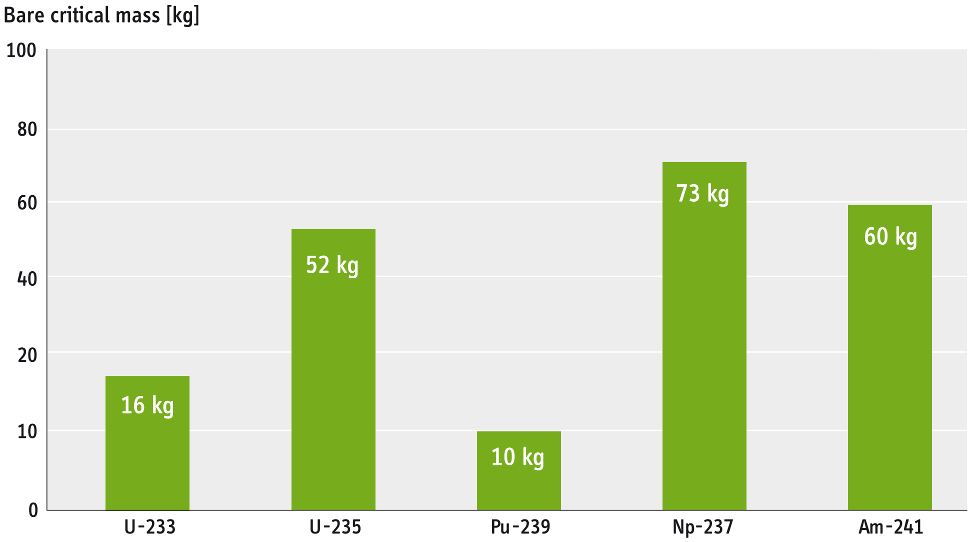


Figure A.2. Bare critical masses for some key fissile isotopes. A bare critical mass is the spherical mass of fissile metal barely large enough to sustain a fission chain reaction in the absence of any material around it. Uranium-235 and plutonium-239 are the key chain-reacting isotopes in highly enriched uranium and plutonium respectively. Uranium-233, neptunium-237 and americium-241 are, like plutonium-239, reactor-made fissile isotopes and could potentially be used to make nuclear weapons but have not, to our knowledge, been used to make other than experimental devices.

Nuclear Weapons

Nuclear weapons are either pure fission explosives, such as the Hiroshima and Nagasaki bombs, or two-stage thermonuclear weapons with a fission explosive as the first stage. The Hiroshima bomb contained about 60 kilograms of uranium enriched to about 80 percent in chain-reacting U-235. This was a "gun-type" device in which one subcritical piece of HEU was fired into another to make a super-critical mass (see Figure A.3, left).

Gun-type weapons are simple devices and have been built and stockpiled without a nuclear explosive test. The U.S. Department of Energy has warned that it may even be possible for intruders in a fissile-materials storage facility to use nuclear materials for onsite assembly of an improvised nuclear explosive device (IND) in the short time before guards could intervene.

The Nagasaki bomb operated using implosion, which has been incorporated into most modern weapons. Chemical explosives compress a subcritical mass of material into a high-density spherical mass. The compression reduces the spaces between the atomic nuclei and results in less leakage of neutrons out of the mass, with the result that it becomes “super-critical” (see Figure A.3, right).

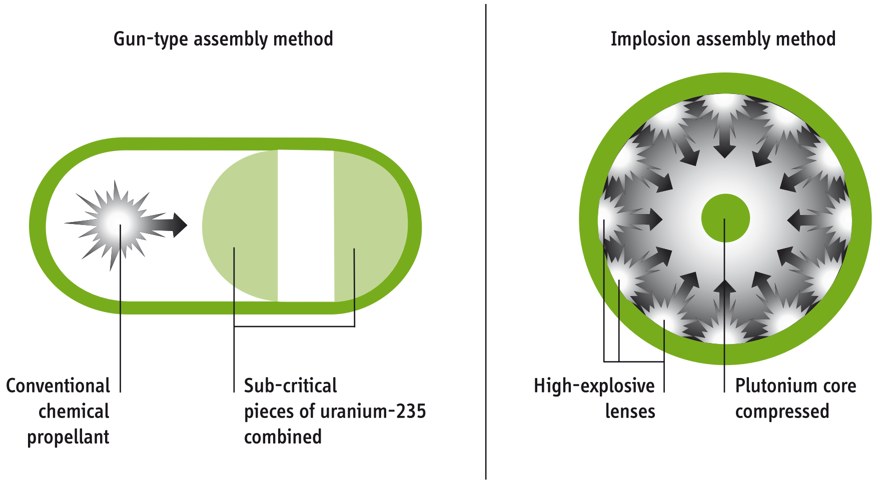


Figure A.3. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated “gun-type” method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow. For plutonium, the faster “implosion” method used in the Nagasaki bomb is required. This involves compression of a mass of fissile material. Much less material is needed for the implosion method because the fissile material is compressed beyond its normal metallic density. For an increase in density by a factor of two, the critical mass is reduced to one quarter of its normal-density value.

For either design, the maximum yield is achieved when the chain reaction is initiated at the moment a chain reaction in the fissile mass will grow most rapidly, i.e., weapon assembly is most supercritical. HEU can be used in either gun-type or implosion weapons. As is explained below, plutonium cannot be used in a gun-type device to achieve a high-yield fission explosion.

In modern nuclear weapons, the yield of the fission explosion is typically “boosted” by a factor of ten by introducing a mixed gas of two heavy isotopes of hydrogen, deuterium and tritium, into a hollow shell of fissile material (the “pit”) just before it is imploded. When the temperature of the fissioning material inside the pit reaches about 100 million degrees, it ignites the fusion of tritium with deuterium, which produces a burst of neutrons that “boost” the fraction of fissile materials fissioned and thereby the power of the explosion.

In a thermonuclear weapon, the nuclear explosion of a fission “primary” generates x-rays that compress and ignite a “secondary” containing thermonuclear fuel, where much of the energy is created by the fusion of the light nuclei, deuterium and tritium (see Figure A.4). The tritium in the secondary is made during the explosion by neutrons splitting lithium-6 into tritium and helium.

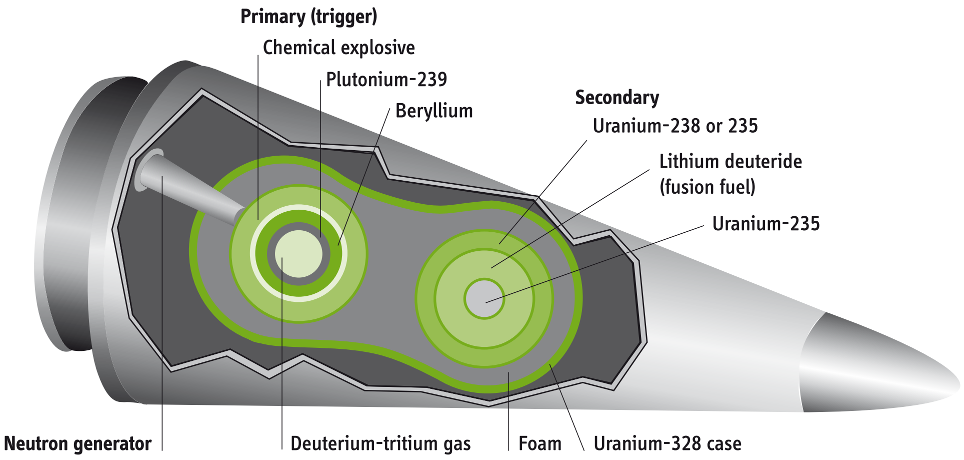


Figure A.4. A modern thermonuclear weapon usually contains both plutonium and highly enriched uranium. Typically, these warheads have a mass of about 200-300 kg and a yield of hundreds of kilotons, which corresponds to about one kilogram per kiloton of explosive yield. For comparison, the nuclear weapons that destroyed Hiroshima and Nagasaki weighed 300 kg per kiloton.

Modern nuclear weapons generally contain both plutonium and HEU. Both materials can be present in the primary fission stage of a thermonuclear weapon. HEU also is often added to the secondary stage to increase its yield without greatly increasing its volume.

Because both implosion and reflection can transform a subcritical into a supercritical mass, the actual amounts of fissile material in the pits of modern implosion-type nuclear weapons are considerably smaller than the bare or unreflected critical mass. Experts advising the IAEA have estimated "significant quantities" of fissile material, defined to be the amount required to make a first-generation implosion bomb of the Nagasaki-type (see Figure A.3, right), including production losses. The significant quantities are 8 kg for plutonium and 25 kg of U-235 contained in HEU. The United States has declassified the fact that 4 kg of plutonium is sufficient to make a nuclear explosive device.

A rough estimate of average plutonium and HEU in deployed thermonuclear weapons can be obtained by dividing the estimated total stocks of weapon fissile materials possessed by Russia and the United States at the end of the Cold War by the numbers of nuclear weapons that each deployed during the 1980s: about 4 kg of plutonium and 25 kg of HEU.

Production of Fissile Materials

Fissile materials that can be directly used in a nuclear weapon do not occur in nature. They must be produced through complex physical and chemical processes. The difficulties associated with producing these materials remains the main technical barrier to the acquisition of nuclear weapons.

Highly enriched uranium (HEU). In nature, U-235 makes up only 0.7 percent of natural uranium. The remainder is almost entirely non-chain-reacting U-238. Although an infinite mass of uranium with a U-235 enrichment of 6 percent could, in principle, sustain an explosive chain reaction, weapons experts have advised the IAEA that uranium enriched to above 20 percent U-235 is required to make a fission weapon of practical size. The IAEA therefore considers uranium enriched to 20 per cent or above "direct use" weapon-material and defines it as highly enriched uranium.

To minimize their masses, however, actual weapons typically use uranium enriched to 90-percent U-235 or higher. Such uranium is sometimes defined as "weapon-grade." Figure A.5 shows the critical mass of uranium as a function of enrichment.

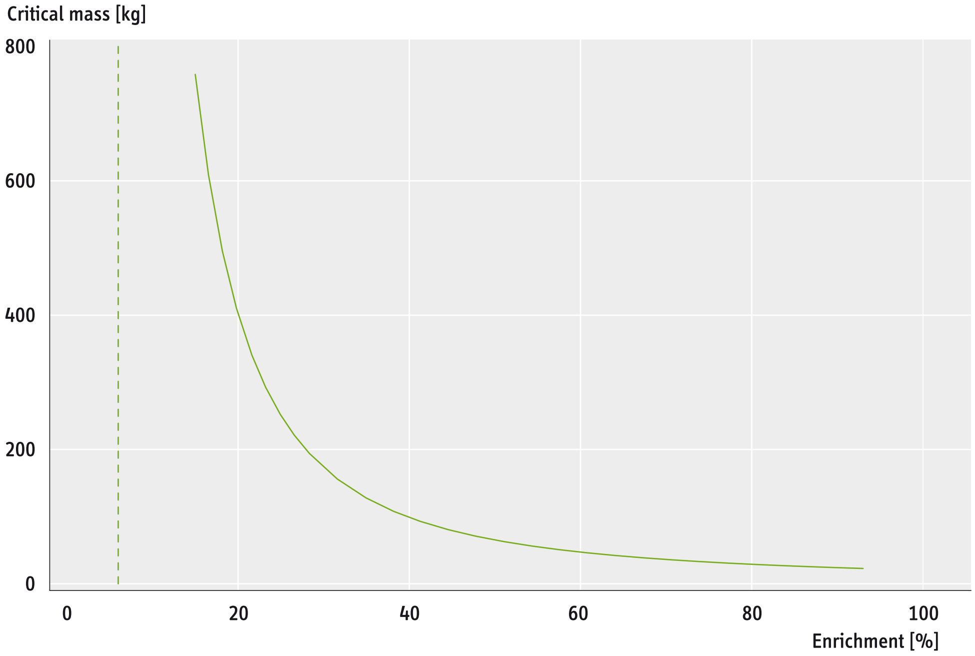


Figure A.5. The fast critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data in the figure is for a uranium metal sphere enclosed in a 5-cm-thick beryllium neutron "reflector" that would reflect about half the neutrons back into the fissioning mass.

The isotopes U-235 and U-238 are chemically virtually identical and differ in weight by only one percent. To produce uranium enriched in U-235 therefore requires sophisticated isotope separation technology. The ability to do so on a scale sufficient to make nuclear weapons or enough low-enriched fuel to sustain a large power reactor is found in only a relatively small number of nations.

In a uranium enrichment facility, the process splits the feed (usually natural uranium) into two streams: a product stream enriched in U-235, and a waste (or "tails") stream depleted in U-235. Today, two enrichment technologies are used on a commercial scale: gaseous diffusion and centrifuges. All countries that have built new enrichment plants during the past three decades have chosen centrifuge technology. Gaseous diffusion plants still operate in the United States and France but both countries plan to switch to more economical gas centrifuge plants.

Gas centrifuges spin uranium hexafluoride (UF_6) gas at enormous speeds, so that the uranium is pressed against the wall with more than 100,000 times the force of gravity. The molecules containing the heavier U-238 atoms concentrate slightly more toward the wall relative to the molecules containing the lighter U-235. This effect can be exploited to separate the two isotopes. An axial circulation of the UF_6 is induced within the centrifuge, which multiplies this separation along the length of the centrifuge, and increases the overall efficiency of the machine significantly (see Figure A.6 for an illustration).

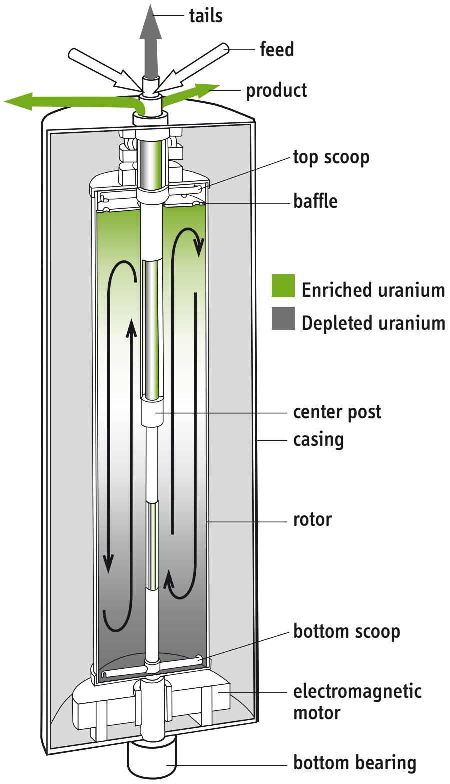


Figure A.6. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small scale prior to and during World War II, but the technology only became economically competitive in the 1970s. Today, centrifuges are the most economic enrichment technology, but also the most proliferation-prone.

Plutonium. Plutonium is an artificial isotope produced in nuclear reactors when uranium-238 (U-238) absorbs a neutron creating U-239 (see Figure A.7). The U-239 subsequently decays to plutonium-239 (Pu-239) via the intermediate short-lived isotope neptunium-239.

The longer an atom of Pu-239 stays in a reactor after it has been created, the greater the likelihood that it will absorb a second neutron and fission or become Pu-240—or absorb a third or fourth neutron and become Pu-241 or Pu-242. Plutonium therefore comes in a variety of isotopic mixtures.

The plutonium in typical power-reactor spent fuel (reactor-grade plutonium) contains between 50 and 60% Pu-239, and about 25% Pu-240. Weapon designers prefer to work with a mixture that is as rich in Pu-239 as feasible, because of its relatively low rate of generation of radioactive heat and relatively low spontaneous emissions of neutrons and gamma rays (see Table A.1). Weapon-grade plutonium contains more than 90% of the isotope Pu-239 and has a critical mass about two-thirds that of reactor grade plutonium.

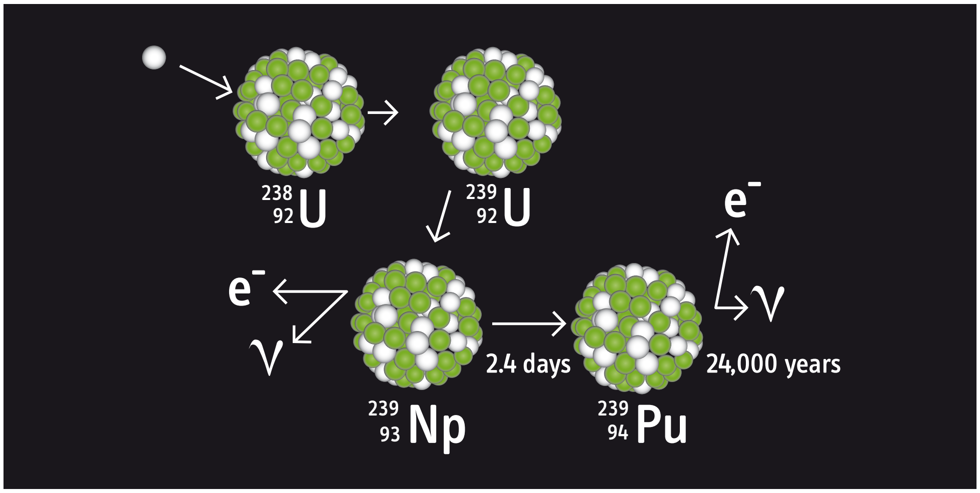


Figure A.7. Making plutonium in a nuclear reactor. A neutron released by the fissioning of a chain-reacting U-235 nucleus is absorbed by the nucleus of a U-238 atom. The resulting U-239 nucleus decays with a half-life of 24 minutes into neptunium, which in turn decays into Pu-239. Each decay is accompanied by the emission of an electron to balance the increase in charge of the nucleus and a neutrino.

Isotope	Critical Mass [kg]	Half Life [years]	Decay Heat [watts/kg]	Neutron Generation [neutrons/g-sec]
Pu-238	10	88	560	2600
Pu-239	10	24,000	1.9	0.02
Pu-240	40	6,600	6.8	900
Pu-241	13	14	4.2	0.05
Pu-242	80	380,000	0.1	1700
Am-241	60	430	110	1.2

Table A.1. Key properties of plutonium isotopes and Am-241 into which Pu-241 decays. Data from: U.S. Department of Energy, "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems," in Technological Opportunities to Increase the Proliferation Resistance of Global Nuclear Power Systems, TOPS, Washington, D.C., U.S. Department of Energy, Nuclear Energy Research Advisory Committee, 2000, www.ipfmlibrary.org/doe00b.pdf, p. 4; see also, J. Kang et al., "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel," *Science & Global Security*, Vol. 13, 2005, p. 169.

For a time, many in the nuclear industry thought that the plutonium generated in power reactors could not be used for weapons. It was believed that the large fraction of Pu-240 in reactor-grade plutonium would reduce the explosive yield of a weapon to insignificance. Pu-240 fissions spontaneously, emitting neutrons. This increases the probability that a neutron would initiate a chain reaction before the bomb assembly reaches its maximum supercritical state. This probability increases with the percentage of Pu-240.

For gun-type designs, such "pre-detonation" reduces the yield a thousand-fold, even for weapon-grade plutonium. The high neutron-production rate from reactor-grade plutonium similarly reduces the probable yield of a first-generation implosion design—but only by ten-fold, because of the much shorter time for the assembly of a super-critical mass. In a Nagasaki-type design, even the earliest possible pre-initiation of the chain reaction would not reduce the yield below about 1000 tons TNT equivalent. That would still be a devastating weapon.

More modern designs are insensitive to the isotopic mix in the plutonium. As summarized in a 1997 U.S. Department of Energy report:

> "[V]irtually any combination of plutonium isotopes…can be used to make a nuclear weapon … reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states …"

> "At the lowest level of sophistication, a potential proliferating state or sub-national group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium."

For use in a nuclear weapon, the plutonium must be separated from the spent fuel and the highly radioactive fission products that the fuel also contains. Separation of the plutonium is done in a "reprocessing" operation. With the current PUREX technology, the spent fuel is chopped into small pieces, and dissolved in hot nitric acid. The plutonium is extracted in an organic solvent which is mixed with the nitric acid using blenders and pulse columns, and then separated with centrifuge extractors. Because all of this has to be done behind heavy shielding and with remote handling, reprocessing requires both resources and technical expertise. Detailed descriptions of the process have been available in the published technical literature since the 1950s.

Spent fuel can only be handled remotely, due to the very intense radiation field, which makes its diversion or theft a rather unrealistic scenario. Separated plutonium can be handled without radiation shielding, but is dangerous when inhaled or ingested.

Endnotes

Chapter 1. Nuclear Weapon and Fissile Material Stockpiles and Production

[1] For the rise and fall of the U.S. and Russian nuclear weapon stockpiles, see *Global Fissile Material Report 2006*, International Panel on Fissile Materials, p. 12, www.ipfmlibrary.org/gfmr06.pdf.

[2] S. N. Kile, V. Fedchenko and H. Kristensen, "World Nuclear Forces, 2007," Appendix 13A in *SIPRI Yearbook 2007*, Oxford University Press, 2007; R. S. Norris and H. Kristensen, "Russian Nuclear Forces, 2007," *Bulletin of the Atomic Scientists*, March/April 2007, pp. 61-64.

[3] Strategic Offensive Reductions Treaty, available at www.state.gov.

[4] R. Norris and H. Kristensen, "The U.S. Nuclear Stockpile, Today and Tomorrow,“ *Bulletin of the Atomic Scientists*, September/October 2007. There are three basic categories of warheads that constitute the U.S. nuclear stockpile. Active, operationally deployed warheads are those on missiles and bombers. Active non-deployed warheads, also known as the responsive force, are spares plus warheads that quickly could be returned to the field as deployed warheads. Lastly, there are inactive warheads, which are intact but have had some of their limited lifetime components, most importantly their tritium boost gas, removed. There are also warheads that have been removed from the stockpile and though still intact are in the process of being retired and dismantlement.

[5] R. S. Norris and H. Kristensen, "Chinese Nuclear Forces, 2006," *Bulletin of the Atomic Scientists*, May/June 2006, pp. 60-63.

[6] Ministry of Foreign Affairs of the People's Republic of China, "Nuclear Disarmament and Reduction of" [sic], *Fact Sheet China*, 27 April 2004, www.fmprc.gov.cn, mirrored at www.ipfmlibrary.org/prc04.pdf.

[7] The U.K. Ministry of Defence announced publicly in 1994 that "we need a stockpile of less than 200 operationally available warheads." U.K. Ministry of Defence, "Deterrence and Disarmament," in *Strategic Defense Review*, Chapter 4, 1994, www.fas.org and www.ipfmlibrary.org/mod94.pdf.

[8] *The Future of the United Kingdom's Nuclear Deterrent*, Cm 6994, Secretary of State for Defence and Secretary of State for Foreign and Commonwealth Affairs, London, December 2006, p. 12, www.ipfmlibrary.org/mod06b.pdf.

[9] *Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, United States, Department of Energy, 2001, www.ipfmlibrary.org/doe01.pdf; and U.K. Ministry of Defence, *Historical Accounting for U.K. Defence Highly Enriched Uranium*, March 2006, www.ipfmlibrary.org/mod06.pdf.

[10] Unless otherwise noted, data from *Global Fissile Material Report 2006*, International Panel on Fissile Materials, www.ipfmlibrary.org/gfmr06.pdf. Values for China and France have been rounded due to the significant uncertainties in their respective military inventories. Values for Russian and U.S. excess military stocks that are subject to blend-down campaigns are for December 2006. The HEU holdings of India and Pakistan have not been adjusted since 2006, even though production is ongoing. Uncertainties in these estimates are much higher than annual production rates.

[11] *Striking a Balance, op. cit.*

[12] France, Russia, the United Kingdom and the United States all have made official declarations to that effect. China announced cessation of HEU production informally. See A. MacLachlan and M. Hibbs, "China Stops Production of Military HEU; All SWU Capacity Now for Civil Use," *Nuclear Fuel*, 13 November 1989, p. 5.

[13] Z. Mian, A. H. Nayyar, R. Rajaraman, and M. V. Ramana, "Fissile Materials in South Asia and the Implications of the U.S.-India Nuclear Deal," *Science & Global Security*, Vol. 14, 2006, pp. 117–143. A more detailed report by the authors has been published by the International Panel on Fissile Materials and is available at www.ipfmlibrary.org/rr01.pdf.

[14] M. Hibbs, "Pakistan Developed More Powerful Centrifuges," *Nuclear Fuel*, Vol.32, No. 3, 29 January 2007; M. Hibbs, "P-4 Centrifuge Raised Intelligence Concerns about Post-1975 Data Theft," *Nucleonics Week*, Vol. 48, No. 7, 15 February 2007.

[15] India's Ratehalli centrifuge plant seems to be expanding from 1000-2000 machines of 2-3 SWU/year to 2000-3000 machines of 5-7 SWU/year. D. Albright and S. Basu, *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, ISIS, January 2007, www.isis-online.org.

[16] Reportedly, China uses LEU or near-LEU fuel in its submarines. On the French transition to LEU, see C. Fribourg, "La Propulsion Nucléaire Navale," *Revue Générale Nucléaire*, March/April 1999, pp. 32-52, where it is reported that France's new *Barracuda*-class attack submarine will use fuel with the same enrichment as France's pressurized-water reactors, which is less than five-percent enriched. See also the discussion by M. B. Davis, "Nuclear France: Materials and Sites," www.francenuc.org.

[17] C. Ma and F. von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Vol. 8, 2001, pp. 86-101.

[18] Upon completion of an international project to provide coal-fired replacement heat and electrical power, Russia's remaining three operating military plutonium-production reactors are to be shut down between 2008 and 2011. *FY 2008 Congressional Budget Request*, U.S. DOE, DOE/CF-014, Vol. 1, February 2007, p. 425, www.ipfmlibrary.org/doe07.pdf. In the meantime, the plutonium that is separated from their fuel is stored and subject to U.S. monitoring.

[19] When U.S. Secretary of Energy Samuel Bodman announced in 2005 that 160 tons of excess weapon HEU would be reserved for use in naval reactor fuel, he stated that this "will have the added benefit of postponing the need for construction of a new uranium-enrichment facility for at least fifty years," Remarks at the 2005 Carnegie International Nonproliferation Conference, Washington, D.C., 7 November 2005. The annual consumption in U.S. naval reactors was 1.1 tons U-235 in the mid-1990s. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Washington, D.C., 1995, p. 166. Assuming an average U-235 burn-up of 35-50%, this is equivalent to HEU requirements of 2000-3000 kg per year. It is unlikely that much higher burn-up levels (above 50-percent U-235) can be achieved because there is no fuel "shuffling" in U.S. naval reactors.

[20] "Policy Relating to Major Combatant Vessels of the Strike Forces of the United States Navy," *National Defense Authorization Act for fiscal year 2008 (Placed on Calendar in Senate)*, Section 1012, available at thomas.loc.gov.

[21] The Navy is also developing a new reactor core that will be able to generate more energy over its life (the Transformational Technology Core), *FY 2008 Congressional Budget Request, op. cit.*, p. 540.

[22] The Russian nuclear-powered icebreaker fleet consists of five Arktika-class icebreakers (Arktika, Sibir, Rossiya, Sovetskiy Soyuz, and Yamal), two Taymyr-class river icebreakers (Taymyr and Vaygach) and the Sevmorput transport ship. Sea trials of the newest Russian icebreaker, *50 Years of Victory*, began in January 2007. For updates, see www.bellona.org.

[23] The United States holds about 45 tons of civilian HEU, which includes about 20 tons in storage at the Y-12 site for future use as HEU in research and space reactors (defined as excess material and *not* shown as civilian in Figures 1.2 and 1A.1), and about 13-15 tons in spent fuel. 10 tons of civilian HEU is in non-nuclear weapon states and 8 tons in the United Kingdom and France. Good estimates for China and Russia are not yet available, but all indications are that Russia's stock of civilian HEU is at least as large as that of the United States. A gun-type weapon would require about 50 kg of weapon-grade uranium.

[24] The IAEA *Annual Report 2005*, Table A20 states that 19.4 tons of HEU were under IAEA safeguards in non-nuclear weapon states at the end of 2005. We have subtracted the approximately 10 tons that the U.S. DOE reports was in the spent fuel of Kazakhstan's shutdown BN-350 breeder reactor, *U.S. Department of Energy, Budget Justification for fiscal year 2008*, p. 515. This HEU was originally less than 26-percent enriched, however, and is likely less than 20-percent enriched today.

[25] This information is published as additions to *IAEA INFCIRC/549*.

[26] The 16 countries that we assume cleaned-out are: Austria, Brazil, Chile, Colombia, Denmark (small quantities remaining), Georgia, Greece, Indonesia (some material remaining, but less than 1 kg), Iraq, Norway, Philippines, Slovenia, South Korea, Spain, Sweden, and Thailand.

[27] See also Chapter 8 of *Global Fissile Materials Report 2006*. An upcoming IPFM research report will report on the subject in detail.

[28] At their September 1998 summit, Presidents Clinton and Yeltsin declared the intentions of the United States and Russia to "remove by stages approximately 50 tons of plutonium from their nuclear weapons programs, and to convert this material so that it can never be used in nuclear weapons." However, because Russia considered only 34 tons of the U.S. material declared excess to be clean weapon-grade material, the 2000 Russian-U.S. Plutonium Management and Disposition Agreement covered only 34 tons each.

[29] The 45 tons that the United States has declared excess includes 7.5 tons of fuel-grade and reactor-grade plutonium that was not originally produced for weapon purposes but was considered for blending with super-grade plutonium to make weapon-grade plutonium during the Reagan Administration. A total of 37.6 tons was declared by the United States as excess separated weapon-grade plutonium. *Plutonium: The First 50 Years: United States Plutonium Production, Acquisition and Utilization from 1944 Through 1994*, U.S. DOE, DOE/DP-0137, 1996, Table 15. www.ipfmlibrary.org/doe96.pdf.

[30] M. Weis, M. Flakowski, R. Haid, F. Plaputta, and F. Völker, "Plutonium-Verwertung: 40 Jahre MOX-Einsatz in Deutschen Kernkraftwerken" [Plutonium-Recycling: 40 Years of MOX-Use in German Nuclear Power Reactors], *atw*, Vol. 51, No. 12, 2006, pp. 793-796.

[31] Data compiled for the forthcoming IPFM research report: O. Reistad, M. Bremer Maerli, and S. Hustveit, *Non-Explosive Nuclear Applications Using Highly Enriched Uranium. Conversion and Minimization towards 2020*, in review. There are 12 European countries with HEU-fueled research reactors. They include: Belarus, Belgium, the Czech Republic, France, Germany, Hungary, Italy, the Netherlands, Poland, Switzerland, the United Kingdom, and the Ukraine. The other 17 countries are: Argentina, Canada, Chile, the DPRK, (North Korea) Ghana, India, Iran, Israel, Jamaica, Japan, Kazakhstan, Mexico, Nigeria, Pakistan, Syria, Uzbekistan, and Vietnam.

[32] The data on military stocks of separated plutonium are from *Global Fissile Material Report 2006*. The plutonium inventories of India and Pakistan have not been adjusted since 2006, even though production is ongoing. Uncertainties in these estimates are much higher than annual production rates.

[33] R. S. Norris, A. S. Burrows, and R. W. Fieldhouse, *Nuclear Weapons Databook, Volume V: British, French, and Chinese Nuclear Weapons*, Boulder, CO., Westview Press, 1994, p. 350. See also, D. Albright and C. Hinderstein, "Chinese Military Plutonium and Highly Enriched Uranium Inventories," ISIS, 30 June 2005.

[34] The Dimona reactor is operating as of Summer 2007, Y. Azoulay, "Nuclear Center Exec Avows Safety of Dimona Reactor," www.haaretz.com, 24 August 2007. However, independent analysts have not increased their estimates of the size of Israel's weapon stockpile for several years.

[35] See for instance the interview with A. Kakodkar, Chairman of the Atomic Energy Commission of India and Head of the Department of Atomic Energy, in *Science*, Vol. 311, 10 February 2006, pp. 765-766, in which he points out that the fast breeder program cannot be put on the civilian list of safeguarded facilities because of its relevance for India's strategic security interests.

[36] Z. Mian et al., *op. cit.* See also: A. Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science & Global Security*, Vol. 15, No. 2, 2007, forthcoming.

[37] "India Building Two Reprocessing Plants," *Platts*, 12 June 2007, www.platts.com.

[38] Picture of Indian breeder-reactor construction site from www.bhavini.nic.in.

[39] D. Albright and P. Brannan, “Commercial Satellite Imagery Suggests Pakistan is Building a Second, Much Larger Plutonium Production Reactor: Is South Asia Headed for a Dramatic Buildup in Nuclear Arsenals?” ISIS, 24 July 2006.

[40] D. Albright and P. Brannan, “Pakistan Appears to be Building a Third Plutonium Production Reactor at Khushab Nuclear Site,” ISIS, 21 June 2007.

[41] This was first reported in January 2007, D. Albright and P. Brannan, “Chashma Nuclear Site in Pakistan with Possible Reprocessing Plant,” ISIS, 18 January 2007. This plant may be sized to process the discharged fuel from one or both of the Khushab plutonium production reactors. At 50 MWt, each reactor could produce about 10 tons of spent fuel per year, if operated at low burn-up (1000 MWd/kg or less) to produce weapon-grade material.

[42] IAEA/OECD, *Uranium 2005: Resources, Production and Demand, Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency*, 2005 (“Red Book”).

[43] ”IAEA Team Confirms Shutdown of DPRK Nuclear Facilities,” IAEA press release, 18 July 2007, www.iaea.org/NewsCenter/PressReleases/2007/prn200712.html.

[44] M. Schneider and Y. Marignac, *Spent Nuclear Fuel Reprocessing in France*, IPFM Research Report Draft, 10 June 2007, and T. Katsuta and T. Suzuki, *Japan’s Spent Fuel and Plutonium Management Challenges*, IPFM Research Report No. 2, September 2006, www.ipfmlibrary.org/rr02.pdf.

[45] “Step 3 of Active Tests Begins at Rokkasho,” Citizens’ Nuclear Information Center, www.cnic.jp/english, mirrored at www.ipfmlibrary.org/cni07.pdf. See also M. Hibbs, “JNFL Walking Tightrope on Rokkasho Schedule,” *Nuclear Fuel*, Vol. 32, No. 9, 2007, p. 1.

[46] T. Katsuta, and T. Suzuki, *Japan’s Spent Fuel and Plutonium Management Challenges, op. cit.*

[47] W. Walker, “Destination Unknown: Rokkasho and the International Future of Nuclear Reprocessing,” *International Affairs*, Vol. 82, No. 4, 2006, pp. 743-761.

[48] There are 4000 tons of contracted fuel to be reprocessed by THORP by March 2011. To reprocess it all in time would require THORP to operate at about 1000 tons per year, which is roughly twice its average rate since beginning operation. CORE, “Further Delay for THORP—Re-Opening Now Unlikely until Mid 2007 at the Earliest,” 2 March 2007, www.corecumbria.co.uk.

[49] “Culture Clubbed,” *Nuclear Engineering International*, 25 April 2007.

[50] “Major U-turn on THORP Reprocessing Policy,” CORE Briefing, No. 02/07, 18 June 2007, www.corecumbria.co.uk.

[51] F. von Hippel, *Managing Spent Fuel in the United States: The Illogic of Reprocessing*, IPFM Research Report No. 3, January 2007, www.ipfmlibrary.org/rr03.pdf.

[52] Plutonium oxide powder, the form in which plutonium is transported from a reprocessing to a fuel fabrication plant, is particularly susceptible to dispersal. The inhalation of a tenth of a milligram would result in a high probability of eventual death from lung or bone cancer. See e.g., S. Fetter and F. von Hippel, “The Hazard from Plutonium Dispersal by Nuclear-Warhead Accidents,” *Science & Global Security*, Vol. 2, 1990, p. 21.

[53] D. Albright, “Shipments of Weapons-Usable Plutonium in the Commercial Nuclear Industry,” ISIS, 3 January 2007.

[54] According to Yannick Rousselet, the Nuclear Campaign Coordinator, Greenpeace France, the truck, which had been under heavy escort by police, military vehicles and helicopters, stopped for fuel at a public gas station. Greenpeace activists, at the station 30 minutes before the truck arrived, were able to approach the truck, and take pictures and film without hindrance for several minutes.

[55] Plutonium shipped to each of the ten German reactors travels about 2000 km, plutonium to each of the twenty French reactors about 1600 km.

[56] Albright, “Shipments of Weapons-Usable Plutonium,” *op. cit.*

[57] *Striking a Balance, op. cit.* For a discussion of the history of this report see S. Aftergood and F. von Hippel, "The U.S. Highly Enriched Uranium Declaration: Transparency Deferred but not Denied," *Nonproliferation Review,* 14 March 2007, p. 149.

[58] The United States exported 21.1 metric tons of HEU to the European Union, 2.2 tons to Canada, 2.1 tons to Japan and 0.26 tons to more than 17 other countries prior to 1993, *Striking a Balance, op. cit.*, Figure 6.3 and Tables 6.7 and 6.8. A total of 6.3 tons of this material was returned as of 30 September 1996. Some of it has been fissioned and some of it has been reprocessed and blended down to LEU. The DOE's Global Threat Reduction Initiative is encouraging the return of no-longer needed HEU in fresh and spent research reactor fuel. As of 30 September 2007, this program expects to have repatriated an additional 0.235 tons of fresh HEU and 1.15 tons of HEU in spent fuel, *U.S. Department of Energy, Budget Justification for fiscal year 2008*, Vol. 1, p. 520, www.mbe.doe.gov.

[59] This estimate is based on *Striking a Balance, op. cit.*, Table 3-3 and Appendix C, Tables C-1 to C-4.

[60] This number was revised to 178 tons in the 2001 report, but more recent official statements quote the 174-ton number again, which remains the official declaration and is the basis of the analysis in this report. The average enrichment of this material was about 62 percent.

[61] See Table 3.3, *Striking a Balance, op. cit.*

[62] R. M. George and D. R. Tousley, "U.S. HEU Disposition Progress," *NEI Nuclear Fuel Supply Forum*, 23 January 2007.

[63] As of mid-2007, ten additional tons had been delivered to the blend-down facilities, but are still to be processed, K. Vogler, "The U.S. Highly Enriched Uranium (HEU) Disposition Program," 48th Annual INMM Meeting, Tucson, Arizona, 8-12 July 2007.

[64] The 2001 *Striking a Balance* report noted that, as of 1996, the "majority of HEU assigned to the Naval Nuclear Propulsion Program is already in or has been used in naval reactor cores. The remainder will be fabricated into fuel in the near future," *Striking a Balance, op cit.*, p. 39.

[65] The U.S. Enrichment Corporation assumes 25 kg HEU per warhead in converting its purchases of excess Russian weapon-grade uranium to weapon equivalents. It is generally assumed that plutonium is used in the primary of a thermonuclear weapon, whereas most or all of the HEU would be located in the secondary of the weapon.

Chapter 2. Disposition of Excess Highly Enriched Uranium

[66] The reason for the use of 1.5-percent blend-stock is to dilute the U-234 in the HEU enough to meet the commercial specifications used in the United States. The ratio of U-234/U-235 in natural uranium in radioactive equilibrium is 0.0077. For 90-percent enriched HEU, because a larger fraction of the U-234 than of the U-235 is extracted from the natural uranium, the ratio is closer to 0.0100. The ratio in depleted uranium is less than 0.005. See e.g., S. Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile-Material Production," *Science & Global Security*, Vol. 3, 1996, p. 237. The western standard for LEU is a ratio of 0.0110, "Standard specification for uranium hexafluoride enriched to less than 5% 235U," ASTM International Standard C 996-04, 2004.

[67] M. Hibbs, "Framatome, Elektrostal Looking to Double Business in Down-Blended HEU Fuel," *Nuclear Fuel*, Vol. 27, No. 17, P. 1, 19 August 2002.

[68] The HEU deal was proposed in 1991 by T. L. Neff, "A Grand Uranium Bargain, " *New York Times*, 24 October 1991. In its commercial implementation, it has become more complicated than first envisioned. In essence, Russia delivers LEU to USEC, a now-private U.S. firm (formerly the U.S. Enrichment Corporation), which pays Russia in cash for the "enrichment component" (that is, the enrichment work that would be involved in producing an equivalent amount of LEU from natural uranium) and transfers to Russian the ownership of the amount of natural uranium USEC would have required, had it enriched the uranium itself. Russia then uses a portion of the natural uranium domestically and markets the rest through a consortium of uranium-marketing companies, including Cameco, Areva, and Nukem.

[69] Data on Russian sales to USEC from "US-Russian Megatons to Megawatts Program, Recycling Nuclear Warheads into Electricity," www.usec.com/v2001_02/HTML/Megatons_history.asp. Data for U.S. based on Table 2.1.

[70] For a description, see M. Bunn (with J. Platte), "Highly Enriched Uranium Transparency," in *Nuclear Threat Initiative Research Library: Securing the Bomb*, Cambridge, Mass., and Washington, D.C., Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, 2006, www.nti.org/e_research/cnwm/monitoring/uranium.asp. See also V. Rybachenkov, *Practical Prerequisites for the Implementation of Transparency and Verification Measures on Fissile Materials*, presentation at the international workshop on International Cooperation in the Combat against Nuclear Terrorism and the Role of Nuclear Arms Control, Geneva, 17-18 December 2002.

[71] D. Horner and M. Knapik, "Tenex's Mikerin Says US-Russia HEU Deal Won't Run Beyond 2013," *Nuclear Fuel*, Vol. 31, No. 13, p. 1, 19 June 2006.

[72] At current prices in the range of $200 per kilogram of uranium and $130 per SWU, a single ton of HEU would bring in some $50 million and 200 tons could bring in $10 billion.

[73] Russia has confirmed that the 1.5% enriched blend-stock is produced by stripping depleted uranium, or "tails," from past enrichment operations but has never publicly revealed the U-235 concentration in the tails being stripped. Some Western analysts believe that Russia is stripping tails with a U-235 concentration of less than 0.2-percent U-235. If, for example, Russia is using tails containing 0.18-percent U-235 and stripping them to 0.15-percent U-235, production of the blend-stock to blend down 30 tons of HEU per year to 4.4-percent LEU would require 5.3 million SWU/yr. Producing the same LEU from natural uranium, with a tails assay of 0.3-percent U-235 would require 5.5 million SWU/yr.

[74] Nuclear Threat Initiative and Atominform, *Joint Conceptual Analysis and Cost Evaluation of the Possibility of Accelerated Disposition of Highly Enriched Uranium No Longer Needed for Defense Purposes*, NTI, Washington, D.C., 2005, www.nti.org/c_press/analysis_HEUfinalrpt.pdf.

[75] One could imagine, for example, some form of matching arrangement in which a certain number of additional SWU could be marketed in the United States for every additional kg of HEU blended down in Russia.

[76] Much of the U.S. depleted uranium contains 0.3%-0.4% U-235. If Russia produced blend-stock by stripping U.S. depleted uranium containing 0.3% U-235 to 0.2% U-235 rather than stripping its own depleted uranium containing 0.18% U-235 to 0.15% U-235, it could save some 1.4 million SWU/yr worth $300 million at a price of $130/SWU. The U.S. DOE had been planning to pay for the disposal of its depleted uranium as waste. With recent increases in uranium prices, however, USEC has proposed to strip additional U-235 out of it.

[77] U.S. Department of Energy, *FY 2008 NNSA Budget Request*, p. 474.

[78] A. MacLachlan and M. Knapik, "TVEL Eyes Collaboration to Serve U.S. Market," *Nuclear Fuel*, Vol. 29, No. 20, 27 September 2004. Interviews with Russian experts indicate that the actual LEU shipped to Europe in recent years under this arrangement is not made from this reprocessed uranium, but from "clean" LEU that meets Western commercial specifications. The LEU made with the Western European reprocessed uranium reportedly is used in Russian reactors.

[79] "AREVA Representatives Have Pointed Out the High Quality of Fuel Fabrication at MSZ," *Atom Pressa*, Vol. 46, November 2006.

[80] For a fuller discussion of this case, see F. von Hippel, "Future Needs for HEU-fueled Reactors," *Proceedings of the International Meeting on Reduced-Enrichment Research and Test Reactors*, Boston, 6-10 November 2005. Picture from IPPE website, www.rssi.ru.

[81] A. MacLachlan, "GKN Says Elektrostal Option Only Solution for RepU Use," *Nuclear Fuel*, p. 11, 30 September 2002.

[82] Interview with Eugene Kudryavtsev, Head of the Nuclear Materials Production Industry of Rosatom, 10 January 2007. It would take 120 tons of 16.5-percent enriched uranium to blend up 500 tons of RepU containing 0.8% U-235 to 4.5%. According to one estimate, the Soviet Union and Russia had produced 570 tons of uranium enriched to an average of 30-percent for its naval reactors as of 1995, O. Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security*, Vol. 6, 1996, p. 59, www.ipfmlibrary.org/sgs06bukharin.pdf.

[83] R. M. George and D. R. Tousley, "U.S. HEU Disposition Progress," paper presented at the Nuclear Energy Institute Nuclear Fuel Supply Forum, Washington, D.C., 23 January 2007.

[84] Specifically, 14.2 tons of UF_6 with an average enrichment of 75% was blended down at the Portsmouth gaseous diffusion plant and 46.6 tons of metal and oxide with an average enrichment of 43.7 percent were blended down at the privately owned BWX Technologies (formerly Babcock & Wilcox) facility in Lynchburg, Virginia, primarily by means of dissolution and blending of solutions.

[85] Much of the excess HEU in both Russia and the United States was produced from reprocessed uranium and contains small quantities of artificial uranium isotopes produced by neutron reactions during irradiation: U-232 (half-life, 69 years), U-233 (160,000 years), and U-236 (23 million years).

[86] George and Tousley, "U.S. HEU Disposition Progress," *op. cit.* NFS built a major new "Blended LEU" facility for this project, and is now designing a new "Cats and Dogs Line," designed to be able to process and blend a wide variety of forms of HEU that exist in DOE's complex. See "The Smart Alternative for DOE Orphans," *NFS Innovation in Action*, Spring 2006, www.nuclearfuelservices.com/images/PDF/innovation06.pdf, p. 24.

[87] Sources: George and Tousley, "U.S. HEU Disposition Progress," *op. cit.*; U.S. Department of Energy, *DOE to Remove 200 Metric Tons of Highly Enriched Uranium from U.S. Nuclear Weapons Stockpile*, Washington, D.C., DOE, 2005, www.energy.gov/news/2617.htm as of 10 July 2007; and R. M. George, personal communication, 23 July 2007.

[88] DOE reported that some 93 tons had been "down-blended or shipped for down-blending" by the end of fiscal year 2006, U.S. Department of Energy, *FY 2008 NNSA Budget Request, op. cit.*, p. 488. Some of the shipped material, however, had not yet been down-blended.

[89] This material includes 14.3 tons of metal, 2.6 tons of oxide, and 0.5 tons of fabricated fuel, with an average enrichment in the range of 80-85%.

[90] Some of this material will be under IAEA safeguards, replacing 10 tons of excess weapon-grade HEU that was planced under IAEA safeguards in 1993 but is being withdrawn from IAEA safeguards to be added to the U.S. naval reactor reserve, U.S. Department of Energy, *FY 2008 NNSA Budget Request, op. cit.,* p. 490.

[91] George and Tousley, "U.S. HEU Disposition Progress," *op. cit.* The 75 tons slated for additional down-blending for commercial use includes 23 tons from the original excess declaration, the 20 tons designated for down-blending in the year-2005 declaration of an additional 200-tons of HEU excess to U.S. weapons needs, and the 32 tons of material in the 200-ton declaration that does not meet Navy specifications. An additional 8 tons of HEU in expected returns from research reactors is not yet incorporated in the excess declarations but is expected to be reprocessed and blended down at Savannah River. DOE is considering some options in which the 23 tons currently slated for disposal would instead be reprocessed, and the uranium recovered as LEU for commercial use. See U.S. Department of Energy, *Disposition of Surplus U.S. Fissile Materials: Comparative Analysis of Alternative Approaches*, Washington, D.C., DOE, 2006.

[92] U.S. Department of Energy, *FY 2008 NNSA Budget Request*, *op. cit.*, p. 488, and George and Tousley, "U.S. HEU Disposition Progress," 2007, *op. cit.*

[93] France and the United Kingdom have declared 6.4 and 1.5 tons of civilian HEU respectively as of the end of 2005 in their INFCIRC/549 declarations. The *IAEA Annual Report 2006*, Table A4. gives 20.2 tons in non-weapon states reports. Reportedly, however, as of the end of 2003, when the IAEA reported 21.7 tons of HEU in non-weapon states, almost 10 tons of the HEU was in either fresh or spent BN-350 fuel, D. Albright and K. Kramer, "Civil HEU Watch: Tracking Inventories of Civil Highly Enriched Uranium," in *Global Stocks of Nuclear Explosive Materials*, ISIS, 2005. The fresh BN-350 HEU fuel has since been blended down and the HEU in the spent fuel, although originally just above 20-percent enriched when fresh, has probably been burned down to less.

[94] For a discussion of these HEU removal efforts and their progress, see M. Bunn, *Securing the Bomb 2007*, Cambridge, Mass., Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, 2007. See also U.S. Department of Energy, National Nuclear Security Administration, *Strategic Plan: Reducing Nuclear and Radiological Threats Worldwide*, Washington, D.C., DOE, 2007.

[95] Data provided by DOE, December 2006. These figures do not include nearly 600 kilograms of HEU removed from Kazakhstan to the United States in Project Sapphire in 1994, or the several kilograms of HEU removed from Georgia to the United Kingdom in Operation Auburn Endeavor in 1998.

[96] "Government of Kazakhstan and NTI Mark Success of HEU Blend-Down Project: Material Could Have Been Used to Make up to Two Dozen Nuclear Bombs," Nuclear Threat Initiative, 8 October 2005, www.nti.org/c_press/release_Kaz_100805.pdf.

[97] D. Albright, F. Berkhout and W. Walker, *Plutonium and Highly Enriched Uranium 1996*, Oxford University Press, 1997, p. 251.

[98] Data provided by DOE, July 2007.

[99] Data provided by DOE, July 2007.

[100] Previously, DOE had selected "melt-and-dilute" technology as the preferred alternative for this fuel, but this technology development program was later terminated.

[101] Data provided by DOE, July 2007.

[102] Data provided by DOE, July 2007.

Chapter 3. Disposition of Excess Plutonium

[103] *Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation*, Washington, D.C., DOE, 2000, www.ipfmlibrary.org/doe00.pdf.

[104] In the United States, South Carolina will not allow the plutonium to be shipped to a consolidation site on its territory unless there is a committed plan for disposition. At one point the Governor of South Carolina threatened to use National Guard troops under his command to stop plutonium shipments on the highway from entering his state. The U.S. Congress has passed legislation that imposes substantial yearly penalties on the Department of Energy if it does not meet promised schedules for plutonium disposition. For a recent discussion of what security benefits plutonium disposition can and cannot offer, and the quantities of plutonium that would have to be subject to disposition to achieve these benefits, see M. Bunn, testimony in Subcommittee on Strategic Forces, Committee on Armed Services, *Disposition of Excess Plutonium: Rethinking Security Objectives and Technological Approaches*, U.S. House of Representatives, 109th Congress, 2nd Session, 26 July 2006, www.ipfmlibrary.org/bun06.pdf.

[105] U.S. Department of Energy, DOE/NN-0007, Washington, D.C., January 1997, pp. 37-39, www.ipfmlibrary.org/doe97.pdf. For the effects of pre-initiation by neutrons in a simple weapon design of the Nagasaki-type, see J. C. Mark, "Explosive Properties of Reactor-Grade Plutonium," and F. von Hippel and E. Lyman, "Appendix: Probabilities of Different Yields," *Science & Global Security*, Vol. 4, 1993, www.ipfmlibrary.org/sgs04mark.pdf. For another authoritative discussion from a committee of the National Academy of Sciences that included several members with extensive weapon design experience and was supported by classified studies by the U.S. national laboratories, see U.S. National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium*, Washington, D.C., National Academy Press, 1994, pp. 32-33. The committee members spoke subsequently about their conclusions on the weapon-usability of reactor-grade plutonium with weapon designers from all five NPT weapon states and found no major disagreements.

[106] Figures for weapon-grade and reactor-grade plutonium at an exposure of 33 Gigawatt-days/ton (GWd/t) from J. C. Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security*, Vol. 4, 1993, pp. 111-128, adjusted for the decay of Pu-241 to Am-241 assuming that the weapon-grade plutonium in question was 20 years old and the reactor-grade plutonium was 10 years old. Figures for super-grade plutonium and blankets from fast-breeder reactors from the same source. Figures for fuel-grade plutonium are from A. Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science & Global Security*, Vol. 14, 2006, pp. 1-24.

[107] *Management and Disposition of Excess Weapons Plutonium*; Washington, D.C., National Academy Press, 1994; and *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, National Academy Press, 1995; full text available at www.nap.edu. These studies built on a range of earlier analyses, including F. Berkhout et al., "Disposition of Separated Plutonium," *Science & Global Security*, Vol. 3, 1993, pp. 161–213, www.ipfmlibrary.org/sgs03berkhout.pdf.

[108] M. Bunn, “Mayak Fissile Material Storage Facility,” in *Nuclear Threat Initiative Research Library: Securing the Bomb*, Cambridge, Mass., and Washington, D.C., Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, 2004,www.nti.org/e_research/cnwm/securing/mayak.asp as of 15 August 2007.

[109] J. P. Holdren and E. P. Velikhov, co-chairs, *Final Report of the US-Russia Independent Scientific Commission on Disposition of Excess Weapons Plutonium*, Washington, D.C., Office of Science and Technology Policy, 1997, www.ipfmlibrary.org/hol97.pdf. The international meeting of G-8 experts was held in Paris in October 1996 in response to a call from the Group of Eight Nuclear Safety and Security Summit held in Moscow earlier that year.

[110] In the long term (after a century or so of cooling), the gamma radiation field around spent fuel will die down to levels that are no longer dangerous enough to deter handling, and additional protective barriers such as deep underground storage would be required, *Management and Disposition of Excess Weapons Plutonium, op. cit.*, p. 205.

[111] *Management and Disposition of Excess Weapons Plutonium, op. cit.*, p. 155. This figure was redrawn for the National Academy report from a 1993 U.S. DOE study.

[112] Private communications, DOE officials. Russia requested U.S. funding for construction of a counterpart facility to the PDCF but dropped the request after the United States made clear that it would require monitoring measures to confirm that what was being processed really was plutonium weapon components.

[113] See, for example, discussion in U.S. Department of Energy, *Plan for Alternative Disposition of Defense Plutonium Materials that were Destined for the Cancelled Plutonium Immobilization Plant*, Washington, D.C., September 2007, Attachment, *Business Case: Department of Energy's Proposed Baseline Approach for Disposing of Surplus Plutonium*, www.em.doe.gov/pages/arodpu.aspx.

[114] For a discussion of typical commercial MOX fabrication costs and prices in the context of the overall fuel cycle, see M. Bunn et al., *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Cambridge, MA, Project on Managing the Atom, Harvard University, 2003, bcsia.ksg.harvard.edu/BCSIA_content/documents/repro-report.pdf.

[115] Assuming operation at full capacity 90 percent of the time and a heat-to-electric energy conversion efficiency of one third. It is also assumed that MOX fuel containing 4 percent by weight plutonium in U-238 has a burnup of 42 gigawatt-days per ton of heavy metal (42 GWd/tHM. Each gigawatt-day would fission about one kilogram of plutonium and uranium.

[116] See e.g. A. Macfarlane, “Immobilization of Excess Weapon Plutonium: A Better Alternative to Glass,” *Science & Global Security*, Vol. 7, 1998, www.ipfmlibrary.org/sgs07macfarlane.pdf.

[117] J. Kang et al., “Storage MOX: A Third Way for Plutonium Disposal?” *Science & Global Security*, Vol. 10, 2002, www.ipfmlibrary.org/sgs10kang.pdf. This idea was originally proposed in the mid-1990s by the Institute of Applied Ecology in Germany (see ref. in Kang et al.).

[118] Joint U.S.-Russian Working Group on *Cost Analysis and Economics in Plutonium Disposition, Cost Estimates for the Disposition of Weapon-Grade Plutonium Withdrawn from Russia's Nuclear Military Programs*, Washington, D.C., U.S. Department of Energy, 2001.

[119] *Russian Weapons Plutonium and the Western Option*, Nuclear Disarmament Forum, Zug, Switzerland, 2002.

[120] For the 2007 date estimated in 2000, see *Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation, op. cit*. For the more recent projection, see Joint U.S.-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition, *Analysis of Russian-Proposed Unified Scenario for Disposition of 34 Metric Tons of Weapon-Grade Plutonium*, Washington, D.C., U.S. Department of Energy, 2006.

[121] H. J. Hebert, “US, Russia Resolve Plutonium Dispute,” *Associated Press*, 15 September 2006.

[122] A. MacLachlan and D. Horner, “Russians, West Still at Standoff on Plutonium Disposition Financing,” *Nuclear Fuel*, Vol. 31, No. 6, 13 March 2006, p. 6; D. Horner and A. MacLachlan, “US, Russia

Sign Liability Accord But Still Face Hurdles in Pu Disposition," *Nuclear Fuel*, Vol. 31, No. 20, 25 September 2006, p. 13. The United States has recently clarified that only funds actually "spent in Russia on the Russian program" will be counted toward the U.S. pledge, and that only $13.3 million that counted toward the pledge had been spent through the end of fiscal year 2006, U.S. Department of Energy, National Nuclear Security Administration, *Report to Congress on the Russian Surplus Fissile Materials Disposition Program*, Washington, D.C., 2007, p. 6.

[123] The initial estimate was given in Joint U.S.-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition, *Cost Estimates for the Disposition of Weapon-Grade Plutonium*, Washington, D.C., U.S. Department of Energy, 2001 and the second in *Analysis of Russian-Proposed Unified Scenario for Disposition of 34 Metric Tons of Weapon-Grade Plutonium*, 2006, *op. cit.*, pp. 12-13.

[124] Assuming 4 percent plutonium in the MOX, 34 tons of plutonium would produce some 850 tons of MOX, at a cost for operations alone of over $2,000 per kilogram of fabricated MOX. This is substantially higher than the operations costs at existing MOX fabrication facilities in France, despite the fact that operations costs of MOX fabrication are primarily labor costs and salaries in Russia are much lower than salaries in France. The detailed budget breakdowns are in Joint U.S.-Russian Working Group on Cost Analysis and Economics in Plutonium Disposition, *Analysis of Russian-Proposed Unified Scenario*, *op. cit.*, pp. 12-13. For a brief review of published estimates relating to capital, operating, and total costs of MOX fabrication in European plants, see Bunn et al., *The Economics of Reprocessing, op. cit.*, pp. 45-51.

[125] D. Horner, "US Officials Say They See Progress in Talks on Russian Pu Disposition," *Nuclear Fuel*, p.12, Vol. 31, No. 16, 31 July 2006.

[126] A. MacLachlan, "Russia, U.S. Could Take Decisive Step in Plutonium Disposition Program," *Nuclear Fuel*, Vol. 32, No. 11, 21 May 2007, pp. 1, 5. As of July 2007, the United States and Russia were negotiating a joint statement on a Russian disposition program relying primarily on the BN-800, interview with Russian officials, May 2007.

[127] MacLachlan, "Russia, U.S. Could Take Decisive Step," *op. cit.*

[128] U.S. Department of Energy, National Nuclear Security Administration, *Report to Congress on the Russian Surplus Fissile Materials Disposition Program*, Washington, D.C., DOE, 2007.

[129] Information provided by DOE, March 2007.

[130] One of the present authors (Bunn) was on the U.S. interagency working group on plutonium disposition at the time.

[131] U.S. Department of Energy, Office of Fissile Materials Disposition, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, Rev. 1, Washington, D.C., DOE, 1996, pp. 4-14.

[132] *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition, op. cit.*, pp. 4-15.

[133] U.S. Department of Energy, *FY 2008 Congressional Budget Request: National Nuclear Security Administration*, Washington, D.C., DOE, 2007, www.ipfmlibrary.org/doe07.pdf, p. 501.

[134] U.S. Department of Energy, *Business Case: DOE's Proposed Baseline Approach for Disposing of Surplus Plutonium*, 2007, *op. cit.*, p. 13.

[135] U.S. Department of Energy, *Disposition of Surplus U.S. Fissile Materials: Comparative Analysis of Alternative Approaches*, Washington, D.C., DOE, 2006. This study estimates the cost (including storage pending disposition) for an alternative including both MOX and immobilization as $15 billion (constant 2006 dollars) through 2050. Without storage, the costs for MOX and immobilization would be just under $10 billion. These are going-forward costs, neglecting the hundreds of millions of dollars already spent. Indeed, Congress has already appropriated nearly $2.5 billion for U.S. plutonium disposition efforts through FY 2006, A. Wier, "Interactive Budget Database," in *Nuclear Threat Initiative Research Library: Securing the Bomb*, Cambridge, MA, and Washington, D.C., Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, 2006, www.nti.org/e_research/cnwm/overview/funding.asp.

[136] U.S. Department of Energy, Office of the Inspector General, *Audit Report: Status of the Mixed Oxide Fuel Fabrication Facility*, DOE/IG-0713, Washington, D.C., 2005, www.ipfmlibrary.org/doe05a.pdf.

[137] The current estimate is that the U.S. MOX plant will have a capital cost of $4.7 billion, compared to the reported capital cost of roughly $540 million (in 2003 dollars) for the Sellafield, U.K. MOX plant, which has more than twice the U.S. plant's design MOX-fuel production capacity, U.S. Department of Energy, *FY 2008 NNSA Budget Request*, p. 500. Official British estimates of the cost of the Sellafield MOX plant, and discussions of a range of other reports of the capital and operating costs for MOX plants in Europe, can be found in Bunn et al., *The Economics of Reprocessing, op. cit.*, pp. 45-51. The operations and maintenance costs for the U.S. MOX plant come to roughly $4,000 per kilogram of MOX fabricated—several times the operations costs of comparable European plants. For the annual operations and maintenance cost figure for the U.S. plant, see U.S. Department of Energy, *FY 2008 NNSA Budget Request*, p. 501. The cost per kilogram of MOX is estimated by assuming an average loading of 6 percent plutonium by weight in MOX fuel, so that 34 tons of plutonium would make 570 tons of MOX. Produced over 13 years, at a cost of $184 million/year, this comes to over $4,000 per kilogram of MOX.

[138] House Appropriations Committee, *Energy and Water Development Appropriations Bill, 2008*, Report 110-185, 11 June 2007, pp. 70-71, 113, 177.

[139] The 13 tons is obtained as follows. Declared excess: 52.5 tons plus up to 4.4 tons in the future. Subtract 34 tons for MOX, 7 tons already in spent fuel and 3 tons in waste to be disposed of in the Waste Isolation Pilot Plant.

[140] For a useful overview of this proposed baseline approach and the possible alternative of eliminating the vitrification plant, with year-by-year cost estimates for the relevant facilities, see *Business Case: DOE's Proposed Baseline Approach for Disposing of Surplus Plutonium, 2007., op. cit.* See also U.S. Department of Energy, "Notice of Intent To Prepare a Supplemental Environmental Impact Statement for Surplus Plutonium Disposition at the Savannah River Site," Federal Register, Vol. 72, No. 59, 28 March 2007, pp. 14,543-546.

[141] *Plutonium Disposition Alternatives Analysis*, Savannah River, S. C., Savannah River Site, 2006; *Business Case: DOE's Proposed Baseline Approach for Disposing of Surplus Plutonium, 2007, op. cit.* Unfortunately, however, DOE's analyses have not appropriately separated the costs of storing excess and non-excess plutonium, or the costs of storing the excess plutonium slated for use as MOX from the costs of storing other excess plutonium. Most of the plutonium slated for use as MOX is stored at the DOE's Pantex warhead assembly/disassembly facility, where nuclear weapons and reserve plutonium will continue to be stored regardless. The additional annual cost of storing excess plutonium at Pantex may be in the range of $5 million per year. Interview with DOE officials, April 2007.

[142] *Disposition of Surplus U.S. Fissile Materials: Comparative Analysis of Alternative Approaches, 2006, op. cit.*

[143] *Disposition of Surplus U.S. Fissile Materials: Comparative Analysis of Alternative Approaches, 2006, op. cit.* An earlier version of this study, from July 2006, indicated that the all-immobilization option would be more expensive than the mixed option. Why this changed has not been publicly explained. Also DOE has only examined immobilization options that would build an entirely new facility using ceramic immobilization rather than vitrification in glass. DOE projects that this would require a further eight years of research and development and that such a plant could not be operational until 2019-2021, U.S. Department of Energy, *Business Case: DOE's Proposed Baseline Approach for Disposing of Surplus Plutonium*, Washington, D.C., DOE, 2007. In 2000, by contrast, DOE estimated that it could design, build, and begin operating a plutonium immobilization plant within eight years, U.S. Department of Energy, Office of Fissile Materials Disposition, *Strategic Plan,* Washington, D.C., DOE, 2000.

[144] One internal Energy Department study, for example, concluded that an immobilization plant capable of handling all the excess plutonium would not come on-line until 2019 and would have to operate for many years, while the HLW vitrification at Savannah River would be done by 2023. Information provided by DOE, July 2006.

[145] Some immobilization experts have raised doubts about the workability of the approach DOE is proposing for this facility. It relies on a melter type that has not been proven at this scale and assumes plutonium concentrations in the glass that have previously led to phase separation of the plutonium from the glass, potentially creating repository performance problems. It also involves an entirely hands-on approach leading to significant worker neutron doses. Finally, installation is proposed in an existing facility designed for other purposes. Personal communication with a DOE laboratory expert, April 2007.

[146] As of mid-2007, the latest DOE documents indicate that the end of HLW vitrification at Savannah River has been delayed until 2028. U.S. Department of Energy, *FY 2008 Congressional Budget Request: Environmental Management*, Washington, D.C., DOE, 2007, www.ipfmlibrary.org/doe07a.pdf, p. 298. If the plutonium immobilization plant began operations in 2013 and could process 3 to 4 tons of plutonium per year rather than two, 38.5 tons of plutonium would have been vitrified by 2026. A rate of 3-4 tons of plutonium per year would require 100-160 canisters of vitrified high-level waste per year. This is compatible with current plans to produce 150-250 canisters per year.

[147] E. S. Lyman, "Letter from UCS Calling on DOE to Suspend MOX Plant Construction," Washington, D.C., Union of Concerned Scientists, 2007.

[148] T. Katsuta and T. Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges*, Research Report #2, International Panel on Fissile Materials, 2006, www.ipfmlibrary.org/rr02.pdf.

[149] For an excellent in-depth examination of disposition options in the United Kingdom from the perspective of critics of reprocessing, see F. Barker and M. Sadnicki, *The Disposition of Civil Plutonium in the U.K.*, 2001.

[150] The Russia-U.S.-IAEA Trilateral Initiative devised arrangements under which the IAEA could verify that canisters containing plutonium pits contained more than a threshold quantity of weapon-grade plutonium metal without revealing sensitive design information, T. Shea, *The Trilateral Initiative: IAEA Verification of Weapon-Origin Fissile Material in the Russian Federation and the United States*, Pacific North West Laboratory, PNNL-16584, 2007.

Chapter 4. Fissile Material Consolidation in the U.S. Nuclear Complex

[151] The total DOE Safeguards and Security budget was $1.51 billion, from which we have subtracted information security ($34 million); cyber security ($118 million); half of personnel security ($21 million); and a prorated share (15%) of Headquarter Security ($49 million), *Department of Energy, FY Congressional Budget Request*, Vol. 2, www.ipfmlibrary.org/doe07b.pdf, pp. 176-186.

[152] This report is based in large part on updates of the Project on Government Oversight's (POGO) reports, *U.S. Nuclear Weapons Complex: Homeland Security Opportunities*, May 2005, www.pogo.org/p/homeland/ho-050301-consolidation.html; and *U.S. Nuclear Weapons Complex: Y-12 and Oak Ridge National Laboratory at High Risk*, October 2006, www.pogo.org/p/homeland/ho-061001-Y12.html. See also P. Stockton's 5 April 2006 testimony before the House Armed Services Committee Subcommittee on Strategic Forces, and N. Schwellenbach and P. Stockton, "Nuclear Lockdown," *Bulletin of the Atomic Scientists*, November/December 2006, p. 44.

[153] "Energy Secretary Abraham says Rocky Flats Weapons Complex is Now Free of Nuclear Weapon Usable Material," DOE press release, 19 August 2003. The press release says that "more than 12 metric tons of plutonium" were removed.

[154] Adapted from *Nuclear Material Control and Accountancy*, U.S. Department of Energy, DOE M 470.4-6, Chapter 1, 14 August, 2006, www.directives.doe.gov, Table I-4, "Graded Safeguards." The IAEA's definitions of Category I and II nuclear materials are somewhat less elaborated and given in *The Physical Protection of Nuclear Material and Nuclear Facilities*, International Atomic Energy Agency, INFCIRC/225/Rev.4 (corrected).

[155] For a more extensive discussion of the history of DOE DBTs, see *U.S. Nuclear Weapons Complex: Y-12 and Oak Ridge National Laboratory at High Risk, op. cit.*

[156] The primary concern is INDs made of HEU, which can be assembled into a supercritical mass using a gun-type method, i.e., by shooting one subcritical mass into another. Plutonium would produce only a low yield if assembled by this relatively slow method since it generates spontaneous neutrons that would start the chain reaction prematurely while the degree of super-criticality was still quite low. Two other fissile materials exist that also produce spontaneous neutrons at a low rate and therefore could be used to create a gun-type IND: uranium-233 and neptunium-237. The Oak Ridge National Laboratory has about a ton of U-233. The Idaho National Laboratory has about 300 kg of neptunium-237, which is used as a target material in nuclear reactors to produce plutonium-238 for radioisotope heat generators.

[157] *Actions Needed by DOE to Improve Security of Weapons-Grade Nuclear Material at its Energy, Science and Environment Sites*, U.S. Government Accountability Office, GAO-05-943T, 2005, p. 2, www.gao.gov/new.items/d05934t.pdf.

[158] The full e-mail from then-NNSA Administrator, Linton Brooks, is reproduced in *U.S. Nuclear Weapons Complex: Y-12 and Oak Ridge National Laboratory at High Risk, op. cit.*, Appendix B.

[159] *Actions Needed by DOE to Improve Security of Weapons-Grade Nuclear Material at its Energy, Science and Environment Sites, GAO, op. cit.*, pp. 5-6.

[160] Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 1, p. 387.

[161] "National Nuclear Security Administration (NNSA) Phase Compliance Timeline for the 2005 Design Basis Threat (DBT) Policy," memo from Clay Sell, Deputy Secretary, DOE, to Linton Brooks, Administrator, National Nuclear Security Administration, 5 December 2006; Department of Energy*, FY 2008 Congressional Budget Request, National Nuclear Security Administration*, DOE/CF-014, Vol. 1, www.ipfmlibrary.org/doe07.pdf, pp. 387-389. It is indicated on pp. 388-9 that NNSA has the objective of "implementing the 2005 Design Basis Threat policy upgrades at Pantex, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Nevada Test Site, and Y-12," i.e., at all NNSA sites other than Sandia. With regard to Hanford, it states (Vol. 5, p. 527) that "[i]n a memorandum signed on April 19, 2006 by the Deputy Secretary of DOE, Richland received an exemption to provide relief from further security upgrades and enhancements that would fully implement threat level and protection strategy requirements outlined in the 2005 Design Basis Threat. This is being done in response to the Department's plans to consolidate plutonium off site." Also NNSA official, personal communication.

[162] The NRC DBT for these facilities is slightly higher than the DBT it uses for commercial nuclear power plants.

[163] U.S. Government Accountability Office, *DOE and NRC Security Requirements*, GAO-07-41c (classified), 2007.

[164] Study chaired by Roger Hagengruber, a former Deputy Director of Sandia National Laboratory. According to several people who read the report, it recommended using the Kirtland Underground Munitions Storage Complex (KUMSEC) at the Kirtland Air Force Base in Albuquerque, New Mexico and the Device Assembly Facility on the Nevada Test Site as design templates for the proposed underground storage facilities.

[165] Representative Edward Markey requested an unclassified version in a 23 January 2002 letter, www.pogo.org/m/ep/ep-markeyscowcroft.pdf, but, to the best of his staff's recollection, never received one.

[166] *Recommendations for the Nuclear Weapons Complex of the Future*, Report of the Secretary of Energy Advisory Board Nuclear Weapons Complex Infrastructure Task Force, 13 July 2005, www.seab.energy.gov/publications/NWCITFRept-7-11-05.pdf., p. 19, Appendices D and G.

[167] *Complex 2030: An Infrastructure Planning Scenario for a Nuclear Weapons Complex Able to Meet the Threats of the 21st Century*, National Nuclear Security Administration, Office of Defense Programs, DOE/NA-0013, October 2006, p. 10.

[168] *National Defense Authorization Act for fiscal year 2007*, Section 4214, A.7.

[169] Criticality experiments are used to check theoretical determinations of whether specific configurations of fissile and other materials can sustain a fission chain reaction. The quantity of fissile materials formerly in TA-18 is reported in *Proposed Relocation of Technical Area 18 Capabilities and Materials at the Los Alamos National Laboratory, Final Environmental Impact Statement*, Department of Energy, DOE/EIS-319, 2002, p. 3-6, www.eh.doe.gov/nepa/eis/eis0319/0319toc.html.

[170] *Sensitive Nuclear Material Out of Los Alamos TA-18 Facility: Most Now Housed at the Highly Secure Device Assembly Facility in the Nevada Desert*, NNSA news release, 2 November 2005, www.nnsa.doe.gov/docs/newsreleases/2005/PR_2005-11-02_NA-05-27.htm.

[171] Image from www.globalsecurity.org.

[172] Remarks of Energy Secretary, Spencer Abraham for the 32nd Annual Security Police Officer Training Competition, 7 May 2004.

[173] *Report on the Plan for Transformation of the National Nuclear Security Administration Nuclear Weapons Complex*, NNSA, 31 January 2007, p. 8 and person communication, senior NNSA security official, 11 August 2007. Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 1, p. 611, states that "Beginning in FY 2007, the focus of [safeguards and security] activities will be to reduce Category I holdings of Special Nuclear Material to minimum levels required to support Program operations with corresponding reductions to follow in subsequent fiscal years." The projected safeguards and security budget declines from $93 million in FY 2006, to $86 million in FY 2008.

[174] The fuel is 35-percent enriched, *Nuclear Research Reactors in the World*, IAEA, 2000. Irradiation results in a fission-product-generated radiation field.

[175] In 1999, the DOE plan was to shift the reactor to full-time production of medical isotopes, "Sandia National Laboraories/New Mexico Site Wide Environmental Impact Statement, Record of Decision," *Federal Register*, No. 64, 15 December 1999, p. 69,996. That plan was abandoned, however, and, in 2006, the DOE Office of Nuclear Energy stated, "the Department will decide in 2006 either to transfer the reactor to the National Nuclear Security Administration or shut it down," Radiological Facilities Management Program, www.ne.doe.gov/pdfFiles/radfac.pdf.

[176] Private communication, GTRI official, 15 February 2007. The ACRR is a TRIGA reactor and replacement LEU fuel is available, "LEU Conversion Status of U.S. Research Reactors," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors*, 7-10 October 1996, Seoul, South Korea.

[177] A description of the plutonium-related activities carried out in the Superblock may be found in "Inside the Superblock," *Science & Technology Review*, March 2001.

[178] Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 1, p. 581.

[179] *Alternative Futures for the Department of Energy National Laboratories*, DOE, 1995, www.lbl.gov/LBL-PID/Galvin-Report/Galvin-Report.html, Chapter 2.3.

[180] "Record of Decision: Final Site-Wide Environmental Impact Statement for Continued Operation of Lawrence Livermore National Laboratory and Supplemental Stockpile Stewardship and Management Programmatic Environmental Impact Statement," National Nuclear Security Administration, *Federal Register*, 29 November 2005, p. 71,491. The limit on the amount of HEU that could be kept on site was kept at 500 kilograms.

[181] *National Defense Authorization Act for fiscal year 2007*, Section 4214, A.7.

[182] *Report on the Plan for Transformation of the National Nuclear Security Administration Nuclear Weapons Complex*, NNSA, 31 January 2007, pp. ii, 8.

[183] Personal communication from a senior NNSA security official, 11 August 2007.

[184] K. Davidson, "Modern Gatling Guns to Defend Against Land, Air Terrorist Attack at Livermore National Laboratory," *San Francisco Chronicle*, 3 February 2006.

[185] Statements of the quantity of U-233 differ widely. C. Forsberg, "Uses for 233U," Oak Ridge National Laboratory, 22 March 2000, states 1.5 tons. The Defense Nuclear Facilities Safety Board Technical Report, *Savannah River Site Canyon Utilization*, March 2002, www.ipfmlibrary.org/dnfsb02.pdf, Table 1 states that DOE has an inventory of 1250 items containing about 815 kg of U-233. DOE claims 450 kg at Oak Ridge in its FY 2007 Budget Request: Environmental Management, www.ipfmlibrary.org/doe07a.pdf, p. 183.

[186] U-233 has an un-reflected critical mass of 16 kg, as compared to 10 kg for Pu-239 and 52 kg for U-235, see Figure A.2.

[187] Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 4, p. 478.

[188] *Draft Environmental Assessment for U-233 Stabilization and Building 3019 Complex Shutdown at the Oak Ridge National Laboratory, Oak Ridge, Tennessee*, DOE/EA-1574, December 2006, www.ipfmlibrary.org/doe06b.pdf.

[189] Department of Energy, *FY 2008 Congressional Budget Request, Environmental Management*, pp. 553-556, www.ipfmlibrary.org/doe07a.pdf.

[190] The House Energy and Water Appropriations Subcommittee provided $50 million for this project in its proposal for the fiscal year 2008 budget "to begin disposition of the material in fiscal year 2008," *Energy and Water Development Appropriations Bill*, 2008, May 2007, p. 119.

[191] *Reduced Enrichment Research and Test Reactor Program Project Execution Plan*, 16 February 2004, Table B4.

[192] J. Roglans-Ribas, "U.S. Domestic Efforts and Commitments to Convert Remaining Civilian HEU Research Reactors," abstract of talk presented at the International Symposium on Minimization of Highly Enriched Uranium in the Civilian Nuclear Sector, 17-20 June 2006, Oslo, Norway.

[193] Department of Energy, *Plutonium: The First 50 Years*, DOE/DP-0137, 1996, www.ipfmlibrary.org/doe96.pdf, p. 29.

[194] Four tons from the Plutonium Finishing Plant from "Hanford's Plutonium Finishing Plant Begins Plutonium Solutions Stabilization," 19 September 2000; and "Hanford's Plutonium Finishing Plant Starts up New Automatic Packaging System," 2 October 2000, both documents available at www.hanford.gov/communication/reporter/. Fifty-five unirradiated FFTF fuel assemblies in 1993 containing approximately 10 kg of plutonium each from DOE, *Programmatic Spent Nuclear Fuel Management and Idaho National Engineering Laboratory Environmental Restoration and Waste Management Programs Final Environmental Impact Statement*, 1995, Vol. 1, Appendix A, Section 2.3.3; and DOE, Office of Civilian Radiation Waste Management, *Canister Handling Criticality Safety Calculations*, 2005, www.ocrwm.doe.gov/documents/design/44370/44370.pdf, p. 30.

[195] *Securing U.S. Nuclear Materials: DOE Needs to Take Action to Safely Consolidate Plutonium*, U.S. Government Accountability Office, GAO-05-665, July 2005, p. 6.

[196] "Section 3155 of the National Defense Authorization Act for fiscal year 2002 provides that if DOE decides not to construct either of the two proposed plutonium disposition facilities at SRS [plutonium immobilization plant and a mixed oxide fuel fabrication facility], DOE is prohibited from shipping plutonium to SRS until a plan to process the material for permanent disposition is developed and submitted to the Congress," *Securing U.S. Nuclear Materials: DOE Needs to Take Action to Safely Consolidate Plutonium, op. cit.*, p. 11. Another complication is that some of the Hanford plutonium is in 12-foot-long unirradiated fuel rods while the Savannah River facility is designed to store plutonium in 5-inch-diameter, 10-inch-long cans, *ibid*. As this report went to press, the Department of Energy released a plan for disposing of all of the plutonium at the Savannah River Site, U.S. Department of Energy, *Plan for Alternative Disposition of Defense Plutonium Materials that were Destined for the Cancelled Plutonium Immobilization Plant*, September 2007. It announced at the same time that, unless Congress disapproved within 30 days, it would ship the canned plutonium at Hanford to Savannah River "over a period of about two or three years." It added that it might transfer to the Savannah River Site as well "unirradiated fuel assemblies [and miscellaneous fuel pins] originally intended for the Fast Flux Test Facility," U.S. Department of Energy, *Amended Record of Decision: Storage of Surplus Plutonium Materials at the Savannah River Site*, 5 September 2007, www.em.doe.gov/pages/arodpu.aspx.

[197] *Department of Energy, FY 2008 Congressional Budget Request, Environmental Management*, pp. 310-311, www.ipfmlibrary.org/doe07a.pdf.

[198] DOE official, personal communication. Table 1 shows 26.2 tons of HEU in 1993, but much of that was and is in naval-reactor and other spent fuel.

[199] The ZPR-6 and ZPR-9 critical assemblies.

[200] INL official, personal communication, 25 January 2007.

[201] "(INL) has disposed of almost three tons of fissile material, including some 600 kg of HEU critical experiment fuel plates. The INL plans to dispose of an additional eight tons of HEU as resources become available over the next several years. Nevertheless, the Laboratory will continue to maintain a smaller inventory of well-protected HEU for various nuclear energy and national security programs," H. McFarlane, "Is it Time to Consider Global Sharing of Integral Physics Data?" *Journal of Nuclear Science and Technology*, Vol. 44, 2007, p. 1.

[202] "The U.S. House Energy and Water Appropriations Bill for fiscal year 2008 provides $50 million for the Material Security and Consolidation Project at Building 651 and 691, Idaho National Labo-

ratory," House Appropriations Committee, *Energy and Water Development Appropriations Bill, 2008*, Report 110-185, May 2007, p. 107. It is not clear, however, why two buildings are required for this purpose.

[203] Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 2, p. 104. Aerial views of the three main INL research areas are shown on an "INL Facilities" fact sheet, www.inl.gov/factsheets/docs/facilities.pdf.

[204] *Draft Environmental Impact Statement for the Proposed Consolidation of Nuclear Operations Related to Production of Radioisotope Power*, DOE/EIS-0373D, 2005. Neutron capture transmutes some of the Np-237 into 88-year half-life plutonium-238, which generates 560 Watts of heat per kilogram of Pu-238.

[205] Department of Energy, *RERTR Program Project Execution Plan*, 16 February 2004, Table B4.

[206] *Securing U.S. Nuclear Materials: DOE Needs to Take Action to Safely Consolidate Plutonium, op. cit.*, p. 12; and Department of Energy, *FY 2008 Congressional Budget Request*, p. 307.

[207] According to a 1996 DOE assessment, two buildings "have approximately 100 metric tons of unstabilized HEU process materials in temporary storage," *Highly Enriched Uranium Working Group Report on Environmental, Safety and Health Vulnerabilities Associated with the Department's Storage of Highly Enriched Uranium*, Vol. I, p. 11, U.S. Department of Energy, 1996.

[208] For a discussion of the manifold security, environmental, operational and safety problems at the Y-12 site, see POGO, *U.S. Nuclear Weapons Complex: Y-12 and Oak Ridge National Laboratory at High Risk, op. cit.*; and R. Alvarez, *Reducing the Risks of Highly Enriched Uranium at the U.S. Department of Energy's Y-12 National Security Complex*, October 2006, www.ips-dc.org/reports/Y12-report.pdf.

[209] *Energy and Water Appropriations Bill, 2007*, Senate Committee Report 109-274, 29 June 2006, p. 155; *Report on the Plan for Transformation of the National Nuclear Security Administration Nuclear Weapons Complex*, NNSA, 31 January 2007, *op. cit.*, Fig. 6.2.

[210] Radiography of weapon components at the TA-8 site has "been shut down in direct response to security issues," personal communication from a senior DOE official, 11 August 2007; and, during FY 2008, DOE plans to eliminate another (unspecified) site at the laboratory that holds Category I materials, Department of Energy, *FY 2008 Congressional Budget Request*, Vol. 1, p. 595.

[211] J. Medalia, *Nuclear Warhead "Pit" Production: Background and Issues for Congress*, Congressional Research Service, 2004.

[212] Six W88 pits were manufactured in FY 2005, www.ipfmlibrary.org/doe06c.pdf, p. 188.

[213] A discussion of the modification requirements for expansion to 80 pits per year may be found in the *Draft Supplemental Programmatic Environmental Impact Statement on Stockpile Stewardship and Management for a Modern Pit Facility*, U.S. Department of Energy, DOE/EIS-0236-S2, 2003, Chapter 1, p. S-4, and Chapter 3, p. S-24. See also "The Pit Production Story," *Los Alamos Science*, Vol. 28, 2003, p. 58.

[214] The estimated cost given in the FY 2007 DOE budget submission was $0.745-0.975 billion, www.ipfmlibrary.org/doe06c.pdf, p. 285.

[215] *Energy and Water Development Appropriations Bill*, House Appropriations Committee Report 109-474, 2006, p. 109.

[216] *Energy and Water Development Appropriations Bill*, 2008, *op. cit.*, May 2007, p. 105.

[217] R. J. Hemley and D. Meiron, et al., *Pit Lifetime*, JSR-06-335, MITRE Corp., November 2006, Executive Summary, www.ipfmlibrary.org/jas06.pdf. For the dates of original manufacture of the pits, see, for example, *The Modern Pit Facility*, American Physical Society Panel on Public Affairs, April 2004.

[218] The U.S. nuclear weapon laboratories are making a new argument for designing and producing replacement warheads with newly manufactured pits, the "Reliable Replacement Warhead Program." The replacement warheads would be safer, have more security against unauthorized use, be simpler in design, and use less toxic materials—except for plutonium. No strong case has yet been made, however, that the current warheads are not safe, secure and reliable enough. The core underly-

ing argument for the program seems to be that, in order to maintain the capability to design new warheads, the weapon laboratories must continue to do so even if new warheads are not needed, J. Medalia, *Nuclear Warheads: The Reliable Replacement Warhead Program and the Life Extension Program*, Congressional Research Service Report # RL33748, 30 January 2007. Even if that argument is accepted, however, it does not mean that the new warheads must be manufactured in quantity.

[219] R. S. Norris and H. Kristensen, "Dismantling U.S. Nuclear Warheads," *Bulletin of the Atomic Scientists*, January/February, 2004, p. 72.

[220] Department of Energy, *Final Environmental Impact Statement for the Continued Operation of the Pantex Plant and Associated Storage of Nuclear Weapon Components*, EIS-0225, 1996, Chapter 5, Section 5.2, available at www.globalsecurity.org. The area within the Device Assembly Facility that would be required is given as 1170 m^2.

[221] www.nuclearfuelservices.com; www.bwxt.com/operations/npd.html.

[222] C. Ma and F. von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Spring, 2001.

Chapter 5. Progress Toward Nuclear Disarmament

[223] U.N.G.A. Resolution 1.1, 24 January 1946.

[224] This does not include the possibility of an Israeli or joint Israeli-South African nuclear test or series of tests in 1979. A declassified U.S. National Security Council memo concludes that the U.S. intelligence community had "high confidence after intense technical scrutiny" that there had been a "low-yield atmospheric nuclear explosion" on 22 September 1979. *South Atlantic Nuclear Event*, National Security Council Memo for Secretary of State, Defense, Energy, etc., www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB190/01.pdf, 22 October 1979.

[225] The NPT Treaty is available at www.disarmament.un.org and www.ipfmlibrary.org/npt68.pdf.

[226] International Court of Justice Advisory Opinion of 8 July 1996, "Legality of the Threat or Use of Nuclear Weapons." See also, J. Burroughs, *The (Il)legality of Threat or Use of Nuclear Weapons*, International Association of Lawyers Against Nuclear Arms, Lit Verlag, Münster, 1997.

[227] R. Johnson, "The 2000 NPT Review Conference: A Delicate, Hard-Won Compromise," *Disarmament Diplomacy*, Issue No. 46, May 2000.

[228] "Establishment of a NWFZ in the Middle East," Explanation of Vote by Mr. Alon Bar, Director of Arms Control, Ministry of Foreign Affairs, Jerusalem, 26 October 2004, www.israel-un.org, mirrored at www.ipfmlibrary.org/bar04.pdf.

[229] Lahore Declaration, 21 February 1999, www.indianembassy.org, mirrored at www.ipfmlibrary.org/vaj99.pdf.

[230] "Joint Statement of the Fourth Round of the Six-Party Talks, Beijing, September 19, 2005," www.state.gov/r/pa/prs/ps/2005/53490.htm. The six parties are China, North Korea, South Korea, Japan, Russia and the United States.

[231] The texts of the 1972 SALT I Treaty, the 1979 SALT II Treaty, the 1987 INF Treaty, and the 1991 START Treaty are available at www.state.gov.

[232] J. Handler, "The 1991-1992 PNIs and the Elimination, Storage, and Security of Tactical Nuclear Weapons," in A. Millar and B. Alexander, eds., *Tactical Nuclear Weapons: Emerging Threats in an Evolving Security Environment*, Brassey's Inc., Washongton D.C., 2003, pp. 20-41. The announcements by President G. H. W. Bush, President Mikhail Gorbachev, and President Boris Yeltsin are given in Appendix A of that book, pp. 167-181.

[233] A. Diakov estimates 3000, personal communication, 15 April 2007. R. Norris and H. Kristensen, "Russian Nuclear Forces 2007," *Bulletin of the Atomic Scientists*, March/April 2007, pp. 61–64, estimates 2300.

[234] The United States is estimated to have 500 operational tactical nuclear weapons and another 790 in its inactive/responsive stockpile. R. Norris and H. Kristensen, "U.S. Nuclear Forces, 2007," *Bulletin of the Atomic Scientists*, January/February 2007, pp. 79-82.

[235] In 2005, there were an estimated 480 U.S. nuclear weapons in Europe. H. Kristensen, *U.S. Nuclear Weapons in Europe: A Review of Post-Cold War Policy, Force Levels, and War Planning*, NRDC, 2005, www.nrdc.org/nuclear/euro/euro.pdf. The number and locations in the various European countries are given in Appendix A, p. 75. The current total of 350 reflects the U.S. removal of nuclear weapons from its Ramstein base in Germany. H. Kristensen, "United States Removes Nuclear Weapons From German Base, Documents Indicate," FAS Strategic Security Blog, www.fas.org/blog/ssp/2007/07/united_states_removes_nuclear.php.

[236] H. Kristensen, Federation of American Scientists, personal communication, 24 July 2007.

[237] Strategic Offensive Reductions Treaty, available at www.state.gov.

[238] A. Diakov and E. Miasnikov, "ReSTART: The Need for a New U.S.-Russian Strategic Arms Agreement," *Arms Control Today*, September 2006, www.armscontrol.org/act/2006_09/restart.asp.

[239] Ambassador William J. Burns, "Atoms for Peace Revisited: A New Agenda for U.S.-Russian Nuclear Leadership," address at the Carnegie Moscow Center, 1 March 2007, moscow.usembassy.gov, mirrored at www.ipfmlibrary.org/bur07.pdf.

[240] H. Kristensen, *U.S. Nuclear Weapons in Europe: A Review of Post-Cold War Policy, Force Levels, and War Planning, op. cit.*

[241] "World Nuclear Forces, 2007," *SIPRI Yearbook 2007*, Oxford University Press, 2007, p. 514.

[242] B. Blair, H. Feiveson and F. von Hippel, "Taking Nuclear Weapons off Hair-Trigger Alert," *Scientific American*, November 1997, pp. 74-81.

[243] Norris and Kristensen, "U.S. Nuclear Forces, 2007," *op. cit.*

[244] *Ibid*.

[245] "US Air Force Decides to Retire Advanced Cruise Missile," FAS Strategic Security Blog, 7 March 2007, www.fas.org/blog/ssp/2007/03/us_air_force_decides_to_retire.php.

[246] R. Norris and H. Kristensen, "Dismantling U.S. Nuclear Warheads," *Bulletin of the Atomic Scientists*, January/February 2004.

[247] "Dismantling the Bomb and Managing the Nuclear Materials," in *Future Disposition of Nuclear Materials from Dismantled Weapons*, OTA, September 1993, www.ipfmlibrary.org/ota93.pdf, p. 80.

[248] Norris and Kristensen, "Dismantling U.S. Nuclear Warheads," *op. cit.*

[249] The figure shows an AL-R8 container used at Pantex and is adapted from GAO, *Problems and Progress in Managing Plutonium*, GAO/RCED-98-68, April 1998, www.gao.gov/archive/1998/rc98068.pdf.

[250] Norris and Kristensen, "Russian Nuclear Forces, 2007," *op. cit.*

[251] R. Norris and H. Kristensen, "The U.S. Nuclear Stockpile, Today and Tomorrow," *Bulletin of the Atomic Scientists*, September/October 2007.

[252] *The Nuclear Turning Point*, H. Feiveson, ed., Brookings Institution Press, 1999.

[253] *Ibid*. Table 7.5, "Notional U.S. and Russian Forces 1000-Warhead (START IV) Nuclear Forces in 2012," p. 149.

[254] S. D. Drell, and J. E. Goodby, *What Are Nuclear Weapons For? Recommendations for Restructuring U.S. Strategic Nuclear Forces*, Arms Control Association, April 2005.

[255] M. Littlejohns and B. Gray, "U.K. has Halted the Build-Up of Nuclear Material," *Financial Times*, 19 April 1995.

[256] Atlantic Council, “Nuclear Weapons and European Security,” *Bulletin*, Vol. 6, 31 October 1995, cited in *The Nuclear Turning Point, op. cit.*, p. 195, Fn. 5.

[257] *Nuclear Turning Point, op. cit.*, Table 7.6, p. 152.

[258] *The Future of the United Kingdom’s Nuclear Deterrent*, Cm 6994, Secretary of State for Defence and Secretary of State for Foreign and Commonwealth Affairs, London, December 2006, www.ipfmlibrary.org/mod06b.pdf.

[259] *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, Washington, D.C., 1994, p. 104.

[260] A. Diakov, personal communication, 24 March 2007.

[261] O. Bukharin, “The Changing Russian and U.S. Nuclear Weapons Complexes: Challenges for Transparency,” in N. Zarimpas, ed., *Transparency in Nuclear and Warheads and Materials*, SIPRI, Oxford University Press, 2003, pp. 180-205, see Table 9.1, p. 182-183. Dismantlement at two other sites: Sarov (Arzamas-16), and Zasrechny (Penza-19), was to end in 2003.

[262] *Dismantling the Bomb and Managing the Nuclear Materials*, U.S. Congress, Office of Technology Assessment, September 1993, www.ipfmlibrary.org/ota93.pdf, Table 12.2, p. 24. An additional 100-400 weapons were dismantled and mostly re-assembled each year for quality assurance and reliability assessment.

[263] Office of Defense Programs, *FY 2000 Stockpile Stewardship Plan*, Department of Energy, 15 March 1999, Appendix E, p. E-2.

[264] W. Pincus, “U.S. to Step Up Disassembly of Older Nuclear Warheads,” *Washington Post*, 4 May 2006.

[265] *Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to their Environmental Consequences*, Office of Environmental Management, Department of Energy, DOE/EM-0319, January 1997, p. 196.

[266] O. Bukharin, “The Russian and U.S. Nuclear Weapon Complexes,” in T*ransparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, N. Zarimpas, ed., Oxford University Press, 2003, p.189, Fn. 15. Out of the 73 bays and cells, 42 are currently in use, with the rest either used for training or not refurbished. Peter Stockton, private communication, 30 May, 2007.

[267] “Pit Storage,” *Pantex Info*, www.pantex.com, June 2007, www.ipfmlibrary.org/pan07.pdf.

[268] *Complex 2030: An Infrastructure Planning Scenario for a Nuclear Weapons Complex Able to Meet the Threats of the 21st Century*, NNSA, DOE/NA-0013, 23 October 2006, p.8, www.ipfmlibrary.org/doe06e.pdf. The plan calls for moving forward the deadline for dismantlement of “legacy weapons currently planned for retirement” from 2034 to 2023.

[269] Norris and Kristensen, “The U.S. Nuclear Stockpile, Today and Tomorrow,“ *op. cit.*

[270] House of Representatives, H.R. 1585, National Defense Authorization Bill for fiscal year 2008, Section 3113, *Report On Retirement and Dismantlement of Nuclear Warheads*, pp. 780-781.

[271] NNSA, “Life Extension Refurbishment Program Completed for W87 Warheads,” 19 November 2004. Estimated number of W-87 warheads from Norris and Kristensen, “The U.S. Nuclear Stockpile, Today and Tomorrow,“ *op. cit.*

[272] “NNSA Achieves Significant Milestone for B61 Bomb,” *NNSA Newsletter*, August 2006.

[273] W80 LEP was cancelled by the Nuclear Weapons Council as of 2006. White House Office of Management and Budget, www.whitehouse.gov/omb/expectmore/detail/10002126.2004.html.

[274] Department of Energy, Office of Inspector General, Office of Audit Services, *W76 Life Extension Project*, DOE/IG-0729, May 2006, www.ipfmlibrary.org/doe06d.pdf.

[275] Norris and Kristensen, “The U.S. Nuclear Stockpile, Today and Tomorrow,“ *op. cit.*

[276] E. H. Beckner, Deputy Administrator for Defense Programs, National Nuclear Security Administration, Statement before the Senate Armed Services Committee, 10 April 2002, www.ipfmlibrary.org/bec02.pdf.

[277] S. Drell, R. Jeanloz, et al., *Remanufacture*, MITRE Corporation, JASON Program Office, JSR-99-300, October 1999, www.ipfmlibrary.org/jas99.pdf, p. 4.

[278] *Ibid*., pp. 4, 8.

[279] R. J. Hemley and D. Meiron, et al., *Pit Lifetime*, JSR-06-335, MITRE Corp., November 2006, p. 16, www.ipfmlibrary.org/jas06.pdf.

Chapter 6. International Safeguards in the Nuclear Weapon States

[280] The Trilateral Initiative, a joint project of the United States, Russia, and the IAEA, was terminated by the Russian and U.S. Governments in 2002 after six years of negotiation and technical development. See T. Shea, *The Trilateral Initiative: IAEA Verification of Weapon-Origin Fissile Material in the Russian Federation and the United States*, Pacific Northwest National Laboratory, PNNL-16584, 2007.

[281] This principle was proposed and developed by one of the authors in D. Albright, F. Berkhout and W. Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies,* SIPRI, Oxford University Press, 1997.

[282] See M. Shaker, *The Nuclear Non-Proliferation Treaty: Origin and Implementation, 1959–1979,* New York, Oceana Publications, 1980, p. 670. An early U.S. proposal during the NPT's negotiation to follow Euratom's example by submitting civilian materials in all member states to IAEA safeguards was abandoned due to the Soviet Union's refusal to accept on-site inspection.

[283] "Source" material is uranium containing the mixture of isotopes occurring in nature, uranium depleted in the isotope U-235; thorium; and any of the foregoing in the form of metal, alloy, chemical compound, or concentrate. "Special fissionable" materials are plutonium-239; uranium-233; uranium enriched in the isotopes 235 or 233; and any material containing one or more of the foregoing, *IAEA Safeguards Glossary*, 2001 Edition.

[284] See C. Coates et al, *Application of International Atomic Energy Agency Safeguards in the United States,* INMM 47th Annual Meeting, 2006.

[285] Euratom was established primarily to promote atomic energy in the European Community and to ensure that member states had equal rights of access to nuclear materials for civil purposes.

[286] *Operation of Euratom Safeguards in 2002,* Report from the Commission to the European Parliament and the Council, COM, 2003. No. 264, Brussels, 10 December 2003, Section 2.

[287] Spent fuel discharged from the dual-purpose U.K. Chapelcross reactors (recently closed) where tritium has been produced for British weapons is also still held outside safeguards.

[288] *Review of the Euratom Safeguards Office by a High Level Expert Group Appointed by the European Commission's Directorate-General for Energy and Transport,* Brussels, 15 February 2002. It resulted, among other things, in the issue of Commission Regulation (Euratom) 302/2005 in place of 3227/76 by which Euratom safeguards had previously been applied after the development of NPT safeguards.

[289] Euratom safeguards are implemented by a division of the Commission's Directorate-General for Energy and Transport that is based in Luxembourg.

[290] *Agreement between the Government of Japan and the European Atomic Energy Community for Cooperation in the Peaceful Uses of Nuclear Energy,* 27 February 2006. This is the first such agreement between Japan and Euratom, supplementing or supplanting a range of bilateral agreements between the Japanese and European governments.

[291] The bilateral agreement between France and Australia, however, anticipates IAEA designation of Australian material sent for processing in France.

[292] They are Store 9, where Magnox plutonium is held, and the THORP product store. Japan's separated uranium at Sellafield also is substituted by a quantity of plutonium-239 and -241 equal to its uranium-235 content. In 1998, the U.K. Government declared 4.4 tons of plutonium, including 0.3 tons of weapon-grade material excess to military requirements. This inventory is held in a store at Sellafield that is not currently designated for safeguarding by the IAEA. At Sellafield, there is also a significant inventory of plutonium (and possibly HEU below weapon-grade) held in spent fuels discharged from submarine reactors since the 1960s. These materials have not been reprocessed. Whether some or all of these materials could be brought under international safeguards is a question that deserves attention from policy-makers.

[293] The MOX facility at Sellafield is not under IAEA safeguards. In any case, the MOX facility has operated little since commissioning in 2001. What is eventually likely to be safeguarded by the IAEA is any MOX fuel product destined for Japan.

[294] The Project's six members were Australia, Germany, Japan, the Netherlands, the United Kingdom and the United States. The Project was conducted in association with Euratom and the IAEA.

[295] The Treaty of Cardiff is the agreement of 12 July 2005 between the governments of Germany, the Netherlands, the United Kingdom, (the Urenco partners) and France, regarding collaboration in centrifuge technology. Article V.2 of the Treaty states that: "Any plant for the enrichment of uranium built on the territory of the French Republic using Centrifuge Technology owned by, held by, or deriving or arising from the operations of ETC shall be placed and remain under safeguards of the IAEA." ETC stands for Enrichment Technology Company, the joint venture between Urenco and Areva which will engage in a range of centrifuge enrichment R&D and production activities.

[296] *Communication Received from France Concerning its Policies Regarding the Management of Plutonium,* INFCIRC/549/Add.5/10, 22 December 2006, Annex C.

[297] *IAEA Annual Report for 2005,* Table A20.

[298] *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium,* INFCIRC/549/Add.8/9, 15 September 2006.

[299] M. Knapik, "DOE Has Limits on HEU Sales this Decade," *Nuclear Fuel,* 31 January 2005.

[300] *Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application of Safeguards,* INFCIRC/540, (corrected), www.iaea.org/Publications/Documents/Infcircs/1998/infcirc540corrected.pdf.

[301] "Strengthened Safeguards System: Status of Additional Protocols," www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html.

[302] They are INFCIRC/369.Add.1, (for China); INFCIRC/263.Add.1. (for the United Kingdom); and INFCIRC/290.Add.1, (for France).

[303] H.R. 5682, 109th Congress: Henry J. Hyde United States-India Peaceful Atomic Energy Cooperation Act of 2006.

[304] To be precise, information gathered under Articles 2.a.(v), (vi) and (vii) of the Additional Protocols are transmitted directly to the IAEA; information gathered under Articles 2.a. (i), (iv), (ix) and (x) are transmitted to the IAEA and copied to Euratom; and information gathered under Articles 2.a. (iii) and (viii) are reported to the IAEA via Euratom.

[305] D. Fischer, *History of the International Atomic Energy Agency: The First Forty Years,* IAEA, 1997, pp. 95–96, www-pub.iaea.org/MTCD/ publications/PDF/Pub1032_web.pdf.

[306] The IAEA's adjusted regular safeguards budget for 2006 was approximately 100 million dollars, International Atomic Energy Agency, *Annual Report 2006*, p. 77. In 2006, the world's nuclear plants generated about 2.7×10^{12} kWh of electrical power, *Nucleonics Week*, 15 February 2007, p. 5. This amounts to a safeguards cost of less than 0.004 cents per nuclear kWh.

Chapter 7. Managing the Civilian Nuclear Fuel Cycle

[307] Nuclear Energy Institute, *World Nuclear Power Generation and Capacity*, as of May 2007.

[308] International Atomic Energy Agency, PRIS database, *Nuclear Power Plants Information: Operational and Long Term Shutdown Reactors by Country*. Updated 3 August 2007.

[309] The nuclear-power community often describes nuclear power reactors as belonging to a "generation." Generation II reactors refer to those operating today. Generation III or III+ reactors are evolutionary designs of light-water reactors now under construction or in advanced development. Generation IV reactors, including, for example, the very high temperature gas reactor, the super-critical water reactor, the lead-cooled fast reactor, the sodium-cooled fast reactor, and the molten-salt reactor, are the subject of research efforts, but few are close to commercialization. In the case of sodium-cooled reactors, this is despite the expenditure of tens of billions of dollars in R&D since the 1960s. A gas-cooled pebble bed modular reactor is under development in China and South Africa, and could conceivably be deployed before 2030. See J. Ahearne, *Advanced Nuclear Reactors: Their Use in Future Energy Supply*, InterAcademy Council, 2005.

[310] International Atomic Energy Agency, *Energy, Electricity and Nuclear Power Estimates for the Period to 2030*, Reference Data Series, No. 1, July 2006 Edition, Vienna, 2006.

[311] Energy Information Administration, *International Energy Outlook 2006*, Table F5.

[312] Nukem, *Data Feature: 2005/2006 World Nuclear Electricity Generating Capacity*, December 2006. The Nukem forecast includes a category of reactors optimistically labeled "anticipated." With few exceptions, for most countries, all the reactors "planned" are assumed to come online after 2017 or later, and the reactors "anticipated," not until 2022 or later. This category is based only on the expressed interest of possible future construction offered by some utilities. The projected Russian increase to 2030 is based on 33.1 GWe new planned capacity and 12.5 GWe anticipated. This is from a platform of 22 GWe now operating. There is great uncertainty about where the funds would come from to pay for all of this new construction (see Chapter 8).

[313] International Energy Agency, *World Energy Outlook 2006*, p. 362.

[314] Map drawn by IPFM based on MIT, *The Future of Nuclear Power*, 2003. The nuclear scenarios are described in detail in the MIT report's Appendix to Chapter 2. The capacities given are "nuclear equivalent capacities" defined as the needed electricity consumption divided by 8760 hours per year. For a 90% capacity factor, actual capacities would be 11 percent greater. The MIT scenarios are based on a Masters thesis submitted to the Department of Nuclear Engineering and the Engineering Systems Division of MIT by C. M. Jones, June 2003.

[315] For example: "Azerbaijan Laying Groundwork for Construction of Nuclear Unit," *Nucleonics Week*, 12 April 2007; "Indonesia announces construction of new nuclear power plant, www.RICS.org, 11 September 2006; "Turkey Plans 70 Pct State Stake in Nuclear Plants," *Reuters*, 25 September 2006; L. Harding, "Chávez Hints at Nuclear Future for Venezuela," *The Guardian*, 29 June 2007. Saudi Arabia, Kuwait, Oman, Qatar, Bahrain and the United Arab Emirates have also shown interest, see: "Gulf Arabs Pursue Nuclear Plans with Riyadh Talks," *Reuters*, 21 May 2007.

[316] Average of high and low projections in the IAEA/OECD series, *Uranium: Resources, Production and Demand* of the indicated years, courtesy of Tony McCormick, Urenco, August 2007.

[317] M. Schneider, L. Mez, and S. Thomas, "Editorial: Nuclear Power in the World 2006," *Energy & Environment*, Vol. 17, No. 3, 2006.

[318] D. Hart, *Nuclear Power in India: A Comparative Analysis*, George Allen and Unwin, London, 1983.

[319] R. Williams, "Can We Afford to Delay Rapid Nuclear Expansion until the World Is Ready for It?" *Bulletin of the Atomic Scientists Future of Nuclear Energy Conference*, Chicago, 1–2 November 2006, Slides 12–13, www.ipfmlibrary.org/wil06.pdf. See also, T. Kreutz, R. Williams, S. Consonni, and P. Chiesa, "Co-Production of Hydrogen, Electricity and CO2 from Coal with Commercially Ready Technology. Part B: Economic Analysis," *International Journal of Hydrogen Energy*, 2004, Table 6, p. 8. This last reference used a real discount rate of 7.8% per year.

[320] *World Energy Outlook 2006, op. cit.*, p. 368.

[321] *World Energy Outlook 2006, op. cit.*, pp. 365–368. The low discount rate is based on a cost of debt of 8.0%, a required return to equity of 12.0%, a debt fraction of 50%, and a capital recovery period of 40 years; the corresponding figures for the high discount rate are debt cost of 10.0%, return to

equity of 15.0%, debt fraction of 40%, and a 25 year capital recovery period. In both cases, a five-year construction period was assumed. Other parameters assumed for nuclear power were a capacity factor of 0.85, a unit cost of nuclear fuel of $0.50 per million BTUs, and a total annual operation and maintenance cost of $65/kWe. The unit cost of fuel translates into approximately 0.5 cents per kWh, and the operations and maintenance into about 1 cent per kWh.

[322] *The Future of Nuclear Power, op. cit.*, pp. 42–43.

[323] P. Rigby, "Time for a New Start for U.S. Nuclear Energy," *Standard & Poor's Ratings Direct*, June 2003.

[324] Estimate by the chief financial officer of the Florida Power and Light Group, Platts Nuclear Energy Conference, 8 February 2007. "Costs for New Plants Still High, Says FPL's Top Financial Officer," *Nucleonics Week*, 15 February 2007, p. 2.

[325] J. Harding, *Costs and Prospects for New Nuclear Reactors*, presentation to the Northwest Power Council, February 2007. The new Asian reactors considered by Harding included the Japanese reactors Genkai-3 ($2818/kWe), Genkai-4 ($2288/kWe), Onagawa ($2409/kWe), KK6 ($2020/kWe), and KK7 ($1790/kWe), as well as the South Korean reactors Yonggwang 5 and 6 ($1800/kWe).

[326] "Further Delay in Construction of Olkiluoto-3 Nuclear Reactor," *Professional Reactor Operator Society*, www.nucpros.com/?q=node/212, accessed 2 August 2007.

[327] The Energy Policy Act extends catastrophic insurance coverage under the Price Anderson Act to include all new plants built and brought on-line by 2025. It also provides: up to $500 million for each of the first two nuclear plants, and $250 million each for the next four plants to cover cost overruns because of regulatory delays; government loan guarantees for up to 80 percent of the costs of advanced nuclear reactors; and a government production tax credit of 1.8 cents/kWh for the first eight years of operation of the first six nuclear plants, subject to a limit of $125 million per gigawatt-year. *Energy Policy Act of 2005*, www.ne.doe.gov/pdfFiles/epactFinal.pdf.

[328] "Credit Aspects of North American and European Nuclear Power," Standard & Poor's, 9 January 2006.

[329] *Electricity and Nuclear Power Estimates for the Period up to 2030, op. cit.*, Table 4, p. 21.

[330] J. Goldemberg and O. Lucon, "The Future of Nuclear Power: A View from the South," under review, *Energy Policy*, 2007.

[331] *Energy, Electricity and Nuclear Power Estimates for the Period to 2030, op. cit.*; the study shows a low and high projection of electricity generation in 2030 of 25,087 TWh and 38,200 TWh. Translating to consumption, i.e., assuming 20% transmission losses, it would be 21 thousand TWh low and 31.5 thousand TWh high.

[332] Goldemberg and Lucon, "The Future of Nuclear Power," *op. cit.*

[333] Nuclear energy is not an option for projects implemented jointly (Article 6), or for the clean development mechanism (CDM, Article 12).

[334] Globescan, "Global Public Opinion on Nuclear Issues and the IAEA," prepared for the International Atomic Energy Agency, October 2005. The poll presented three choices: 1) Nuclear is safe, build more plants; 2) Use what's there, don't build more; and 3) Nuclear is dangerous, close down all plants. The fractions of support for these three options were 28%, 34%, and 25%. The countries polled were: Argentina, Australia, Cameroon, Canada, France, Germany, Great Britain, Hungary, India, Indonesia, Japan, Jordan, Mexico, Morocco, Russia, Saudi Arabia, South Korea, and the United States.

[335] The weight of the carbon dioxide, in which the carbon is embedded, is 3.66 times greater. For details, see supporting online material for S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, Vol. 305, pp. 968–972, 13 August 2004. Assuming a lower heat-to-electricity conversion efficiency for coal of 50% and for gas of 60%—both numbers higher than yet realized—the authors show that a coal plant would emit about 186 g-C/kWh and a gas plant about half that. A 1-GWe plant at 90% capacity factor produces about 8 TWh of electricity per year. On this basis, a 1-GWe coal plant emitting 186 g-C/kWh would emit about 1.5 million metric tons of carbon per year, and a gas plant half as much.

[336] "At the point of use, the largest contributor to avoided carbon dioxide emissions is improved end-use efficiency, accounting for nearly two-thirds of total savings," in *World Energy Outlook 2006, op. cit.*, p. 190; "The electricity saved in the residential and commercial sectors combined accounts for two-thirds of all the electricity savings in the Alternative Policy Scenario. By 2030, the savings in these two sectors avoid the need to build 412 GWe of new capacity", p. 213.

[337] United Kingdom Sustainable Development Commission, *The Role of Nuclear Power in a Low Carbon Economy*, 2006, www.sd-commission.org.uk.

[338] *World Energy Outlook 2006, op. cit.*, p. 493.

[339] In 2004, coal plants generated 795 GWe-years and emitted 7600 million metric tons of carbon dioxide, containing about 2100 million metric tons of carbon. Since a coal plant at 50% efficiency emits 186 grams of carbon per kWh, this implies an overall efficiency of about 30%, *World Energy Outlook 2006, op. cit.*, p. 493. This calculation is only approximate because the carbon emissions given by the *World Energy Outlook 2006* include emissions from heat plants as well as electric power generation.

[340] *World Energy Outlook 2006, op. cit.*, pp 140–141.

[341] The coal electricity generated in 2030 is projected to be 14,703 TWh and the emissions from all coal power generation and heat plants to be 12,946 million metric tons of carbon dioxide containing 3540 million metric tons of carbon, *World Energy Outlook 2006, op. cit.*, p. 493. This implies an overall efficiency of about 40%. Were the overall efficiency raised to 45%, the carbon savings would be approximately 400 million metric tons per year.

[342] In 2004, coal plants in China operating at an average 65% capacity factor generated 1739 TWh of the national total 2237 TWh. In 2003, the average coal consumption per kWh was reported as 391 grams in China, compared to about 320 grams in advanced foreign countries, translating into an electricity efficiency of about 23% in China, compared to nearly 30% in industrialized countries, *World Energy Outlook 2006, op. cit.*, p. 517. See also J. Wang, *Energy for Sustainable Development*, Vol. VII, No. 4, December 2003.

[343] *World Energy Outlook 2006, op. cit.*, p. 517. China coal electric generation in 2030 is projected to be 5980 TWh, and total carbon emitted by coal power generation and heat plants to be 1490 million metric tons. This implies an average efficiency of 37%. Raising the efficiency to 42% would save about 170 million metric tons per year, which could alternatively be effected by the deployment of 110 GWe of nuclear power operating at a 90-percent capacity factor instead of 50-percent efficient coal-fired plants. For the IEA's projection of China's nuclear capacity, see *World Energy Outlook 2006, op. cit.* p. 517.

[344] *Nukem, Market Report*, April 2006.

[345] P. Upson, CEO, Enrichment Technology Company (ETC), a joint venture of Urenco and Areva; remarks at IPFM meeting, the Hague, 1 March 2006.

[346] For a fuel burn-up of 50MWd/kg, 4.3% enriched LEU would be required. For a depleted-uranium assay of 0.25% U-235, about 6.5 SWU would be required per kilogram of fuel. For a heat-to-electricity conversion efficiency of 0.33, a doubling of the SWU price from $120/SWU to $240/SWU would, therefore, contribute an additional 0.2 cents/kWh to the cost of electricity.

[347] The White House, *Fact Sheet: Strengthening International Efforts against WMD Proliferation*, 11 February 2004.

[348] These countries include Argentina, Australia, Canada, Kazakhstan, South Africa, and the Ukraine.

[349] International Atomic Energy Agency, *Expert Group Report on Multilateral Nuclear Approaches*, INFCIRC/640, 2005.

[350] IAEA Special Event on Assurances of Nuclear Supply and Non-Proliferation, Vienna, September 2006.

[351] Off-the-record comment by a participant from a non-weapon state.

[352] More exactly, by the Dutch Government, the state-owned British Nuclear Fuels and the German utility, RWE, Ann MacLachlan, "Urenco, Areva close ETC deal; GB II startup targeted for 2009," *Nuclear Fuel*, Vol. 31 No. 15, July 17, 2006.

[353] President Putin, statement on the peaceful use of nuclear energy, St. Petersburg, 25 January 2006.

[354] Department of Trade and Industry, United Kingdom, *The Future of Nuclear Power: The Role of Nuclear Power in a Low Carbon UK Economy*, May 2007, p. 28.

[355] Armenia, Belgium, Bulgaria, Czech Republic, Finland, Germany, Hungary, Slovak Republic, Spain, Sweden, Switzerland, and the Ukraine.

[356] For a critique of this idea, see F. von Hippel, *Managing Spent Fuel in the United States: The Illogic of Reprocessing*, International Panel on Fissile Materials, January 2007, www.ipfmlibrary.org/rr03.pdf.

[357] Over nine tons per year of plutonium were recycled between 2000 and 2002, 12.1 tons in 2003, 10.7 tons in 2004, and 8.4 tons in 2005. Euratom Supply Agency, *Annual Report 2005*, p. 22.

[358] If one assumes 9 kg of natural uranium per kilogram of LEU and 7% plutonium in the MOX fuel, then 10 tons of plutonium recycled translates into 1300 tons of natural uranium saved.

[359] von Hippel, *Managing Spent Fuel in the United States, op. cit.*, pp. 26–28.

[360] U.S. Nuclear Regulatory Commission, *Waste Confidence Decision Review*, Federal Register, No. 55, 18 September 1990, p. 38,474; see also *Waste Confidence Decision Review*, Status, Federal Register 64, 6 December 1999, p. 68,007.

[361] Nuclear Energy Institute, *Fact Sheet: Status of Used Fuel Storage at U.S. Commercial Nuclear Plants*, September 2006. Fifty-seven reactors (including a few research reactors and shutdown reactors) were listed as having dry cask storage as of 31 December 2004, and 48 as having such storage under construction or planned.

[362] In a fuel cycle in which all LEU spent fuel was reprocessed and the recovered plutonium recycled, about seven out of eight spent fuel assemblies would be reprocessed; with the eighth, a spent MOX assembly, stored indefinitely without reprocessing. No country has such a fuel cycle in place. France reprocesses most of its spent LEU fuel, however, and Japan plans to do so.

[363] *The Future of Nuclear Power, op. cit.*, pp. 146–147. The MIT study assumed a cost of $400/kg for geological storage of LEU spent fuel; $300/kg of reprocessed spent fuel for geological storage of HLW; and $400/kg for MOX storage and disposal.

[364] Nuclear Energy Agency, *Plutonium Fuel: An Assessment*, OECD, 1989, p. 51.

[365] In the French Government's comparison of reprocessing and plutonium recycle, it was estimated that the "end of cycle," costs, i.e., the summed cost of long-term storage and disposal of reprocessing wastes and spent MOX fuel on the one hand, and spent LEU fuel on the other after 2049 were virtually the same, J. M. Charpin, B. Dessus and R. Pellat, *Economic Forecast Study of the Nuclear Power Option: Report to the Prime Minister, 2000*, p. 215, www.ipfmlibrary.org/cha00.pdf.

[366] The reprocessing and MOX fabrication costs cited here are the base case assumptions of the MIT Study. However, the MIT study assumed a price for natural uranium of $30/kg, which now looks too low. At that price, the extra cost of MOX would be about 2.2 cents per kilowatt-hour. The estimated cost for reprocessing also may be too low. In a paper presented at the Nuclear Renaissance Workshop in Washington, M. Crozat of DOE estimated for a modern reprocessing plant of 2500 metric tons capacity per year an overnight cost of $12 billion, a marginal unit cost of $360/kg, an investor rate of return of 16%, an investment debt fraction of 40%, an interest rate of 10%, and a finance period of 30 years. With these figures, the separation cost would be about $1400/kg. Crozat noted that, with government loan guarantees, this could drop to just under $1000/kg, see: M. Crozat, "Evaluating the Economics for GNEP Deployment," *Nuclear Renaissance Workshop*, Washington, D.C., 6 December 2006.

[367] For example, the Global Nuclear Energy Partnership (GNEP), launched by the U.S. Department of Energy in May 2006, has as its explicit goal to move the United States to a closed fuel cycle in which plutonium and other transuranics contained in the reactor spent fuel would be separated and then recycled repeatedly into a fleet of fast reactors. See www.gnep.energy.gov.

[368] For the 1500 GWe projection, the LWR and fast reactor capacities are 815 GWe and 685 GWe respectively. *The Future of Nuclear Power, op. cit.*, Appendix to Chapter 4, p. 126.

[369] J. Kang and F. von Hippel, “Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel,” *Science & Global Security*, Vol. 13, 2005, p. 169.

Chapter 8. Russia’s Nuclear-Energy Complex and its Roles as an International Fuel-Cycle-Services Provider

[370] Rostov-2 (VVER-1000) is to start operation in 2009, Kalinin-4 (VVER-1000) in 2011, and the Kursk-5 (RBMK-1000) and Beloyarsk-4 (BN-800) in 2012, *NUKEM Market report*, December 2006.

[371] License extensions are given in increments of 5 years by the regulatory agency, Rostechnadzor, after a comprehensive examination. This has already allowed the continued operation of 2.75 GWe of generating capacity. Interview with Stanislav Antipov, General Director of Rosnergoatom, *Vedomosti*, No. 152, p. 1433, 18 August 2005.

[372] *Nuclear Power in Russia,* World Nuclear Association, December 2006, www.world-nuclear.org/info/inf45.html; Spent-fuel holdings from *On Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management*, Russian Federation National Report, prepared for the Second Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and Safety of Radioactive Waste Management, Vienna, 15-24 May 2006.

[373] *Strategy of Development*, Atom Press, No. 27, p. 710, July 2006; “Russia Will Build 42 Nuclear Reactors by 2030, Nuclear Chief Says,” Associated Press, 28 November 2006.

[374] Federal program on “The Development of the Nuclear Energy Production Complex,” “Rosatom Cuts down a Budget Request,” *Commersant*, No. 133, 24 July 2006.

[375] Russian Government Decision #1019, p. 15, July 2006, *Atom Pressa*, No. 30, p. 713, August 2006.

[376] One unit at Sosnovy Bor Nuclear Power Plant #2 and two new units at Novovoronezhskaya Nuclear Power Plant #2 are to be initiated for completion in 2012 and 2013 respectively, “New NPP Project Slated for Launch in Russia Next Year,” *RIA Novosti*, 30 December 2006.

[377] Between them, the Russian Government and Rosenergoatom have committed a total of $50 billion between 2006 and 2015. This is about $5 billion/yr for construction at a pace of about 2 GWe per year. “According to the Nuclear Society of Russia, after 2015, new nuclear units will be financed from funds generated by Rosatom enterprises, with no money from the federal budget,” *Nukem Market Report*, December 2006, p. 60. In 2015, Rosenergoatom would have a capacity of 33 GWe. Assuming that the nuclear reactors operate at an 80% capacity factor, they would generate 0.23 trillion kWh per year. Rosenergoatom would have to be raising 2 cents for capital investment per kwh generated. This capital charge could make nuclear power noncompetitive relative to natural-gas-fired combined-cycle power plants.

[378] In June 2007, Sergei Kirienko, head of Rosatom, stated that “Our confirmed reserves and resources are about 850,000 tonnes in Russia,” “Enrichment Capacity at Angarsk to Be Boosted,” *World Nuclear News*, 25 June 2007, www.world-nuclear-news.org. Operating at a 90-percent capacity factor, a 1-GWe VVER would require 140-200 tons of natural uranium per year, assuming enrichment leaves 0.1-0.3 percent U-235 in the depleted uranium. In 45 years, 100 GWe of VVER capacity would, therefore, require 630,000-900,000 tons of natural uranium. *Uranium 2005: Resources, Production and Demand*, OECD Nuclear Energy Agency, 2005, gives Russia’s “Reasonably Assured Resources” plus uranium in “inferred” extensions of explored deposits recoverable at up to $80/kgU as 175,000 metric tons plus 450,000 tons in known deposits for which recovery costs have not yet been determined. In addition, “prognosticated” resources (estimated resources in partially explored geologies and “speculative” resources, undiscovered resources based on statistical inferences from geological types) recoverable at costs up to $130/kgU amount to 650,000 tons. During the 1990s the price of natural uranium averaged about $30/kgU. During the 1980s, however, it averaged around $150/kgU (2003 dollars) and recent prices have been even higher.

[379] It is assumed that reactors will be licensed for a total life of 45 years and that, beyond 2012, each year Russia will put into operation two new VVER-1200 reactors with a net output of 1.15 GWe each.

[380] A. MacLachlan, "Pilot Processing Center Proposed in Russia as Inpro Model Project," *Nuclear Fuel*, No. 23, October 2006.

[381] N. N. Oshkanov, M. V. Bakanov, and O. A. Potapov, "Experience in Operating the BN-600 Unit at the Belyiyar Nuclear Power Plant," *Atomic Energy*, Vol. 96, No. 5, 2004, p. 315.

[382] The central value break-even cost for natural uranium would be $340/kgU in the United States for breeder reactors costing $200/kWe more than light-water reactors with utility financing; $1000 per kilogram heavy metal (HM) reprocessing cost for LWR spent fuel; $1500/kgHM for breeder reactor fuel fabrication and a breeding ratio of 1.12. M. Bunn, S. Fetter, J. Holdren and B. van der Zwaan, "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel," *Nuclear Technology*, No. 150, June 2005, p. 209.

[383] "The first offshore nuclear heat and electrical power plant of small capacity is planned to operate in October 2010 in Severodvinsk (Arkhangelsk district)," Rosatom press release, 15 December 2006; "The project for the construction of floating nuclear thermal power plants (FNTPP) was discussed during a conference on Dec 20," Rosenergoatom press release, 20 December 2006.

[384] Russia ended producing Generation 7 centrifuges and began producing Generation 8 centrifuges in 2004. The former Federal Atomic Energy Agency reported that a total of 0.17 million Generation 6 and 0.75 million Generation 7 centrifuges had been produced and that 2 million Generation 8 machines would be produced by 2010, *Russian Uranium Enrichment Industry, Status and Prospects, Annual Report 2006*, Table A.7.1, www.ibr.ru.

[385] Russian federal program on "Modernization of Separation Processes in the Period 2002-2005 and up to 2010," *Russian Enrichment Industry Status and Prospects: Annual Reports 2004* and *2006,* www.ibr.ru.

[386] D. Albright, L. Barbour, C. Gay and T. Lowery, *Ending the Production of Fissile Material for Nuclear Weapons: Background Information and Key Questions*, Institute for Science and International Security (ISIS), Washington, D.C., 1999, Chapter II, with permission. The image appeared originally in a Russian Ministry of Atomic Energy publication.

[387] Russia sells to the United States each year LEU obtained from blending down 30 tons of 90% enriched uranium. Assuming that the LEU is on average, 4.5 percent enriched, the quantity of 1.5-percent enriched blend stock would be 856 tons. Russia is enriching depleted uranium to produce the 1.5 percent enriched uranium. It would take about 5.5 million SWUs to produce 856 tons of 1.5-percent enriched uranium by stripping 0.225-percent depleted uranium down to 0.1 percent enrichment. If the LEU were produced from natural uranium with 0.3 percent U-235 in the depleted uranium "tails," the separative work required would be 5.5 million SWUs.

[388] The head of Rosatom has announced, however, that Russia will no longer enrich foreign depleted uranium after the current contracts end, www.regnum.ru, 22 June 2007, mirrored at www.ipfmlibrary.org/reg07.pdf (in Russian). Reference courtesy of Pavel Podvig.

[389] A. M. Dmitriev, "Current Status of Government Regulation of Activities Associated with the Import of Spent Nuclear Fuel into the Russian Federation," in G. E. Schweitzer and A. C. Sharber (eds.), *An International Spent Nuclear Fuel Storage Facility-Exploring a Russian Site as a Prototype*, National Academies Press, Washington D.C., 2005, www.nap.edu.

[390] *On Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste management, op. cit.*

[391] "Putin Orders Atomic Energy Holding," *Moscow Times*, 2 May 2007, p. 5; G. Mukhatzhanova, "Russian Nuclear Industry Reforms: Consolidation and Expansion," Monterey Institute for International Studies, Monterey Center for Nonproliferation Studies, 22 May 2007, cns.miis.edu.

[392] Interview with Stanislav Antipov, General Director of Rosnergoatom, *Vedomosti, op cit*.

[393] The websites of these companies have been assembled at a single site, which is available in English at: www.rosatom.ru/en/.

[394] "Russia and Kazakhstan are Setting up a Joint Nuclear Industry," *RIA Novosti*, 12 October 2006.

[395] Kazakhstan's ambition is to become the world's largest uranium producer, "NAC Kazatomprom: The Next Steppe," *RWE Nukem Market Report*, March 2006, p. 4. It has reasonably assured resources

of 514,000 tons, inferred resources of 302,000 tons, prognosticated resources of 310,000 tons and speculative resources of 500,000 tons recoverable at costs less than $130/kgU, *Uranium 2005, op. cit.*

[396] "Enrichment Capacity at Angarsk to Be Boosted," *op. cit.*

[397] See www.minatom.ru, text mirrored at www.ipfmlibrary.org/min07.pdf. The IAEA is reluctant to expend its limited resources on safeguarding facilities in the weapon states, however, and is likely to limit its monitoring to uranium enriched for non-weapon states, personal communication from an IAEA official, 30 March 2007.

[398] V. Putin, Statement on the peaceful use of nuclear energy, St. Petersburg, 25 January 2006, www.kremlin.ru.

[399] "Enrichment Capacity at Angarsk to Be Boosted," *op. cit.*

[400] "Rosatom Nuclear Chief Says Int'l Uranium Center to Be Set Up in Siberia," *ITAR-TASS*, 19 September 2006.

[401] "Russia to Place Angarsk Plant under IAEA Control—Kiriyenko," *ITAR-TASS*, 31 October 2006; "Head of Rosatom Confirms that Establishment of the International Uranium Enrichment Center is Completed", *RIA Novosti*, 10 May 2007.

[402] "The New Spin of Russian Enrichment," *RWE Nukem Market Report*, April 2006, with permission.

[403] "AREVA Representatives Have Pointed out the High Quality of Fuel Fabrication at MSZ," *Atom Pressa*, No. 46, November 2006.

[404] A. MacLachlan, "CEZ Picks TVEL Over Westinghouse for Fuel," *Nuclear Fuel*, Vol. 31, No. 11, 22 May 2006; "Fortum Has Signed a Nuclear Fuel Supply Contract with TVEL Corp of Russia," 22 December 2006, www.world-nuclear.org.

[405] K.G. Kudinov, "Creating an Infrastructure for Managing Spent Nuclear Fuel," in *An International Spent Nuclear Fuel Storage Facility-Exploring a Russian Site as a Prototype, op. cit.*

[406] "Nuclear Power in Ukraine," World Nuclear Association, August 2005, www.world-nuclear.org.

[407] "Ernst & Young Will Monitor International Tenders on Construction of Spent Nuclear Storage Facility," *Interfax*, 2 July 2005. The storage facility is designed to hold 2500 VVER-1000 and 1080 VVER-440 spent fuel assemblies.

[408] "Nuclear Power in Bulgaria," World Nuclear Association, January 2007, www.world-nuclear.org. The initial capacity is to be for 2800 VVER-440 spent fuel assemblies with later expansion to accommodate a total of 8000 VVER-440 and 2500 VVER-1000 assemblies.

[409] Article 50 of the Law of the Russian Soviet Federal Republic (RSFSR) on Environmental Protection, 10 July 2001, No. 93-FL; Federal Law on the Use of Atomic Energy, 10 July 2001, No. 94-FL; and 10 July 2001, No. 92-FL.

[410] A. Emel'yaninkov, "Kirienko's Renaissance," *Rossiyskaya Gazeta*, 5 July 2006.

[411] "Kirienko: Russia is Not Planning to Bring Foreign Spent Fuel," *Interfax*, 11 July 2006. This policy change was confirmed by Rosatom's secretary, Igor Konyshev; A. MacLachlan and D. Horner, "Russia Drops Plans for Taking in Foreign Spent Fuel, Citing other Priorities," *Nuclear Fuel*, No. 31, July 2006.

Chapter 9. Detection of Clandestine Fissile Material Production

[412] *Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application of Safeguards,* INFCIRC/540 (corrected), IAEA, September 1997. Article 18 defines location-specific environmental sampling as "the collection of environmental samples (e.g., air, water, vegetation soil, smears) at, and in the immediate vicinity of, a location specified by the Agency for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities at the specified location." It defines wide-area environmental as "the

collection of environmental samples (e.g., air, water, vegetation soil, smears) at a set of locations specified by the Agency for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities over a wide area."

[413] Article 9 of the *Model Protocol,* INFCIRC/540 (corrected), IAEA, September 1997.

[414] The basic technique is described in *Global Fissile Material Report 2006*, Chapter 5.

[415] K. J. Moody, I. D. Hutcheon and P. M. Grant, "Chronometry," in *Nuclear Forensic Analysis*, Taylor and Francis, 2005, Chapter 6.

[416] B. Jasani and G. Stein, *Commercial Satellite Imagery: A Tactic in Nuclear Weapon Deterrence*, Springer, 2002.

[417] H. Zhang and F. von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *Science & Global Security*, Vol. 8, 2000, pp. 261–313.

[418] G. Wotawa et al., "Atmospheric Transport Modeling in Support of CTBT Verification—Overview and Basic Concepts," *Atmospheric Environment*, Vol. 37, No. 18, 2003, pp. 2529–2537. The simulation can be stopped at the known release time when this can be estimated from the ratios of short-lived isotopes. If the release time is unknown, the model can be stopped when the release size reaches a maximum probable value. If multiple samples come from a single station, then the release must be located where the possible source regions overlap. The overlap region also puts constraints on the possible release time since a plume starting from within the region could only have reached the detector at the detected time if it had been released during a certain interval.

[419] Krypton-85 can be removed from reprocessing off-gas cryogenically. Such a system operated at the Idaho Chemical Processing Plant, where the United States reprocessed spent naval-reactor fuel. Bendixsen et al., *Rare-Gas Recovery Facility at the Idaho Chemical Processing Plant,* Idaho Nuclear Corporation, IN-1221, 1969. A krypton recovery facility was also designed for Japan's Tokai Reprocessing Plant. R. V. Ammon, H. G. Burkhardt, E. Hutter and G. Neffe, "Development of a Cryogenic Krypton-Separation System for the Off-Gas of Reprocessing Plants, *Proceedings of the 15th DOE Nuclear Air Cleaning Conference,* 1978, p. 640; and D.T. Pence, "Critical Review of Noble Gas Treatment Systems, *16th DOE Nuclear Air Cleaning Conference,* 1980, p. 988.

[420] The plot is taken from K. Winger, J. Feichter, M. B. Kalinowski, H. Sartorius and C. Schlosser, "A New Compilation of the Atmospheric Krypton-85 Inventories from 1945 to 2000 and its Evaluation in a Global Transport Model," *Journal of Environmental Radioactivity*, Vol. 80, 2005, pp. 183–215.

[421] The two U.S. military reprocessing plants at the DOE's Hanford Site in Washington and its Savannah River Site in South Carolina have been shut down. Russia's two large Siberian military reprocessing plants are being shut down. The United Kingdom plans to shut down its civilian reprocessing plants by 2012.

[422] R. S. Kemp and C. Schlosser, "A Performance Estimate for the Remote Detection of Nuclear-Fuel Reprocessing by Atmospheric ^{85}Kr," unpublished. The values given here are calibrated for weapon-grade plutonium production by taking the release of 16 GBq of Krypton-85 to be equivalent to one gram of weapon-grade plutonium recovered, assuming 0.91 grams plutonium produced per gram of U-235 fissioned and a 100-day cooling period.

[423] M. B. Kalinowski, H. Sartorius, S. Uhl, and W. Weiss, "Conclusions on Plutonium Separation from Atmospheric Krypton-85 Measured at Various Distances from the Karlsruhe Reprocessing Plant," *Journal of Environmental Radioactivity*, Vol. 73, 2004, pp. 203–222. WAK had a design capacity of 35 metric tons of heavy metal throughput per year.

[424] Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *op. cit*.

[425] It is possible to identify open-pit mines and most overt uranium-refining plants via satellite imagery. However, uranium recovery using in-situ leaching, in which uranium is recovered by pumping acid into a uranium deposit, or the recovery of byproduct uranium from the mining of other minerals such as phosphate and copper, is much less detectable. R. S. Kemp, "On Safeguarding Uranium Mines," *Nonproliferation Review*, July 2006, p. 417.

[426] *Urananreicherungsanlage Gronau Umwelterklärung* [Environmental Report of the Gronau Uranium Enrichment Plant], Urenco Deutschland GmbH, Gronau, 2005, p. 18.

[427] International Atomic Energy Agency, *IAEA Use of Wide Area Environmental Sampling in the Detection of Undeclared Nuclear Activities*, STR-321, 27 August 1999.

[428] R. S. Kemp, "Initial Analysis of the Detectability of Aerosols Produced by UF_6 Released from Uranium Conversion Plants," unpublished.

[429] Estimate based on Canada's Cameco Conversion Facility, which releases an average of 3.7 grams of uranium per ton of uranium in UF_6 produced. The Honeywell/Converdyn conversion facility in the United States releases an average of 16.5 grams of uranium per ton. Both plants use modern air-cleaning methods, including HEPA (high efficiency particulate air) filtration, to meet environmental and safety regulations. Sources: *Facility Effluent Reports from Honeywell Specialty Chemicals to the U.S. Nuclear Regulatory Commission*, July 1999 to June 2003; and Cameco, *Quarterly Environmental Compliance Reports for Port Hope Facility*, Q1 2005 to Q4 2006. Details in R. S. Kemp, "Source Term Estimates for Uranium Conversion Facilities," unpublished.

[430] One gram per day is about 20 times the release rate that would be expected for producing one significant quantity per year at the best modern conversion plants using HEPA filtration. On the other hand, we have made a worst-case assumption that the atmospheric aerosol load is typical of an urban area. Large cities have aerosol loadings around 100 $\mu g/m^3$. Non-arid rural regions have aerosol loadings around 4 $\mu g/m^3$. A detector located in a rural area, therefore, would have a 25 times greater sensitivity. For typical atmospheric loadings, see T. Valmari et al., *Aerosol Sampling Methods for Wide Area Environmental Sampling (WAES)*, Säteilyturvakeskus Strälsäkerhetscentralen [Finnish Radiation and Nuclear Safety Authority], Helsinki, 2002, STUK-YTO-TR 183, p. 9.

[431] Contours calculated assuming a continuous release of 1 gram per day using the U.S. National Oceanic and Atmospheric Administration's HYSPLIT model for an area in Texas with flat terrain, and during a period in which no storms, high winds or precipitation events were recorded. The contours shown here represent the 70th percentile (based on the extent of the contours) from a collection of about 30 simulations.

Glossary

Additional Protocol. The voluntary agreement between the International Atomic Energy Agency (IAEA) and a state to accept more stringent international safeguards than those originally required to verify compliance with the Nonproliferation Treaty or other safeguards agreements. Devised in the 1990s following the discovery of Iraq's clandestine uranium-enrichment programs, it broadens the information on nuclear activities a state declares to the IAEA and provides additional rights for IAEA inspectors to verify this declaration, including environmental sampling to check for possible undeclared nuclear activities in a country.

Americium-241 (Am-241). A fissile isotope with a half-life of 433 years produced from decay of plutonium-241. There is no public information that americium has ever been used to build a nuclear weapon but it is considered an "alternative nuclear material" by the IAEA.

Breeder reactor. A nuclear reactor designed to consume less fissile material in its core than it produces in a surrounding blanket of "fertile" material, e.g. uranium-238 (U-238) or thorium. Most research and development has been focused on fast-neutron reactors cooled with liquid sodium. Despite many attempts, breeder reactors have not been successfully commercialized.

Burn-up. A measure of the fission energy generated by a mass of fuel in a reactor, usually given at the time of discharge from the reactor, measured in units of thermal megawatt-days per kilogram or thousand thermal megawatt-days per metric ton.

Cascade. The arrangement of isotope separation elements (for example, centrifuges) in a uranium enrichment facility. The cascade is organized as a series of "stages" in each of which centrifuges operate in parallel. The stages are connected so that material from one stage is passed to another for further enrichment or depletion of the uranium in the isotope uranium-235. If the feed into the cascade is natural uranium, the final output streams are enriched and depleted uranium.

Centrifuge. A rapidly rotating cylinder used for the enrichment of uranium in which the heavier isotope (uranium-238) in uranium hexafluoride gas is forced to higher concentrations near the cylinder's walls, while the lighter isotope (uranium-235) concentrates closer to the center of the cylinder.

Chain reaction. A continuing process of nuclear fissioning in which the neutrons that are released from one fission trigger other nuclear fissions. In a nuclear weapon, an extremely rapid, multiplying chain reaction causes an explosive release of energy.

In a reactor operating at constant power, the chain reaction is controlled so that each fission causes, on average, exactly one fission.

Critical mass. The minimum amount of a fissile material required to sustain a chain reaction. The exact mass of material needed to sustain a chain reaction varies according to its geometry, the mixture of fissile isotopes and other elements it contains, its density, and the neutron-reflecting properties and thickness of the surrounding materials.

Depleted uranium. Uranium having a smaller percentage of uranium-235 than the 0.7 percent found in natural uranium. It is a by-product of the uranium enrichment process.

Disposition. A variety of means to physically transform fissile materials into forms that cannot be easily converted to make nuclear weapons. These include down-blending of highly enriched uranium; fabrication of plutonium into mixed-oxide fuel and its irradiation in a reactor; and mixing plutonium with high-level radioactive waste and immobilizing it in a glass or ceramic form.

Down-blending. The dilution of highly enriched uranium with depleted, natural or slightly enriched uranium (known as blend-stock) to produce low enriched uranium that can be used to fuel light-water reactors. This is the usual method for disposing of stocks of weapon-grade highly enriched uranium.

Enrichment. The process of increasing the concentration of one isotope of a given element. In the case of uranium, increasing the concentration of uranium-235.

Environmental sampling. The set of techniques used by the IAEA to collect and analyze air, water, soil and vegetation samples and to take swipes of surfaces within and around nuclear facilities in states that have signed the Additional Protocol of the NPT. The aim is to detect the chemical and isotopic indications of the undeclared production of fissile materials, such as the presence of plutonium, fission products, or highly enriched uranium.

Fast neutron reactor (fast reactor). A type of nuclear reactor in which the chain reaction is sustained by fast neutrons. It requires fuel that has a 20-30 percent concentration of plutonium or U-235 in uranium—much higher than reactors, such as light-water reactors, in which the neutron energy is “moderated” to the level of the thermal motions in the reactor coolant. When the core of a fast reactor is surrounded by a blanket of uranium or thorium, it can produce more fissile material than it consumes and is known as a breeder reactor.

Fertile material. Nuclear isotopes that are transmuted by neutron absorption and radioactive decay into fissile materials. One such element is uranium-238, which, after it absorbs a neutron, decays in two steps into plutonium-239.

Fissile material. Material that can sustain an explosive fission chain reaction—notably highly enriched uranium or plutonium of almost any isotopic composition.

Fission. The process by which a nucleus or a heavy atom such as uranium or plutonium splits after absorbing a neutron or, in some cases, spontaneously. During the process of nuclear fission, typically two or three high-speed neutrons are emitted along with gamma rays.

Fission products. Isotopes such as krypton-90 and barium-144 that result from the fission of heavy isotopes.

Fissionable material. A heavy isotope with an atomic nucleus that can undergo fission when struck by a neutron. Uranium-238 is a fissionable isotope, in that it can be fissioned by high-energy neutrons. Unlike uranium-235, which is fissile as well as fissionable, it cannot sustain a fission chain reaction.

Fizzle yield. The reduced explosive energy that is released by a nuclear weapon when the chain reaction is initiated at the first moment when the explosive assembly becomes critical. For an implosion weapon using reactor-grade plutonium, however, even a fizzle yield could release energy equivalent to roughly the explosion of one thousand tons (one kiloton) of TNT.

Gamma rays. High energy X-rays which carry off the extra energy when a nucleus makes a transition from an excited to its lowest energy ("ground") state.

Gaseous diffusion. A method of isotope separation based on the fact that gas molecules carrying isotopes with different masses can diffuse through a porous barrier or membrane at different rates. When repeated about a thousand times, the method can produce highly enriched uranium from natural uranium, in the form of uranium hexafluoride molecules. Because the gas is pumped up to high pressure, it requires significant amounts of electric power.

Gun-type nuclear explosive. A nuclear explosive in which a supercritical mass is created by firing one subcritical mass into another. This type of design works for highly enriched uranium but not plutonium. The Hiroshima bomb was a gun-type device.

Half-life. The time required for one-half of the nuclei in a quantity of a specific radioactive isotope to decay.

Heavy metal. Typically used to describe the mass of uranium and plutonium in reactor fuel. For example, when used to characterize oxide fuels, the mass of heavy metal is the total fuel mass minus the the oxygen content.

Heavy-water reactor (HWR). A reactor that uses heavy water as a neutron "moderator," i.e., to slow the neutrons between fissions. Most of the hydrogen in heavy water is deuterium, whose nucleus, unlike that of ordinary hydrogen, contains a neutron as well as a proton. Only about one in ten thousand hydrogen atoms in nature is deuterium. Heavy water is made by concentrating water molecules containing deuterium. Heavy water reactors typically use natural uranium as fuel. It is impossible to sustain a chain reaction in natural uranium in a reactor moderated by ordinary water because the "light" hydrogen in the water absorbs too many neutrons.

High-level waste (HLW). The radioactive waste containing fission products and non-plutonium "transuranic" elements (i.e., neptunium, americium and curium) resulting from the reprocessing of spent fuel.

Highly enriched uranium (HEU). Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to 20 percent or more. A large fraction of HEU is 90-percent enriched or higher because it was originally produced for weapon use.

Immobilization. Methods for the disposition of separated plutonium that involve mixing it with high level waste from reprocessing and either glass ("vitrification") or ceramic forming material. The resulting mixtures would be placed in a deep-underground geological repository.

Implosion-type nuclear explosive. A nuclear explosive in which a supercritical mass is created by compressing a subcritical mass to higher density. The Nagasaki bomb, whose core was plutonium, was an implosion-type device.

Integrated gasification combined cycle (IGCC). An emerging thermal power plant design that transforms fossil fuel, usually coal, to produce a synthetic gas (mainly hydrogen and carbon monoxide) that is then burned to drive a turbine to generate electricity. The waste heat from both gas production and combustion is also used to make steam to generate additional electricity. It is significantly more fuel-efficient and produces less carbon emissions than conventional power plants in which pulverized coal is burned directly.

International Atomic Energy Agency (IAEA). An independent organization, established in 1957 under the United Nations, that is responsible for both promoting the peaceful use of nuclear technology and implementing "safeguards" agreements with non-weapon states under which it checks that fissile material is not diverted from peaceful uses or produced in undeclared facilities.

Improvised nuclear explosive device (IND). A crude nuclear weapon assembled quickly using fissile material in forms that are on hand in a nuclear facility. It may be possible to assemble such a device using highly enriched uranium and achieve a kiloton-range nuclear yield. This would be much more difficult with plutonium.

Isotope. A form of any element whose nucleus contains a specific number of neutrons. It is usually designated by the sum of the number of protons and neutrons in its nucleus (e.g. uranium-235 has 92 protons and 143 neutrons). Because all isotopes of an element have the same number of protons in the nucleus (92 for uranium) and therefore the same number of electrons, they have virtually the same chemical properties. But, because they have different numbers of neutrons in the nucleus, they have different atomic weights and nuclear properties. Uranium-235 can sustain a fission chain reaction, for example, while uranium-238, whose nucleus contains three more neutrons, cannot.

Kiloton TNT (kt). A unit used to measure the energy of a nuclear explosion, roughly the energy released by the explosion of one thousand tons of TNT, by definition equal to 10^{12} calories (4.184×10^{12} joules). The fission of 1 kilogram of fissile material releases about 18 kilotons of TNT equivalent.

Light water. Ordinary water (H_2O) as distinguished from heavy water (D_2O) that contains deuterium, a heavier isotope of hydrogen.

Light-water reactor (LWR). A reactor that uses ordinary water to cool the reactor and to "moderate" the speed of neutrons between fissions and increase the probability of their capture in U-235. LWRs usually use low-enriched uranium as fuel. It is the most common nuclear power reactor design.

Low-enriched uranium (LEU). Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to less than 20 percent. The fuel of light-water reactors is usually enriched to 4-5 percent.

Magnox reactor. A natural uranium fueled, graphite moderated, carbon-dioxide cooled nuclear reactor designed and widely used in the United Kingdom. It was the design for the world's first commercial nuclear power plant, which came on-line in 1956. The United Kingdom also used such reactors for producing weapon-grade plutonium. These reactors are now being retired.

Megawatt (MW). One million watts. Used as a measure of electrical power output of a nuclear power plant: 1 million watts of electric power (megawatts-electric, or MWe). Also used to measure the rate at which heat is released in research or plutonium-production reactors: 1 million watts of thermal energy (megawatts-thermal, or MWt). A typical light water power reactor today has a peak electricity generation capacity of approximately 1000 MWe—that is, 10^9 watts. Such a reactor would generate about 3000 MWt.

Megawatt-day (MW-day). A unit of energy. The cumulative amount of heat that would be released in a day by a reactor producing heat at a rate of one megawatt. The fission of one gram of uranium or plutonium releases approximately one MW-day of thermal energy.

Metric ton (sometimes tonne). One thousand kilograms. Equal to about 1.1 short tons. A short ton equals 2000 pounds.

Mixed-oxide fuels (MOX). Nuclear reactor fuel composed of a mixture of plutonium and natural or depleted uranium in oxide form, commonly referred to as MOX fuels. The plutonium replaces the uranium-235 in low-enriched uranium as the primary fissioning material in the fuel. MOX is used in Europe—and its use is planned in India and Japan—to recycle plutonium recovered from spent fuel through reprocessing. The United States and Russia hope to dispose of some of their excess weapon plutonium in MOX fuel.

Natural uranium. Uranium as found in nature, containing 0.7 percent of uranium-235, 99.3 percent of uranium-238, and trace quantities of uranium-234 (the last is formed by the decay of U-238).

Neptunium-237 (Np-237). A 2-million-year half-life fissile isotope produced in nuclear reactors by two successive neutron captures on U-235. There is no public information that Np-237 has actually ever been used in a nuclear weapon, but its properties make it as suitable as U-235. The IAEA considers it an "alternative nuclear material."

Neutron. An uncharged elementary particle with a mass slightly greater than that of a proton. Neutrons are found in the nuclei of every atom heavier than hydrogen. Neutrons provide the links in a fission chain reaction.

Nuclear fuel. Usually a mixture of fissile and fertile isotopes. The most commonly used nuclear fuels are low-enriched and natural uranium. Highly enriched uranium and mixed-oxide fuel are also used to fuel some reactors.

Nuclear fuel cycle. The chemical and physical operations needed to prepare nuclear material for use in reactors and to dispose of or recycle the material after its removal from the reactor. Existing fuel cycles begin with the mining of uranium ore and produce fissile plutonium as a by-product by absorption of neutrons in uranium-238 while the fuel is in the reactor. Some proposed fuel cycles would use natural thorium as a fertile material to produce the fissile isotope uranium-233, which would then be recycled in reactor fuel. An "open" fuel cycle stores the spent fuel indefinitely. A "closed" fuel cycle reprocesses it and recycles the fissile and fertile material once or more and stores the fission products and other radioactive isotopes.

Nuclear reactor. An arrangement of nuclear and other materials designed to sustain a controlled nuclear chain reaction that releases heat. Nuclear reactors fall into three general categories: power and propulsion reactors, production reactors (for producing fissile materials such as plutonium, tritium and also radioactive isotopes used in medicine) and research reactors. The heat generated by a power or propulsion reactor is converted into electrical or mechanical power. Most reactors produce plutonium in their irradiated fuel.

Nuclear Suppliers Group (NSG). A group of nuclear technology and material exporting countries organized in 1977 with agreed export guidelines. The guidelines currently include a “trigger list” of items that the suppliers agree to export only to a non-nuclear weapon state or state outside the NPT if that state has an agreement with the IAEA that allows the Agency to safeguard all its nuclear activities.

Nuclear waste. Usually, fission products, transuranic elements and activation products such as cobalt-60 produced by neutron capture in reactor structural material. Most fission products and transuranic elements are initially contained in spent fuel. If spent fuel is reprocessed, new categories of waste result.

Nuclear Weapon Free Zone (NWFZ). A region in which non-nuclear weapon states have reaffirmed collectively, through a treaty, their decision not to manufacture, acquire, test, or possess nuclear weapons and their requirement that nuclear-weapon states not store nuclear weapons on their territories.

Pit. A hollow shell of plutonium (sometimes a composite of highly enriched uranium and plutonium) clad by a protective metal such as steel. In a nuclear weapon, the pit is surrounded by high explosive that, when triggered, compresses the fissile material into a supercritical state where it can undergo an explosive chain reaction.

Plutonium-239 (Pu-239). A fissile isotope with a half-life of about 24,000 years produced when uranium-238 captures an extra neutron. The plutonium that has been used in the core of nuclear weapons typically contains more than 90-percent Pu-239.

Plutonium-240 (Pu-240). An isotope with a half-life of 6600 years produced in reactors when a plutonium-239 nucleus absorbs a neutron instead of fissioning. Its high rate of neutron emission from spontaneous fission makes it undesirable in weapon plutonium.

Plutonium-241 (Pu-241). A fissile isotope with a half-life of 14 years produced in reactors by neutron absorption on plutonium-240. Pu-241 decays into americium-241.

Power reactor. A reactor whose purpose is to produce heat to generate electricity—usually by generating high-pressure steam that drives a turbine.

Production reactor. A reactor designed primarily for the large-scale production of plutonium for weapons and/or tritium. Some production reactors have been dual purpose, generating power as a byproduct.

Radioactivity. The spontaneous disintegration of an unstable atomic nucleus resulting in the emission of electrons (beta decay) or helium nuclei (alpha decay). Often the new nucleus is produced in an “excited” state which emits its excess energy in the form of gamma rays (high-energy X-rays).

Reactor-Grade Plutonium. The United States defines reactor-grade plutonium as containing more than 18 percent plutonium-240—much more than in weapon-grade plutonium. Reactor-grade plutonium can be used, however, to make a nuclear explosive.

Recycle. The fabrication of new fuel out of the uranium and/or plutonium recovered from spent fuel in a reprocessing plant.

Reprocessing. The chemical treatment of spent reactor fuel to separate plutonium and uranium from fission products. Because of the intense radioactivity of the fission products, this has to be done remotely, behind heavy shielding.

Research reactor. A reactor designed primarily to supply neutron irradiation for experimental purposes. It may also be used for training, the testing of materials, and the production of radioisotopes.

Safeguards. Measures aimed at detecting in a timely fashion the diversion of significant quantities of fissile material from monitored, peaceful, nuclear activities. For non-nuclear weapon states that are parties to the Nonproliferation Treaty, the safeguards are implemented by the IAEA. See *Significant Quantity*.

Separative Work Unit (SWU). A measure of the work done by a machine or plant that separates uranium into streams with higher and lower fractions of U-235. Sometimes referred to as a kilogram-SWU to distinguish it from a ton-SWU (1000 SWUs).

Significant quantity (SQ). The amounts of fissile material required to manufacture a first-generation nuclear explosive device from different fissile materials. In designing its fissile-material safeguards, the IAEA assumes these quantities to be: 8 kg of Plutonium containing less than 80-percent Pu-238, 8 kg of U-233, and 25 kg of U-235 in highly enriched uranium.

Source material. Material that is not enriched in a chain-reacting isotope and that can be converted into fissile material via neutron absorption: Natural uranium or uranium depleted in the isotope 235 or thorium in the form of metal, alloy, chemical compound, or concentrate (IAEA usage).

Special fissionable material. Plutonium-239, uranium enriched in the isotopes U-235 or U-233 or any material containing one or more of the foregoing (IAEA usage).

Spent fuel. Fuel elements that have been removed from a reactor because the fissionable material they contain has been depleted to a level near where it can no longer sustain a chain reaction. The high concentration of radioactive fission products in spent power-reactor fuel creates a gamma-radiation field around it that makes spent light-water reactor fuel “self protecting” for about one hundred years. A few years after discharge, the gamma field at a distance of a meter would be lethal in minutes. A century after discharge it would be lethal in a few hours.

Strategic Arms Limitation Treaties (SALT). A series of arms control agreements between the United States and Soviet Union that limited nuclear launchers (missile silos, ballistic-missile submarines and intercontinental bombers) and deployed missiles. SALT I was signed in 1972 and SALT II in 1979.

Strategic Arms Reduction Treaty (START). The 1991 START I treaty limits the United States and Russia to 1600 strategic nuclear weapon delivery systems (long-range missiles and bombers) each and capped the number of warheads that they carry (missiles) or are equipped to carry (bombers). It expires in 2009.

Strategic Offensive Reduction Treaty (SORT). An agreement between the United States and Russia that entered into force in June 2003 to reduce the number of their operationally deployed strategic nuclear warheads to 1700-2200 warheads each by the end of 2012. Excluded by the term "operationally deployed" are warheads associated with ballistic-missile submarines that are being overhauled.

Thermonuclear explosive. A type of nuclear weapon that produces much of its energy through nuclear fusion reactions of the heavy hydrogen isotopes deuterium and tritium (also known as a hydrogen bomb). These fusion reactions require temperatures around one hundred million degrees created by a fission explosive "trigger." Thermonuclear weapons can have yields much larger than simple fission weapons.

Thorium-232 (Th-232). The naturally-occurring isotope of thorium. It is "fertile" in that neutron absorption in it produces the fissile isotope uranium-233.

Transuranic. Any element whose atomic number is higher than that of uranium. All transuranics are produced artificially and are radioactive. The most commonly produced transuranic isotopes, in order of increasing weight, are neptunium, plutonium, americium and curium.

Tritium. The heaviest hydrogen isotope, containing one proton and two neutrons in its nucleus. It is produced in reactors and in thermonuclear weapons by bombarding lithium-6 with neutrons. In the fission triggers of modern thermonuclear weapons, the fusion of tritium with deuterium heated in the interior of a chain-reacting mass of plutonium is used to produce extra neutrons that cause additional fissions and "boost" the explosive's power.

Uranium. The element with 92 protons and electrons. The two principal natural uranium isotopes are uranium-235 (0.7-percent of natural uranium), which is a fissile material, and uranium U-238 (99.3-percent of natural uranium), which is not.

Uranium dioxide (UO_2). The chemical form of uranium used in heavy-water and light-water power reactor fuel. Powdered uranium dioxide is pressed and then sintered into ceramic fuel pellets.

Uranium hexaflouride (UF_6). A volatile compound of uranium and fluorine. UF_6 is a solid at atmospheric pressure and room temperature, but can be transformed into gas by heating. UF_6 gas is the feedstock in gas-centrifuge and gaseous-diffusion uranium enrichment processes.

Uranium oxide (U_3O_8). The most common oxide of uranium found in typical ores. Uranium oxide is extracted from the ore during the milling process. The ore may contain only 0.1-percent U_3O_8. Yellowcake, the product of the milling process, contains about 80-percent U_3O_8.

Uranium-233 (U-233). An artificial fissile isotope produced by neutron absorption in thorium-232. Like HEU and plutonium, it is weapon-usable. It has been used in at least one nuclear test but not in deployed nuclear weapons—perhaps because a small amount of U-232 is produced with it. A decay product of U-232 produces gamma radiation at levels higher than the levels produced by weapon-grade plutonium resulting in greater radiation doses for those working with it. U-233 has been of interest as a reactor fuel for heavy and light-water moderated reactors because its fission by low-energy neutrons releases more neutrons than does the fission of plutonium-239.

Uranium-235 (U-235). The only naturally occurring chain-reacting isotope. Natural uranium contains 0.7- percent U-235. Light-water reactors use fuel containing 4-5 percent U-235. Weapon-grade uranium normally contains at least 90-percent.

Uranium-238 (U-238). Natural uranium contains approximately 99.3-percent U-238.

Weapon-grade. Fissile material with the isotopic makeup typically used in fission explosives: uranium enriched to over 90-percent U-235 or plutonium that is more than 90-percent Pu-239. The uranium used in the Hiroshima weapon was enriched to about 80-percent. Uranium enriched to greater than 20-percent and plutonium containing less than 80-percent Pu-238 are not weapon grade but are considered weapon-useable.

Yellowcake. A uranium concentrate produced during the process of extracting uranium from ore or “milling” that contains about 80-percent U_3O_8. In preparation for uranium enrichment, the yellowcake is converted to UF_6. In the preparation of natural uranium heavy-water power reactor fuel, yellowcake is processed into uranium dioxide (UO_2).

Yield. The total energy released in a nuclear explosion—usually measured by the number of kilotons of TNT whose explosion would release the same amount of energy.

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Over the past six decades, our understanding of the nuclear danger has expanded from the threat posed by the vast nuclear arsenals created by the superpowers in the Cold War to encompass the proliferation of nuclear weapons to additional states and now also to terrorist groups. To reduce this danger, it is essential to secure and to sharply reduce all stocks of highly enriched uranium and separated plutonium, the key materials in nuclear weapons, and to limit any further production.

The mission of the IPFM is to advance the technical basis for cooperative international policy initiatives to achieve these goals.

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