



IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2010

Balancing the Books: Production and Stocks

Fifth annual report of the International Panel on Fissile Materials

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On the cover: the map shows existing and planned uranium enrichment and plutonium separation (reprocessing) facilities. See pages 25 – 26 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 seventeen 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 and naval fuel 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 hundreds of Hiroshima-type bombs, a design potentially within the 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, Ireland, Japan, South Korea, Mexico, the Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. 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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Overview

Accounting for Fissile Material Production and Stocks in Nuclear Weapon States

Global Fissile Material Report 2010: Balancing the Books reviews the official declarations of fissile material production and stocks by the United States and the United Kingdom and provides revised estimates of the past production and current holdings of highly enriched uranium (HEU) and plutonium for six nuclear weapon states that have not declared their holdings and for the non-weapon states collectively. Fissile material production by North Korea, the one nuclear weapon state not covered in this volume, was discussed in *Global Fissile Material Report 2009*.¹ This is the first comprehensive public update of this information since the groundbreaking work done by Albright, Berkhout, and Walker in the 1990s.²

Under the Nonproliferation Treaty (NPT), non-nuclear-weapon state parties to the treaty are obligated to declare all their nuclear materials to the International Atomic Energy Agency (IAEA) and make them available for its safeguards. These declarations are considered confidential, however, and are not made public. As the world moves toward nuclear disarmament, it will be necessary for the weapon states as well to make such declarations and to accept IAEA monitoring on their civilian and excess weapon materials. In a disarmed world, all fissile material would have to be accounted for and under international safeguards.

This overview chapter addresses three broad issues:

- Why it is important for the weapon states to develop and make public detailed accounts of their fissile material production, disposition and stocks;
- The issues they face in developing the basis for such fissile material declarations, and how the declarations could be sequenced; and
- Why international verification of declarations, to the extent feasible, is important, and the importance of carrying out international “nuclear archaeology” projects before shutdown production facilities are decommissioned and production waste is permanently disposed of.

Chapter 1 summarizes the current status and our current knowledge of global and national nuclear weapon and fissile material stockpiles. The following chapters discuss in detail the production histories and current status of public understanding of the

fissile-material stocks of the individual nuclear weapon states, other than North Korea, and of the non-weapon states collectively.

The Importance of National Accounts of Fissile-material Production, Use and Stocks

All nuclear-weapon states maintain accounting systems for fissile materials that, at a minimum, track their current inventories. In addition, some states have fissile-material accounting systems that provide a detailed record of production, use, and transfers between facilities. The United States has a Nuclear Materials Management and Safeguards System (NMMSS) that currently tracks 17 types of nuclear materials, including enriched uranium in different enrichment ranges, plutonium, and other fissile isotopes including uranium-233, neptunium-237, and americium-241.³

Despite the fact that there are today no NPT requirements on states to make information on their fissile-materials stocks available to other governments or the public, some non-weapon and weapon states have made public information on their holdings of fissile material. Under the Plutonium Management Guidelines, nine states (the NPT weapon states plus Belgium, Germany, Japan, and Switzerland), annually declare their holdings of civilian plutonium, and three (France, Germany, and the United Kingdom) now also make public their holdings of civilian HEU. In addition, the United Kingdom and United States have declared their military HEU and plutonium inventories.

As detailed in Chapter 2, the United States has provided historical production data by year and site with the HEU divided into enrichment ranges and its plutonium into Pu-240 percentage ranges, i.e., weapon-grade and non-weapon-grade stocks. After declaring its military stocks in 1998,⁴ the United Kingdom published in 2000 and 2006 respectively much more limited information on its plutonium and HEU production and use.⁵ These declarations are reviewed in Chapter 5.

The justifications given by the United States and United Kingdom for making the information on fissile materials public are worth quoting. In its first (1993) report on HEU, the United States asserted that:

“The American public will have information that is important to the current debate over proper management and ultimate disposition of uranium... The quantities may aid in public discussions of issues related to uranium storage safety and security. The data will be of some aid to regulators who will oversee environmental, health and safety conditions at the national laboratories [and] have valuable nonproliferation benefits by making potential International Atomic Energy Agency safeguards easier to implement.”

The 1996 U.S. plutonium report argues that:

“Openness is essential to public accountability and trust ... The DOE believes that this report will aid in discussions of plutonium storage, safety, and security with stakeholders as well as encourage other nations to declassify and release similar data. These data will also be available for formulating policies with respect to disposition of excess nuclear materials.”

In its 2006 report on HEU, the United Kingdom asserted the importance of such declarations for the verification of nuclear disarmament:⁶

“The UK believes that transparency about fissile material acquisition for defence purposes will be necessary if nuclear disarmament is to be achieved; since achieving that goal will depend on building confidence that any figures declared for defence stockpiles of fissile material are consistent with past acquisition and use.”

The United Kingdom also urged that other countries should prepare such declarations for themselves as soon as possible, because of the problem of ephemeral and inadequate records. In this connection, the authors of the UK report offered as a cautionary example the problems that they had encountered with such production records:⁷

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

Thus, the United Kingdom learned that its national accounting system was inadequate to provide a complete record of its production and use of fissile materials. This may be one reason why the United Kingdom did not attempt to produce detailed historical reports of production and disposition such as those of the United States. Other nuclear weapon states are probably in a similar position.

The U.S. and British experiences show the discipline imposed by public declarations of fissile stocks is needed to ensure that the nuclear weapon states maintain the highest standards of accounting and management of their fissile materials. All organizations where fissile materials are handled should have to account for and assure the accuracy of their holdings and governments should develop consistent and comprehensive systems to track all fissile material production and transfers.

A comprehensive accounting system also would strengthen central oversight of security of the materials. Audits and consistency checks are necessary not only for the verification of disarmament but to detect the diversion of fissile materials. As discussed in Chapters 2 and 8, for example, the U.S. government continues to debate whether up to 300 kilograms of weapon-grade uranium—enough for over ten first-generation nuclear weapons—were diverted from a U.S. naval propulsion reactor fuel fabrication plant to Israel in the late 1960s.

Declarations also would open up the policy debate on nuclear reductions by making clearer which countries have excess stocks.

Decisions to Make Public Fissile Material Declarations

Despite the initiatives of the United States and the United Kingdom, starting in the 1990s, to make public declarations of their fissile material holdings, no other weapon state has done so.

As discussed in Chapter 6, France has been open about the shutdown of its military uranium enrichment and plutonium production facilities. It invited international observers to witness that the sites were not operating and were being dismantled. France has made no information public, however, on the size of its military fissile-material stocks.

Russia's declarations in the 1990s that it had at least 500 tons of weapon-grade HEU and 50 tons of weapon-grade plutonium beyond its post-Cold War military requirements made clear that Russia is not shy of revealing that it possesses very large quantities of these materials.⁸ Its reluctance to go into further detail may stem from a resurgent culture of secrecy and an inadequate historical accounting system. As shown in Chapters 3 and 4, however, technical articles and memoirs have been making increasing amounts of information available about Russia's plutonium and HEU production histories. This has allowed a significant reduction in previous uncertainties about the size of Russia's stocks of these materials.

China's stockpiles are much smaller than those of Russia and the United States and, at present, China does not feel secure enough to make public exactly how much less.⁹ As with Russia, however, there are new sources of official and unofficial information that allow for more accurate independent estimates of the histories of China's plutonium and HEU production and of its current stocks. Chapter 7, for instance, uses newly released official information about the early years of China's nuclear program and media reports and memoirs to show that China's plutonium stockpile may be significantly smaller than many previous estimates.

Israel opposes any public discussion of its nuclear weapons for fear of provoking its neighbors to produce their own and/or increasing international pressure on it to disarm. As discussed in Chapter 8, despite official Israeli efforts, Mordechai Vanunu, who worked as a technician at the Dimona nuclear facility from November 1976 until October 1985 made public a considerable amount of information about its plutonium-production program. Independent technical assessments using commercial satellite imaging have been made more difficult by a 1997 U.S. law discouraging commercial companies from releasing high-resolution imagery of Israeli sites. Israel may no longer be building up its nuclear arsenal. If this is the case, it could signal that fact to the international community by shutting down the Dimona plutonium-production reactor.¹⁰

India and Pakistan are locked in a nuclear-arms race, with India also looking over its shoulder at China. Neither India nor Pakistan is interested in an open domestic or international debate over how much fissile material it needs. Chapter 9 shows that there is enough new information available, however, to suggest that India's stockpile of weapon-grade plutonium may be smaller than previously estimated. Chapter 10 discusses the continuing uncertainties about the number and capacities of Pakistan's enrichment plants and hence about the size its HEU stocks.

Pakistan perceives a fissile-material gap relative to India and has been using this as a basis for blocking talks on a Fissile Material Cutoff Treaty at the United Nations Conference on Disarmament in Geneva.¹¹

Phased declarations of increasing detail. Fissile-material declarations as comprehensive as those of the United States cannot be expected from all nuclear weapon states in the near term. All should, however—if only for internal security reasons—start the process of preparing the accounting basis for public declarations. This will require both a careful inventory of current stocks and, to the extent possible, a reconstruction of the history of past fissile material production and removals. This could provide the basis for a phased series of declarations of increasing detail.

An initial declaration could simply be of total current holdings of plutonium and HEU. In its most basic form, such a declaration would consist of two numbers. This is what the United Kingdom did in 1998.¹² Russia and France could make such declarations today. The next step would be to declare separately the total amounts of HEU and plutonium separately in warheads, naval reserves, excess military material, civilian stocks, and spent fuel. Declarations organized along these lines would not go beyond information that the United States has already made public.¹³

International Verification

International verification of declarations would start with rough consistency checks. During the Cold War and since, the United States and Soviet Union/Russia each devoted substantial resources to studying each other's nuclear complexes and those of the other nuclear weapon states. They therefore would be expected to check declarations of production-histories against their own observations.

Declaring countries could further strengthen the credibility of their declarations if they made available to the IAEA and each other copies of their detailed production records. In 2008, North Korea reportedly shared with the United States eighteen thousand pages of operating records of its plutonium production operations.¹⁴ It would be very difficult to alter or counterfeit such a comprehensive set of records in a consistent way.

Once nuclear weapon states release production histories by site and facility, physical checks could be made. This process would involve “nuclear archaeology,” which could reveal evidence of the quantities and types of fissile materials that had been produced at each site.¹⁵ Such international verification projects could initially be limited in scope to selected individual sites.

The best-established example of nuclear archaeology for plutonium production relies on measurements of the transmutation of trace isotopes in the graphite of graphite-moderated plutonium production reactors. This so-called Graphite Isotope-Ratio Method (GIRM) estimates the cumulative neutron flow through the graphite and thereby the cumulative plutonium production in the reactor.¹⁶ Equivalent methods are being investigated for heavy-water-moderated reactors, which also have played important roles in the production of weapons plutonium.¹⁷

There is no corresponding evidence of cumulative production of HEU left behind in the processing equipment used in enrichment plants. Detailed evidence exists, however, in the associated depleted uranium that is often stored for decades in cylinders next to the plants. Preliminary analyses suggest that the relative content of uranium-234 and uranium-235 in a particular cylinder could, at the very least, clarify whether

the sampled material was associated with LEU or HEU production.¹⁸ Analysis of the depleted uranium could also determine its age and, through the presence or absence of uranium-232 and uranium-236, which are produced by neutron capture in natural uranium, whether reprocessed uranium had been enriched.

Samples of the fissile materials themselves would provide additional information. For example, the fraction of plutonium-239 in a given batch of material would confirm the discharge burnup of the fuel from a given production reactor.

A window of opportunity. Today, fissile material production facilities are being shut down and prepared for decommissioning and dismantlement in a number of weapon states.

The United States has started decommissioning the five heavy-water production reactors at its Savannah River Site and is planning to dismantle eight out of the nine graphite-moderated production reactors at its Hanford site. The United Kingdom and France have started decommissioning their principal production reactors. Russia and China have not yet decommissioned their shutdown production reactors.

Countries should not dismantle key components of their production reactors until international bilateral and multilateral nuclear-archaeology initiatives can be set up, under IAEA supervision, and with participation from non-weapon states, to develop and implement on-site sampling methods and benchmark computer simulations that can be used to verify the fissile material production history at each facility. The weapon states might begin by each identifying one production reactor as a potential test bed for international studies to clarify the capabilities and limits of nuclear archaeology.

The weapon states also should build nuclear archaeology into their plans to dispose of the depleted uranium that was produced in association with their highly enriched uranium. Once, this depleted uranium is disposed of, a valuable opportunity to provide evidence about enrichment program histories will have been lost.

Plutonium and HEU-containing wastes also should not be irreversibly disposed before international checks can be made of the total amounts of material that they contain. It is unfortunate in this context that the IAEA did not take advantage of a U.S. offer to verify the amount of plutonium that the United States is disposing in its deep-underground Waste Isolation Pilot Plant (WIPP) in New Mexico. It may be impractical to open up the chambers where the United States has already sent about 3 tons of plutonium in wastes from defense facilities but the planned disposal of many more tons of plutonium there could still be checked.

Societal Verification. There will clearly be limits on how accurately outside inspectors could reconstruct all of a country's past production. For the United States and Russia, even one percent uncertainties in the reconstruction of fissile material stocks would be equivalent to hundreds of warheads.

For this reason, verification regimes for nuclear disarmament will also have to rely on "societal verification," i.e., citizen and insider "whistle blowing" on significant violations of nuclear disarmament agreements. Hundreds of personnel would have to be involved in such a deception, including officials, scientists, engineers, and guards. Any one of them could become a whistleblower and, in a well-designed verification regime, would be encouraged to do so.¹⁹

In the interim, as shown in this report, independent analysts have been able to make informed guesses and estimates about fissile production facilities and activities, even in nuclear weapon states that have not made formal declarations of their fissile material stocks. Such assessments can help advocates of international transparency within internal government debates to argue that a country has little to lose in making public information for which approximate estimates have already been published. The availability of credible independent estimates such as those reported here—even if uncertain—also can provide a basis for public calls to end arms races and make deeper reductions in nuclear weapons and fissile material stockpiles.

1 Nuclear Weapon and Fissile Material Stockpiles and Production

In 2010, the global stockpile of highly enriched uranium (HEU) was about 1475 ± 125 tons,* enough for more than 60,000 simple, first generation fission weapons. About 98% of this material is held by the nuclear weapon states, with the largest HEU stockpiles being held by Russia and the United States. The large uncertainty in the estimate is due to Russia not declaring how much HEU it produced before stopping production in the late 1980s. The United States, which ended production in 1992, has published an official history of its HEU production.

Today, only India and Pakistan are believed to be producing HEU. But their programs are relatively small scale. As a result, the global HEU stockpile is shrinking as Russia and the United States together blend down HEU that they have declared as excess to military needs at a rate of over 30 tons per year to produce low-enriched uranium for power reactor fuel.

The non-nuclear weapon states account for about 20 tons of HEU, almost all of which was provided to them as research reactor fuel by the weapon states. This stockpile is declining as research reactors are converted to low-enriched uranium fuel or closed down and the HEU fuel is blended down or returned to the country of origin.

The global stockpile of separated plutonium in 2010 was about 485 ± 10 tons. About half of this stockpile was produced for weapons, while the other half has mostly been produced in civilian programs in nuclear weapon states. As a result, about 98 per cent of all separated plutonium is in the nuclear weapon states. There are more than 10 tons of plutonium in the non-weapon states, most of which is in Japan, the only non-weapon state with a large program to separate plutonium from spent nuclear fuel.

The stockpile of separated plutonium for weapons continues to increase because of production in Israel, India, and Pakistan. As yet, this new production is not being offset by fabrication of excess Russian and U.S. weapon plutonium into reactor fuel. The five NPT nuclear-weapon states stopped production decades ago.

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

The global plutonium stockpile in civilian programs is growing at a faster rate than the military stockpile. Active weapon plutonium production programs operate on a much smaller scale than the commercial reprocessing programs in France, Russia, and the United Kingdom. Japan's reprocessing program continues to be stalled with the start-up of the Rokkasho plant now delayed till late 2012.

Nuclear Weapon Stocks

There are today nine nuclear weapon states. In historical order they are: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan, and North Korea. Estimates of their nuclear-weapon stocks are shown in Table 1.1.

Country	Current Nuclear Warheads
United States	about 9400, with about 4000 awaiting dismantlement
Russia	about 10,000, with a large fraction awaiting dismantlement
France	fewer than 300
United Kingdom	fewer than 225
China	about 240
Israel	100 – 200
Pakistan	70 – 90
India	60 – 80
North Korea	fewer than 5

Table 1.1. Estimated nuclear-weapon stockpiles, 2010. Source: FAS/NRDC.²⁰

The United States, Russia, France, and the United Kingdom have been reducing their deployed arsenals from Cold War levels. China and Israel may have kept their arsenals roughly constant for decades, while India and Pakistan are building up their weapon stockpiles. North Korea, having carried out nuclear weapon tests in October 2006 and again in April 2009, effectively capped its plutonium stockpile by halting production and disabling parts of its production facilities.

United States and Russia. The United States and Russia signed the New-START agreement in April 2010, limiting the two countries to 1550 deployed strategic warheads each. This limit is to be reached within seven years of the treaty entering into force. As with previous bilateral U.S.-Russian agreements, New-START does not require the dismantlement of warheads taken off deployment. The United States seeks to include tactical weapons and strategic warheads held in reserve in the scope of the next U.S.-Russia arms reduction agreement.²¹

United States. In May 2010, the United States declared a stockpile of 5113 warheads as of the end of September 2009.²² This stockpile included almost 2000 strategic warheads deployed on about 800 missiles and bombers, 500 non-strategic warheads and 2,600 warheads in reserve. An additional 3500–4500 warheads are awaiting dismantlement.²³ The 2010 U.S. *Nuclear Posture Review Report* indicated that the number of warheads in the dismantlement queue will increase as warheads are removed from deployment to meet New-START targets, and that eliminating the dismantlement backlog will take over a decade.²⁴

Along with the current size of its nuclear arsenal, the United States announced that from fiscal years 1994 through 2009, it dismantled 8748 nuclear warheads (Figure 1.1).²⁵ The United States dismantled 356 warheads in 2009, compared to an average dismantlement rate of over 1000 warheads per year in the late 1990s. The current low rate of dismantlement is due to the greater priority accorded warhead life-extension programs at the assembly and disassembly facility in Pantex, Texas. Life-extension programs replace components and, in some cases, add new capabilities to the warheads.²⁶

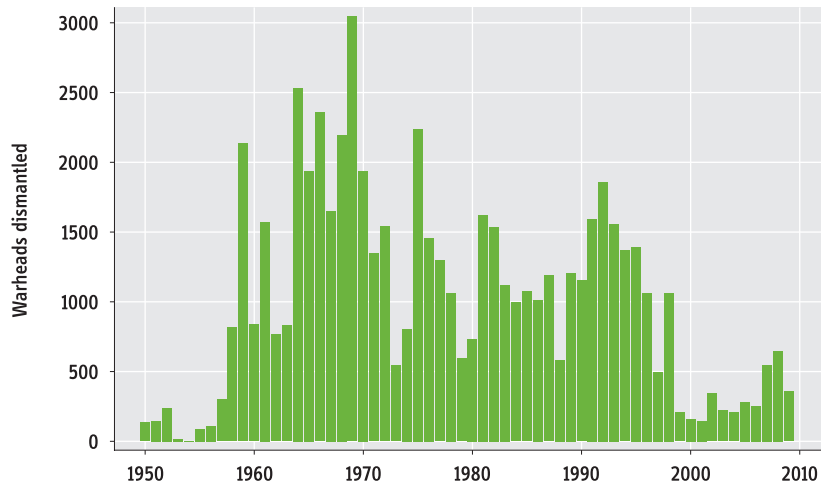


Figure 1.1. U.S. warhead dismantlement rates from 1945 to 2010. The United States dismantled fewer than 400 warheads in 2009, about one fourth the average dismantlement rate in the early 1990s. *Source: FAS and U.S. Departments of Defense and Energy.*²⁷

Russia. Russia continues to maintain secrecy over the total size and composition of its nuclear arsenal. Until the START Treaty expired in 2009, Russia and the United States exchanged information on their deployed strategic warheads. Such exchanges are to resume once New START is ratified.

United Kingdom. In May 2010, Foreign Secretary William Hague told Parliament that the UK’s total stockpile of nuclear warheads would not exceed 225 warheads, and the United Kingdom would retain up to 160 operationally available warheads.²⁸ The 65 remaining warheads are maintained intact to support the logistics and maintenance requirements of the operational arsenal.²⁹

In October 2010, as part of military spending cuts, the UK Strategic Review announced plans to cut the arsenal by the mid-2020s to no more than 120 operationally available warheads, reduce the overall nuclear weapon stockpile to no more than 180, to delay decision on new Trident missile submarines till 2016—in effect extending the life of the current submarine fleet—and defer a new nuclear warhead until at least the late 2030s.³⁰

France. France has not revealed whether or not it has yet met the target announced in 2008 by President Nicolas Sarkozy of reducing the arsenal to “fewer than 300 nuclear warheads.”³¹

There is no significant new information concerning the active nuclear arsenals or nuclear weapon plans of China, Israel, India, Pakistan, and North Korea.

Highly Enriched Uranium Stocks

The estimates for national highly enriched uranium (HEU) stockpiles presented here and in Figure 1.2 are discussed at length in the country chapters in this report. The United States and United Kingdom are still the only states to have declared the size of their HEU stockpiles.

The new estimates, and the significant uncertainties associated with them, do not change the fundamental fact that about 98 per cent of all highly enriched uranium is held by the nuclear weapon states, and that most of this material is held by Russia and the United States. The current global inventory of highly enriched uranium is estimated to be about 1475 ± 125 tons.

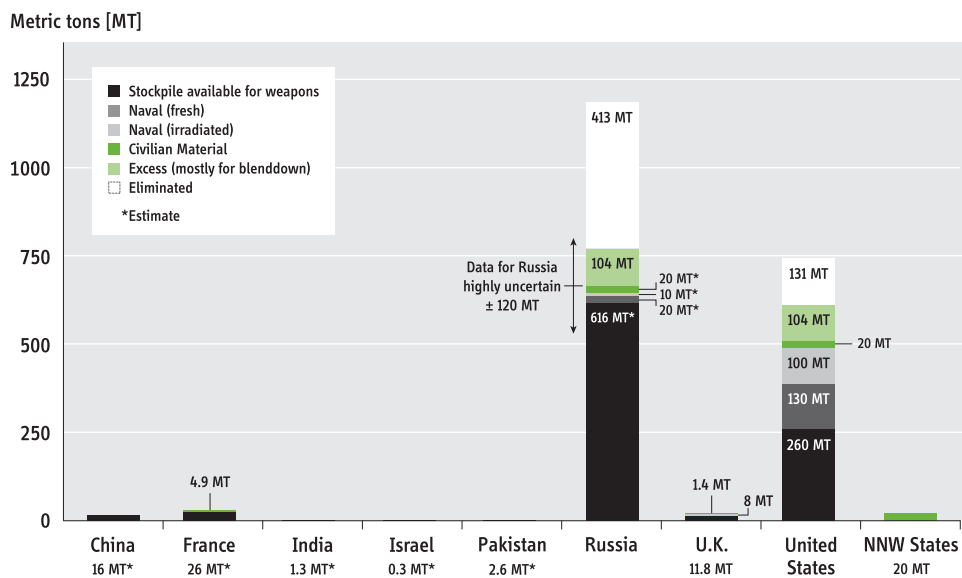


Figure 1.2. National stocks of highly enriched uranium as of 2010. The numbers for the United Kingdom and United States are based on their publications. The civilian HEU stocks of France, the United Kingdom are based on their public declarations to the IAEA. Numbers with asterisks are IPFM estimates, often with large uncertainties.³² HEU in non-nuclear weapon (NNW) states is under IAEA

safeguards. A 20% uncertainty is assumed in the figures for total stocks in China and for the military stockpile in France, about 30% for Pakistan, and about 40% for India. The 413 tons of eliminated Russian HEU include 400 tons from the 500-ton HEU deal and 13 tons from the Material Consolidation and Conversion (MCC) project. About 4 tons of HEU remain for blend-down within the MCC project.

Russia. The largest stockpile of HEU is held by Russia, which is estimated to have produced about 1250 ± 120 tons of 90% enriched HEU (Chapter 4). This figure does not include the 220 tons of HEU that was used to manufacture fuel for naval reactors, research reactors and fast reactors, most of which contained less than 90% uranium-235. This is consistent with the 1993 statement made by Viktor Mikhailov, Russia's Minister of Atomic Energy that "the 500 metric tons of [weapon-grade] HEU that is up for sale represents somewhere around 40 percent of all reserves that we [Russia] possess."³³ This would suggest that as of 1993 the Russia had a stockpile of about 1250 tons of 90%-

enriched HEU. Mikhailov's statement suggests the Soviet Union may have produced a total of 1340 tons of 90%-enriched HEU, since an estimated 90 tons was consumed by that date in nuclear-weapon tests, in plutonium and tritium production reactors, and lost in processing waste.³⁴

As of mid-2010, Russia has an estimated 770 ± 120 tons of highly enriched uranium. This includes material in and available for weapons, and reserved for naval and research reactor fuel. As of September 2010, this stockpile included 100 tons of HEU that was to be blended down by 2013 as part of the 1993 U.S.-Russia HEU purchase Agreement. Russia had blended down a total of 400 tons of the 500 tons of weapon-grade HEU that it committed to blend down under this agreement.³⁵

United States. The United States made public a report of its production and consumption of HEU as of the end of September 1996 and subsequently updated this declaration to the end of September 2004. This information is analyzed in Chapter 2. The total U.S. HEU stockpile continues to decline because of the continuing blend-down of 210 tons of HEU declared as excess to military requirements. As of April 2010, the United States had blended down a total of about 131 tons of this excess HEU.³⁶

France. For more than thirty years, France operated a dedicated gaseous diffusion enrichment plant near Pierrelatte (in the South-East of France) for the production of weapon-grade uranium. As of 2010, there is virtually no information publicly available on the capacity of the plant and its operational history. The lifetime HEU production of the plant therefore remains highly uncertain. France also operated high-power HEU-fueled reactors for the production of plutonium and tritium, which may have consumed 5–7 tons of its HEU stockpile, and also used the Pierrelatte plant to produce fuel for naval and power reactors. Both factors add to the uncertainties in any stockpile estimate based on the open literature. In Chapter 6, we estimate France's current inventory of military HEU to 26 ± 6 tons, a large fraction of which—possibly up to 20 tons—could be declared excess today. In addition, France has declared a civilian HEU inventory of 4.9 tons, which includes 3.3 tons of unirradiated material.

United Kingdom. In 1998, as part of its *Strategic Defence Review*, the United Kingdom announced an inventory of 21.9 tons of military HEU.³⁷ Almost the same amount was declared in 2006 in a follow-on report of an audited stock of 21.86 tons of HEU as of 31 March 2002.³⁸

Over half of the HEU in the UK stockpile was supplied by the United States. Some was bartered for UK-supplied LEU, plutonium, and tritium. Both countries have officially declared that 7.5 tons of HEU were transferred between 1960 and 1979. They have not made public, however, how much U.S. HEU was transferred to the United Kingdom subsequently. In Chapter 5, it is estimated that more than 6.5 tons of U.S. HEU were transferred to the United Kingdom after 1980, bringing the total to at least 14 tons of weapon-grade uranium received from the United States. The United Kingdom is estimated to have produced about 9–13 tons of HEU between 1955 and 1962 at the gaseous diffusion plant (GDP) at Capenhurst (see Chapter 5). In 1963, the Capenhurst GDP switched to producing LEU, and it was shutdown in 1982.

The United Kingdom appears to have 10–15 tons of fresh (unirradiated) highly enriched uranium in reserve. Most if not all of this material is probably earmarked for future use in naval propulsion reactors and would be sufficient to fuel the UK nuclear fleet of current size for about a century.

China. China maintains great secrecy about its military stockpiles of fissile materials. In Chapter 7, it is estimated that China may have produced 20 ± 4 tons of HEU, and now may have a stockpile of about 16 ± 4 tons of HEU. These estimates take into account removals, i.e., China's use of HEU in nuclear-weapon tests and in research reactor fuel, as well as the use of its enrichment plants to produce LEU for naval-reactor fuel.

The estimate in Chapter 7 of China's HEU holdings is lower than most previous values. It is based upon a new assessment of the capacity and operating history of the Lanzhou and Heping gaseous diffusion plants where China produced its highly enriched uranium. The Lanzhou gaseous diffusion enrichment plant is believed to have produced HEU from 1964 to 1980, before switching to produce LEU until it was finally shutdown in 1987. The Heping plant is believed to have produced HEU from 1975 to 1987. Previous estimates typically assumed that these plants ended HEU production in 1987 and 1989, respectively.³⁹

Pakistan. Pakistan continues to produce highly enriched uranium for weapons. There is great uncertainty about the evolution of Pakistan's enrichment capacity, especially over the past decade (see the discussion in Chapter 10). It is estimated that, as of 2010, Pakistan would have produced 2.7 ± 1 tons of weapon-grade (90%-enriched) HEU. Pakistan's six nuclear weapon tests in 1998 would have consumed on the order of 0.1 tons, leaving it with an HEU stockpile of 2.6 ± 1 tons of HEU.

India. To date, India's HEU production has been principally intended to fuel its nuclear submarine propulsion program. This HEU may be much less than weapon-grade (see Chapter 9). Assuming an enrichment level of 30%, India is estimated to have had a stockpile of 1.3 ± 0.5 tons of highly enriched uranium as of 2010.

India's prototype submarine was launched in July 2009. As of September 2010, its reactor was not yet operational.⁴⁰ The hulls of two more submarines have been completed.⁴¹ India is expected to build a fleet of three to five nuclear submarines.⁴² India has been increasing its uranium enrichment capacity. In October 2009, the Director of the Bhabha Atomic Research Center (BARC) announced that India's installed enrichment capacity had been "substantially enhanced," in part by installing more powerful centrifuges.⁴³ Recent satellite imagery suggests that India also may be adding new enrichment halls at its Rare Materials Plant (RMP) in Rattehalli, Mysore (Karnataka).⁴⁴ India is planning a second enrichment facility, the "Special Material Enrichment Facility," in Chitradurga district in Karnataka, which may be used to produce low-enriched uranium to fuel commercial light-water power reactors.⁴⁵

Civilian Use of HEU

There are more than a hundred civilian facilities worldwide in which HEU is used as reactor fuel. This includes research reactors, critical assemblies, pulsed-power reactors, which have lifetime cores that can contain large quantities of barely-irradiated HEU, and Russian nuclear-powered icebreaker and container ships. Table 1.2 lists the types, numbers and locations of HEU facilities in operation as of April 2010.

In April 2010, the United States convened a Nuclear Security Summit in Washington, DC, to promote the goal of securing what was described as "all vulnerable nuclear material" in four years. The forty states that participated (including eight of the nine nuclear weapon states) agreed in the final communiqué that "highly enriched uranium and separated plutonium require special precautions and [we] agree to promote measures to secure, account for, and consolidate these materials, as appropriate; and

encourage the conversion of reactors from highly enriched to low enriched uranium fuel and minimization of use of highly enriched uranium, where technically and economically feasible.”⁴⁶

	Russia and NIS	China	Europe	United States	Other	Total
Critical assemblies	36	1	4	5	2	48
Pulsed reactors	16	0	3	3	0	22
Steady-state reactors (<0.25 MW)	2	3	4	1	11	21
Steady-state reactors (0.26 – 1 MW)	1	0	0	0	0	1
Steady-state reactors (1.1 – 2 MW)	0	0	0	0	0	0
Steady-state reactors (2.1 – 10 MW)	6	0	0	2	1	9
Steady-state reactors (> 10 MW)	9	0	7	4	0	20
In nuclear powered civilian vessels	11	0	0	0	0	11
Total	81	4	18	15	14	132

Table 1.2. Civilian HEU-fueled reactors worldwide, 2010.⁴⁷ The table does not include military naval reactors.

As part of this summit, Chile committed to remove 18 kg of HEU; Ukraine to remove all HEU by the next Nuclear Security Summit, to be held in South Korea in 2012; and Mexico and Vietnam committed to convert their research reactors to LEU fuel.⁴⁸ No commitments were made to reduce civilian stockpiles of separated plutonium.

As of April 2010, twenty-one non-weapon states had been virtually cleared of HEU, defined as holding less than one kilogram of highly enriched uranium (see Chapter 11). The non-weapon states still possess about 20 tons of HEU, a significant fraction of which is in spent research reactor fuel (about half of this HEU is in Kazakhstan, and is only about 20% enriched). Figure 1.3 shows the location of civilian HEU worldwide. Most is located in a few weapon states.

Canada’s NRU reactor, which was shut down in May 2009 after operators discovered a heavy-water leak, is now ready to resume production of medical isotopes using HEU targets.⁴⁹ Canada has committed to end the use of HEU for this purpose by 2016 when the NRU is scheduled to shut down. HEU targets are also used in Europe and Russia. The conversion of the FRM-II reactor in Germany from 93 percent to 50 percent uranium-235 enriched fuel originally planned for December 2010 has been postponed until at least 2018.⁵⁰ FRM-II uses up to 40 kg of weapon-grade uranium in fuel each year. The status of HEU in civilian research reactors in these and other non-weapon states and the prospects for conversion and cleanout are discussed in Chapter 11.

In Russia and China, new HEU fueled reactors are coming on line. Start-up of the new high-flux PIK research reactor fueled with 90% highly enriched uranium, at the Saint Petersburg Institute of Nuclear Physics in Russia which was due to start in 2010 was delayed for at least a year.⁵¹ It is the first new research reactor to use HEU-based fuel since Germany’s FRM-II reactor went critical in 2004. Based on its power level of 100 MWt, the estimated HEU demand could be on the order of 100 kg per year.

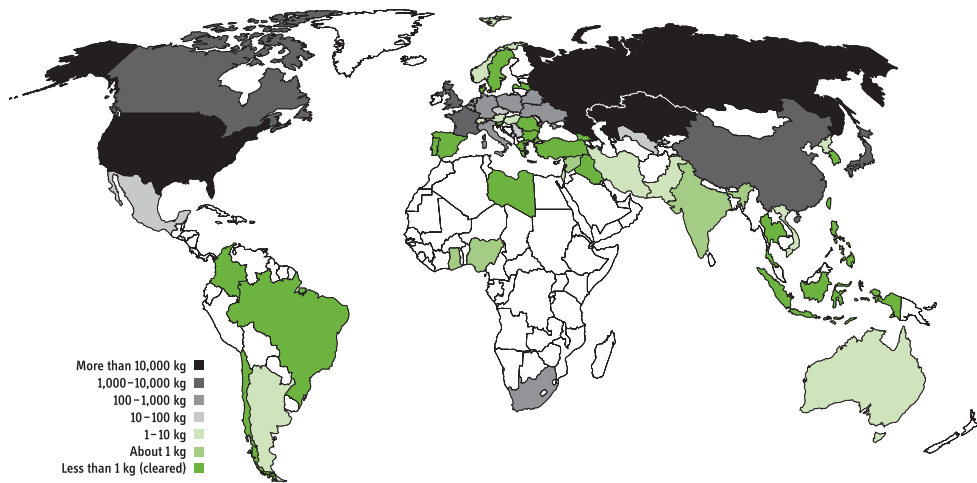


Figure 1.3. Distribution of civilian HEU worldwide as of 2010. There are still more than 50 sites in about 30 countries where the material can be found in significant quantities, at operational or shut down, but not yet decommissioned HEU-fueled reactors. See also Table 11.1.

In China, a 60 MWt Experimental Fast Reactor (CEFR) went critical in July 2010.⁵² It is fueled with about 250 kg of 65-percent enriched HEU provided by Russia.⁵³ China is seeking to purchase two Russian designed BN-800 reactors.⁵⁴ The CEFR is to use plutonium-uranium fuel in later loadings.

Civilian Uranium Enrichment Plants

The number and capacities of civilian enrichment plants, operating, under construction, and planned, continues to grow (Appendix 1A). Some of the planned projects have suffered problems in the past year and may be delayed. Currently, civilian enrichment plants in ten states produce low-enriched uranium for power-reactor fuel. Thus far, India and Pakistan have only military enrichment programs. Iran has begun producing uranium enriched to almost 20%, which sets a precedent for a non-weapon state. North Korea revealed a small centrifuge enrichment plant in November 2010.

United States. In June 2010, the European enrichment consortium Urenco began operations of its Urenco-USA uranium centrifuge enrichment facility in Eunice, New Mexico.⁵⁵ The facility is the first new enrichment plant in the United States since 1956; it is expected to reach a capacity of 5.9 million SWU per year.

In May 2010, the U.S. Department of Energy announced a \$2 billion loan guarantee for Areva’s 6.6 million SWU Eagle Rock Enrichment Facility near Idaho Falls, Idaho.⁵⁶ The loan is conditioned on the facility obtaining a construction and operating license from the Nuclear Regulatory Commission. The license application was submitted in 2008. The NRC submitted a draft Environmental Impact Statement for the facility in July 2010. Areva plans to begin construction in 2011 and begin operation in 2014.

Two other planned enrichment facilities in the United States have both faced problems. In July 2010, the USEC American Centrifuge Plant (Figure 1.4) was denied a \$2 billion loan guarantee by the United States Department of Energy.⁵⁷ The DOE determined that USEC had insufficient experience with its technology to overcome problems of “either

major cost overruns or reliability problems or both.” USEC subsequently resubmitted its loan-guarantee application after addressing DOE concerns and having acquired new financial backing from Toshiba and Babcock & Wilcox.⁵⁸



Figure 1.4: Centrifuges developed by USEC for the American Centrifuge Plant. The USEC AC100 centrifuge has a design capacity of 350 SWU per year and is over 12 meters tall. For comparison, a current Urenco centrifuge, the TC-21, has a capacity of 90-100 SWU per year and a height of about 6 meters, while Russian centrifuges are typically of the order of 5 SWU per year and have a height of about 1 meter.⁵⁹ Source: www.usec.com.

In August 2010, the Global Laser Enrichment (GLE) project in North Carolina delayed again a decision on building a commercial-scale facility.⁶⁰ The decision was originally expected in 2009 but is now scheduled for 2012. Owned by a consortium of General Electric (United States), Hitachi (Japan) and Cameco (Canada), GLE is based on an Australian laser enrichment method, SILEX. Independent analysts concerned about the prospect of the world’s first commercial laser enrichment facility are demanding that the U.S. Nuclear Regulatory Commission (NRC) consider proliferation implications in deciding whether to license the GLE facility.⁶¹ The NRC has so far been reluctant to consider such an assessment.⁶²

Russia. Russia’s state-owned nuclear corporation Rosatom has offered to sell up to 49% of its ownership of the Urals Electrochemistry Combine uranium enrichment plant at Novouralsk to Kazakhstan’s Kazatomprom.⁶³ This marks the first possible sale of a share in an existing Russian nuclear enterprise to a foreign company. It replaces an earlier agreement to expand the uranium enrichment capacity at Angarsk by building a new facility there. Unlike Angarsk, the Novouralsk facility was a major contributor to the production of Russia’s HEU stockpile.

China. China is reported to have developed and to be operating its own centrifuge enrichment plant, with a capacity of about 500,000 SWU.⁶⁴ The uranium enrichment plant is described as a demonstration project that started in 2007 at a site in Lanzhou and may have gone on-line early in 2010. This facility is in addition to the Russian-supplied enrichment plants in China, which have a combined capacity of 1.5 million SWU per year.

Iran. Iran's main enrichment site is Natanz, where both a Pilot Fuel Enrichment Plant (PFEP) and the underground fuel enrichment plant (FEP) are located. In September 2009, a second uranium enrichment plant was disclosed to be under construction near the city of Qom in Iran (Figure 1.5). The Fordow fuel enrichment plant (FFEP) is to be located inside a mountain, apparently to protect the site against attack. Iran declared that, "based on [its] sovereign right of safeguarding ... sensitive nuclear facilities through various means such as utilization of passive defense systems ... [Iran] has decided to construct a new pilot fuel enrichment plant (up to 5% enrichment)" at this site.⁶⁵ The IAEA has verified that the FFEP is designed to hold a total of about 3000 centrifuges. As of September 2010, however, no centrifuges had been installed.⁶⁶



Figure 1.5. Iran's second enrichment plant (34.885 N, 50.996 E), near the city of Qom.

The partially-built Fordow fuel enrichment plant (FFEP) was disclosed on 25 September 2009, during a G20 summit in Pittsburgh, PA. At about the same time, Iran submitted a letter to the IAEA declaring the plant. IAEA inspectors first visited the site in late October 2009 and confirmed that the plant could eventually hold about 3000 centrifuges.⁶⁷

Source: Google Earth.

In February 2010, Iran started production of 19.75 percent enriched uranium at its Pilot Fuel Enrichment Plant (PFEP) at Natanz. Reportedly, this enriched uranium is intended to produce fuel for the Tehran Research Reactor TRR-1. As of November 2010, Iran had produced about 33 kg of 20% enriched uranium.⁶⁸ Iran has announced that it is planning to start building a third uranium enrichment plant in early 2011.⁶⁹

Since October 2010, various reports began to suggest that a sophisticated computer malware (worm) attack may have targeted Iranian nuclear facilities for more than a year, which could help explain why the number of operational centrifuges at Natanz began to decrease after May 2009.⁷⁰ In November 2010, Symantec published a detailed report analyzing the malware (Stuxnet). The report confirms that the worm is most prevalent in Iran (more than 60% of infected hosts) and designed to sabotage industrial control systems and, even though not explicitly considering enrichment plants, reveals that frequency converters (operating between 800 and 1200 Hz, i.e., a typical frequency range for gas centrifuges) are the main target of the attack.⁷¹ In late November, some reports suggested that Iran had temporarily halted all enrichment activities.⁷²

Argentina. In October 2010, Argentina announced that it was preparing to resume uranium enrichment at its Pilcaniyeu gaseous diffusion plant, with the first enriched product expected in September 2011.⁷³ According to Argentina's National Atomic Energy Commission (CNEA), the reactivation of the plant will allow Argentina to remain and establish itself in the "select group of nine countries that control enrichment technology."⁷⁴ The plant previously operated from 1983 to 1989 with a capacity of 20,000 SWU per year. The plant has been under safeguards by the IAEA and by the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) since 1993. It is reported that the refurbished facility will have an expanded capacity eventually on the order of 3 million SWU.⁷⁵

North Korea. In November 2010, North Korea provided U.S. observers access to a newly constructed uranium enrichment plant set up since early 2009 inside a pre-existing building at the Yongbyon site. The facility is reported to contain up to 2000 centrifuges, with a total enrichment capacity of 8,000 SWU per year, and is intended to produce LEU enriched to 3.5% in uranium-235.⁷⁶ This LEU is meant to fuel a 100 MWT light-water reactor also being constructed at the site. North Korean operators suggested that the centrifuges were modeled after the centrifuges at Urenco's Almelo plant and at Japan's Rokkasho enrichment plant.⁷⁷

Separated Plutonium

The global stockpile of plutonium, estimated as 485 ± 10 tons, continues to grow, with most of the increase coming from civilian reprocessing programs rather than production for weapons (Figure 1.6 and Appendix 1B). The global military plutonium stockpile will begin to shrink when Russia and the United States, which have the largest stocks of weapons plutonium, begin disposing of the 34 tons of weapon plutonium they each have declared excess to their military needs. The civilian plutonium stockpile will increase if Japan, India, and China go forward with their currently planned reprocessing programs.

The amount of weapon-state separated plutonium under IAEA safeguards and monitoring is expected to increase. In April 2010, the United States and Russia agreed on a revision of their Plutonium Management and Disposition Agreement, originally signed in 2000.⁷⁸ In September 2010, they submitted a joint letter to the IAEA requesting that the Agency establish verification measures with respect to their excess weapon-grade plutonium disposition programs.⁷⁹ The United States and Russia have set the goal of preparing the appropriate verification agreements in 2011.

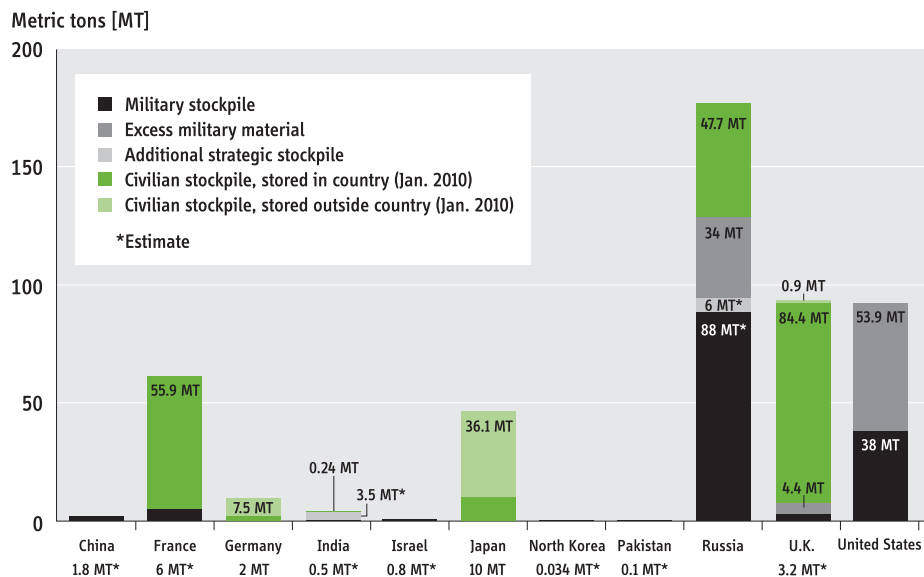


Figure 1.6. National stocks of separated plutonium. Civilian stocks are based on the most recent INFCIRC/549 declarations for January 2010 and are listed by ownership, not by current location. Weapon stocks are based on non-governmental estimates except for the United States and United Kingdom whose governments have made declarations. Uncertainties of the military stockpiles for China, France,

India, Israel, Pakistan, and Russia are on the order of 10–30%. The plutonium India separated from spent heavy-water power-reactor fuel has been categorized by India as “strategic,” and not to be placed under IAEA safeguards. Russia has 6 tons of weapon-grade plutonium that it has agreed to not use for weapons but not declared excess.

Weapons Plutonium

Russia and the United States have the largest stockpiles of plutonium produced for weapons. While the United States has declared its history of production and utilization of weapon plutonium, there remain considerable uncertainties in estimates of Russia's stockpile. These uncertainties are significantly reduced, however, as a result of a careful reanalysis of public information (Chapter 3). Like the United States, the United Kingdom has declared its plutonium production and these reports are discussed in Chapters 2 and 6 respectively. Along with the United States, the United Kingdom has declared its plutonium production and these reports are discussed in Chapter 2 and 6, respectively.

Chapters 7 and 9 present significantly lowered estimates of weapon plutonium production in China and India. The estimates for Israel and Pakistan (Chapters 8 and 10, respectively) are consistent with earlier analyses.

Russia. It is estimated that Russia produced about 130 ± 8 tons of plutonium for weapons before ending production in 1994 (Chapter 3). The last plutonium production reactor, ADE-2 at Zheleznogorsk, was shut down in April 2010.⁸⁰ Under a Russian-U.S. agreement, plutonium produced since 30 September 1994 by this reactor and its counterparts, ADE-4 (shut down in April 2008) and ADE-5 in Seversk (shut down in June 2008) will not be used in Russia's weapons program. During this period, the three reactors produced about 15 tons of weapon-grade plutonium. This material will be consolidated at Zheleznogorsk. Nine tons of this plutonium are included in the 34 tons that Russia has committed to blend down.

Under the agreement with the United States on plutonium management and disposition, which was revised in 2010, Russia will use 25 tons of excess weapon-origin plutonium to produce MOX for its BN-600 and BN-800 fast-neutron reactors. Russia plans to have the BN-800 ready for operation by 2012–2013 and the BN-600 adapted to use MOX fuel by 2013–2014. MOX use in these reactors is not planned to begin, however, until 2018. As the first step in this process, in August 2010, Russia's state-owned nuclear corporation Rosatom announced a decision to construct a MOX production plant at the Mining and Chemical Combine, Zheleznogorsk.⁸¹

France. France has used a fleet of dedicated production reactors at its Marcoule site in the South-East of France, and most likely also several natural-uranium-fueled power reactors, to produce its stockpile of weapons plutonium. Due to the diversity of reactor types employed, and the possibility of using them at different times in different ways for military purposes, estimates of France's inventory of weapons plutonium remain highly uncertain. We find that 4.6 ± 0.5 tons of weapon-grade plutonium were produced in the dedicated production reactors. Six power reactors in France and one in Spain could have contributed another 1.7 tons to that stockpile. Overall, France appears to have much more weapons plutonium today (about 6 tons) than it needs for its current nuclear arsenal (about 1.5 tons).

China. China is estimated to have produced 2 ± 0.5 tons of plutonium for weapons (Chapter 7). Subtracting about 0.2 tons consumed in its nuclear tests, China's current inventory of weapon-grade plutonium would be 1.8 ± 0.5 tons.

This value is smaller than earlier estimates because of a new assessment of the power levels and the operating histories of the two Chinese plutonium production reactors at Jiuquan and Guangyuan, which operated from 1966–1984 and from 1973–1990, respectively. The reactors are now believed to have had an original design power of about 250 MWt each, considerably less than earlier estimates for Guangyuan.

This inference is based in part on information released in 2010 about an underground complex of three 80 MWt Chinese plutonium-production reactors at Fuling, in Sichuan province, which were intended originally as a backup for the Jiuquan reactor. The Fuling underground reactors were abandoned before they were completed and China instead built the Guangyuan reactor, which appears to be a copy of Jiuquan.

India. The revised estimate for India (Chapter 9) is that it has a stockpile as of 2010 of weapon-grade plutonium of 0.5 ± 0.15 tons, slightly less than previous estimates. About 0.09 tons may have been consumed in nuclear weapons tests and in the first core of the Fast Breeder Test Reactor (FBTR).

The stockpile estimate is lower than previous values largely due to the assumption of reduced lifetime capacity factors for India's two plutonium production reactors at the Bhabha Atomic Research Centre (BARC), in Mumbai. The 40 MWt CIRUS reactor, which began operating in 1963, is to be shut down in December 2010, and there are plans to build a new 100 MWt reactor in Vizag, Andhra Pradesh.⁸² This would be the same capacity as Dhruva, the second BARC production reactor, which was commissioned in 1985.

The estimate of India's current reactor-grade plutonium stockpile, separated from the spent fuel discharged by India's unsafeguarded heavy-water power reactors, has also been reduced. This stockpile is now estimated to be 3.5 ± 0.5 tons. A total of about 9 tons of plutonium may have been produced in unsafeguarded spent fuel as of 2010. About 2 tons of plutonium may have been fabricated into fuel for the FBTR and for the first core of the 500 MWe Prototype Fast Breeder Reactor (PFBR) which is under construction.

Israel. Israel has produced plutonium for nuclear weapons at its Dimona reactor and its associated reprocessing plant since the mid-1960s. As detailed in Chapter 8, there are important uncertainties about the power of the Dimona reactor, which may have been increased from an initial design value of 24 MWt to 40 MWt and then to 70 MWt, with the reactor power possibly reaching 150 MW for a period in the late 1970s and early 1980s. It is estimated that, as of 2010, Israel's cumulative production of plutonium is 0.8 ± 0.15 tons.

Pakistan. Pakistan has been building its second and third production reactors (Chapter 10). It may have produced 0.06–0.13 tons of weapon-grade plutonium from its Khushab-I reactor, assuming a reactor power of 40–50 MWt and an average capacity factor of 50–80%. The second production reactor has been completed at Khushab and may have started operation in late 2009 or early 2010.⁸³ A third production reactor is nearing completion.⁸⁴ Based on the number and sizes of their mechanical cooling towers, all three reactors appear to be of similar power.

North Korea. North Korea resumed reprocessing activities in April 2009, after having agreed in 2007 to halt its weapons program and started disabling its production reactor and reprocessing plant. In November 2009, North Korea announced that it had completed reprocessing the 8000 remaining spent nuclear fuel rods from its Yongbyon production reactor to separate their plutonium for weapons.⁸⁵ This could have added 8–12 kg of plutonium to its stockpile, giving North Korea a stockpile in 2010 estimated at 34 kg.

Civilian Plutonium

The separation of plutonium in civilian programs in France, the United Kingdom, Russia, and Japan is taking place at a higher rate than the worldwide production of plutonium for weapons. Since 1996, nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and United States) have submitted annual declarations of their stocks of civilian plutonium to the IAEA (INFCIRC/549), which posts them on its website.⁸⁶ Appendix 1C and Figure 1.7 summarize this data.

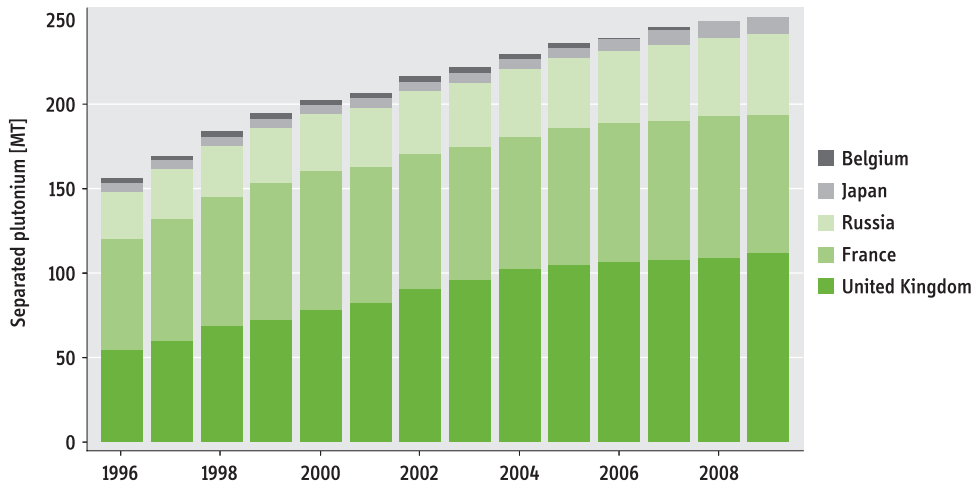


Figure 1.7. Civilian separated plutonium, as declared in the INFCIRC/549 declarations for December 31st of the respective years. In contrast to the stockpiles shown in Figure 1.6, these values are by listed

by storage location not by ownership. Weapons plutonium declared excess by the United States (and Russia) is not included in this chart.

France. France declared that its total holdings of civilian plutonium as of 31 December 2009 were about 82 tons, of which about 26 tons is foreign-owned. The total holdings have gone down by 2 tons from 2008.⁸⁷ The amount of separated plutonium owned by France has grown slightly, however, from 55.5 tons in 2008 to 55.9 tons in 2009. The reduction is due to the end of foreign reprocessing contracts and the reduction of foreign separated plutonium held in France by 2.4 tons. The 2010 French National Radioactive Materials and Wastes Management Scheme projects that the civilian separated stockpile will be 54 tons in 2020 and 53 tons in 2030.⁸⁸

United Kingdom. The United Kingdom's Magnox reprocessing plant (B205) continues to operate poorly as does the THORP plant, in which foreign LWR fuel is reprocessed. B205 was originally scheduled to be shut down in 2012. In August 2010, however, the UK Nuclear Decommissioning Authority pushed back to 2017 the expected date for B205 to complete reprocessing the backlog of Magnox power reactor spent fuel and to be shutdown, noting that this "assumes that there are no events or issues that significantly interrupt spent fuel transport or reprocessing."⁸⁹ The THORP reprocessing plant also continues to limp along. It is currently restricted to reprocessing 200–300 tons per year of spent fuel, less than a quarter of its design throughput of 1200 tons per year.⁹⁰

India. The completion of India's Prototype Fast Breeder Reactor (PFBR) is reported to be delayed.⁹¹ The reactor is now expected to go critical in March 2012.⁹² Construction of the 500 MWe reactor started in 2004 and it was initially expected to be commissioned by December 2010. India's Department of Atomic Energy is seeking approval to

begin work in 2011 on dedicated fuel fabrication and reprocessing plants to support the PFBR.⁹³ The new facilities will be co-located with the breeder reactor at Kalpakkam, with two additional breeder reactors planned for the site.⁹⁴

In March 2010, the United States and India signed an agreement that will allow India to reprocess U.S.-supplied light-water-reactor nuclear fuel and spent fuel produced in American reactors supplied to India.⁹⁵ The “Arrangements and Procedures Pursuant to Article 6(iii) of the Agreement for Cooperation Concerning Peaceful Uses of Nuclear Energy” allows for India to set up at least two and possibly three or more new safeguarded plants for reprocessing such fuel:

“The Government of the United States of America and the Government of India understand the need for sufficient indigenous Indian capacity to reprocess or otherwise alter in form or content, under IAEA safeguards, U.S.-obligated nuclear material subject to the Agreement for Cooperation. Based on this understanding, the Parties agree to pursue the steps necessary, consistent with their national laws, to permit reprocessing or alteration in form or content of nuclear material subject to the Agreement for Cooperation *at one or more new additional national facilities in India*, (beyond the two facilities provided for in these Arrangements and Procedures) established by the Government of India and dedicated to the reprocessing and, as required, other alteration in form or content of safeguarded nuclear material under IAEA safeguards.” [Emphasis added]

India currently has three plants for reprocessing heavy-water reactor fuel: Trombay at Mumbai (50 tons of fuel per year, commissioned in 1964), PREFRE at Tarapur (100 ton capacity, commissioned in 1977), and KARP at Kalpakkam (100 ton capacity, commissioned in 1998).

Japan. Japan has not yet begun separating plutonium at its 800 tons per year Rokkasho reprocessing plant except during startup tests of the facility. Local inventories have therefore remained rather stable, reaching a new maximum of 10 tons in December 2009. The start of commercial operations at the Rokkasho reprocessing plant, expected in October 2010, will be delayed by at least two years.⁹⁶ This latest announcement marks the eighteenth time that the facility has been delayed. Operation was originally planned to start by December 1997. The current problem is related to the melter, in which highly radioactive liquid waste generated by reprocessing spent nuclear fuel is to be mixed into glass for long-term storage. As a result, Rokkasho did not continue its testing program and separated no plutonium in the past year.

The rationale for Japan’s reprocessing program was to produce plutonium fuel for a planned fleet of fast breeder reactors. The breeder reactor program has suffered its own problems. Japan’s prototype fast breeder reactor, Monju, suffered an accident in August 2010, in which a 3-ton refueling device fell inside the reactor vessel while being removed.⁹⁷ The accident occurred while the reactor was being prepared to restart operation for the first time since a December 1995 shutdown due to a major sodium leak and fire.⁹⁸ The 1995 accident occurred during the first year after the reactor first went critical. The accident will further delay the reactor resuming operation.

China. China has completed a pilot reprocessing plant with a capacity of 50–60 tons of spent fuel per year capable of being expanded to 100 tons per year. The reprocessing plant was expected to begin ‘hot tests’ with spent fuel in early 2010.⁹⁹ As of October

2010, the plant had not been allowed to separate any plutonium and normal operation is now not expected till 2012.¹⁰⁰

In October 2010, China's National Nuclear Corporation (CNNC) signed an agreement for Belgonucleaire and two other companies to build a pilot MOX fuel fabrication facility.¹⁰¹ Together the reprocessing plant and the MOX plant will allow China to separate and use plutonium in the civilian fuel cycle. The China National Nuclear Corporation plans to build a much larger (800 tons per year) reprocessing plant, to begin operation in 2025, and presumably will build a matching MOX plant.¹⁰²

Germany. Germany declares its plutonium holdings annually to the IAEA, but these declarations are only partially useful, because these documents apparently list plutonium stocks even when plutonium-uranium (MOX) fuel has already been loaded into power reactors, but not yet reached a minimum burnup level.¹⁰³ Accordingly, this fuel is considered "unirradiated," suggesting larger plutonium stockpiles than are actually present outside reactors. In addition, Germany does not report stockpiles located outside the country.¹⁰⁴

For Germany's current plutonium holding and our estimate of future trends, we use the response of the German Federal Government to a request for information from members of the German Bundestag.¹⁰⁵ Accordingly, 62.4 tons of plutonium will have been separated and used once the German program of plutonium-use in power reactor ends.¹⁰⁶ As of 31 December 2008, almost 60 tons of this total had already been separated with the final 2.5 tons awaiting separation in the United Kingdom. As of that date, 50.8 tons of plutonium had been loaded to reactors and 2.1 tons of fresh MOX were stored at German reactor sites (compared to 5.6 tons listed in the INFCIRC/549 declaration for the same date). In other words, 9.5 tons of German plutonium remained in foreign countries, 7 tons of which already were separated as of 31 December 2008.

Figure 1.8 summarizes the situation and expected future trends: by the end of 2008, 11.6 tons (62.4 minus 50.8 tons) of plutonium remained for use in Germany between 2009 and 2016.

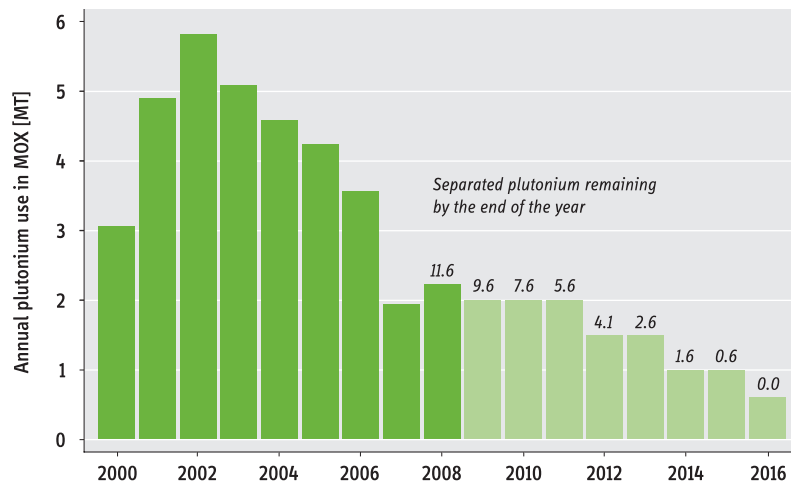


Figure 1.8. The end of plutonium use in Germany is in sight. According to information made public by the German Bundestag, 11.6 tons of plutonium remained as of 31 December 2008. It is currently planned that

MOX use will end by 2016 when a total of 62.4 tons of separated plutonium have been used as MOX in German reactors. Plutonium usage for the period of 2000–2008 is estimated from an industry source.¹⁰⁷

Appendix 1A. Uranium Enrichment Plants

Facility	Type	Operational Status	Safeguards Status	Capacity [tSWU/yr]
Argentina				
Pilcaniyeu	Civilian	Resuming operation	yes	20–3000
Brazil				
Resende	Civilian	Under construction	yes	120
China				
Shaanxi	Civilian	Operating	(yes)	500–1000
Lanzhou II	Civilian	Operating	offered	500
Lanzhou (new)	Civilian	Operating	no	500
France				
George Besse I	Civilian	Scheduled for shutdown	yes	10800
George Besse II	Civilian	Under construction	yes	7500–11000
Germany				
Gronau	Civilian	Operating	yes	2200–4500
India				
Ratehalli	Military	Operating	no	15–30
Iran				
Natanz	Civilian	Under construction	yes	120
Qom	Civilian	Under construction	yes	5–10
Japan				
Rokkasho	Civilian	Operating	yes	<< 1050
Netherlands				
Almelo	Civilian	Operating	yes	3800
North Korea				
Yongbyon	?	?	no	?
Pakistan				
Kahuta	Military	Operating	no	20–30
Gadwal	Military	Operating	no	Unknown
Russia				
Angarsk	Civilian	Operating	no	2200–5000
Novouralsk	Civilian	Operating	no	13300
Zelenogorsk	Civilian	Operating	no	7900
Seversk	Civilian	Operating	no	3800
United Kingdom				
Capenhurst	Civilian	Operating	yes	5000
United States				
Paducah, Kentucky	Civilian	Scheduled for shutdown	offered	11300
Piketon, Ohio	Civilian	Under construction	offered	3800
Eunice, NM	Civilian	Operating	offered	5900
Areva Eagle Rock, Idaho	Civilian	Planned	(offered)	3300–6600
GLE, Wilmington, NC	Civilian	Planned	?	3500–6000

Appendix 1B. Reprocessing Plants

Facility	Type	Operational Status	Safeguards Status	Capacity (tHM/yr)
China				
Pilot Plant	Civilian	Starting up	(no)	50-100
France				
UP2	Civilian	Operating	yes	1000
UP3	Civilian	Operating	yes	1000
India				
Trombay	Military	Operating	no	50
Tarapur	Dual	Operating	no	100
Kalpakkam	Dual	Operating	no	100
Israel				
Dimona	Military	Operating	no	40-100
Japan				
Rokkasho	Civilian	Starting up	yes	800
Tokai	Civilian	Temporarily shut down	yes	200
North Korea				
Yongbyon	Military	On standby	no	100-150
Pakistan				
Nilore	Military	Operating	no	20-40
Chashma	Military	Under construction	no	50-100
Russia				
RT-1	Dual	Operating	no	200-400
Seversk	Dual	To be shutdown after cleanup	no	6000
Zheleznogorsk	Dual	To be shutdown after cleanup	no	3500
United Kingdom				
B205	Civilian	To be shutdown after cleanup	yes	1500
THORP	Civilian	Temporarily shut down	yes	1200
United States				
H-canyon, SRP	Converted	Special Operations	no	15

Appendix 1C. Civilian Plutonium Stockpile Declarations

	Belgium (Addendum 3)		France (Addendum 5)		Japan (Addendum 1)		Russia (Addendum 9)		United Kingdom (Addendum 8)		United States (Addendum 6)	
1996	2.7	n.d.	65.4	30.0	5.0	0.0	28.2	0.0	54.8	6.1	45.0	0.0
		?		0.2		15.1		0.0		0.9		0.0
1997	2.8	n.d.	72.3	33.6	5.0	0.0	29.2	0.0	60.1	6.1	45.0	0.0
		0.8		<0.05		19.1		0.0		0.9		0.0
1998	3.8	n.d.	75.9	35.6	4.9	0.0	30.3	0.0	69.1	10.2	45.0	0.0
		1.0		<0.05		24.4		0.0		0.9		0.0
1999	3.9	n.d.	81.2	37.7	5.2	0.0	32.0	0.0	72.5	11.8	45.0	0.0
		0.9		<0.05		27.6		0.0		0.9		0.0
2000	2.7	n.d.	82.7	38.5	5.3	0.0	33.4	0.0	78.1	16.6	45.0	0.0
		0.6		<0.05		32.1		0.0		0.9		0.0
2001	2.9	n.d.	80.5	33.5	5.6	0.0	35.2	0.0	82.4	17.1	45.0	0.0
		1.0		<0.05		32.4		0.0		0.9		0.0
2002	3.4	n.d.	79.9	32.0	5.3	0.0	37.2	0.0	90.8	20.9	45.0	0.0
		0.4		<0.05		33.3		0.0		0.9		0.0
2003	3.5	n.d.	78.6	30.5	5.4	0.0	38.2	0.0	96.2	22.5	45.0	0.0
		0.4		<0.05		35.2		0.0		0.9		0.0
2004	3.3	n.d.	78.5	29.7	5.6	0.0	39.7	0.0	102.6	25.9	44.9	0.0
		0.4		<0.05		37.1		0.0		0.9		0.1
2005	2.8	n.d.	81.2	30.3	5.9	0.0	41.2	0.0	104.9	26.5	45.0	0.0
		0.0		<0.05		37.9		0.0		0.9		0.0
2006	0.6	0.3	82.1	29.7	6.7	0.0	42.4	0.0	106.9	26.5	44.9	0.0
		0.0		<0.05		38.0		0.0		0.9		0.0
2007	1.4	1.4	82.2	27.3	8.7	0.0	44.9	0.0	108.0	26.8	53.9	0.0
		0.0		<0.05		37.9		0.0		0.9		0.0
2008	0.3	0.3	83.8	28.3	9.6	0.0	46.5	0.0	109.1	27.0	53.9	0.0
		0.0		<0.05		37.8		0.0		0.9		0.0
2009	0.0	0.0	81.8	25.9	10.0	0.0	47.7	0.0	112.1	27.7	53.9	0.0
		0.0		<0.05		36.15		0.0		0.9		0.0

Inventory held in country
 Foreign-owned (included in local inventory), n.d. = not disclosed
 Stored outside the country (not included in local inventory)

Since 1996, nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and United States) have been declaring annually and publicly their stocks of civilian plutonium to the IAEA (INFCIRC/549). Russia does not include in its declaration excess weapons plutonium, whereas the United States does. The annual inventories (as of December 31st of the respective year) listed in the table are in metric tons. The declarations give the fissile material stocks at reprocessing plants, fuel-fabrication plants, reactors, and elsewhere, divided into non-irradiated forms and irradiated fuel. In December 2009, the civilian stockpile of separated plutonium reached a new maximum value of 251.6 tons, not including the weapons plutonium declared excess by the United States and Russia.¹⁰⁸

2 United States

The United States was the first country to produce highly enriched uranium and plutonium for weapons. In the 1990s, it published official histories of its historical production and use of these materials, based on data in the national Nuclear Material Management and Safeguards System. *Plutonium: The First 50 Years* describes the history of U.S. production, use, and stocks of plutonium as of the end of 1994. *Highly Enriched Uranium: Striking a Balance* provides the corresponding information for HEU through the end of September 1996 and *Highly Enriched Uranium Inventory* updates this information through the end of September 2004.¹⁰⁹ The plutonium report is currently being updated.

Cumulatively, the United States produced about 850 tons of HEU. The bulk was for weapons and was mostly produced before the mid-1960s, when the U.S. nuclear-warhead stockpile peaked at over 30,000 weapons. U.S. production of HEU for weapons ended in 1964.¹¹⁰ Additional HEU, enriched to more than 96% in uranium-235, was produced for naval-reactor fuel through 1992. Thereafter, huge quantities of weapon-grade uranium became available from excess Cold War weapons. This HEU is being stockpiled for future use in naval-reactor fuel.

As of the end of September 2004 (the end of the U.S. fiscal year), about 180 tons of HEU had been consumed in nuclear reactor fuel, nuclear tests, transfers to foreign countries, and down-blending to low-enriched uranium (LEU). About 100 tons had been fabricated into naval fuel that is to be disposed of in a geological repository after use, another 130 tons have been designated for the naval-fuel reserve, and yet another 174 tons had been declared excess for all military purposes and are mostly to be blended-down to LEU. This leaves about 260 tons of HEU in or available for U.S. nuclear weapons.

U.S. production of weapon-grade plutonium also peaked in the 1950's and early 1960's. During the 1960s, nine of the fourteen U.S. production reactors were shut down. Five continued to operate into the 1980s, primarily to produce tritium, the 12-year half-life heavy hydrogen isotope used in "boost" gas to increase the yield of the fission triggers in modern weapons.¹¹¹ All U.S. production reactors were finally shut down in 1987.¹¹²

Cumulatively, the United States produced and acquired about 110 tons of plutonium. As of the end of September 1994, the United States had used about 10 tons of this plutonium and still had about 85 tons of weapon-grade plutonium and 15 tons of non-weapon-grade but weapon-usable plutonium. All of the non-weapon-grade plutonium and 47 tons of the weapon-grade plutonium have been declared excess for military use, leaving about 38 tons remaining in or available for nuclear weapons.

Although the United States has reduced its stocks of weapons HEU and plutonium, using as weapons equivalents 20 kg of HEU and 4 kg of plutonium,¹¹³ the remaining stocks available for weapons use are still sufficient for about 10,000 weapons. In May 2010, the United States declared that it had 5113 warheads in its active stockpile plus “several thousand” that had been retired and were awaiting dismantlement.¹¹⁴

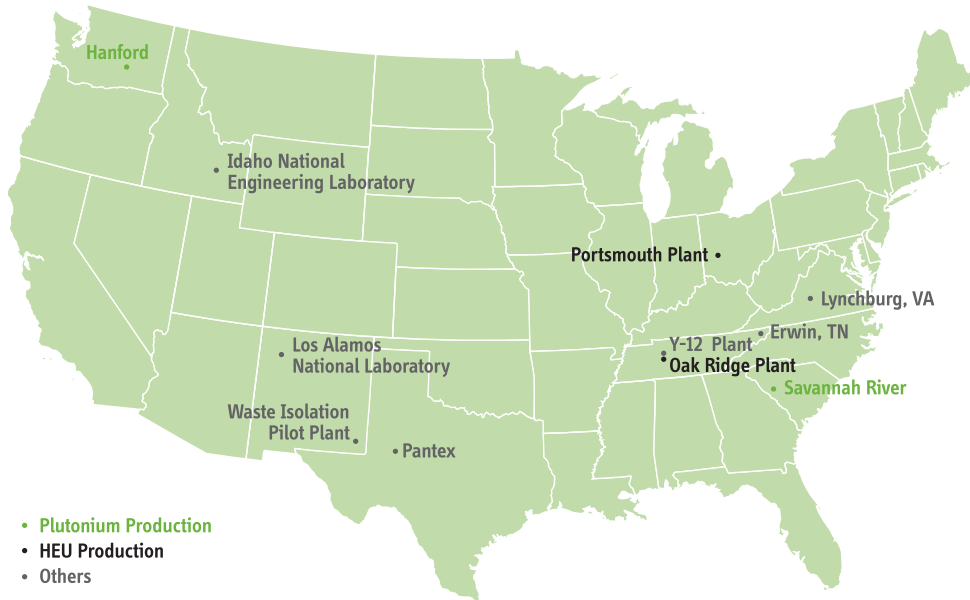


Figure 2.1. U.S. HEU and plutonium sites. Lynchburg, VA, and Erwin, TN, host HEU fuel fabrication sites.

Highly Enriched Uranium (HEU)

Highly enriched uranium was first produced for the Hiroshima bomb, which contained about 60kg of uranium enriched to an average of 80% in the chain-reacting isotope U-235. Natural uranium contains about 0.7-percent U-235 mixed with non-chain-reacting U-238. Uranium enriched to more than 20% in U-235 is considered weapon-usable and is designated as “highly enriched uranium” or HEU. Several isotope separation techniques have been used for enriching uranium. These are described in Appendix A to this report.

During 1945–47, a little over a ton of HEU was produced by electromagnetic separation at the Manhattan Project’s Y-12 plant near Oak Ridge, Tennessee. The focus of U.S. HEU production shifted quickly, however, to two huge gaseous diffusion plants (GDPs), one at Oak Ridge, Tennessee, and one at Portsmouth, Ohio (Table 2.1).¹¹⁵

Site	Isotope Separation Technology	HEU Production	Peak Annual Production (U-235 in HEU)
Oak Ridge, Tennessee	Electromagnetic	1945–1947	0.7 tons in 1946
Oak Ridge, Tennessee	Gaseous diffusion	1945–1964	37 tons/yr in 1958–1962
Portsmouth, Ohio	Gaseous diffusion	1956–1992	39 to 40 tons/yr in 1960–1962

Table 2.1. The enrichment plants that produced U.S. HEU.¹¹⁶

The Oak Ridge Gaseous Diffusion Plant (GDP), whose construction began during World War II, produced HEU for weapons during 1945–1964 and thereafter produced only low-enriched uranium for nuclear power-plant fuel until 1985. The Portsmouth GDP (Figure 2.2) started production in 1956 and also produced HEU for weapons until 1964 when the U.S. stockpile peaked. Then it shifted to producing mostly low-enriched uranium for power-reactor fuel and HEU enriched to an average of 97.4%, for naval-propulsion reactor fuel. Cumulatively, 164 tons of super-grade uranium were produced at a net average rate of about 6 tons per year. This ended in 1992, when huge quantities of excess weapon-grade HEU (greater than 90% enriched) became available due to the first post-Cold War downsizing of the U.S. weapons stockpile. Future U.S. naval reactors are being designed to be fueled with this uranium.¹¹⁷ Figure 2.3 shows the history of net U.S. HEU production, measured by its contained U-235 by site and by year.

Table 2.2 shows a summary of the U.S. government’s declarations of its HEU acquisitions, removals and stocks as of 30 September 2004. It indicates that, of the approximately 850 tons of HEU that the United States originally produced and acquired, about 690 tons remained in 2004. Of that remainder, about 260 tons was available for nuclear weapons and associated research and development. The remainder was mostly in or reserved for naval-fuel or programmed for disposition.

There was an “inventory difference” of 3 tons between the recorded difference between production, use and waste and measured stocks. This inventory difference included both the inaccuracy of the records and historic measurements and the possibilities of diversions. Three tons are only 0.4 percent of the total production but would be sufficient to make 150 nuclear weapons. Some of the entries in the table are discussed below.



Figure 2.2. The U.S. Portsmouth Gaseous Diffusion Plant when it was operating. The three large buildings contained 1812 enrichment stages and cover an area of 0.36 square kilometers. When operating at its design capacity of 8.3 million

separative work units (SWUs) per year, it required 2.1 GWe of electrical power. Note the plumes of condensed water vapor coming out of its cooling towers. Source: U.S. Enrichment Corporation.

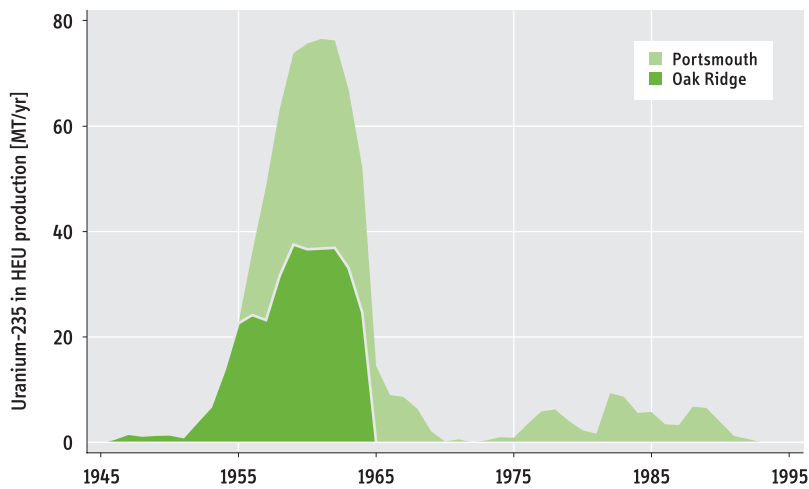


Figure 2.3. History of net U.S. production of HEU by site (tons/year U-235 content).¹¹⁸ At the peak of

U.S. HEU production, enough material was being produced for more than 4,000 warheads per year.

U.S. exports and imports of HEU. The United States exported about 35 tons of U-235 in HEU to other countries for use in research and naval-reactor fuel and in neutron targets for the production of medical isotopes. Of this, 18.6 tons had been exported for non-military uses as of September 30, 1996.¹¹⁹ An additional 0.3 tons was exported for such uses between 1996 and 2004. As of the end of September 2004, of the material shipped abroad for research-reactor fuel and other purposes, HEU originally containing 4.7 tons of U-235 had been returned (see Chapter 11 for an update). In addition, in 1994, the United States acquired from Kazakhstan 0.65 tons of formerly Soviet HEU and blended it down to LEU.¹²⁰

Almost all of the remaining U.S. HEU exports, containing 16 tons of U-235 were shipped to the United Kingdom for use in naval-reactor fuel (Chapter 5). About half a ton was shipped to France to fuel naval prototype reactors.¹²¹

Consumption in production-reactor fuel. An estimated 56.8 tons of U-235 in HEU were either fissioned or transmuted into U-236 in production and other reactors. More than 80% of this consumption was in the Savannah River plutonium/tritium production reactors.¹²²

Losses of HEU in nuclear explosions and to fission in naval-reactor fuel. For secrecy reasons, the U.S. HEU declarations do not separate HEU used in nuclear explosions from fissions and transmutations in naval-reactor fuel. Combined, as of 30 September 1996, these uses were reported to total about 32 tons of U-235. This combined number was not updated to 2004, however, because there were no nuclear tests after 1992 and the amount of U-235 consumed in naval reactors between 1996 and 2004 therefore would have been revealed. It is not clear why the U.S. Navy considers the U-235 consumption rate to be sensitive information. Below is a rough attempt to estimate the amount that would have been consumed in nuclear tests.

It is assumed that an average U.S. warhead contains 20 kg of HEU. If this is applied to the average U.S. nuclear test, one thousand U.S. tests would have used 20 tons of HEU. Based, however, on the fact that only 358 U.S. tests had yields above 20 kilotons,¹²³ most U.S. tests were of fission triggers, which contain little or no HEU. If the explosives

with yields above 20 kilotons had second stages containing 20 kilograms of 85%-enriched uranium each,¹²⁴ then the amount of U-235 used in nuclear explosions would be about 7 tons and the residual of about 25 tons would have been consumed in naval-reactor fuel.

	Material Balance Category	U-235 (tons)	HEU
Acquisitions	Domestic enrichment ¹²⁵	860.9	1045.4
	From blending	0.3	3.1
	Less re-feed into enrichment plants	-114.2	-194.6
	Receipts from foreign countries	5.3	n/a
	Miscellaneous receipts and classified transactions	1.3	n/a
	Total acquisitions	751.9	n/a
Removals	Fission and transmutation in non-naval reactor fuel	-56.8	-51.0 ¹²⁶
	Losses in explosions & fissions in naval-reactor fuel (as of 1996)	-31.9	n/a
	Waste ("normal operating losses")	-5.4	n/a
	Transfer to foreign countries: peaceful uses	-18.9	n/a
	Transfers to foreign countries: military uses	-16.0	n/a
	Down-blending	-31.3	-61.0
	Total removals	-160.3	n/a
	Calculated U.S. inventory, 30 Sept. 2004	593.3	n/a
Stocks	Measured U.S. HEU Inventory, 30 Sept. 2004	590.5	686.6
	In warheads, naval fuel or Pantex and Y-12 sites	546.6	621.2
	At other DOE sites	43.9	65.4
	- fabricated into naval fuel	-97.4	-100.0
	- reserved for naval reactor fuel	-120.6	-129.0
	- slotted for blend-down to LEU or a waste repository	-122.0	-174.0
	- reserved for research and space reactors	-18.7	-20.0
	Remainder in and available for weapons	231.8	231.8
Inventory difference	Acquisitions - Removals - Stocks	≈ 3	n/a

Table 2.2. U.S. HEU acquisitions, removals and stocks as of 30 Sept. 2004. The DOE's Pantex site near Amarillo, Texas is where U.S. nuclear warheads are assembled and disassembled. The HEU-con-

taining thermonuclear "secondaries" are produced and dismantled at the DOE's Y-12 site in Oak Ridge, Tennessee. "n/a" means that the information is not available in the DOE report.¹²⁷

We assume that the DOE estimate of the amount of U-235 consumed in naval reactor fuel only covers spent naval fuel that has been returned to the DOE. Based on the 83 percent residual enrichment of the uranium in the spent naval fuel stored at Idaho National Laboratory in 1996,¹²⁸ one can estimate that about 49% of the U-235 originally in this fuel was consumed and that there would have been somewhat more than 50 tons HEU originally in the naval reactor fuel.¹²⁹

It is stated in *Highly Enriched Uranium: Striking a Balance* that, as of 30 September 1996, about one hundred metric tons of HEU were "in naval reactor cores [or to be] fabricated into fuel in the near future."¹³⁰ If the 100 tons were distributed between U.S. nuclear ships and submarines in proportion to their shaft horsepower, then the two reactor cores of a *Nimitz* aircraft carrier would contain about 5 tons and the single reactors of *Trident* ballistic-missile submarines would contain about 1 ton each.¹³¹

The resulting spent fuel is shipped for interim storage at the Idaho National Laboratory. It is expected that this spent naval reactor fuel will go to a deep-underground repository.¹³² The 100 tons plus the amount of HEU originally in the spent fuel transferred to DOE before 30 September 1996 plus 50-odd tons of HEU in naval spent fuel that was transferred to DOE is roughly consistent with the 162 tons of super-grade HEU that was produced for the Navy.

“Normal operating losses” of HEU. As of the end of September 1996, HEU losses to various waste streams were estimated as containing cumulatively about 5 tons of U-235, about equally distributed between Department of Energy facilities and private facilities that fabricate naval and research reactor fuel.¹³³ An additional 0.5 tons of U-235 was assigned to normal operating losses between 1996 and 2004.¹³⁴

“Inventory differences.” After estimation of all the removals, as of 2004, about 3 tons of U-235 in HEU remained unaccounted for.¹³⁵ At the site level, contributions to this total include about 1 ton at the Y-12 plant in Oak Ridge, Tennessee, where the thermo-nuclear components for U.S. nuclear weapons are made and dismantled; and about one third ton each at the Portsmouth Gaseous Diffusion Plant (where about half of U.S. HEU was produced), the former Apollo HEU fuel fabrication plant, the Nuclear Fuel Services fuel fabrication plant, and the Rocky Flats Plant (where composite HEU-plutonium pits for nuclear-weapon primaries were apparently produced). The most plausible explanation for most of these differences is underestimates of losses to waste. At the Apollo plant, however, a major HEU theft (hundreds of kilograms) probably did take place.¹³⁶ At the Savannah River Site, where HEU fuel was used in the production reactors and reprocessed, the inventory difference was negative by about 0.4 tons, i.e., there was more HEU than could be accounted for. Perhaps the losses there had been overestimated.



Figure 2.4. The cores of the two reactors powering each Nimitz-class aircraft carrier contain several tons of weapon-grade uranium. *Image Source: U.S. Department of Defense.*¹³⁷

Disposition of HEU declared excess for weapon purposes. In 1994, the United States declared 174 tons of HEU excess for military purposes. Of this, 156 tons are being blended down to low-enriched uranium. The remaining 18 tons include about 17 tons of naval-reactor spent fuel.¹³⁸

In 2005, another 200 tons of U.S. HEU were declared excess for weapon purposes. Of this, 20 tons were placed in a reserve to supply research and space reactors.¹³⁹ Another 20 tons are to be blended down to low-enriched uranium (LEU) for power reactor fuel.¹⁴⁰ The remaining 160 tons were to be placed in a reserve for naval-reactor fuel but about 31 tons were later determined as likely not to meet Navy specifications and instead will be blended down to LEU. Another 10 tons of HEU has been identified in domestic and foreign research-reactor spent fuel that might either be disposed of in a repository or recovered by reprocessing in the Savannah River Site H-canyon and blended down to LEU.

Altogether, 235 tons of U.S. HEU (containing 153 tons U-235) have been designated for blend-down to LEU or for geological disposal. Of this, as of the end of March 2010, 131 tons of HEU (75 tons U-235) had been blended down and 104 tons (78 tons U-235) remained to be eliminated.¹⁴¹ Given that 61 tons HEU (31 tons U-235) had been blended down as of 30 September 2004, the remaining disposition program as of that date will further reduce the U.S. HEU stockpile by 174 tons (122 tons U-235).

After disposition of these materials, the United States will still have about 260 tons of HEU (230 tons U-235) available for weapons and about 130 tons of weapon-grade uranium reserved for naval-reactor fuel.

Plutonium

The world's first nuclear reactors were built for the United States' World War II nuclear-weapon program. The first significant amounts of plutonium produced in the United States were used in the nuclear explosive that was tested in New Mexico on 16 July 1945 and then the bomb based on that design that was detonated over the Japanese city of Nagasaki on 9 August 1945. This plutonium was produced by the first three graphite-moderated, water-cooled reactors built on the U.S. Department of Energy's (DOE's) Hanford site on the Columbia River in Washington State. Later, an additional six such production reactors were built at Hanford and another five, moderated and cooled by heavy water, were built on the DOE's Savannah River Site in South Carolina. The primary mission of the Savannah River reactors was to produce tritium for U.S. nuclear weapons but they produced a great deal of weapon-grade plutonium as well (Table 2.3 and Figure 2.5).¹⁴²

Hanford Site	Dates of operation	Savannah River Site	Dates of Operation
B-reactor	1944 - 1968	R-reactor	1953 - 1964
D-reactor	1944 - 1967	P-reactor	1954 - 1988
F-reactor	1945 - 1965	K-reactor	1954 - 1992
H-reactor	1949 - 1965	L-reactor	1954 - 1988
DR-reactor	1950 - 1964	C-reactor	1955 - 1985
C-reactor	1952 - 1969		
KW-reactor	1955 - 1970		
KE-reactor	1955 - 1971		
N-reactor	1963 - 1987		
Peak site Pu-production rate	5.3 tons in 1965		2.1 tons in 1964

Table 2.3. U.S. production reactors and their periods of operation.¹⁴³

Eight of the nine Hanford production reactors were shut down permanently between 1964 and 1971—the period during which the U.S. nuclear stockpile peaked. The Hanford N-reactor continued to operate during 1971–82, primarily to produce electric power, with fuel-grade plutonium for the U.S. breeder-reactor program as a byproduct. In 1983, in response to plans by the Reagan Administration to increase the size of the U.S. stockpile, the N reactor was shifted back to producing weapon-grade plutonium but was shut down in 1987 after the 1986 Chernobyl accident provoked concerns about its lack of an accident-containment building.¹⁴⁴

Table 2.4 summarizes the information in the DOE’s 1996 report on the U.S. Government’s acquisition, use and stocks of plutonium as of the end of 1994.¹⁴⁵ Below, some of the elements of this table are briefly discussed.

Production. Figure 2.5 shows the declared historical production of plutonium at the two U.S. production sites. According to the production records, the Hanford reactors produced cumulatively 67 tons of plutonium and the Savannah River reactors 36 tons.

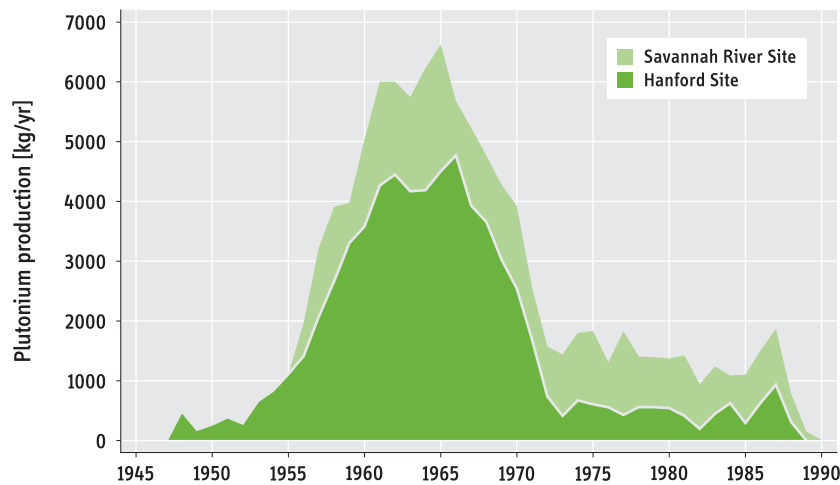


Figure 2.5. Declared historical production of U.S. plutonium at the two U.S. plutonium-production sites. Source: *Plutonium: The First 50 Years, Tables 2 and 3.* These sites produced a total of 103 tons of plutonium.

All of the plutonium produced by the Savannah River reactors was “weapon-grade” (relatively pure Pu-239 containing less than 7% Pu-240), but 12.9 tons of the Hanford plutonium—although weapon-usable was not weapon-grade. This includes 4 tons of plutonium that was never separated from the irradiated fuel within which it was created (see below).

In addition to plutonium, the Hanford reactors were used to produce on the order of a ton of U-233 and some tritium.¹⁴⁶

	Material Balance Category	Plutonium (tons)
Acquisitions	Domestic production reactors	103.4
	Other U.S. Government-owned reactors	0.6
	Abroad (almost entirely from UK)	5.7
	Power-reactor fuel reprocessed at West Valley, NY, 1966–72	1.7
	Total acquisitions	111.4
Removals	1030 nuclear tests and the Nagasaki bomb	-3.4
	Waste (but see Appendix 2A).	-3.4
	Exported, mostly for breeder-reactor R&D	-0.7
	Fissioned in test breeder reactors and transmuted ¹⁴⁷	-1.2
	Decayed (mostly 14.1-year half-life Pu-241)	-0.4
	To U.S. civilian industry	-0.1
	Total removals	-9.2
	Acquisitions less removals	102.2
	Inventory difference	-2.7
Stocks	Actual U.S. inventory, 31 December 1994	99.5
	Declared excess for weapon purposes in 1995 and 2007	-61.2
	Available for nuclear weapons	38.3
	In weapons & reserve/excess plutonium pits at Pantex Plant	66.1
	Rocky Flats pit-production facility (since removed) ¹⁴⁸	12.7
	Hanford and Savannah River production sites ¹⁴⁹	13.0
	Los Alamos and Livermore ¹⁵⁰ weapon laboratories	3.0
	Idaho National Laboratory (mostly for breeder reactor R&D) ¹⁵¹	4.5
	Elsewhere	0.2

Table 2.4. U.S. acquisition, use and stocks of plutonium as of the end of 1994. *Source: Plutonium: The First 50 Years, Table 1 and Figure 4.*

Imports and exports. The United Kingdom reported in 2000 that it had transferred 5.9 tons of plutonium to the United States. This includes: 5.4 tons “under Barter arrangements” (in exchange for HEU and tritium) and 0.5 tons in a context that is not described.¹⁵² The United States exported 0.7 tons of plutonium to Western Europe and Japan, mostly in support of plutonium breeder reactor research programs.¹⁵³

Wastes. The main uncertainty with regard to removals of plutonium from stockpile has to do with wastes. In the 1996 DOE report, it was estimated that about 3.4 tons of U.S. plutonium went into various waste streams.¹⁵⁴ Since 1996, large investments have been made in getting better estimates of the plutonium in waste and it has been found that losses to wastes were greatly underestimated at some sites, notably at the Hanford and Idaho National Laboratory sites. Also, residues containing an estimated 3.5 tons of plutonium from the Rocky Flats site, and 0.2 tons from the Hanford site, from which it had been planned to recover plutonium, have been reclassified as wastes. As a result of these and other such changes, the estimated amount of plutonium in waste has increased greatly, to about 12.7 tons (Appendix 2A). This development has led the U.S. Government to commission an update of the 1996 plutonium report that will focus especially on the waste situation. The update is to be completed by the end of 2010. It should clarify how much of the growth in waste quantities is as a result of reclassification. To the extent that additional plutonium has been found in waste, a recalculation

of the inventory difference will be required.¹⁵⁵ The reassessment also may reveal that, because plutonium going into waste was underestimated, more plutonium was produced than originally estimated.

Plutonium declared excess. The United States has declared “excess to its national-security needs” 61.2 tons of plutonium, including 53.9 tons of separated plutonium and the 7.6 tons of plutonium in unprocessed government-owned spent fuel.¹⁵⁶ This leaves 38.3 tons of weapon-grade plutonium in: weapons; “reserve” pits stored at the DOE’s Pantex warhead assembly/disassembly plant in Texas;¹⁵⁷ the Los Alamos nuclear-weapon laboratory, where plutonium R&D and pit production is carried out; and for criticality experiments in the high-security Device Assembly Facility (DAF) on the Nevada Test Site.

Most U.S. excess weapon-grade plutonium is still in warheads or in pits stored at the Pantex Plant in Amarillo, Texas, where U.S. warheads are assembled and disassembled.¹⁵⁸ The plutonium in spent fuel is to be disposed of eventually with other spent fuel in a deep underground repository. Plutonium in dilute waste is being shipped to the Waste Isolation Pilot Plant (WIPP) in New Mexico.¹⁵⁹ About three tons from the former Rocky Flats pit production facility have already been deposited there.¹⁶⁰ The remainder of the plutonium that has been declared excess is being shipped to the former K-production-reactor building at DOE’s Savannah River Site (SRS) which has been converted into an interim plutonium-storage facility. Four tons of plutonium from the Zero Power Plutonium Reactor, currently at the Idaho National Laboratory, have been declared excess for weapons use but some of this plutonium may be shipped to the DAF at the Nevada Test Site.¹⁶¹

At the Savannah River Site, at least 34 tons of the excess U.S. separated weapon-grade plutonium, including that from excess pits, is to be manufactured into mixed-oxide (MOX, uranium-plutonium) fuel for commercial nuclear power reactors as agreed under a U.S.-Russian plutonium disposition agreement.¹⁶² A MOX fuel-fabrication plant is currently being built for this purpose. Some impure plutonium may be reprocessed in the “H-canyon,” where the HEU “driver fuel” of the Savannah River production reactors was formerly reprocessed. The extracted plutonium would either be used as feed for the MOX plant or “vitrified” (glassified) and disposed of in canisters of solidified radioactive waste that are being produced from high-level reprocessing waste there.¹⁶³

The Window of Opportunity for Nuclear Archaeology

In the 1980s, independent analysts collected data on the histories of the U.S. Government’s purchases of natural uranium, its uranium-enrichment activities, and the thermal power generated by U.S. plutonium-production reactors.¹⁶⁴ These are broadly consistent with the subsequent government declarations.¹⁶⁵

Two specific opportunities to do nuclear archaeology to check U.S. declarations of its HEU and plutonium production would be analyses of:

1. The trace isotopes in the depleted uranium associated with U.S. HEU production; and
2. Trace isotopes and transmutation products in the graphite of the Hanford plutonium-production reactors.

Such studies could be carried out as the DOE disposes of the depleted uranium and the graphite in eight of the nine reactors.

Depleted uranium. As of 30 June 1992, the U.S. Department of Energy (DOE) reported that it had an inventory at its Paducah, Kentucky, and Portsmouth, Ohio, gaseous diffusion plants of about 360,000 tons of depleted uranium.¹⁶⁶ This is more than the 250,000 tons of natural uranium purchased by the DOE's predecessor organization, the U.S. Atomic Energy Commission, to produce HEU for weapons and reactor fuel.¹⁶⁷ Some of the DOE's depleted uranium is from its enrichment of uranium for utilities that purchased and delivered their own natural uranium to the government-owned enrichment plants.

Of the depleted uranium, about 98,000 tons are reported to have enrichments greater than 0.31% U-235. This indicates that the United States has not yet gone back to extract more U-235 from the high-U-235 depleted uranium produced by U.S. enrichment prior to 1964.¹⁶⁸ That depleted uranium remains available in its original state for forensic analysis. The window for doing such analysis is beginning to close, however, as the Department of Energy has built a conversion facility at each of its two storage sites to convert most of the depleted uranium hexafluoride into oxide form for disposal.¹⁶⁹ The DOE also has decided to offer for sale for re-enrichment about 75,000 tons of depleted uranium hexafluoride with a U-235 assay greater than 0.35%.¹⁷⁰

Hanford production reactors. Above, it was noted that U.S. plutonium production may have been underestimated because it was not realized at the time how much plutonium was going into waste. An independent estimate of cumulative "plutonium-equivalent" production in the graphite-moderated reactors (including their relatively small amount of U-233 and tritium production) could be made through measurements of trace elements and their transmutation products in the graphite. The fraction of trace elements transmuted would provide a measure of the cumulative neutron "fluence" through the graphite, which is in turn related to the cumulative plutonium-equivalent production of the reactor.¹⁷¹

Here too, the opportunity to make these measurements will not be available indefinitely. The DOE has developed a tentative plan to dismantle the graphite cores of eight of the nine Hanford production reactors, starting with the K-East reactor in 2013.¹⁷² The B-Reactor (Figure 2.6) has been turned into a museum.

Such forensic analyses, although incomplete, could provide additional consistency checks on U.S. production declarations. To provide a credible basis for verifying disarmament, such measurements should be done by international teams.

For the United States to be able to account internationally for all the plutonium it produced, it also is important that additional U.S. plutonium waste not be disposed of irretrievably in the deep-underground Waste Isolation Pilot Plant (WIPP) in New Mexico before the IAEA is able to verify by random checks that the drums buried do indeed contain, within measurement error,¹⁷³ the declared quantities of plutonium.¹⁷⁴

Measurements also should be taken on random containers of the vitrified high-level waste at the Savannah River and Hanford sites to confirm that they contain the declared quantities of plutonium before they are disposed of in a geological repository. This could be done most reliably by taking samples of the feed going into the vitrification process.¹⁷⁵

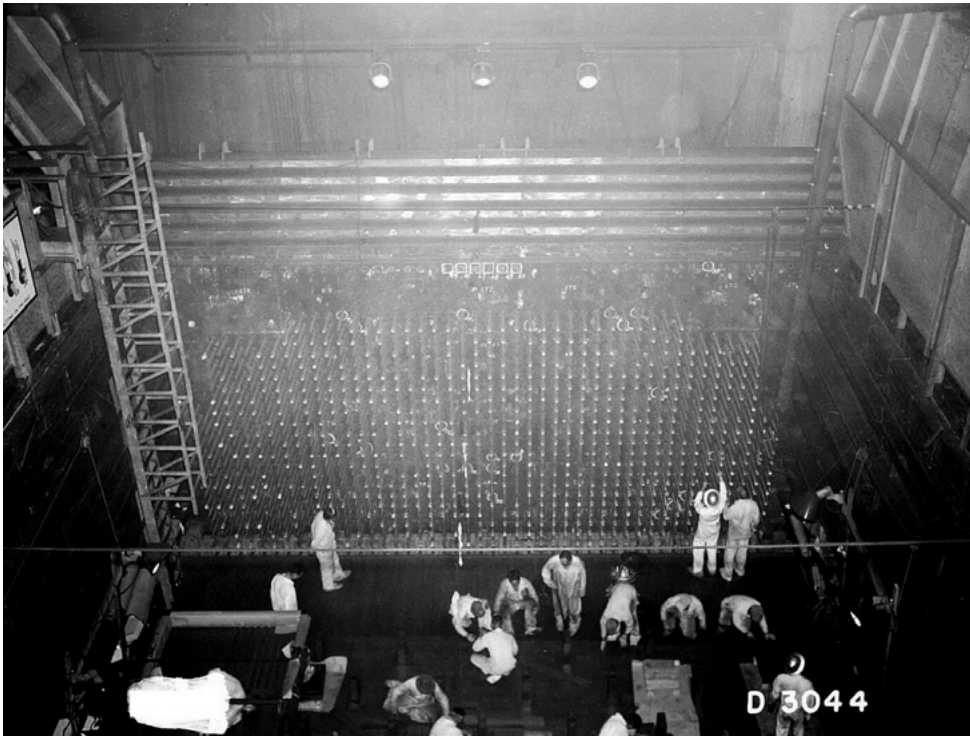


Figure 2.6. Loading face of the Hanford “B” plutonium-production reactor under construction during World War II. The fuel was loaded into the ends of the tubes protruding from the graphite moderator

while the reactor was operating. Cooling water then flowed through the same tubes until the irradiated fuel was pushed out of the back of the reactor into a storage pool. *Source: U.S. Department of Energy.*¹⁷⁶

Appendix 2A.

Plutonium Wastes from the U.S. Nuclear Weapons Complex¹⁷⁷

In 1996, the U.S. Department of Energy (DOE) estimated that the United States produced and acquired 111.4 tons of plutonium. DOE reported that 12 tons of this plutonium was no longer available for use, including an estimated 3.4 tons lost to waste.¹⁷⁸ The “inventory difference” between the book inventory, based on the DOE’s records and estimates of production, acquisitions and removals, and the measured quantity in the physical inventory was 2.8 tons, i.e., 2.8 tons of the plutonium produced was not accounted for.¹⁷⁹

Based on more recent waste characterization data,¹⁸⁰ approximately 12.7 tons—more than 10 percent of the total amount of Pu-239 produced and acquired—is now estimated to have gone into waste streams. Five DOE sites are responsible for about ninety-nine percent of these wastes (Figure 2A.1).

Of the 12.7 tons listed in Table 2A.1, about:

- 2.7 tons are in high-level radioactive wastes stored as liquids in tanks or granulated material in bins on the sites of former U.S. military reprocessing plants;
- 7.9 tons are in solid waste, which DOE is in the process of disposing in the Waste Isolation Pilot Project (WIPP), a geological repository in New Mexico for transuranic wastes; and
- 2.1 tons are in solid and liquid wastes buried in soil prior to 1970 or held up in facilities at several DOE sites. DOE considers most of this plutonium to be permanently disposed.

The dramatic increase from the DOE’s 1996 waste estimate is due to:

1. Reclassification as waste of more than 3.7 tons of plutonium in process residues at Rocky Flats and Hanford originally set aside for plutonium recovery for weapons; and
2. Improvements in waste characterization data.

Accounting for Plutonium in Waste

Plutonium-bearing waste is produced at reprocessing plants and where plutonium is fabricated into weapon components and fuel. Plutonium is a “transuranic” element because it has heavier than uranium. Transuranic (TRU) waste is defined by the U.S. Environmental Protection Agency (EPA, 40 CFR 91) as having a concentration greater than 100 nano-Curies per gram of alpha-emitting isotopes with half-lives greater than twenty years. For plutonium-239, the transuranic that dominates in DOE TRU waste, 100 nano-Curies/gm translates into 1.6 milligrams of Pu-239 per kg of waste.

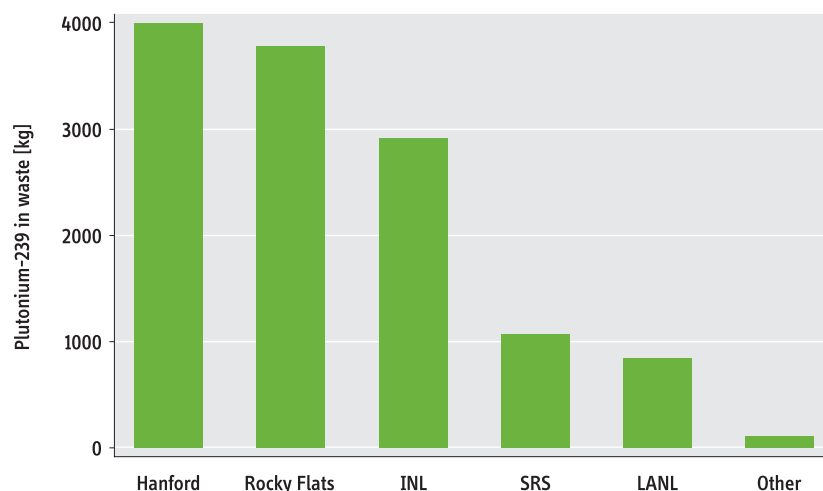


Figure 2A.1. Plutonium-239 in wastes at DOE Sites. Data from Table 2A.1 below.

Prior to the early 1970's, TRU wastes were disposed as low-level radioactive wastes directly into the ground. In 1970, however, the U.S. Atomic Energy Commission (DOE's predecessor agency) decided to require disposal of TRU wastes in a geologic repository designed to contain them for at least 10,000 years. Since 1970, pending deep disposal, U.S. TRU wastes have been stored in retrievable interim storage containers.

In 1980, the U.S. Congress authorized the design and construction of the deep-underground Waste Isolation Pilot Project (WIPP) near Carlsbad, New Mexico, for TRU waste generated for military purposes.¹⁸¹ A bedded salt formation was chosen because of its long-term stability and self-sealing properties. The WIPP facility is located 660 meters underground and has an authorized disposal capacity of 175,000 cubic meters. Based on recent waste characterization data, DOE estimates that 83,050 cubic meters of TRU wastes containing 7.9 tons of plutonium will be disposed in WIPP. About half of this plutonium already has been emplaced.¹⁸²

Reclassification. During the Cold War, residual plutonium from production processes was stored and recovered if the cost was less than making new plutonium in production reactors. After the down-sizing of its Cold War warhead stockpile, DOE no longer needed these residues and reclassified them as waste. About 3.5 tons of plutonium in residues from DOE's Rocky Flats plant have been disposed at WIPP.¹⁸³ At Hanford, 0.2 tons of plutonium in residues, originally set aside for recovery for weapons, also is bound for disposal at WIPP.¹⁸⁴ Additional amounts of plutonium at the Savannah River Site, Hanford, and Los Alamos have also been reclassified as waste.¹⁸⁵

Better waste characterization. Prior to 1970, when most of U.S. plutonium production occurred, material measurement technologies "were less accurate than today."¹⁸⁶ In recent years, environmental compliance agreements with host states have resulted in more rigorous measurements of plutonium in wastes, which in some cases has resulted in dramatic increases. The amount of plutonium in Hanford high-level radioactive waste tanks, for example, has been found to be more than twice the amount estimated in 1996.¹⁸⁷

Indeed, the re-measurements at Hanford may require an increase in the estimates of the original amount of plutonium produced there. According to a 2001 study of nuclear material flow and accounting at Hanford: “The quantities of NM [nuclear material] removed from the inventory as NOL [normal operating losses] do not agree with the quantities of NM classified as waste in the waste management inventory of waste. [...] Significantly more NM was produced in the reactors but not recovered in the separation facilities and was discharged along with fission waste.”¹⁸⁸

Site	Description	DOE-1996 (a)	DOE Waste Data
Rocky Flats	Solid waste (now in WIPP)	47	3,783 (b)
Hanford	High-level waste	455	1,115 (c)
Hanford	Solid waste (to go to WIPP)	875	1,965 (b)
Hanford	Buried solid waste		452 (d, e)
Hanford	Buried liquid waste	192	205 (f)
Hanford	Liquid waste in facilities and tanks	–	264 (f)
Los Alamos National Laboratory (LANL)	Solid waste (to go to WIPP)	610	791 (b)
LANL	Buried waste	–	50 (g, h)
Idaho National Laboratory (INL)	Solid wastes (to go to WIPP)	1,106	1,062 (b)
INL	Pre-1970 solid waste (to go to WIPP)	–	1,078 (i)
INL	Calcined High-level waste	72	771 (j)
INL	Solutions stored in tank farms	8	8 (a)
Savannah River Site (SRS)	High-level waste	575	847 (k)
SRS	Solid waste (to go to WIPP)	193	193 (b)
SRS	Buried Waste	–	25 (l)
Other DOE Sites	Solid Waste (WIPP Bound)	59	82 (b)
Other DOE Sites	Buried Waste	–	27 (m, n, o)
Total		3,919	12,718

Table 2A.1. Plutonium in waste (kg). Notes: **(a)** *Plutonium: The First 50 Years*, Department of Energy, 1996; **(b)** *Annual Transuranic Waste Inventory Report 2009*, DOE/TRU-09-3425, Department of Energy, 2009; **(c)** *Tank Waste Inventory Network System, Best Basis Estimate*, 090803, Department of Energy, September 2003; **(d)** W. O. Greenhalgh, *Pre 1970 Transuranic Solid Waste at Hanford*, Westinghouse Hanford Company, WHC-SD-WM-ES-325, 1995; **(e)** *Final Environmental Impact Statement, Commercial Low-Level Radioactive Waste Disposal Site Richland, Washington, Vol. 1*, DOH Publication 320-031, Department of Health, Washington State, May 2004; **(f)** *Draft Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*, DOE/EIS-039, Department of Energy, October 2009, Appendix S; **(g)** *Summary Data on the Radioactive Waste, Spent Nuclear Fuel, and Contaminated Media Managed by the U.S. Department of Energy*, DOE/EM-00-0384, Department of Energy, 2000; **(h)** Memo from Richard J. Guimond, Office of Environmental Management, re: Plutonium in Waste Inventories, Department of Energy,

30 January 1996; **(i)** T. A. Batcheller, et al, *Colloidal Plutonium at the OU 7-13/14 Subsurface Disposal Area: Estimate of Inventory and Transport Properties*, Bechtel BWTX Idaho LLC, IC P/EXT-04-00253, May 2004; **(j)** *Idaho High-Level Waste and Facilities Disposition, Final Environmental Impact Statement*, DOE/EIS-0287, Department of Energy, Appendix C-7, Table C.7; **(k)** *SRS High-Level Waste Data*, Department of Energy, 1999; **(l)** *Work Plan/RCRA Facility Investigation/Remedial Investigation Report for the Old Radioactive Waste Burial Ground 643-E, S01-S22, Vol. I-Text and Vol. II-Appendices*, Department of Energy, WSRC-RP-97-00127, Rev. 1.4, August 2000; **(m)** J. R. Trabalka, *Buried Transuranic Wastes at ORNL: Review of Past Estimates and Reconciliation with Current Data*, ORNL RM-13487, 1997; **(n)** J. R. Cochran, et al., *Intermediate Depth Burial of Classified Transuranic Wastes, Arid Alluvium*, LA-UR-99-639, April 1999; and **(o)** G. Shott, et al., *Special Analysis of Transuranic Waste in Trench T04C at the Area 5 Radioactive Waste Management Site, Nevada Test Site, Nye County, Nevada*, DOE/NV/25946-47, May 2008.

Plutonium wastes at Hanford. At the Hanford site (Figure 2A.2), natural or slightly-enriched uranium (primarily 0.95% and 1.25% U-235) uranium metal was clad with aluminum to make fuel for the production reactors. Irradiated fuel was discharged into basins of water to allow for cooling and decay of short-lived radionuclides before being sent for chemical separation of plutonium and uranium. Irradiated fuel ruptures and corrosion led to residual plutonium in storage basins and contamination of the nearby environment.¹⁸⁹

Plutonium was extracted from about 99,000 metric tons of spent fuel in four chemical separations plants that operated during overlapping periods.¹⁹⁰ Additional amounts of plutonium came from offsite processing facilities and foreign sources.¹⁹¹ About 70 percent of the irradiated fuel was processed at the PUREX facility, whose chemical process was subsequently used in reprocessing plants all over the world. After chemical separation, liquid reprocessing waste containing residual amounts of plutonium and other transuranics were mostly transferred to high-level radioactive waste tanks. Liquid waste containing plutonium was also discharged into cribs, trenches, and ponds.¹⁹²

Beginning in 1949, separated plutonium nitrate from the reprocessing plants was sent to the Hanford Plutonium Finishing Plant (PFP), where plutonium was purified into metal and oxides.¹⁹³ Liquid wastes were discharged into unlined soil disposal sites until 1973, after which they were sent via a transfer line to high-level waste tanks.¹⁹⁴ About 86 percent of Hanford's plutonium-containing liquid waste discharges occurred in the PFP zone.¹⁹⁵

According to DOE's 1996 plutonium declaration, about 2 percent of the total plutonium produced at Hanford went into waste (1.1 tons).¹⁹⁶ More recent waste characterization data indicates about 6 percent of the plutonium produced at Hanford went into waste (4 tons)—more than at any other DOE site.

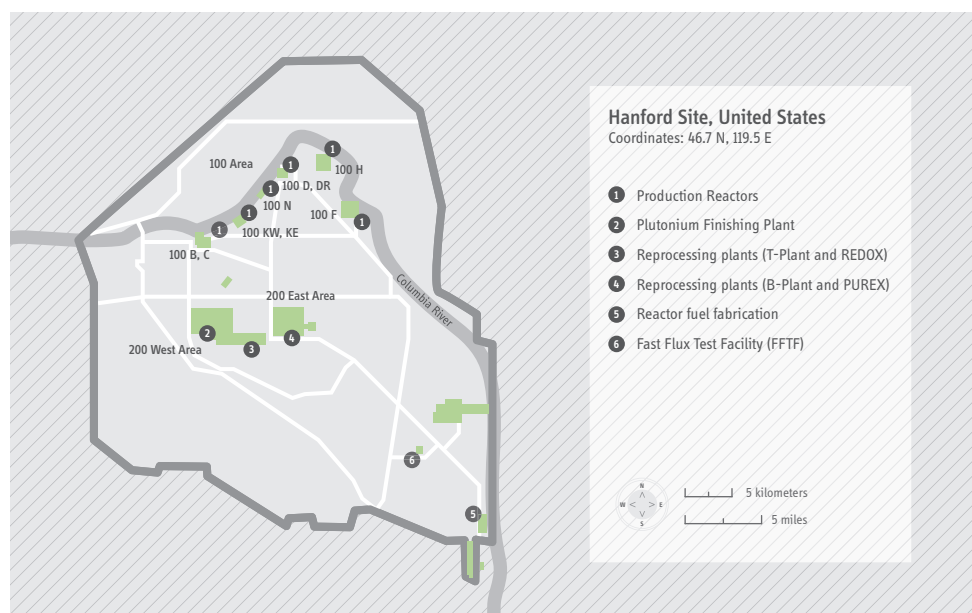


Figure 2A.2. Plutonium production at Hanford. Source: Adapted from DOE/EIS-0189, 1996.

Of this amount, about 2.7 tons of plutonium in liquid and solid wastes were mostly discharged, or buried in soil; 1.1 tons of residual plutonium—mostly from reprocessing plants—were discharged into the high-level radioactive waste tanks;¹⁹⁷ and an estimated 264 kg are held up in laboratories, reprocessing plants, and holding tanks. DOE plans to convert the plutonium-containing high-level radioactive waste into glass logs for geological disposal.

Prior to 1970, about 371 kilograms of plutonium in solid wastes were dumped in containers such as cardboard boxes into unlined trenches mostly associated with the PFP.¹⁹⁸ Between the mid 1960's and 1980, about 100 kg of plutonium was disposed in a similar fashion in a commercial radioactive waste landfill located in the Hanford 200-East area.¹⁹⁹

Production records at Hanford appear to understate plutonium losses. As researchers noted in 2001, “the ability to measure the plutonium content of waste streams was vastly inferior compared to the ability to measure plutonium in the primary feed and product streams.”²⁰⁰ A case in point is 216-Z-9 Crib, a soil disposal site roughly 10 meters by 20 meters in area, which operated during 1955–1962, receiving wastes from the RECUPLEX facility, a scrap recovery operation in the PFP zone, which discharged approximately 1 million gallons of plutonium-bearing wastes.²⁰¹ Although processing records indicated that approximately 27 kilograms were discarded into the crib, samples taken in the years following closure of the 216-Z-9 Crib indicated that it may have contained as much as 150 kg of plutonium, with soil concentrations as high as 34.5 grams per liter.²⁰² This was enough so that water intrusion could possibly have set off a nuclear criticality event that could have resulted in near-lethal doses to workers.²⁰³ By the late 1970s, 58 kilograms of plutonium had been removed from the top 30 centimeters of soil using remotely-controlled equipment.²⁰⁴

About 2 tons of the plutonium buried on the Hanford site is planned for disposal in WIPP.²⁰⁵ The remaining 0.7 tons was buried prior to 1970.²⁰⁶ According to the Government Accountability Office, “DOE has long considered pre-1970s buried wastes permanently disposed.”²⁰⁷ Migration beneath Hanford disposal sites has been enhanced by solvents, acids, and concentrated salts.²⁰⁸ Based on borehole measurements, plutonium contamination at Hanford is relatively uniform with depth and exceeds the 100 nano-Ci/g limit required for removal and geological disposal down to depths greater than 100 feet (30 meters). Deep contamination of the unsaturated soil (i.e., the so-called vadose zone) at Hanford appears to be orders of magnitude greater than at DOE's Idaho site, which has a greater concentration of buried pre-1970 TRU wastes (Figure 2A.3).

Plutonium wastes at the Idaho National Laboratory. INL is estimated to have buried about 1.1 tons of plutonium-239 before 1970.²⁰⁹ Beginning in 1954, plutonium-contaminated wastes from the DOE's Rocky Flats plant, which made plutonium weapons components, were disposed at INL. After a major fire in August 1969 at Rocky Flats resulted in burial of an unprecedented amount of plutonium-239 in Idaho,²¹⁰ the state resisted further disposal and demanded removal of these wastes from the site. Idaho's opposition contributed to DOE's decision to establish the WIPP repository and to require that TRU wastes generated after 1970 be retrievably stored. In 1995, Idaho entered into an agreement with DOE and the Environmental Protection Agency that required the removal of high-level radioactive wastes, spent reactor fuel, and transuranic wastes from the state by 2035. Until the Federal District Court in Idaho ruled in favor of the state in 2008, however, DOE refused to remove transuranic wastes buried at INL prior to 1970.²¹¹

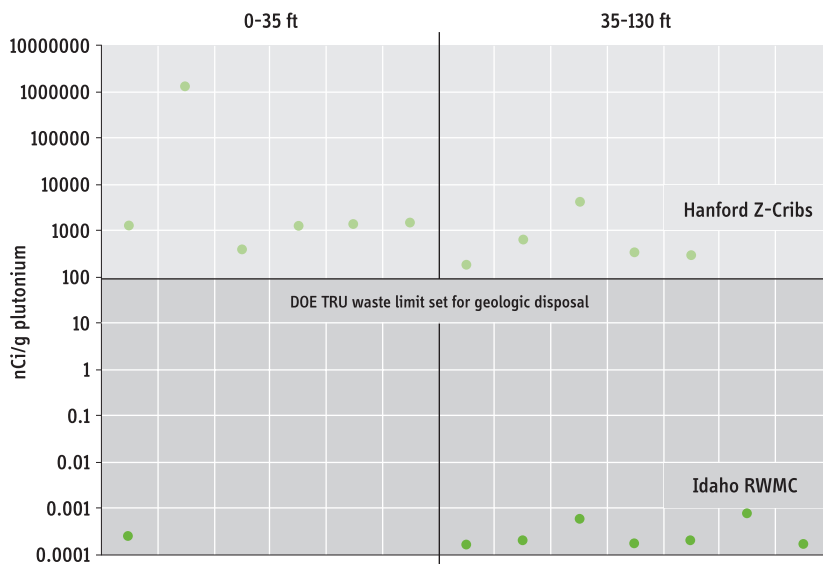


Figure 2A.3. Subsurface contamination at the DOE's Hanford and Idaho Sites.²¹² The contamination level at the Hanford Z-Cribs is above the DOE's threshold for removal to the WIPP repository down to a depth of 130 feet (about 40 meters).

Summary

The U.S. Department of Energy's 1996 report, *Plutonium: The First 50 Years*, showed an inventory difference between the book inventory based on records and estimates of plutonium production, acquisitions, and removals compared to the measured quantities in stocks of 2.8 tons, i.e., 2.8 tons were not accounted for. With the new and revised waste data, most or all of this inventory difference will be removed. Depending upon how much of the increase in waste is due to reclassification and how much due to improvements in waste characterization data, estimates of plutonium production might have to be raised slightly from the 1996 figure.

DOE is responsible for the Nuclear Materials Management and Safeguards System (NMMSS), the U.S. government's information system containing current and historic data on the possession, use, and shipment of nuclear materials. The recent radiological waste characterization data has not been incorporated in NNMMS system, however, because data on plutonium in material declared to be waste is not systematically updated. This creates significant accountability problems at both the national and international levels. Fortunately, DOE has decided to update its 1996 declaration to reflect improved data on the quantities of plutonium in waste. This will reduce uncertainties in historical plutonium production, and provide additional quality assurance for waste data.

Although IAEA monitoring of wastes already emplaced at WIPP may be impractical, it is worth exploring whether future waste shipments to WIPP should be monitored by the IAEA and the declared plutonium content in the wastes checked to provide a basis for international confidence in U.S. declarations of its plutonium disposition declarations and to provide a template for the disposition of plutonium-bearing wastes in other countries.

3 Russia: Plutonium

Russia has not published a comprehensive account of fissile-material production for military purposes during the Soviet and post-Soviet periods. Non-governmental analysts, however, have made estimates of Russia's stocks of weapon-grade plutonium based on assumptions about the power history of the production reactors.²¹³ Such estimates are uncertain, but new publications of historical documents and memoirs on the designs and operation of the former production reactors allow improved estimates.²¹⁴

Based on this new public information, it is estimated below that 145 ± 8 tons of weapon-grade plutonium were produced. This includes 15 tons of plutonium produced after September 1994, when production for weapons ended, by three plutonium-production reactors that continued operating to supply district heat and electricity to the Siberian cities of Tomsk and Zheleznogorsk. Under the 1997 Russian-U.S. Plutonium Production Reactor Agreement, the Russian government committed that this plutonium would not be used in weapons. It is being stored at the production sites in oxide form and is subject to bilateral transparency measures to provide assurance that it will not be used in weapons.

About 17 tons of Russia's weapon-grade plutonium have been used in nuclear-weapon tests, lost in waste, or lost in warheads in three submarines that sank.

Under the 2000 Russian-U.S. agreement on the disposition of excess weapons plutonium, the Russian Government has committed that 25 tons of the military stock plus 9 tons of the post-September-1994 stock will be fabricated into fuel for Russia's demonstration breeder reactors.

This will leave a total of 88 ± 8 tons of weapon-grade plutonium available for weapons plus 6 tons of the post-September-1994 stock. This is much more than the U.S. stockpile of 38 tons (Chapter 2) and much more than the 25 tons or so that would be required to sustain the stockpile of about 4,600 operational and active reserve warheads that Russia is believed to retain.²¹⁵

At its Mayak RT-1 reprocessing plant in the Urals, Russia also has separated reactor-grade plutonium from the spent fuel of first-generation light-water power reactors (VVER-440s), its demonstration fast-neutron reactors, and its naval, ice breaker, isotope production, and research reactors.

As of the end of 2009, 47.7 tons of reactor-grade plutonium had been accumulated.²¹⁶ This civilian plutonium is being saved to fuel plutonium breeder reactors.

Design and Operation of the Production Reactors

Almost all Russia's plutonium was produced in graphite-moderated reactors. Each reactor is built around a cylindrical stack of graphite blocks (Figure 3.1).²¹⁷

The graphite blocks in the stack have gaps between them to allow for circulation of nitrogen coolant. The stack also is pierced vertically with channels for fuel and water coolant and rests on a supporting structure with holes under the channels to allow discharge of the irradiated fuel. Each channel is lined with a thin-walled aluminum-alloy tube. Most channels contained 70 fuel rods, but some are used for control rods. Cooling water flows through the tubes and around the fuel rods. Cooling water flows through the tubes and around the fuel rods.

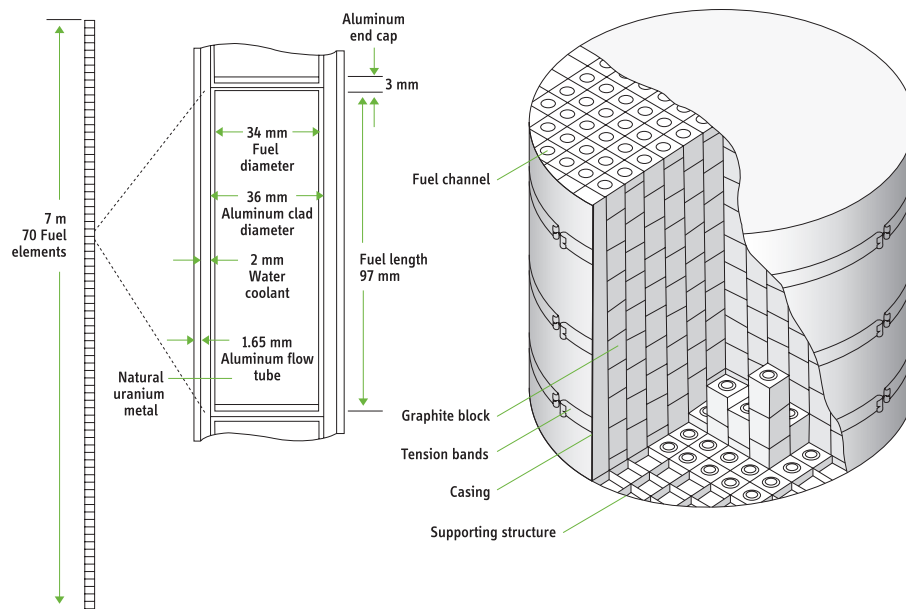


Figure 3.1. Production-reactor graphite stack.

Sources: N. S. Burdakov, "Some pages from the history of technology development for production of uranium-graphite reactors", Ozersk, 1996; and

D. F. Newman et al., *Summary of near-term options for Russian plutonium production reactors*, PNL-9982, Pacific Northwest Laboratory, Richland, Washington, July 1994.

The Soviet Union built fourteen of these graphite-moderated water-cooled production reactors at three sites in Russia: six at the Mayak Production Association in Ozersk (formerly Chelyabinsk-65) near Chelyabinsk in the Urals, five at the Siberian Chemical Combine in Seversk (formerly Tomsk-7) near Tomsk, and three at the Mining and Chemical Combine in Zheleznogorsk (formerly Krasnoyarsk-26) near Krasnoyarsk. Twelve were designed to produce plutonium and two to produce tritium and other isotopes. In addition four heavy-water-moderated production reactors were operated at the Mayak site.

The leaders of the Soviet atomic project constantly pressed for more plutonium. In response, efforts were made to operate the reactors at higher power. The design power of the first production reactor at Mayak, Reactor A, was initially 100 MWt. After obtaining experience at this power, Igor Kurchatov, the scientific leader of the Soviet nuclear-

weapons program, suggested operating it at up to 170–190 MWt during the winter and 140–150 MWt during summer when the cooling water was warmer. That allowed the reactor to produce up to 130–140 grams of plutonium per day. After it was found that a higher percentage of Pu-240 could be tolerated in weapons plutonium, Kurchatov also proposed extending the amount of time the fuel spent in the reactor to increase the concentration of plutonium in the irradiated uranium.²¹⁸

In 1952, a systematic scientific-technical study was initiated on how to further increase the operating power levels of the production reactors by:²¹⁹

1. Increasing the flow of cooling water through the reactor cores
2. Increasing the corrosion resistance of the channel liners and fuel cladding
3. Diminishing the rate of graphite oxidization, and
4. Increasing the internal operating temperature of the fuel elements.

The cooling water throughput was increased by allowing more space for water flow between the channel wall and the fuel.²²⁰ The corrosion problem was solved by selecting appropriate aluminum alloys and adding sodium bi-chromate to make the cooling water more alkaline (pH of 6.0–6.2). The problem of graphite oxidization was solved by using nitrogen instead of air for graphite cooling. By the end of the 1950s, improvements also had been introduced in fuel design. These included uranium alloying to reduce radiation-induced swelling, thermal hardening of the uranium rods, improvements of cladding corrosion resistance and quality-control during fuel production. These innovations made it possible to boost the reactor power levels several-fold, as described below.



Figure 3.2. Loading fuel elements into a channel while the reactor was operating.
Source: Luchistaya Energetika. Sibirskaya AES: Istoria s prodolzheniem (Radiant Power Engineering. Siberian AES: History with continuation), Sarov, 2008.

Plutonium Production

Figure 3.3 summarizes the estimated annual quantities of plutonium produced at each of the three plutonium production sites.

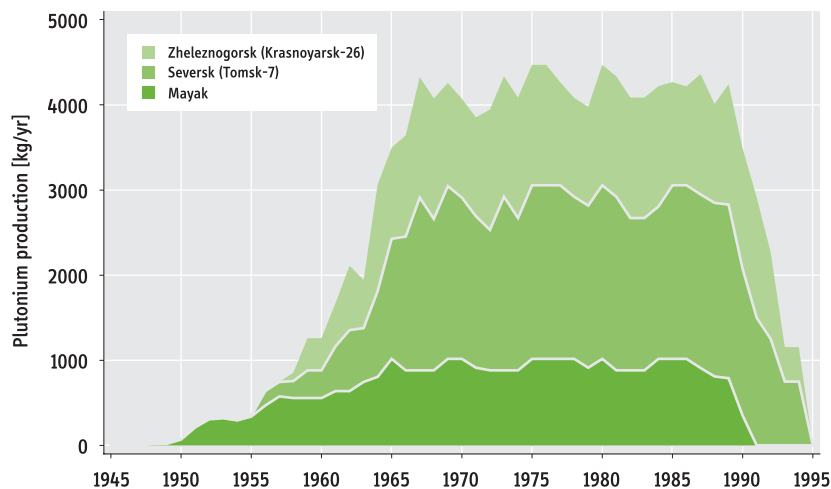


Figure 3.3. Russia's estimated annual production of weapon-grade plutonium by site. Production from the sites is shown cumulatively so that the combined production was about 4.5 tons/year during the period 1965–90.

Mayak Production Association (Chelyabinsk-65). The periods of operation of the five graphite-moderated Mayak production reactors and their original design and final up-graded operating power levels are shown in Table 3.1. All had a single-pass cooling system in which cooling water was pumped from an external body of water through the cooling channels and discharged into open water ponds.

Reactor A. The first plutonium-production reactor (“A”) was designed under the leadership of N. A. Dollezhal to operate at 100 MWt.²²¹ The reactor has 1149 vertical fuel and control channels in a graphite block of total mass 1050 tons. All but 25 channels were loaded with natural uranium fuel with a total mass of about 120–130 tons. Seventeen channels were used for control rods, and eight for experiments. The maximum design operating temperature of the graphite core was 220°C. The maximum design heat production per fuel element in the central channels was 3.45 kWt. The reactor’s original production rate was 0.1 kg of plutonium per day with an average of 0.1 kg of plutonium per ton of irradiated uranium fuel.²²²

Reactor A first went critical on 10 June 1948, and reached its design power level twelve days later. The fuel was discharged after about 100 days irradiation and reprocessed after 30–40 days of cooling in a storage pool.²²³ The first plutonium metal was separated on 16 April 1949.

The early period of operation revealed many technological deficiencies. The main difficulties were corrosion of the aluminum channel liners and fuel-element cladding, swelling and breakage of uranium rods, and leakage of cooling water into the graphite core. After each water leak, the reactor was shut down for up to ten hours to air-dry the

graphite. By January 1949, water leakage had become so frequent that it was decided to stop reactor operation and replace all the channel liners. This took about three months and the reactor was put in operation again on 26 March 1949. During 1948 and 1949, Reactor A produced 16.5 kg and 19 kg of plutonium respectively.²²⁴

Reactor A's plutonium production during the period 1950–1954 is estimated assuming that the average reactor power was 180 ± 5 MW.²²⁵ Ninety-five of the approximately 130 tons of natural uranium in its core were discharged after 94 effective-full-power-days of operation.²²⁶ Taking into account the time required to reload fuel and to carry out preventive maintenance, the total duration of one cycle would have been 103 days. Approximately 340 tons of spent fuel containing about 58 kg of plutonium therefore would have been discharged from the reactor annually.

Reactor Name	Power (MWt) (design/upgraded)	Start-Up Date	Shutdown Date
A	100/900	19 June 1948	16 June 1987
AV-1	300/1200	5 April 1950 ²²⁷	12 August 1989 ²²⁸
AV-2	300/1200	6 April 1951 ²²⁹	14 July 1990 ²³⁰
AV-3	300/1200	15 September 1952	1 November 1990 ²³¹
AI-IR	40/100	22 December 1952	25 May 1987

Table 3.1. The five Mayak graphite-moderated production reactors.

The next stage of upgrading Reactor A's power started in 1954 with an increase of its cooling water throughput to 7000 m³/hr and the discharge water temperature to 95 °C. Nitrogen was now used to cool and dry the graphite stack and the graphite temperature was increased from 300 to 675 °C. The reactor operated at an average power of about 650 MWt until October 1963, producing about 152 kg of plutonium annually.²³² The frequency of stoppages increased to 165 per month in 1963, however, and it was finally decided to renovate the reactor.

Reactor A resumed operation in April 1964 and operated at an average power 900 MWt from 1965 until it was shut down on 16 June 1987. Assuming that there were two shutdowns of 180 days each for major maintenance, the reactor produced 4.6 tons of plutonium during this period (Table 3A.1).

AV reactors. On 25 September 1948, it was decided to construct three AV-type reactors with a capacity to produce of 200–250 grams of plutonium per day. These reactors were designed by the OKBM design bureau under the supervision of chief designer A. Savin.²³³ All have 1996 channels, 65 of which are used for control rods. The design power and annual plutonium-production capacity were 300 MWt and about 100 kg plutonium per year, respectively.²³⁴ Each channel was equipped with a leak detector. This made it possible to replace tube liners without shutting down the reactor.

In their first year, operating at design power, the AV reactors each produced about 260 grams of plutonium per day.²³⁵ During its first several years of operation the reactor AV-3 was used to produce both tritium and plutonium. Starting in their second year of operation, the power of the reactors was gradually increased and reached 600 MWt by 1963.²³⁶ The first renovations of the AV reactors were carried out after 6–7 years of op-

eration. Major upgrades were made in the beginning of 1960s after the second capital renovation, when important problems with the channel liners and fuel elements were solved. Thereafter, power levels of 1200 MWt and annual plutonium production of 270 kg/year were sustained by all three reactors until their shutdown (Table 3A.1).²³⁷

AI-IR reactor. The AI reactor, which was put into operation on 22 December 1951 with a design power of 40 MWt,²³⁸ was originally designed to produce tritium.²³⁹ Its graphite stack had 248 channels. The reactor was initially fueled with uranium enriched to about 2% U-235. The decrease in the U-238/U-235 ratio, from about 140 in natural uranium to about 50, reduced plutonium production and made more neutrons available for tritium production. The reactor produced a considerable amount of plutonium as well but, because of the high burnup of the fuel and the resulting high percentage of Pu-240, the plutonium was not used in weapons.

During 1952–1956, the power level of the AI reactor was approximately 50 MWt. In 1956, it was reconstructed,²⁴⁰ fueled with uranium enriched to about 10%, and its power level increased. In 1966, the reactor was overhauled and, starting in January 1967, the fuel enrichment increased again to 80–90%. From 1967 to 1987, it operated with an average power of 100 MWt. During this period, the reactor was used primarily for irradiation tests of candidate channel-liner and fuel-element-cladding materials. It also produced Cobalt-60 and Polonium-210. It was shutdown on 25 May 1987.

Heavy-water reactors. Four heavy-water-moderated and cooled production reactors were also built at the Mayak site (Table 3.2). All were designed by OKBM.

The OK-180 reactor was loaded with 15 tons of uranium fuel and 37.4 tons of heavy water and was able to produce 0.1 kg of plutonium per day or 32 kg per year.²⁴¹ Although initially intended to produce plutonium, after two years of operation it was loaded with 2% enriched uranium and used to produce U-233, Cobalt-60, Phosphorus-32 and tritium.²⁴² The other three heavy-water reactors were used to produce tritium for weapons and other isotopes. The only heavy-water reactor still operating, the LF-2 reactor or “Ludmila,” is producing some tritium but 75% of its capacity is used for medical isotope production.²⁴³

Name	Power (MWt) (design/upgraded)	Start-up	Shutdown
OK-180	100/233 ²⁴⁴	17 October 1951	3 March 1966
OK-190	300	27 December 1955	8 November 1965
OK-190M	300	16 April 1966	16 April 1986
LF-2 “Ludmila”	800	May 1988	in operation

Table 3.2. Mayak heavy-water reactors.

Light-water reactor. The reactor “Ruslan” is a graphite-reflected light-water pool reactor with a design power about 800 MWt.²⁴⁵ It was put into operation on 12 June 1979 to produce tritium. Starting in 1985, its power was increased to 1100 MWt. While this reactor is currently used mainly to produce tritium, it is also used for “doping” electronic silicon with phosphorous.²⁴⁶

The reactor-by-reactor, year-by-year estimates of plutonium production at the Mayak site are summarized in Table 3A.1.

Siberian Chemical Combine (Tomsk-7). Five plutonium-production reactors were built and operated at the Tomsk-7 site (see Table 3.3). All were graphite-moderated, light-water-cooled reactors. The first, I-1, had a single-pass cooling system, while the four others had closed primary cooling circuits with heat exchangers to generate steam for electricity generation and district heat.

Name of reactor	Type	Power (MWt) (design/upgraded)	Start-Up Date	Shutdown Date
I-1	once-through	400/1200	20 Nov. 1955	21 Sept. 1990
EI-2	closed-circuit	400/1200	24 Sept. 1958	31 Dec. 1990
ADE-3	closed-circuit	1450/1900	14 July 1961	14 Aug. 1990
ADE-4	closed-circuit	1450/1900	26 Feb. 1964	20 April 2008
ADE-5	closed-circuit	1450/1900	27 June 1965	5 June 2008

Table 3.3. Tomsk-7 production reactors.²⁴⁷

The I-1 and EI-2 reactors were designed by NIKIET (chief designer N. Dolezhal). I-1 has 2001 channels (65 channels for control rods) and its design and power were practically the same as those of the AV reactors. The EI-2 reactor was the first dual-purpose reactor constructed in the Soviet Union. Its primary role was plutonium production but the fission heat released during this process was utilized to generate 100 megawatts of electricity and 300 megawatts of heat for district heating. The reactor's graphite stack has the same number of channels as the I-1 reactor but the primary cooling-water circuit is closed and operated at higher pressure and temperature than in the once-through I-1. As a result of the added complexity, the operators were confronted with difficulties, especially during the first years.

The three ADE reactors also were designed by OKBM to produce district heat and electricity as well as plutonium and to operate at 1450 MWt. Their graphite stacks have 2832 channels each, of which 132 were used for control rods. To increase the neutron flux in the outer core, 92 fuel channels were loaded with 90% enriched "spike" cermet fuel.²⁴⁸ The reactor cores each contained more than 300 tons of natural uranium fuel and, with their power upgraded to 1900 MWt, discharged about 69 kg of plutonium after 42 equivalent full-power days.²⁴⁹ Annually, more than 1200 tons of irradiated fuel, containing approximately 500 kg of plutonium, were discharged from each reactor (Table 3A.2).²⁵⁰

Mining and Chemical Combine (Krasnoyarsk-26). Three plutonium production reactors of the AD and ADE types were built at the Zheleznogorsk (Krasnoyarsk-26) site between 1958 and 1963 (Table 3.4). They were located in underground tunnels to protect them from U.S. nuclear attack. Like the ADE-type reactors in Tomsk-7, the Krasnoyarsk reactors were designed by the OKBM with a design power of 1450 MWt each. The AD reactor had once-through cooling. The ADE-1 and ADE-2 reactors were designed to be dual-purpose, but the ADE-1 was operated in a once-through mode.

The Krasnoyarsk-26 reactors produced an estimated 45.7 tons of weapon-grade plutonium, including 4.5 tons of plutonium produced during 1995–2010 while the ADE-2 reactor was operated at reduced power exclusively to produce district heat (Table 3A.3) Figure 3.4 gives the estimated cumulative amounts of plutonium produced at the three plutonium production sites separately and together.

Reactor	Type	Power (MWt) (design/upgraded)	Start-up date	Shutdown date
AD	once-through	1450/2000	25 August 1958	30 June 1992
ADE-1	once-through	1450/2000	20 July 1961	29 September 1992
ADE-2	closed-circuit	1450/1800	January 1964	15 April 2010

Table 3.4. Krasnoyarsk plutonium-production reactors.

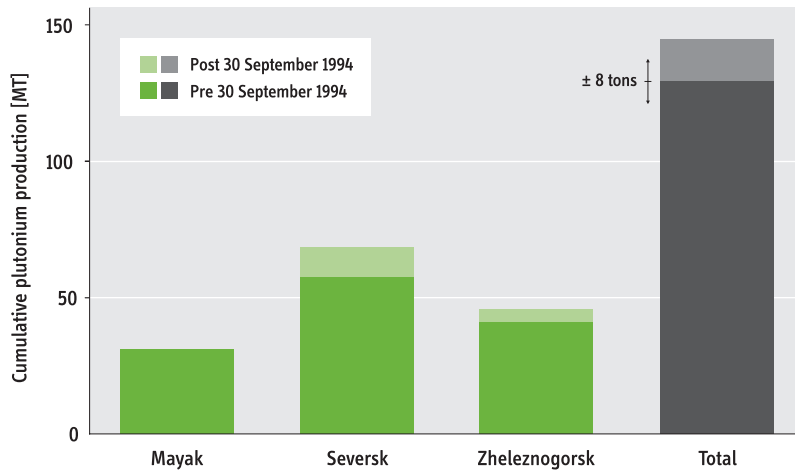


Figure 3.4. Estimated production of weapon-grade plutonium by site and total (metric tons). In exchange for U.S. assistance in refurbishing and

building replacement coal-fired district-heating plants, Russia has agreed not to use for weapons plutonium produced after 30 September 1994.

Uncertainties. The uncertainties of the above estimates stem primarily from the uncertainties of the power levels of the individual production reactors and the assumed durations of their operation at those power levels.

The most important uncertainty relates to the rates at which the powers of the reactors were increased above their original design levels and the power levels to which they were boosted. The estimates made here assume that, for the first and second-generation reactors (A, AV and I), the process of power ramp-up took 6–12 years, while, for the third generation reactors, it took 3–5 years. This leads to a ± 5 tons uncertainty in plutonium production. Assuming that the uncertainty in the upgraded reactor power levels is $\pm 5\%$ gives another ± 6 tons uncertainty.

With regard to the duration of the startup period for each reactor, the estimates made here assume a startup period of three weeks. But it took more than one month to bring some reactors up to their design power. These uncertainties result in an additional uncertainty of about ± 0.3 tons plutonium.

With regard to shutdowns due to operating problems, most were relatively short and the reactors went back into operation after 20–30 minutes. But it took days to weeks to restore normal operation after an overheating and meltdown of fuel elements and aluminum channel liners. Such accidents happened about 150 times. Assuming that cleanup and repairs were accomplished on average in 4 to 10 days would result in an uncertainty of about ± 0.75 tons of plutonium.

Assuming that the above uncertainties are random and uncorrelated, the total uncertainty of Russia's cumulative production of weapon-grade plutonium would be around ± 8 tons.

Plutonium Losses and Uses

Some of the plutonium produced in the production reactor fuel was not recovered and ended up in high-level waste. Some was used in nuclear tests and critical assemblies and a small amount was lost in the warheads that were in three submarines that sank.

Reprocessing losses. In the beginning of the 1950s, about 13 percent of the plutonium in the production-reactor fuel was being lost to high-level waste.²⁵¹ By the middle 1960s, the losses had decreased to 3–5 percent. Based on this information, the quantity of plutonium in reprocessing waste is estimated to be about 5.5 tons. In that case, 139 ± 8 tons of weapons plutonium would have been recovered from the production reactors.

Fabrication losses. Some quantity of plutonium was lost during the fabrication of plutonium weapon-components. Based on the U.S. experience where such losses were about 5 percent, the quantity of plutonium lost in this way is estimated to be 7 tons.

Use in nuclear tests. The Soviet Union tested a total 939 nuclear explosive devices.²⁵² Assuming that each device contained on average 4 kg of plutonium, 3.9 tons of plutonium would have been used in tests.

Use in critical assemblies. About 0.54 tons of weapon-grade plutonium is currently in critical assemblies.

Lost warheads. Three Soviet submarines equipped with twenty-five nuclear warheads containing a combined 0.1 tons of plutonium were lost.²⁵³

The above estimates of production, losses and uses are summarized in Table 3.5.

	Material Balance Category	Plutonium (tons)
Production	Mayak Site	30.9
	Seversk Site	68.3
	Zheleznogorsk Site	45.7
	Total	144.9
Removals	Waste	-5.5
	Losses in fabrication	-7.0
	Tests	-3.9
	Losses of warheads	-0.1
	Research assemblies	-0.5
	Total	-17.0
Stocks (2010)		127.9
Declared excess		-34.0
Not available for weapons		-6.0
Available for weapons		87.9

Table 3.5. Production, removals, and stocks of Russian weapon-grade plutonium.

Appendix 3A.

Estimated Plutonium Production by Reactor and Year

Year	Reactor					Annual total	Cumulative total
	A	AV-1	AV-2	AV-3	OK-180		
1948	16 kg					16 kg	16 kg
1949	19 kg					19 kg	35 kg
1950	30 kg	39 kg				69 kg	104 kg
1951	58 kg	100 kg	50 kg		3 kg	211 kg	315 kg
1952	58 kg	100 kg	100 kg	24 kg	25 kg	307 kg	622 kg
1953	58 kg	108 kg	108 kg	20 kg	25 kg	319 kg	941 kg
1954	58 kg	108 kg	108 kg	20 kg		294 kg	1235 kg
1955	76 kg	135 kg	108 kg	20 kg		339 kg	1574 kg
1956	152 kg	162 kg	135 kg	20 kg		469 kg	2043 kg
1957	152 kg	162 kg	162 kg	100 kg		576 kg	2619 kg
1958	152 kg	81 kg	162 kg	162 kg		557 kg	3176 kg
1959	152 kg	162 kg	81 kg	162 kg		557 kg	3733 kg
1960	152 kg	162 kg	162 kg	81 kg		557 kg	4290 kg
1961	152 kg	162 kg	162 kg	162 kg		638 kg	4928 kg
1962	152 kg	162 kg	162 kg	162 kg		638 kg	5566 kg
1963	152 kg	270 kg	162 kg	162 kg		746 kg	6312 kg
1964	103 kg	270 kg	270 kg	162 kg		805 kg	7117 kg
1965	207 kg	270 kg	270 kg	270 kg		1017 kg	8134 kg
1966	207 kg	135 kg	270 kg	270 kg		882 kg	9016 kg
1967	207 kg	270 kg	135 kg	270 kg		882 kg	9898 kg
1968	207 kg	270 kg	270 kg	135 kg		882 kg	10780 kg
1969	207 kg	270 kg	270 kg	270 kg		1017 kg	11797 kg
1970	207 kg	270 kg	270 kg	270 kg		1017 kg	12814 kg
1971	103 kg	270 kg	270 kg	270 kg		913 kg	13727 kg
1972	207 kg	135 kg	270 kg	270 kg		882 kg	14609 kg
1973	207 kg	270 kg	135 kg	270 kg		882 kg	15491 kg
1974	207 kg	270 kg	270 kg	135 kg		882 kg	16373 kg
1975	207 kg	270 kg	270 kg	270 kg		1017 kg	17390 kg
1976	207 kg	270 kg	270 kg	270 kg		1017 kg	18407 kg
1977	207 kg	270 kg	270 kg	270 kg		1017 kg	19424 kg
1978	207 kg	270 kg	270 kg	270 kg		1017 kg	20441 kg
1979	103 kg	270 kg	270 kg	270 kg		913 kg	21354 kg
1980	207 kg	270 kg	270 kg	270 kg		1017 kg	22371 kg
1981	207 kg	135 kg	270 kg	270 kg		882 kg	23253 kg
1982	207 kg	270 kg	135 kg	270 kg		882 kg	24135 kg
1983	207 kg	270 kg	270 kg	135 kg		882 kg	25017 kg
1984	207 kg	270 kg	270 kg	270 kg		1017 kg	26034 kg
1985	207 kg	270 kg	270 kg	270 kg		1017 kg	27051 kg
1986	207 kg	270 kg	270 kg	270 kg		1017 kg	28068 kg
1987	100 kg	270 kg	270 kg	270 kg		910 kg	28978 kg
1988		270 kg	270 kg	270 kg		810 kg	29788 kg
1989		250 kg	270 kg	270 kg		790 kg	30578 kg
1990			130 kg	220 kg		350 kg	30928 kg
Totals	6138 kg	8508 kg	8407 kg	7822 kg	53 kg	30928 kg	

Table 3A.1. Mayak site.

Year	Reactor					Annual total	Cumulative total
	I-1	IE-2	ADE-3	ADE-4	ADE-5		
1955	10 kg					10 kg	10 kg
1956	170 kg					170 kg	180 kg
1957	170 kg					170 kg	350 kg
1958	170 kg	29 kg				199 kg	549 kg
1959	170 kg	155 kg				325 kg	874 kg
1960	170 kg	155 kg				325 kg	1199 kg
1961	170 kg	155 kg	202 kg			527 kg	1726 kg
1962	170 kg	155 kg	392 kg			717 kg	2443 kg
1963	85 kg	155 kg	392 kg			632 kg	3075 kg
1964	270 kg	78 kg	392 kg	268 kg		1008 kg	4083 kg
1965	270 kg	155 kg	392 kg	392 kg	202 kg	1411 kg	5494 kg
1966	270 kg	260 kg	250 kg	500 kg	292 kg	1572 kg	7066 kg
1967	270 kg	260 kg	500 kg	500 kg	500 kg	2030 kg	9096 kg
1968	270 kg	260 kg	500 kg	250 kg	500 kg	1780 kg	10876 kg
1969	270 kg	260 kg	500 kg	500 kg	500 kg	2030 kg	12906 kg
1970	135 kg	260 kg	500 kg	500 kg	500 kg	1895 kg	14801 kg
1971	270 kg	260 kg	500 kg	500 kg	250 kg	1780 kg	16581 kg
1972	270 kg	130 kg	500 kg	250 kg	500 kg	1650 kg	18231 kg
1973	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	20271 kg
1974	270 kg	270 kg	250 kg	500 kg	500 kg	1790 kg	22061 kg
1975	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	24101 kg
1976	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	26141 kg
1977	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	28181 kg
1978	135 kg	270 kg	500 kg	500 kg	500 kg	1905 kg	30086 kg
1979	270 kg	135 kg	500 kg	500 kg	500 kg	1905 kg	31991 kg
1980	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	34031 kg
1981	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	36071 kg
1982	270 kg	270 kg	250 kg	500 kg	500 kg	1790 kg	37861 kg
1983	270 kg	270 kg	500 kg	250 kg	500 kg	1790 kg	39651 kg
1984	270 kg	270 kg	500 kg	500 kg	250 kg	1790 kg	41441 kg
1985	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	43481 kg
1986	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	45521 kg
1987	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	47561 kg
1988	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	49601 kg
1989	270 kg	270 kg	500 kg	500 kg	500 kg	2040 kg	51641 kg
1990	202 kg	270 kg	250 kg	500 kg	500 kg	1722 kg	53363 kg
1991			500 kg	500 kg	500 kg	1500 kg	54863 kg
1992			250 kg	500 kg	500 kg	1250 kg	56113 kg
1993				250 kg	500 kg	750 kg	56863 kg
1994				500 kg	250 kg	750 kg	57613 kg
1995-2008				5300 kg	5400 kg	10700 kg	68313 kg
Totals	8237 kg	7452 kg	14020 kg	19460 kg	19144 kg	68313 kg	

Table 3A.2. Siberian Chemical Combine (Seversk,Tomsk-7).

Year	Reactor			Annual total	Cumulative total
	AD	ADE-1	ADE-2		
1958	101 kg			101 kg	101 kg
1959	378 kg			378 kg	479 kg
1960	378 kg			378 kg	857 kg
1961	378 kg	130 kg		508 kg	1365 kg
1962	378 kg	378 kg		756 kg	2121 kg
1963	189 kg	378 kg		567 kg	2688 kg
1964	505 kg	378 kg	368 kg	1251 kg	3939 kg
1965	505 kg	189 kg	378 kg	1072 kg	5011 kg
1966	505 kg	505 kg	378 kg	1188 kg	6199 kg
1967	505 kg	505 kg	405 kg	1415 kg	7614 kg
1968	505 kg	505 kg	405 kg	1415 kg	9029 kg
1969	505 kg	505 kg	202 kg	1212 kg	10241 kg
1970	252 kg	505 kg	405 kg	1162 kg	11403 kg
1971	505 kg	252 kg	405 kg	1162 kg	12565 kg
1972	505 kg	505 kg	405 kg	1415 kg	13980 kg
1973	505 kg	505 kg	405 kg	1415 kg	15395 kg
1974	505 kg	505 kg	405 kg	1415 kg	16810 kg
1975	505 kg	505 kg	405 kg	1415 kg	18225 kg
1976	505 kg	505 kg	405 kg	1415 kg	19640 kg
1977	505 kg	505 kg	202 kg	1212 kg	20852 kg
1978	252 kg	505 kg	405 kg	1162 kg	22014 kg
1979	505 kg	252 kg	405 kg	1162 kg	23176 kg
1980	505 kg	505 kg	405 kg	1415 kg	24591 kg
1981	505 kg	505 kg	405 kg	1415 kg	26006 kg
1982	505 kg	505 kg	405 kg	1415 kg	27421 kg
1983	505 kg	505 kg	405 kg	1415 kg	28836 kg
1984	505 kg	505 kg	405 kg	1415 kg	30251 kg
1985	505 kg	505 kg	202 kg	1212 kg	31463 kg
1986	505 kg	252 kg	405 kg	1162 kg	32625 kg
1987	505 kg	505 kg	405 kg	1415 kg	34040 kg
1988	252 kg	505 kg	405 kg	1162 kg	35202 kg
1989	505 kg	505 kg	405 kg	1415 kg	36617 kg
1990	505 kg	505 kg	405 kg	1415 kg	38032 kg
1991	505 kg	505 kg	405 kg	1415 kg	39447 kg
1992	250 kg	360 kg	405 kg	1015 kg	40462 kg
1993			405 kg	405 kg	40867 kg
1994			405 kg	405 kg	41272 kg
1995–2010			4462 kg	4462 kg	45734 kg
Totals	15433 kg	14184 kg	16317 kg	45734 kg	

Table 3A.3. Mining and Chemical Combine (Zheleznogorsk, Krasnoyarsk-26).

4 Russia: Highly Enriched Uranium

During 1949–1963, the Soviet Union built four large industrial uranium-enrichment plants. All initially used gaseous diffusion for isotope separation. Starting in 1964, however, the Soviet Union began introducing gas centrifuges and this transition was completed in the early 1990s.

In 1989, the Soviet government announced that “it is ceasing the production of highly enriched uranium.”²⁵⁴ In fact, all production of HEU had already stopped in 1987–1988 and, because of the huge excess quantities of HEU that have become available as a result of the down-sizing of the Soviet Cold War nuclear stockpile, it has apparently not resumed since.

We estimate that by the time the production of HEU was ended, the Soviet Union had produced about 1250 ± 120 tons of 90%-enriched uranium. This number does not include the enriched uranium that was used to manufacture naval fuel, fuel for research reactors, and fast reactors, most of which was produced as less than 90%-enriched HEU (220 tons of 90%-enriched equivalent).²⁵⁵ Of the 1250 tons of HEU, 500 tons have been committed to be blended down to low-enriched uranium (LEU) to be sold to the United States, with about 400 tons already blended down as of September 2010. A total of 90 tons of HEU were consumed in separate blend-down programs for fuel for tritium-production reactors and research-reactors, in “spike fuel” for the plutonium-production reactors, in nuclear weapon tests, and lost to processing waste.

It is estimated that Russia had 770 tons of HEU remaining as of September 2010 and that its total holdings will have been reduced to about 665 tons by the end of the HEU blend-down program in 2013. This includes material in and available for weapons and reserved for fueling naval, research and civilian reactors. At 20 kg per warhead, this would be sufficient for more than 30,000 warheads. Obviously, more could be declared excess.

Figure 4.1 shows the estimated evolution of installed separative work capacity by enrichment facility and by technology. Cumulatively, about 400 million SWU had been produced by the end of 1987. Below, it is estimated that 107 million of these SWU was used to produce fuel for Russia’s power reactors and for export; 28.5 million to produce HEU fuel with various enrichment levels for Russia’s naval and icebreaker reactors; and 0.5 million to produce medium-enriched uranium fuel for research reactors. This would leave 264 million SWU available to produce weapon-grade uranium.

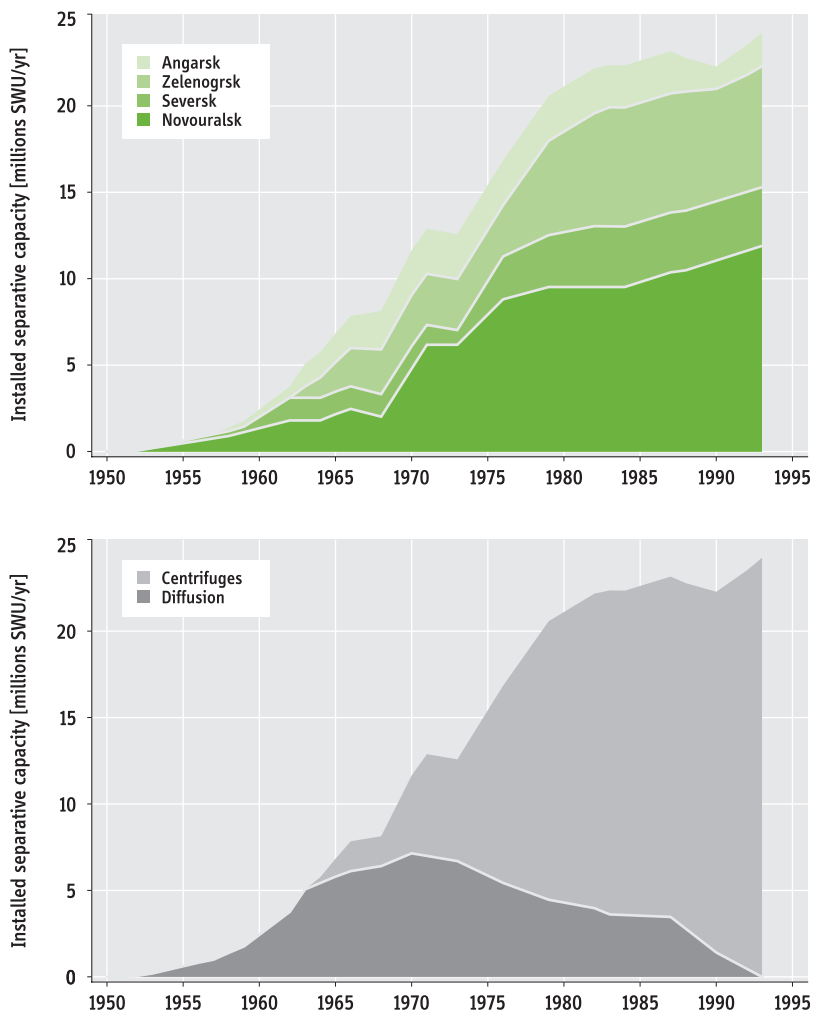


Figure 4.1. Growth of Soviet/Russian installed enrichment capacity by site (top) and by technology (bottom) from 1950 through 1993. The Soviet Union built four major uranium enrichment plants which

started out with gaseous diffusion technology and over time were replaced by gas centrifuges. All four sites are operational.

These estimates are based on a large array of data on the history of the Soviet enrichment program that is summarized in Appendix 4A. Most of the uncertainty is related to dates of plant modernization and equipment upgrades. Overall, the uncertainty in the cumulative production of SWUs is estimated to be about ± 5 percent.

Another source of uncertainty in estimates related to production of enriched uranium is the lack of information about the percentage of U-235 remaining in the depleted uranium “tails.” The central estimate provided here assumes that the gaseous diffusion process and the centrifuges operated with tails assays of 0.3% and 0.25% respectively.²⁵⁶ Taking into account that centrifuges produced about 70% of all separative work until 1988, the average tails assay would have been about 0.265%. This value is used in all estimates of enriched uranium production in this chapter. Assuming that the actual average value falls between 0.25 and 0.3%, the resulting uncertainty in the HEU production also would be about ± 5 percent.

Non-weapon Requirements for Separative Work and HEU

In addition to production of HEU for nuclear weapons, the Soviet Union and Russia enriched uranium for reactor fuel for power reactors, naval reactors, plutonium and tritium-production reactors, and research reactors.

Fuel for nuclear power reactors. By the time the Soviet Union ended production of HEU in 1988, it had built a fleet of 76 nuclear power reactors of several different types, most of which used low-enriched uranium fuel.²⁵⁷ In calculating the SWU requirements for power reactor fuel, it is assumed that, by 1988, the Soviet Union had produced enough enriched uranium to support reactor operations through the end of 1989.

Reactors of the most popular class at the time were light-water reactors with a gross electrical generating capacity of 440 MWe (VVER-440).²⁵⁸ The Soviet Union's next-generation light-water reactor was the 1000-MWe VVER-1000.²⁵⁹ These reactors used fuel with enrichment of 3.5% and 4.4% respectively.

In addition, the Soviet Union built graphite-moderated RBMK reactors until the 1986 Chernobyl accident, which used fuel with an enrichment of 1.8 to 2.0%.²⁶⁰ Their fuel was produced by enriching uranium and, during 1981–1991, also by blending down HEU recovered in the course of reprocessing naval and research-reactor fuel at the Mayak RT-1 plant.²⁶¹

The Soviet Union also built and operated four small EGP-6 graphite-moderated reactors to generate heat as well as electricity for the north-Siberian gold-mining town of Bilibino. These reactors are designed to produce 62 MWt of heat each and use 3 to 3.6% enriched uranium in their cores.²⁶² Two graphite-moderated reactors, AMB-100 and ABM-200, part of the Beloyarsk nuclear power plant, used fuel with enrichments ranging from 1.5% to 21% with an average enrichment about 3 percent.²⁶³ They were shut down in 1983 and 1989, respectively. The fuel for these reactors originally contained about 210 tons of LEU, which required 0.8 million SWU to produce.

Finally, the Soviet Union operated two liquid-sodium-cooled fast-neutron reactors: the BN-350 in Shevchenko (now Aktau), Kazakhstan, and the BN-600 at the Beloyarsk nuclear power plant. These two reactors began producing electricity in 1973 and 1980 respectively. The BN-350 used uranium in the range of 20% enrichment in its core.²⁶⁴ The BN-600 used fuel with enrichments ranging from 17 to 33%.²⁶⁵

Beginning in the 1970s, the Soviet Union also supplied enrichment services to Western Europe, for a total of 40 million SWU by the end of 1988.²⁶⁶

Table 4.1 summarizes the estimates of SWU requirements for nuclear-power fuel. Altogether, the Soviet Union had used about 107 ± 7 million SWU to enrich power-reactor fuel by the time it stopped producing HEU.

Naval reactors. Starting with the *K-3* submarine, which entered sea trials in 1958, the Soviet Union and Russia built 255 nuclear-powered submarines of more than twenty different types. Most were equipped with twin reactors, for a total of 456 nuclear reactors. Five nuclear-powered military surface ships had ten reactors between them, and 10 civilian Arctic icebreakers and container ships were equipped with 17 reactors that used HEU fuel.²⁶⁷ With the exception of eight submarines that used liquid-metal-cooled reactors, the reactors were water-cooled and went through three generations of development. It is estimated these naval reactors, in total, required about one-quarter as much enrichment work as the power reactors.

Reactors	Power MW(e)	Years of operation	Number of units	Enrichment of Fuel (percent)	Total enriched uranium consumed (tons)	Cumulative separative work (millions of SWUs)
VVER-440	440	1972 –	36	3.5	6,200	29.0
VVER-1000	1000	1981 –	17	4.4	2,200	14.2
RBMK-1000	1000	1974 –	18	1.8 – 2.4	3,600 ²⁶⁸	6.6
LWGR	12 108 160	1974 – 1964 – 1983 1967 – 1990	6	1.5 – 21	270	1.0
BN-350	90	1973 – 1999	1	17, 21, 26	100	4.5
BN-600	600	1980 –	1	17, 21, 26	240	11.3
Export						40
Total						107

Table 4.1. Estimated SWUs used to produce nuclear-power-reactor fuel through 1987.

The Soviet Union's first-generation submarine reactors, known as VM-A, used 6 to 21 percent enriched fuel.²⁶⁹ A typical core contained about 250 kg of uranium.²⁷⁰ Two first-generation VM-A reactors were installed in each of 55 submarines that were built in the 1950s and 1960s, most of which remained in service until the late 1980s. The available information on their operation and overhauls suggests that submarines of this class were refueled three to four times during their service lives.

Second-generation VM-4 reactors, installed in submarines starting in the late 1960s, used 21 % enriched fuel.²⁷¹ According to one estimate, their cores each contained about 550–660 kg of uranium.²⁷² The initial design of the VM-4 reactor apparently called for reactor refueling about every eight years.²⁷³ This means that submarines that were built in the late 1960s and early 1970s went through at least two refueling operations. It is assumed that submarines built after 1975 were refueled only once because fleet operations were dramatically scaled down in the 1980s and a large number of submarines were decommissioned in the 1990s (Figure 4.2).²⁷⁴

The design thermal power of third-generation OK-650 submarine reactors was 190 MWt, more than twice that of their predecessors' 90 MWt. They reportedly use fuel elements with at least two levels of enrichment: 21 % and 45 %.²⁷⁵ An OK-650 reactor core is estimated to contain 200 kg.²⁷⁶ Submarines with third-generation reactors began entering service in 1981 and it is therefore unlikely that they required refueling during the 1980s. In the 1990s, the intensity of their operations was drastically scaled back. As a result, in 1992–2008 the Northern Fleet refueled only one submarine with a third-generation reactor.²⁷⁷ It is assumed that all but one submarine equipped with third-generation reactors still operate with or were decommissioned with their initial cores.

In recent years the Russian Navy has completed construction of only two new nuclear-powered submarines, the ballistic-missile submarine, *Yuri Dolgoruki*, in 2009 and the attack submarine, *Severodvinsk*, in 2010. Each is believed to have one fourth-generation reactor. The fuel inventory per reactor is assumed to be the same as third-generation reactors and is included in the totals for the third-generation reactors.

The Soviet Union also developed and built eight submarines powered by liquid-metal-cooled reactors: an experimental one-of-a-kind Project 645 (*November*) submarine with two reactors, and a series of Project 705 (*Alfa*) ships that had single reactors of a different type. Both types of reactors used molten-lead-bismuth alloy as a coolant and

90%-enriched uranium as their fuel. It is estimated that each core contained 200 kg of U-235.²⁷⁸ The Project 645 submarine had its two reactors refueled in 1967. None of the Project 705 submarine reactors were refueled, but one ship had its entire reactor compartment replaced after an accident.²⁷⁹ This means that the eight submarines used a total of 12 cores.²⁸⁰

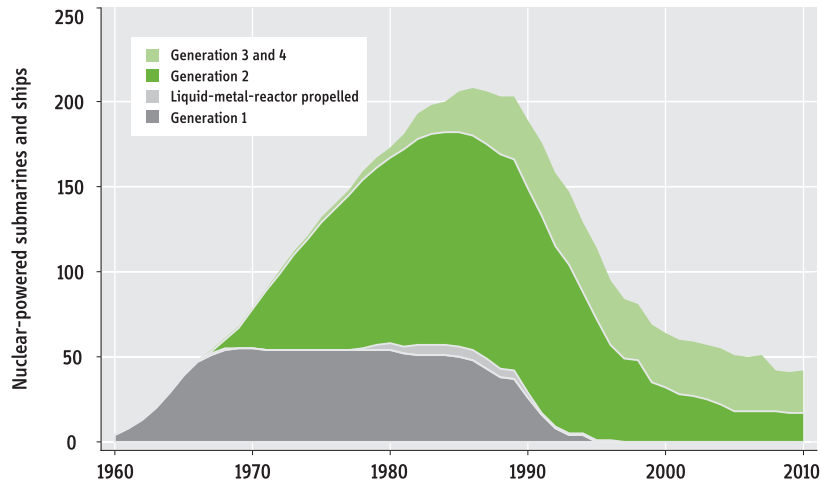


Figure 4.2. Soviet/Russian nuclear-powered submarines and ships by generation of nuclear-propulsion reactors. Since the 1950s, the Soviet Union and Russia constructed 255 nuclear-powered submarines of more than twenty different types, five nuclear-powered naval ships and 10 ice-breakers and container ships.

The military nuclear-powered surface ships built in the Soviet Union included four large missile cruisers of the Project 1144 (*Kirov*) class and one service ship of the Project 1941 class. Each ship had two water-cooled nuclear reactors of the KN-3 class, which appear to be similar to the third-generation submarine reactors. Therefore, it is assumed that each of these reactors contained 200 kg of U-235 in uranium enriched to between 21 and 45%.²⁸¹ Of these ships, only the fourth Project 1144 cruiser, *Piotr Velikiy*, is currently in active service and most likely has not yet required refueling of its reactors.

Russia also built nine nuclear-powered icebreakers and one container ship. The first nuclear icebreaker, *Lenin*, used two different types of reactors during its lifetime: during 1959–1967, three OK-150, which were each refueled once; and during 1970–1989, two OK-900. Since the OK-150 used LEU fuel and required relatively little enrichment work, the six cores of this type are not counted in the aggregate numbers.²⁸² After 1967, the three OK-150 reactors on *Lenin* were replaced by two reactors of the OK-900 type, similar to those used on the six icebreakers of the *Arktika* class. These reactors used HEU fuel with two zones enriched to 36% and 60%.²⁸³ A normal reactor core load contains 302 kg of uranium.²⁸⁴ Assuming (rather arbitrarily) that about one third of the core contains 60% enriched uranium, it is estimated that each core contains about 130 kg of U-235. About 70 OK-900 reactor cores have been used so far.²⁸⁵

The *Sevmorput* container ship and *Taimyr* and *Vaigach* icebreakers use KLT-40 and KLT-40M reactors, respectively (each ship has one reactor). These reactors use fuel enriched to 90%. A fresh reactor core contains 167 kg of uranium and 150 kg of U-235.²⁸⁶ Prior to 2000, the reactor cores on these three ships were replaced five times.²⁸⁷ Assuming that this refueling rate continued, they received an additional five cores in 2000–2010, for a total of 13 KLT-40 reactor cores.

	Ships	Reactors	Number of cores	Total U-235 (tons)	Enrichment (percent)	Total Uranium (tons)	Millions of SWU
Submarines							
1 st generation	55	110	466	27.5	20	137.5	5.6
2 nd generation	143	269	686	82.3	21	392	16.8
3 rd generation	41	60	61	12.2	21, 45	29.0 (21%) 13.6 (45%)	1.2 1.3
with liquid-metal-cooled reactors	8	9	12	2.4	90	2.7	0.5
small	8	8	8				
Military surface ships	5	10	14	2.8	21, 45	6.7 (21%) 3.1 (45%)	0.3 0.3
Civilian ships	7	14	70	9.1	36, 60	14 (36%) 7.0 (60%)	1.1 0.9
	3	3					
			13	1.95	90	2.17 (90%)	0.4
Total				138			28.5

Table 4.2. Enriched uranium requirements of Soviet and Russian naval reactors.

The above estimates are summarized in Table 4.2.²⁸⁸ If all HEU used to manufacture naval fuel up until today was produced before 1988, its production would have consumed about 28.5 million SWU with an uncertainty of 20% or ± 6 million SWU. Of the 150 tons (90% equivalent) HEU consumed as naval fuel about 10 tons remains in spent fuel.

Research reactors. The Soviet Union built about 170 research reactors and critical and subcritical assemblies, a large fraction fueled with HEU. About 70 HEU-fueled research reactors are currently located at the nuclear-weapon laboratories and other Rosatom research institutes, and other Russian research and graduate-educational institutes and agencies. A number of reactors fueled with Soviet and Russian HEU also are located in the former Soviet republics and in other foreign countries.²⁸⁹

Most research reactors operate at relatively low power. Their fuel requirements therefore are not as large as those of power reactors or production reactors.²⁹⁰ Overall, however, research reactors consumed considerable amounts of enriched uranium. Data on the operating histories of reactors suggest that, by the end of 2009, the research reactors that were designed and built by the Soviet Union had used about 6 tons of HEU with enrichment of 36%, 1.2 tons of 80% enriched uranium, and 11.3 tons of 90% HEU.²⁹¹

In addition, a substantial amount of HEU is held up in cores of critical assemblies and pulsed reactors. For example, two critical assemblies at the Institute of Physics and Power Engineering (IPPE) in Obninsk were reported to hold 8.7 tons of uranium with enrichment of 36% and 90%.²⁹² Most of this material, however, has not been exposed to any significant burnup, so it should be considered part of the HEU inventory.

Production of 6 tons of 36% enriched uranium used in research reactors required about 0.5 million SWU. In addition to that, by the end of 2009, research reactors used about 12.3 tons of 90%-enriched HEU assuming that the 80%-enriched uranium was produced by diluting weapon-grade HEU. Accuracy of these estimates is estimated to be no better than 20%.

Plutonium and tritium-production reactors. As described in Chapter 3, the Soviet Union built and operated a fleet of dedicated production reactors that provided materials for its nuclear weapons. Plutonium-production reactors were built at Ozersk (Chelyabinsk-65), Seversk (Tomsk-7), and Zhelesnogorsk (Krasnoyarsk-26). Four graphite-moderated plutonium-production reactors (A, AV, AV-2, and AV-3) were built at the Mayak facility in Ozersk during 1948–1952 and operated until the late 1980s. Another graphite-moderated reactor at Mayak (AI) was used to produce tritium. Mayak also operated four heavy-water reactors that were dedicated to tritium production (OK-180, OK-190, OK-190M, and *Lyudmila*).²⁹³ A light-water tritium-production reactor, known as *Ruslan*, began operations in 1980. *Ruslan* and *Lyudmila* are the only two production reactors that continue to work to this day, producing a range of isotopes and maintaining the capability to produce tritium.

The Siberian Chemical Combine in Seversk built five graphite-moderated plutonium production reactors during 1955–1965 (I-1, EI-1, ADE-3, ADE-4, and ADE-5). The first three were shut down in 1990. The last two operated until 2008 because they produced district heat and electric power in addition to plutonium.

Finally, three graphite-moderated plutonium-production reactors were built underground during 1958–1964 at the Mining and Chemical Combine in Zheleznogorsk (AD, ADE-1, and ADE-2). The first two were shut down in 1992. ADE-2 continued to operate until 2010 because it too produced district heat and electric power.

All graphite-moderated reactors, with the exception of the AI reactor at Mayak, used natural uranium as their primary fuel. They also used HEU-containing “spike” fuel elements in some of the channels, however. For example, each of the ADE reactors had in their cores about 100 HEU fuel rods that contained a total of about 80 kg of 90%-enriched uranium.²⁹⁴ These fuel rods reportedly stayed in the core for about two and a half years of normal operation, which corresponds to one ADE reactor consuming about 32 kg of 90% HEU per year while it produced about 500 kg of weapon-grade plutonium.²⁹⁵ Assuming that the other graphite production reactors also used HEU spike fuel starting in 1955 and that the HEU requirements stayed constant, it is estimated that plutonium production reactors together used about 9 tons of 90% HEU in the course of producing an estimated 145 tons of weapon-grade plutonium.²⁹⁶

The AI reactor began operating in 1952 with 2% enriched uranium in its core.²⁹⁷ In 1958, the enrichment level was increased to about 10%. It was further increased to 80% in 1967, and finally to 90% in 1969.²⁹⁸ The reactor’s nominal thermal power was also increased from about 40 MWt to 100 MWt.²⁹⁹ The reactor was shut down in 1987. Assuming that it operated with a 70% capacity factor, it would have used the equivalent of about 2 tons of 90% HEU during its lifetime.

The heavy-water tritium production reactors built by the Soviet Union also used enriched uranium fuel. The first, OK-180, which had a design power of 100 MW (later increased to about 250 MW)³⁰⁰ used natural uranium fuel when it first started in 1951 but was switched to uranium with 2% enrichment in 1954. Its core contained 15 tons of uranium.³⁰¹ The reactor operated until 1966.³⁰² The OK-190, similar to OK-180 but larger, began operations in 1955 and was shut down in 1965.³⁰³ It was then replaced by the OK-190M reactor, which operated during 1966–1986.³⁰⁴ In the early 1960s, fuel elements were developed for the OK-180 and OK-190 that contained 80% enriched uranium.³⁰⁵ It is estimated that these reactors used about 5.5 tons of 90% HEU during their cumulative 42 reactor-years of operation.³⁰⁶

To replace the OK-class heavy-water reactors, which were plagued by heavy-water leaks, the Soviet Union built two new reactors: *Ruslan*, a light-water reactor that began operating in 1979, and LF-2, also known as *Lyudmila*, a heavy-water reactor that began operating in 1988. Both reactors continue to operate today, producing various isotopes as well as maintaining a tritium production capability. Each reactor reportedly has a design thermal power of 1000 MWt and uses HEU fuel. Each could use about 550 kg of 90% HEU annually.³⁰⁷ As the end of 2010, the two reactors have accumulated about 52 reactor-years and therefore would have required a total of about 28.5 tons of 90% HEU.

Overall, production of plutonium and tritium for weapons as well as other isotopes required about 45 tons of 90% HEU with an estimated uncertainty of about 20%.

Other Removals

During 1949–1990, the Soviet Union carried out 715 test detonations of 969 nuclear devices.³⁰⁸ No information of the amount of HEU used in the tests is available. The amount of HEU used in the test program can be estimated, however, based on information about the test yields. Of the 969 explosive devices 677 yielded less than 20 kilotons (kt), 183 had yields of 20–150 kt, 78 from 150 kt to 1.5 megatons (Mt), 25 from 1.5 to 10 Mt, and 6 had yields of more than 10 Mt of chemical explosive equivalent. The tests that involved devices with yields of less than 20 kt were most likely tests of plutonium fission primaries. Tests with larger yields may have involved operational warheads. We assume rather arbitrarily that on average warheads with yield of 20–150 kt used 15 kg of HEU, and tests with yields of 150–1500 kt used 25 kg of HEU. Larger tests probably used from 50 to 100 kg of HEU. Overall, we estimate that the Soviet nuclear testing program consumed about 7 tons of HEU. The uncertainty of this estimate is probably quite high, and we assume it is no better than 50%. However, it does not contribute significantly to the accuracy of the final estimate of the size of the HEU inventory.

The most important reduction in the size of Russia's HEU inventory has been as a result of the 1993 agreement between Russia and the United States, sometimes known as the "Megatons to Megawatts" deal. Under this agreement, Russia agreed to down-blend 500 tons of weapon-origin HEU with an average enrichment of 90% and sell the resulting low-enriched uranium (LEU) material to the United States to be used in power reactor fuel.³⁰⁹ The first shipment of LEU from Russia to the United States took place in 1996 and, as of September 2010, Russia had blended down 400 tons of weapon-grade HEU.³¹⁰ The 500 tons of HEU will have been blended down in 2013 and it is unlikely that the deal will be extended beyond that.

The Material Conversion and Consolidation (MCC) program, which is run by the U.S. National Nuclear Security Administration, eliminates excess non-weapons HEU from various Russian facilities by buying it and having it down-blended to LEU at agreed Russian facilities. The goal of the program is to eliminate 17 tons of HEU by the end of FY2015. As of the end of 2009, the program had down-blended 12.6 tons of HEU.³¹¹

As was mentioned in the discussion of production of LEU for power reactors, during 1981–1991 the Soviet Union blended down reprocessed uranium from the RT-1 reprocessing plant to produce fuel for RBMK reactors. This process consumed in addition an estimated 1.8 tons of fresh 90% HEU.³¹²



Figure 4.3. HEU shavings removed from an excess Russian weapon component, produced in the first stage of conversion to low-enriched uranium for sale to the United States as a part of the deal under which Russia is eliminating 500 tons of excess weapon HEU. Source: U.S. Department of Energy.³¹³

Russia's HEU inventory

As estimated above, by the time the Soviet Union stopped production of highly enriched uranium for weapons, its enrichment plants had produced about 400 million SWU. Of this amount, about 67 million SWU was used to produce LEU to fuel power reactors in the Soviet Union, Eastern Europe, and Finland and a further 40 million SWU were used to enrich LEU for Western Europe. Production of naval-reactor fuel used about 28.5 million SWU and 0.5 million SWU went into production of medium-enriched fuel for research reactors. Thus, the separative work capacity available for producing weapon-grade uranium would have been about 264 million SWU.³¹⁴

Assuming that the Soviet Union produced its weapon-grade HEU from uranium recovered from plutonium production with concentration of U-235 of 0.667%, 264 million SWU would produce about 1250 tons of 90% HEU from about 280,000 tons of reprocessed uranium.³¹⁵ The actual amount of HEU produced was somewhat larger. It is estimated here as 1470 tons (90%-enriched equivalent), including the HEU of medium and high enrichment produced for naval reactors.

The uncertainty of this estimate is dominated by the uncertainty in the amount of separative work available for HEU production and, to a smaller extent, the uncertainty in the estimate of the average tails assay used in production of enriched uranium. Assuming that the accuracy of the cumulative SWU production is 5% or ± 20 million SWU and taking into account uncertainties in the amount of separative work used for non-weapon related enrichment, the amount of SWU used to produce HEU is 264 ± 22 million SWU, which translates into ± 110 tons accuracy of the HEU amount. The assumed 5% uncertainty in the average tails assay corresponds to an accuracy of ± 40 tons of HEU. Assuming that these two values are statistically independent, the uncertainty in the amount of produced HEU is about ± 120 tons.

The above removals are summarized in Table 4.3. Of the total of 1250 tons of HEU produced by the end of 1988, 500 tons have been set aside for down-blending as part of the HEU-LEU deal (400 tons had been blended down as of September 2009). In addition, 12.6 tons of HEU have been blended down by the MCC program. Plutonium and tritium production reactors have consumed about 45 tons of HEU. About 1.8 tons of HEU was spent in the RBMK reactor fuel production process in 1981–1991. It is estimated that nuclear tests required about 7 tons of HEU. In the United States, the “normal operating losses” were determined to be 4.9 tons of U-235.³¹⁶ Given that the Soviet Union produced almost twice as much HEU as the United States, its operating losses are estimated to be 10 tons of HEU.

HEU in tons (amount remaining to be down-blended)	
Production	
Produced as 90% HEU	1250
Produced for naval fuel and MEU for research and fast-neutron reactors (90% HEU equivalent)	220
Total production	1470
Removals	
Down-blended by HEU Deal (remaining, September 2010)	400 (+100)
Naval fuel	140
Fast-neutron reactors	68
Pu and tritium production reactors	45
Research reactors	14.3
Down-blended by MCC program	12.6 (+4.4)
Nuclear tests	7
RT-1 plant	1.8
Losses to waste	10
Total removals	700 (+104.4)
Total	770 (-104.4)

Table 4.3. Estimate of Russia's HEU stock.

Combining these numbers, as of September 2010, Russia could have about 770 tons of HEU. This includes 104.4 tons that are committed to down-blending programs. While the accuracy of estimates of some removals is relatively poor, it does not significantly affect the uncertainty of the final number. The overall uncertainty is taken to be ± 120 tons or about 15%.

Russia has not publicly reserved a stock of HEU for future use as naval fuel. However, it can be estimated that to support operations of its current and under construction submarine and icebreaker fleets upto 2050, Russia would need about 20 tons of HEU. To support continued operation of its current research reactors and to allow for a future generation of HEU-research reactors, it is estimated Russia would need to set aside an estimated 20 tons of HEU.

Appendix 4A.

History of Soviet/Russian Enrichment Capacity

Russia's four enrichment plants are the:

- Urals Electrochemical Combine (UEKhK) in Novouralsk (designated as Sverdlovsk-44 during the Soviet period, 57.2744 N, 60.1071 E)
- Isotope Separation Plant at the Siberian Chemical Combine in Seversk (Tomsk-7, 56.6188 N, 84.8636 E)
- Electrochemical Plant in Zelenogorsk (Krasnoyarsk-45, 56.1139 N, 94.5008 E)
- Electrolyzing Chemical Combine in Angarsk (52.4655 N, 103.8751 E)

The operating history of these facilities is described briefly below.

The Urals Electrochemical Combine at Novouralsk (Sverdlovsk-44). The first gaseous diffusion isotope separation plant, D-1, in Sverdlovsk-44 became operational in November 1949.³¹⁷ Initially, the plant was able to produce about 0.178 kg of 75% enriched HEU per day.³¹⁸ Uranium had to be enriched to weapon-grade (90%) at the SU-20 electromagnetic isotope separation facility at the Elektrokhimpribor plant in Sverdlovsk-45 (currently Lesnoy). By the end of 1952, however, after modernization of the existing machines and installation of new ones, the D-1 plant was able to produce “tens of kilograms of HEU annually”.³¹⁹ These numbers are consistent with an initial capacity of about 0.01 million SWU/year.

A second enrichment facility, D-3, equipped with more advanced machines began producing 90% HEU in 1952–1953, increasing the combined separative capacity of the Urals Electrochemical Combine six-fold. This suggests that the D-3 facility had a capacity of 0.05 million SWU/year.³²⁰ The D-4 and the SU-3 intermediate-enrichment plants began operations in 1954 and 1955 respectively, with the capacity of each plant estimated to have been 0.1 million SWU/year.

The last gaseous diffusion facility at the Novouralsk, D-5, was brought into operation in several stages during 1955–1957 using next-generation machines. After it reached full capacity, the total output of the Novouralsk combine was described as 100 times larger than that of the D-1 facility in 1950.³²¹ (The D-1 plant was dismantled when the first stages of D-5 began operation.) Taking into account data on the productivity of the diffusion machines, it is estimated that D-5 had a capacity of 0.65 million SWU/yr.³²² This means that the combined production capacity of the D-3, SU-3, D-4, and D-5 UEKhK diffusion plants reached 0.9 million SWU/y at the end of 1957.

During 1958–1962, the gaseous-diffusion facilities at Sverdlovsk-44 underwent upgrades.³²³ The modernization program was said to have doubled the separation capacity of Sverdlovsk-44, i.e., to about 1.8 million SWU/yr in 1962.³²⁴ The D-3, D-4, and SU-3 facilities were shut down and dismantled in 1966–1967. During 1970–1987, the D-5 plant underwent further modernization.³²⁵

In the meantime, a pilot centrifuge facility was installed in the former D-1 plant and began operation in 1957 with about 2400 second-generation centrifuges.³²⁶ The plant's enrichment capacity was reported to be 0.0015 million SWU/yr, which is consistent

with estimates of the separative capacity of Soviet 2nd-generation centrifuges.³²⁷ The success of the pilot plant led to a decision to build a full-scale facility in Novouralsk. The new facility, Plant 53 (GTZ-1), apparently using 3rd-generation centrifuges, was brought on-line in three phases during 1964–1966 and increased the overall capacity in Novouralsk by about 40%.³²⁸ This means that the new plant had a capacity of about 0.72 million SWU/yr.³²⁹

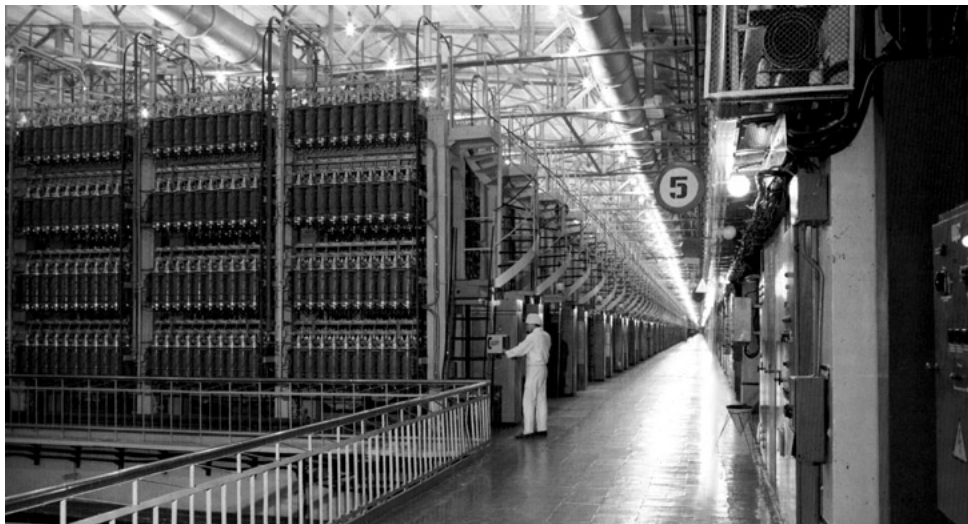


Figure 4A.1. Inside a centrifuge hall in Novouralsk in the 1990s. Source: U.S. Department of Energy.³³⁰

In 1967, the Urals Combine began to replace its diffusion cascades with centrifuge cascades.³³¹ Fifth-generation centrifuges were installed in the buildings of the D-4 diffusion plant and D-1 pilot centrifuge plant with floor areas of about 60,000 m² each.³³² This resulted in an increase in the estimated capacity of the plants, to more than 2 million SWU/yr. In 1971, with two additional centrifuge plants in operation in new buildings (Plant 24 and 45), the total capacity of the centrifuges at Sverdlovsk-44 reached 4.88 million SWU/yr. Another 1.3 million SWU/yr was still provided by the D-5 diffusion plant, the last diffusion plant in Sverdlovsk-44.

Dismantlement of D-5 began in 1973, when the combine began the next wave of expansion of its centrifuge capacity. At this stage, the centrifuges in Plant 53 were replaced with fifth-generation machines. New centrifuges were also deployed in the D-5 plant (now known as Plant 54). The D-5 buildings were also used to host the Chelnok facility, which was built in 1973 to allow the combine to export enrichment services. Assuming that the centrifuges deployed at this stage were similar to the ones installed at Plants 24 and 45, by 1979, when the modernization was completed, the total enrichment capacity of the Urals Electrochemical Combine had reached 9.5 million SWU/yr.

The next wave of modernization, which involved installation of centrifuges of the sixth generation, began around 1984.³³³ By 1993, when this process was completed, the full capacity of the Novouralsk plant was about 11.9 million SWU/yr.

The Siberian Chemical Combine at Seversk (Tomsk-7). The Tomsk-7 Isotope Separation Plant (ZRI) began operation in July 1953 and reached full capacity in 1961, when all of its six buildings became operational.³³⁴ An estimate based on the data about

historical growth of separative capacity in Seversk suggests that at that point the total separative capacity of the Isotope Separation Plant had reached about 1.3 million SWU/yr.³³⁵ The plant operated in this configuration until 1973, when Tomsk-7 began the process of replacing its gaseous diffusion facilities with gas centrifuges. Conversion of the first two buildings was probably completed by 1976 and the third by 1982. At that point the plant had a capacity of about 3.5 million SWU/yr, most of which was provided by centrifuges. Diffusion machines in the last two buildings at ZRI were dismantled by 1993. By that time, fifth-generation centrifuges in one of the buildings had been replaced by sixth-generation machines, bringing the total capacity of the plant to about 3.4 million SWU/yr.

Electrochemical Plant at Zelenogorsk (Krasnoyarsk-45). The Krasnoyarsk-45 plant began producing enriched uranium in October 1962.³³⁶ The gaseous diffusion equipment was deployed in three buildings (902, 903, and 904). Assuming that the machines installed in Krasnoyarsk-45 were similar to those deployed at the time in Sverdlovsk-44 and Tomsk-7, each building provided about 0.65 million SWU/yr and the plant provided about 1.95 million SWU/yr of separative capacity when they became fully operational in 1970.

Deployment of centrifuges at Zelenogorsk began shortly after the first diffusion facility went into operation. The first centrifuges, installed in Building 901 (formally known as the “chemical purification plant”) began operating in June 1964. The plant reached its original design capacity in 1970.³³⁷ The centrifuges deployed at the facility were most likely fourth-generation machines, which would mean that the plant had a capacity of about 1 million SWU/yr, bringing the total capacity of the plant to 3 million SWU/yr.³³⁸

In 1976, Krasnoyarsk-45 began to replace its gaseous-diffusion capacity and the old centrifuges in Building 901 with fifth-generation centrifuges. The first of the gaseous-diffusion buildings had been converted to centrifuges by 1979 and the second one by 1983. This brought the total capacity of the plant to about 6.2 million SWU/yr in 1983. Gaseous diffusion machines in Building 902 remained in operation until 1990, when it was converted to activities not related to enrichment. In 1988, the Zelenogorsk plant apparently began to transition to sixth-generation centrifuges and the total capacity of the plant reached 7 million SWU/yr in 1993.

Electrolyzing Chemical Combine at Angarsk. This plant produced its first enriched uranium in October 1957 and installation of equipment in the four buildings of the plant was completed in 1963. Assuming that the gaseous diffusion machines at Angarsk were similar to those deployed in Novouralsk and Seversk at the time, in 1963, the plant could have had a capacity of about 1.3 million SWU/yr. This capacity had almost doubled by 1970 after the older machines installed in the first two buildings were replaced by new or upgraded ones. It is estimated that the plant had a capacity of about 2.6 million SWU/y until about 1982, when some of the diffusion machines began to be dismantled. The Angarsk plant was the last one to be converted to centrifuges, apparently because of concerns about operating centrifuges in a seismically active area. The problem of developing centrifuges that can withstand seismic events was solved in the late 1980s and installation began in 1990. By 1993, all the gaseous diffusion capacity had been taken out of service. At that point the plant provided about 2 million SWU of separative capacity and continued to increase it by installing additional new centrifuges.

5 United Kingdom

The United Kingdom has made several declarations concerning its fissile material stockpiles and nuclear weapons inventories since the mid 1990s. On 18 April 1995, the UK announced that it “had ceased the production of fissile material for explosive purposes.”³³⁹ In 1998, in its Strategic Defence Review (SDR), it announced that its “current defence stocks” of fissile material consisted of “7.6 tonnes of plutonium, 21.9 tonnes of highly enriched uranium and 15,000 tonnes of other forms of uranium.”³⁴⁰ As discussed below, the amount of military plutonium was later reduced to 3.2 tons, when the United Kingdom subsequently declared 4.4 tons of plutonium excess. This surplus material included only 0.3 tons of weapon-grade plutonium. The United Kingdom has declared its civilian stockpiles of plutonium and HEU annually since 1997 and 1999, respectively.³⁴¹

The amount of plutonium in the UK military stockpile far exceeds the amount of material in its nuclear weapons arsenal. On 26 May 2010, UK Foreign Secretary William Hague reconfirmed that the United Kingdom possessed no more than 160 operationally deployed warheads, and announced for the first time that the total number of nuclear weapons in the UK stockpile would not exceed 225.³⁴² This is somewhat higher than previous independent estimates.³⁴³ Assuming an average of 4 kilograms of plutonium per warhead, and allowing for a “working stock” of 20–25%, the United Kingdom requires slightly more than one ton of plutonium in its weapons arsenal, leaving about two tons without apparent purpose. This material should therefore be available for declaration as excess. The recently released *Strategic Defence and Security Review* announced that by the mid 2020s the United Kingdom’s arsenal would be cut to a maximum of 180 warheads, potentially enabling even more material to be declared as excess.³⁴⁴

We estimate that the UK stockpile of military HEU includes about 8 tons of irradiated material. Somewhat over 2 tons of this material is in reactors in operating submarines. Most of the remainder is spent naval fuel. If a UK warhead uses on average 10 kg of HEU,³⁴⁵ then up to 2.8 tons would be contained within the weapon stockpile (again including working stocks of 20%). The United Kingdom appears, therefore, to have about 11 tons of fresh (unirradiated) highly enriched uranium in reserve. Most, if not all of this material is probably earmarked for future use in naval propulsion reactors and would be sufficient to fuel the UK nuclear fleet of current size for about 75 years.³⁴⁶

The United Kingdom has pursued an extensive program of reprocessing spent fuel from power reactors with minimal plutonium recycle. This has resulted in the largest stockpile of civilian plutonium in the world, including 84.4 tons of UK and 27.7 tons of foreign separated plutonium stored in the United Kingdom as of the end of 2009.

With regard to the history of its plutonium production, the United Kingdom has stated that “the military and civil nuclear cycles have been run in parallel and to some extent were entwined during the early years of the nuclear programme.”³⁴⁷ This makes an independent review of the UK fissile material stockpile challenging until more details about historical reactor operations are made public.

This chapter reviews the publicly available information about the UK production complex and history, compares the consistency of this data with the UK declarations, and makes recommendations for further steps that the UK government could take to increase the transparency of its fissile-material and nuclear-weapon programs.

Highly Enriched Uranium

In 1998, the United Kingdom declared an inventory of 21.9 tons of military highly enriched uranium (HEU).³⁴⁸ Essentially the same number was reported in 2006 in a six-page report that reported an audited stock of 21.86 tons of HEU as of 31 March 2002.³⁴⁹ Remarkably, and to some extent inexplicably, the declared inventory did not change significantly between 1998 and 2002. Since 2002, additional U-235 would have been consumed and the fraction of irradiated HEU increased. This suggests that naval fuel may be measured according to its original HEU content—a source of ambiguity that is discussed below.³⁵⁰

	Highly Enriched Uranium
Total HEU acquisitions since 1940s	26.36 tons
Total HEU removal	-4.72 tons
Balance	21.64 tons
Total audited stock (31 March 2002)	21.86 tons
Estimated HEU removals since March 2002	-0.7 tons
Estimated HEU inventory 2010	21.2 tons

Table 5.1. UK account of HEU acquisitions and removals, 2002, and estimate for 2010. The stock audited in 2002 is higher than the reported balance, resulting in an “apparent gain” of 220 kilograms. The official declaration notes that “this discrepancy is understandable given the missing records,

the difficulties of interpreting remaining records, and measurement inaccuracies particularly in the early years of the programmes.” The United States encountered similar difficulties in reconstructing its fissile material production history.

Overall, the 2006 UK declaration contains very little information besides the total HEU inventory. It is stated there that “after careful review it has been judged that much of the underpinning detail cannot be published in this report. This is because of the need to protect defence-sensitive information on the design of the UK weapon stockpile and the performance of the nuclear submarine fleet.”³⁵¹ Specifically, the United Kingdom does not specify the average enrichment level of its HEU stockpile or, equivalently, the amount of U-235 it contains—information the United States has provided in its declaration. The United Kingdom also does not provide information on how much HEU is committed to weapons uses, how much to naval fuel use, or how much is in spent naval reactor fuel.

Acquisitions. The United Kingdom acquired HEU from two sources: production in its Capenhurst gaseous diffusion plant and supply from the United States pursuant to the 1958 Mutual Defense Agreement.

Prior to 1980, the United Kingdom bartered 5.4 tons of separated plutonium for 7.5 tons of HEU and 6.7 kg of tritium from the United States.³⁵² Subsequently, the United Kingdom sent low-enriched uranium produced in the first centrifuge enrichment plant at Capenhurst (A3) to the United States and received an ‘equivalent’ amount of weapon-grade HEU for naval fuel in return.³⁵³ The United Kingdom has not made public how much HEU it produced domestically or the amount received from the United States after 1980. The analysis below however suggests that more than half of the United Kingdom’s HEU stockpile originated from the United States.

Transfers from the United States. The United Kingdom remains reluctant to release information about the amounts of highly enriched uranium received from the United States since 1980, i.e., beyond the 7.5 tons it bartered for plutonium. In contrast, the United States has provided a good indication about the quantity involved in its 2001 HEU declaration.

The U.S. declaration specifies that a total of 32.2 tons of U-235 in HEU was removed from the U.S. stockpile through transfers to foreign countries and classified transactions.³⁵⁴ The amount of HEU exported for civilian research reactor fuel is given elsewhere in the report as 18.6 tons of U-235 contained in 25.6 tons of HEU. This leaves up to 13.6 tons of U-235 that have been supplied to foreign countries for military purposes. The average enrichment of this material is not known. If it were weapon-grade (93%-enriched) it would correspond to 14.6 tons of HEU; if it were of a lower enrichment level, the total quantity of material would be higher. Given that only about 0.5 tons were reportedly delivered to France for military purposes,³⁵⁵ virtually all of this material apparently went to the United Kingdom.³⁵⁶

Table 5.2 shows the sources of UK HEU acquisitions based on this information. Domestic production has been inferred from the difference required to account for the total. If the average enrichment of the U.S.-supplied material was lower than weapon-grade, then more material could have been supplied to the United Kingdom, reducing the estimate for domestic HEU production at Capenhurst. However, since U.S. HEU transferred since the 1980s was probably destined for use in naval-reactor fuel, it is unlikely that much non-weapon-grade material was delivered.

Average enrichment of U.S. supply	Scenario A	Scenario B
	93%-enriched	80%-enriched
Total HEU acquisitions since 1940s	26.4 tons	26.4 tons
Transfers from the United States	at least 14.0 tons	at least 16.0 tons
1958–1979	7.5 tons	7.5 tons
1980–1993	> 6.5 tons	> 8.5 tons
Domestic production (remainder)	up to 12.4 tons	up to 10.4 tons

Table 5.2. Total HEU acquisition through transfers from the United States and domestic production. The United Kingdom received about 13 tons of uranium-235 in HEU from the United States. Depending

on the average enrichment level of the material, this corresponds to at least 14 tons. In other words, more than half of the UK HEU stockpile was supplied by a third party.

Capenhurst Gaseous Diffusion Plant. The Capenhurst gaseous-diffusion enrichment plant (53.265 N, -2.955 W) produced highly enriched uranium between 1954 and 1962.³⁵⁷ It reportedly consisted of one cascade with 4,808 stages.³⁵⁸ Following the end of HEU production, the cascade was reshaped for civilian but unsafeguarded LEU production, largely to provide fuel for Britain’s fleet of advanced gas-cooled reactors (AGRs). The plant has been undergoing decommissioning and demolition since 1982 when enrichment operations ended there. Of the original building’s 23 sections or “bays,” nine are to be preserved for extended storage of depleted uranium.³⁵⁹

There is not sufficient public information available to make an accurate independent estimate of the total amount of HEU produced at Capenhurst. The average enrichment level of the HEU produced at the plant is unknown and, as the analysis below suggests, may have been lower than weapon-grade (90–93%). Also, there are few official statements about the separative capacity of the plant during the HEU-production period (1954–1962). The UK Nuclear Decommissioning Authority (NDA) reports a capacity of 400,000 kg SWU/yr, whereas the IAEA lists the capacity of the plant upon shutdown in 1982 as 350,000 kg SWU/yr.³⁶⁰ In the initial years of operation, however, the capacity apparently was much smaller. Albright et al. report that the original capacity of the plant was on the order of 100,000–150,000 kg SWU/yr, before it was increased to its final capacity between 1956 and 1959.³⁶¹ Based on these data points, the following assumptions are made in estimating the quantity of HEU produced at Capenhurst: HEU production began in 1954 with a capacity of 125,000 SWU/yr; the plant’s capacity increased linearly between 1956 and 1959 to 400,000 SWU/yr; and HEU production continued at this capacity until the end of 1961.

Based on these assumptions, we estimate the total production of highly enriched uranium at Capenhurst to be 9–13 tons (Figure 5.1). This range of estimates is significantly higher than earlier independent estimates, which were on the order of 4–5 tons,³⁶² but is consistent with the acquisitions declared by the UK Government less the transfers from the United States.

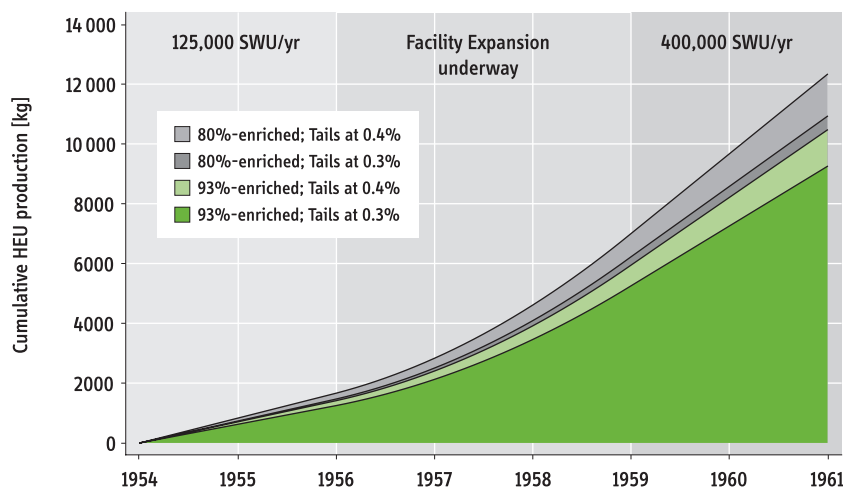


Figure 5.1. Estimated cumulative HEU production at the Capenhurst Gaseous Diffusion Plant. Between 1954 and 1961, the capacity of the plant increased from 125,000 kg SWU/yr to 400,000 kg SWU/yr. Depending on the average enrichment level of the product (between 80% and 93%) and the residual uranium-235 content of the depleted tails (between 0.3% and 0.4%), cumulative HEU production at Capenhurst could range from 9.0 to 12.5 tons.

Removals. The 2006 report specifies that, by 2002, the United Kingdom had used a total of 4.72 tons of its HEU. The principle use was as fuel in submarine propulsion reactors. In addition, the United Kingdom has also used HEU in nuclear weapon tests and military research reactors, while some HEU has been lost in waste.³⁶³

Class	Boats	Service dates	Cores per boat	Total cores	Submarine years	Mass U-235 fissioned
SSN Dreadnaught	1	1963-1980	3	3	17	90 kg
SSN Valiant	2	1966-1994	3	6	52	270 kg
SSN Churchill	3	1970-1992	3	9	61	320 kg
SSN Swiftsure	6	1973-2010	3	16	164	860 kg
SSN Trafalgar	7	1983-	2	14	160	840 kg
SSN Astute	1	2010-	1	1	1	5 kg
SSBN Resolution	4	1967-1996	3	12	108	890 kg
SSN Vanguard	4	1993-	2	7-8	57	470 kg
Total				69-72	620	3750 kg

Table 5.3. Use of HEU in UK naval propulsion reactors.³⁶⁴ The United Kingdom operates a fleet of HEU-fueled attack submarines (SSNs) and ballistic missile submarines (SSBNs). Given the uncertainties in the average operating power of naval-propulsion

reactors, the estimated values of uranium-235 consumed are probably only accurate to within about $\pm 25\%$. In addition to the one Astute-class vessel listed in the table, a further six are to be built.

The United Kingdom's estimated use of HEU in naval propulsion reactors is summarized in Table 5.3. The number of reactor cores produced has been inferred from publicly available information about submarine refits.³⁶⁵ To date, the UK nuclear navy has seen about 620 submarine-years of service, including refits and time at dock. 110 of these years have been accumulated since 2002, the cut-off date for the most recent UK HEU declaration. We assume that, on average, UK attack submarines (SSNs) and ballistic missile submarines (SSBNs) consume, respectively, about 7 kg and 11 kg of uranium-235 per year when they are operating but that, on average, they spend one out of every four years in refit (when, to a good approximation, they do not fission any uranium).³⁶⁶ Given these assumptions, we estimate that the total mass of uranium-235 consumed by the UK fleet since the 1960s is about 4 tons, of which about 0.7 tons have been fissioned since 2002.³⁶⁷ Assuming an average fuel burnup of 50% and an average enrichment level of 97.4%, i.e., the same enrichment level as the HEU produced for the U.S. Navy prior to 1993,³⁶⁸ about 8 tons of HEU have been used to fabricate submarine fuel and are in the form of irradiated fuel today. Some of this material is in the United Kingdom's 12 operating nuclear-powered submarines, which includes, one Astute-class attack submarine, seven Trafalgar-class attack submarines, and four Vanguard-class ballistic missile submarines. We estimate that these vessels currently contain about 2.2 tons of uranium in their reactor cores (measured according to their initial uranium content).³⁶⁹ Additional cores for future Astute-class vessels may also have been fabricated. Given the uncertainties in the average operating power of submarine reactors (amongst others), these estimates are probably only accurate to about $\pm 25\%$.

In addition to use in naval propulsion reactors, the United Kingdom may have used about 700 kg of HEU in the 45 weapons tests that the country conducted between 1952 and 1991.³⁷⁰

The United Kingdom's use of HEU in military research reactors is estimated at about 700 kg. The United Kingdom appears to have had five HEU-fueled military research reactors (Table 5.4),³⁷¹ even though the 2006 HEU declaration lists only four reactors. Other sources indicate, however, that there are in fact two—not one—submarine test reactors at the Vulcan Naval Reactor Test Establishment (VNRTE) near Dounreay, one of which has been shut down and the other of which is operating. These two reactors could have fissioned about 650 kg of uranium assuming that they operate at twice the capacity factor as reactors on submarines and hence fission about 14 kg of uranium per year. The quantity of HEU consumed by other British military reactors was probably much smaller.

The 4.7 tons of HEU that the United Kingdom reported it had used prior to 2002 can therefore be accounted for by use in naval reactors (3.3 tons), nuclear testing (0.7 ton) and use in research reactors (0.7 ton).

Reactor (Location)	Type	Purpose	Power	Criticality	Shutdown
JASON (RNC)	Argonaut	Training	10 kW	1959	1996
HERALD (AWE)	Pool	Materials testing	5000 kW	1960	1988
VIPER (AWE)	Fast burst	Weapons program	0.5 kW	1967	2007
DSMP (VNRTE)	PWR	Submarine reactor	Unknown	1965	mid-1980s
STF (VNRTE)	PWR	Submarine reactor	Unknown	mid-1980s	Still in use

Table 5.4. HEU-fueled military research reactors in the United Kingdom. Sites and facilities include the Royal Naval College (RNC), the Atomic Weapons Establishment (AWE), the Vulcan Naval Reactor Test Establishment (VNRTE), the Dounreay Submarine Prototype (DSMP), and the Shore Test Facility (STF).³⁷² The 2006 declaration lists only one submarine test reactor at VNRTE.

The United Kingdom also declares about 1.4 tons of civilian HEU as part of its INF-CIRC/549 declarations.³⁷³ This material is currently largely stored or used at laboratories and research centers.

Plutonium

The main production site for UK military plutonium was the Sellafield complex (54.42 N, -3.50 W), shown in Figure 5.2. Sellafield hosted a total of six production reactors: the two Windscale Piles and the four Calder Hall reactors, and all reprocessing operations. The United Kingdom operated four additional dual-use reactors at Chapelcross, whose fuel was also sent to Sellafield for reprocessing. When the United Kingdom announced in 1995 that it had stopped production of fissile material for military purposes, arrangements were made to bring most of its military fuel cycle under Euratom and, in some cases, IAEA safeguards.³⁷⁴ Safeguarded facilities included the four dual-use Calder Hall reactors at Sellafield, but not the four reactors at Chapelcross, which were still producing tritium for the weapons program at the time, and presumably not the spent-fuel storage ponds at Sellafield containing naval reactor fuel. The two Windscale Piles at Sellafield were shut down after a graphite fire in 1957. The four Calder Hall reactors were shut down in March 2003 and the four Chapelcross reactors in June 2004.

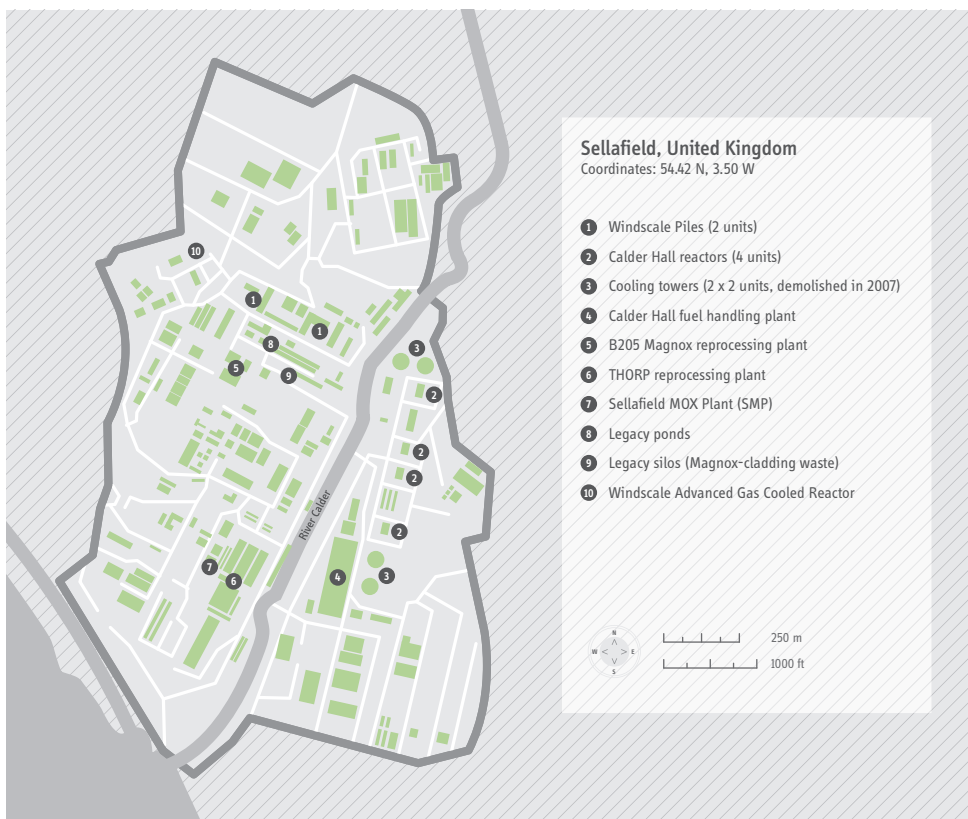


Figure 5.2 Sellafield Site (54.42 N, 3.50 W). The United Kingdom operated six (out of ten) plutonium production reactors and sited all reprocessing

activities at the Sellafield site on the Cumbrian coast in Northwest England.

The United Kingdom, in its 1998 Strategic Defense Review, declared a stockpile of 7.6 metric tons of military plutonium, which included 3.5 tons of weapon-grade material. A summary of the more detailed follow-up report published in 2000 stated, however, that the 4.1 tons of non-weapon grade material had never been delivered to Aldermaston and was “stored at Sellafield, now under EURATOM safeguards and liable to inspection by the International Atomic Energy Agency.”³⁷⁵ The 2000 report itself stated that the UK Ministry of Defence “has never had a requirement for the reactor grade plutonium stored at Sellafield in the weapons programme and it has been regarded more as a by-product of material production.”³⁷⁶ To date, the United Kingdom has declared excess 4.1 tons of non-weapon-grade and 0.3 tons of weapon-grade plutonium. As of 2010, the UK defense stockpile therefore stands at 3.2 tons of weapon-grade plutonium (Table 5.5).

The 2000 plutonium report focused on the flows into and out of Aldermaston, where all UK nuclear weapon components containing fissile material were (and are) manufactured.³⁷⁷ The report stated that “Aldermaston also provided fuel for civilian research or prototype reactors, which makes a material balance based on Aldermaston’s throughput more challenging.”

Table 5.5 summarizes the overall balance for UK military plutonium, primarily based on the material throughput of Aldermaston, which received 17.12 tons of plutonium

over time, including material being recycled from early-generation warheads. Removals from the site fall into various categories: 7.51 tons were shipped to four sites: Dounreay and Winfrith (both civilian), Harwell (civilian and military), and back to Sellafield;³⁷⁸ 5.84 tons were shipped to the United States, partly in return for highly enriched uranium, tritium and plutonium; 0.20 tons were used in nuclear weapon tests, which is equivalent to an average of 4.4 kg per test; and 0.07 tons were lost in waste. The remainder of 3.5 tons constituted the declared UK defense stockpile of weapon-grade plutonium before 0.3 tons were declared excess.

The plutonium exchanges with the United States are particularly interesting. It has been known for some time that the United Kingdom bartered 5.37 tons of plutonium for highly enriched uranium and tritium from the United States. However, the 2000 declaration reveals—for the first time—an additional ‘classified’ shipment of 0.47 tons of plutonium from the United Kingdom to the United States, as well as a shipment of equal size from the United States to the United Kingdom. No more information about these shipments is given and they do not appear in the United States’ 1996 declaration. It appears that one of the countries may have “loaned” plutonium to the other.

	Plutonium
Shipments from Sellafield, Dounreay, Winfrith, Harwell	15.99 tons
Shipments from the United States	0.47 tons
Shipments from unidentified sites	0.37 tons
Inventory difference	0.29 tons
Total Aldermaston acquisitions	17.12 tons
Shipments to UK non-weapon sites (net)	-7.51 tons
Shipments to the United States (swaps)	-5.37 tons
Shipments to the United States (classified)	-0.47 tons
Nuclear weapon tests	-0.20 tons
Discards and transfers to waste	-0.07 tons
Declared stockpile (based on Aldermaston balance)	3.50 tons
Reactor-grade military plutonium at Sellafield	4.10 tons
Total military stockpile (1998)	7.60 tons
Excess military plutonium, reactor-grade, at Sellafield	-4.10 tons
Excess military plutonium, weapon-grade	-0.30 tons
Military stockpile (2010)	3.20 tons

Table 5.5. UK military plutonium balance, 2010.

The UK plutonium declaration does not specify the total amount of unsafeguarded plutonium produced in the British fleet of production reactors—and it is difficult to infer this from the information made public to date.³⁷⁹ At a minimum, however, production must have yielded 3.7–3.8 tons of weapon-grade material, which includes the 3.5 tons in the current inventory (3.2 + 0.3 tons), material used in weapon tests (0.2 tons), and discards to waste. Additional production would have taken place, if there was a net transfer of weapon-grade plutonium to the United States, and/or if some of the plutonium used at Dounreay, Winfrith, or Harwell was weapon-grade. The discussion that follows shows how the UK reactor fleet may have produced this stockpile.

Windscale. The United Kingdom's first plutonium production reactors were the two air-cooled graphite-moderated "Windscale Piles." (Windscale was the original name for Sellafield.³⁸⁰ Construction on these reactors started in 1947. Pile 1 became operational in April 1951 and operated at 76 MWt (thermal), and Pile 2 followed in October 1951 at 104 MWt. After 1953, the power output was increased to about 110 MWt and 140 MWt respectively. The inventory of natural uranium fuel per reactor was about 180 tons.³⁸¹ Both reactors shifted to slightly enriched fuel in 1954 and also began tritium production, which reduced their effective plutonium production rates.³⁸² Both piles were shut down following a graphite fire in Pile 1 in October 1957.³⁸³ Based on these assumptions, and using an effective plutonium production rate of 0.92 g/MWd (see Appendix B), the cumulative plutonium production of the Windscale plants can be estimated to about 350 kg, as summarized in Table 5.5.³⁸⁴ This is similar to the value published by Simpson, who estimated a production of 388 kg.³⁸⁵



Figure 5.3. A helicopter of the Royal Air Force taking air samples during the 1957 Windscale Fire, with one of the reactors in the background. On 10 October 1957, the graphite core of Windscale Pile 1 caught fire during a routine graphite-annealing procedure, releasing substantial amounts of radioactivity, including an estimated 20,000 Curies of iodine-131 and 1000 Curies of cesium-137. This remains the worst accidental radioactive release outside the Soviet Union to date. Both Windscale Piles were closed as a result.³⁸⁶ Plutonium production continued at the Calder Hall and later also the Chapelcross reactors. *Image courtesy of Louise Rawling.*

Calder Hall and Chapelcross. The eight dual-purpose graphite-moderated, carbon dioxide-cooled Calder Hall and Chapelcross reactors came online between mid-1956 and early 1960. The Calder Hall reactors were used, on and off, to produce military plutonium until 1989.³⁸⁷ The Chapelcross reactors were used to produce plutonium until 1964 and tritium thereafter. Both sets of reactors were dual-purpose, that is, they also produced electric power. The two groups of reactors were shut down in 2003 and 2004 respectively and their cooling towers demolished in 2007.³⁸⁸

The eight reactors were initially optimized for plutonium production, their fuel being irradiated to about 400 MWd/t.³⁸⁹ Their power level varied between 180 MWt and 240 MWt thermal over time. In 1964, operation of all eight reactors was optimized for electricity production. They operated with an average fuel burnup of 4,500 MWd/t, which means that the plutonium produced would not have been weapon-grade.³⁹⁰ Reportedly, there were shorter periods of time later on, however, during which weapon-grade plutonium production resumed at Calder Hall. The first discharges of spent fuel from five other, nominally civilian Magnox reactors was also put towards the military stockpile. Their total contribution to the stockpile was probably on the order of 0.2–0.3 tons.³⁹¹

When operated in military mode, the effective production rate for the Calder Hall and Chapelcross reactors was about 0.92 grams of plutonium per megawatt-day.³⁹² To estimate cumulative production of weapon-grade plutonium at these reactors, and to compare it with the declared inventory, assumptions have to be made about the fractional

use of the reactor fleet for weapons-plutonium production. Here, we assume that 20% of the total energy output of the Calder Hall reactors was associated with weapons-plutonium production. For the Chapelcross reactors, we use a usage fraction of only 10% because they came online later and were more extensively used for tritium production. These are necessarily crude estimates, which can be improved once more information about the operational history of the reactors is made public.

Based on these assumptions, the total quantity of weapon-grade plutonium produced in the United Kingdom would have been about 4.0 tons, consistent with the UK declaration. If the transfers to the United States involved weapon-grade plutonium, the usage fractions of the eight Calder Hall and Chapelcross reactors for this purpose would have been higher than assumed above.

	Pile	Operation	Total Energy Output	Usage Fraction	Military Plutonium
Windscale	1	1951-1957	173 GWd*	100 %	0.16 tons
	2	1951-1957	208 GWd*	100 %	0.19 tons
Weapon-grade plutonium production at Windscale, 1951 – 1957					0.35 tons
Calder Hall	1	1956-1995	3160 GWd*	20 %*	0.58 tons
	2	1957-1995	3125 GWd*	20 %*	0.58 tons
	3	1958-1995	3040 GWd*	20 %*	0.56 tons
	4	1959-1995	2955 GWd*	20 %*	0.54 tons
Chapelcross	1	1959-1995	2965 GWd*	10 %*	0.27 tons
	2	1959-1995	2935 GWd*	10 %*	0.27 tons
	3	1959-1995	2905 GWd*	10 %*	0.27 tons
	4	1960-1995	2895 GWd*	10 %*	0.27 tons
Calder Hall and Chapelcross, total weapon-grade plutonium					3.35 tons
Weapon-grade plutonium production elsewhere (Magnox reactors)					0.30 tons
Total weapon-grade plutonium production, 1951 – 1995					4.0 tons

Table 5.6. Weapon-grade plutonium production, 1951–1995. Asterisks indicate authors' estimates. Effective production rates of weapons and non-weapons plutonium (kg/GWd) are based on neutronics calculations summarized in Appendix B. Assumed usage fractions for the Calder Hall and Chapelcross reactors are consistent with the

declared weapon-grade and non-weapon grade plutonium inventories. The United Kingdom could make public additional information about these usage fractions and cumulative energy output of all reactors to support the consistency and correctness of its declaration.

Civilian plutonium. The United Kingdom also has separated large quantities of reactor-grade plutonium produced both by its commercial power plants and its fleet of dual-use reactors (Calder Hall and Chapelcross) when they were operated in civilian-mode.³⁹³ The United Kingdom also has had contracts to reprocess the spent power-reactor fuel of several other European countries and of Japan.

The United Kingdom currently has two reprocessing plants at Sellafield. The B-205 plant reprocesses metal natural-uranium fuel from first-generation “Magnox” reactors, the last of which are to be shut down in 2012.³⁹⁴ THORP reprocesses oxide fuel from British AGR reactors and foreign LWR reactors.

As with other countries that embarked on reprocessing, the United Kingdom did so originally in the expectation that the plutonium would be used to provide initial cores for plutonium-breeder reactors. Unlike France and Japan, however, the United Kingdom has ceased research and development efforts into fast reactors and has not yet developed alternative disposition plans for its separated plutonium. Recently, however, the UK Government has begun a discussion of its plutonium-disposition options.³⁹⁵

Very little of the separated plutonium stockpiled in Sellafield has been fabricated into MOX and used as fuel in thermal reactors. As a consequence, the civilian stockpile of separated plutonium in the United Kingdom has been growing for decades and reached 112.1 tons in December 2009, including 27.7 tons of plutonium belonging to foreign customers (Figure 5.4).³⁹⁶ If existing contracts are fulfilled, this amount will increase to about 130 tons, including 30 tons of foreign-owned plutonium. “Because of the cumulative effect of several failures at the THORP reprocessing and supporting facilities with the resulting loss of throughput”, the September 2010 *Draft Strategy* of the United Kingdom’s Nuclear Decommissioning Authority pushed the completion of reprocessing activities at THORP back from 2010 to 2020.³⁹⁷ Even so, the *Draft Strategy* cautions that this new estimate “relies on the continued successful operation of the reprocessing infrastructure. As the supporting infrastructure nears the end of its life the completion of THORP reprocessing may continue to extend.”

The reprocessing of the remaining irradiated Magnox fuel will probably have to be completed because the fuel is metallic uranium that corrodes easily.³⁹⁸

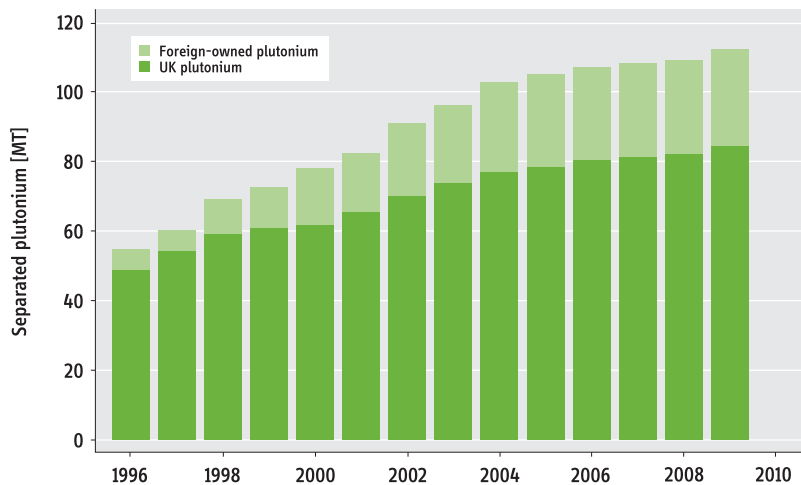


Figure 5.4. Separated civilian plutonium in the United Kingdom. Inventories are as of December 31 of the respective years. The United Kingdom’s plutonium stockpile has grown to 112 tons, of which

84 tons are domestic and about 28 tons have been separated from foreign-owned spent fuel under contract.



Figure 5.5. Plutonium store at Sellafield, UK. Sellafield in West Cumbria is the UK's center for reprocessing spent nuclear fuel from Britain's nuclear power stations and overseas customers. More than 100 tons of plutonium are stored at this site. *Credits: British Nuclear Fuels and IAEA ImageBank.*

Verifying the UK Fissile Material Declarations

For several years, the United Kingdom has been engaged in a joint initiative with Norway exploring warhead dismantlement verification options.³⁹⁹ Given its interest in this area, and given that the UK government has described its country as a “disarmament laboratory,”⁴⁰⁰ it would be natural to pursue steps towards developing the techniques and approaches needed to verify fissile material declarations and to use the UK HEU and plutonium production complexes, now undergoing decommissioning, as test beds to demonstrate the methods.

Whether it will be possible to verify the quantity of HEU produced at Capenhurst depends on the fate of the depleted uranium “tails.” If, at some point, the tails were used as feedstock for further enrichment—as apparently they may have been—verification would be effectively impossible. However, if the tails are still in storage (perhaps in the shell of the gaseous diffusion plant building along with the tails cylinders from LEU production), then verification might be feasible. As part of its ongoing efforts to clean up nuclear sites in the United Kingdom, the Nuclear Decommissioning Authority is planning to “deconvert uranium hexafluoride to a passive oxide form over a period of eight years” starting in about 2020.⁴⁰¹ This could provide an opportunity for international verification of the HEU output from Capenhurst through isotopic measurements on the uranium tails, if the tails are indeed available.⁴⁰² Verifying the HEU transferred from the United States to the United Kingdom is potentially more challenging. Since this material was exchanged for LEU produced in the A3 facility at Capenhurst, verifying the output of the A3 facility might help build confidence that the declared amounts are correct, if both governments decided to disclose this information. Moreover, the linkage between the UK and U.S. fissile material inventories and declarations could be advantageous from a verification perspective because it provides opportunities for some consistency checks.

The bulk of the UK consumption of military HEU was in naval reactors. According to a 2002 UK government report, 51 spent submarine reactor cores were in pool storage in the UK's Sellafield reprocessing complex at the time.⁴⁰³ This would appear to represent almost all, if not all, of the spent submarine fuel in the United Kingdom. With sufficient access to this fuel, its inventory of HEU could be verified and the amount of HEU consumed could be estimated—although, in practice, UK concerns about revealing secret fuel design information would be a complicating factor.⁴⁰⁴ The much smaller quantity of material used in military research reactors could be verified assuming that the spent fuel were available. As with other countries, however, it would be extremely difficult to independently verify the quantity of material used in nuclear tests.

Plutonium. From a verification perspective, the fact that all British military plutonium was produced in graphite-moderated reactors is a significant advantage because it would allow the application of established nuclear-archaeological methods. The graphite isotope-ratio method (GIRM) has been successfully tested on the Trawsfynydd Unit II Magnox reactor.⁴⁰⁵ All ten UK military production reactors have now been shut down. Under current decommissioning plans, their graphite moderators will be left intact for many years to come. The reactor structures, including their graphite moderator, are not due to be dismantled until the final phase of site clearance, which is currently scheduled to take place in 2041–2065 for Windscale, 2105–2117 for Calder Hall, and 2116–2128 for Chapelcross.⁴⁰⁶ Ongoing decommissioning work, however, should provide opportunities to take samples much sooner.

Conclusion

The United Kingdom's declarations about its fissile material stocks are consistent with publicly-available information about its production and use of military fissile materials. The United Kingdom could and should, however, make available much more information about its fissile materials holdings. This would enable a better understanding of its declarations and make those declarations more useful as a transparency measure than they are today. Specifically, with regard to highly enriched uranium, the United Kingdom could release information about the enrichment level, i.e., about the uranium-235 content in its stockpile, and specify the amount of material by category (fresh and irradiated, reserved for naval fuel, etc.). More generally, the UK fissile-material declarations of highly enriched uranium and plutonium so far focus exclusively on present inventories (based on total acquisitions minus removals) and reveal very little about how these inventories have been produced or otherwise acquired. The UK government could follow the U.S. example and prepare more comprehensive declarations that focus on historic acquisition of both its highly enriched uranium and plutonium. The secrecy surrounding the U.S./UK military collaboration, including swaps of fissile materials, is unnecessary and should be reconsidered. Finally, the UK should take the opportunity afforded by decommissioning its fissile material production facilities to enable international verification of its declarations.

6 France

French nuclear development started during World War II with the U.S. Manhattan project, in which a number of French scientists participated and played a significant role.⁴⁰⁷ Immediately after the war, France established its Atomic Energy Commission (*Commissariat à l'Énergie Atomique*, CEA) and began exploring the possibility of developing its own nuclear weapons program in the early 1950s. Most significantly, the CEA secretly established a “Nuclear Explosives Committee” (*Comité des Explosifs Nucléaires*, CEN) in November 1954, which immediately devised plans for acquiring source materials (namely uranium and heavy water) and constructing the first plutonium production reactors at Marcoule.⁴⁰⁸

The French nuclear establishment pursued nuclear weapons options before a clear political decision had been taken to acquire or even seriously consider them. In particular, France had already started production of weapons plutonium in mid-1955,⁴⁰⁹ and yet it was only after the Suez Crisis in late 1956 that the French government formulated a more explicit but still ambiguous position. Bertrand Goldschmidt quoted an agreement signed in the aftermath of the crisis under which “the CEA was to carry out preparatory research into atomic explosions and, should the government then decide to proceed further, preliminary research leading to the production of prototypes and the staging of tests.”⁴¹⁰ Only when General Charles De Gaulle returned to power in June 1958, first as Prime Minister and then as President, was the weapons program fully endorsed politically. Given the extensive preparations, it then proceeded rapidly. Only twenty months later, on 13 February 1960, France detonated its first nuclear weapon in the French-Algerian Sahara desert.

As a consequence of the CEA's organizational setup, France did not develop separate civilian and military facilities and fuel cycles. On the contrary, the 1973 CEA annual report points out that, “in order to limit costs, the CEA must adapt the production of military nuclear material to rapidly changing needs by taking advantage of technical progress and civilian programs, which themselves have greatly benefited from military programs.” As a result, estimating France's stockpile of military fissile materials is extremely difficult.

Large-scale production of plutonium for military purposes ceased in 1992.⁴¹¹ France announced the definitive halt of fissile material production for weapons purposes on 22 February 1996 and, by the end of June 1996, the gaseous diffusion enrichment plant at Pierrelatte stopped producing highly enriched uranium (HEU).⁴¹² In March

2008, French President Sarkozy announced that he had “decided to invite international experts to observe the dismantlement of our Pierrelatte and Marcoule military fissile material production facilities.”⁴¹³ A series of visits have taken place since then, but they apparently have not included any meaningful discussions about the possibility of verification of past production.

Based on the data available, we estimate France’s stockpile of military plutonium to be on the order of 6 ± 1 tons. The current HEU inventory is estimated to be 26 ± 6 tons of weapon-grade-equivalent HEU, but this figure is more uncertain because of a lack of public information about the capacity of the Pierrelatte enrichment plant.

France has so far been extremely reluctant to make public any information about its fissile-material stockpiles. France also has not officially declared any fissile material as excess for military purposes even though it must have significant amounts of both plutonium and HEU without apparent military use. Its nuclear arsenal is now half the size of the Cold War peak and France no longer uses HEU for naval-reactor fuel. The large stockpile of fissile material may be a result of France’s plan in the early 1980s to build a much larger nuclear arsenal for the 1990s and beyond—a plan that was never carried out.⁴¹⁴

Highly Enriched Uranium

France produced highly enriched uranium (HEU) at a dedicated enrichment complex near Pierrelatte at the Tricastin site (Figure 6.1). Construction of the Pierrelatte enrichment plant began in 1960. It consisted of four different buildings or units of decreasing size and capacity: the “low plant” (*usine basse*, UB) enriched up to 2%, the “middle plant” (*usine moyenne*, UM) up to 7%, the “high plant” (*usine haute*, UH) up to 25%, and the “very-high plant” (*usine très haute*, UTH) to 90% and higher, reportedly to 95%.⁴¹⁵ The first unit to come online was the low plant in 1964, and production of highly enriched uranium using all four units started in early 1967.⁴¹⁶ The total capacity of the plant has not been declared.

The Pierrelatte enrichment complex is separate from a second enrichment plant, the Eurodif plant, on the same site. Construction of the Eurodif plant started much later, in 1976, and its first production of LEU began in 1979. In 1982, the plant reached enrichment levels of 3.5% and its nominal capacity of 10.8 million SWU per year.⁴¹⁷

The Eurodif and Pierrelatte plants were not operated independently, however. Between 1979 and 1982, product from the Eurodif plant was transferred to the low and middle plants of Pierrelatte for further enrichment. In 1982, when the Eurodif plant finally achieved the capability to enrich uranium to 3.5%, the low and middle plants at Pierrelatte were shut down.⁴¹⁸ Thereafter, production of HEU at Pierrelatte used pre-enriched material that it received from the Eurodif plant. HEU production at Pierrelatte ended in late June 1996.

Before Eurodif came online, a fraction of Pierrelatte’s capacity and low-enriched product was used for power and naval reactor fuels, further complicating an estimate of the French HEU stockpile.

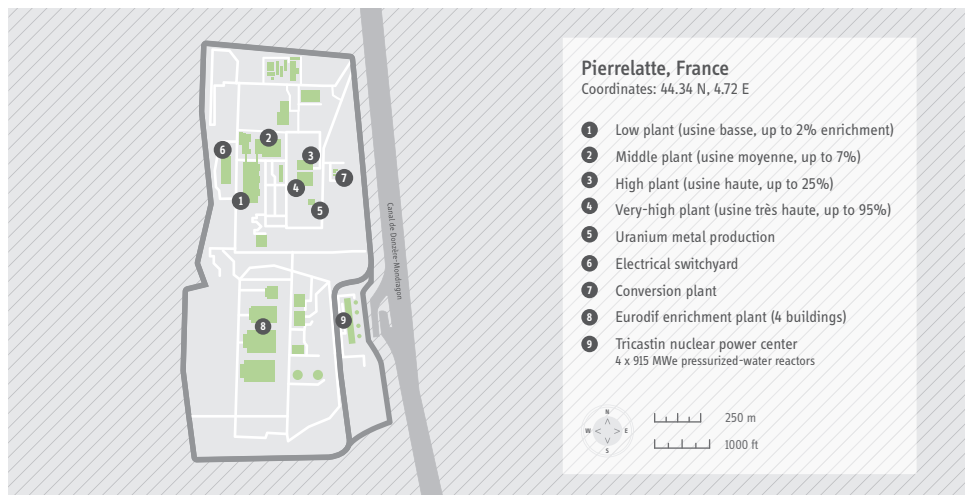


Figure 6.1. Pierrelatte gaseous diffusion enrichment plant (44.34 N, 4.72 E). Between 1967 and 1996, France produced an estimated 35 ± 5 tons of highly enriched uranium for weapons and naval fuel at the Pierrelatte plant. France, unlike the United States

and the United Kingdom, has not declared its HEU production. The safeguarded Eurodif enrichment plant on the same site will be shut down once a new centrifuge enrichment plant (George Besse II) comes online.

Estimating the Capacity of Pierrelatte. There is very little information available about the original capacity of the plant. In 1956, French officials set the military requirements of the weapons program at “a minimum of 600–700 kg of weapon-grade HEU per year,” equivalent to enrichment capacities between 120,000 and 200,000 SWU per year.⁴¹⁹ One 1996 publication authored by CEA officials quotes the capacity as “several 100,000 SWU per year.”⁴²⁰

Three approaches, using different types of information, offer means to constrain an estimate of Pierrelatte’s enrichment capacity:

- **Uranium-hexafluoride supply:** The dedicated conversion plant at Pierrelatte (SUCP, *Société des Usines Chimiques de Pierrelatte*, now Comurhex) was designed to produce 500 tons of uranium in uranium-hexafluoride (UF_6) per year.⁴²¹ For typical depletion levels of 0.3–0.4%, this feedstock would be sufficient to support a plant (producing weapon-grade uranium) with a capacity of 300,000–450,000 SWU per year.
- **Electricity consumption:** The electricity demand of Pierrelatte has been listed as 250 MW.⁴²² More modern gaseous diffusion plants require about 2500 kWh/SWU, but Pierrelatte was much less efficient: a specific energy demand of 3500–5000 kWh/SWU has been suggested for the plant,⁴²³ which would be equivalent to 440,000–600,000 SWU per year. If the relative performance of Pierrelatte barriers (20% compared to the Eurodif barriers)⁴²⁴ is used to scale electricity demand, then the capacity could have been on the order of 200,000 SWU per year.
- **Comparison with Capenhurst:** The CEA specifies the roofed footprint of the Pierrelatte plant as 120,000 m², which is consistent with available satellite imagery.⁴²⁵ This area is close to the footprint of the British gaseous diffusion plant at Capenhurst (53.265 N, –2.955 W). Similarly, the electricity demand of both plants was comparable: 250 MW versus 300 MW for Pierrelatte and Capenhurst, respectively. Capenhurst’s enrichment capacity was initially 100,000–150,000 SWU/yr and eventually increased to 400,000 SWU per year—and Pierrelatte’s capacity should therefore be in a similar range.⁴²⁶

Other indirect ways of estimating Pierrelatte's capacity yield comparable estimates.⁴²⁷ The stockpile estimate below assumes a value of 300,000 SWU per year as the lifetime average capacity of the Pierrelatte plant. At this capacity, the plant would have produced a total of 9 million SWU in its almost thirty years of operation, i.e., from early 1967 through mid-1996.⁴²⁸

The Pierrelatte plant was also used for the production of low-enriched uranium for civilian use and for naval fuel, in particular before Eurodif became fully operational in 1982. Albright et al. offer a detailed discussion estimating the total enrichment work that was dedicated for these purposes.⁴²⁹ They assign about one million SWU for civilian LEU and one million SWU for naval-core production, some of which used highly enriched fuel. Using these values, and based on the reference value of 9 million SWU for the cumulative enrichment work delivered by the plant, leaves 7 million SWU available for HEU production, which corresponds to about 35 ± 5 tons of weapon-grade HEU.

The main removals from this HEU stockpile were due to the operation of the two HEU-fueled Célestin tritium-production reactors, which were also used for plutonium and special-isotope production, and are discussed in more detail below. Each reactor was rated at 190 MW thermal and may have required about 145 kg of HEU fuel per year at a capacity factor of 75%.⁴³⁰ For about 20 years, both reactors operated simultaneously (1970–1990), while only one reactor was operating at a time between 1991 and final shutdown in 2009. Overall, this operational history corresponds to about 60 reactor years, requiring about 8.7 tons of HEU. Allowing for additional temporary outages, and the possibility of using recycled HEU fuel, lifetime HEU demand of the Célestin reactors could be on the order of 5–7 tons.

Nuclear weapon tests constitute the second major category of HEU removals. France conducted a total of 210 tests, which would have consumed 2–4 tons of HEU, assuming that the test devices contained 10–20 kg of HEU on average. France ended its nuclear testing program in January 1996, signed the Comprehensive Test Ban Treaty, and shut-down its test site in the South Pacific.



Figure 6.2. The first ingot of highly enriched uranium produced at Pierrelatte. This ingot was presented to General De Gaulle in 1967. HEU produced in Pierrelatte was used in the first test of a French thermonuclear weapon in August 1968. Material enriched to 25% for the core of “Le Redoutable” submarine was also delivered in 1968. *Source: Commissariat à l’Energie Atomique, reproduced in Daviet, 1993, op. cit.*

With the shutdown of the Célestin reactors in December 2009, France should no longer be consuming HEU on a large scale. Accordingly, it is estimated that France's remaining stock of (unirradiated) HEU should be on the order of 26 ± 6 tons.

France has declared its total stockpile of nuclear weapons in March 2008 as "fewer than 300" warheads.⁴³¹ These warheads are believed to have yields ranging from 100 to 300 kt.⁴³² This number of modern two-stage thermonuclear weapons would require about 3–6 tons of HEU. France could therefore declare the larger part of its military HEU stockpile as surplus today.

Finally, France has declared a stock of 4.85 tons of civilian HEU, including 3.27 tons of fresh HEU, as of December 2009.⁴³³ Some of this material may have been produced domestically, but a significant fraction is probably of U.S. and Russian origin for use in research-reactor fuel.

Plutonium

Large-scale plutonium production for military purposes in France started in 1956 and ceased in 1992. To support its weapons program, France built a series of dedicated production reactors at its Marcoule Site (Figure 6.3), but also used several civilian reactors owned and operated by *Electricité de France* (EDF) to produce additional weapon-grade plutonium (and tritium). With the exception of the fast-neutron reactor Phénix and the two Célestin heavy-water reactors, both located at Marcoule and discussed further below, all other reactors were graphite-moderated and gas-cooled (*Uranium Naturel Graphite Gaz*, UNGG) and are being decommissioned.⁴³⁴

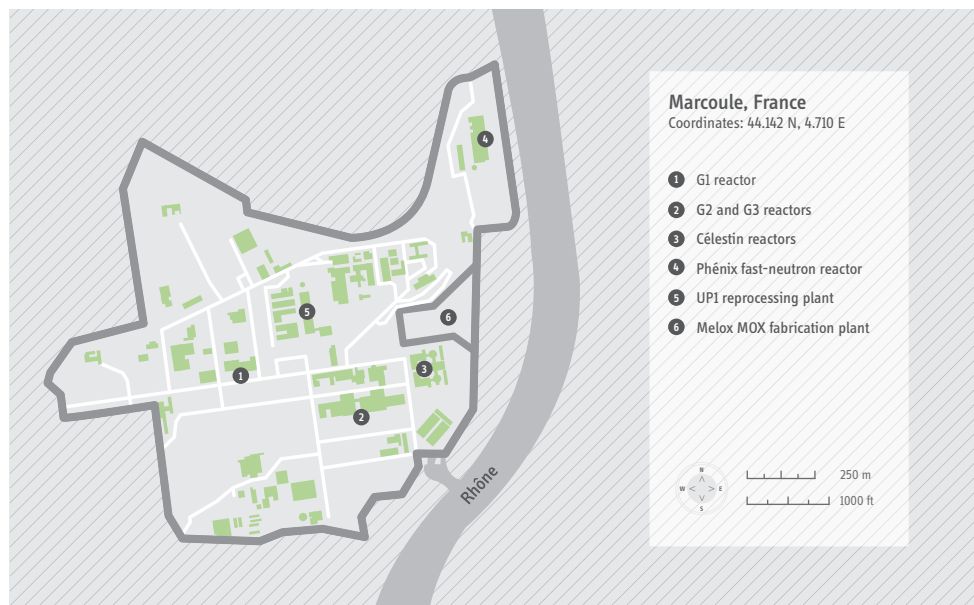


Figure 6.3. The Marcoule Site near Avignon in the South of France (44.142 N, 4.710 E). In addition to the military reprocessing plant UP1, the site hosted several reactors that were used for dedicated plutonium (G1, G2, G3, and Phénix) and tritium produc-

tion (two Célestin reactors, which also were used for plutonium and special-isotope production). With the shutdown of both Célestin reactors in December 2009, no operational production reactors remain at Marcoule. Map adapted from CEA drawing.

G1, G2, and G3 reactors. The first dedicated production reactor at Marcoule (G1) was air-cooled and had a thermal power of 46 MW.⁴³⁵ Routine production of weapons plutonium began in 1956 and ended in 1968. According to the 1962 CEA Annual Report, G1 had produced a total of 59.6 GW-days of fission heat by the end of 1962, including 12.4 GW-days produced in that year.⁴³⁶ Assuming the same annual output between 1963 and 1968,⁴³⁷ the energy generated in G1 during its lifetime would be on the order of 134 GW-days. Using an effective production rate of 0.95 grams of plutonium per MW-day (see Appendix B), the cumulative plutonium production in G1 is estimated to be 125–130 kg.⁴³⁸

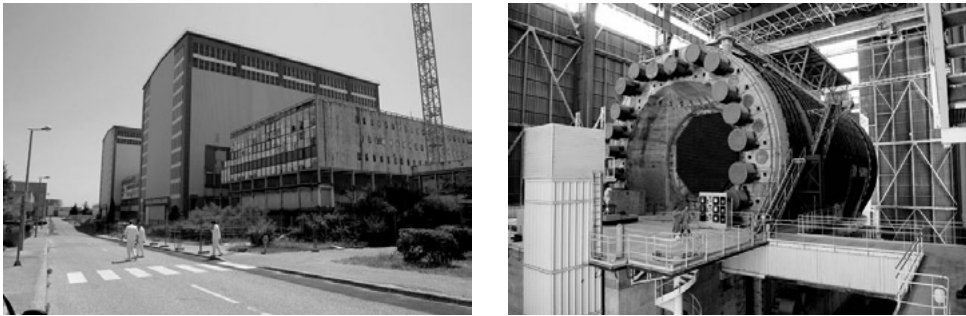


Figure 6.4. G2 and G3 reactors in June 2009 (left) and view of the G2 reactor unit (right). These reactors produced the bulk of the French weapons plutonium. Until the early 1970s, the target burnup of the fuel in these reactors was very low.

As a result, the bulk of French weapons plutonium is super-grade, with over 95 % plutonium-239. Both reactors are now being dismantled. Source: www.francetnp2010.fr

The most important plutonium-production facilities in the French nuclear weapons complex were the follow-on reactors G2 and G3 (Figure 6.4), which came online in 1958 and 1959. These two identical reactors were carbon-dioxide-cooled and reportedly achieved a power level of about 250 MW thermal each,⁴³⁹ or possibly more as discussed below. For extended periods of time, these reactors also produced electricity.⁴⁴⁰

In 1980, the National Atomic Energy Trade Union (SNPEA) of the French Democratic Confederation of Labor (CFDT) published a 500-page account of the French nuclear program: *Le dossier électronucléaire*.⁴⁴¹ The information included annual throughput and average fuel burnup for the production reactors G1, G2, and G3 through 1977. Combined with neutronics calculations, this data can be used to calculate annual plutonium production and the isotopics of the material produced in those years (Table 6.2 and Figure 6.5). The results indicate that these three reactors produced a combined total of 3.56 tons of weapons plutonium by 1977. This value is surprisingly high and implies that G2 and G3 were operated at 300–350 MW throughout the 1970s. Such a power level has not been confirmed by other sources, which quote a maximum of 260 MW,⁴⁴² but the information published by SNPEA/CFDT appears credible and is used for the stockpile estimate below.

According to the data published in the *dossier électronucléaire*, the average burnup of the fuel discharged from G2 and G3 increased continuously over time. After 1975, it had reached 1000 MWd/t, which—if correct—implies that these reactors were no longer producing weapon-grade material. It is possible that, by then, the mission of the reac-

tors had shifted, to the production of startup fuel for the C elestin and Ph enix reactors.⁴⁴³ Alternatively, newly produced non-weapon-grade plutonium could have been used for blending with super-grade plutonium produced until the mid-1960s.

To estimate post-1977 plutonium production in G2 and G3, we assume 70,000 MWd/yr per reactor and a plutonium production rate of 0.8 g/MWd, which corresponds to burnup levels on the order of 1000 MWd/t. Together, G2 (in 2 years) and G3 (in 6.5 years), may have developed an additional 595 GW-days and produced about 0.4–0.5 tons of plutonium, between 1978 and final shutdown.

In total, we estimate that G1, G2, and G3 produced about 4 tons of weapons plutonium with an average plutonium-239 content of about 94.9%. This estimate is significantly higher than previous estimates by Albright et al. (2.9 ± 0.2 tons) or historic estimates by the U.S. Central Intelligence Agency (“over 2.5 tons”).⁴⁴⁴ If sub-weapon-grade plutonium produced after 1975 was not added to the stockpile of weapons plutonium, and served a different purpose, then the total production of weapon-grade plutonium in the G-reactors would be about 3.2 tons instead (96% Pu-239). The CIA estimate however confirms the total throughput of about 10,000 tons of uranium.⁴⁴⁵

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
Throughput	190	130	320	620	640	760	850	820	960	730	890
Burnup	100	100	100	200	200	300	300	300	400	400	450
Eff. Pr. Rate	0.98	0.98	0.98	0.96	0.96	0.94	0.94	0.94	0.92	0.92	0.91
Pu TOT [kg]	18.5	12.6	31.1	116.7	120.5	210.1	235.0	226.7	347.5	264.3	359.4
Pu 239 [kg]	18.3	12.5	30.8	114.5	118.2	204.2	228.4	220.4	334.8	254.6	344.7
Pu 239 [%]	99.1%	99.1%	99.1%	98.1%	98.1%	97.2%	97.2%	97.2%	96.3%	96.3%	95.9%

	1970	1971	1972	1973	1974	1975	1976	1977	Total
Throughput	530	570	460	480	240	280	260	170	9900 tons
Burnup	450	450	500	600	700	800	1000	1200	about 400 MWd/t*
Eff. Pr. Rate	0.91	0.91	0.90	0.89	0.87	0.86	0.83	0.80	0.89 g/MWd*
Pu TOT [kg]	214.0	230.2	204.7	252.4	145.0	190.5	214.8	164.0	3558 kg
Pu 239 [kg]	205.3	220.8	195.5	238.8	136.0	177.1	196.4	147.4	3398 kg
Pu 239 [%]	95.9%	95.9%	95.5%	94.6%	93.8%	93.0%	91.4%	89.9%	95.5%*

Table 6.2. Annual plutonium production in G1, G2, and G3, 1959–1977. In 1980, the French Democratic Confederation of Labor (CFDT) published a detailed account of the French nuclear program. Using this data, it is estimated that the reactors had a combined production of 3.56 tons of plutonium with an average Pu-239 content of 95.5% (between 1959

and 1977). It has to be emphasized, however, that the data implies that G2 and G3 operated at 300–350 MW throughout the 1970s, i.e., about 20–40% above the power level reported elsewhere. Throughput is given in metric tons of heavy metal, burnup in MW-days/ton, and effective production rate in g/MW-day. Asterisks (*) indicate weighted averages.

Ph enix. The Marcoule site also hosted the fast-neutron reactor *Ph enix*, which went critical in mid-1973 and, until the late 1990s, operated at a power level of 250 MWe (563 MWt).⁴⁴⁶ It is widely believed that plutonium from this reactor has contributed to the French military stockpile of fissile material.⁴⁴⁷

Phénix achieved capacity factors of almost 60% in the late 1980s before it began experiencing more serious operational problems.⁴⁴⁸ Throughout the 1990s, the reactor was mostly shut down. We therefore assume that its military mission ended in 1990.⁴⁴⁹ The reactor restarted operation in 2003 at a reduced power level before its final shutdown in September 2009.⁴⁵⁰

To estimate the contribution of Phénix to the French stockpile of weapons plutonium, it is assumed that only the *surplus* plutonium—not the total amount of weapon-grade plutonium—extracted from the blankets was transferred to the weapons program.⁴⁵¹ The surplus fissile plutonium M_{Δ} produced in a breeder reactor can be calculated from the definition of breeding ratio $BR = 1 + M_{\Delta}/M_c$, where M_c is the total amount of fissile material consumed in the reactor during the same time period.⁴⁵² A fast-neutron reactor consumes about 1.07 grams of fissile material per megawatt-day thermal. Phénix generated an estimated 1.98 million MW-days until 1990 and therefore consumed about 2115 kg of fissile material. Combined with the reported breeding ratio of 1.16,⁴⁵³ these numbers can be used to estimate plutonium production available for weapons as about 340 kilograms.⁴⁵⁴

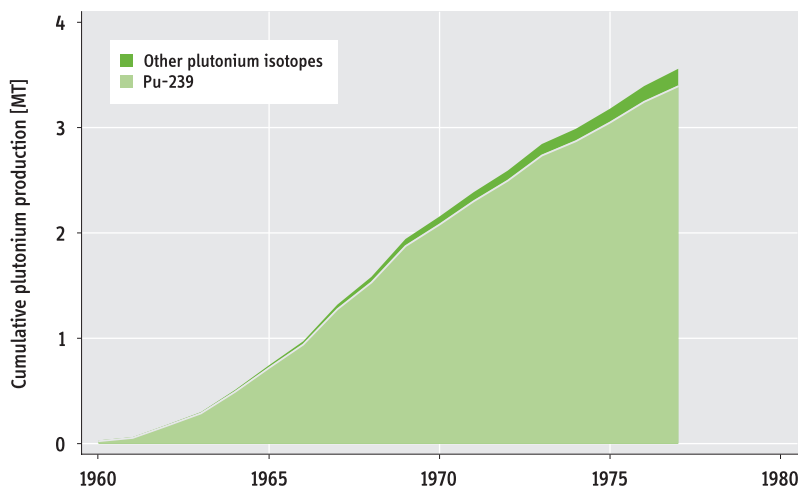


Figure 6.5. Cumulative plutonium production in G1, G2, and G3, up to 1977, according to the data published by the French Democratic Confederation of Labor (CFDT). France produced super-grade plutonium (95–98% Pu-239) until the early 1970s, after which the discharge burnup of fuel from G2 and G3 started to increase.

Célestin. France operated two dedicated tritium-production reactors at Marcoule. These identical 190 MW (thermal) reactors came online in 1967 and 1968. When France decided to discontinue production of plutonium in 1992, the Célestin reactors began to operate in an alternating mode, with only one operating at a time.⁴⁵⁵ Both reactors were finally shut down on 23 December 2009, without much prior notice or further explanation.⁴⁵⁶ Reportedly, future tritium production will be carried out in a new naval test reactor (RES), which is under construction on the Cadarache site (at 43.702 N, 5.758 E).⁴⁵⁷

By the 1970s, it had become clear that the two Célestin reactors would produce more tritium than needed for the French nuclear arsenal. The mission then shifted from tritium production to the production of plutonium and special radioisotopes for both

civilian and military purposes.⁴⁵⁸ To estimate the contribution of the Célestin reactors to the French stockpile of weapons plutonium, we assume that large-scale plutonium production began when G2 and G3 were being prepared for shutdown. Between 1982 and 1991, the Célestin reactors together may have developed about 1.14 million MW-days.⁴⁵⁹ Assuming an effective production rate for plutonium of 0.6–0.7 g/MW-day, which would still allow for concurrent tritium production,⁴⁶⁰ this corresponds to 700–800 kilograms of plutonium.

Dual-use Gas-Graphite Power Reactors. In addition to its dedicated military reactors, France has also used its fleet of gas-graphite power reactors to produce plutonium for military purposes. Albright, Walker, and Berkhout have a rather detailed discussion of these reactors and their operational history.⁴⁶¹ In principle, these reactors could have made a substantial contribution to the French stockpile of weapons plutonium.

The estimate summarized in Table 6.3 uses lifetime energy production values published by the IAEA for the six French and one French-supplied Spanish gas-graphite power reactors.⁴⁶² Even for limited military usage fractions, these gas-graphite reactors would have produced about 1.7 tons of weapons plutonium.⁴⁶³ The uncertainty in this estimate cannot be specified with confidence based on the available information: if this production strategy proved “inconvenient” (e.g. led to disagreements with the operator EDF)⁴⁶⁴ or proved ultimately unnecessary, the reactors may not have been used for production of weapons plutonium in any systematic way—and their net contribution to the stockpile of weapons plutonium could be small.

	Reactor	Operation	Total Energy Developed	Usage Fraction	Weapon-grade Plutonium	Uncertainty
Marcoule	G1	1956–1968	0134 GWd	100 %	3.0–4.0 tons	±10 %
	G2	1958–1980	4450 GWd	100 %		±10 %
	G3	1959–1984				
	Célestin-1	1967–2009	n/a	1140 GWd	0.75 tons	±20 %
	Célestin-2	1968–2009				
	Phénix	1973–2009	2372 GWd	80 %	0.35 tons	±20 %
Total weapon-grade plutonium production at Marcoule					4.6 ± 0.5 tons	

Chinon	A1	1962–1973	500 GWd	(50%)*	(0.20 tons)	large uncertainty depending on scope and extent of this strategy (if systematically pursued at all)
	A2	1965–1985	4150 GWd	(10%)*	(0.38 tons)	
	A3	1966–1990	5090 GWd	(10%)*	(0.46 tons)	
Saint Laurent	A1	1969–1990	7550 GWd	(¹ / ₃ of first core)	(0.13 tons)	
	A2	1971–1992	7820 GWd	(¹ / ₃ of first core)	(0.16 tons)	
Bugey	1	1972–1994	9220 GWd	(¹ / ₃ of first core)	(0.18 tons)	
Vandellos/Spain	1	1972–1990	8940 GWd	(¹ / ₃ of first core)	(0.17 tons)	
Potential weapon-grade plutonium production at other sites					up to 1.7 tons	

Table 6.3. Production of weapons plutonium in France. Estimating France’s historic weapons plutonium production is difficult because a fleet of different reactor-types have been available for

that purpose, including dual-use power reactors. In the early 1980s, France was planning to buildup its nuclear forces and may have considered these options.⁴⁶⁵ *Estimate.

Overall, cumulative production of weapons plutonium at Marcoule adds up to 4.6 ± 0.5 tons of plutonium. The total stockpile could be significantly higher if the gas-graphite power reactors played a significant role in the production program. In that case, the amount produced could have been significantly over 6 tons. We assume here a value of 7 ± 1 tons as the cumulative production of weapons plutonium.

Between 1960 and 1996, France conducted 210 nuclear weapon tests, which would have consumed about one ton of plutonium. The estimate for the current stockpile is therefore about 6 ± 1 tons. This is consistent with previous assessments, but with substantially different contributions from the different production reactors. This estimate is broadly in line with a leaked U.S. Department of Energy estimate published in 1999 that France had a stockpile of 6–7 tons of weapon-grade plutonium.⁴⁶⁶ Today, assuming an arsenal of 300 warheads, France uses about 1.5 tons of plutonium for military purposes.⁴⁶⁷ If the production estimate presented here is correct, France could declare almost 70% of its stockpile of weapon-grade plutonium as excess to military requirements.

Civilian Plutonium Separation and Use

The French nuclear establishment carried out large-scale separation of plutonium for military and civilian purposes between 1958 and 1997 at the UP1 plant at the military Marcoule site. Reprocessing of gas-graphite reactor fuel started at UP2 at La Hague in Normandy in 1966 and ended in 1987. Around 4900 tons of metal fuel were reprocessed during this period. In 1974, the CEA also started reprocessing at UP1 fuel from EDF's gas-graphite reactors, including fuel with higher burnups than needed for military uses. UP1 stopped the separation of plutonium for military purposes in 1993. By 30 September 1997, when reprocessing at Marcoule ended, a total of 13,330 tons of gas-graphite fuel had been reprocessed at UP1. In total, CEA/COGEMA reprocessed over 18,000 tons of spent gas-graphite fuel at UP1 and UP2, including 1913 tons of fuel from the Spanish Vandellós reactor.⁴⁶⁸ The La Hague UP2 plant started reprocessing oxide fuel from light-water reactors (LWR) in 1976. A first major extension, called UP3, financed mainly through contracts with foreign customers, started operating in 1989 and a second enlargement, named UP2-800, followed in 1994. The nominal capacity of the La Hague site was thus increased by more than a factor of four to 1700 tons per year (Figure 6.6).



Figure 6.6. The La Hague reprocessing site. The 700-acre site includes the two reprocessing plants UP2-800 and UP3, a plutonium store, four large

spent fuel storage pools, and multiple storage facilities for low, medium and high level wastes. *Source: IAEA ImageBank.*

Between 1976 and the end of 2009 a total of over 25,000 tons of LWR fuel were put through La Hague. Fuel of French, German, and Japanese origin dominated the throughput (59%, 22%, and 12%, respectively), but additional smaller contracts existed with Belgium, Italy, the Netherlands, and Switzerland.⁴⁶⁹ In 2005, Areva-NC added a head-end for the processing of research reactor fuel, and minor contracts to process such fuels have been signed with Australian, Belgian and French clients.

The reason for the early, massive engagement of foreign utilities in the build-up of the French plutonium infrastructure was the planning in the 1970s for the large-scale introduction of fast breeder reactors—especially in Europe. This vision had entirely dissipated by the middle of the 1980s, however, even before France’s Superphénix—the first and only commercial-size plutonium-fueled fast breeder reactor ever built—had started operating in 1986. By that time, all the other European nations had ended public spending for fast breeders.⁴⁷⁰ French nuclear planners considered the political price too high to abandon the extension of the La Hague plutonium separation facilities.

In the absence of a successful breeder reactor program, the operation of the four-fold larger plutonium production capacity at La Hague inevitably would rapidly lead to a large stockpile of separated plutonium. To absorb the French power-reactor plutonium that was still being separated at Marcoule and increasingly also at the La Hague facilities, in 1987 France launched a LWR MOX program.

Plutonium-use in French light water power reactors began with the introduction of a third of a core loading of MOX fuel into one EDF 900-MWe reactor. In 2010, twenty-two 900-MWe reactors are licensed to be 30-percent fueled with MOX. Nevertheless, the EDF stockpile of separated plutonium grew from less than one ton in 1988, to 55.9 tons in 2009 (see Figure 6.7).

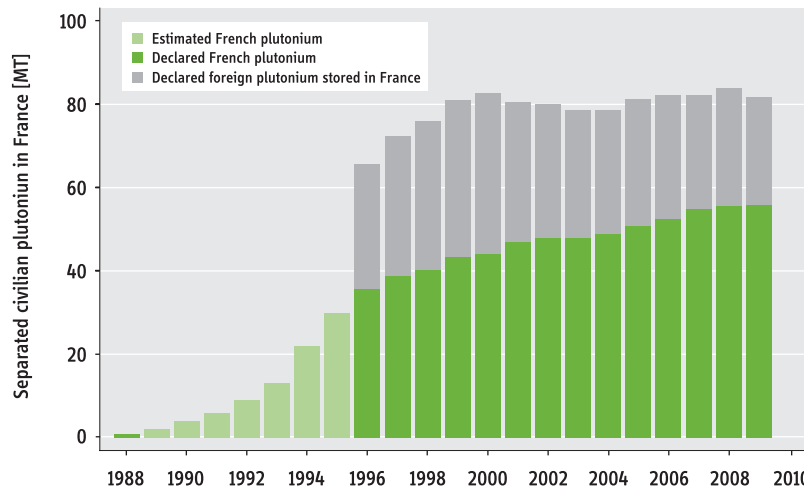


Figure 6.7. Growth of France’s stockpile of separated plutonium from December 1988 to 2009. Sources: *French Declarations to the IAEA 1997–2010; WISE-Paris.*

With the phasing out of reprocessing of foreign fuel and the approaching end of reuse of separated plutonium belonging to Germany and other foreign customers, the amount of foreign plutonium stored in France decreased between 2000 and 2009 from 38.5 to

25.9 tons (see Figure 6.7). The remaining material is mostly owned by Japan, whose MOX plans have been delayed for a decade by public opposition. As of the end of 2009, there was only 3.4 tons of foreign fuel left in France for reprocessing (see Table 6A.1).

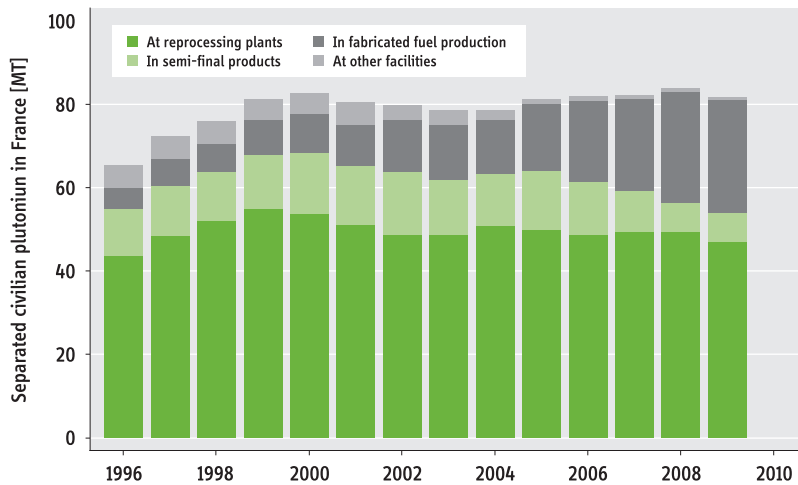


Figure 6.8. Unirradiated plutonium in France by location and form. Sources: French Declarations to the IAEA 1997–2010.

The distribution of the physical form of the separated plutonium held in France has changed significantly over time. In 1999 the amount of separated plutonium held at reprocessing plants reached a maximum with 55 tons, decreasing to about 47 tons in 2009. The amount of separated plutonium in MOX fabrication facilities (as oxide or in semi-final products like fuel pellets) reached a maximum in 2002 of 15 tons and was reduced by more than half to about 7 tons in 2008. The decreases were offset, however, by a continuous increase of unirradiated plutonium in fresh MOX or “other fabricated products,” which increased from 1.8 tons in 1994 to 27.2 tons in 2009 (Figure 6.8).

As of the end of 2009, 60 tons of separated plutonium was stored at La Hague of which about 37 tons (62%) belonged to France. France and Japan, together owned 54 tons or 90% of the separated plutonium stored at La Hague (Table 6A.2).

A significant share of France’s separated plutonium in the category “other fabricated products” is present in the spent-fuel pools at La Hague. As of the end of 2001, a total of 98 tons of MOX scrap assemblies with a plutonium content of at least 5% were stored at La Hague.⁴⁷¹ No updates of this information have been made publicly available.⁴⁷²

EDF has shifted its strategy towards a “MOX-parity”, aiming at matching the amount of plutonium it uses to the quantity separated annually. With annual spent fuel reprocessing at La Hague increasing from some 850 tons to 1050 tons and MOX fuel use planned to reach 120 tons—both as of 2010—it expected that use will finally match supply. It remains unclear how and in what timeframe the substantial backlog of separated plutonium is supposed to be absorbed.

Appendix 6A. Civilian Plutonium Stocks in France

	Reprocessed	To Be Reprocessed	Period of Processing
Germany	5,483.00 MT	0	1977–2008
Netherlands	326.00 MT	0	1979–2006
Japan	2,944.00 MT	0	1982–1999
Belgium (LWR)	671.00 MT	0	1980–2001
Switzerland	771.00 MT	0.15 MT	1976–2011
Belgium (RR)	0.25 MT	0.21 MT	2012
Australia (RR)	0.15 MT	0.13 MT	2012
Italy	160.30 MT	2.90 MT	2014
Total	9,843.70 MT	3.40 MT	(1976–2014)

Table 6A.1. Foreign spent fuel reprocessing 1978–2014. Source: Areva NC, *Traitement des Combustibles Usés Provenant de l'Étranger Dans les*

Installations d'Areva NC de La Hague, Rapport 2009, 2010.

Country	Quantity (tHM)	Share (in %)
France	37.14	61.9%
Japan	16.86	28.1%
Italy	5.70	9.5%
Netherlands	0.30	0.5%
Australia	0	< 0.1%
Belgium	0	< 0.1%
Germany	0	0
Total	60.00	100.0

Table 6A.2. Plutonium stored at La Hague as of 31 December 2009.

7 China

China launched its nuclear-weapon program in the mid-1950s and began to construct fissile-material production facilities with assistance from the Soviet Union in the late 1950s. Highly enriched uranium (HEU) production began in 1964 and plutonium production in 1966. In the late 1960s, China began to construct a second set of plutonium and HEU production facilities in Southwest China, far from the coast and from the border with the Soviet Union, which came into operation in the 1970s. This “Third Line” program was intended to provide China with backup facilities in case the first production facilities were destroyed.

China has kept information about its stocks of fissile materials and nuclear weapons secret. While China has not declared officially that it has ended HEU and plutonium production for weapons, it is believed to have done so after Beijing began to give priority to its economic and political reforms in 1978. China moved to reduce military HEU and plutonium production, switching some facilities to civilian purposes and closing others, finally stopping production of HEU in 1987 and of plutonium by about 1990.

Table 7.1 summarizes the start-up and shut-down dates for China’s military uranium enrichment and plutonium production facilities.

Facility	Start up	Status
Enrichment plants		
Lanzhou gaseous diffusion plant	1964	Stopped HEU production in 1979
Heping gaseous diffusion plant	1975	Stopped HEU production in 1987
Plutonium production reactors		
Jiuquan reactor	1966	Shutdown in 1984
Guangyuan reactor	1973	Shutdown in 1989 (?)
Reprocessing facilities		
Jiuquan intermediate pilot plant	1968	Shutdown in early 1970s
Jiuquan reprocessing plant	1970	Shutdown around 1984
Guangyuan reprocessing plant	1976	Shutdown around 1990

Table 7.1. Operating history of China’s military fissile-material-production facilities.

Without knowledge of the operating history and power of China's plutonium-production reactors and the capacities of its uranium enrichment plants, any estimates of China's fissile material stocks will necessarily have great uncertainties.

Based on new public information, the revised estimates reported in this chapter are that China produced 20 ± 4 tons of HEU, 2 ± 0.5 tons of plutonium and currently has stockpiles of about 16 ± 4 tons of HEU and 1.8 ± 0.5 tons of plutonium available for weapons.⁴⁷³ The values for China's fissile material production are at the low end of most previous independent estimates, which range from 17–26 tons for HEU and 2.1–6.6 tons for plutonium.⁴⁷⁴ The new plutonium estimate is consistent, however, with a U.S. Department of Energy assessment from 1999 that China had a stockpile of 1.7–2.8 tons of plutonium for weapons.⁴⁷⁵ Arguments supporting a lower estimate for China's fissile material stockpile and its implications can be found in the chapter on China in the 2008 IPFM volume of country perspectives on a Fissile Material (Cutoff) Treaty.⁴⁷⁶

Highly Enriched Uranium

China has produced highly enriched uranium (HEU) for weapons in two complexes:

- The Lanzhou gaseous diffusion plant (Plant 504), and
- The Heping gaseous diffusion plant (Plant 814), a "Third Line" facility

China used these enrichment plants also to produce HEU for its research reactors and LEU for naval reactors. Today, China operates two centrifuge enrichment plants at Hanzhong (Shaanxi province), and at Lanzhou (Gansu province) to produce LEU for civilian purposes. There are also reports of a new plant using Chinese centrifuges near Lanzhou that began operating in 2010.⁴⁷⁷

Lanzhou Gaseous Diffusion Plant. In 1958, with help from the Soviet Union, China started the construction of a gaseous diffusion plant on a bank of the Yellow River in Lanzhou, in Gansu province (Figure 7.1). Two years later, the Soviet Union withdrew its technical experts.⁴⁷⁸ The Lanzhou plant produced its first weapon-grade HEU in January 1964 and, over the next few months, enough for China's first nuclear test in October 1964.

There were early efforts by the United States to assess the enrichment capacity of the Lanzhou plant using aerial and satellite imagery, but it proved to be difficult to make reliable estimates. The United States used the U-2 spy plane to photograph the Lanzhou site in September 1959.⁴⁷⁹ Progress was revealed by further U-2 photos taken in March and June 1963. U.S. intelligence believed, however, that the processing building was large enough to contain only about 1800 compressor stages, substantially less than the 4000 stages required to produce weapon-grade materials.⁴⁸⁰ Moreover, the U.S. government worked on the presumption that plutonium, not uranium, would be the fissile material in China's first bomb.⁴⁸¹ It was therefore a surprise when analysis of residues in the atmosphere from China's first nuclear explosion identified it as an HEU-based bomb.⁴⁸² In December 1964, a U-2 flight equipped with infrared detection systems confirmed that the Lanzhou plant was indeed operating.⁴⁸³

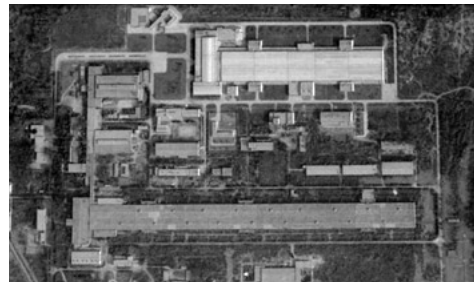


Figure 7.1 The Lanzhou gaseous diffusion plant in May 1966 and in January 2005 (Coordinates: 36.1507 N, 103.5184 E). The new building visible in the more recent imagery could be the Lanzhou centrifuge

enrichment plant (Lanzhou 2), which began operation in 2005 and is listed with a capacity of 500 tSWU/yr. Sources: KH-7 Mission 4028 (left)⁴⁸⁴ and Google Earth (right).

In 1972, the U.S. Defense Intelligence Agency estimated that Lanzhou was producing 150–330 kg per year of HEU.⁴⁸⁵ This production rate is equivalent to 23,000–51,000 SWU per year at a tails assay of 0.5 per cent, or 29,000–64,000 SWU per year for 0.3 per cent tails.⁴⁸⁶

China's official nuclear history notes that the capacity of the Lanzhou facility was increased after it started operating, including by the use of a new type of separation membrane.⁴⁸⁷ Chinese media reports suggest the design capacity of the Lanzhou plant doubled by the end of the 1970s.⁴⁸⁸ Western sources indicate Lanzhou had achieved a capacity of 180,000 SWU per year by 1978.⁴⁸⁹

In 1978, China adopted a policy of economic reform. As part of this shift, it appears that, in 1980, Lanzhou stopped production of HEU and shifted to making LEU for civilian power reactors.⁴⁹⁰ In 1981, China began to supply LEU for the international market.⁴⁹¹ Previous estimates of China's HEU production generally have assumed the Lanzhou plant stopped HEU production for weapons in 1987.

Enrichment capacity at Lanzhou increased further during the 1980s, and it was reported in 1989 that the plant was operating at a capacity of about 300,000 SWU per year.⁴⁹² In 1998, however, it was decided to decommission the Lanzhou facility as part of a project aimed at replacing China's gaseous diffusion technology with centrifuge enrichment.⁴⁹³ A new centrifuge enrichment facility provided by Russia with a capacity of 0.5 million SWU per year began operation in 2001. By agreement with Russia, this plant produces only LEU for non-weapons purposes.⁴⁹⁴

Based on the above information, it is estimated that operating continuously at full capacity up to 1980, the Lanzhou plant would have produced 1.1 million SWU.⁴⁹⁵ This would be sufficient to produce about 6 tons of weapon-grade (90%-enriched) HEU. It is assumed that, thereafter, the Lanzhou plant produced LEU until 1987, when it ended operations.

Heping Gaseous Diffusion Plant. China built its second gaseous diffusion plant as part of its “Third Line” defense program. The Heping facility (Coordinates: 29.2354 N, 103.0618 E, also known as Plant 814) is located in the Heping Yizu area of Jinkouhe, in Sichuan province. It is believed to have started operating around 1975 and stopped HEU production in 1987.⁴⁹⁶ In the late 1980s, based on China’s “military-to-civilian conversion” policy, this plant was converted to other purposes, including fluorine production.

Given the paucity of public information available about this plant, there is little basis for more than a rough estimate of its HEU production. Based on satellite imagery the Heping plant had a slightly larger processing building than that of the Lanzhou facility. It is assumed the original capacity of the Heping plant was not significantly larger than that of the Lanzhou plant in 1975, i.e., about 90,000 SWU per year.⁴⁹⁷ This reflects the fact that, when Beijing decided to build the Third Line fissile-material production facilities, its first production facilities were just coming into operation and there was no reason for Beijing to build significantly larger backup facilities than those that were being backed up.⁴⁹⁸ It also is assumed that, like the Lanzhou plant, the Heping plant roughly doubled its capacity by the end of the 1970s. This is consistent with a report that the output of Heping plant before it shut down was 200,000–250,000 SWU per year.⁴⁹⁹

In this scenario, operating continuously at full capacity up to 1987, the Heping plant would have produced 2.7 million SWU, sufficient to produce about 14 tons of HEU.⁵⁰⁰

Together, the Lanzhou and Heping gaseous diffusion plants therefore would have produced roughly 3.8 million SWU, enough to make about 20 tons of weapon-grade HEU. This estimate assumes that China used only natural uranium feed for its enrichment program. It is possible that some of China’s HEU was produced from reprocessed uranium recovered from its plutonium production reactors.⁵⁰¹ Enriching reprocessed uranium, which contains less uranium-235 than natural uranium, would have required more SWUs per kilogram of HEU produced but the effect would not have been large.⁵⁰²

Other demands for uranium enrichment. In addition to producing HEU for nuclear-weapons, China’s gaseous diffusion plants also would have supplied enriched uranium for research and naval reactors.

Research reactor fuel. China has had two HEU-fueled research reactors: the 125 MWt High Flux Experimental and Test Reactor (HFETR) and the 5 MWt Min Jiang Test Reactor (MJTR).⁵⁰³ The HFETR reached criticality in 1979 and converted to LEU fuel in 2007. The MJTR arrived at criticality in 1991 and converted to LEU fuel in 2007. Before conversion, the two reactors would have used together about 1 ton of HEU.⁵⁰⁴ This would correspond to about 200,000 SWU at a tails assay of 0.3 per cent.

Russia has supplied China with some HEU fuel for research reactors.⁵⁰⁵ China, as of 2003 was estimated to have about 1 ton of civil HEU enriched by itself and by Russia.⁵⁰⁶ This civilian HEU supply would have been sufficient to supply China’s research reactors. China’s use of HEU for research reactors in the future may be insignificant.

China’s Experimental Fast Reactor (CEFR), which reached criticality in July 2010, has a first loading of almost 240 kg of HEU (enriched to 64.4 percent uranium-235), provided by Russia.⁵⁰⁷ The CEFR will use plutonium-uranium fuel in later loadings, as will China’s planned future fast reactors.

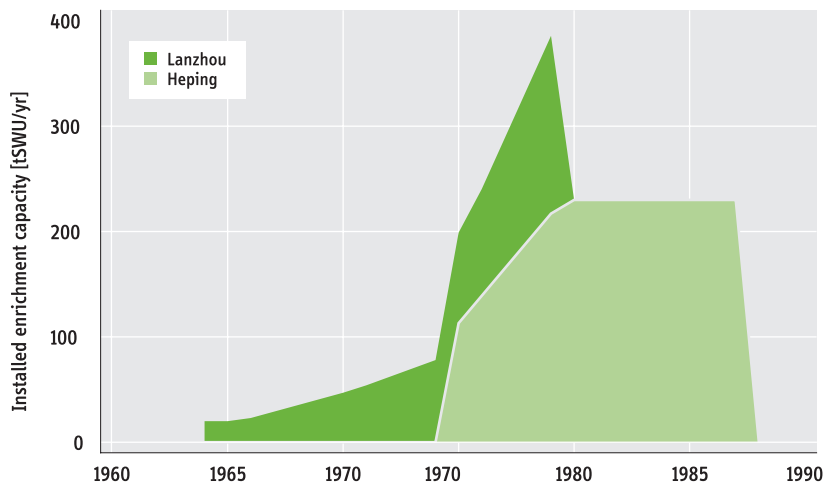


Figure 7.2. Reconstructed history of total enrichment work done by the Lanzhou and Heping GDPs during the periods when they were producing HEU.

Naval reactor fuel. China launched a nuclear-powered submarine program in 1958. Desiring that these submarines not compete with the nuclear-weapon program for HEU, China decided to use less than 5% enriched LEU fuel for its naval reactors.⁵⁰⁸ A land-based prototype reactor began tests in May 1970, becoming fully operational in July 1970. The whole-life test of the reactor core ended in December 1979 and the spent fuel was discharged in 1981.⁵⁰⁹

China's first Type 091 Han-class nuclear-powered attack submarine entered service in 1974, and was retired in 2000. It is reported that China currently has four Han-class and two new Type 093 Shang-class nuclear-powered attack submarines in service.⁵¹⁰ The first nuclear-powered strategic ballistic missile submarine (SSBN, Type 092 Xia-class) was launched in 1982 and went on patrol in 1986. One Xia-class SSBN is operational today but it has never gone on patrol.⁵¹¹

Each of these submarines has one 90 MWt pressurized-water reactor.⁵¹² If the reactor cores are designed to have lifetimes of 10 years, it is estimated that each fuel load of China's naval reactors would require about 2.3 tons of 5% LEU.⁵¹³ The Lanzhou and/or Heping plants would have needed to produce LEU for about 10 naval reactor cores before 1980 to meet the demand for one core for the land-based prototype reactor, five cores for the Han-class submarines, one core for the Xia-class SSBN, and a few spares.⁵¹⁴ This would have reduced the SWU available for making HEU for weapons by about 170,000 SWUs at a tails assay of 0.3 per cent.⁵¹⁵

Altogether, China's two gaseous diffusion plants would have supplied roughly 360,000 SWU of enriched uranium for non-weapon purposes. This would have left an estimated 3.4 million SWU available for producing weapons HEU, sufficient to produce about 17 tons of weapon-grade material.

Losses and uses of HEU produced for weapons. Some of the HEU produced for weapons was consumed in nuclear weapon tests and process losses.

Nuclear tests. China conducted 45 nuclear-weapon tests.⁵¹⁶ The first seven were carried out before China had plutonium available for weapons and presumably all were HEU weapons, including the 3-megaton thermonuclear weapon test in June 1967. About 200 kg of weapon-grade uranium could have been consumed in these seven tests.⁵¹⁷ In later tests China may have moved to more compact plutonium-based pits for fission weapons and as primaries for two-stage thermonuclear weapons. Assuming that tests with yields significantly above 20 kT were thermonuclear weapons with secondaries containing weapon-grade HEU, then about 550 kg of HEU would have been consumed in these thermonuclear tests.⁵¹⁸ Altogether, nuclear weapons testing may have consumed about 750 kg of HEU or the equivalent of 0.15 million SWU.

Process losses. We assume process losses of about 1 percent, somewhat larger than those reported for the U.S. uranium enrichment program. In this case, about 200 kg of weapon-grade uranium would have been lost during production.⁵¹⁹

Other. China may have used tens of kilograms of HEU to fuel a tritium-production reactor—say 10,000 SWU.

A. Q. Khan has claimed that China provided 50 kg of weapon-grade HEU to Pakistan in 1982 and 5 tons of LEU enriched to 3%, but many Chinese experts doubt this.⁵²⁰ Table 7.1 summarizes the above estimates.

Activity	Millions of SWUs produced or consumed
Enrichment work produced when China was producing HEU	3.8
Enrichment work used for non-weapon purposes	
Research-reactor fuel	-0.20
Naval-reactor fuel	-0.17
Tritium-production-reactor fuel	-0.01
Process losses	-0.04
Nuclear tests	-0.15
Provided to Pakistan (?)	-0.01
Total remaining available for weapons HEU	3.2

Table 7.1. China's estimated production and use of enrichment work.

Military inventory of HEU. It is estimated that China could have a current inventory of about 16 ± 4 tons of HEU for weapons.⁵²¹ This is at the low end of previous estimates.⁵²²

Plutonium

China has produced plutonium for weapons at two sites:

1. Jiuquan Atomic Energy Complex (also referred as Plant 404) near Yumen in Gansu province. This site includes China's first plutonium reactor, the associated reprocessing facilities; and
2. Guangyuan plutonium production complex (Plant 821), located at Guangyuan in Sichuan province. This "Third Line" site included a plutonium reactor and reprocessing facility.

It is believed that production of plutonium for weapons has ended at both sites. China is interested, however, in reprocessing civilian power-reactor fuel and has built a pilot commercial reprocessing plant. As of late 2010, the facility has not started normal operation.

Jiuquan complex. The Jiuquan plutonium production reactor is a graphite-moderated, water-cooled reactor. It was designed in 1958 with Soviet assistance, and construction started in March 1960. China had not, however, received the key components of the reactor when the Soviet Union ended its support in August 1960.⁵²³ Completion of the reactor project was significantly delayed as Beijing decided to concentrate on completing the Lanzhou enrichment plant. Work resumed on the Jiuquan reactor after the enrichment plant went into operation in 1964. The reactor went critical in October 1966 and went into full operation in 1967.⁵²⁴



Figure 7.3. The Jiuquan plutonium production reactor, 1 September 2007 (Coordinates: 40.2231 N, 97.3559 E). Credit: Google Earth.

During its early years, the reactor encountered a number of technical problems and was frequently shutdown. During the late 1960s and early 1970s, its operation also was affected by the political turmoil of the Cultural Revolution.⁵²⁵ After 1970, however, the reactor ran without an unscheduled shutdown until it was shut down in 1974 for most of the year for tests, repair and maintenance.⁵²⁶

The reactor reached its design power by the first half of 1975.⁵²⁷ Thereafter, the power and performance of the reactor were increased significantly.⁵²⁸ As a result of these improvements, by the end of the 1970s, the plutonium production rate had increased 20% (realizing the “1.2 reactor” goal).⁵²⁹ The reactor was most likely shut down in 1984.⁵³⁰

Construction of a pilot reprocessing plant near the reactor site started in 1965 and the plant began operation in September 1968. The plant had two production lines that could together process 0.4 tons of spent fuel per day and operated over 250 days a year.⁵³¹ This capacity could separate about 70 kg of weapon-grade plutonium per year.⁵³² It separated the plutonium for China’s first test of a plutonium-based weapon, which occurred in December 1968.⁵³³ The pilot reprocessing plant stopped plutonium separation when a larger plant, also built near the reactor site, began operating in April 1970.

Power of the reactor. One approach to estimating the Jiuquan reactor’s power is through the size of its six cooling towers. Based on commercial satellite images, it appears that

the towers have a top diameter of about 30 meters, which suggests a design power of about 14–140 MWt per tower.⁵³⁴ Assuming that 85% of the heat was dissipated through the cooling towers and that two towers were kept on standby, the reactor power would be between 70 MWt and 660 MWt.⁵³⁵ Thus, the cooling tower sizes do not provide the basis of an accurate estimate but do, at least, provide a consistency check for other estimates.

Since Russia helped design the Jiuquan reactor in the late 1950s, the power of Russia's graphite-moderated plutonium production reactors at Mayak at that time may be relevant. Russia's first production reactor, the A reactor, had an initial design thermal power of 100 MWt and, in the period 1950–1954 was operating at about 180 MWt, while subsequent reactors at Mayak were designed with a capacity of 300 MWt (Chapter 3). This suggests China's Jiuquan reactor could have had an initial design power in the range of 200–300 MWt.

Newly declassified information about the unfinished Chinese plutonium-production reactors (Plant 816) at Fuling, in Sichuan province, also provides a way to constrain estimates of the power of the Jiuquan reactor. Beijing decided in 1966 to build three 80 MWt graphite-moderated, water-cooled plutonium-production reactors and associated reprocessing facilities in caves under a mountain near Fuling as a "Third Line" project.⁵³⁶ If the goal of the project was to build a back-up capacity to the Jiuquan reactor, the planned total power of 240 MWt at the new site probably matched that of the Jiuquan reactor.

Construction started on the Fuling reactors in February 1967. In 1969, given the very slow progress of the work in the mined-out caverns and increasing tensions with the Soviet Union, Beijing decided to meet its urgent need to have a backup for the Jiuquan complex by quickly building a plutonium-production complex at Guangyuan (see below). In 1984, with the Guangyuan reactor operating, and a more benign international security situation, Beijing decided to end Project 816 at Fuling. By then about 85 percent of the civil engineering work had been finished and over 60 percent of the plant equipment had been installed. None of the reactors were ever loaded with fuel, however. The plant was converted to fertilizer production, the project was declassified in 2003, and part of the site was opened as a domestic tourist attraction in 2010 (Figure 7.4).



Figure 7.4. Left: Entrance to the Fuling nuclear complex. The sign in Chinese above the tunnel reads "816 Underground Nuclear Project." Right: Project 816 reactor control room. This image shows

core arrangements for three reactors: two to the left and one to the right of the circular display. Source: www.chinadaily.com.cn/cndy/2010-06/22/content_10000111.htm.

The history of the Jiuquan reactor and a reasonable set of assumptions about its increase in power from an initial design value of 250 MWt and in its capacity factor indicate how the reactor could have met the goal of the “1.2 reactor.” This suggests the Jiuquan reactor could have produced a total of 1050 GWt-days of fission energy and generated a total of about 0.9 tons of weapon-grade plutonium.⁵³⁷

Guangyuan complex. As already noted, in 1968, given the slow pace of work on the underground reactor complex at Fuling, Beijing decided to build an alternative “Third Line” plutonium production complex, Plant 821 at Guangyuan, also in Sichuan province. Like the Jiuquan reactor, the Guangyuan reactor was graphite-moderated and water-cooled and presumably of the same design power.



Figure 7.5. The Guangyuan reactor site, 13 February 2006 (Coordinates: 32.4956 N, 105.5901 E). Source: Google Earth.

Construction started in 1969, and the reactor achieved criticality in December 1973 and design power by October 1974.⁵³⁸ By increasing the power and uranium-235 burn-up, the plutonium production rate of this reactor was increased 30 percent by 1978, leading to it being dubbed the “1.3 reactor.”⁵³⁹ Thus, combined with Jiuquan’s “1.2 reactor,” the Jiuquan and Guangyuan reactors were described as “2.5 reactors” by the end of the 1970s.⁵⁴⁰ This description reinforces the assumption that the Jiuquan and Guangyuan reactors had similar design power.

It is reasonable to assume that the Guangyuan plant stopped plutonium production by 1989, when, following the new policy of “military-to-civilian conversion,” the plant began to convert to civilian use, including aluminum manufacture.⁵⁴¹ The Guangyuan plant was reportedly shut down by 1991.⁵⁴² The complex is being decommissioned. The reprocessing plant at the complex started operation in 1976 and reached its design capacity in 1977.⁵⁴³ It presumably closed in the early 1990s after the last batch of fuel from the reactor had been reprocessed. Given the above information and a reasonable set of assumptions about the increase in operating power and capacity factor of the Guangyuan reactor that helped it achieve the goal of the “1.3 reactor,” the Guangyuan reactor could have produced a total of 1,300 GWd and generated a total of about 1.1 tons of weapon-grade plutonium.⁵⁴⁴

Use in nuclear tests. China carried out 38 nuclear tests after it began producing plutonium. Most of these tests could have contained weapon-grade plutonium, either in a simple fission weapon, a compact boosted fission weapon, or as the fission primary in a two-stage thermonuclear weapon. A total of about 200 kilograms of plutonium would have been used in these tests, assuming an average of 5 kg of weapon-grade plutonium per test.⁵⁴⁵

Plutonium inventory. Thus, China's two plutonium production reactors produced an estimated 2 ± 0.5 tons of weapon-grade plutonium.⁵⁴⁶ Subtracting the 200 kg of plutonium estimated to have been consumed in China's nuclear tests, its current inventory of weapon-grade plutonium would be 1.8 ± 0.5 tons.

This estimate is at the low end of a U.S. Department of Energy estimated range, reported in 1999, of 1.7–2.8 tons of weapons plutonium.⁵⁴⁷ It is also smaller than most previous non-governmental estimates. It is smaller due largely to the assumption that the Jiuquan reactor and Guangyuan reactors had a design power of 250 MWt, whereas earlier estimates assumed that the Guangyuan reactor had a power twice that of the Jiuquan reactor. Earlier estimates also assumed that the power of these reactors increased much more than the 20–30% presumed here.⁵⁴⁸ The resulting decrease in estimated plutonium production due to the lower reactor power levels assumed here is somewhat offset by the assumption of higher capacity factors.

China reports no inventory of separated civilian plutonium in its declaration to the IAEA, the most recent of which was for the end of 2007.⁵⁴⁹ This situation can be expected to change soon, however. In 2010, China completed and began testing a pilot commercial reprocessing plant with a capacity of 50–100 tons of spent fuel per year. The China National Nuclear Corporation has also proposed to build a commercial-scale reprocessing plant with a capacity of 800 tons per year by 2025.⁵⁵⁰ Such a plant could separate about 8 tons of plutonium per year. This would quickly provide China with a civilian inventory of separated plutonium much larger than its military stockpile.

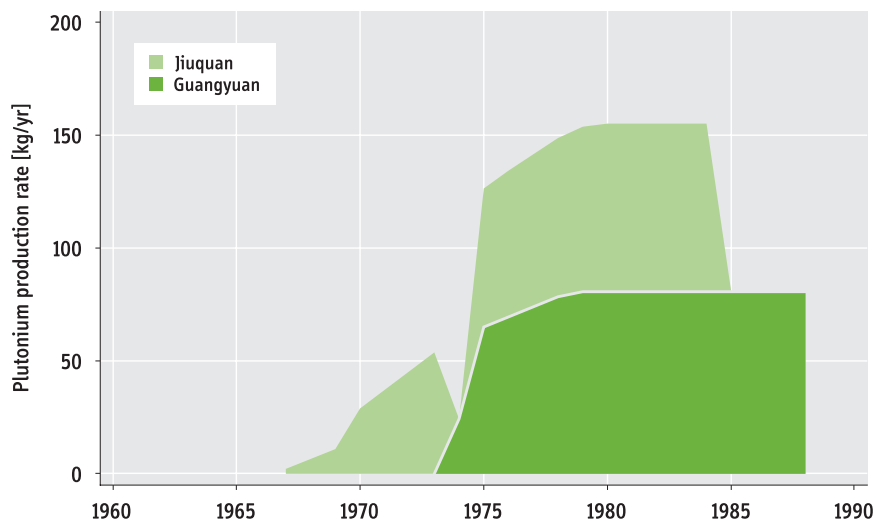


Figure 7.6. Reconstructed history of total production of weapon-grade plutonium by Jiuquan and Guangyuan reactors (tons per year). The two reac-

tors could have produced a total of about 2 tons of weapons plutonium.

8 Israel

Israel launched its nuclear-weapon program in the 1950s, building a reactor and associated reprocessing plant with French assistance at a secret nuclear center at Dimona in the Negev Desert. The site is home as well to other activities involved in the manufacture of nuclear weapons. These include the production of tritium. Israel's demonstrated interest and expertise in the use of lasers and centrifuges to enrich uranium also lend credence to claims that production of enriched uranium using both of these technologies has taken place at Dimona. Israel does not officially confirm the existence of the nuclear weapon program.

Israel has been extracting plutonium for nuclear weapons from spent fuel since the mid-1960s. It is estimated that the cumulative production of plutonium to date is 800 ± 125 kg. No estimate is made of the possible production of HEU.

Understanding Israel's Program

The best single reference to the origins and subsequent history of Israel's nuclear-weapon program through the end of the 1960s remains the book by Avner Cohen, which focuses on the political rather than the technical aspects of the program.⁵⁵¹ The most detailed revelations about the technical operations at Israel's nuclear facility at Dimona were published in a front-page article in the London-based *Sunday Times* in October 1986.⁵⁵² That article was based on information supplied by Mordechai Vanunu, who was employed as a technician at Dimona from November 1976 until October 1985. Vanunu worked in various areas of the Dimona facility, in particular, where the irradiated fuel elements from the Dimona reactor are reprocessed to extract the contained plutonium, and where lithium is enriched in the isotope Li-6 in order to produce tritium via neutron irradiation of rods of Li-6 that are inserted into the core of the reactor and subsequently processed to extract tritium.

Besides his notes about the operations at Dimona, Vanunu left Israel in January 1986 with about 60 color photographs that he had secretly taken within the facility, including models of weapons components. Some of the information that he revealed to the individuals who debriefed him in London, notably the journalist Peter Houghton and his associates at the *Sunday Times*, and the British scientist, Frank Barnaby, as well as a selection of the pictures, appeared in the article.⁵⁵³ More details from Vanunu's notes, as well as the complete set of pictures (Figure 8.1) soon began to circulate, however, and these became the subject of intense scrutiny and speculation among both weapons experts and non-experts who share a strong interest in Israel's nuclear activities. For

example, the investigative reporter Seymour Hersh subsequently wrote a book about the Israeli nuclear program including claims about Israel's nuclear arsenal and policy based on what U.S. weapons experts supposedly had deduced from Vanunu's revelations as well as information from other sources.⁵⁵⁴



Figure 8.1. Two of the pictures taken by Vanunu inside Dimona in September 1985, showing mock-up bomb components (left) and a control room of the Dimona plant (right). Vanunu shared these photos, along with his notes about the operation of the facility, with reporters for the London *Sunday Times*.

A front-page story based on this information was published by the *Times* on 5 October 1986. By that time, Vanunu had been kidnapped by Israeli intelligence agents and taken to Israel where he was tried in secret and sentenced to 18 years in prison.⁵⁵⁵

Vanunu's data and subsequent analyses of it are used as the basis for this assessment of Israel's plutonium production. Vanunu also claimed that Israel was using lasers and centrifuges to enrich uranium at Dimona, but he didn't have access to the areas where these activities were supposedly taking place, and thus was not able to supply further details. In addition to its potential use in nuclear weapons, Israel could have used enriched uranium as fuel in the Dimona reactor to increase its production of tritium. Although tritium is not a fissile material, Israel's need to offset the decay of its stock may help explain the continued operation of the Dimona reactor. For these reasons, the production of tritium and possible production of enriched uranium are discussed in the following.

Independent technical assessments of Israel's plutonium-production program using commercial satellite imaging have been made more difficult by the fact that the U.S. Congress passed a law as part of the National Defense Authorization Act for 1997 that restricts the collection and dissemination of satellite imagery with respect to Israel. Under this law, commonly referred to as the Kyl-Bingaman Amendment, U.S. commercial companies such as Space Imaging are prohibited from collecting and releasing imagery of Israel at a resolution more precise than that routinely available commercially world wide. For example, because the Russian firm Sovinformspudnik, would not make available for commercial sale 1-meter or sub-meter imagery of Israel, Space Imaging had to degrade its IKONOS image of Dimona acquired in 2000 from one to two meters.⁵⁵⁶

Plutonium Production

The primary source of public information about French assistance to Israel in the construction of a plutonium production reactor and an associated reprocessing plant is Pierre Péan's book, *Les Deux Bombes*.⁵⁵⁷ Péan notes that the reactor was of the EL-3 type,⁵⁵⁸ a heavy-water-moderated-and-cooled research reactor that started operating at Saclay in 1957.⁵⁵⁹ However, while the EL-3 was designed to achieve a high neutron flux for materials testing and used slightly enriched uranium fuel, the Dimona reactor—also designated “EL-102”—uses natural uranium and was designed to produce plutonium. An attractive feature of the EL-3 in this regard was that its design permitted a significant increase of the reactor power with a concomitant increase in plutonium production.⁵⁶⁰

While Péan's book was published in 1982, the fact that the Dimona reactor was patterned after the EL-3 had already been disclosed by the director of Dimona, Manes Pratt, to two American scientists, U. M. Staebler and J. W. Croach, Jr., during their one-day visit to the site in May 1961.⁵⁶¹ Specifically, Pratt told them that the reactor design “is very much influenced by the French EL-3;” that the design calculations were done by the French, and that “natural uranium was selected as fuel for the reactor because of a desire to be able to produce as much as possible within their own borders.” Pratt also gave them a summary of the reactor design parameters including the fact that there were three coolant loops, each of 13 MWt thermal capacity, which indicated that the reactor could operate at a power of 40 MWt instead of the specified 24–26 MWt.⁵⁶² To this date, the IAEA lists the Dimona reactor (IRR-2) with a power level of 26 MWt.⁵⁶³

Indeed, Péan notes the potential for an even larger upgrade:⁵⁶⁴

“When the (French) team in charge of building the plutonium extraction plant read the file on the reactor (in 1957), it was surprised by its capacity. It appeared to them to be twice or three times more powerful than what had been indicated in the agreement between France and Israel. The cooling ducts, for example, were three times bigger than needed for a 24 MW reactor.”⁵⁶⁵

According to unnamed U.S. officials, the thermal power of the Dimona reactor (it produced no electricity) was probably increased from about 40 MWt shortly after it went critical in December 1963 to about 70 MWt prior to 1977 when Vanunu began working at Dimona.⁵⁶⁶ This is consistent with Péan's information about the size of the cooling ducts, and with a statement attributed to Vanunu by Barnaby, which also claims that the reactor power was further increased “presumably to about 150 MWt” prior to his arrival.⁵⁶⁷ The latter claim in turn is in rough agreement with an internally consistent set of data that Vanunu provided that: (a) the ratio of plutonium to uranium in the dissolved fuel in the reprocessing plant was 0.0004;⁵⁶⁸ (b) 36 kg of plutonium was extracted from the spent nuclear fuel per year,⁵⁶⁹ and (c) about 10% of the plutonium contained in the metallic “buttons” was lost in weapon fabrication, but subsequently recovered and recycled back into buttons.⁵⁷⁰

The plutonium-uranium ratio implies a fuel discharge fuel burnup of about 450 MWd/ton. According to neutronics calculations summarized in more detail in Appendix B, for this fuel burnup, the effective plutonium production rate of this reactor is 0.96 grams per MWd (Figure 8.2).⁵⁷¹ Then, with 270 days/yr of operation, a plutonium production of 36 kg/yr from the spent fuel implies a reactor power of 140 MWt,⁵⁷² i.e., somewhat lower but close to the value attributed to Vanunu. A power level of 140 MWt is used in the following as a hypothetical maximum power level of the reactor.

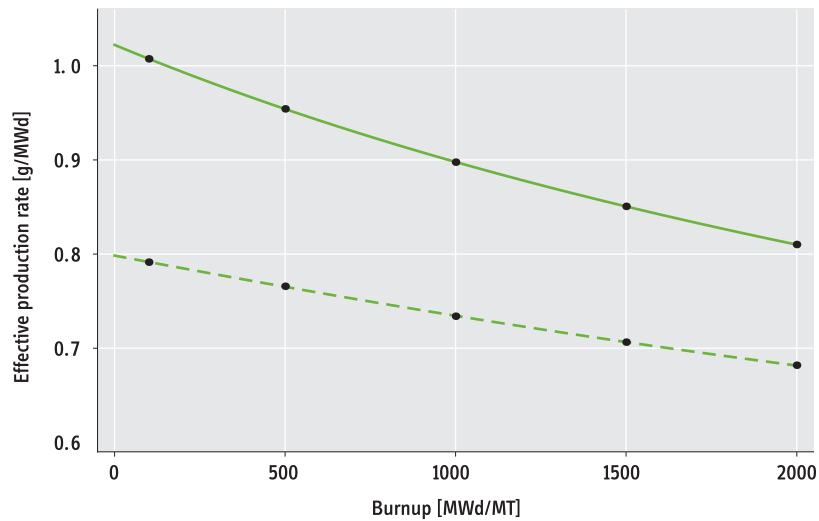


Figure 8.2. Effective plutonium production rate in Dimona (“EL-102”), a modified version of the French EL-3, using natural uranium (solid line) and slightly enriched uranium (1.0% U-235, dashed line). Results based on computer simulations sum-

marized in Appendix B. The use of slightly enriched uranium would increase the capability to produce tritium in the reactor while reducing the plutonium-production rate by about 20%.

Such a large upgrade in reactor power from 40 MWt eventually to 140 MWt has been questioned on the grounds that it would require major modifications of the reactor itself as well as the associated heat exchangers and cooling towers. In addition, for a fixed burnup of the fuel, i.e., for a given amount of energy (and plutonium) produced per mass of fuel, increasing the reactor power requires a proportional increase in fuel throughput. Reportedly, the original design of the “EL-102” had an inventory of about 8 tons of uranium.⁵⁷³ A reactor operated at 40 MWt for 270 days per year with an average fuel burnup of 450 MWd/ton would require 24 tons of fuel per year.⁵⁷⁴ This is consistent with three annual core reloads and a 90-day exposure in the reactor.⁵⁷⁵ One way to increase the power while maintaining the 90-day reloading schedule would be to increase the uranium inventory in the reactor. The design of the “EL-102” could permit roughly a doubling of the fuel inventory to 40–45 tons without increasing the diameter of the vessel, consistent with a power up-rate to 70 MW. Beyond that, however, either the reactor vessel might have to be enlarged to accommodate still more fuel in the core, or the power per ton of uranium in the fuel—and therefore also the refueling rate—would have to be increased.⁵⁷⁶

Finally, higher power would also require a greater capacity to transfer heat from the fuel through the heat exchangers for release to the environment via the two cooling towers. These cooling towers are clearly visible and appear unchanged in satellite photos of the Dimona site taken in 1971 and 2002 (Figure 8.3).⁵⁷⁷ Indeed, the fact that no additional cooling towers are visible in the later image is often cited as evidence that the reactor power had not been increased significantly during this period. However, both the heat exchanger and cooling-tower internals could have been upgraded,⁵⁷⁸ or an alternative cooling system may have been installed.⁵⁷⁹



Figure 8.3. The cooling towers of the Dimona reactor are clearly visible and identifiable in satellite imagery. Comparison of declassified Corona imagery taken in 1971 (KH-4 Mission 1115-2, 29 September 1971) with more recent imagery (26 January 2002,

acquired by IKONOS, GeoEye) indicates that no new cooling towers were added between those dates.⁵⁸⁰ It has been argued that this strongly suggests that the power level of the reactor was not increased significantly between those dates.

Nevertheless, doubts that the reactor power was upgraded to about 140 MWt persist, and several explanations of why the output of the reprocessing plant cited by Vanunu may not be an accurate indicator of the power level of the reactor have been suggested.⁵⁸¹ One frequently cited explanation is that the plutonium production of about 36 kg/yr from spent fuel represents the surge-capacity of the reprocessing plant, i.e., the capacity when it was operated to process a backlog of irradiated fuel created by an extended shutdown of the plant, and that the steady-state production rate matches the assumed 70 MWt power level of the reactor during the period when Vanunu worked at Dimona. This scenario cannot fully explain, however, operation at such high throughput for the entire 8-year period that Vanunu worked there.

A plausible rationale for an increase in reactor power from 40 MW to 70 MW and possibly 140 MW during the 1970s and a subsequent decrease in power in the 1980s and 1990s is that, after the 1973 Yom Kippur war, Israel embarked on a major upgrade of the size and quality of its nuclear arsenal.⁵⁸² In particular, research and development was conducted on both two-stage thermonuclear nuclear weapons and battlefield weapons, e.g., nuclear artillery shells. However, while it is believed that the thermonuclear weapons have been incorporated into the arsenal, Israel apparently decided in the early 1980s not to produce and deploy battlefield nuclear weapons, and therefore reduced the production of plutonium while maintaining the level of tritium production required for thermonuclear weapons. If the Dimona reactor is operated today primarily for tritium production, Israel could be reprocessing its spent fuel and separating the plutonium, but not using it to make weapons.

Figure 8.4 illustrates various scenarios for the historic power level of the Dimona reactor. Using results from burnup calculations summarized in Appendix B to this report, these scenarios can be used to estimate cumulative plutonium production in Dimona. As of 2010, the value could be as low as 465 kg if the reactor power never exceeded 40 MWt. This Scenario A is considered highly unlikely. The remaining four scenarios yield a total plutonium production of 800 ± 125 kg. Scenarios B, D, and E reflect various possibilities for reductions of reactor power starting in the 1980s. Evidence for such reductions might be obtained from historic satellite imagery of the cooling towers.

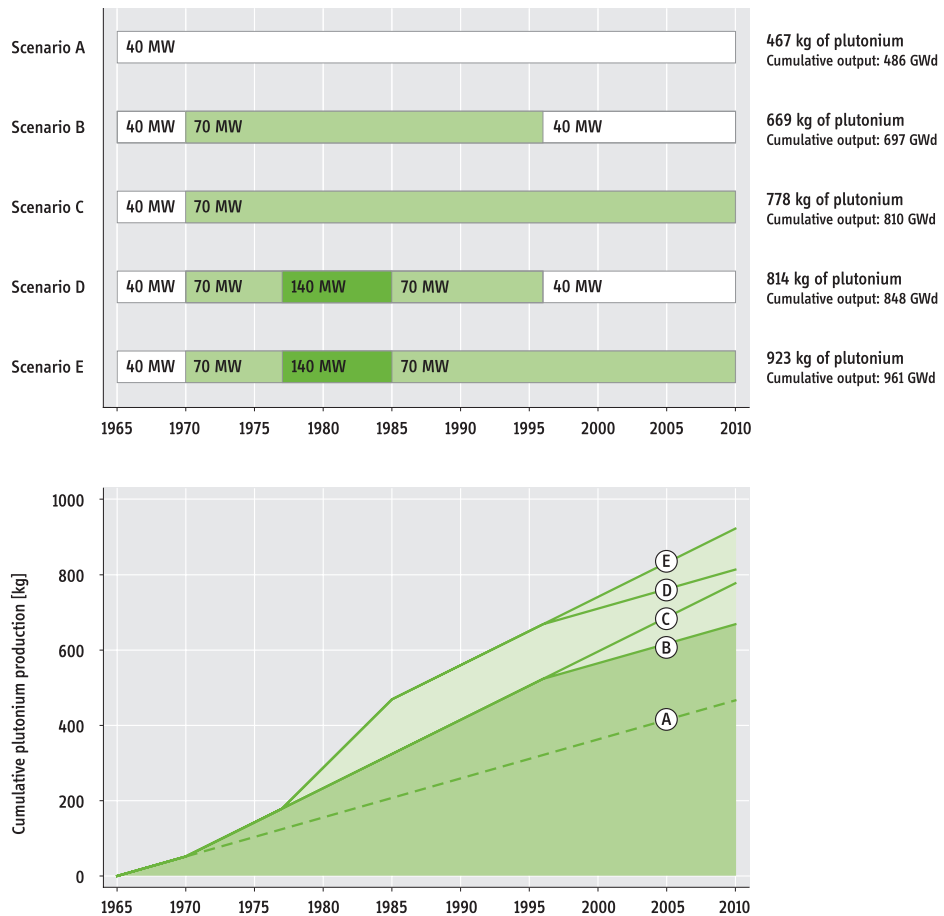


Figure 8.4. Scenarios of Dimona's historic power level, 1965–2010. The historic power level of the reactor is unknown, but an up-rate to 70 MW by 1970 has been widely reported. A second power up-rate may have occurred in the mid-1970s and would explain some observations made by Vanunu. Based on this information, five different scenarios are considered and illustrated above. Assuming a capacity

factor of about 75% (270 effective full-power days per year), these scenarios can be used to estimate the total energy release (in GW-days thermal) and thereby the cumulative plutonium production at Dimona. Not including Scenario A, our estimate as of 2010 is about 800 ± 125 kg. If Dimona's power level never exceeded 40 MWt, cumulative plutonium production would be about 500 kg.

Production of Lithium-6 and Tritium

The lithium isotope, lithium-6 (Li-6), which constitutes about 7.5% of natural lithium, is utilized for two purposes in nuclear-weapon production: 1) To produce tritium via neutron irradiation in a reactor for “boosting” the yield of a fission “primary” in a nuclear weapon,⁵⁸³ and 2) as a source of fusion material in the “secondary” of a thermonuclear weapon, where it is combined with deuterium to produce lithium-6 deuteride.

According to Vanunu, in 1977, Israel built a pilot plant at Dimona to enrich Li-6 from its concentration of 7.5% in natural lithium to about 85%.⁵⁸⁴ This facility is located underground in Machon 2 where the spent-fuel reprocessing also is carried out (Figure 8.5). After solving some initial problems, a production plant was built which was in full production by 1984. In the first year, the plant produced about 36 kg of enriched lithium. During the next two years, another 130 kg were produced for a total of about 170 kg before the plant was shut down.



Figure 8.5. Map of the Dimona site and reported designations and purposes of separate units. Based on drawings published in a 1961 U.S. government

memo and in a 1989 book on the arms race in the Middle East.⁵⁸⁵

The product Li-6 was subsequently alloyed with aluminum and fashioned into small rods that were inserted into the core of the reactor. If all of this Li-6 was devoted to tritium production, about 40 kg of tritium could have been produced.⁵⁸⁶ However, as noted, Li-6 is also utilized to produce lithium-deuteride fusion fuel for thermonuclear weapons, and kilogram quantities of Li-6 would be needed for a weapon with a fusion yield on the order a hundred kilotons.⁵⁸⁷ According to the late Theodore Taylor and other experts who have studied the pictures of weapons components taken by Vanunu,

they provide evidence of a two-stage thermonuclear device with such yields. If such weapons have been incorporated into the Israeli arsenal in significant numbers, the requirements for Li-6 in the secondaries would predominate over the requirements for tritium production in the Dimona reactor.

Thus, information on the quantity of Li-6 produced by Israel does not provide a basis for an accurate estimate of Israel's tritium requirements. Assuming, rather arbitrarily, that: (1) Israel has about 100 weapons; (2) half of them are boosted; (3) they require a minimum of 4 grams of tritium to operate; and (4) the design life of the weapon before the need for replenishing the tritium is 12 years (i.e., one tritium half life), then the initial tritium inventory for these 50 boosted weapons would be about $50 \times 4 \times 2 = 400$ grams, and the refueling requirement in the steady state would be about 20 g/yr.

Although tritium on a large scale, i.e., kilograms to tens of kilograms, has usually been produced in reactors dedicated to that purpose, smaller amounts can be produced by inserting Li-6 targets and/or substituting Li-6 for boron control rods in the core of reactors whose main purpose is the production of electricity or plutonium. To get a rough estimate of the capability of the Dimona reactor to produce tritium in this manner, it is assumed that small concentrations of lithium-6 can be added to the semi-permanent aluminum-sleeves enclosing the fuel rods in the Dimona reactor's core.⁵⁸⁸ Computer simulations find that up to 0.5 grams of lithium-6 can be loaded for every kilogram of uranium in the reactor, while still achieving the target burnup of 450 MWd/ton without loss of criticality and therefore without negatively affecting plutonium production in the reactor.⁵⁸⁹ Assuming a power level of 70 MWt and 270 effective full-power days per year, about 14 grams of tritium could be produced in this way per year.⁵⁹⁰ A more effective production strategy using dedicated lithium-rods might be able to increase this production rate to about 20 g/yr. The rate could be increased further with the use of slightly enriched fuel if a reduced plutonium production rate is accepted (see below).

Production of Tritium from Heavy Water

In his book on Israel's nuclear program, Seymour Hersh, quoting Vanunu, states that, even before the startup of the Li-6 production plant, Israel had been "painstakingly" removing tritium from the reactor heavy water since the 1960s in order to manufacture boosted fission weapons.⁵⁹¹ The *Transcripts* contain the following statement that adds credence to Hersh's claim:⁵⁹²

"The American inspection teams were systematically fooled, by methods ranging from the installation of fake walls to blank off the entrance to the plutonium facility, to the building of a specialized plant to remove tritium from the reactor's heavy water ..."

The statement about tritium removal is plausible from a technical perspective since processes to strip tritium from heavy water that has been irradiated in a reactor and simultaneously produce a concentrated stream of tritium were developed in Europe in the 1960s. All the processes involve the transfer of tritium from the tritiated heavy water to hydrogen that is then used as feed for a cryogenic distillation column.⁵⁹³

Because of the very small cross section for neutron absorption in deuterium, the build-up of tritium in heavy water reactors is only about 0.3–0.4 grams of tritium per ton of heavy water (D₂O) per year. For Dimona, which is estimated to use about 20 tons of heavy water at a power level of 40 MWt, this amounts to an annual production of about seven grams—which, accumulated over a period of about ten years, might explain how Israel was in a position to trade 30 grams of tritium to South Africa for 500 tons of natural uranium during 1977–78, even if tritium production from lithium-6 in the reactor was not yet operational.⁵⁹⁴

Production of Enriched Uranium

According to Vanunu, the production of enriched uranium at Dimona using gas centrifuges started in 1979 or 1980. There is additional supporting evidence for Israel's interest in centrifuges, if not for the construction and operation of an actual plant.⁵⁹⁵ In particular, shortly before his death in 2008, centrifuge pioneer Gernot Zippe revealed that, in the mid-1960s, he was persuaded to meet with Israeli scientists and security agents who wanted him to give them information about centrifuge equipment suppliers, ostensibly to prevent acquisition of the technology by states hostile to Israel.⁵⁹⁶ Zippe came to believe, however, that they wanted the information for a centrifuge program of their own. As support of Zippe's conjecture, Israeli scientists have published extensively on centrifuge theory and participated in conferences on the subject.⁵⁹⁷

Vanunu also claims that the production of enriched uranium at Dimona using lasers started in 1981. By contrast with the secrecy surrounding the alleged centrifuge operation, however, Israeli research at Dimona on the Atomic Vapor Laser Isotope Separation (AVLIS) process for enriching uranium, which was co-invented in the 1960s by an Israeli scientist, Isaiah Nebenzahl, was publicly acknowledged,⁵⁹⁸ although as in the case of centrifuge enrichment, there is no public information to support Vanunu's claim of the operation of a production plant.

Another possible source of enriched uranium was NUMEC, a nuclear fuel facility in the United States near Pittsburgh. The allegation that hundreds of kilograms of weapon-grade uranium were secretly transferred from the NUMEC plant to Israel in the 1960s, with the cooperation of the plant's owner, Zalman Shapiro, has been the subject of intense investigation and speculation.⁵⁹⁹ Besides being used directly in weapons, the enriched uranium could have been blended with natural or depleted uranium and used in the Dimona reactor to increase the production of tritium, as noted above, or to decrease the amount of fresh fuel required for operating the reactor.⁶⁰⁰

The use of enriched instead of natural uranium to increase tritium production would cause a decrease in the production of plutonium by about 30%, which can be estimated from the reduced production rate of about 0.77 g/MWd for fuel enriched to 1% compared to 0.96 g/MWd for natural uranium (Figure 8.2).⁶⁰¹ This might be the favored mode of operation if the goal was to maintain the tritium inventory for the existing stockpile rather than to produce plutonium for more weapons. Enriched uranium could also be used for blending with irradiated and slightly depleted uranium so that it can be recycled back into the reactor.⁶⁰²

Conclusion

Despite the revelations of Mordechai Vanunu, there remain large uncertainties in independent estimates of Israel's inventory and its current rate of production of plutonium and tritium for weapons. As of 2010, Israel is estimated to have produced a total of 800 ± 125 kg of weapon plutonium.

Plutonium production may be continuing along with that of tritium, with the latter used in boosted fission weapons and in the fission triggers of two-stage thermonuclear weapons. Tritium has a 12-year half-life and must be replenished regularly in weapons. This could be the principal reason why Israel continues to operate Dimona. It could make tritium in other ways, however, if it chose to shut down Dimona.

Israel's interest in enriched uranium is well documented. There is some evidence that Israel illicitly acquired up to a few hundred kilograms of weapon-grade HEU from a plant in the United States. It has not proved possible to estimate how much highly enriched uranium may have been produced in the centrifuge and laser enrichment programs at Dimona described by Vanunu. There is no independent evidence that these programs went beyond research and development.

9 India

India's nuclear program was launched in the mid-forties, around the time the country gained independence from over two centuries of British rule, and soon after the U.S. bombing of Hiroshima and Nagasaki. Officially, the program was only for peaceful purposes, i.e., aimed at producing electricity for development, but its leaders never lost sight of the possibility that the facilities constructed and expertise gained in this process could be used for military purposes. From the very beginning, India's Department of Atomic Energy (DAE) was generously funded, and it embarked on an ambitious program aimed at having indigenous capability for covering the entire nuclear fuel cycle. Over the years, the DAE mined uranium, fabricated fuel, manufactured heavy water, constructed reactors, reprocessed spent fuel to extract plutonium and, more recently, enriched uranium.

There is little information available from India's Government on nuclear-weapon matters except at the most general level. With regard to the size of India's stockpiles of fissile materials, unofficial estimates have considerable uncertainties. What is known is that India produces highly enriched uranium (HEU) and weapon-grade plutonium. So far, the enriched uranium seems to have been intended for use in a nuclear submarine reactor. India also has an ambitious fast breeder-reactor program and has separated relatively large quantities of reactor-grade plutonium to fuel these future reactors. As of 2010, India is estimated to have a stockpile of about 0.2–0.5 tons of U-235 in HEU with an enrichment level of 30–45%, a stockpile of 0.3–0.7 tons of weapon-grade plutonium, and a stockpile of 3.3–3.9 tons of reactor-grade plutonium. This chapter describes the basis for these estimates.

Weapon-grade Plutonium

Historically, India chose the plutonium route for its nuclear weapons because HEU was believed to be more expensive and difficult to produce.⁶⁰³ India's weapon-grade plutonium is produced in two reactors: the 40 megawatt thermal (MWt) CIRUS and the 100 MWt Dhruva, both located in the Bhabha Atomic Research Centre (BARC) complex near Mumbai. CIRUS is a heavy-water-moderated, light-water-cooled, natural-uranium-fueled reactor of the same design as the Canadian NRX reactor.⁶⁰⁴ Financial assistance for the construction of the reactor was provided by Canada as part of the Commonwealth's Colombo Plan.⁶⁰⁵ The heavy water was supplied by the United States. CIRUS became critical in 1960 and fully operational in 1963. An extended refurbishment of CIRUS started in October 1997, and it resumed operation in October 2003.⁶⁰⁶

When Canada and the United States agreed to provide assistance in building India's CIRUS research reactor, India committed to use the facility and the fissile material coming out of it for peaceful purposes.⁶⁰⁷ By describing its 1974 test a "peaceful nuclear

explosion”—which was well within the terms of nuclear discourse at that time—India maintained that it had not violated its commitment. Nevertheless, the test ended almost all U.S. and Canadian cooperation with India in nuclear technology for three decades.

India subsequently built a larger research reactor called Dhruva, which is modeled after CIRUS, but uses heavy water as both coolant and moderator so as to further reduce neutron losses. Dhruva was commissioned in 1985, but it had operating problems during its first few years; it is reported to have begun normal operations in 1988.⁶⁰⁸

Public details of the operating histories for CIRUS and Dhruva are sparse. One figure that has been published is the availability factor, which is the fraction of time that the reactor is operable. CIRUS is reported to have an “availability factor of over 70%.”⁶⁰⁹ In 2000, Dhruva was claimed to have “achieved an availability factor of over 68% during the year which is the highest so far.”⁶¹⁰ Similarly, in 2005, it was reported to have an availability factor of 70%.⁶¹¹ Without knowing the power level of the reactor one cannot translate this figure into a capacity factor.⁶¹²

There have been a couple of rare instances where both availability factors and power levels were reported in official statements.⁶¹³ These suggest capacity factors in the range of 40–50%.⁶¹⁴ These are lower than other figures typically seen in the nonproliferation literature.⁶¹⁵

Earlier estimates of plutonium production at CIRUS and Dhruva assumed that the reactors operated at full power when they were available, and provided “an upper-bound estimate of plutonium production.”⁶¹⁶ The low capacity factors that have been reported since suggest that this is likely to be an over-estimate. Therefore, two scenarios are considered: one in which the average capacity factors of CIRUS and Dhruva during normal operations are 40% and one in which they are 65%.⁶¹⁷



Figure 9.1. Image of the CIRUS reactor by the KH-7 reconnaissance satellite on 19 February 1966. The acronym “CIR” stands for Canada India Reactor and the “US” was added after the United States supplied heavy water for the reactor. It became critical in 1960 and its spent fuel was reprocessed at the

Trombay reprocessing plant that started operating in 1964 to produce the plutonium used in the 1974 nuclear weapon test. The reprocessing plant is in the same complex but outside the frame in this image. CIRUS is due to be shutdown at the end of 2010. *Source: National Security Archive.*

Spent fuel from CIRUS and Dhruva has generally been reprocessed at the Trombay reprocessing plant, the first in India.⁶¹⁸ When the Trombay plant was shut down in the 1970s for refurbishment, some CIRUS spent fuel was also sent to the Power Reactor Fuel Reprocessing Plant (PREFRE), which is nominally a civilian plant for reprocessing power-reactor spent fuel.⁶¹⁹ It is only safeguarded, however, when the plant is reprocessing spent fuel from reactors that are under safeguards.⁶²⁰ Because the amounts of spent fuel produced by CIRUS and Dhruva are generally much lower than the nominal reprocessing capacity of the Trombay plant, especially after its recommissioning, reprocessing capacity would not have been a major constraint on separation of weapon-grade plutonium from CIRUS and Dhruva spent fuel. The backlog accumulated during periods when the Trombay reprocessing plant was shut down could be processed within a few years of the plant's restart.

At a capacity factor of 65%, CIRUS would produce about 7.9 tons of spent fuel each year, containing about 7.1 kg of weapon-grade plutonium, and Dhruva would produce about 19.8 tons of spent fuel each year containing 17.8 kg of weapon-grade plutonium.⁶²¹ At the lower capacity factor of 40%, CIRUS and Dhruva would produce 4.9 tons and 12.2 tons of spent fuel each year, containing 4.4 kg and 11 kg of weapon-grade plutonium, respectively.

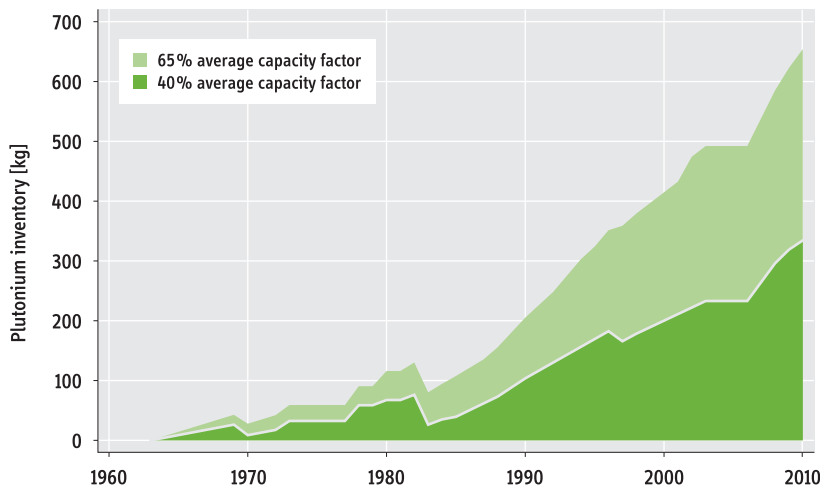


Figure 9.2. Weapon-grade plutonium inventory from CIRUS and Dhruva. The decline around 1970 is due to the use of plutonium to construct the PURNIMA facility. The subsequent upturn is due to the facility being shutdown and plutonium being recovered, some of which was used in the 1974 nuclear weapon test. The inventory stays constant through much of the 1970s because the Trombay reprocessing plant

has been shutdown. The three small increases between 1978 and 1982 come from the use of the PREFRE plant to reprocess CIRUS spent fuel. The sharp declines in 1983 and 1997 are due to the use of plutonium in the initial core of the Fast Breeder Test Reactor and the manufacture of the nuclear weapons tested in 1998.

Another source of weapon-grade plutonium may be the first discharges from pressurized heavy water power reactors.⁶²² These should have roughly 6 kilograms of plutonium with the concentration of Pu-239 greater than 90 percent.⁶²³ Till 2010, such low burnup spent fuel would have been discharged from eleven unsafeguarded 220 MW PHWRs and two 540 MW PHWRs. Together these reactors may have produced at most 95 kg of weapon-grade plutonium.⁶²⁴

There is much uncertainty about whether India has added such plutonium to its stockpile. Doing so would require that the first discharges of spent fuel be reprocessed separately from the other, regular burnup spent fuel. Because this is technically feasible, this early-discharge plutonium is included in the higher estimate but not in the lower estimate.

In all, the total production of weapon-grade plutonium in India as of the end of 2009 is estimated to be between 0.4 and 0.7 tons.

Plutonium use. The earliest use of India's separated plutonium was to construct the PURNIMA facility in 1972. This system used 22 kg of plutonium.⁶²⁵ However, this facility was subsequently dismantled and so it is assumed that all the plutonium was recovered.⁶²⁶ The withdrawal and recovery are assumed to have taken place in 1970 and 1973 respectively. Next, 5–7 kg of plutonium is assumed to have been withdrawn in 1973 for use in the 1974 nuclear weapon test.⁶²⁷

The largest single withdrawal of weapon-grade plutonium has been for the initial core of the Fast Breeder Test Reactor (FBTR). The FBTR was constructed before any unsafeguarded reactor-grade plutonium was available and was therefore fueled with weapon-grade plutonium. Since the FBTR was commissioned in 1985, it is assumed that sufficient plutonium for the first core should have been available in 1983. The plutonium inventory of the FBTR's first core has been estimated as 50 kg.⁶²⁸

Finally it is assumed that about 20–30 kg of weapon-grade plutonium was taken out of the stockpile in 1997 and used to construct the devices exploded in the 1998 nuclear weapon tests.

Subtracting these amounts from the total production, the current inventory is estimated at somewhere between 0.33 and 0.65 tons. These figures are roughly comparable to earlier estimates.⁶²⁹

	Higher Estimate	Lower Estimate
CIRUS and Dhruva production	630 kg	420 kg
Power Reactor first discharges	95 kg	–
Total consumption	–76 kg	–87 kg
Total stockpile	650 kg	330 kg

Table 9.1. Weapon-grade plutonium inventory. The higher estimate assumes that the two production reactors have operated at a capacity factor of 65% each, whereas it is 40% for the lower estimate. The higher estimate assumes that the first discharges of low burnup spent fuel from the power reactors

have been separately reprocessed and the resulting plutonium added to the weapon-grade plutonium stockpile. The two estimates also differ in the estimates of the amount of plutonium consumed in the 1974 and 1998 nuclear weapon tests. Estimates have been rounded off to two significant figures.

Power-reactor (reactor-grade) plutonium

India's fleet of unsafeguarded Pressurized Heavy Water Reactors (PHWR) is the source of its large stockpile of reactor-grade plutonium. Though this chapter does not deal with the subject, the tritium accumulating in the heavy water due to neutron absorption has been separated and reportedly used to boost the yield of nuclear weapons.⁶³⁰ The spent fuel generated by these reactors is reprocessed in two reprocessing plants: PREFRE and

the Kalpakkam Reprocessing Plant (KARP). Both have a nominal capacity of 100 tons. The annual production rate of reactor-grade plutonium in spent HWR fuel is estimated from the yearly electricity production figures as reported by the International Atomic Energy Agency's Power Reactor Information System (PRIS) database. There is little information available, however, on the performance of the reprocessing plants.

PREFRE was the only reprocessing plant dedicated to dealing with power reactor spent fuel prior to 1998, and it seems to have operated at very low capacity factors.⁶³¹ Its net effective capacity factor for the period 1987 to 2010 is assumed to be about 50%.⁶³²

The Kalpakkam Reprocessing Plant (KARP) has been operating since 1998, but it underwent major modifications starting 2004; the plant restarted in March 2009.⁶³³ KARP is assumed to have operated at a capacity factor of 35% during the years when it was being modified, and 70% in other "normal" years. With these assumptions, KARP's net effective capacity factor for the period 1998 to 2010 is 53%.⁶³⁴

In all cases, the spent fuel is assumed to be stored for at least 3 years after discharge before being sent to the reprocessing plant; in those years when there is insufficient reprocessing capacity to deal with all the cooled spent fuel, it may continue to be stored till such capacity becomes available.

The estimated production of reactor-grade plutonium by year based on these assumptions is shown in Figure 9.3. In all, the estimate for total plutonium separated as of the beginning of 2010 is about 3.5 tons.⁶³⁵ Approximately 5.5 tons of reactor-grade plutonium is in the accumulated 2400 tons of spent fuel from non-safeguarded PHWRs that is to be reprocessed. About 660 tons and 540 tons of spent fuel, from safeguarded PHWRs and BWRs respectively, are stored in spent fuel pools or in dry casks. An estimated 0.24 tons of plutonium has been separated from the spent fuel of safeguarded PHWRs and is under safeguards.

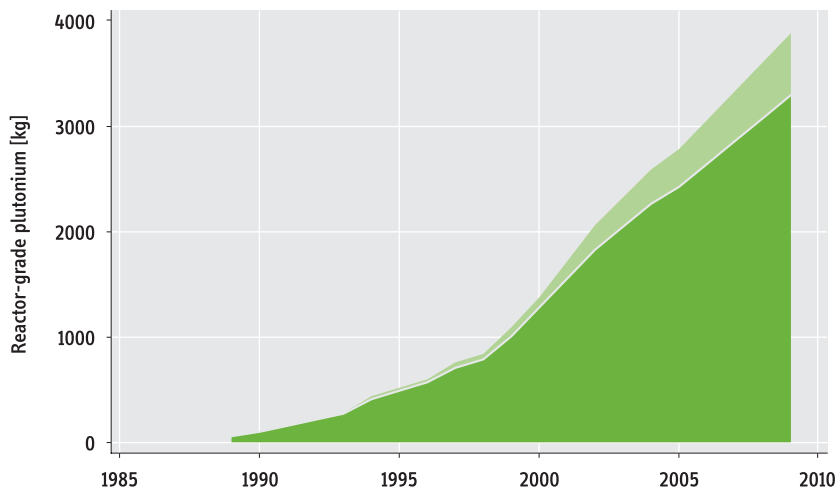


Figure 9.3. Cumulative production of separated reactor-grade plutonium. The lower estimate (3.3 tons) corresponds to a burnup of 7000 MWd/t with the PREFRE and KARP reprocessing facilities operating at average capacity factors of 44% and

48% respectively. The higher estimate (3.9 tons) corresponds to a burnup of 6600 MWd/t with KARP and PREFRE operating at higher average capacity factors of 65% and 49% respectively

The major source of uncertainty in the amount of separated plutonium is the capacity factor with which the two reprocessing plants have operated. A second source of uncertainty is the average burnup; DAE documents use values ranging from 6600 MWd/t to 7000 MWd/t.⁶³⁶ An upper bound can be estimated by assuming that KARP has operated with an 80% capacity factor during normal years, a capacity factor of 50% in other years, and the burnup is 6600 MWd/t.⁶³⁷ As a likely lower bound, it is assumed that both KARP and PREFRE operate with a capacity factor of 60% during normal years, a capacity factor of 35% in other years, and the burnup is 7000 MWd/tU.⁶³⁸ The estimated total separated plutonium stockpiles in these two cases are 3.9 and 3.3 tons. This is comparable to some earlier estimates.⁶³⁹

Plutonium use. There are two chief uses to which reactor-grade plutonium has been put. The oldest use was to fuel the FBTR after its first core of weapon-grade plutonium. The second was to prepare the core of the Prototype Fast Breeder Reactor (PFBR), which is expected to be commissioned over the next year or two.⁶⁴⁰

The FBTR was initially designed to produce 40 MWt of heat, but it never reached this level.⁶⁴¹ The total plutonium consumed is estimated to be about 120 kg.⁶⁴² The PFBR design requires an initial inventory of 1.9 tons of plutonium in its core.⁶⁴³ This amount may have been withdrawn from the stockpile of reactor-grade plutonium in 2007.⁶⁴⁴ Once the reactor begins operating, the first two or three fuel loadings, i.e., before the spent fuel arisings from the PFBR are reprocessed, will also require plutonium from the reactor-grade stockpile. But this is unlikely to have been taken out already.

A third minor requirement for reactor-grade plutonium is for MOX rods that have been used in the Boiling Water Reactors at Tarapur and various PHWRs in the country as part of experiments to study the impacts of MOX use on burnup and uranium consumption,⁶⁴⁵ which is likely to have consumed about 50 kg in all.⁶⁴⁶

Highly Enriched Uranium

India's interest in uranium enrichment dates back to the early 1970s.⁶⁴⁷ But it was only in 1986 that Indian Atomic Energy Commission Chairman Raja Ramanna announced that uranium had successfully been enriched.⁶⁴⁸ According to one report, a pilot-scale plant was set up in the Bhabha Atomic Research Center (BARC) in 1985.⁶⁴⁹ A larger centrifuge plant reportedly has been operating at Rattehalli in southern India since 1990.⁶⁵⁰ This plant, officially known as the Rare Materials Project (RMP), is still India's main uranium enrichment facility. There is also an experimental laser enrichment program.

The original and probably still primary purpose of the Rattehalli plant is to enrich uranium for nuclear-submarine fuel.⁶⁵¹ This effort to develop a nuclear submarine, officially termed the Advanced Technology Vessel (ATV) program, was started in the 1970s. By the late 1990s, a design for the reactor of this submarine was finalized. Testing of a prototype reactor commenced at Kalpakkam in southern India somewhere around 2000–2001.⁶⁵²

Construction of the Rattehalli plant started in the mid 1980s.⁶⁵³ During its initial years of operation, the plant reportedly had “frequent breakdowns as a result of corrosion and failure of parts.”⁶⁵⁴ These problems seem to have been overcome by the end of that decade. There is no official information on the plant's capacity or performance, and we

base our estimates below on two kinds of sources: statements by Indian officials and an analysis of procurement information carried out by David Albright and Susan Basu of the Institute for Science and International Security (ISIS).⁶⁵⁵ This was partly corroborated in 2008 by the Director of BARC who stated that:

“Great strides have been made in development of advanced gas centrifuges for uranium enrichment program. The latest fourth generation design, with output 10 times the early design, has been successfully developed and an experimental cascade is in operation at BARC. These would soon be ready for induction at RMP. Third generation design, with 5 times output of early designs, are presently being inducted at RMP.”⁶⁵⁶

It appears that the Rattehalli facility has had three generations of uranium centrifuges.

- The first generation of centrifuges was installed in the early 1990s,⁶⁵⁷ and resulted in a total enrichment capacity in the range 500–2000 SWU/yr.⁶⁵⁸
- The second generation of centrifuges was installed starting in the late 1990s,⁶⁵⁹ and resulted in a total enrichment capacity in the range 3000–7000 SWU/yr by 2000.⁶⁶⁰ The lower end of this range was determined by constraints from the design of the nuclear submarine as we describe below. Around 2005–2007, another 9000–12,000 SWU/yr of centrifuges using the same design seem to have been installed.⁶⁶¹
- The third generation of centrifuges with an additional capacity of 7000–13,000 SWU/yr was installed in the 2007–2009 period as described by the Director of BARC.⁶⁶²

One constraint on the uranium enrichment capacity in the late 1990s can be obtained by working backwards from the announcement that the prototype of the ATV reactor’s core was tested in 2000–2001.⁶⁶³ This implies that between 1990 and the late 1990s, RMP should have produced at least sufficient enriched uranium to fabricate the reactor core.⁶⁶⁴ Characteristics of the submarine reported in the media and the resultant requirements for U-235 content are in Table 9.2.

	Specification
Submarine displacement	6000 tons
Maximum Speed	25 knots (46 km/h)
Reactor power ⁶⁶⁵	80–90 MWth
Fuel enrichment	30–45%
U-235 content ⁶⁶⁶	65–73 kg

Table 9.2. Characteristics of India’s ATV nuclear submarine and naval reactor.⁶⁶⁷ There are no official figures on the technical characteristics of the ATV. Only the dimensions of the vessel and its maximum

speed have been made public.⁶⁶⁸ The figures for reactor power and fuel enrichment are plausible ranges based on many media reports.

It would take about 200 SWU to produce a mass of 30-45 percent enriched HEU that contains one kilogram of uranium-235, assuming depleted uranium tails of 0.3%.⁶⁶⁹ To produce 65 kg of U-235 in this enrichment range, the total cumulative enrichment needed by the late 1990s would have been about 13,000 SWU, which, in turn, implies a minimum enrichment capacity at the beginning of 2000 of about 3000 SWU/yr.⁶⁷⁰ Thus, the requirement that there be sufficient enrichment capacity to produce an adequate amount of enriched uranium for the submarine core brings up the lower end of the range from 1950 to 3000 SWU/yr. The capacity at the beginning of 2000 is estimated to be between 3000 and 7000 SWU/yr.

In all, the capacity at the end of 2009 is an estimated 14,000 to 31,000 SWU/yr, enough to produce one or two submarine-reactor cores per year. As of the beginning of 2010 and assuming 0.3% depleted uranium tails, this growth of capacity corresponds to an estimated production of 0.2 to 0.5 tons of U-235 in HEU enriched to 30 to 45%.



Figure 9.4. Satellite images of the Rattehalli uranium centrifuge site on 27 April 2005 and 2 March 2010 (12.357 N, 76.510 E). The two images show evidence of construction on the site and provide some indication of plans for further expansion in the future.⁶⁷¹ The two rows of centrifuge halls shown

in the image are approximately 3150 square meters (90 meters by 35 meters) each. Using the rule of thumb of one centrifuge per square meter,⁶⁷² these could have up to 6,300 centrifuges. This is somewhat larger than the current capacity. *Source: Google Earth.*

HEU use. As mentioned earlier, the primary aim of the Indian uranium centrifuge program was to produce HEU for the nuclear submarine program. Once the prototype submarine has been tested, India is likely to maintain a fleet of somewhere between three to five nuclear submarines.⁶⁷³ It has been reported that the hulls of two more submarines have already been completed.⁶⁷⁴ Assuming that all of these submarines use roughly the same amount of HEU as the current design, i.e., incorporating about 70 kg of U-235 in the core, the estimated current stockpile of HEU would suffice for three to seven cores. The estimated enrichment capacity could produce sufficient HEU for three cores per year. Thus, the estimates of current enrichment capacity and HEU stockpiles laid out here dwarf what might be needed any time in the reasonable future for the submarine program. The question, therefore, is what else enriched uranium might be used for?

There are at least three categories of uses: in research reactors, in thermonuclear weapons, and in power reactors. The research reactors, the refurbished Apsara,⁶⁷⁵ and the proposed Multipurpose Research Reactor,⁶⁷⁶ might require about 5000 SWU/y of enrichment capacity, about 40 percent of the requirements for a single submarine core. The second potential use for HEU is in nuclear weapons, either in secondaries of thermonuclear weapons or in composite pits. However, there is no evidence that the DAE tested such designs in 1998.

The only indigenously designed power reactor that might require LEU is the Advanced Heavy Water Reactor (AHWR).⁶⁷⁷ This is currently at the design stage and would use low-enriched uranium plus thorium as a fuel.⁶⁷⁸ Not enough is known publicly to estimate how much LEU it will use. However, since the announcement also mentioned that “the reactor is manageable with modest industrial infrastructure within the reach of developing countries,” it is reasonable to assume that India would provide the necessary LEU to fuel the reactor.⁶⁷⁹

A more likely possibility is that once the enrichment capacity has expanded sufficiently, India might consider producing LEU for use in LWRs. Till recently, the DAE had not evinced any interest in doing this. However, in a September 2010 newspaper interview, the head of the DAE revealed plans for a new site which would allow for producing “a much larger quantity of enriched uranium” to produce fuel for “large-scale commercial nuclear power stations.”⁶⁸⁰

10 Pakistan

Pakistan launched its nuclear research and development program in 1954, taking advantage of the U.S. “Atoms for Peace” program. Pakistan now has facilities covering the fuel cycle from uranium mining through uranium enrichment, fuel fabrication, and the reprocessing of spent nuclear fuel to recover plutonium. Pakistan also has built and operates a plutonium-production reactor.⁶⁸¹

The civilian component of Pakistan’s nuclear program, which was built with foreign assistance, is under International Atomic Energy Agency (IAEA) safeguards, and consists of two operating power reactors provided by Canada and China. A third power reactor is under construction by China. Since 1974, Pakistan’s nuclear complex also has had a significant military component. The extent of foreign assistance with the nuclear weapons program is unclear, but there are indications that China provided material and technology support.

There is no official quantitative information available on Pakistan’s fissile-material-production capacities or histories. It is widely acknowledged, however, that Pakistan has been using gas centrifuges to produce highly enriched uranium (HEU) for nuclear weapons at least since the early 1980s and a plutonium-production reactor has been operating since the late 1990s. In 1998, Pakistan carried out six nuclear tests, none of which is believed to have involved a thermonuclear weapon. Since then, Pakistan’s fissile-material production program has been undergoing a large expansion. Pakistan may, however, be constrained from an even larger expansion of its fissile-material production by its limited domestic uranium production capacity.

It is estimated here that, as of 2010, Pakistan had produced about 1.6–3.8 tons of weapon-grade (90%-enriched) uranium, giving a mid-range value of 2.7 ± 1 tons. About 100 kg of this HEU would have been consumed in the six nuclear weapon tests in 1998, leaving Pakistan with an HEU stockpile currently on the order of 2.6 ± 1 tons. Pakistan also may have produced 60–130 kg of weapons plutonium in its Khushab-I reactor, with a mid-range value of about 100 kg. As the recently completed Khushab-II reactor and the new Khushab-III reactor come on-line, the size of Pakistan’s plutonium stockpile will grow much more rapidly than over the past decade.

Uranium Mining and Acquisition

Uranium was discovered in Pakistan in 1959 by the Geological Survey of Pakistan at Baghalchore (Baghalchur), near Dera Ghazi Khan, in Punjab province.⁶⁸² Both underground and surface mining operations were launched, and a uranium mill established close by in 1977–78,⁶⁸³ with large-scale mining starting after about 1980.⁶⁸⁴ The mill's design capacity is reported variously as 300 tons of ore per day,⁶⁸⁵ and 30 tons of uranium per year.⁶⁸⁶ The Baghalchore mine was described as being nearly exhausted by 1998,⁶⁸⁷ and as having been closed in 1999. The site is now used to dump low-level radioactive waste.⁶⁸⁸

A second uranium mine was opened at Qabul Khel (also spelled Kubel-Khel) in 1992, and mining of deposits at Nanganai and Taunsa (both located near Dera Ghazi Khan) started in 1996 and 2002, respectively, all using *in-situ* leaching technology.⁶⁸⁹ This method of mining is typically used for low-grade ores and involves pumping a solvent through the ore-body to dissolve the uranium and bring it to the surface. The three mines in Pakistan have an average grade of 0.02%–0.03% uranium, significantly below the grade exploited in most commercial uranium mining today.⁶⁹⁰ The IAEA's World Distribution of Uranium Deposits database reports an initial resource of 500–1000 tons of uranium at the Qabul Khel site.⁶⁹¹ Figure 10.1 shows OECD/IAEA *Red Book* estimates for cumulative uranium production from 1980 to 2009, a total of 791 tons, and projected to 2010 assuming uranium production has continued at 40 tons per year.⁶⁹² Pakistan has launched a costly search for new uranium sources.⁶⁹³ The Shanawa Uranium Mine, in the North West Frontier Province, which also will use *in-situ* leaching, is planned to be completed in 2014, and would increase uranium production in Pakistan to 60 tons per year.⁶⁹⁴

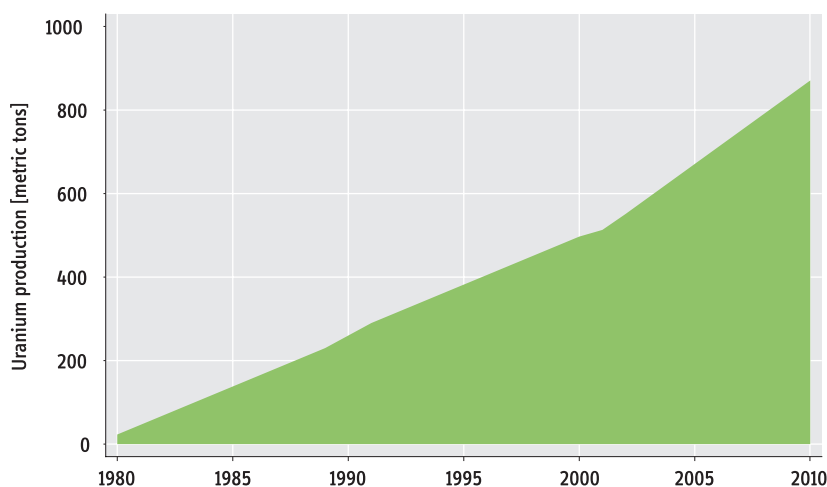


Figure 10.1. Estimated uranium production in Pakistan, 1980 to 2010. The value for 2010 is a projection assuming that uranium production is continuing at an average rate of 40 tons per year. A total of about

800 tons has been produced. Source: OECD/IAEA *Uranium: Resources, Production and Demand (Red Books) 1990–2009*.

Uranium imports. Pakistan signed a safeguards agreement with the IAEA in 1977 for the import of uranium concentrate (commonly known as yellowcake) from Niger.⁶⁹⁵ It is reported to have bought at least 60–110 tons of uranium directly from Niger.⁶⁹⁶ Since it was safeguarded, it is not accounted for here as contributing to Pakistan's unsafeguarded stocks of HEU and plutonium.

Pakistan also received natural uranium fuel for its KANUPP power reactor, purchased from Canada, which began operating in 1970. Following the 1974 Indian nuclear test and Pakistan's refusal to sign the Non-Proliferation Treaty (NPT), Canada ended its fuel supply. In response, Pakistan developed its own fuel fabrication capability, producing its first test fuel bundle in 1978.⁶⁹⁷ The total uranium consumption for KANUPP from 1980 to 2010 amounts to about 148 tons, based on its declared electricity production in this period.⁶⁹⁸ Since this reactor is safeguarded, we assume the uranium feed was largely taken from the safeguarded imported material rather than unsafeguarded domestic production.

Pakistan may have received 15 tons of uranium hexafluoride from China in 1982 in the form of 10 tons of un-enriched uranium hexafluoride and 5 tons enriched to 3%.⁶⁹⁹ This is not included in the accounting here. China also supplies all the low-enriched uranium (LEU) fuel for the 300 MWe Chashma-I reactor that it sold to Pakistan and is expected to provide fuel for the second reactor, currently under construction, as well as for the two additional reactors that Pakistan is seeking from China. China provided LEU for the safeguarded 10 MWt U.S.-supplied PARR-1 research reactor after the reactor was converted in 1992 from HEU to LEU fuel.

Highly Enriched Uranium (HEU)

Pakistan initially explored a number of techniques for uranium enrichment.⁷⁰⁰ In November 1974, a decision was made to proceed with a gas centrifuge enrichment plant.⁷⁰¹ Pakistan contracted with a German company to build a uranium hexafluoride plant, with a reported capacity of about 200 tons per year, which apparently began work in 1980.⁷⁰² The plant is not under safeguards. According to A.Q. Khan, Pakistan also received uranium hexafluoride from China in 1982.⁷⁰³

Enrichment capacity history. Pakistan achieved separation of uranium isotopes in its prototype centrifuge in June 1978 and a first cascade of 54 machines was set up by early 1979.⁷⁰⁴ Pakistan was able to enrich natural uranium up to a few percent uranium-235 by 1980,⁷⁰⁵ and up to weapon-grade by 1982.⁷⁰⁶ A 1983 U.S. State Department briefing paper noted, however, that Pakistan had “not yet produced significant quantities of enriched uranium.”⁷⁰⁷ By 1984, A. Q. Khan claimed that Pakistan had produced enough uranium for a nuclear test.⁷⁰⁸ By 1988, it was reported that Pakistan had enough weapon-grade uranium for four to six weapons (i.e., 100–150 kg of HEU).⁷⁰⁹ A U.S. official claimed in late 1991 that Pakistan had sufficient HEU for as many as six weapons.⁷¹⁰ This suggests Pakistan was enriching only a fraction of the uranium it had mined up to that time, and may have built up a small natural-uranium stockpile during this period.

The United States imposed sanctions on Pakistan in 1990, and in an attempt to have sanctions lifted, Pakistan may have adopted in 1991 an indefinite moratorium on HEU production,⁷¹¹ limiting itself to producing low-enriched uranium, possibly up to 5%.⁷¹² A.Q. Khan later denied there had been a HEU production suspension.⁷¹³ It is assumed here there was no moratorium.⁷¹⁴ The estimated cumulative production and thus the size of the current stockpile of HEU does not depend on this assumption, however.⁷¹⁵

Pakistan may have been working during the 1990s to increase its enrichment capacity. Satellite imagery suggests a second production area was added at some stage to the Kahuta facility, possibly replacing the original enrichment halls.⁷¹⁶ During this time, Pakistan developed the indigenous capability to produce maraging steel and some other components for centrifuges. It also imported components, including in

1995 the purchase from China of 5000 ring magnets, which serve as part of the upper bearings of centrifuges, and would allow for building perhaps several thousand additional machines.⁷¹⁷ In 1998, following the nuclear tests, along with two pilot centrifuge plants, and the Kahuta facility, the U.S. Department of Commerce listed an “enrichment plant” at Gadwal as subject to export restrictions.⁷¹⁸

A possible Pakistani cascade design can be inferred from cascade plans, described as being “adapted by Pakistan test results, experience and reference calculations,” that were provided by the A.Q. Khan network to a South African company hired to manufacture an enrichment plant for export to Libya.⁷¹⁹ The plan shows four blocks of cascades totaling 5832 centrifuges. There are separate feed and withdrawal stages for each of these cascades. This would allow, in principle, each of these enrichment stages to be carried out in separate facilities. A cascade design of half this size (about 3000 machines) is also feasible. This is consistent with reports that the plans for Kahuta in the late 1980s called for 2000–3000 centrifuges and a claim by a U.S. official that by 1991 Kahuta had about 3000 machines operating.⁷²⁰ If these 3000 machines were P-1 or P-2 centrifuges, with 3 or 5 SWU per year enrichment capacity each respectively, this would give a total capacity of 9000 or 15,000 SWU for the full cascade. At some stage, probably in the mid-1980s, Pakistan abandoned its use of P-1 machines altogether, and committed to using only P-2.⁷²¹ Pakistan may have started developing more powerful P-3 and P-4 centrifuges at this time.⁷²² These may have been ready to introduce into service in the late 1990s.

There remains, however, great uncertainty in the estimate of HEU stocks because of the lack of reliable information both on the later enrichment capacity and operating history of Pakistan’s centrifuge plants. Several possible scenarios for the history of the growth of Pakistan’s enrichment capacity can be considered, all of which share a common early history:

- a) No substantial enrichment capacity till 1982;
- b) Sufficient capacity to make 20 kg per year of HEU by 1983–1985 (3000 SWU per year, produced by 1000 centrifuges of 3 SWU each);
- c) An increase from 3000 SWU per year in 1985 to 15,000 SWU per year by 1990, with a move from P-1 to P-2 machines;
- d) No significant increase in enrichment capacity from 1991 until the 1998 nuclear tests.

After the 1998 tests, Pakistan may have maintained a constant enrichment capacity of 15,000 SWU per year or, more likely, increased it to 30,000 SWU per year or even 45,000 SWU per year. This could have been achieved from 6000–9000 P-2 machines, or a smaller number of P-3 or P-4 machines.⁷²³ Enrichment to weapon-grade need not all be at one site, but could be distributed across several sites. The enrichment plant at Gadwal has been reported as enriching uranium (presumably from Kahuta) to weapon-grade.⁷²⁴

Figure 10.2 shows the cumulative HEU production as of 2010. For enrichment capacities of 15,000 to 45,000 SWU per year, with tails of 0.2–0.3%, Pakistan could have produced between 1.6 tons and 3.8 tons of highly enriched uranium (90% uranium-235)—rounded to the nearest 100 kg. This would have required 283–821 tons of natural

uranium feed, respectively. Pakistan would not have sufficient domestic uranium resources to sustain an enrichment capacity of 45,000 SWU per year with tails of 0.4 %. In sum, it is estimated that, as of 2010, Pakistan may have produced about 2.7 tons of highly enriched uranium (with an uncertainty of about ± 1 ton, or roughly 30%). This would be consistent with an enrichment capacity of 30,000 SWU per year and tails of 0.3%.

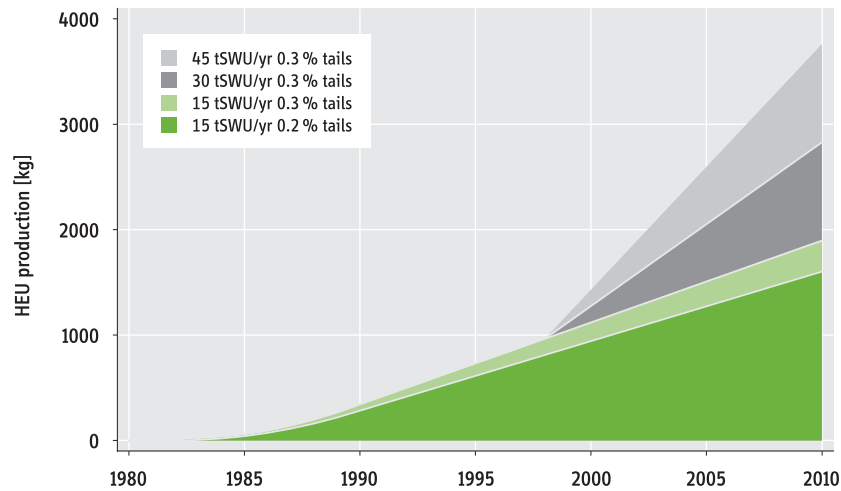


Figure 10.2. HEU production, 1980 – 2010.

HEU imports and exports. Pakistan has imported HEU both from the United States and China. The United States supplied Pakistan’s PARR-1 research reactor in 1963 and its HEU-fuel. After the reactor’s conversion to LEU fuel in 1992, the fuel was supplied by China. The PARR-2 reactor, and its 1 kg of long-lived HEU fuel, was supplied by China.⁷²⁵ Both reactors and their spent fuel are under IAEA safeguards. In addition, A.Q. Khan claims that in 1982 Pakistan received 50 kg of weapon-grade HEU from China.⁷²⁶ Given the uncertainty in Pakistan’s total HEU production, these acquisitions do not add substantially to the estimate of Pakistan’s stockpile.

HEU utilization. Pakistan carried out six nuclear weapon tests in 1998, with five tests on May 28 and one test on May 30. These are generally believed to have been HEU-based implosion weapons. Assuming that each weapon contained 12–18 kg of weapon-grade uranium per core, the tests would have consumed about 100 kg of HEU.⁷²⁷ Pakistan does not use HEU for naval propulsion or to produce fuel for its two safeguarded research reactors. Pakistan is not reported to have exported any HEU. This suggests that as of 2010, Pakistan may have a total HEU stock of 1.5–3.6 tons.

Plutonium

Pakistan has two power reactors and two plutonium production reactors. A new power reactor and production reactor are under construction. Pakistan does not reprocess its safeguarded power reactor spent fuel. It does not have a fast reactor program, nor does it use MOX fuel or have critical reactors or pulsed reactors that it fuels. Therefore, unlike India, it does not have a civilian plutonium program.

Production Reactors. Pakistan's Khushab-I plutonium production reactor is reported to be a heavy-water-moderated, light-water-cooled, natural-uranium-fueled reactor with a capacity of about 40–50 MWt.⁷²⁸ It seems to be based on the Canadian NRX reactor, which was 40 MWt, as is India's CIRUS reactor. Work on Khushab-I started in 1986–87 and the reactor came on line in 1998.⁷²⁹ China is believed to have helped in its construction.⁷³⁰

A second production reactor has been completed at Khushab and may have started operation in late 2009 or early 2010.⁷³¹ A third production reactor is under construction—work on it started in 2005 or 2006.⁷³² Imagery from September 2010 shows that construction of Khushab-III may be completed possibly sometime in 2011.⁷³³

U.S. government sources have suggested that the Khushab-II reactor “appeared to be roughly the same size as the small one Pakistan currently uses to make plutonium for its nuclear program.”⁷³⁴ The cooling towers of Khushab I and Khushab II are nearly identical arrays of eight mechanical-draft cooling towers of about 5 meter diameter each. The Khushab II and III reactors appear identical to each other, with similar arrays of cooling towers (Figure 10.3), suggesting that the new reactors have a power of 40–50 MWt each, like Khushab-I.

It is possible, however, that Khushab-II and Khushab-III could be heavy-water-moderated and cooled, unlike Khushab-I. This would allow an increase plutonium production without an increase in the power of these new reactors. See Appendix B for the effect on plutonium production rates of different kinds of reactors.



Figure 10.3. Khushab-II reactor (right) and Khushab-III reactor (left), as of September 2010.

The two reactors are housed in similar structures, with arrays of cooling towers similar to each other and to the Khushab-I reactor, suggesting all three reactors may be of about equal power. Coordinates 32.0094 N, 72.1725 E. Source: DigitalGlobe, courtesy of ISIS.

Reprocessing. Pakistan reprocesses spent fuel from Khushab-I at its New Labs facility near Rawalpindi, which has an estimated capacity of 10–20 tons per year of heavy metal.⁷³⁵ In March 2000, air samples reportedly showed traces of krypton-85, indicative of active reprocessing.⁷³⁶ If Khushab-I began operating in 1998, the first batch of Khushab-I spent fuel could have been taken out in 1999, cooled and reprocessed by early 2000. Pakistan has built a second reprocessing plant at the New Labs, which looks similar in size to the original reprocessing plant (Figure 10.4).⁷³⁷



Figure 10.4. Reprocessing facilities at the New Labs complex, Rawalpindi. The large building on the upper right of the image is the new reprocessing plant, with a chimney stack similar in size to that of the earlier plant on the left. Coordinates: 33.649 N, 73.255 E. Source: Google Earth.

Between 2002 and 2006 Pakistan worked on completing a larger reprocessing plant at Chashma, originally to have been supplied by France in the late 1970s, and designed to handle 100 tons of spent fuel per year.⁷³⁸ There is no evidence that it has become operational as yet.

Plutonium production. The timeline for the Khushab production reactors suggests that Pakistan has been accumulating weapon-grade plutonium since 2000 from Khushab-I. It is assumed that the Khushab-reactor operates to produce weapons plutonium at a rate of 0.78 g of plutonium per megawatt (thermal) day.⁷³⁹ A reactor of 40–50 MWt operating at 50% capacity will produce about 5.7–7.1 kg of weapon-grade plutonium per year, and at 80% capacity would produce about 9–11.5 kg of plutonium per year.⁷⁴⁰ As of 2010, Pakistan could have accumulated about 60–130 kg of plutonium (rounded to the nearest 10 kg). The Khushab-I reactor would discharge about 6 to 12 tons of low-burnup spent fuel per year depending upon its capacity factor. Along with weapons plutonium, reprocessing this spent fuel would provide Pakistan with a stock of 65–130 tons of reprocessed uranium, containing about 0.6% uranium-235. This could be fed into the enrichment plant to produce HEU should Pakistan wish to increase its production of fissile materials for weapons from its limited natural uranium production or it could recycle the reprocessed uranium one or more times through the production reactor.

With Khushab-II starting in 2010, and allowing time to irradiate and cool the fuel before reprocessing, the first plutonium from the new reactor could become available by 2011. This would at least double Pakistan's annual production of weapon plutonium. Plutonium from Khushab-III could become available in 2012–2013, if not before.

Barring a possible Fissile Material Cutoff Treaty, the Khushab reactors might produce weapon-grade plutonium for Pakistan's nuclear arsenal for several decades. India's CIRUS reactor operated for over 30 years before undergoing a major refurbishment in the 1990s, and is now expected to be shut-down in 2010.⁷⁴¹

Summary

As of 2010, Pakistan may have produced about 2.7 ± 1 tons of highly enriched uranium. Allowing for HEU utilization in the six nuclear weapon tests in 1998, Pakistan may have currently 1.6–3.6 tons of highly enriched uranium, with a mid-range estimate of 2.6 ± 1 tons.

Pakistan also may have produced 60–130 kg of weapons plutonium, with a mid-range estimate of 100 kg.

As a result of its enrichment and reprocessing operations, along with the respective fissile material stockpiles for weapons, Pakistan would have accumulated 280–820 tons of 0.2–0.3% depleted uranium tails and 65–130 tons of reprocessed uranium and associated high level waste from reprocessing.

Some portion of Pakistan's stock of depleted uranium has been used to produce depleted uranium munitions.⁷⁴² It may still be possible to reconstruct and partially verify its history of uranium enrichment from the remaining uranium tails. It should be possible also to carry out nuclear archaeology on Pakistan's plutonium production reactors, since none has been shut-down, decommissioned, and dismantled.

11 The Non-weapon States

Almost all the highly enriched uranium (HEU) and separated plutonium in the non-weapon states today were produced by or separated in the nuclear weapon states. The exceptions are plutonium separated by Japan and HEU produced by South Africa. All this material is under IAEA safeguards.

During the period 1997–2009, the IAEA had under safeguards in non-weapon states on the order of ten tons of separated plutonium—sufficient for more than one thousand nuclear weapons. Most of this separated plutonium was in Japan. Three other non-weapon states, Belgium, Germany and Switzerland, recycle plutonium in “mixed-oxide” (MOX) fuel fabricated in France and the United Kingdom, but the fuel is loaded quickly into their reactors and none of the three countries has renewed its spent-fuel reprocessing contracts with France or the United Kingdom. Increasingly therefore, plutonium stocks in the non-weapon states will be an issue relating to Japan. South Korea, however, is exploring the possibility of launching its own domestic reprocessing program.

HEU is more widely distributed because, during the Cold War, the competitive U.S. and Soviet “Atoms for Peace” programs provided HEU-fueled research reactors to 36 countries. The number of non-weapon states with HEU-fueled research reactors increased further in 1991 as a result of the breakup of the former Soviet Union and Yugoslavia.

Today, the number of countries with 1 kg or more of HEU has dropped by almost half. This is due largely to the U.S.-led Global Threat Reduction Initiative (GTRI) converting HEU-fueled research reactors to low-enriched uranium (LEU) and shipping irradiated and unused fresh HEU fuel back to the United States and Russia.

The non-weapon states still possess about 7 tons of U-235 in HEU, which, by the IAEA’s metric, would be sufficient for about three hundred nuclear weapons.⁷⁴³ The prognosis for further reductions in this stockpile is good, however. Most of the 41 reactors in non-weapon states that used HEU in fuel or in targets as of the end of 2009 will be shut down or converted to low-enriched uranium by 2020. Some difficult cases are likely to remain, however, along with tens of HEU-fueled reactors still in the weapon states.

Plutonium

As of the end of 2008, Japan accounted for almost all of the separated plutonium in the non-weapon states (Figure 11.1). Japan separates plutonium domestically.⁷⁴⁴ In the past, Belgium, Canada, Germany, and Italy all had pilot-scale reprocessing and MOX-fuel-fabrication plants. These facilities have been decommissioned, and all plutonium has been removed from them.⁷⁴⁵ Today, Belgium, Germany, and Switzerland have plutonium-recycle programs but the separation of their plutonium from spent fuel and its fabrication into mixed-oxide fuel is done in France and (to a very limited extent) in the United Kingdom. This plutonium therefore appears only briefly in unirradiated form in these non-weapon states before it is loaded into power reactors.

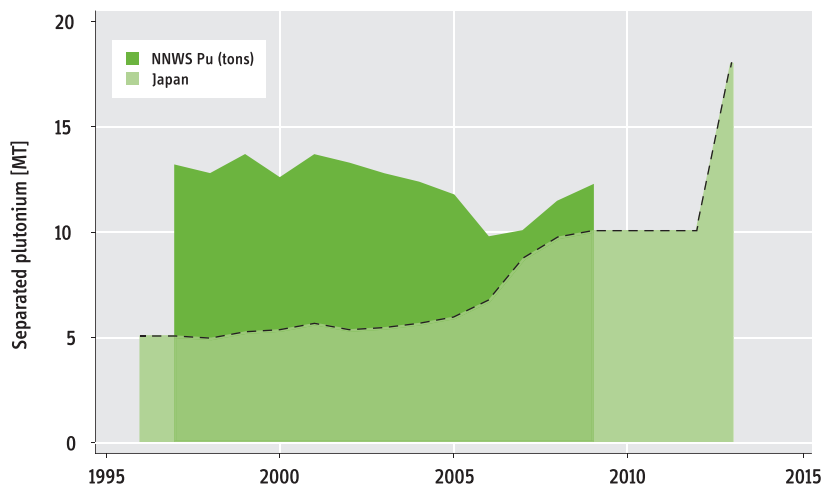


Figure 11.1. Japan accounts for an increasing share of the total separated plutonium in the non-weapon states. If the Rokkasho Reprocessing Plant begins to operate at full capacity, Japan's stockpile of plutonium will increase by 8 tons annually for some

years until its MOX-fuel fabrication plant can be completed and plutonium-recycle programs in about 20 additional reactors can be organized. (Based on *IAEA Annual Reports* and Japan's annual public INFCIRC/549 reports to the IAEA).

As of the end of 2009, France and the United Kingdom held at their reprocessing and fuel-fabrication plants respectively 25.9 and 27.7 tons of non-weapon-state separated plutonium.⁷⁴⁶ Japan owned about two thirds of these stocks, 18.9 tons stored in France and 17.3 tons in the United Kingdom.⁷⁴⁷ Japan has not been able to take back these stocks yet because of delays in its MOX program.

In France, reprocessing of foreign spent fuel has largely come to an end. As of the end of 2009, all Belgian, German, Japanese, and virtually all Swiss spent fuel had been reprocessed, and all the resulting separated plutonium had been shipped to France's Melox MOX fuel-fabrication plant. Any remaining plutonium owned by Belgium, Germany, and Switzerland in France will soon have been recycled.⁷⁴⁸ Italy, the Netherlands, and Spain, which have each sent relatively small amounts of spent fuel to France for reprocessing, apparently have contracted to have the recovered plutonium recycled in French reactors.

In the United Kingdom, all of Japan's spent fuel has been reprocessed.⁷⁴⁹ Completion of the German and Swiss reprocessing contracts has been delayed for at least a decade, however, by technical problems and accidents at the THORP reprocessing plant.⁷⁵⁰ The United Kingdom has the same minor customers as does France (Italy, Spain, and the Netherlands), which do not recycle their separated plutonium. Britain currently stores its own separated plutonium, however, and cannot contract to dispose of foreign stocks until it has worked out a policy for its own.

Today, therefore, Japan is the only non-weapon state that reprocesses spent fuel and fabricates plutonium-containing fuel. Its domestic plutonium stock is expected to grow rapidly in the next few years because it has built a full-scale domestic reprocessing plant at Rokkasho Village in Aomori Prefecture that is designed to reprocess 800 tons of spent fuel, separating over 8 tons of plutonium annually. A MOX fuel fabrication plant is planned for completion in 2015 to make it possible to recycle the domestically-separated plutonium. In the interim, however, unless the Rokkasho Reprocessing Plant remains non-operational, Japan's domestic stockpile of separated plutonium will grow dramatically.

Meanwhile, the large-scale commercialization of plutonium breeder reactors, the original rationale for Japan's reprocessing, has receded into the distant future. In 1956, commercialization was projected for 1970. Today, it is projected as an "option" after 2050.⁷⁵¹

The new rationale for reprocessing in Japan has become the fact that many spent-fuel pools at Japan's reactor sites are filling up. Tacitly, however, Japan's spent-fuel-management policy has begun to shift toward interim storage. Japan's last shipments of spent fuel to France and the United Kingdom for reprocessing were in 1998.⁷⁵² Commissioning of its domestic Rokkasho Reprocessing Plant was originally scheduled for 2000,⁷⁵³ but construction and commissioning have been repeatedly delayed by technical problems and full operation is currently projected for 2012 (the 18th such delay).⁷⁵⁴ A dry-storage facility with a capacity of 5,000 tons is being built near Mutsu in Aomori Prefecture and more dry-storage facilities are being proposed.⁷⁵⁵

In the meantime, South Korea is arguing that it has the same spent-fuel storage problems as Japan and should have the same right to reprocess. It is currently negotiating a new Agreement of Cooperation on Civil Uses of Atomic Energy with the United States to replace the existing agreement, which will expire in 2014.⁷⁵⁶

Highly Enriched Uranium

Virtually all of the HEU in the non-weapon states originally came from the United States or Soviet Union/Russia, with small amounts from China, France and the United Kingdom.⁷⁵⁷ South Africa is the only non-weapon state that produced its own stockpile of HEU, which is a legacy of its nuclear-weapon program. Figure 11.2 shows the amount of HEU and contained U-235 reported by the IAEA to be in the non-weapon states during 1997–2009.

It will be seen that the total amount of HEU under IAEA safeguards approximately doubled between 2001 and 2002, while the contained U-235 increased by about 50 percent. This almost certainly is due to approximately ten tons of HEU in spent fuel from Kazakhstan's shutdown demonstration BN-350 breeder reactor coming under IAEA safeguards.⁷⁵⁸ The increase in the amount of contained U-235 was much less because the original enrichment of the HEU was barely greater than the 20 percent uranium-235 dividing line between HEU and LEU.⁷⁵⁹

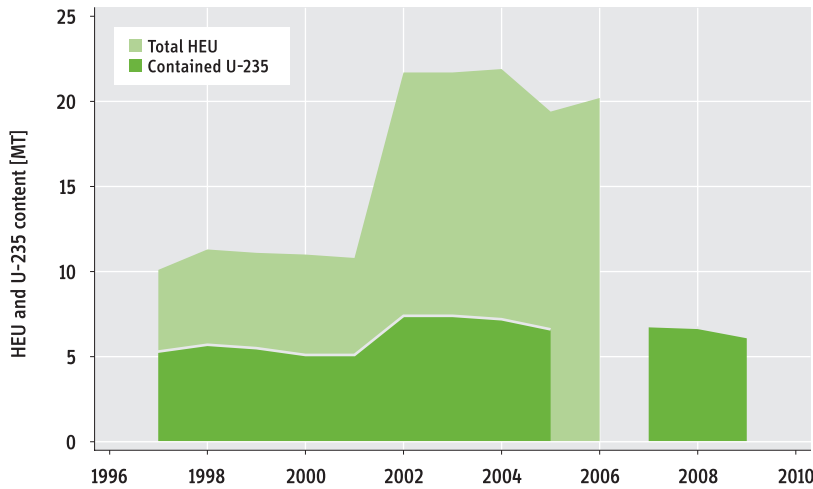


Figure 11.2. Trends in HEU and contained U-235 under IAEA safeguards in non-weapon states between 1997 and 2008, based on IAEA Annual Reports.⁷⁶⁰

Although the United States and Russia continue to export HEU fuel to research reactors that have not yet been converted to low-enriched uranium, the net flow of HEU from the weapon states to the non-weapon states has reversed. Since 2002, Russia and the United States have cooperated in efforts to repatriate unused fresh and spent HEU fuel from the non-weapons states. Between 1996 and January 2010, foreign research reactor fuel originally containing 1.63 tons of HEU was repatriated to the United States and 0.915 tons to Russia.⁷⁶¹ As of 22 April 2010, twenty-one non-weapon states had been cleared of HEU to a level where the residual amount of HEU in country is less than 1 kg (Figure 11.3). More than 25 countries still have 1 kg or more HEU, however (Table 11.1).

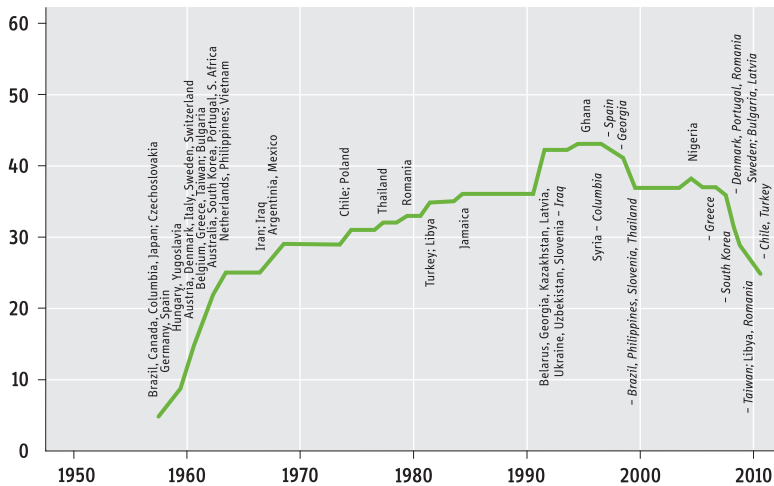


Figure 11.3. Number of non-weapon states that have possessed more than one kg of HEU. The increase in the early 1990s is due to the breakup of the Soviet Union. Semicolons divide countries into U.S. and Soviet supplied. Countries are cleared out when they appear in italics.⁷⁶²

Civilian HEU in country	Countries
> 10,000 kg	Kazakhstan, mostly in BN-350 spent fuel but 73.7 kg removed in Russian origin spent research reactor fuel. ⁷⁶³
1,000–10,000 kg	Canada and Japan ⁷⁶⁴
100–1,000 kg	Belarus, Belgium, Germany, ⁷⁶⁵ Italy, Netherlands, Poland, ⁷⁶⁶ South Africa, Ukraine
10–100 kg	Czech Republic, ⁷⁶⁷ Mexico, Serbia, ⁷⁶⁸ Uzbekistan ⁷⁶⁹
1–10 kg	Argentina, ⁷⁷⁰ Australia, Austria, Hungary, ⁷⁷¹ Iran, Norway, ⁷⁷² Switzerland, Vietnam ⁷⁷³
≈ 1 kg ⁷⁷⁴	Ghana, Jamaica, Nigeria, Syria
<1 kg ("cleaned out")	U.S. origin; ⁷⁷⁵ Brazil, Chile, ⁷⁷⁶ Colombia, Denmark, Greece, Indonesia, Portugal, Philippines, S. Korea, Romania (also from Russia) Slovenia, Spain, Sweden, Taiwan, Thailand, Turkey; Soviet/Russian origin: Bulgaria, ⁷⁷⁷ Georgia, ⁷⁷⁸ Iraq ⁷⁷⁹ (also from France), Latvia, ⁷⁸⁰ Libya, ⁷⁸¹ Romania ⁷⁸² (also from the United States)

Table 11.1. HEU holdings of non-weapon states that have possessed more than one kilogram.⁷⁸³
Due to the continuing operation of the FRM-II

research reactor, Germany will soon move into the category of states having more than 1000 kg of highly enriched uranium.

U.S. exports and returns. During 1965–77, the United States exported an average of 1.45 tons of HEU annually with an average enrichment of about 70 percent (Figure 11.4). After India used U.S. Atoms-for-Peace assistance to acquire plutonium for its 1974 “peaceful nuclear explosion,” however, efforts were launched to end U.S. HEU exports. The Reduced Enrichment for Research and Test Reactors (RERTR) program was established in 1978 for the purpose of converting foreign and domestic HEU-fueled reactors to low-enriched uranium (LEU) fuel.⁷⁸⁴ The conversion is achieved by replacing weapon-grade HEU fuel with fuel containing an approximately five-times higher concentration of uranium. This makes it possible for the fuel to contain a little more U-235 fuel—but diluted with added U-238 to slightly less than the 20-percent enrichment dividing HEU from LEU.

Concerns about the proliferation dangers of exported HEU fuel were reinforced when it was learned that, on the eve of the 1991 Gulf War, Saddam Hussein had ordered a “crash program” aimed at recovering for use in a nuclear weapon about 50 kg of HEU in research-reactor fuel provided by France and Russia.⁷⁸⁵

In 1992, the U.S. Congress passed the “Schumer Amendment,” which required countries that imported U.S. HEU to commit to convert to LEU fuel as soon as it became available. A second condition was that, if appropriate LEU fuel was not already available, the United States must have an active program underway to develop it.⁷⁸⁶ These requirements resulted in U.S. HEU exports dropping to zero during 1994–1997 before resuming at a much lower level. The United States only exported a total of about 0.393 tons of U-235 in HEU during 1998–2008.

According to the U.S. Department of Energy report, *Highly Enriched Uranium: Striking a Balance*,⁷⁸⁷ as of the end of 30 September 1996, the United States had transferred 25.4 metric tons of HEU to foreign countries for peaceful purposes.⁷⁸⁸ Of this exported HEU, 6.3 tons, mostly in spent fuel, had been returned as of 1988, when the original Congressional authorization to repatriate HEU spent fuel expired.⁷⁸⁹

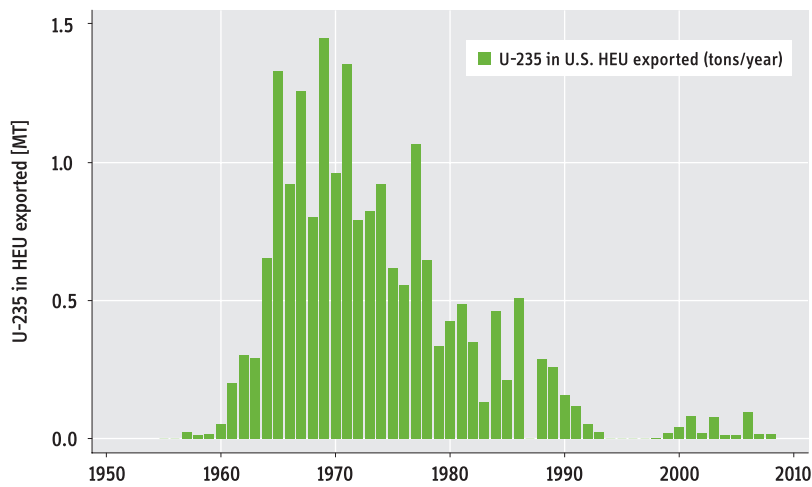


Figure 11.4. U.S. annual exports of HEU for civilian purposes measured in tons of contained U-235. Information provided by Alan Kuperman.⁷⁹⁰

Of the original exported U.S. HEU, 16.7 tons containing 11.5 tons of U-235 were shipped to non-weapon states.⁷⁹¹ Table 11.2 shows a breakdown of the original destinations of this HEU. The IAEA assumes that 25 kg of U-235 in HEU is sufficient to make a first-generation nuclear weapon.⁷⁹²

Of the total U.S. U-235 in HEU exported to the non-weapon states, 66% was exported to Germany, 18% to Canada, 9% to Japan, and the remaining 7% to twenty-six other countries. There were many subsequent retransfers, however. In 1993, the U.S. Nuclear Regulatory Commission (NRC) reported to Congress a net retransfer of 1.16 tons of U.S. HEU to non-European countries. Transfers within the European Union (EU) are not fully visible to the U.S. Government because it is not officially informed about them. Table 11.2 also shows the NRC numbers for net exports of U.S. HEU as of the end of 1992, including its estimates of retransfers within the EU. Balancing out U.S. shipments to the non-weapon states; retransfers between France, the United Kingdom and the non-weapon states; and repatriation to the United States, there had been a net flow of 11.6 tons of U.S. HEU to the non-weapon states.

In 1996, Congress renewed the U.S. Department of Energy’s authority to repatriate HEU in two common types of research-reactor fuel, from reactors whose operators had committed to convert to LEU fuel.⁷⁹³ Largely as a result of this provision, there has been a reduction of 1.2 tons in the net amount of U.S. HEU shipped to non-weapon states (Table 11.2).

	HEU (and contained U-235) in tons		
	Original Exports though 1994 ⁷⁹⁴	After retransfers & returns, end of 1992 ⁷⁹⁵	Exports less returns, 1995 – May 2010 ⁷⁹⁶
European Union before 1993 (Austria, Belgium, Denmark, Germany, Greece, Italy, Netherlands, Portugal, Spain)	12.0 (8.3)	7.9	-0.24 (0.19)
Canada	2.2 (2.0)	1.2	0.14 (0.13)
Japan	2.1 (1.0)	2.0	-0.66 (0.35)
All others (Argentina, Australia, Brazil, Chile, Columbia, Iran, Jamaica, Mexico, Philippines, Romania, South Africa, South Korea, Norway, Slovenia, Sweden, Switzerland, Taiwan, Thailand, Turkey)	0.27 (0.24)	0.48	-0.45 (0.36)
Total	16.7 (11.5)	11.6	-1.21 (0.78)

Table 11.2. U.S. cumulative net HEU exports to non-weapon states through 2009.

Soviet/Russian exports and returns. Soviet/Russian-origin HEU fuel has been exported to Belarus, Bulgaria, the Czech Republic, Georgia, Germany, Hungary, Iraq, Kazakhstan, North Korea, Latvia, Libya, Poland, Romania, Yugoslavia (Serbia and Slovenia), Ukraine, Uzbekistan, Vietnam, and to the European Union via France.⁷⁹⁷

In parallel with the establishment of the U.S. RERTR program in 1978, the Soviet Union too established a program to reduce the enrichment of its exported research-reactor fuel from 80 percent HEU. By the late 1980s, the Soviet Union was exporting only 36-percent enriched fuel.⁷⁹⁸

Prior the breakup of the Soviet Union, it was routine for research-reactor spent fuel to be shipped back to the Mayak reprocessing plant near Chelyabinsk in the Urals from reactors in the Soviet Union but not from Eastern Europe. Afterwards, shipments from the non-Russian republics became more difficult to arrange and the spent HEU fuel accumulated at all the non-Russian reactor sites. Starting in 2002, in a cooperative program with the United States, however, Russia began to accept back Soviet and Russian-origin fresh and spent fuel. As of early 2010, six of the 17 non-weapon states that had been recipients of Soviet/Russian HEU had been cleaned out (Table 11.1).

Other factors influencing non-weapon-state stocks. In addition to U.S. and Russian exports and repatriation, the net amount of HEU in the non-weapon states is subject to other influences, including shipment to France for reprocessing and blend-down, shipments of Russian HEU to France for fuel fabrication for non-weapon states, and special situations.

Shipment to France for reprocessing and blend-down. Between 1998 and 2006, France received for reprocessing 0.4 tons of HEU in spent fuel from Belgium and, between 2000 and 2005, 0.2 tons of UK-origin HEU in spent fuel from Australia.⁷⁹⁹ It was reprocessed with power-reactor fuel and thereby blended down to LEU. Research-reactor fuel containing HEU was also reprocessed in Belgium and the United Kingdom but it appears that most of the recovered HEU was recycled into new HEU fuel.⁸⁰⁰

Shipments from Russia via France. In addition to its continuing supply of 36-percent enriched HEU to Soviet-designed reactors, pending their conversion or shutdown, Russia shipped to France about a ton of weapon-grade (90-percent enriched) uranium to be fabricated into fuel for Western European research reactors. France's Cerca fabricates research-reactor fuel for virtually all research reactors in the European Union and also redistributes unused fresh HEU within the European Union.

The primary beneficiary of the Russian shipments is the FRM-II, a German research reactor located in Bavaria that started operating in 2004 and uses about 40 kg of HEU per year.⁸⁰¹ Since there is no plan for conversion of the FRM-II to LEU fuel, it is not eligible to receive U.S. HEU.

In 1996, Russia agreed to sell France 0.62 tons of HEU over nine years. In 1998, the German government contracted directly with Russia for up to an additional 1.2 tons of 93-percent-enriched uranium for the FRM-II to be delivered to Cerca. 400 kg had been delivered as of 2003 when a new German government suspended the contract.⁸⁰²

Germany's INFCIRC/549 HEU declarations to the IAEA⁸⁰³ show that the amount of HEU in irradiated fuel stored in Germany has been increasing despite shipments of more than 100 kg to the United States during 2000–2008.⁸⁰⁴ This growth will continue as long as the FRM-II operates on HEU fuel because spent FRM-II fuel is not qualified for U.S. take-back⁸⁰⁵ and, by German law, spent fuel can no longer be shipped to France for reprocessing.

The FRM-II is difficult to convert because its designers used HEU in an early medium-uranium-density fuel design that had been developed to convert reactors to LEU. Its operators are committed to reduce the enrichment of the FRM-II fuel to 50 percent by using a higher-uranium-density fuel,⁸⁰⁶ and probably could go to a still lower enrichment using the highest density fuel that can be developed (uranium-metal alloy) but they believe that conversion to LEU fuel would require unacceptable compromises in performance.⁸⁰⁷

Special situations. The drop in 2005 of the amount of HEU in the non-weapon states shown in Figure 11.2 is associated with the down-blending to LEU of 2.9 tons of HEU in unirradiated BN-350 fuel in an operation that was completed in 2005 by a partnership of the government of Kazakhstan and a U.S. NGO, the Nuclear Threat Initiative. The total amount of U-235 under safeguards changed much less because the enrichment of the HEU was barely above 20 percent.⁸⁰⁸

Prognosis for further reductions. Figure 11.2 shows that the global HEU cleanout effort has not yet greatly reduced the amount of HEU in the non-weapon states. Figure 11.3 shows, however, that it has been dramatically decreasing the number of countries with one kilogram or more of HEU. Looking into the future, one can expect more progress, but there will also be difficult cases. Below, the situation is discussed for groups of countries, classified according to their estimated stocks of HEU (Table 11.1).

Countries with about 1 kg (Ghana, Jamaica, Nigeria, Syria). Canada and China have projects at an advanced stage to convert to LEU the Slowpoke reactor that Canada exported to Jamaica and the Miniature Neutron Source reactors that China exported to Ghana, Nigeria, and Syria. These conversions will not be that significant, however, because the quantities of HEU involved are very small compared to weapon quantities.

Countries with 1–10 kg (Argentina, Australia, Austria, Hungary, Iran, Norway, Switzerland, Vietnam). Argentina, Australia, and Vietnam are in the final stages of cleanout. The operators of the Austrian research reactor have political concerns about converting its fuel, but its core contains only a small amount of HEU.⁸⁰⁹ Switzerland's HEU-fueled reactor is to be shut down. If the issue of refueling Iran's Teheran Research Reactor with LEU fuel could be worked out, removing its spent HEU fuel would probably be part of the deal. Hungary is cooperating in the Russian-U.S. conversion and take-back program while Norway plans to dispose of its HEU domestically.

Countries with 10–100 kg (Czech Republic, Mexico, Serbia, Uzbekistan). All countries in this group are on track to be cleaned out in the next few years. The Czech Republic's LWR-15 reactor should be converted in 2010. At the April 2010 Nuclear Security Summit, Mexico's President committed that its HEU-fueled research reactor would be converted to LEU fuel.⁸¹⁰

Countries with 100–1000 kg (Belarus, Belgium, Germany, Italy, Netherlands, Poland, South Africa, Ukraine). Belarus is undertaking HEU repatriation and conversion projects and Ukraine committed at the April Nuclear Security Summit to eliminate its HEU stock within two years.⁸¹¹ Poland's reactor will be converted within a few years. Belgium is waiting for the development of the high-density LEU fuel that will make possible conversion of its BR2 reactor. That fuel is expected to be available in 2016. The Netherlands and South Africa have already converted their research reactors to LEU fuel.

HEU is also used as a neutron target in Belgium, the Netherlands and South Africa, which, along with Canada, are the major producers of the fission product, molybdenum-99 (Mo-99) whose decay product, technetium-99m, is the most widely used medical radioisotope. In 2009, a U.S. National Academy of Sciences panel found that the major producers could all convert to LEU, but that conversion would cost tens of millions of dollars, take up to several years, and potentially disrupt production during the conversion process.⁸¹² South Africa, however, plans to convert in 2010.⁸¹³ Once it has done so, South Africa will no longer have a reason to preserve the HEU stockpile that is a legacy of its pre-1991 nuclear-weapon program.

A major incentive for such shifts to LEU targets is U.S. legislation that encourages a shift to using Mo-99 produced with LEU from domestic sources if the foreign producers do not shift to LEU. Although the United States accounts for about half of the global market for Mo-99, it does not currently produce the isotope. The U.S. Global Threat Reduction Initiative proposes to provide financial support, however, to a number of domestic organizations interested in producing Mo-99 without the use of HEU.⁸¹⁴

In Italy, the primary obstacle to HEU cleanout is the Tapiro fast-neutron reactor. Since its fuel is weapon-grade uranium-metal alloy, the traditional method of converting to higher density LEU fuel is not available. The reactor is little used, however, and should be decommissioned.⁸¹⁵

Finally, as discussed above, Germany does not plan to convert the FRM-II and therefore could become the last non-weapon state with a HEU-fueled reactor.

Countries with 1000–2000 kg (Canada and Japan). Canada has been importing about 15 kg of weapon-grade uranium annually from the United States for neutron targets in the NRU reactor to produce Mo-99.⁸¹⁶ The NRU production reactor is to be retired in 2016. Canada's government has expressed an interest in shifting to accelerator-based production of medical radioisotopes using non-fission nuclear reactions⁸¹⁷ but MDS Nordion, the company distributing Mo-99 produced in Canada has opted, in the near term, at least, to purchase Mo-99 made with HEU targets in Russia.⁸¹⁸

Canada has committed to returning the NRU's pre-conversion spent HEU fuel to the United States⁸¹⁹ but has not yet focused on how to dispose of the hundreds of kilograms of HEU in the Mo-99 production-target waste. Finally, Canada has three *Slowpoke* reactors that are fueled with lifetime cores containing one kilogram of weapon-grade uranium each. Although these reactors could be converted to LEU in parallel to the conversion of the *Slowpoke* that Canada exported to Jamaica, Canada has not announced that it intends to do so.

In Japan, the most difficult HEU issue is the Fast Critical Assembly (FCA), which is designed to test the criticality of fast-neutron-reactor cores. The FCA has about 200 kg of weapon-grade uranium as well as plutonium and 20% enriched uranium.⁸²⁰ Since Japan has no intention of fueling its breeder reactors with HEU it does not need HEU fuel for the FCA.⁸²¹ Japan also has a fast-neutron critical facility, *YAYOI*, at the University of Tokyo that is very similar to Italy's *Tapiro* reactor, and is to be shut down.⁸²²

Kazakhstan and its 10,000 kg of HEU. Kazakhstan is in a special category only because it has custody of the spent fuel from the shutdown Soviet BN-350 breeder reactor whose HEU fuel was originally enriched to slightly above 20%. It is possible that enough of the U-235 in this spent fuel has been fissioned and transmuted so that most of the uranium is no longer even HEU.⁸²³ Kazakhstan also has two high-powered research reactors that are fueled with HEU and that currently do not have a well-defined mission. If they have a future, they could be converted.

In summary, as of November 2009, the GTRI program counted in the non-weapon states 41 HEU-fueled research reactors as converted to LEU or shut down and 26 still HEU fueled.⁸²⁴ Of these, three reactors: the FRM-II in Germany, *Tapiro* in Italy, and the Fast Critical Assembly (FCA) in Japan, pose the most serious challenges to cleaning out HEU from non-weapon states. Increasingly, however, the problem of HEU-fueled reactors is concentrated in Russia.⁸²⁵

Appendix A

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 more than 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 describes 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 in a “critical mass” of fissile material (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.

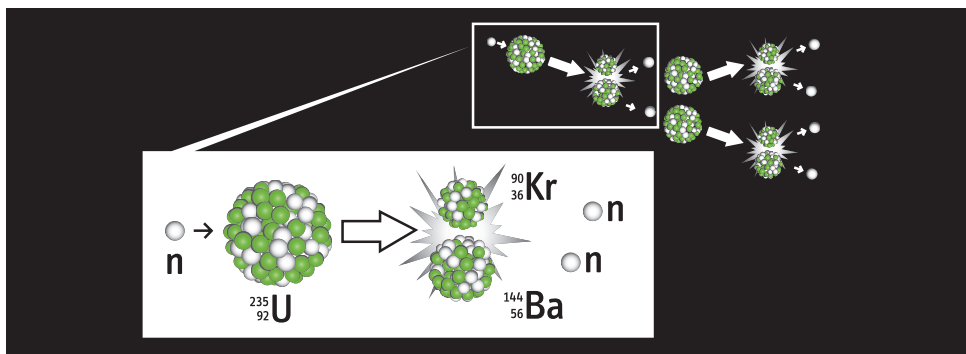


Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission 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.

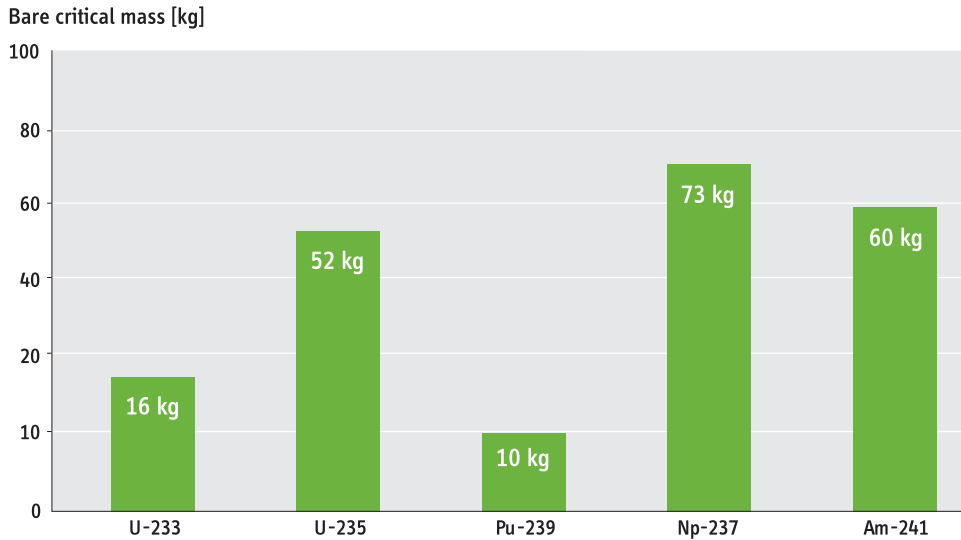


Figure A.2. Bare critical masses for some key fissile isotopes. A bare critical mass is the spherical mass of fissile metal barely large enough to sustain a fission chain reaction in the absence of any material around it. Uranium-235 and plutonium-239 are the key chain-reacting isotopes in highly enriched

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 (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 (Figure A.3, right).

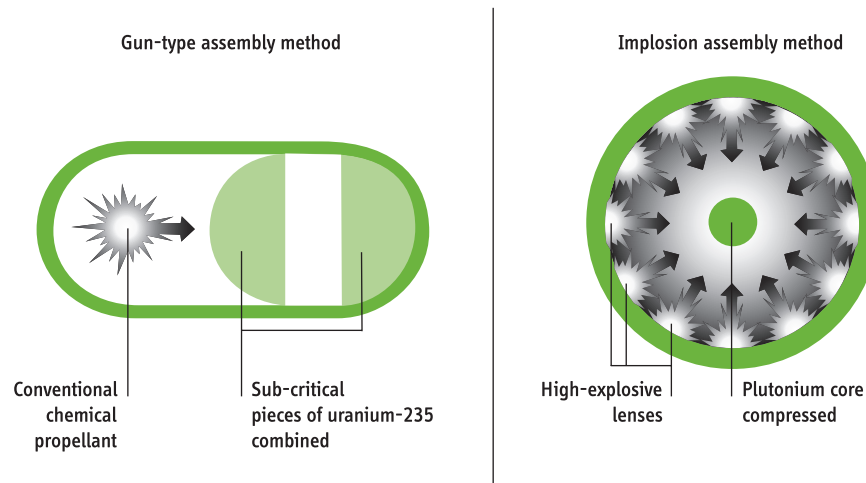


Figure A.3. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated “gun-type” method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow. 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 in the fissile mass at the moment when it will grow most rapidly, i.e., when the mass 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.

Because both implosion and neutron-reflecting material around it can transform a sub-critical into a supercritical mass, the actual amounts of fissile material in the pits of modern implosion-type nuclear weapons are considerably smaller than a 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 uranium-235 contained in HEU, including losses during production. The Nagasaki bomb contained 6 kg of plutonium, of which about 1 kg fissioned. A similar uranium-based first generation implosion weapon could contain about 20 kg of HEU (enriched to 90% uranium-235, i.e. 18 kg of uranium-235 in HEU).

The United States has declassified the fact that 4 kg of plutonium is sufficient to make a more modern nuclear explosive device. As the IAEA significant quantities recognize, an implosion fission weapon requires about three times as much fissile material if it

is based on HEU rather than plutonium. This suggests a modern HEU fission weapon could contain only about 12 kg of HEU.

In modern nuclear weapons, the yield of the fission explosion is typically “boosted” by an order of magnitude 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 increases 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 (Figure A.4). The tritium in the secondary is made during the explosion by neutrons splitting lithium-6 into tritium and helium.

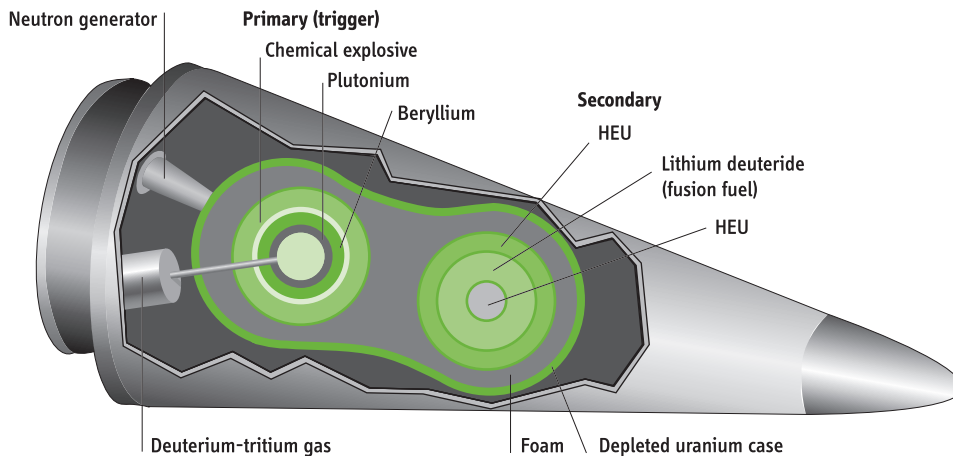


Figure A.4. A modern thermonuclear weapon usually contains both plutonium and highly enriched uranium. Typically, these warheads have a mass of about 200–300 kg and a yield equivalent to hundreds of thousands of tons (kilotons) of chemical explosive, which corresponds to about one kiloton of explosive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

and Nagasaki weighed about 300 kg per kiloton. Source: *Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China, January 3, 1999.*⁸²⁶ The report identifies this design as a U.S. W-87 warhead, with a yield of 300 kt.

Modern nuclear weapons generally contain both plutonium and HEU (Figure A.4). The primary fission stage of a thermonuclear weapon can contain either plutonium or HEU or both plutonium and HEU (the latter is known as a composite core or pit). HEU also is often added to the secondary stage to increase its yield, as a ‘spark-plug’ to generate neutrons and as a tamper for the thermonuclear fuel. Natural or depleted uranium is also used in the outer radiation case, which confines the X-rays from the primary while they compress the thermonuclear secondary. Neutrons from thermonuclear reaction induce fission in this uranium, which can contribute one-half of the yield of the secondary.

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. Many of the older US and Russian strategic weapons had yields in excess of 1 MT and may have contained more than 25 kg HEU, lower yield thermonuclear weapons of the kind in use today (typically around 100–500 kt) could contain 10–20 kg of HEU.

	Plutonium	HEU	Yield	Example
IAEA Significant Quantity (SQ)	8 kg	25 kg*		
1 st -generation gun-type weapon	n/a	50–60 kg	20 kt	Hiroshima
1 st -generation implosion-type weapon	5–6 kg	15–18 kg	20 kt	Nagasaki (6 kg Pu)
2 nd -generation single-stage weapon	4–5 kg	12 kg	40–80 kt	(levitated or boosted pit)
Two-stage low-yield weapon	3–4 kg Pu and 4–7 kg HEU		100–160 kt	W76
Two-stage medium-yield weapon	3–4 kg Pu and 15–25 kg HEU		300–500 kt	W87/W88
Two-stage high-yield weapon	3–4 kg Pu and 50+ kg HEU		1–10 MT	B83

Table A.1. Nuclear weapon generations and estimated respective fissile material quantities. Warhead types are U.S. warhead-designations. The estimates assume about 18 kt per kilogram of nuclear material fissioned, a fission-fraction of

50 % for a 2nd-generation and two-stage weapon, and a yield fraction of 50 % in the secondary from fission in the two-stage weapon. *The significant quantity specifies uranium-235 contained in highly enriched uranium.

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 percent 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.

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.

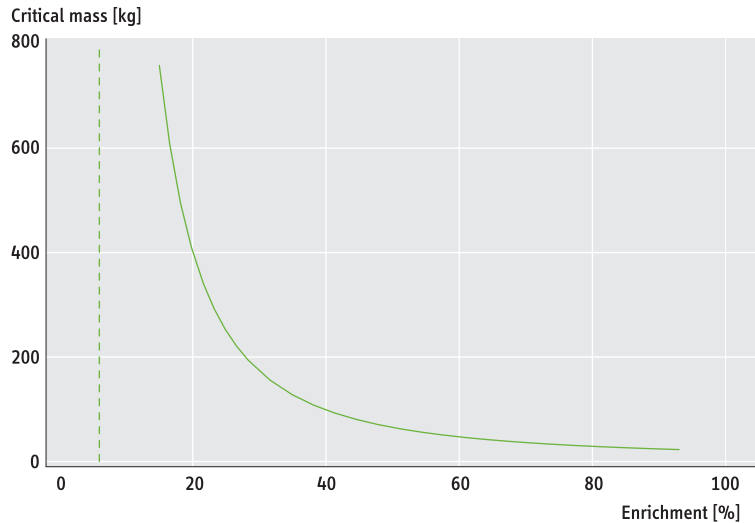


Figure A.5. The fast-neutron critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data

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.

Electromagnetic separation relies on introducing a beam of uranium-containing ions into a magnetic field and separating the ions into two beams by virtue of the fact that the path of the electrically charged ions containing the heavier U-238 atoms is bent less by the magnetic field. This method was used by the United States during the Manhattan Project.

Gaseous diffusion enrichment, also invented during the Manhattan Project, exploits the fact that, in a uranium-containing gas, the lighter molecules containing U-235 move more quickly through the pores in a barrier than those containing U-238. The effect is only a few tenths of a percent, however, and the molecules have to be pumped through thousands of barriers before HEU is produced.

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. 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).

Plutonium. Plutonium is an artificial isotope produced in nuclear reactors after 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 50–60% 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 (Table A.2). Weapon-grade plutonium contains more than 90% of the isotope Pu-239 and has a critical mass about three-quarters that of reactor grade plutonium.

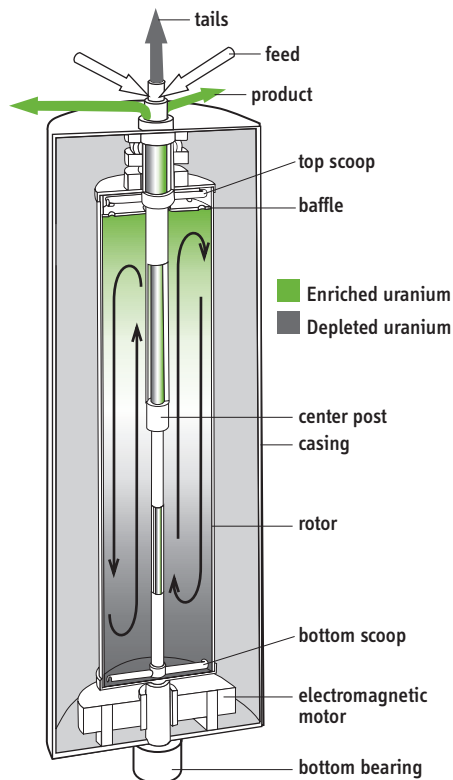


Figure A.6. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small 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.

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 reached its maximum supercritical state. This probability increases with the percentage of Pu-240.

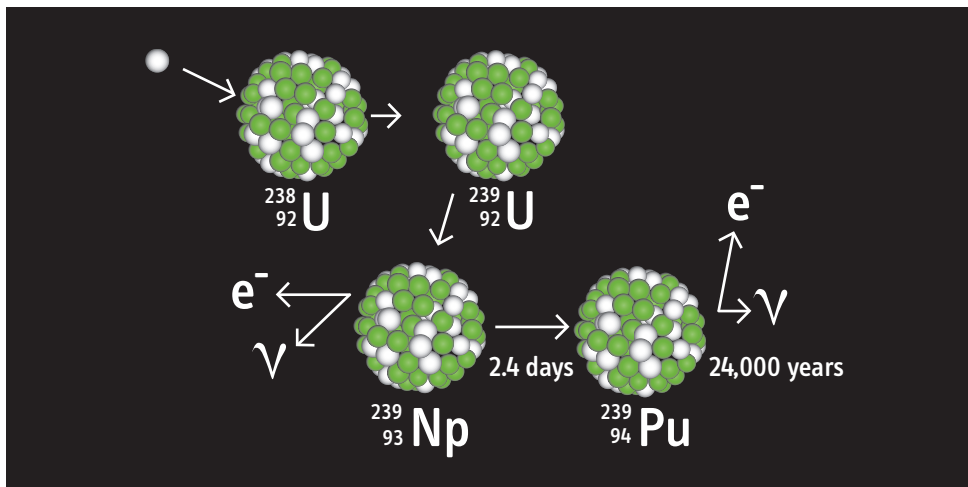


Figure A.7. Making plutonium in a nuclear reactor. A neutron released by the fissioning of a chain-reacting U-235 nucleus is absorbed by the nucleus of a U-238 atom. The resulting U-239 nucleus decays

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.

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 supercritical 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: “Virtually any combination of plutonium isotopes ... can be used to make a nuclear weapon.” The report recognizes that “not all combinations, however, are equally convenient or efficient,” but concludes that “reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states.”⁸²⁷

The same report also noted that, “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 that 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, however, since the 1950s.

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

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
WPu (94 % Pu-239)	10.7		2.3	50
RPu (55 % Pu-239)	14.4		20	460

Table A.2. 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, DC, 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.

Appendix B

Production of Highly Enriched Uranium and Plutonium for Weapons

Separative Work and the Production of Highly Enriched Uranium

The capacity of a uranium enrichment plant is measured in separative work units (SWUs). Both kilogram-SWU and ton-SWUs (1000 kg-SWU) units are used in the literature. In IPFM publications kg-SWUs are used, referred to simply as SWUs. Enrichment typically separates natural uranium feed (F) containing a U-235 fraction, $x_F = 0.0072$ (by atoms), into an enriched product (P) and depleted “tails” (T) with U-235 fractions of x_P and x_T , respectively. The amount of product produced per unit of feed is determined by these U-235 fractions as follows:

$$\frac{P}{F} = \frac{x_F - x_T}{x_P - x_T}$$

The amount of separative work, measured in SWUs (ΔU) required to produce a kg of product for a specified tails assay, is

$$\frac{\Delta U}{P} = V(x_P) - V(x_T) - \left(\frac{F}{P}\right) \left[V(x_F) - V(x_T) \right]$$

where $V(x)$, the value function is given by

$$V(x) = (2x - 1) \ln \left(\frac{x}{1 - x} \right)$$

SWU calculators to carry out calculations conveniently may be found on the web.⁸²⁸ The user needs to put in only the amount of desired product (e.g. one metric ton), the percentages of U-235 in the feed (usually natural uranium, $x_F = 0.0072$), the desired product, and the desired depleted uranium assay and then hit the “calculate” button and the remaining boxes are filled in, showing: the required amount of enrichment work (measured in ton-SWUs, i.e., 1000 kg-SWUs) and feed (in metric tons) and quantity of depleted uranium (in metric tons) that will be produced. Tonnages are also shown for the corresponding amounts of UF_6 , the chemical form in which uranium is enriched by the gaseous diffusion and gas centrifuge methods.

Figures B.1 and B.2 illustrate the dependencies of enriched product and required enrichment work.

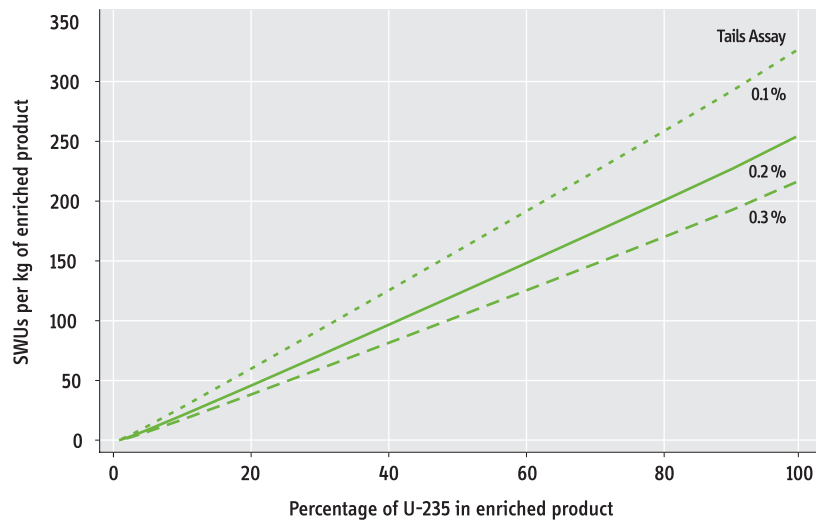


Figure B.1. Amount of enrichment required to produce a kilogram of enriched product as a function of enrichment for three different tails assays. Above

10 percent enrichment, the amount of enrichment work (SWUs) required per kg of enriched product is roughly proportional to the percentage enrichment.

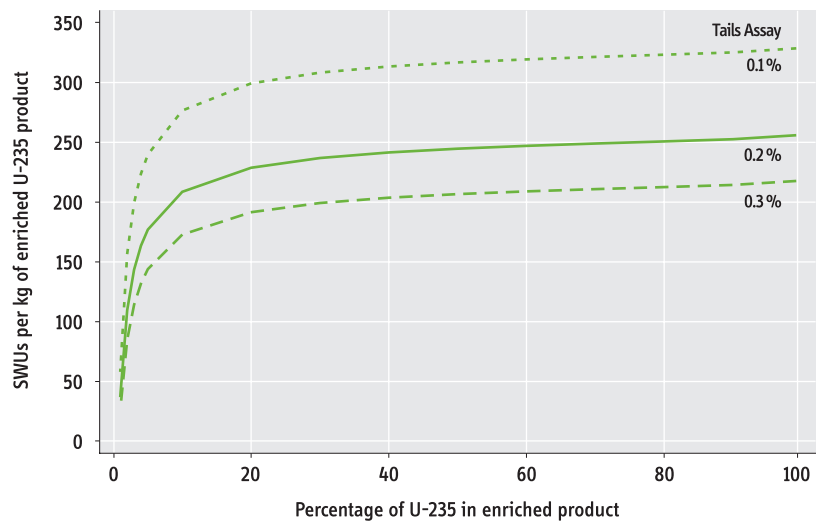


Figure B.2. Amount of enrichment required to produce a kilogram of product of varying enrichment per kilogram of U-235 contained in the product for three different tails assays. The data shows equivalently that, per kg of U-235 in the product, most of the enrichment work has been done by the time

that uranium has been enriched to 10%. One way to understand this is that, by 10% enrichment, of the 140 U-238 atoms per atom of U-235 in the original natural uranium, all but ten have been separated from the U-235 atoms in the product.

Plutonium Production in Natural-Uranium Fueled Reactors

Virtually any reactor type can be used for the production of weapon-grade plutonium by limiting the burnup of the uranium fuel, but plutonium production is maximized in natural-uranium-fueled reactors. High-purity graphite or heavy water (D₂O) has to be used with natural uranium fuel for moderation to minimize parasitic neutron absorption. Reactor designs that permit continuous refueling are preferred for dedicated production reactors in order to facilitate frequent discharge and reloading of fuel elements for extraction of the plutonium. All weapon states relied on natural-uranium-fueled reactors to produce most of their weapons plutonium (Table B.1).

	Graphite-moderated		Heavy-Water moderated	
	H ₂ O-cooled	Gas-cooled	H ₂ O-cooled	D ₂ O-cooled
United States	Hanford	-	-	Savannah River
Russia	"Tomsk-7"	-	-	-
United Kingdom	-	Calder Hall	-	-
France	-	G-Series	-	Célestin
China	"Jiuquan"	-	-	-
Israel	-	-	-	Dimona
India	-	-	Cirus/NRX	Dhruva
Pakistan	-	-	Khushab	-
North Korea	-	Yongbyon	-	-

Table B.1. Table 4.1. Select natural-uranium fueled plutonium production reactors, by country.⁸²⁹

Graphite-moderated reactors were dominant in the early weapons programs of the first five nuclear

weapon states. Some of these countries also used reactors that relied on highly enriched driver fuel and depleted-uranium targets. These are not listed in this table.

In order to obtain accurate plutonium production rates for these reactors, we have performed a series of infinite-lattice burnup calculations. Specifically, we have carried out calculations for (a) a Hanford-type reactor, which reportedly also served as a model for most Russian and Chinese production reactors; (b) a Calder-Hall-type reactor, which is representative for most UK production reactors and also for the French G-Series and for North Korea's Yongbyon reactor; (c) an NRX-type reactor used in India as CIRUS and possibly in Pakistan; and (d) a modified French EL3-type reactor, which served as a model for Israel's Dimona reactor, originally designated "EL-102."⁸³⁰ In addition, we have generated effective plutonium production rates for CANDU-type reactors, which may have had some relevance for India's weapon program.

Hanford-type reactor. The nine reactors at the Hanford site were all graphite-moderated and light-water-cooled, but their designs evolved over time. The power levels of all Hanford reactors increased significantly to accelerate plutonium production.⁸³¹ We modeled the first and conceptually most simple design, the B Reactor, which had an initial power level of 250 MW thermal. 2004 process tubes penetrate the reactor core, each 8.5 meters long. Russia and China reportedly used several production reactors that were virtually identical to the original early U.S. reactors operated at the Hanford site. We do not attempt to model these reactors here separately.

Calder-Hall-type reactor. In the 1950s, the United Kingdom built numerous dual-use reactors that were used for both electricity and military plutonium production. These reactors were graphite-moderated and gas-cooled, and used a unique cladding material (magnesium non-oxidizing or *Magnox* alloy). The power levels of the four Calder Hall reactors ranged from 180 MW to 240 MW thermal.⁸³² North Korea later adapted the Calder-Hall design, apparently based on information published in the 1950s, and built a downsized (20–25 MW thermal) version of the reactor in the 1980s, reportedly based on a slightly different core geometry.⁸³³

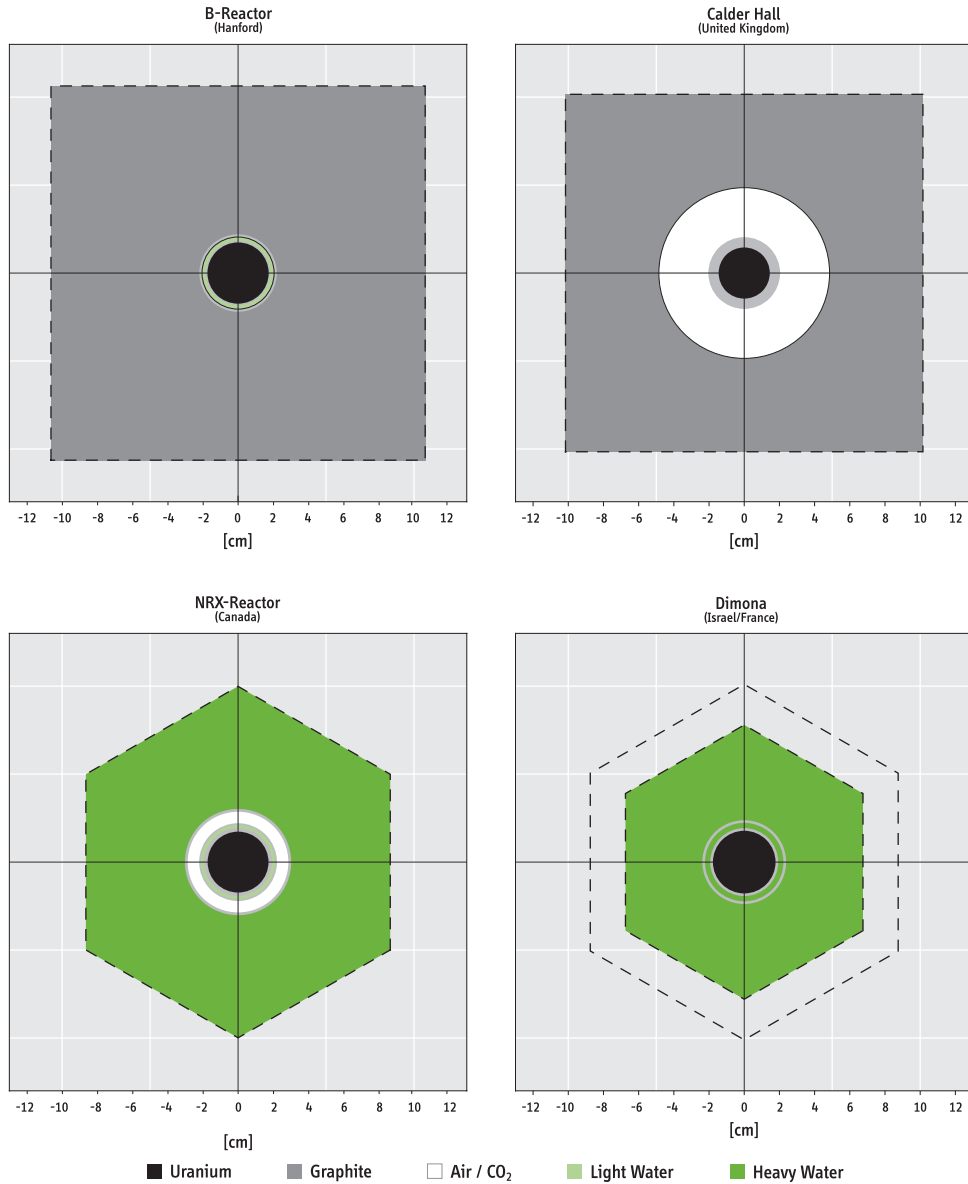


Figure B.3. Unit cells of production reactors examined in this analysis. The dashed contour of Dimona's unit cell indicates the original (larger) cell of the French EL-3 reactor, on which the design

for Israel was based. The reduced lattice pitch has a significant impact on the effective plutonium production rate of Dimona.

NRX-type reactor. The NRX is a heavy-water-moderated and light-water-cooled reactor, originally designed as a plutonium-production reactor but used in Canada for civilian purposes.⁸³⁴ The original NRX reactor went critical in July 1947 with a power level of 20 MW, later increased to 40 MW and finally to 42 MW thermal. As shown in Figure B.3, it uses a hexagonal lattice. India obtained a copy of the NRX reactor (CIRUS),⁸³⁵ which went critical in 1960 and became fully operational in 1963. Reportedly, Pakistan's 50 MW Khushab-I reactor, which has been operational since 1998, is also similar to NRX/CIRUS. Pakistan is currently building two additional plutonium production reactors, Khushab-II and Khushab-III, at the same site.⁸³⁶

Dimona-type reactor. Very little design information about this reactor is publicly available, but Dimona was built with French assistance and is reportedly based on a modified design of the EL-3 reactor.⁸³⁷ The original version of the EL-3 was designed for 50 MW and natural-uranium fuel. The original EL-3 is very similar to the NRX, but the channel tubes are semi-permanent sleeves surrounding the fuel rods. For the basic model of the Dimona reactor, we assume that the outer diameter of the fuel rod was increased from the original 2.9 cm to 4.0 cm and that power up-rates did not require changes that would significantly affect the neutronics of the design. More significant power up-rates might be possible with modified fuel designs increasing the surface-to-volume ratio of the fuel.⁸³⁸

CANDU-type reactor. The CANDU (Canada Deuterium Uranium) reactor is a pressurized heavy-water power reactor (PHWR) originally developed in Canada. It evolved from the NRX design, featuring the characteristic calandria, but using heavy water as both moderator and coolant. The majority of today's CANDU fleet is deployed in Canada, but several other countries operate variations of this reactor design.⁸³⁹ Compared to light-water reactors using low-enriched fuel, natural-uranium-fueled CANDU reactors have a much lower target burnup. This results in higher plutonium production rates and higher Pu-239 fractions (but lower absolute concentrations) in the spent fuel. Furthermore, CANDU are refueled continuously, which requires somewhat more difficult safeguards approaches. A number of India's PWRs are derivatives of the Canadian design and are not under IAEA safeguards.

All calculations below have been carried out with MCODE,⁸⁴⁰ a computer-code system linking the Monte Carlo neutron-transport code MCNP and the general point-depletion code ORIGEN2.⁸⁴¹ All MCNP input decks used for this analysis are available at www.ipfmlibrary.org/mcnp-input. In general, plutonium production scales with the total power level of a particular reactor design, but the production rate is rather insensitive to the actual power density in the core. In the neutronics calculations for all production reactors considered for this analysis, the power density was set to 3 watts per gram of uranium in the core; in other words, the average fuel burnup increases by 300 MWd/t for every 100 effective full-power days in the reactor.

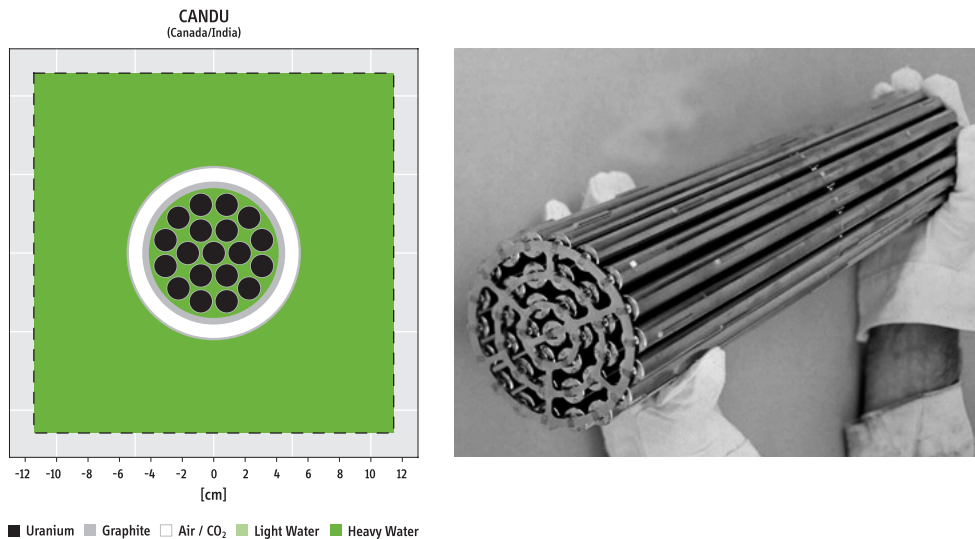


Figure B.4. Unit cell of a 19-pin CANDU fuel bundle (left). The picture on the right shows a more recent

37-pin fuel bundle used in the Bruce power stations, Ontario, Canada. *Source: canteach.candu.org*

The main results of these calculations are summarized in Figure B.5:

- **Plutonium concentration**, specified in grams of plutonium per kilogram of uranium.⁸⁴² Concentrations range from 0.42 to 0.48 g/kg(U) for 500 MW-days/ton and from 0.79 to 0.90 g/kg(U) for 1000 MWd/t.
- **Effective production rates**, specified in grams per MW-day (thermal) of operation. The most efficient plutonium producer per MW-day is the Dimona-type reactor, i.e., a variation of the French EL-3 design with a tighter lattice. Among those considered here, the heavy-water-cooled NRX is the least efficient machine. In between are graphite-moderated reactors whose production rates are initially high but drop more sharply than of heavy-water-moderated reactors because neutron absorption in plutonium is more pronounced for these designs. This effect increases the overall contribution of plutonium fission and conversion of Pu-239 to Pu-240.
- **Plutonium quality**, specified in weight percent of plutonium-239 in total plutonium. Heavy-water moderated reactors yield the highest Pu-239 content for a given burnup level of the fuel. As discussed above, the more pronounced neutron absorption in plutonium in graphite-moderated reactors explains the reduced Pu-239 content.

Figure B.6 shows the same results for the reference CANDU reactor. Its use of oxide instead of metal fuel design permits burnup values of 6000–8000 MW-days/t. The Pu-239 content for this burnup level is on the order of 70%. The material is not weapon-grade—but still weapon-usable—and contains significantly more Pu-239 than plutonium discharged from a light-water reactor.

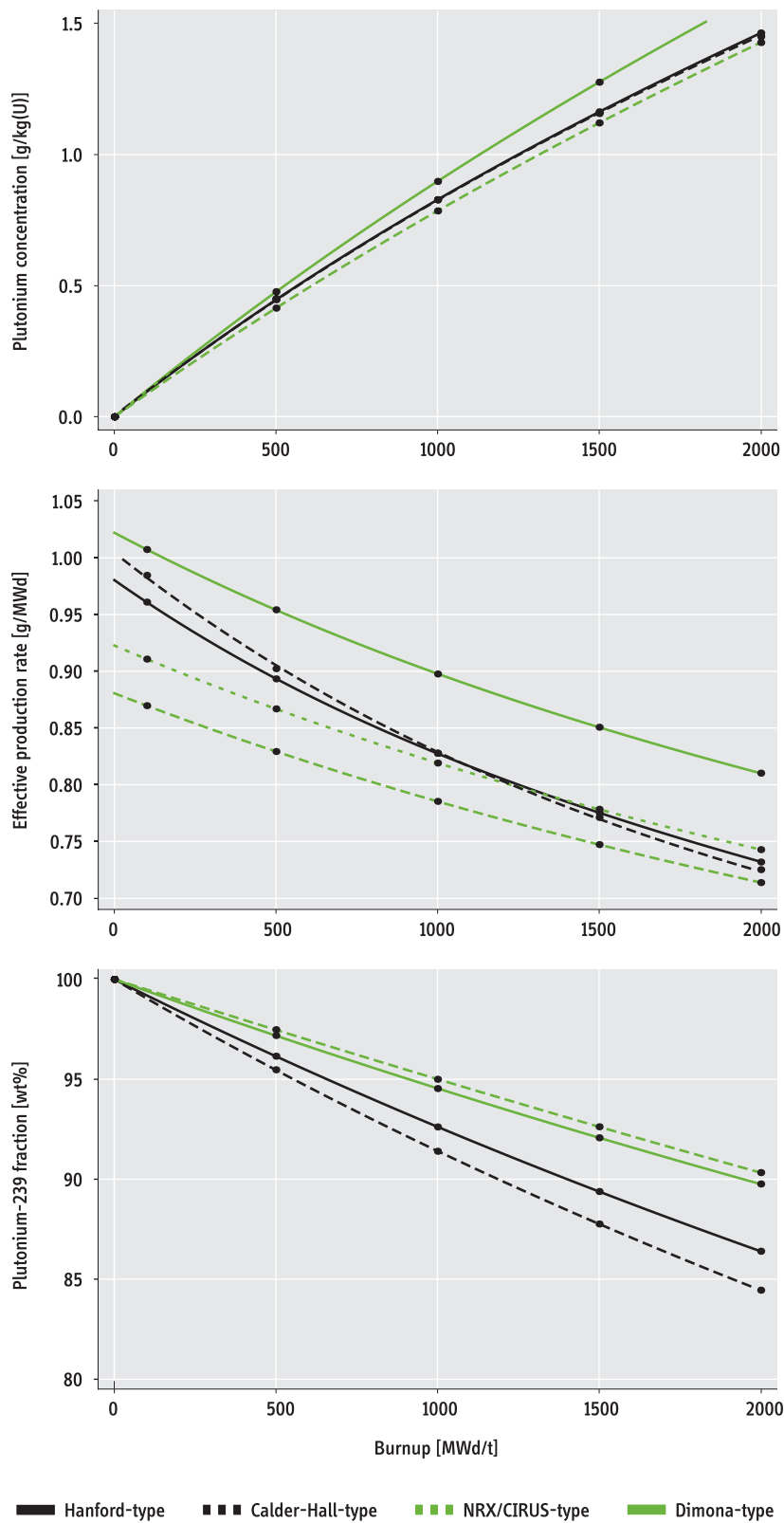


Figure B.5. Plutonium concentration, effective production rate, and plutonium-239 fraction for the Hanford, Calder Hall, NRX/Cirus, and EL-102/Dimona. The dotted line in the center chart shows the

effective production rate for EL-3, i.e., the original French reactor that served as a model for the Dimona reactor.

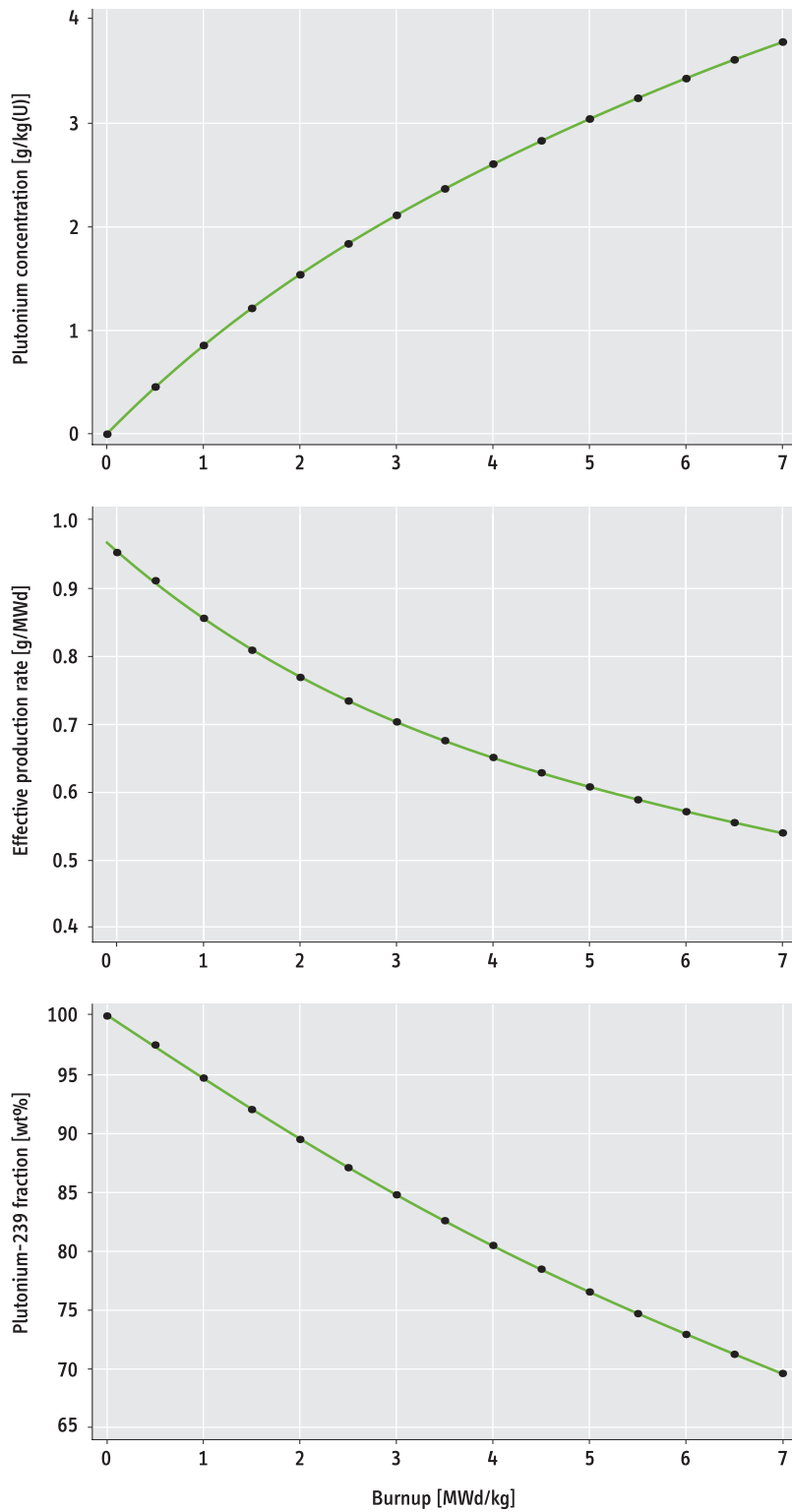


Figure B.6. Plutonium concentration, effective production rate, and plutonium-239 fraction for a CANDU reactor. These simulations are based on the

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Endnotes

Overview

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Chapter 1. Nuclear Weapon and Fissile Material Stockpiles and Production

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Chapter 2. United States

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- ¹¹¹. In modern nuclear-warhead designs, the fusion of a few grams of tritium with deuterium is used to generate neutrons that cause additional fissions and thereby “boost” the yield of the first stage of the explosion.
- ¹¹². Tritium for U.S. nuclear weapons is currently produced in government-owned nuclear-power reactors operated by the Tennessee Valley Authority, “Fact Sheet on Tritium Production,” U.S. Nuclear Regulatory Commission, May 2003, www.nrc.gov/reading-rm/doc-collections/fact-sheets/tritium.html.
- ¹¹³. U.S. nuclear weapons are mostly two-stage explosives with plutonium in the fission “pit” and HEU in the fusion-fission “secondary.”
- ¹¹⁴. “Increasing Transparency in the U.S. Nuclear Weapons Stockpile,” U.S. Department of Defense Fact-sheet, 3 May 2010.
- ¹¹⁵. A third gaseous diffusion plant, in Paducah, Kentucky, which was still operating in 2010, produced only low-enriched uranium, including re-enriching depleted uranium from the other two plants.
- ¹¹⁶. *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, Tables 5.2, 5.3, 5.4.
- ¹¹⁷. *FY 2009 Congressional Budget Request*, U.S. Department of Energy, Volume 1, DOE/CF-024, p. 550; and FY 2011, p. 457.
- ¹¹⁸. Based on *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, Tables 5-1, 5-3, 6-2, 6-3 and 6-4. The United States produced HEU containing about 102 tons of U-235, enriched to less than 90%. Of this, HEU containing 60 tons of U-235 was re-fed into the enrichment plants. Fifty-eight tons of weapon-grade uranium (> 90%-enriched) also was re-fed.
- ¹¹⁹. *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, p. 96.
- ¹²⁰. *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, p. 69.
- ¹²¹. *Agreements for Cooperation for Mutual Defense Purposes*, Hearings before the Subcommittee on Agreements of Cooperation of the U.S. Congressional Joint Committee on Atomic Energy, June–July 1959, p. 51; and David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997., p. 89: “[A]bout 0.5 tonnes of weapon-grade uranium” were shipped to France for this purpose (no source given).
- ¹²². *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, p. 87, The ratio of 0.11 atom of U-235 transmuted per atom fissioned cited there is less than the ratio 0.18 used elsewhere in this paper based on Alexander Glaser, “Isotopic Signatures of Weapon-Grade Plutonium from Dedicated Natural Uranium–Fueled Production Reactors and Their Relevance for Nuclear Forensic Analysis,” *Nuclear Science and Engineering* 163, 2009, p. 26, Table III.
- ¹²³. Tom Cochran, personal communication, 19 May 2010. Assuming that 17 tests with yields given as ≤100, ≤150 or ≤1000 kt had yields of 20 kt or more.
- ¹²⁴. The average enrichment of U.S. HEU, excluding naval HEU enriched to greater than 96%, was 85.2%, *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, Tables 5.1 and 6.1.
- ¹²⁵. Including 1.7 tons enrichment plant process holdup, *Highly Enriched Uranium Inventory*, *op.cit.*, Table 2.
- ¹²⁶. The reduction in HEU is less than the reduction in the contained U-235 because some U-235 is not fissioned but rather converted by neutron absorption to U-236. This conversion reduces the mass of U-235 but not that of the HEU.
- ¹²⁷. *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, Table 4-1 and p. 96 and *Highly Enriched Uranium Inventory*, *op.cit.*, Tables 1 and 2, except where noted. The DOE tracks HEU primarily through its U-235 content but the quantities of total HEU are shown when they are available.
- ¹²⁸. *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, Table C-2.
- ¹²⁹. An original enrichment of 97.4 percent is assumed and that, for every fission, 0.18 atoms of U-235 are converted to U-236. On this basis, the ratio of U-235 in total uranium originally enriched to 97.4% would be $(0.974 - B)/(1 - 0.85 B)$ where B is the total amount of U-235 either fissioned or converted to U-236.
- ¹³⁰. *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, p. 39.
- ¹³¹. In 1996, the U.S. nuclear fleet contained 85 submarines plus two under construction plus one land-based prototype submarine reactor and 8 aircraft carriers and 4 cruisers with a total of about 6 million shaft horsepower. Dividing 100 tons of HEU by 6 million shaft horsepower gives about 1.7 tons per 100,000 shaft horsepower. The *Nimitz* aircraft carriers and the *Trident* submarines have about

280,000 and 60,000 shaft horsepower respectively. For the number of ships, see *Highly Enriched Uranium: Striking a Balance*, *op.cit.*, p. 144. For the shaft horsepower see, for example, Chunyan Ma and Frank von Hippel, "Ending the Production of Highly-enriched Uranium for Naval Reactors," *Nonproliferation Review*, Spring 2001, p. 86.

132. As of the end of September 1996, 7.4 tons of U-235 in spent naval fuel was stored at Idaho International Laboratory (Table C-2). Until 1992, spent naval and HEU research-reactor fuel were reprocessed at the Idaho Chemical Processing Plant and the recovered HEU was recycled into fuel for the Savannah River production reactors, *Idaho Chemical Processing Plant and Plutonium-Uranium Extraction Plant Phaseout/Deactivation Study*, Westinghouse Hanford Co., WHC-EP-0693, 1994.
133. *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, pp. 92–93.
134. *Highly Enriched Uranium Inventory*, *op. cit.*, Table 2.
135. *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, Tables 6-9 and 6-10.
136. Victor Gilinsky and Roger J. Mattson, "Revisiting the NUMEC affair," *Bulletin of the Atomic Scientists*, March/April 2010, p. 61.
137. The nuclear-powered aircraft carrier *USS Abraham Lincoln* (CVN-72) underway at high speed, 1993, www.defenseimagery.mil, Collections, Best of the U.S. Navy Set 1, Image DN-ST-95-01174.
138. Robert M. George, Office of Fissile Materials Disposition, U.S. Department of Energy, personal communication, May 2010.
139. Eight U.S. research reactors remain to be converted. All are to be converted to low-enriched uranium before 2020. All are awaiting the qualification of new fuel that is currently under development. It is expected that all but three DOE reactors: the High Flux Isotope Reactor at the Oak Ridge National Laboratory, the Advanced Test Reactor (ATR) at the Idaho National Laboratory and the critical facility associated with the ATR will be converted in 2015. The three DOE reactors will be "a little later" because of the complex geometry of their fuel, personal communication, Parrish Staples, Global Threat Reduction Initiative, July 2010. Currently, there are no authorized U.S. space-reactor projects.
140. Remarks Prepared for Energy Secretary Sam Bodman, 2005 Carnegie International Nonproliferation Conference, Washington, DC, 7 November 2005.
141. Robert M. George, personal communication, May 2010.
142. Early in the U.S. "hydrogen-bomb" development project, it was believed that large amounts of tritium might be required to ignite the fusion of deuterium nuclei in the thermonuclear second stage, Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb*, Simon and Schuster, 1995. Later, it was realized that tritium could be made during the explosion by neutron capture on lithium-6. The use of pre-produced tritium in modern nuclear weapons is to fuse with deuterium gas during the initial fission explosion to create an extra burst of neutrons that cause extra fissions and thereby "boost" the fission yield of the "primary."
143. *Plutonium: The First 50 Years*, *op. cit.*, pp. 25, 30.
144. Congress scaled back the Reagan Administration's plans considerably and the U.S. stockpile increased by only about 700 warheads between 1982 and 1987.
145. *Plutonium: The First 50 Years*, Table 1.
146. 640 kg of U-233 was authorized to be produced during 1969 and 1970, internal Atomic Energy Commission telegram dated 29 January 1968, www5.hanford.gov/ddrs/common/findpage.cfm?AKey=D199020827. Tritium production with slightly enriched fuel was discussed by D.W. Peacock et al, "2.1 enriched uranium-lithium loading memorandum—fuel and target performance," 24 July 1967, www5.hanford.gov/ddrs/common/findpage.cfm?AKey=D1344939. The Savannah River reactors produced, in addition to plutonium and tritium, relatively small amounts of uranium-233, americium-242, curium-244, polonium-210, cobalt-60, plutonium-238, plutonium-242, and californium-252, *Plutonium: The First 50 Years*, *op. cit.*, p. 30.
147. One transmutation product is californium-252, which has a short half-life (2.6 years). Three percent of its decays are by spontaneous fission. It is therefore a popular neutron source.
148. "Rocky Flats Site, Colorado," Fact Sheet, U.S. Department of Energy, www.lm.doe.gov/rocky_flats/Sites.aspx. Intact pits were shipped to Pantex and the Livermore (LLNL) and Los Alamos nuclear-weapon laboratories, Marylia Kelley, "Plutonium to LLNL from Rocky Flats," 27 August 1999, www.cpeo.org/lists/military/1999/msg00295.html. Plutonium in transuranic waste was shipped to the Waste Isolation Pilot Plant, an underground repository in New Mexico; and scraps and more concentrated wastes to the Savannah River Site for possible recovery and disposition.

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- ¹⁵⁰ All significant quantities of plutonium and HEU are being removed from Lawrence Livermore National Laboratory, "NNSA Ships Additional Special Nuclear Material from Lawrence Livermore National Laboratory as Part of De-inventory Project," Press Release, U.S. Department of Energy, 30 September 2009.
- ¹⁵¹ Includes four tons of plutonium in fuel for the Zero Power Research Reactor, a critical assembly for simulating the cores of full-sized breeder reactors, which is to be removed.
- ¹⁵² *A Summary Report by the Ministry of Defence on the Role of Historical Accounting for Fissile Material in the Nuclear Disarmament Process, and on Plutonium for the United Kingdom's Defence Nuclear Programme*, UK Ministry of Defence, 2000, §10, webarchive.nationalarchives.gov.uk/+www.mod.uk/publications/nuclear_weapons/accounting.htm.
- ¹⁵³ *Plutonium: The First 50 Years*, *op. cit.*, pp. 68–69.
- ¹⁵⁴ In Appendix 2A, an updated estimate of 3.9 tons of plutonium in waste was given but not integrated into the mass balance of the overall report.
- ¹⁵⁵ The estimated plutonium in Hanford, Idaho and Savannah River Site high-level reprocessing waste increased from 0.455 to 1.115 tons, 0.072 to 0.771 tons and 0.575 to 0.847 tons respectively. Pre-1970 buried waste at the Idaho site (1.078 tons) did not even appear on the 1996 inventory, *Plutonium: The First 50 Years*, *op. cit.*, Table 16.
- ¹⁵⁶ The initial declaration of excess plutonium covered 38.2 tons of separated weapon-grade plutonium, *Plutonium, the First 50 Years*, *op. cit.*, Table 15 plus the entire U.S. government 14.5-ton stock of non-weapon-grade plutonium, including 7.6 tons of plutonium in irradiated fuel. In 2007, an additional 9 tons of weapon-grade plutonium was added, IAEA, "Communication Received from the United States of America Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.6, 31 March 1998 and INFCIRC/549/Add.6/11, 30 October 2008.
- ¹⁵⁷ In 2004, there were reportedly 5,000 reserve pits, "Dismantling U.S. nuclear warheads," *Bulletin of the Atomic Scientists*, January/February 2004.
- ¹⁵⁸ The excess pits will remain stored at the Pantex site until a plutonium extraction capability can be built on the Savannah River Site.
- ¹⁵⁹ The dilution must be such that a single container does not contain more than one gram of "plutonium fissile equivalent" (in effect, Pu-239) per liter, *Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*, Revision 6.5 DOE/WIPP-02-3122, 30 June 2010, www.wipp.energy.gov/library/wac/wac.pdf, Table 3.3.2.
- ¹⁶⁰ U.S. Department of Energy, "Amended Notice of Intent to Modify the Scope of the Surplus Plutonium Disposition Supplemental Environmental Impact Statement and Conduct Additional Public Scoping," *Federal Register*, Vol. 75, No. 137, 19 July 2010, p. 41850.
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- ¹⁶² "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, 2000," as amended by a 2010 Protocol.
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- ¹⁶⁵ Frank von Hippel, "Consistency checks for U.S. declarations of highly-enriched uranium and plutonium production," submitted to *Science & Global Security*.

- ¹⁶⁶ Peter Diehl, "Composition of the U.S. DOE Depleted Uranium Inventory" (undated) www.wise-uranium.org/pdf/duinve.pdf, Table 1. The source cited is T.J. Hertzler and D.D. Nishimoto: *Depleted Uranium Management Alternatives*, EGG-MS-11416, August 1994.
- ¹⁶⁷ *U.S. Nuclear Warhead Production*, *op. cit.*, Table 3.17. The data on U.S. acquisitions of natural uranium during the period 1956–71 also can be found in *Statistical Data of the Uranium Industry*, U.S. Department of Energy, Grand Junction Area Office, Colorado.
- ¹⁶⁸ *U.S. Nuclear Warhead Production*, *op. cit.*, Table D.1.
- ¹⁶⁹ The conversion facilities at both sites are to begin operating in fiscal year 2011, Department of Energy, FY 2011 *Congressional Budget Request DOE/CF-0051*, Volume 5. "Environmental Management," pp. 162, 174.
- ¹⁷⁰ *Disposition of DOE Excess Depleted Uranium, Natural Uranium, and Low-Enriched Uranium, Final Environmental Assessment DOE/EA-1607*, U.S. Department of Energy, 2009, Table 2-1.
- ¹⁷¹ Samples of the graphite could be taken and ratios of trace isotopes to their transmutation products analyzed to determine the fluence. It has been shown that, with this information, a neutronics model of the reactor can produce a good estimate of the amount of plutonium produced in the fuel of a graphite-moderated reactor, C. J. Gesh, A Graphite Isotope Ratio Method Primer—*A Method for Estimating Plutonium Production in Graphite Moderated Reactors*, Pacific Northwest National Laboratory, PNNL-14568, February 2004.
- ¹⁷² Annette Cary, "DOE to decide whether to raze K East Reactor," *Tri-City Herald*, 14 April 2010, www.tri-cityherald.com/2010/04/14/975793/doe-to-decide-whether-to-raze.html.
- ¹⁷³ The measurement error (relative standard deviation) is required to be less than 30 percent, *Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant*, *op. cit.*, p. A-10.
- ¹⁷⁴ Two of the underground storage "rooms" in WIPP have apparently already been backfilled, Jon Goldstein, formerly of the New Mexico Environment Department, personal communication August 2010.
- ¹⁷⁵ A large amount of vitrified waste has already been produced at the Savannah River site but, as of 2010, this waste reportedly contained less than 1 ton of plutonium (Appendix 3.A).
- ¹⁷⁶ www5.hanford.gov/ddrs/common/findpage.cfm?AKey=N1D0029049.
- ¹⁷⁷ This is a shortened version of an article that is to appear in *Science & Global Security*.
- ¹⁷⁸ *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, Figures 12 and 14, pp. 77–82, www.ipfmlibrary.org/doe96a.pdf. The 3.4 tons are identified as normal operating losses (NOL). Table 16, based on extrapolations of direct measurement of the wastes indicated a waste amount of 3.9 tons (see Table 2A.1). The 0.5-ton difference is attributed to two primary causes as explained in the DOE report. One, waste inventories are tracked for environmental, safety, and health reasons, and are therefore not necessarily calculated like normal operating losses. Two, the direct waste calculation includes off-site sources, while the normal operating losses include only waste generated from government on-site production.
- ¹⁷⁹ *Plutonium: The First 50 Years*, *op. cit.*, Figure 1, p. 3.
- ¹⁸⁰ See footnotes to Table 2A.1 and endnote references below for information on the specific sites of transuranic wastes.
- ¹⁸¹ *National Security and Military Applications of Nuclear Energy Authorization Act of 1980*, U.S. Department of Energy, Public Law 96–164.
- ¹⁸² *Annual Transuranic Waste Inventory Report, 2009*, DOE/TRU-09-3425, Rev. 0, U.S. Department of Energy, Tables, 3-1, 3-2, 3-11 and 12, www.wipp.energy.gov.
- ¹⁸³ "Record of Decision on Management of Certain Plutonium Residues and Scrub Alloy Stored at the Rocky Flats Environmental Technology Site," *Federal Register*, Vol. 63, No. 230, 1 December 1998; *Supplemental Analysis for the Disposal of Certain Rocky Flats Plutonium-Bearing Materials at the Waste Isolation Pilot Plant*, DOE/EIS-0026-SA-3, November 2002, www.wipp.energy.gov/Documents_All_Title.htm; and "Management of Certain Plutonium Residues and Scrub Alloy Stored at the Rocky Flats Environmental Technology Site," *Federal Register*, Vol. 66, No. 12, 18 January 2001, nepa.energy.gov/nepa_documents/rods/2001/4803.pdf.
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- ¹⁹². *Ibid.*, p. 4–4.
- ¹⁹³. *Ibid.*, p. 4–5.
- ¹⁹⁴. *Ibid.*, p. 4–6.
- ¹⁹⁵. CH2MHILL, *Hanford Soil Inventory Model Data (SIM 2005)*, PFP, WTP-ETF-A-C- Farm, Unassigned 200 Areas 1 and 2, U Plant, T-Plant, T-Farm, S U Farm, Semi-Works, Redox, PUREX, 200E Ponds, 200 W ponds, B-Pant, WM, NRDWL-BC-Control, and PFP zones, 2005, PFP Zone, U.S. Department of Energy, 2005.
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Chapter 3. Russia: Plutonium

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- ²²² “Vannikov’s letter to Beriya on A reactor, February 3, 1949,” Document 228 in *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. II, *Atomic bomb*, 1945–1954, Book 4.
- ²²³ Ya. P. Dokuchaev, “From plutonium to plutonium bomb: from memories of participants of events”, in *History of the Soviet Nuclear Project*, *op. cit.*
- ²²⁴ “Igor Kurchatov’s suggestion on increasing plutonium production at A reactor, April 9, 1949,” *op. cit.*; and “L. Beriya report to I. Stalin about accomplishment of the governmental plan on development of atomic industry, March 26, 1951,” Document 293 in *USSR Atomic Project: Documents and Materials*, *op. cit.*, Volume II, *Atomic bomb*, 1945–1954, Book 5, Moscow-Sarov, 2005.
- ²²⁵ B. V. Brokhovich, *Chemical combine “Mayak,” op. cit.*, p. 130.
- ²²⁶ This corresponds to 0.17 kg of plutonium per ton of fuel, “Igor Kurchatov’s suggestion on increasing plutonium production at A reactor, April 9, 1949,” *op. cit.*
- ²²⁷ B. V. Brokhovich, *Chemical combine “Mayak,” op. cit.*, p. 78.

- ²²⁸ N. S. Burdakov, *Some pages from the history of technology development for production of uranium-graphite reactors*, *op. cit.*
- ²²⁹ V. N. Novoselov, V. S. Tolstikov, *Sekrety "sorokovki" (Secrets of "Fortieth")*, Ekaterinburg, IPP Uralskiy rabochiy, 1995.
- ²³⁰ N. S. Burdakov, *Some pages from the history of technology development for production of uranium-graphite reactors*, *op. cit.*
- ²³¹ *Ibid.*
- ²³² B. V. Brokhovich, *Chemical combine "Mayak"*, *op. cit.*, p. 136.
- ²³³ Document 46, "The Council of Ministers decision on construction of aggregate AV" in *USSR Atomic Project: Documents and Materials*, *op. cit.*, Volume II, Atomic bomb, 1945–1954, Book 4.
- ²³⁴ Document 300, "Summary of information on nuclear reactors", *USSR Atomic Project: Documents and Materials*, *op. cit.*, Volume II, Atomic bomb, 1945–1954, Book 5.
- ²³⁵ Document 293, "Annex 1 to L. Beriya report to I. Stalin on accomplishment of the Government program on the development of nuclear industry," 26 March 1951, *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. II, Atomic bomb, 1945–1954, Book 5.
- ²³⁶ Document 180 "B. L. Vannikov's and others letter to L. Beriya", 12 April 1952, *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. III, Hydrogen bomb, 1945–1954, Book 1, Moscow-Sarov, 2008.
- ²³⁷ "Zavod 23," *Ozerskiy vestnik ("Plant 23," Ozersk's Messenger)*, No. 48/49, 1993, p. 7, www.libozersk.ru/pbd/mayak/link/17.htm.
- ²³⁸ P. A. Zhuravlev, *Moi atomny vek (My nuclear century)*, Hronos Press, 2003, p. 134; and V. M. Kuznetsov, "Production Association Mayak: The History of Association," www.libozersk.ru/pbd/Mayak60/link/237.htm.
- ²³⁹ Document 122 "The order of USSR Council of Ministers 13030-rs/op on construction AI aggregate for tritium production," 18 August 1950, *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. III, Atomic bomb, 1945–1954, Book 1, Moscow-Sarov, 2008.
- ²⁴⁰ N. S. Burdakov, *Some pages from the history of technology development for production uranium-graphite reactors*, *op. cit.*
- ²⁴¹ Document 306, "About situation of the work on the development of atomic industry", 16 November 1951, *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. II, Atomic bomb, 1945–1954, Book 5.
- ²⁴² Document 187, "B. Vannikov and others report to L. Beriya on reordering of the factory No. 3 (OK-180) for production of U-233," 6 May 1952, *USSR Atomic Project: Documents and Materials*, *op. cit.*, Vol. III, Atomic bomb, 1945–1954, Book 1, Moscow-Sarov, 2008; A. K. Kruglov, "O pervykh v nashey strane reaktorakh s tyazhelyoy vodoy" ("About the first heavy-water reactors in our country"), in *Creation of the first Soviet nuclear bomb*, p. 313, Energoatomizdat, Moscow, 1995.
- ²⁴³ V. Gubarev, "Ruslan and Ludmila: Reactors for thermonuclear weapons," *Nauka i Zhizn*, No. 6, 1997.
- ²⁴⁴ G. Chernetskaya, "Reactoromuzavody – 50 let" ("Reactor plant's 50 years"), *Chelyabinsk*, 2000, No. 2, p. 27, www.libozersk.ru/pbd/mayak/link/43.htm.
- ²⁴⁵ B. V. Brokhovich, *Chemical combine Mayak*, *op. cit.*, p. 130.
- ²⁴⁶ V. M. Kuznetsov, "Production Association Mayak: The History of Association," www.libozersk.ru/pbd/Mayak60/link/237.htm. When stable silicon-30 captures a neutron, it becomes Si-31, which decays with a half-life of 2.6 hours to stable phosphorus-31.
- ²⁴⁷ The EI-2 reactor was initially put into operation in February 1958 in a once-through mode pending installation of the steam generator and turbine. It shifted to dual-purpose operation on 24 September 1958, P. A. Zhuravlev, *My nuclear century*, *op. cit.*, pp. 252–254.
- ²⁴⁸ The cermet fuel contains 8.5% UO₂ dispersed in aluminum. The concentration of U-235 in the cermet fuel is the same as in the natural uranium fuel and therefore generates the same amount of heat but the near-absence of U-238 in the fuel reduces its neutron absorption and thereby offsets the greater leakage of neutrons out of the reactor's surface from the outer portion of the core.
- ²⁴⁹ The natural uranium was discharged with a burnup of 468 MWd/ton and contained 420 grams of plutonium per ton of uranium. Thus, at this burnup, the reactors produced approximately 0.90 grams of plutonium per MWd. An additional 65 MWt was generated by the spike fuel. Overall therefore, the reactor generated about 0.87 grams of plutonium per MWd.

- ²⁵⁰. The estimates were made assuming that the reactors were operated at design power during their first several years. Also, it has been assumed that, beginning in 1995, after the order for weapon-grade plutonium was canceled, the reactors ADE-4 and ADE-5 operated at 75% power, i.e., 1425 MWt.
- ²⁵¹. Document No. 300, "Summary of information on nuclear reactors", *USSR Atomic Project: Documents and Materials*, op. cit., Volume II, Atomic bomb, 1945–1954, Book 5, Moscow-Sarov, 2005.
- ²⁵². I. A. Andrushin, A. K. Chernyshev, Yu. A. Yudin, *Ukrochenie yadra (Subduing of the nucleus)*, Sarov, 2003, p. 164.
- ²⁵³. The submarine K-129 sank in 1968 with three ballistic missiles each equipped by one warhead and two nuclear-armed torpedoes. The submarine K-219 sank in October 1986 with sixteen ballistic missiles, each equipped with one nuclear warhead, and two nuclear-armed torpedoes. The submarine Komsomolez sank in 1989 with two nuclear-armed torpedoes.

Chapter 4. Russia: Highly Enriched Uranium

- ²⁵⁴. V. F. Petrovsky, Deputy head of the USSR Delegation to the 44th UN General Assembly, in "Statement on the Item Entitled 'Report of the International Atomic Energy Agency,'" 25 October 1989. Quoted in Thomas B. Cochran, Robert S. Norris, and Oleg A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, Boulder, 1995, p. 52.
- ²⁵⁵. Production of this HEU is accounted in the separative work capacity that was available for HEU production.
- ²⁵⁶. The exact tails assays are unknown. Enrichment tails have been reported to contain from 0.2% or 0.24% to 0.36% U-235, Oleg Bukharin, *Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex*, Program on Science and Global Security, Princeton University, January 2004, p. 29. It is likely that some gaseous diffusion cascades operated with higher than 0.3% tails assays and some centrifuge cascades with lower than 0.25%.
- ²⁵⁷. Reactor data are from the IAEA Power Reactors Information System (PRIS), www.iaea.org/programmes/a2.
- ²⁵⁸. Each VVER-440 contained in its core 42 tons of uranium enriched to 3.5% in U-235. By the end of 1989, the 36 reactors of this class had accumulated 336 full reactor-years of operation. Assuming that annual refueling replaced one third of the core, the total amount of uranium consumed by VVER-440 reactors was equivalent to 148 full cores (6,200 tons). Producing this amount of LEU would have required 29 million SWUs. Refueling frequency from "VVER-440 Nuclear Fuel", Mashinostroitelny Zavod Elemash, www.elemash.ru/en/production/Products/NFCP/VVER440.
- ²⁵⁹. Each VVER-1000 core contained 71 tons of uranium enriched to 4.4%. This reactor operated on a cycle in which one fourth of its core was replaced annually. The 17 reactors of this class that were producing electricity as of 1989 required the equivalent of 31 full cores or 2200 tons of low-enriched uranium (LEU) for their operations through the end of 1989. Production of this LEU required 14.2 million SWU. Data on refueling is from "VVER-1000 Nuclear Fuel", Mashinostroitelny Zavod Elemash, www.elemash.ru/en/production/Products/NFCP/VVER1000.
- ²⁶⁰. Since RBMKs are capable of refueling without shutting down, their LEU requirements are estimated based on fuel burnup. By the end of 1989, 18 RBMK reactors had generated about 860,000 gigawatt-hours of electric energy, which, assuming a heat to electricity conversion efficiency of 30%, corresponds to 120,000 GWt-days of thermal power. Assuming that the reactors operated at the design fuel burn-up of 22.2 MWt-days of fission heat generated per kg of uranium, RBMK reactors required 5,500 tons of LEU. Burn-up data from Don Bradley, *Behind the Nuclear Curtain: Radioactive Waste Management in the Former Soviet Union*, Battelle Press, 1997, p. 93.
- ²⁶¹. The amount of 2% enriched uranium produced by blend-down of HEU from reprocessed breeder, naval and research-reactor fuel has been estimated to be 1900 tons. Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security*, Vol. 6, 1996, pp. 64–65. This process also consumed about 1.8 tons of fresh 90% HEU. Producing the remaining 3600 tons of LEU required by the RBMKs through 1989 would have used about 6.6 million SWU.
- ²⁶². By 1989, the EGP-6 reactors had used about 60 tons of fuel, which would require about 0.2 million SWU to produce. Based on data in V. I. Kalinkin et al., "Khranenie otrabotavshego yadernogo topliva energeticheskikh reaktorov (Storage of spent nuclear fuel of power reactors)," Preprint VNIPIET, St.-Petersburg, 2009, p. 13.

- ²⁶³ The active zone of the first BN-350 core contained about 210 fuel assemblies with two different initial enrichment levels: 17% and 26%. The total mass of uranium in the core was 6.4 tons, originally containing 1.3 tons of U-235. In 1976 the core was modified to contain fuel elements with three enrichment levels: 17%, 21%, and 26%. The modification increased the mass of U-235 to 1.43 tons. N. V. Gorin, Ya. Z. Kandiev, and Yu. I. Chernukhin, "Validation of Nuclear and Radiation Safety of a Container for Spent AMB Reactor Fuel Assemblies at the Beloyarskaya Nuclear Power Plant," *Atomic Energy*, Vol. 100, No. 6, 2006, p. 396.
- ²⁶⁴ The BN-350 is estimated to have required 4.5 million SWU to produce its fuel, assuming that the average fuel burnup was 50,000 MWd/ton and the lifetime average thermal power of the reactor was 580 MWt. It is estimated that the BN-350 used two full "old-type" cores during its first three years of operation and about 14 new-type cores before the end of 1998, when the reactor was finally shut down. The BN-350 would have required about 32 tons of uranium with 17% enrichment, 17 tons of 21% enriched uranium, and 50 tons of 26% enriched uranium. I. I. Vasilyev et al., "Narabotka radionuklidov v aktivnoi zone reaktora BN-350," Presentation at Kazatomexpo 2010, MAEK Kazatomprom, Aktau, 2010. This assumes that all enriched uranium used to manufacture new BN-350 fuel was produced before 1988.
- ²⁶⁵ The BN-600 is estimated to have required 11.3 million SWU to produce its fuel. The initial BN-600 reactor core contained 8.26 tons of enriched uranium in 369 fuel assemblies with enrichments of 21% and 33%. The reactor went critical in 1981 and operated with its original fuel configuration until 1987. During that time, it was refueled at least six times, i.e. used seven full cores or 58 tons of enriched uranium. Of these, 33 tons contained uranium enriched to 21% and 25 tons to 33%, corresponding to a total requirement of 3.2 million SWU. In 1987, the size of the core was increased to 11.63 tons uranium with three different enrichment levels: 17%, 21%, and 26%. This modification significantly reduced fuel failures and, the reactor operated without unscheduled refueling. During 1987–1990 it operated at an average fuel burn-up of 45,000 MWd/ton, and after that with burn-up of 60,000 MWd/ton. This means that the BN-600 operations after 1987 required about 185 tons of enriched uranium fuel through the end of 2009: 68, 47 and 70 tons were uranium with enrichment levels of 17%, 21%, and 26% respectively. It is assumed that this material was produced before 1989 and required 8.1 million SWU, bringing the total SWU requirement for BN-600 fuel to 11.3 million SWU. The data on BN-600 is from Yu. K. Buksha et al. "Operation experience of the BN-600 fast reactor," *Nuclear Engineering and Design*, 173, 1997, pp. 67–79. Estimates of the fuel consumption are in agreement with information on the amount of spent fuel of BN-350 and BN-600 reactors reprocessed at Mayak. By 2002, Mayak had reprocessed 250 tons of spent fuel from these reactors, Vladimir Korotkevich, Evgeny Kudryavtsev, "Tekhnologia i bezopasnost obrashcheniya s obluchennym yadernym toplivom v Rossiiskoi Federatsii (Technology and safety of handling of irradiated nuclear fuel in Russian Federation)," *Bulleten po atomnoy energii*, TsNIIAtominform, No. 12, 2002, p. 26.
- ²⁶⁶ O. Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security*, Vol. 6, 1996, p. 68.
- ²⁶⁷ This does not include three OK-150 reactors on the nuclear-powered icebreaker *Lenin*.
- ²⁶⁸ This takes into account savings from recycling reprocessed uranium.
- ²⁶⁹ Ole Reistad, Morten Bremer Mærli, and Nils Bøhmer, "Russian Naval Nuclear Fuel and Reactors," *Nonproliferation Review*, 12:1 (2005), p. 173; V. A. Lebedev, "Yadernaya energetika i atomny podvodny flot (Nuclear power industry and nuclear submarine fleet)," *ProAtom.ru*, 18 May 2009, gives the numbers 6, 7.5, and 21 percent for enrichment of uranium in fuel of first-generation reactors. See also *Predicted radionuclide release from marine reactors dumped in the Kara Sea*, IAEA-TECDOC-938, International Atomic Energy Agency, April 1997, p. 21. For the purposes of this estimate, the average enrichment in the first-generation reactor fuel is assumed to be 20 percent, so that each core would have contained about 50 kg of U-235.
- ²⁷⁰ P. M. Rubtsov and P. A. Ruzhanskii, "Estimate of the Radiation Characteristics of Spent Fuel from Submarine and 'Lenin' Icebreaker Reactors Scuttled in the Region of the Archipelago Novaya Zemlya," *Atomic Energy*, Vol. 81, No. 3, 1996, p. 657.
- ²⁷¹ V. M. Kuznetsov, "Energeticheskie bloki atomnogo podvodnogo flota" ("Power reactors of the nuclear submarine fleet"), www.proatom.ru, 24 January 2007.
- ²⁷² Ole Reistad and Povl L. Ølgaard, *Russian Nuclear Power Plants for Marine Applications*, Nordic Nuclear Safety Research (NKS) Report, NKS-138, April 2006, pp. 33, 35. It is assumed that each core contained 600 kg of 20% enriched uranium or 120 kg of U-235.
- ²⁷³ A. Vyrsky, V. Ulyanov, *Istoriya podvodnogo flota Rossii (History of the Russian submarine fleet)*, Moscow, 2002.

- ²⁷⁴. For the data on the annual number of Russian submarine patrols, see Hans Kristensen, “Russian Strategic Submarine Patrols Rebound,” Federation of American Scientists Strategic Security Blog, 17 February 2009, www.fas.org/blog/ssp/2009/02/russia.php.
- ²⁷⁵. Kuznetsov, *op. cit.*
- ²⁷⁶. Ole Reistad and Povl L. Ølgaard, “Russian Nuclear Power Plants for Marine Applications,” Nordic Nuclear Safety Research (NKS) Report, NKS-138, April 2006, p. 36.
- ²⁷⁷. V. A. Vinokurov, “Perezaryadka korabelnykh reaktorov” (“Refueling of ship reactors”), www.proatom.ru, 10 September 2009.
- ²⁷⁸. *Russian Nuclear Power Plants for Marine Applications, op. cit.*, p. 40.
- ²⁷⁹. Thomas Nilsen, Igor Kudrik and Alexandr Nikitin, *The Russian Northern Fleet*, Bellona Report No. 2:96, August 1996.
- ²⁸⁰. The Soviet Union also constructed eight small nuclear-powered submarines and special-purpose underwater ships. These are small underwater ships of the Project 1851 (3 ships), Project 1910 (3), and Project 10831 (1) classes, and a submarine of the Project 651E class. The amount of U-235 used in these ships reactors is assumed to be small compared to the uncertainty of the overall estimate.
- ²⁸¹. The service ship of the Project 1941 class was decommissioned almost immediately after it entered service, so its reactors were not refueled. The two lead cruisers of the Project 1144 class, completed in 1981 and 1985, were removed from service in 1999. They may therefore have had their reactors refueled in the late 1980s. The third ship of this class, *Admiral Nakhimov*, was completed in 1989 and decommissioned in 1999, most likely with its original reactor cores. Construction of the fourth Project 1941 cruiser, *Piotr Velikiy*, was completed in 1998.
- ²⁸². The initial core of each OK-150 reactor has been estimated to contain 85 kg of U-235 in 5% enriched uranium. *Russian Nuclear Power Plants for Marine Applications, op. cit.*, p. 18. After refueling, the amount of uranium in one of the reactors was increased so that the three reactors together contained 279 kg of U-235 in 5% enriched uranium. *Predicted radionuclide release from marine reactors dumped in the Kara Sea, op. cit.*, p. 21.
- ²⁸³. N. N. Melnikov et al., “Long-term safe storage of spent nuclear fuel from ship power units in underground storage facility in the North-west region of Russia,” in Ashot Arakelovich Sarkisov, Alain Tournyol Du Clos, eds., *Scientific and Technical Issues in the Management of Spent Fuel of Decommissioned Nuclear Submarines*, Springer, 2006, p. 285.
- ²⁸⁴. N. N. Melnikov et al., *op. cit.*, p. 278.
- ²⁸⁵. The refueling history of the OK-900 reactors has been reported for the period before 2000. During 1970–1999, icebreakers with these reactors received 33 new reactor cores in addition to 12 initial cores. Four icebreakers continued operating after 1999, with one, *Arktika*, decommissioned in 2008 and one, *50 Let Pobedy* entering service in 2007. Assuming the same refueling rate, we can estimate that operations of the icebreaker fleet in 2000–2010 required about 25 new reactor cores. Ole Reistad and Povl L. Ølgaard, *Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications*, Nordic Nuclear Safety Research (NKS) Report, NKS-139, April 2006, p. 26.
- ²⁸⁶. *Russian Nuclear Power Plants for Marine Applications, op. cit.*, p. 23.
- ²⁸⁷. *Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications, op. cit.*, p. 26.
- ²⁸⁸. The Soviet Union apparently used some of the HEU recovered from the spent fuel of plutonium and tritium production reactors to manufacture naval fuel, see Bukharin, “Analysis of the Size and Quality of Uranium Inventories in Russia,” *op. cit.*, p. 69. Assuming that this was the practice during 1981–1991, the Soviet Union would have recovered about 7 tons of reprocessed HEU from 17 tons of fresh HEU that had been used in production-reactor fuel by the end of the 1980s. There is almost no information about the scope of this program, but since there are some disadvantages of using high burn-up reprocessed uranium as a fuel, this practice was probably rather limited and, for the purposes of this estimate, the SWU savings that resulted are not taken into account.
- ²⁸⁹. Pavel Podvig and Susan S. Voss, “Use of highly-enriched uranium in Russian reactors”, *Proceedings of the 50th Annual Meeting of the Institute for Nuclear Material Management*, 12–16 July 2009; Pavel Podvig, *Consolidating Fissile Materials in Russia’s Nuclear Complex*, IPFM Research Report No. 7, May 2009, www.ipfmlibrary.org/rr07.pdf.
- ²⁹⁰. Ole Reistad, and Styrkaar Hustveit, “HEU Fuel Cycle Inventories and Progress on Global Minimization,” *The Nonproliferation Review*, 15 (2), 2008, pp. 265–287.

- ²⁹¹ Based on data in Reistad and Hustveit, *op. cit.*
- ²⁹² Reistad and Hustveit, *op. cit.*, p. 268. Also, according to Rosatom data, in 2002, the Obninsk institute stored 14.4 tons of spent research reactor fuel containing 12.8 tons of U-235 (see Korotkevich and Kudryavtsev, *op. cit.*, p. 25). Most of this material appears to be HEU from various decommissioned critical assemblies and therefore can be considered part of the HEU stock. This number most likely includes the 3.5 tons of HEU in BFS-1 and BFS-2 critical assemblies mentioned in the text. The only reactor that exposed HEU fuel to significant burn-up was BR-10 fast reactor. This reactor consumed an estimated 1.5 tons of 90% HEU.
- ²⁹³ During 1951–1953, OK-180 produced plutonium.
- ²⁹⁴ D. F. Newman, C. J. Gesh, E. F. Love, and S. L. Harms, *Summary of Near-Term Options for Russian Plutonium Production Reactors*, PNL-9982 (UC-520), Pacific Northwest Laboratory, Richland, WA, July 1994.
- ²⁹⁵ See Chapter 3.
- ²⁹⁶ The total amount of weapon-grade plutonium produced in the Soviet Union and Russia is estimated to be 145 tons, of which 1235 kg had been produced before 1955, see Chapter 3.
- ²⁹⁷ V. F. Konovalov et al., “Development of uranium and lithium elements for production of plutonium and tritium,” in A. M. Petrosyants, ed., *Russia’s Nuclear Industry*, Moscow, Energoatomizdat, 1999.
- ²⁹⁸ AID-80 and AID-90 uranium-oxide fuel elements respectively. The reactor may have also used AID-21 fuel elements with 21% enrichment, which were developed around the same time. Konovalov et al., *op. cit.*
- ²⁹⁹ I. N. Beckman, *Radiokhimiya*, Moscow, 2006.
- ³⁰⁰ V. I. Sadovnikov and A. P. Zharov, *Istoriya atomnoy promyshlennosti SSSR (History of the nuclear industry of the USSR)*, Ozersk, 2000.
- ³⁰¹ B. L. Ioffe, O. V. Shvedov, “Heavy water reactors and nuclear power plants in the USSR and Russia: Past, present, and future,” *Atomic Energy*, Vol. 86, No. 4, 1999, p. 297.
- ³⁰² The reactor was also used to produce plutonium in 1951–1953, Chapter 3.
- ³⁰³ G.V. Kiselev, V.N. Konev, “History of the realization of the thorium regime in the Soviet Atomic Project,” *Uspekhi Fizicheskikh Nauk*, 177 (12), 2007, pp. 1361–1384.
- ³⁰⁴ V. I. Sadovnikov and A. P. Zharov, *op. cit.*
- ³⁰⁵ Ye. N. Sokolov et al., “The 50-Year History of the Central Machine-Building Design Bureau,” in A. M. Petrosyants, ed., *Russia’s Nuclear Industry*, Moscow, Energoatomizdat, 1999.
- ³⁰⁶ This assumes that the reactors operated at a U-235 burn-up of about 60% and a capacity factor of about 70%.
- ³⁰⁷ This assumes that the reactors operated at U-235 burn-up of 60% and with a capacity factor of 70%. This is in agreement with the data on reprocessing of fuel of the Ruslan and Lyudmila reactors at the RT-1 facility at Ozersk. By 2002, the RT-1 had plant reprocessed 20 MTHM of HEU fuel of these reactors. Vladimir Korotkevich, Evgeny Kudryavtsev, *op. cit.*, p. 26.
- ³⁰⁸ Pavel Podvig, ed., *Russian Strategic Nuclear Forces*, MIT Press, 2001, p. 480.
- ³⁰⁹ Oleg Bukharin, “Understanding Russia’s Uranium Enrichment Complex,” *Science & Global Security*, Volume 12, 2004, pp. 202–204.
- ³¹⁰ “Material for 16,000 Nuclear Warheads Eliminated by Megatons to Megawatts,” US Enrichment Company press release, 9 September 2010.
- ³¹¹ U.S. Department of Energy, *FY 2011 Congressional Budget Request: National Nuclear Security Administration*, Vol. 1, p. 377.
- ³¹² Oleg Bukharin, “Analysis of the Size and Quality of Uranium Inventories in Russia,” *Science & Global Security*, Volume 6, 1996, pp. 64–65.
- ³¹³ The IPFM thanks Matthew Bunn of Harvard University for sharing his copy of this image.
- ³¹⁴ Earlier estimates also accounted for production losses that were taken to be about 3% of the total separative capacity (David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, p. 112). We do not take this into account here, since the actual production capacity is not known with this level of accuracy.

- ³¹⁵. This estimate is consistent with the statement made by Viktor Mikhailov, then Minister of Atomic Energy, in 1993. Commenting on the U.S.-Russian HEU-LEU deal, Mikhailov said that “The 500 metric tons of HEU that is up for sale represents somewhere around 40 percent of all reserves that we [Russia] possess.” (*NUKEM Market Report*, Sept. 17, 1993). This suggests that the Soviet Union had about 1250 tons of HEU at the time. Detailed comparison of these estimates is difficult since it is not known what was included in the number given by Mikhailov. This number probably would not include HEU produced for naval fuel and fuel of some research and fast reactors, which is also not accounted for in our estimate. Mikhailov’s number, however, would also not include HEU consumed in production reactors, nuclear tests, and losses, while our estimate does include these amounts. Our estimate is also consistent with the data on the amount of reprocessed uranium available for enrichment. By the end of 1988 the Soviet Union had produced about 115 tons of plutonium, which required about 280,000 tons of natural uranium fuel at 420 grams of plutonium produced per ton of uranium irradiated (chapter 3). On using reprocessed uranium to produce weapon-grade HEU see Bukharin, “Analysis of the Size and Quality of Uranium Inventories in Russia,” *op. cit.*, p. 63.
- ³¹⁶. *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*, Rev. 1, Draft, U.S. Department of Energy, January 2001 (publicly released in 2006), p. 92.
- ³¹⁷. The first machines installed at D-1 were OK-7, OK-8, OK-9, and later OK-6, A. K. Kruglov, *Kak sozdavalas atomnaya promyshlennost v SSSR (This is how the nuclear industry of the USSR was created)*, TsNIAtominform, Moscow, 1995, p. 183.
- ³¹⁸. Yu. V. Yegorov et al., *Ostanovitsya, oglyanutsya (To take a pause and look back)*, Ekaterinburg, UMTS UPI, 2009, p. 10.
- ³¹⁹. OK-6 machines were added to the upper cascade. Yegorov et al., *op. cit.*; Kruglov, *op. cit.*, p. 187.
- ³²⁰. D-3 was equipped with T-45, T-46, T-47, and T-49 machines, Yu. L. Golin et al., “Urals Electrochemical Combine (UEKhK), in A. M. Petrosyants, ed., *Russia’s Nuclear Industry*, Moscow, Energoatomizdat, 1999.
- ³²¹. The D-5 plant was equipped with OK-26 and T-51 machines, Golin et al., *op. cit.*
- ³²². For data on productivity of diffusion machines, see Kruglov, *op. cit.*, p. 191.
- ³²³. Golin et al., *op. cit.*
- ³²⁴. On doubling of productivity of the UEKhK, see Golin et al., *op. cit.*
- ³²⁵. Golin et al., *op. cit.*
- ³²⁶. Viktor Myasnikov, *Oruzhie Urala*, Ekaterinburg, Pakrus, 2000.
- ³²⁷. Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 106.
- ³²⁸. Yu. V. Yegorov et al., *op. cit.*, p. 136.
- ³²⁹. This is in agreement with the information that the first plant had 700,000 centrifuges, assuming that third-generation centrifuges had a capacity of about 1 SWU/yr. For the number of centrifuges see Viktor Myasnikov, *Oruzhie Urala*, Ekaterinburg, Pakrus, 2000. For the capacity of centrifuges, see Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 106.
- ³³⁰. *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, U.S. Department of Energy, DOE/NN-0007, Washington, DC, January 1997, p. 51, www.ipfmlibrary.org/doe01b.pdf.
- ³³¹. Yegorov et al., *op. cit.*, p. 136.
- ³³². The D-3 and SU-3 plants were shut down in 1967. Installation of centrifuges was completed in 1971. This is in agreement with the reports of numerous failures of fifth-generation centrifuges that the Soviet Union had to deal with in 1972. Oleg Bukharin, *Russia’s Gaseous Centrifuge Technology and Uranium Enrichment Complex*, Program on Science and Global Security, Princeton University, January 2004, p. 11.
- ³³³. Deployment of sixth-generation centrifuges reportedly began in 1984. Bukharin, “Understanding of Russia’s Uranium Enrichment Complex,” *op. cit.*, p. 197.
- ³³⁴. V. M. Kondakov, “Siberian Chemical Combine,” in A. M. Petrosyants, ed., *Russia’s Nuclear Industry*, Moscow, Energoatomizdat, 1999.
- ³³⁵. K. Ye. Galetskaya, *Tekhnologii razdeleniya izotopov na primere Sibirskogo khimicheskogo kombinata (Isotope separation technologies: the example of the Siberian chemical combine)*, Seversk, 2008.

- ³³⁶ Oleg Bukharin, Thomas Cochran and Robert Norris, *New Perspectives on Russia's Ten Secret Cities*, Natural Resources Defense Council, October 1999, p. 33.
- ³³⁷ *Elektro-khimicheskii zavod. Istoriya (Electro-chemical combine. History)*, Krasnoyarsk regional information center, Rosatom, www.krasminatom.ru/enterprises/ehz/history.html.
- ³³⁸ This assumes that fourth-generation centrifuges had about 40% higher capacity than third-generation machines. Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 106.

Chapter 5. United Kingdom

- ³³⁹ *Plutonium and Aldermaston: A Historical Account*, UK Ministry of Defence, 2000, originally published online at www.mod.uk, available at www.fas.org, mirrored at www.ipfmlibrary.org/mod00.pdf, §11.
- ³⁴⁰ *The Strategic Defence Review*, UK Ministry of Defence, Cm 3999, July 1998, §72, www.ipfmlibrary.org/mod98.pdf.
- ³⁴¹ *Communication Received from Certain Member States [the United Kingdom of Great Britain and Northern Ireland] Concerning their Policies Regarding the Management of Plutonium*, INFCIRC/549/Add. 8, International Atomic Energy Agency, Vienna, 31 March 1998.
- ³⁴² www.twitter.com/WilliamJHague/status/14768923283.
- ³⁴³ Robert S. Norris and Hans M. Kristensen, "Nuclear Notebook: Worldwide deployments of nuclear weapons, 2009," *Bulletin of the Atomic Scientists*, 65 (6), November/December 2009, pp. 86–98 estimated 185 warheads.
- ³⁴⁴ *Securing Britain in an Age of Uncertainty: The Strategic Defence and Security Review*, Cm 7948, HM Government, London, 2010, p. 38.
- ³⁴⁵ We use 10 kg, rather than a more usual higher figure of 20 kg because (i) at 100 kiloton (kT) UK warheads are relatively low yield for thermonuclear warheads and (ii) The fission of the U-235 is probably about 50%. The fission of 5 kg of uranium would yield about 85 kT. For the yield of UK warheads see Robert S. Norris and Hans M. Kristensen, "British Nuclear Forces, 2005," *Bulletin of the Atomic Scientists*, 61 (6), November/December 2005, pp. 77–79.
- ³⁴⁶ The UK submarine fleet currently consumes about 100 kg of U-235 per year. This calculation further assumes that, in future, submarine reactors might reach a burn-up of about 70% and the fuel is enriched to 97.4% (the standard for U.S. submarine fuel).
- ³⁴⁷ *Plutonium and Aldermaston*, *op. cit.*
- ³⁴⁸ *Strategic Defence Review*, *op. cit.*, Chapter 4, §72.
- ³⁴⁹ *Historical Accounting for UK Defence Highly Enriched Uranium*, UK Ministry of Defence, March 2006, www.ipfmlibrary.org/mod06.pdf.
- ³⁵⁰ The 2006 report listing the inventory for March 2002 remains silent about why this inventory did not decrease between 1998 and 2002. The inventory change may have been obscured for classification reasons because publishing it would have allowed inference of the naval fuel consumption rate.
- ³⁵¹ *Historical Accounting*, *op. cit.*
- ³⁵² *Plutonium and Aldermaston*, *op. cit.*, §§ 30 and 31.
- ³⁵³ Note that there are various ways of how "equivalent" could have been defined as part of such an agreement, e.g. having the same uranium-235 content or requiring the same amount of separative work to produce, etc.
- ³⁵⁴ This information can be inferred from Table 4-1, *Striking a Balance*, *op. cit.*
- ³⁵⁵ The U.S. HEU delivered to France for military purposes was probably destined for the naval-propulsion program.
- ³⁵⁶ See section on U.S. exports in Chapter 2 of this report.
- ³⁵⁷ Construction of the plant started in 1951, but it is not clear when routine HEU production began. "Capenhurst stopped production of HEU for military purposes in 1962," *Historical Accounting*, *op. cit.*
- ³⁵⁸ The number of stages in the Capenhurst plant is given in: *Affordable Cleanup? Opportunities for Cost Reduction in the Decontamination and Decommissioning of the Nation's Uranium Enrichment Facilities*, National Research Council, U.S. National Academy Press, Washington, DC, 1996.

- ³⁵⁹ *Lifetime Plan: Capenhurst Site Summary*, UK Nuclear Decommissioning Authority, 2006, www.ipfmlibrary.org/nda06b.pdf.
- ³⁶⁰ Both are somewhat higher than previous independent estimates by Albright, Berkhout, and Walker, who assumed a final plant capacity of 325,000 SWU/yr. The IAEA NFCIS Facility Report (350,000 SWU/yr) has been retrieved from www-nfcis.iaea.org in May 2010.
- ³⁶¹ David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, pp. 117–118.
- ³⁶² Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 120, Table 4.9.
- ³⁶³ Given that the United Kingdom only reports the total mass of HEU and not its enrichment level, consumption in naval and other reactors will only include, to a good approximation, actual fission of uranium-235 atoms, and does not take into account the reduced enrichment level of irradiated fuel.
- ³⁶⁴ Sources: *Jane's Fighting Ships* (Various editions); Hansard (House of Commons Daily Debates) Archive, www.publications.parliament.uk/pa/cm/cmhansrd.htm; and www.royalnavy.mod.uk. *HMS Dreadnaught* was powered by a Westinghouse reactor. Most, if not all, of its fuel was fabricated in the United States (John Simpson, *Independent Nuclear State: The United States, Britain and the Military Atom*, Second Edition, MacMillan, Basingstoke, 1986, pp. 181–183). Two boats of the *Swiftsure*-Class (HMS *Swiftsure* and HMS *Splendid*) were retired early and were probably only refitted once each. It is not known whether the cores for the third and fourth *Astute*-Class boats (HMS *Artful* and HMS *Audacious*) have yet been fabricated. One boat of the *Vanguard* Class (HMS *Vengeance*) is yet to be refitted. It is not known whether its replacement core has yet been fabricated.
- ³⁶⁵ We thank Brian Radzinsky from the Carnegie Endowment for International Peace, for compiling the data used in constructing this table. The data is consistent with two known data points. A 1981 *Financial Times* article stated that as of mid-1981 the United Kingdom had fabricated 37 submarine reactor cores. A 2002 government study stated that 51 spent cores were in storage at Sellafield. The refit data used to compile Table 5.2 puts these numbers at, respectively, 30–35 (including three cores fabricated for land-based prototype reactors) and 49 (including four used cores from land-based test reactors). See Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 119, Footnote 83; *Implications of Declaring UK Uranium Stocks as Waste*, NIREX Technical Note, Document 375301, 26 March 2002, www.nda.gov.uk, mirrored at www.ipfmlibrary.org/nir02.pdf.
- ³⁶⁶ The rate of U-235 consumption is estimated in *Global Fissile Material Report 2008*, *op. cit.*, p. 78. The assumption that UK submarines spend, on average, one out of every four years in refit is based on the fact that, at any given time, one of the United Kingdom's 4 SSBNs is in refit.
- ³⁶⁷ Since 2002, the UK SSN and SSBN fleets have seen about 80 and 30 submarine-years of service, respectively.
- ³⁶⁸ A burnup of 50% means that half of the initial U-235 has been fissioned or converted to U-236.
- ³⁶⁹ In making this estimate we assume that the fuel is enriched to 97.4% and that its maximum burn-up is 65%. Given data on refueling, the lifetime of reactors installed in the Trafalgar- and Vanguard-class submarines is known to be about 15 and 20 years, respectively. The new *Astute*-class does not require refueling and is expected to have a service life of more than 25 years, so we assume its core has a lifetime of 30 years. Under these assumptions the mass of fuel contained in the cores of *Astute*- and *Vanguard*-class vessels is essentially the same. This is consistent with reports that they share the same reactor cores.
- ³⁷⁰ We use 10 kg for the average quantity of HEU in a current UK warhead. Because some earlier designs were higher yield, we take the quantity of HEU per test explosion as 15 kg.
- ³⁷¹ "Vulcan Leads the Way for Navy Nuclear Reactors," *Navy News*, 7 January 2003, www.navynews.co.uk, mirrored at www.ipfmlibrary.org/nav03.pdf.
- ³⁷² *Historical Accounting*, *op. cit.*; "Vulcan Leads the Way," *op. cit.*; and IAEA Research Reactor Database, www.iaea.org/worldatom/rrdb. The IAEA data on criticality and shut down of DSMP appears unreliable and has not been used.
- ³⁷³ As of 31 December 2009, 1404 kilograms, *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium: Statements on the Management of Plutonium and of High Enriched Uranium*, INFCIRC/549/Add.8/13, International Atomic Energy Agency, Vienna, 16 August 2010.
- ³⁷⁴ The entire civilian sector was already safeguarded. For a summary of safeguards in the United Kingdom, see *Global Fissile Material Report 2007*, pp. 73–76.

- ^{375.} *The United Kingdom's Defence Nuclear Weapons Programme*, undated, www.ipfmlibrary.org/mod00b.pdf.
- ^{376.} *Plutonium and Aldermaston*, *op. cit.*, §29.
- ^{377.} Methodologically, this is very different from the U.S. plutonium declaration, which calculated the inventory from explicit acquisition and removal categories, e.g., from annual production rates at reactors, consumption in nuclear tests, etc.
- ^{378.} We assume that the material returned to Sellafield was never part of the defense stockpile or, if so, was eventually shipped back to Aldermaston, e.g., after cleanup and purification.
- ^{379.} Wastes produced at Aldermaston were sent to Sellafield where plutonium was extracted and sent back to Aldermaston. The 17.12 tons of plutonium acquired by Aldermaston appears to include an unspecified quantity of 'double counted' material.
- ^{380.} Simpson, *The Independent Nuclear State*, *op. cit.*, pp. 62–65 and Appendix 4.
- ^{381.} A. E. Sheil, W. Botzem, and C. K. Johnston, "Decommissioning of Windscale Pile 1," *WM'99 Conference*, February 28–March 4, 1999, www.ipfmlibrary.org/she99.pdf, p. 2.
- ^{382.} These power levels are listed in Simpson, *op. cit.*, and primarily based on M. Growing with L. Arnold, *Independence and Deterrence*, Vol. 2, Macmillan, 1974.
- ^{383.} For a detailed account of the accident, see: Lorna Arnold, *Windscale 1957: Anatomy of an Accident*, Third Edition, Palgrave/Macmillan, Hampshire, 2007.
- ^{384.} The following additional assumptions are made for this estimate: The use of slightly enriched uranium reduced the plutonium production rate by about 15% between 1954 and 1957, and the piles had a capacity factor of about 82% (300 days of operation per year).
- ^{385.} Simpson, *The Independent Nuclear State*, *op. cit.*, Appendix 4.
- ^{386.} Richard Wakeford, "The Windscale Reactor Accident—50 Years On," *Journal of Radiological Protection*, 27 (3), 2007, pp. 211–215; and J. A. Garland and R. Wakeford, "Atmospheric Emissions from the Windscale Accident of October 1957," *Atmospheric Environment*, 41 (18), June 2007, pp. 3904–3920. See also "Appendix IX: Estimates of Fission Product and Other Radioactive Releases Resulting from the 1957 Fire in Windscale Pile No. 1," in Arnold, *Windscale 1957*, *op. cit.*
- ^{387.} Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 63.
- ^{388.} "Chapelcross Cooling Towers," UK Nuclear Decommissioning Authority, 21 May 2007, www.nda.gov.uk; "Sellafield towers are demolished," *BBC*, 29 September 2007, www.ipfmlibrary.org/bbc07.pdf.
- ^{389.} Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 61.
- ^{390.} On the burnup of the Calder Hall reactor, when operated in civilian mode, see Table 1 in B. D. Murphy, *ORIGEN-ARP Cross-Section Libraries for Magnox, Advanced Gas-Cooled, and VVER Reactor Designs*, ORNL/TM-2003/263, Oak Ridge National Laboratory, February 2004.
- ^{391.} For a more detailed discussion of UK reactor operation, see Albright, Berkhout, and Walker, 1997, *op. cit.*, pp. 59–66.
- ^{392.} This value is based on neutronics calculations summarized in Appendix B.
- ^{393.} The history and legacy of the UK reprocessing program has been reviewed in: Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, IPFM Research Report No. 5, International Panel on Fissile Materials, July 2008, www.ipfmlibrary.org/rr05.pdf.
- ^{394.} In October 2010, the last two UK Magnox reactors (Wylfa site, 0.475 GWe each) received approval to operate until 2012, *Two More Years for Wylfa*, World Nuclear News, 14 October 2010, www.world-nuclear-news.org/RS-Two_more_years_for_Wylfa-1410104.htm. As of the end of 2007, there were an estimated 6000 tons of Magnox fuel still to be reprocessed, including the spent fuel expected to be discharged from the remaining operating Magnox power plants, Forwood, *Legacy of Reprocessing*, *op. cit.*, p. 7; and "The Magnox Operating Programme," British Nuclear Energy, July 2006. Assuming 2.4 kg of plutonium per ton of spent fuel, the 6000 tons of spent Magnox fuel would contain about 14.4 tons of plutonium, Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 480.
- ^{395.} *Pre-consultation discussion paper on the key factors that could be used to compare one option for long term plutonium management with another*, UK Nuclear Decommissioning Authority, 30 January 2009; and *Plutonium, Topic Strategy: Credible Options Technical Analysis*, UK Department of Energy and Climate Change, July 2009.

- ³⁹⁶. *Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning its Policies Regarding the Management of Plutonium: Statements on the Management of Plutonium and of High Enriched Uranium*, INFCIRC/549/Add.8/13, International Atomic Energy Agency, Vienna, 16 August 2010.
- ³⁹⁷. *Draft Strategy*, UK Nuclear Decommissioning Authority, 2010, www.nda.gov.uk/documents/upload/Draft-Strategy-published-September-2010-for-consultation-full-colour-version.pdf, p. 29.
- ³⁹⁸. The magnesium alloy cladding (“Magnox”) is easily corroded. When water penetrates to the cladding, it oxidizes the uranium metal releasing hydrogen, which is absorbed into the metal. If the fuel subsequently contacts air, the hydrogen can spontaneously ignite.
- ³⁹⁹. See for example, *The United Kingdom-Norway Initiative: Research Into the Verification of Nuclear Warhead Dismantlement*, Working paper submitted by Norway and the United Kingdom of Great Britain and Northern Ireland, NPT/CONF.2010/WP.41, 26 April 2010, 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, New York, 3–28 May 2010.
- ⁴⁰⁰. Former UK Secretary of State for Foreign Affairs Margaret Beckett, *A World Free of Nuclear Weapons?*, Keynote address at the Carnegie International Nonproliferation Conference, Washington, DC, 25 June 2007, transcript available at www.carnegieendowment.org/events/?fa=eventDetail&id=1004.
- ⁴⁰¹. *Lifetime Plan*, *op. cit.*
- ⁴⁰². See Chapter 4 in *Global Fissile Material Report 2009*, www.ipfmlibrary.org/gfmr09.pdf.
- ⁴⁰³. *Implications of Declaring UK Uranium Stocks as Waste*, NIREX Technical Note, Document 375301, 26 March 2002, www.nda.gov.uk, mirrored at www.ipfmlibrary.org/nir02.pdf.
- ⁴⁰⁴. Since UK and U.S. naval reactors may be similar, revealing fuel-design information could raise objections from the U.S. Navy as well.
- ⁴⁰⁵. Thomas W. Wood, Bruce D. Reid, John L. Smoot and James L. Fuller, “Establishing Confident Accounting for Russian Weapons Plutonium,” *The Nonproliferation Review*, 9 (2), Summer 2002, pp. 126–137, cns.miis.edu/npr/pdfs/92wood.pdf.
- ⁴⁰⁶. For detailed decommissioning plans see the “Lifetime Plans” for Windscale, Calder Hall, and Chapelcross, all available at www.nda.gov.uk.

Chapter 6. France

- ⁴⁰⁷. Prominent French scientists involved in the U.S. Manhattan project included Hans von Halban, Lew Kowarski, Pierre Victor Auger, Jules Guéron, and Bertrand Goldschmidt.
- ⁴⁰⁸. Jean Crépin (Général d’armée), “Histoire du Comité des Explosives Nucléaires,” *L’Aventure de la Bombe: De Gaulle et la Dissuasion Nucléaire (1958–1969)*, Librairie Plon, Paris, 1985, pp. 77–85.
- ⁴⁰⁹. Statement by Pierre Guillaumat (Administrateur Général, CEA) in June 1959, quoted by Jean Crépin, *op. cit.*, p. 84.
- ⁴¹⁰. Bertrand Goldschmidt, *The Atomic Complex: A Worldwide Political History of Nuclear Energy*, American Nuclear Society, La Grange Park, IL, 1982, p. 137.
- ⁴¹¹. See www.francetnp2010.fr/spip.php?article7.
- ⁴¹². See www.francetnp2010.fr/spip.php?article67, mirrored at www.ipfmlibrary.org/tnp10.pdf.
- ⁴¹³. Speech by President Nicolas Sarkozy, Presentation of SSBM Le Terrible in Cherbourg, 21 March 2008, www.ipfmlibrary.org/sar08.pdf.
- ⁴¹⁴. In the early 1980s, France considered the massive deployment of tactical nuclear weapons and the development of an enhanced radiation weapon (“neutron bomb”), which by some estimates would have required an additional 5–10 tons of plutonium, Ann MacLachlan, “France Not Ruling Out Using Superphénix Plutonium For Weapons,” *Nucleonics Week*, 24 (17), 28 April 1983. A 1983 report by the U.S. Center for Naval Analyses noted that French nuclear forces were expected to expand dramatically in the coming two decades since “the current force is small and is capable of limited target coverage against Soviet territory and against Warsaw Pact forces invading western territory” while “by the mid-1990s, the new force will be theoretically capable of inflicting massive destruction against the Soviet Union as well as inflicting significant damage against Warsaw Pact military targets in eastern Europe,” Robin F. Laird, *French Nuclear Forces in the 1980s and 1990s*, Professional Paper 400, Center for Naval Analyses, Alexandria, VA, August 1983, www.cna.org/documents/5500040000.pdf.

- ⁴¹⁵. Jean-Pierre Daviet, *Eurodif: Histoire de l'Enrichissement de l'Uranium (1973–1993)*, Fonds Mercator, 1993.
- ⁴¹⁶. Memo available at www.francetnp2010.fr, mirrored at www.ipfmlibrary.org/cea10.pdf.
- ⁴¹⁷. www.aveva.com/EN/operations-792/eurodif-s-a-georges-besse-plant-uranium-enrichment.html.
- ⁴¹⁸. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, p. 123. Information on Pierrelatte's operation is also reported on www.francenuc.org (maintained by Mary Byrd Davis), which quotes: Delacroix, Presentation at the Technology Outlook Meeting, Cogéma Conf. 90-3, 18–19 April 1990.
- ⁴¹⁹. Daviet, 1993, *op. cit.*, p. 169.
- ⁴²⁰. Pierre Plurien and Jean-Hubert Coates, *La diffusion gazeuse in France, de Pierrelatte à Eurodif*, Uranium Enrichment Symposium, Pierrelatte, France, 20 March 1996, www.ipfmlibrary.org/plu96.pdf.
- ⁴²¹. Daviet, 1993, *op. cit.*, p. 200.
- ⁴²². Daviet, 1993, *op. cit.*, p. 204.
- ⁴²³. Daviet, 1993, *op. cit.*, p. 127.
- ⁴²⁴. The performance value is listed in Plurien and Coates, 1996, *op. cit.* Using barrier performance to correlate capacity and electricity demand is plausible because the compressors require most of the energy in a gaseous diffusion plant.
- ⁴²⁵. Memo available at www.francetnp2010.fr, mirrored at www.ipfmlibrary.org/cea10.pdf. See also: Christophe Behar, Philippe Guiberteau, Bernard Duperret, and Claude Tausin, "D&D of the French High Enrichment Gaseous Diffusion Plant," *WM'03 Conference*, 23–27 February 2003, Tucson, AZ.
- ⁴²⁶. See Chapter 5 in this report.
- ⁴²⁷. For example, one additional estimate can be obtained from the reported barrier efficiency and number: The performance of the barriers used at Pierrelatte have been specified as 5-times below those used later in the Eurodif plant. At the same time, Eurodif uses ten-times as many barriers as Pierrelatte did (Plurien and Coates, 1996, *op. cit.*). Based on the known capacity of Eurodif (almost 11 million SWU/yr), this could suggest a capacity of the Pierrelatte plant of about 200,000 SWU/yr.
- ⁴²⁸. Albright, Berkhout, and Walker, 1997, *op. cit.*, have used 9.2 million SWU for the lifetime enrichment work delivered by Pierrelatte (p. 122–124). The authors distinguish, however, different periods of operation, beginning with 200,000 SWU/yr (1967–1969), followed by a period of "full" capacity of 500,000 SWU/yr (1970–1982), and a reduced capacity of 200,000 SWU/yr again (1983–1995).
- ⁴²⁹. Albright, Berkhout, and Walker, 1997, *op. cit.*, pp. 124–125.
- ⁴³⁰. This estimate assumes a burnup of 50% U-235 and a capacity factor of 82% (300 days per year). A reactor fueled with weapon-grade HEU consumes about 1.26 grams U-235 per MWd; see A. Glaser, *Neutronics Calculations Relevant to the Conversion of Research Reactors to Low-Enriched Fuel*, Ph.D. Thesis, Department of Physics, Darmstadt University of Technology, April 2005, Table 2.1.
- ⁴³¹. In March 2008, France's President Nicolas Sarkozy announced that, after a planned reduction, "I can tell you that our arsenal will include fewer than 300 nuclear warheads." He also revealed that France "has no other weapons beside those in its operational stockpile," Speech by President Nicolas Sarkozy, Presentation of SSBM Le Terrible in Cherbourg, 21 March 2008, www.ipfmlibrary.org/sar08.pdf.
- ⁴³². Robert S. Norris and Hans M. Kristensen, "French Nuclear Forces 2008," *Bulletin of the Atomic Scientists*, September/October 2008, pp. 52–54.
- ⁴³³. *Communication Received from France Concerning its Policies regarding the Management of Plutonium State-ments on the Management of Plutonium and of High Enriched Uranium*, INFCIRC/549/Add.5/14, International Atomic Energy Agency, Vienna, 8 September 2010.
- ⁴³⁴. *La Déconstruction des Centrales Nucléaires de Première Génération*, www.ipfmlibrary.org/edf07.pdf
- ⁴³⁵. *Marcoule: G1, G2 and G3 Reactors for Plutonium Production*, Commissariat à l'Énergie Atomique (CEA), 2009, memo available at www.francetnp2010.fr, mirrored at www.ipfmlibrary.org/cea10c.pdf. According to Albright, Berkhout, and Walker, 1997, *op. cit.*, quoting an IAEA directory of research reactors, the power level of G1 may have been 38–42 MW between 1956 and 1962.
- ⁴³⁶. *CEA Rapport Annuel 1962*, Commissariat à l'Énergie Atomique.
- ⁴³⁷. At 46 MW thermal, 12.4 GW-days/year correspond to about 270 effective full-power days per year.
- ⁴³⁸. This estimate is consistent with the estimate by Albright, Berkhout, and Walker, 1997, *op. cit.*

- ⁴³⁹. *Marcoule: G1, G2 and G3 Reactors*, 2009, *op. cit.*
- ⁴⁴⁰. According to the IAEA's Power Reactor Information System (PRIS), the G2 reactor produced 847.3 GWh(e) between 1976–79, and the G3 reactor produced 10,498.4 GWh(e) between 1971–1984, or a total of 11,345.7 GWh(e). This is consistent with information made public by the CEA, specifying a combined electricity production in G2 and G3 of 11 billion kWh; *Marcoule: G1, G2 and G3 Reactors*, 2009, *op. cit.* The reported electricity generation cannot be used, however, to estimate plutonium production because it only covers the period between 1971 and 1984.
- ⁴⁴¹. *Le Dossier Electronucléaire*, Syndicat CFDT (Confédération Française Démocratique du Travail) de l'Energie Atomique, Editions du Seuil, January 1980. For an excerpt, see www.ipfmlibrary.org/cfdt80.pdf.
- ⁴⁴². Albright, Berkhout, and Walker, 1997, *op. cit.*, p. 69. Albright, Berkhout, and Walker also quote from the 1963 CEA Annual Report, which indicated that “the operators did their best to increase the reactors’ thermal power as much as possible in order to increase plutonium production.”
- ⁴⁴³. The Célestin reactors initially used plutonium driver fuel and were only later shifted to highly enriched uranium. Similarly, Phénix used some highly enriched uranium in its core because of a plutonium shortage at the time.
- ⁴⁴⁴. *French Nuclear Reactor Fuel Reprocessing Program*, Central Intelligence Agency, September 1984, released in July 1992, www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB184, mirrored at www.ipfmlibrary.org/cia84.pdf, p. 2.
- ⁴⁴⁵. *French Reprocessing*, 1984, *op. cit.*, p. 2.
- ⁴⁴⁶. Jean-François Sauvage, *Phénix, 30 Years of History: The Heart of a Reactor*, Electricité de France and Commissariat à l'Energie Atomique, Bagnols-sur-Cèze, July 2004, available at www.iaea.org/inis/nkm/nkm/aws/fnss/phenix/book/index.html, mirrored at www.ipfmlibrary.org/sau04.pdf.
- ⁴⁴⁷. “According to several sources, the Phénix 250-Mw prototype breeder reactor near Marcoule has provided plutonium to the military branch of the CEA. (The French government refused a request for Euratom safeguards at Phénix, on the grounds, according to a CEA spokesman, that Phénix was ‘not accessible to international safeguards since it is susceptible of working for defense needs’),” Ann MacLachlan, *Nucleonics Week*, 28 April 1983, *op. cit.*
- ⁴⁴⁸. According to the IAEA Power Reactor Information System (PRIS), Phénix achieved a cumulative capacity factor of 58% between 1974 and 1990, www.iaea.org/programmes/a2. For a detailed discussion of the French fast-breeder program, see: Mycle Schneider, “Fast Breeder Reactors in France,” Chapter 2 in *Fast Breeder Reactor Programs: History and Status*, IPFM Research Report No. 8, International Panel on Fissile Materials, Princeton, NJ, February 2010, www.ipfmlibrary.org/rr08.pdf.
- ⁴⁴⁹. France ended production of plutonium for weapons in 1992.
- ⁴⁵⁰. *Mise à l'Arrêt Définitive du Réacteur Phénix*, Commissariat à l'Energie Atomique, Press release, 17 September 2009, www.cea.fr/le_cea/actualites/arret_definitif_du_reacteur_phenix-22415.
- ⁴⁵¹. In other words, the reactor was operated in a “self-sufficient” mode and did not require make-up (non-weapon-grade plutonium) from a different source. For a detailed discussion of how a fast-neutron reactor can be used in conjunction with other types of power reactors to maximize production of weapon-grade plutonium, see: A. Glaser and M. V. Ramana, “Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor,” *Science & Global Security*, 15 (2), 2007, pp. 85–105.
- ⁴⁵². Fissile material includes primarily plutonium-239, plutonium-241, and uranium-235.
- ⁴⁵³. Sauvage, 2004, *op. cit.*, p. 65.
- ⁴⁵⁴. This is far less than previously reported, given the more conservative assumptions underlying this estimate. Albright, Berkhout, and Walker, 1997, *op. cit.*, specify a range of 570–1150 kg for weapons plutonium contributed by Phénix (p. 73).
- ⁴⁵⁵. See www.nuclearweaponarchive.org/France/FranceFacility.html.
- ⁴⁵⁶. *CEA Rapport Annuel 2009*, Commissariat à l'Energie Atomique, 2010, www.cea.fr/var/cea/publications/rapport_annuel/2009/Rapport-Annuel-CEA-2009.pdf, p. 13.
- ⁴⁵⁷. Jean-Michel Boucheron, *Défense*, 3320-40 (Rapport 3320, Annexe 40), Assemblée Nationale, 14 November 2001, available at www.jmboucheron.fr/textes/pagefini/200110T2.PDF; Mary Byrd Davis first referenced this document on www.francenuc.org/en_mat/tritium_e.htm.

- ⁴⁵⁸. An article from 1970 indicates this evolving mission: “Principalement utilisés pour la production de tritium destiné à l’armement nucléaire de la France, ils ont participé, dès 1970, à une notable partie de la production nationale de radioéléments et de transuraniens, et cette part est susceptible de s’accroître dans l’avenir” (p. 36), *Les Réacteurs Célestin*, Bulletin d’Informations Scientifiques et Techniques (B.I.S.T.), 153–154, Commissariat à l’Energie Atomique, November/December 1970, pp. 36–48, www.ipfmlibrary.org/cea70.pdf.
- ⁴⁵⁹. This estimate assumes 300 effective full-power days per year: 190 MW x 2 x 300 d/yr x 10 yr.
- ⁴⁶⁰. A production rate of 0.6–0.7 grams per MW-day is also similar to the rate achieved in the U.S. Savannah River heavy-water reactors of similar design. The amount of plutonium produced at the U.S. Savannah River Site peaked in 1964 at 2123 kg. The site hosted five production reactors, all rated at 2500 MW. In the same year, the total energy developed at the site was 3.225 million MW-days (according to Table 3.2 in Thomas B. Cochran, *U.S. Nuclear Warhead Production*, Ballinger, 1987), suggesting an effective plutonium production rate of about 0.66 g/MW-days. On the U.S. plutonium production data, see: *Plutonium: The First 50 Years: United States Plutonium Production, Acquisition and Utilization from 1944 Through 1994*, U.S. Department of Energy, DOE/DP-0137, 1996, www.ipfmlibrary.org/doe96.pdf.
- ⁴⁶¹. Albright, Berkhout, and Walker, 1997, *op. cit.*, pp. 70–73.
- ⁴⁶². IAEA Power Reactor Information System (PRIS), www.iaea.org/programmes/a2. A thermal efficiency of 25% is used to convert from electricity production to thermal energy production.
- ⁴⁶³. This estimate is based on a plutonium production rate of 0.9 g/MWd when the reactors operated in military mode.
- ⁴⁶⁴. Discharging fuel at low burnup increases the refuelling rate, which may not have been in the interest of the reactor operator (EDF) as it increases uranium demand and complicates reactor operations.
- ⁴⁶⁵. See Endnote 414.
- ⁴⁶⁶. The leaked U.S. Department of Energy estimate was reported in Robert S. Norris and William M. Arkin, “World Plutonium Inventories,” *Bulletin of the Atomic Scientists*, September/October 1999, p. 71, available at www.thebulletin.org, mirrored at www.ipfmlibrary.org/nor99.pdf.
- ⁴⁶⁷. This estimate assumes 5 kilograms of plutonium per warhead: 4 kilograms in the warhead itself, plus a 25% working stock.
- ⁴⁶⁸. The plutonium from the Vandellós plant has not been returned to Spain and its final use is unknown.
- ⁴⁶⁹. *Rapport de Sûreté Nucléaire et de Radioprotection 2009*, Areva NC, 2010.
- ⁴⁷⁰. See Thomas B. Cochran et al., *Fast Breeder Reactor Programs: History and Status*, Research Report 8, International Panel on Fissile Materials, February 2010, www.ipfmlibrary.org/rr08.pdf.
- ⁴⁷¹. Including 11 tons of material from the German Hanau MOX plant cleanup.
- ⁴⁷². Since it has not been reported that any of the MOX scrap assemblies were reprocessed, it is to be assumed that the amount has remained at least constant. It is more likely that this inventory has increased. Also, the shut-down of the Cadarache MOX fabrication plant, ATPu, is generating significant quantities of scrap material that is to be transferred to La Hague.

Chapter 7. China

- ⁴⁷³. China’s highly enriched uranium is assumed to be 90% uranium-235 and weapon-grade plutonium is taken to be 94% plutonium-239.
- ⁴⁷⁴. For previous estimates of China’s fissile material stocks, see e.g. Robert S. Norris, A. S. Burrows, and R. W. Fieldhouse, *Nuclear Weapons Databook, Volume V: British, French, and Chinese Nuclear Weapons*, Westview Press, Washington, DC, 1994; David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997; David Wright and Lisbeth Gronlund, “Estimating China’s Production of Plutonium for Weapons,” *Science & Global Security*, Volume 11, 2003, p. 61; David Albright and Corey Hinderstein, *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, ISIS, 30 June 2005. These estimates have drawn mainly on translations of China’s official nuclear history: Li Jue, Lei Rongtian, Li Yi and Li Yingxiang, eds., *China Today: Nuclear Industry*, China Social Science Press,

Beijing, 1987 (in Chinese); selections were translated and published by the U.S. Foreign Broadcast Information Service, JPRS-CST-88-002, 15 January 1988; and JPRS-CST-88-008, Washington, DC, 26 April 1988; and John W. Lewis and Litai Xue, *China Builds the Bomb*, Stanford University Press, Stanford, California, 1988.

- ⁴⁷⁵ The U.S. Department of Energy (DOE) estimate was first reported in Bill Gertz and Rowan Scarborough, "A Nation Inside the Ring", *The Washington Times*, 9 July 1999. A more detailed report appeared in Robert S. Norris and William M. Arkin, "World Plutonium Inventories," *Bulletin of the Atomic Scientists*, September/October 1999, p. 71. The DOE estimate also assigned China a stockpile of 1.2 tons of civil plutonium.
- ⁴⁷⁶ "China" in *Banning the Production of Fissile Materials for Nuclear Weapons: Country Perspectives on the Challenges to a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008, pp.7–13, www.fissilematerials.org/ipfm/site_down/gfmr08cv.pdf.
- ⁴⁷⁷ Sam Trantum, "China's Indigenous Centrifuge Enrichment Plant," *Uranium Intelligence Weekly*, 25 October 2010.
- ⁴⁷⁸ *China Today: Nuclear Industry*, *op. cit.* (in Chinese), p. 172. Subsequent references are to this Chinese version.
- ⁴⁷⁹ Director of Central Intelligence, Special National Intelligence Estimate (SNIE) 13-2-63, "Communist China's Advanced Weapons Program," 24 July 1963, National Security Archive. www.nsarchive.org.
- ⁴⁸⁰ "Summary and Appraisal of Latest Evidence on Chinese Communist Advanced Weapon Capabilities," U.S. Arms Control and Disarmament Agency, ACDA-957, 10 July 1963. As of August 1964, U.S. intelligence agencies still believed the Lanzhou uranium enrichment plant was not complete. The CIA assumed that China would not have enough fissile material for a test until after the end of 1964. Director of Special Intelligence, "The Chances of an Imminent Communist Chinese Nuclear Explosion", Special National Intelligence Estimate, 13-4-64, 26 August 1964, declassified version in K. C. Ruffner (ed.), *CIA Cold War Records: America's First Satellite Program*, CIA Center for the Study of Intelligence: Washington, DC, 1995.
- ⁴⁸¹ Joel Ullom, "Enriched Uranium versus Plutonium: Proliferant Preferences in the Choice of Fissile Material," *Nonproliferation Review*, Volume 2, No. 1, Fall, 1994, pp. 1–5. A reactor was detected at Baotou nuclear complex by a March 1963 U-2 flight. U.S. intelligence mistakenly believed that it was a production reactor with a thermal power around 30 MWt, able to produce plutonium for one or two bombs a year. They estimated that a likely date for China to test its first plutonium-based device would be late 1964 or early 1965. ACDA-957, *op. cit.*
- ⁴⁸² William Burr and Jeffrey Richelson, "Whether to 'Strangle the Baby in the Cradle,'" *International Security*, Volume 25, No.3, Winter 2000/2001, pp. 91.
- ⁴⁸³ See, e.g. R. E. Lawrence and Harry W. Woo, "Infrared Imagery in Overhead Reconnaissance," *Studies in Intelligence*, Volume 11, No. 2, Summer, 1967, pp. 17–40.
- ⁴⁸⁴ Historic satellite imagery from: www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB186/
- ⁴⁸⁵ U.S. Defense Intelligence Agency, *People's Republic of China Nuclear Weapons Employment Policy and Strategy*, Report no. TCS-654775-72, Washington, DC, March 1972. The Manhattan Project physicist Ralph Lapp used the early experience at the U.S. Oak Ridge gaseous diffusion plant to estimate in 1971 that, at start-up, the Lanzhou plant may have produced about 130 kg per year of weapon-grade HEU and been able to double its annual production by 1966 as operators gained experience with the enrichment process; Lapp projected that the production capacity could increase to over 350 kg per year of HEU by the 1970s, Charles Murphy, "Mainland China's Evolving Nuclear Deterrence," *Bulletin of the Atomic Scientists*, January 1972, pp. 28–35.
- ⁴⁸⁶ *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, *op. cit.* By leaving more of the uranium-235 in the tails (i.e. a tails assay of 0.5% rather than 0.3%), China could achieve a given HEU production rate with a lower enrichment capacity. This would require about twice the amount of natural uranium feed, however.
- ⁴⁸⁷ *China Today: Nuclear Industry*, *op. cit.*, p. 179.
- ⁴⁸⁸ Xie Wuzhan, "504 Chang: Gongheguo Nongsuoyou Shiyue de Lingpaozhe" ("Plant 504: the leading runner of the cause of China's uranium enrichment"), *Gansu Daily*, 31 May 2008.
- ⁴⁸⁹ "Mainland China Talking to French, Germans, about Nuclear Power," *Nucleonics Week*, 12 January 1978.

- ^{490.} “Zhongguo Younongsuo ji Ranliao Yuanjian Zhizao” (“China’s uranium enrichment and fuel fabrication”), 28 March 2009, www.cnnuclear.cn/2009/0328/189.html, and discussions with Chinese experts.
- ^{491.} *China Today: Nuclear Industry*, *op. cit.*, p. 180.
- ^{492.} Ann MacLachlan and Mark Hibbs, “China Stops Production of Military Fuel: All SWU Capacity Now for Civil Use,” *Nuclear Fuel*, 13 November 1989.
- ^{493.} Mark Hibbs, “China Said to be Preparing for Decommissioning Defense Plants,” *Nuclear Fuel*, 17 May 1999.
- ^{494.} It is not clear if the contract also allows the production of LEU for naval-reactor fuel.
- ^{495.} It is assumed that Lanzhou had a capacity of 20,000 SWU per year (with a tails assay of 0.5%) for 1964 and 1965; there was a linear increase to 50,000 SWU per year until the end of 1970; a further linear increase to 90,000 SWU per year, but with a tails assay of 0.3 per cent from 1971 through 1975; and a linear increase to 180,000 SWU per year at a tails assay of 0.3 per cent until HEU production stopped in 1980.
- ^{496.} *Chinese Military Plutonium and Highly Enriched Uranium Inventories*, *op. cit.*
- ^{497.} In its 1972 estimate, the Defense Intelligence Agency estimated that this plant could produce 750–2950 kg of weapon-grade uranium per year. This would correspond to about 145,000–569,000 SWU per year at a tails assay of 0.3 per cent. Since this estimate was made several years before the plant was put into operation, it is not clear whether it was based on the existing building or on an assumption that the building would be expanded, *People’s Republic of China Nuclear Weapons Employment Policy and Strategy*, *op. cit.*
- ^{498.} It is assumed that the plutonium production reactor at Guangyuan, which was built as a Third Line facility, has the same design power as the original Jiuquan reactor that it was backing up.
- ^{499.} See, e.g., “Zhongguo Younongsuo ji Ranliao Yuanjian Zhizao,” *op. cit.*
- ^{500.} It is assumed that, from 1975 through 1979, Heping’s capacity increased linearly from 100,000 to 230,000 SWU per year at a tails assay of 0.3 per cent and that it operated at this capacity from 1980 to 1987.
- ^{501.} China began in 1970 enriching uranium recovered from the irradiated fuel discharged from its plutonium production reactors. *China Today: Nuclear Industry*, *op. cit.*, p. 186.
- ^{502.} Producing about 2 tons of plutonium would have resulted in about 4000 tons of reprocessed uranium. To enrich all of this uranium to 90% HEU, with a tails assay of 0.3 percent, would require about 3.2 million SWU. This is 154,000 SWU more than would be required to produce the same amount of HEU from natural uranium.
- ^{503.} China also has about 4 Miniature Neutron Source Reactors (MNSR). Each requires a long-lived core containing about 1 kg of 90% HEU. One of them shut down in 2007 and China has decided to shut-down the other three MNSRs and replace them with LEU-fueled neutron sources. In addition, China sold one MNSR each to Ghana, Iran, Nigeria, Pakistan, and Syria. China has a project to convert those reactors to LEU cores. www.nti.org/db/heu/china.html.
- ^{504.} Assuming that the 125 MWt HFETR had an average burnup of 40% of the U-235 in its fuel and operated 12 weeks per year (IAEA research reactor database), and assuming 1.26 g of uranium-235 would be consumed per MWd (thermal) the HFETR would have used about 994 kg of 90%-enriched HEU before conversion. Alexander Glaser, *Neutronics Calculations Relevant to the Conversion of Research Reactors to Low-Enriched Fuel*, Ph.D. Dissertation, Darmstadt, 2005. The 5 MWt MJTR, with an average burnup of 45% and an operation of 14 weeks per year (IAEA research reactor database), would have used about 25 kg before conversion.
- ^{505.} T. Dedik, I. Bolshinsky, and A. Krass, “Russian Research Reactor Fuel Return Program starts Shipping Fuel to Russia,” *25th International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR)*, Chicago, Illinois, USA, 5–10 October 2003, www.rertr.anl.gov/RERTR25/PDF/Dedik.pdf.
- ^{506.} David Albright and Kimberly Kramer, *Civil HEU Watch: Tracking Inventories of Civil Highly Enriched Uranium*, ISIS, February 2005, revised August 2005, www.isis-online.org/global_stocks/end2003/civil_heu_watch2005.pdf.
- ^{507.} “Entering a New Era,” *Nuclear Engineering International*, 8 January 2010. www.neimagazine.com/story.asp?storyCode=2055118.

- ⁵⁰⁸. *China Today: Nuclear Industry, op. cit.*, p. 239.
- ⁵⁰⁹. *China Today, Nuclear Industry, op. cit.*, pp. 305–306.
- ⁵¹⁰. It is expected that China's first third-generation attack submarine (Type 095) will come into service around 2015, Hans Kristensen, "China's Noisy Nuclear Submarines." www.fas.org/blog/ssp/2009/11/subnoise.php.
- ⁵¹¹. China reportedly has been building two (Type 094 *Jin*-class) ballistic-missile submarines since around 2003-2004. It is expected that about five such SSBNs will be built. Hans Kristensen, "Two More Chinese SSBNs Spotted," www.fas.org/blog/ssp/2007/10/two_more_chinese_ssbn_spotted.php.
- ⁵¹². See, e.g., Type 091 (Han Class) Nuclear-Powered Attack Submarine. www.sinodefence.com/navy/sub/type091han.asp.
- ⁵¹³. It is assumed the reactor operates with an average output of one-sixth of full power and the spent fuel has a uranium-235 burnup of 50%, and one kg of uranium-235 fission generates about 940 Megawatt-days of energy. Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Volume 8, Spring 2001, p. 95.
- ⁵¹⁴. If a submarine was scheduled for launch before 1985, LEU may have had to be produced before 1980 to allow time for fuel fabrication, loading fuel into the reactor, and possible delays. The launch and initial operational capacity (IOC) of Han-class nuclear attack submarines are: Changzheng 1 (launched December 1970; IOC August 1974); Changzheng 2 (launched December 1977; IOC December 1980); Changzheng 3 (launched October 1983; IOC December 1984); Changzheng 4 (launched December 1985; IOC December 1987); Changzheng 5 (launched April 1990; IOC December 1990). Assuming the refueling interval is ten years, then a total five cores were used for SSNs launched before 1985: Changzheng 1 (2 cores), Changzheng 2 (1 core), Changzheng 3 (1 core), Changzheng 4 (1 core), Changzheng 5 (0 core). "Type 091 (Han Class) Nuclear-Powered Attack Submarine," www.sinodefence.com/navy/sub/type091han.asp.
- ⁵¹⁵. For natural uranium feed, producing 1 kg of 5% LEU with a tails assay of 0.3 percent requires 7.2 SWU.
- ⁵¹⁶. *China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments*, www.nti.org/db/china/testlist.htm.
- ⁵¹⁷. This assumes 20 kg of HEU was used in each of the fission weapon tests. In the June 1967 3.0–3.3 MT thermonuclear weapon test, it is assumed that about 20 kT of the total yield came from the fission primary and about one-quarter of the yield in the thermonuclear secondary came from the fission of HEU, with about half of the HEU having fissioned. Frank von Hippel, Princeton University, personal communication, September 2010. This test would have consumed about 100 kg of HEU in the secondary. After plutonium became available in 1968, China may have shifted to using plutonium or composite uranium-plutonium pits since they allow the primaries to be more compact.
- ⁵¹⁸. There were 18 tests after 1968 with yields above 20 kT that are assumed to have been thermonuclear weapon tests. The total yield of these 18 tests was about 19 MT.
- ⁵¹⁹. In the U.S. enrichment program, "normal operating losses" were about 5 tons out of a total production of about 1000 tons from gaseous diffusion plants, i.e., 0.5% losses. See discussion in Chapter 2.
- ⁵²⁰. Simon Henderson, "Nuclear Scandal: Dr. Abdul Qadeer Khan," *Sunday Times*, 20 September 2009.
- ⁵²¹. One contribution to the $\pm 25\%$ uncertainty assumed for the estimated HEU production is due to the range of possible tails. For natural uranium feed producing 90% HEU, at a given separative work capacity, a tails assay of 0.5% would produce about 25% more HEU than a tails assay of 0.3%. There is no official information about tails assays in China's gaseous diffusion enrichment program.
- ⁵²². This is significantly less than the 21.5 ± 4.5 tons of HEU estimated in *Chinese Military Plutonium and Highly Enriched Uranium Inventories, op. cit.*
- ⁵²³. *China Today: Nuclear Industry, op. cit.*, p. 205.
- ⁵²⁴. *Ibid.*, pp. 210–211.
- ⁵²⁵. W. Lewis and L. Xue, "Chinese Strategic Weapons and the Plutonium Option," *Critical Technologies Newsletter*, U.S. Department of Energy, Washington, DC, April/May 1988, p. 12.
- ⁵²⁶. *China Today: Nuclear Industry, op. cit.*, p. 211.
- ⁵²⁷. *Ibid.*, p. 212.
- ⁵²⁸. The reactor's power was increased by 10–15 percent through improvements in the cooling system. Fuel burn-up also was increased, and the number of full-power days went from the original design value of 288 days to 324 days per year. *Ibid.*, p. 214.

- ⁵²⁹ See, e.g., Zhou Zhi, “Hegongyue 404 Jidi Chuangyue Huiyi” (“Recollections of the pioneering work of Plant 404”), 19 August 2007. The author was vice-minister of the former Ministry of Nuclear Industry; www.qkzz.net/Announce/Announce.asp?BoardID=17100&ID=10015168.
- ⁵³⁰ During the early 1980s, China planned to convert the reactor to the dual mission of producing electric power as well as plutonium. Work started in September 1984 and was planned to be completed in 1987, but the modification seems not to have been finished. No electricity substation or transmission lines connected to the site have been seen in satellite images, *China Today: Nuclear Industry*, *op. cit.*, p. 91.
- ⁵³¹ *China Today, Nuclear Industry*, *op. cit.*, p. 227.
- ⁵³² For a burn up of 800 MWt-days/ton, each ton of spent fuel would contain about 0.7 kg weapon-grade plutonium. See Appendix B.
- ⁵³³ *China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments*, www.nti.org/db/china/testlist.htm.
- ⁵³⁴ Hui Zhang and Frank von Hippel, “Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants,” *Science & Global Security*, Volume 8, 2000, p. 219, Figure A-2 shows that for a seasonal average temperature of 10°C and a typical temperature increase between 5°C and 15°C, the amount of heat discharged by the cooling towers would range from 0.02 MWt/m² to 0.2 MWt/m². For a top diameter of 30 meters, this corresponds to 14–140 MWt for each tower.
- ⁵³⁵ Operating at a capacity factor of 80 percent, a reactor of power 70–660 MWt could produce about 20–200 kg per year of weapon plutonium. This is a large range but it excludes a 1972 U.S. intelligence estimate that the Jiuquan reactor produced 300–400 kilograms of plutonium per year. *People's Republic of China Nuclear Weapons Employment Policy and Strategy*, *op. cit.*
- ⁵³⁶ See, e.g., “News from Chongqing Cable TV,” 26 April 2010; Peng Yining, “Nuclear reaction to tourist attraction,” *China Daily*, 22 June 2010, www.chinadaily.com.cn/cndy/2010-06/22/content_10000111.htm; and “Former nuclear plant opening as tourist attraction,” *China Daily*, 13 April 2010, www.chinadaily.com.cn/china/2010-04/13/content_9719335.htm.
- ⁵³⁷ This estimate assumes that, between 1967 and June 1975, the reactor power increased linearly to the design power of 250 MWt, with the capacity factor increasing from 40% at startup to the design value of 80% by 1969; the reactor was shut down for maintenance during 1974; from July 1975 through 1979, the reactor linearly increased its plutonium production rate to 1.2 times the initial design value; and, from 1980 until shutdown in 1984, plutonium production remained at this higher rate. It also assumes the amount of plutonium produced per MWt-day by the Jiuquan reactor is the same as for the U.S. Hanford graphite-moderated, water-cooled reactors (see Appendix B). Between 1967–1969, the reactor operated at an average burn-up of about 400 MWt-days/ton and produced 0.9 grams of plutonium per MWt-day. From 1970 till 1984, the reactor operated at an average burn-up of 800 MWd/t and produced 0.85 g/MWt-day.
- ⁵³⁸ Zheng Jingdong, retired senior engineer from Plant 821, “Zai Qiangjian 821 Chang de Rizhi Li” (“The days of racing to complete Plant 821”), 26 September 2009, www.blog.163.com/zjd_8213701/blog/static/33582026200982663110991.
- ⁵³⁹ “The days of racing to complete Plant 821,” *op. cit.*; and “Liangwei Hedian Gongchen de Zhihui Rensheng, Jiangsu Gonggong Kejiwang Wendang: Ren Wu” (“The intelligent life of two heroes of nuclear power,” document web of Jiangsu public science and technology: *People*), 14 May 2007, www.hi.baidu.com/lovechild/blog/item/f43d1a7a00a1eac2e73b359.html.
- ⁵⁴⁰ “The intelligent life of two heroes of nuclear power,” *op. cit.*
- ⁵⁴¹ The new enterprise was called the Sichuan Wuzhou Industry Company, a subsidiary of the China National Nuclear Company. The company declared bankruptcy in 2009 and the residents in the complex will move to new living areas. www.cnn.com.cn/publish/portal0/tab283/info47848.htm.
- ⁵⁴² *British, French, and Chinese Nuclear Weapons*, *op. cit.*, p.350.
- ⁵⁴³ See, e.g., “The days of racing to complete Plant 821,” *op. cit.*
- ⁵⁴⁴ This estimate assumes that: from 1973–1974, the reactor power increased linearly to the design power of 250 MWt with a capacity factor of 40 percent, and that from 1975 through 1978, the plutonium production rate increased linearly to 1.3 times the design rate of the Jiuquan reactor. The reactor maintained this higher production rate until the end of 1988, when plutonium production ended. The reactor is assumed to have produced 0.85 grams of plutonium per MWt-day for the whole operating period.

- ⁵⁴⁵. This is halfway between the 6 kg used in the first U.S. plutonium nuclear weapons and the 4 kg assumed for the pits of modern nuclear weapons.
- ⁵⁴⁶. The uncertainty of $\pm 25\%$ stems primarily from the uncertainty of the initial design powers of the two reactors.
- ⁵⁴⁷. Reported by Bill Gertz and Rowan Scarborough in "A Nation Inside the Ring", *Washington Times*, 9 July 1999; and Robert Norris and William Arkin, "World Plutonium Inventories," *Bulletin of the Atomic Scientists*, September/October 1999, p. 71.
- ⁵⁴⁸. See, e.g. Wright and Gronlund, "Estimating China's Production of Plutonium for Weapons," *op. cit.* For the Jiuquan reactor, they assume a design power of 250 MWt that was later increased to 500 MWt. For the Guangyuan reactor, they assume a design power of 500 MWt that increased to 1000 MWt.
- ⁵⁴⁹. *Communication received from China Concerning Its Policies Regarding the Management of Plutonium*, IAEA, INFCIRC/549/Add.7/8, 1 April 2008.
- ⁵⁵⁰. Deng Guoqing, China National Nuclear Corporation, "Overview of spent fuel management in China," International Conference on Management of Spent Fuel from Nuclear Power Reactors," Vienna, 31 May–4 June 2010, www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.htm.

Chapter 8. Israel

- ⁵⁵¹. Avner Cohen, *Israel and the Bomb*, Columbia University Press, New York, 1998.
- ⁵⁵². Peter Hounam et al., "Revealed: the secrets of Israel's nuclear arsenal", *Sunday Times*, 5 October 1986, pp. 1–3.
- ⁵⁵³. The transcripts of the information given to Hounam et al., hereafter referred to as *Transcripts*, are unpublished; Barnaby subsequently published his deductions from both these transcripts and his own subsequent interviews with Vanunu in Frank Barnaby, *The Invisible Bomb*, I. B. Tauris, London, 1989. According to the *Sunday Times*, the information in the *Transcripts* and the photos were scrutinized by experts besides Barnaby, including the late Theodore Taylor of the United States and individuals in the United Kingdom familiar with nuclear-weapon production and reactor operations who chose to remain anonymous. All agreed that Vanunu was an authentic and generally reliable source but there was a difference of opinion with regard to the credibility of some of his assertions, e.g., about the power of the Dimona reactor. Since the *Transcripts* are unpublished, the following is based mainly to the *Sunday Times* article and Barnaby's book. However, there is some intriguing information in the *Transcripts* not contained in these other sources that is also noted.
- ⁵⁵⁴. Seymour Hersh, *The Samson Option*, Random House, New York, 1991.
- ⁵⁵⁵. Vanunu was released from prison in 2004.
- ⁵⁵⁶. See: www.globalsecurity.org/wmd/world/israel/dimona_kyl-bingaman.htm. According to John Pike, personal communication, September 2010, the restrictions of the Kyl-Bingaman Amendment are still in effect.
- ⁵⁵⁷. Pierre Péan, *Les Deux Bombs*, Fayard, Paris, 1982. English translation by the Congressional Research Service (CRS).
- ⁵⁵⁸. EL-3 stands for "Eau Lourde 3" (Heavy-Water 3), i.e., the third French heavy water reactor.
- ⁵⁵⁹. Péan, *op. cit.*, CRS translation, p. 4. For a detailed description of the EL-3, see G. B. Melese, "France's New High-Flux Research Reactor", *Nuclear Engineering*, Vol. 3, No. 24, March 1958, pp. 115–120; and: J. Robert, J. Hainzelin, and V. Raievski, "The EL-3 Reactor," A/CONF. 15/P/335 Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, www.ipfmlibrary.org/rob58.pdf.
- ⁵⁶⁰. G.B. Melese, *op. cit.*, p. 115.
- ⁵⁶¹. U. M. Staebler and J. W. Crouch, Jr., *Notes on Visit to Israel*, Draft, 23 May 1961. Available at www.gwu.edu/~nsarchiv/israel/documents/first, mirrored at www.ipfmlibrary.org/sta61.pdf.
- ⁵⁶². Cohen, *op. cit.*, p. 365, Footnote 19 cites Remi Carle of the French CEA as stating that the Dimona reactor was designed to operate at a power of 40 MWt with an option to increase it in the future.
- ⁵⁶³. www.iaea.org/worldatom/rpdb, retrieved 23 September 2010.
- ⁵⁶⁴. Péan, *op. cit.*, CRS translation, p. 11.

- ⁵⁶⁵. The original text fragment (in French) is available at www.ipfmlibrary.org/pea82.pdf.
- ⁵⁶⁶. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, pp. 258–259.
- ⁵⁶⁷. Barnaby, *op. cit.*, p. 28.
- ⁵⁶⁸. *Transcripts, op. cit.*, “Unit 14: Here the fluid is concentrated to 450 grams/litre of uranium with 170/180 mgms/litre of plutonium.”
- ⁵⁶⁹. *Transcripts, op. cit.*, The net production rate of 36 kg/yr at Dimona can be computed as follows: the reprocessing plant operates nonstop for 242 days per year. The flow rate in one particular section of the plant (Unit 14) averages 35 liters per hour, and the process solution contains 170–180 milligrams of plutonium per liter. This yields 34.6–36.6 kg/yr or about 35.6 kg/yr on average.
- ⁵⁷⁰. Vanunu did not state explicitly that there was a loss of about 10% to scrap, but this figure is consistent with a plutonium extraction rate from the spent fuel of 36 kg/yr (see Endnote 19) and a button production rate of 40 kg/yr cited in Barnaby, *op. cit.*, p. 31. The button production rate of 40 kg/yr can also be inferred from the *Transcripts, op. cit.*: accordingly, 9 buttons are fabricated per week during 8 months per year (242 days, 34.6 weeks), each button containing 130 grams of plutonium. This corresponds to a button production rate of 40.45 kg/yr. The transcripts incorrectly compute a rate of 32 kg/yr from this data.
- ⁵⁷¹. More precisely, in our simulations, a plutonium-uranium ratio of 0.0004 corresponds to a burnup of 415 MWd/ton. Alexander Glaser, submitted to *Science & Global Security*, see also Appendix B.
- ⁵⁷². $36 \text{ kg} / (0.00096 \text{ kg/MWd} \times 270 \text{ d}) = 138.9 \text{ MW}$.
- ⁵⁷³. U. M. Staebler and J. W. Crouch, 1961, *op. cit.*
- ⁵⁷⁴. $40 \text{ MW} \times 270 \text{ d} / 450 \text{ MWd/ton} = 24 \text{ tons}$.
- ⁵⁷⁵. Both the transcripts and Barnaby, *op. cit.*, specify an in-core residence time of “three months.”
- ⁵⁷⁶. Increasing the refueling rate appears more realistic, but would be inconsistent with Vanunu’s observation that the fuel remains in the reactor for three months. One possibility is that the fuel was shipped to the reprocessing plant only every 90 days, but was unloaded from the reactor more frequently, e.g., every 45 days for the 140 MW scenario.
- ⁵⁷⁷. Image credits: Keyhole imagery available from the National Security Archive, www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB186/index.htm (1971), and IKONOS imagery courtesy of Space Imaging Middle East/GeoEye (2002).
- ⁵⁷⁸. Edward Block, MIT Nuclear Reactor Laboratory, personal communication, July 2010.
- ⁵⁷⁹. According to the *Sunday Times, op. cit.*, p. 1, “An ingenious cooling system disguises the (higher) output.” One possibility would be the use of an underground aquifer to carry away some of the heat.
- ⁵⁸⁰. This imagery is available at: www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB186.
- ⁵⁸¹. Albright, Berkhout, and Walker, *op. cit.*, p. 261.
- ⁵⁸². Avner Cohen, *The Worst Kept Secret: Israel’s Bargain with the Bomb*, Columbia University Press, 2010, pp. 81–84.
- ⁵⁸³. When tritium fuses with deuterium in the fission trigger of a nuclear weapon, it releases a neutron, which can create additional fissions that “boost” the yield of the primary (see Appendix A).
- ⁵⁸⁴. See Barnaby, *op. cit.*, pp. 38–40.
- ⁵⁸⁵. U. M. Staebler and J. W. Crouch, 1961, *op. cit.*, and Barnaby, *op. cit.*, Appendix III, p. 213.
- ⁵⁸⁶. This assumes that only about 50% of the lithium (85 kg) can be transmuted into tritium due to the loss of structural integrity (“buckling”) beyond that point of the Li-6 targets due to gas pressure. Note that 85 kg of lithium-6 when fully converted via $\text{Li-6} + \text{n} \rightarrow \text{He-4} + \text{T}$ would result in the production about 42.6 kg of tritium because, per atom, tritium weighs half as much as Li-6. See, e.g., Warren Stern, *Nuclear Weapons Material Control: Verification of Tritium Production Limitations*, Master’s Thesis, MIT Department of Nuclear Engineering, January 1988, p. 53, Footnote 32.
- ⁵⁸⁷. The complete fusion with deuterium of the tritium produced by transmuting one kg of lithium-6 would yield 90 kilotons of explosive yield. Barnaby, *op. cit.*, p. 25, quotes a personal communication from Keith Barham: “Roughly 6 kg of Li-6 D or 4.5 kg of Li-6 are needed to construct a thermonuclear weapon.”
- ⁵⁸⁸. See Appendix B for a hypothetical geometry of the Dimona reactor, a modified version of the EL-3.

- ⁵⁸⁹. Estimate by A. Glaser.
- ⁵⁹⁰. An alternative estimate can be obtained based on excess-reactivity considerations as follows: In a 70 MW reactor, fission events produce about 5.5×10^{18} neutrons per second, or, if the reactor operates for 270 days, about 220 moles of neutrons per year. Assuming an average excess core reactivity of 2.5%, which is a typical value for natural-uranium-fueled reactors, then up to 0.025×220 moles = 5.5 moles of neutrons are available for absorption in lithium-6, producing 5.5 moles or about 16.5 grams of tritium per year. For an excess reactivity of 12.5%, a value that could be achieved with slightly enriched fuel, this production rate could be increased significantly to about 80 grams of tritium per year.
- ⁵⁹¹. Hersh, *op. cit.*, p. 200.
- ⁵⁹². *Transcripts, op. cit.*
- ⁵⁹³. A brief description of the processes is given by Marvin Miller, *Technology to Extract Tritium from Heavy Water*, October 1987, unpublished manuscript available at www.ipfmlibrary.org/mil87.pdf.
- ⁵⁹⁴. For the transfer of the 30 grams of tritium, see, e.g., Sasha Polakow-Suransky, *The Unspoken Alliance*, Pantheon, New York, 2010, p. 125.
- ⁵⁹⁵. R. Scott Kemp, *Nonproliferation Strategy in the Centrifuge Age*, Doctoral Dissertation, Princeton University, June 2010, pp. 59–61.
- ⁵⁹⁶. Stephanie Cooke, *In Mortal Hands: A Cautionary History of the Nuclear Age*, Bloomsbury, 2009, pp. 231–232.
- ⁵⁹⁷. Kemp, *op. cit.*
- ⁵⁹⁸. See, e.g., Robert Gillette, “Uranium Enrichment: Rumors of Israeli Progress with Lasers”, *Science*, Vol. 183, 22 March 1974, pp. 1172–1174.
- ⁵⁹⁹. In his book, *The Samson Option, op. cit.*, pp. 241–257, Seymour Hersh noted that the approximately 100 kg of enriched uranium missing in a 1965 inventory of the NUMEC plant was recovered when the plant was decommissioned and dismantled, beginning in 1978 by its subsequent owner, Babcock and Wilcox. Hersh’s conclusion was that there had been no diversion, specifically to Israel. Indeed, during decommissioning, 126 kg of enriched uranium was recovered or estimated to be in the structure. But by then the cumulative “material unaccounted for”—the unexplained missing amount—for the entire period of enriched uranium operations, 1957–1978, was 463 kg, mostly from the period 1957–1968, when NUMEC operated the plant. Subtracting the found 126 kg still left 337 kg missing. Thus, the decommissioning result did not bear, as Hersh claimed, on the possibility of diversion. While this doesn’t provide conclusive evidence that a diversion did indeed occur, it indicates why suspicions still persist. For more details, see Victor Gilinsky and Roger J. Mattson, “Revisiting the NUMEC affair”, *Bulletin of the Atomic Scientists*, March/April 2010.
- ⁶⁰⁰. In their book, *Every Spy a Prince*, Houghton Mifflin, Boston, 1990, p. 326, Dan Raviv and Yossi Melman claim that: “The facility [the Dimona reactor] had been fed by the extra uranium obtained from Zalman Shapiro’s NUMEC Company in America and in the ship-switching “Plumbat” ruse on the Mediterranean in 1968.”
- ⁶⁰¹. For example, plutonium production at 70 MWt would drop from 18.1 kg to 14.5 kg per year.
- ⁶⁰². The reprocessed uranium from irradiation of natural uranium fuel contains about 0.66% U-235 instead of the 0.72% in natural uranium, which is still sufficient for operation at the desired fuel burnup. Recycling uranium a second or third time, however, may require blending with enriched uranium.

Chapter 9. India

- ⁶⁰³. In his 1955 speech to the First International Conference on the Peaceful Uses of Atomic Energy in Geneva, Homi Bhabha, the founder of the Indian nuclear program, explicitly stated “it is the intention in India to avoid the construction of a gaseous diffusion plant”, Homi J. Bhabha, “The Role of Atomic Power in India and Its Immediate Possibilities,” *First International Conference on the Peaceful Uses of Atomic Energy*, Geneva, 1955. This idea was revised and in 1970 the Atomic Energy Commission declared, “In 1960, plants for the enrichment of U-235 were considered out of the question for India due to their high costs as well as their enormous consumption of electric power. This analysis was based on the use of the gaseous diffusion process. Since then, there has been marked progress of the gas centrifuge process which is less expensive to establish...India is late in interesting itself

with serious developmental work for enrichment of uranium-235. This lacuna must be made good in view of the present evaluation of gas centrifuge technology... Substantial Research and Development effort must therefore be devoted to master the sophisticated chemistry and machine technology as well as production of materials which are strong and corrosion resistant, such as carbon filaments, which would be needed for this program," *Atomic Energy and Space Research: A Profile for the Decade 1970–80*, Atomic Energy Commission, 1970.

- ⁶⁰⁴ The NRX reactor was known to be an efficient producer of plutonium because of its high neutron economy and some Canadian diplomats realized that supplying the CIRUS reactor could lead to potential acquisition of weapons useable plutonium by India. Nevertheless the initiative went through because it was argued that India would be able to acquire a reactor from some other source. Despite consistent efforts on the part of the Canadians, India, led by Bhabha, adamantly refused to accept any kind of voluntary controls or safeguards on the spent fuel produced, Ruth Fawcett, *Nuclear Pursuits: The Scientific Biography of Wilfrid Bennett Lewis*, McGill-Queen's University Press, Montreal, 1994, pp. 110–114.
- ⁶⁰⁵ Robert Bothwell, *Nucleus: The History of Atomic Energy of Canada Limited*, University of Toronto Press, Toronto, 1988, pp. 350–371.
- ⁶⁰⁶ After start up, reactor power was raised to 30 MWt in February 2004 and then to 40 MWt in November 2004. See R. C. Sharma and S. K. Agarwal, "CIRUS Research Reactor: Its Refurbishment and Future Utilisation," *BARC Newsletter*, June 2004 and Anonymous, "BARC's Refurbished Reactor Attains Full Power Operation," *The Hindu News Update Service*, 19 November 2004.
- ⁶⁰⁷ There were no strict safeguards on the plutonium produced, but Canada reportedly got a commitment in a secret annex to the CIRUS agreement that India would use the reactor and resultant fissile materials only for peaceful purposes, George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation*, University of California Press, Berkeley, 1999, p. 27. On India's interpretation of its sovereign rights over the fissile material produced in reactors, see Itty Abraham, *The Making of the Indian Atomic Bomb: Science, Secrecy and the Postcolonial State*, Zed Books, New York, 1998.
- ⁶⁰⁸ Brahma Chellaney, "Indian Scientists Exploring U Enrichment, Advanced Technologies," *Nucleonics Week*, Vol. 28, No. 10, 1987; Mark Hibbs, "Dhruva Operating Smoothly within Refueling, Availability Limits," *Nucleonics Week*, Vol. 33, No. 13, 1992.
- ⁶⁰⁹ Sharma and Agarwal, "CIRUS Research Reactor: Its Refurbishment and Future Utilisation," *op. cit.*
- ⁶¹⁰ *Annual Report 2000*, Bhabha Atomic Research Centre, 2001.
- ⁶¹¹ *Annual Report 2004–2005*, Department of Atomic Energy, 2005.
- ⁶¹² The capacity factor is the ratio of the total energy produced over a certain period of time divided by the total energy that might have been produced if the reactor operated at full design power for 100% of the time.
- ⁶¹³ In his New Year message for 2008, the director of BARC reported availability factors of 90.2 percent and 82.7 percent for CIRUS and Dhruva respectively, and [average] power levels of 20 MW and 60 MW for the two reactors, www.barc.ernet.in/publications/nl/2008/20080102.pdf. This corresponds to capacity factors of 45.1 percent and 49.6 percent for CIRUS and Dhruva respectively. Another instance was the BARC director's ceremonial speech on 26 January 2010 (India's Republic day) where he reported availability factors of 82 percent and 78 percent for CIRUS and Dhruva respectively, and power levels of 20 MW and 55 MW for the two reactors, www.barc.ernet.in/publications/nl/2010/2010010202.pdf. This corresponds to capacity factors of 41 percent and 42.9 percent for CIRUS and Dhruva respectively. It seems from the speech that these figures refer only to the performance for the previous years.
- ⁶¹⁴ These figures are consistent with relatively less specific statements about power levels and availability factors of CIRUS and Dhruva in the 2006–07 Annual Report of the Department of Atomic Energy.
- ⁶¹⁵ In the 1990s, U.S. Government experts cited lifetime capacity factors of 40% for these reactors.. In the late 1980s, there were problems with fabricating fuel for CIRUS, and the reactor was operated at 20 MWt for six months beginning August 1989 to conserve fuel. Similarly, there are reports of design problems with Dhruva leading to its operating power being reduced to 80 MWt, during the first decade of its operations, Hibbs, "Dhruva Operating Smoothly within Refueling, Availability Limits," *op. cit.*
- ⁶¹⁶ *Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal*, IPFM Research Report No. 1, 2006, p. 10, www.ipfmlibrary.org/rr01.pdf

- ⁶¹⁷. We emphasize that these are lifetime capacity factors and there would be specific years when the reactor would operate with higher and lower capacity factors. The two periods where normal operations are not assumed are 1985 to 1988 in the case of Dhruva, when we assume a capacity factor of 0.25, and 1990 to 1997 for CIRUS, when it is assumed to be operating at 80% of its average capacity factor.
- ⁶¹⁸. The decision to construct it was taken in July 1958 and the plant started operating in 1964, C. V. Sundaram, L. V. Krishnan, and T. S. Iyengar, *Atomic Energy in India: 50 Years*, Department of Atomic Energy, Government of India, Mumbai, 1998. The first quantities of plutonium oxide and samples of plutonium metal were produced later that year or early the following year. The Trombay plant was designed initially to reprocess 30 tons of spent fuel per year. The plant “failed to work properly for almost seven years after formal commissioning. The chief problem was the separation of plutonium from the fission products. The concentration of the latter in the final product continued to be too high for the material to be handled and used for any purpose”, Ashok Parthasarathi, *Technology at the Core: Science and Technology with Indira Gandhi*, Pearson Longman, New Delhi, 2007, p. 17. This presumably was solved by the late 1960s because the plant did produce enough plutonium to set up a low energy critical system called PURNIMA (Plutonium Reactor for Neutron Investigations in Multiplying Assemblies) facility in 1972 that was used to verify neutronics calculations in preparation for the 1974 test. The Trombay reprocessing plant had to be shut down in 1972 for decontamination and partial decommissioning. The process took till 1983. When the plant was recommissioned its capacity was increased from 30 to 50 tons/year. The Trombay plant was also shut down from 2004 to 2006 or 2007 for “major revamping”. The assumption here is that the Trombay reprocessing plant has operated at a capacity factor of 70% on average except between 1972 and 1983, and 2004 and 2006.
- ⁶¹⁹. This should not be surprising because there could have been only a modest stockpile of plutonium after the 1974 nuclear test, which wasn’t growing because the Trombay reprocessing plant was down. CIRUS fuel was reprocessed during the first three campaigns on PREFRE in 1978–79, 1980–81, and 1982–83, *Annual Report 1977–1978*, Department of Atomic Energy, 1978, p. 52; *Annual Report 1978–1979*, Department of Atomic Energy, 1979, p. 32; *Annual Report 1979–1980*, Department of Atomic Energy, 1980, p. 28; *Annual Report 1980–1981*, Department of Atomic Energy, 1981, p. 31; *Annual Report 1981–1982*, Department of Atomic Energy, 1982, p. 26; *Annual Report 1982–1983*, Department of Atomic Energy, 1983, p. 31.
- ⁶²⁰. In 1995, the U.S. Congress’s Office of Technology Assessment reported that the PREFRE plant was “only safeguarded during three campaigns between 1982 and 1985, when safeguarded fuel was present”, *Nuclear Safeguards and the International Atomic Energy Agency*, U.S. Congress, Office of Technology Assessment, 1995, p. 117. Based on DAE annual reports, it is clear that these campaigns involved spent fuel from the two reactors at the Rajasthan Atomic Power Station that were imported from Canada and were under safeguards. The stores of plutonium recovered from these campaigns are still under safeguards.
- ⁶²¹. This assumes that the plutonium concentration in the spent fuel is 0.9 kg/t. According to the MCNP calculations described in Appendix B, this corresponds to a burnup of about 1200 MWd/tU and a plutonium-239 content of nearly 94%.
- ⁶²². Even without trying to optimize these PHWRs for weapon-grade plutonium production, the first spent fuel discharges from PHWRs have relatively low burnup and contain small concentrations of the higher isotopes of plutonium.
- ⁶²³. Refuelling typically starts once the core has been operating for about 100 full-power days (FPD) when the excess reactivity in the initial core has fallen to a small value, Shao-hong Zhang and Ben Rouben, “CANDU Fuel Management,” *China Journal of Nuclear Power Engineering*, Vol. 20, No. 6, 1999. The core reaches equilibrium around 400 to 500 FPD. Assuming that 500 FPD corresponds to a burnup of 7000 MWd/tU, 100 FPD would correspond to about 1400 MWd/tU. The plutonium-239 fraction remains above 90 percent for a burnup of just under 2000 MWd/tU; see Appendix B. This would correspond to about 140 FPD of operations. There are 3672 fuel assemblies in each 220 MWe (756 MWth) reactor. Therefore, the power generated by each assembly is 0.206 MWth. At a burnup of 7000 MWd/tU, the energy generated by each assembly, which has 13.4 kg of uranium, should be 93.8 MWthd. Therefore, each fuel assembly stays for about 455 FPD in the reactor core. In other words, at equilibrium, each day 8 fuel assemblies are discharged. Therefore, about 320 fuel assemblies would have accumulated by the time the reactor achieves 140 FPD of operations. At these burnups, the amount of plutonium produced is roughly 1.4 g/kgU. In all, therefore, there would be about 6 kg of plutonium. The assumption here is that the only deliberate action performed to get this weapon-grade plutonium is to reprocess the first discharges separately, without any changes in the way the reactor is fueled or operated. This estimate corresponds roughly to the 5 kg that others

have used, David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, p. 268.

- ^{624.} Assuming that the 540 MW reactors discharge about 15 kg of weapon-grade plutonium. For calculating the annual plutonium inventory, it is assumed that the low burnup spent fuel is reprocessed after one year of cooling.
- ^{625.} P. K. Iyengar, *Briefings on Nuclear Technology in India*, www.pkiyengar.in/yahoo_site_admin/assets/docs/New_version_book_May_2009.124232514.pdf, mirrored at www.ipfmlibrary.org/iye09.pdf
- ^{626.} The amount of plutonium that would have fissioned in this pulsed reactor is relatively small.
- ^{627.} According to former Atomic Energy Commission Chairman P. K. Iyengar, one of the physicists involved in the test, the design involved a “device” that weighed about 1500 kg, with 5–7 kilograms of plutonium, “Scientist on Cost of Nuclear Weapons,” *Economic Times*, 20 May 1998.
- ^{628.} See Albright, Berkhout, and Walker, 1997, *op.cit.*, p. 268. Another source mentions that the reactor’s first (Mark-I) core “contains 745 positions, most of which are occupied by steel and nickel reflectors, plus six control rods and 27 plutonium- and uranium-carbide fuel assemblies containing about 60 kilograms total plutonium” Mark Hibbs, “Kalpakkam FBR to Double Core, Load First Thorium-232 Blanket,” *Nucleonics Week*, Vol. 38, No. 48, 1997. However, numerous papers by Indian scientists and engineers specify the Mark I core as having 22 fuel assemblies (for example, G. Srinivasan et al., “The Fast Breeder Test Reactor—Design and Operating Experiences,” *Nuclear Engineering and Design*, Vol. 236, 2006). A lower value is therefore chosen.
- ^{629.} See for example David Albright, “India’s Military Plutonium Inventory, End 2004,” ISIS, 7 May 2005, www.isis-online.org/uploads/isis-reports/documents/india_military_plutonium.pdf
- ^{630.} T. S. Gopi Rethinaraj, “Tritium Breakthrough Brings India Closer to an H-Bomb Arsenal,” *Jane’s Intelligence Review*, January 1998.
- ^{631.} In the 1990s, PREFRE was reportedly running “substantially” below its nominal capacity, with an average capacity factor of 25%, Mark Hibbs, “PREFRE Plant Used Sparingly, BARC Reprocessing Director Says,” *Nuclear Fuel*, Vol. 17, No. 7, 1992; Mark Hibbs, “Tarapur-2 to Join Twin BWR in Burning PHWR Plutonium,” *Nuclear Fuel*, Vol. 20, No. 20, 1995. Several Annual Reports of the DAE mention PREFRE as being revamped or being started up after revamping, indicating that it must not have been operating for extended periods of time, *Annual Report 1991–1992*, Department of Atomic Energy, 1992, p. 2.24; *Annual Report 1994–1995*, Department of Atomic Energy, 1995, p. 2.2; *Annual Report 1995–1996*, Department of Atomic Energy, 1996, p. 18; *Annual Report 1997–1998*, Department of Atomic Energy, 1998, p. 2.2; *Annual Report 2004–2005*, p. 37. In March 2003 it was reported that “PREFRE had been shut for an entire year, and would remain idle for another six months, because of technical problems”, Mark Hibbs, “DAE Reprocessing Program Remains Modest in Scope,” *Nuclear Fuel*, Vol. 28, No. 8, 2003.
- ^{632.} More precisely, the assumption is that PREFRE was down during all of 2002, had a capacity factor of 25% for the period from 1987 to 1992, 35% for subsequent years when PREFRE is reported as being shut down for part of the year, and 70% otherwise. In this scenario PREFRE has an effective capacity factor of 49%.
- ^{633.} *Annual Report 2004–2005*, *op. cit.*, p. 38; Srikumar Banerjee, “Founder’s Day 2009 Address,” Bhabha Atomic Research Centre, www.barc.ernet.in/talks/fddir09.pdf
- ^{634.} For comparison, the British THORP reprocessing plant has reportedly operated at 50% capacity factor, Paul Brown, “Sellafield Shutdown Ends the Nuclear Dream,” *The Guardian*, 26 August 2003. Similarly the Tokai reprocessing plant in Japan operated at less than 45% capacity between 1977 and 2005, William Walker, “Japan, Europe, the United States and the Politics of Plutonium,” *International Affairs*, Vol. 82, No. 4, 2006.
- ^{635.} This assumes a net electricity production of 92% of gross and a plutonium concentration of 2.29 kg per ton of spent fuel at a burnup of 7000 MWd/t, Appendix B. Earlier estimates of plutonium concentrations were significantly higher, and would therefore lead to higher estimates of plutonium production. See for example Albright, Berkhout, and Walker, 1997, *op. cit.*
- ^{636.} P. K. Dey, “Spent Fuel Reprocessing: An Overview,” *Proceedings of Nuclear Fuel Cycle Technologies: Closing the Fuel Cycle*, Kalpakkam, 2003 and K. C. Sahoo and S. A. Bhardwaj, “Fuel Performance in Water Cooled Nuclear Reactors,” *Proceedings of Nuclear Fuel Cycle Technologies: Closing the Fuel Cycle*, Kalpakkam, 2003.

- ⁶³⁷. This implies that KARP has an effective lifetime capacity factor of 65%. Given what is known of PREFRE's history, it is unlikely to have achieved such high performance.
- ⁶³⁸. This implies effective lifetime capacity factors of 48% and 41% for KARP and PREFRE respectively.
- ⁶³⁹. "World Plutonium Inventories," *Bulletin of the Atomic Scientists*, September/October 1999.
- ⁶⁴⁰. The PFBR was supposed to start operating in 2010, but this has been delayed. Currently, the reactor is expected to become operational in March 2012. See T.S. Subramanian, "Prototype Fast Breeder Reactor Crosses Milestone," *The Hindu*, 14 May 2010.
- ⁶⁴¹. Till 1992, the FBTR was operated at 1 MWt. The operating level went up in steps till it reached 17.4 MWt in 2002. At the original design value of 40 MWt, only 13.2 MW would be converted to electricity by the turbines. Thus, its power specifications are sometimes written as 40 MWt/13.2 MWe.
- ⁶⁴². For most of the first one and a half decades of the FBTR's life, operations were affected by several accidents of varying intensity. Over the first twenty years of its life, FBTR has operated for only 36,000 hours or 75 days a year, implying that the availability factor is only about 20%. The burnup of the fuel has reached 150,000 MWd/tHM. Assuming an average burnup of 100,000 MWd/tHM, an average availability factor of 20% and an average power rating of 10 MWt, implies that the total amount of uranium and plutonium required will be 7.3 kg. The current FBTR core has a mixture of different kinds of fuel elements; approximately two-thirds have a plutonium content of 70% and the remaining one-third have a plutonium content of 55%. This implies an average annual consumption of about 4.75 kg of plutonium, and a total lifetime consumption since 1985 of about 120 kg.
- ⁶⁴³. *Design of Prototype Fast Breeder Reactor*, Indira Gandhi Centre for Atomic Research, www.igcar.ernet.in/broucher/design.pdf.
- ⁶⁴⁴. In September 2007, it was announced that "production of the mixed oxide fuel for PFBR has already commenced", Anil Kakodkar, "Statement," *Proceedings of 51st General Conference*, Vienna, 2007.
- ⁶⁴⁵. H.S. Kamath, K. Anantharaman, and D.S.C. Purushotham, "MOX Fuel for Indian Nuclear Power Programme," *Proceedings of MOX Fuel Cycle Technologies for Medium and Long Term Deployment*, Vienna, 1999.
- ⁶⁴⁶. Each fuel assembly with MOX for PHWRs is assumed to contain about 0.022 kg of plutonium, K. Balu, D.S.C. Purushotham, and A. Kakodkar, "Closing the Fuel Cycle-a Superior Option for India," *Proceedings of Fuel Cycle Options for Light Water Reactors and Heavy Water Reactors*, Victoria, Canada, 1998. The amount of plutonium used in MOX fuel assemblies for the BWR at Tarapur is higher. There are no public estimates of how many fuel assemblies have been used and so a quantitative estimate of plutonium consumption by these is not possible. However, since this is only an experimental program the amounts should be relatively small.
- ⁶⁴⁷. Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, 1997, *op. cit.*, pp. 269–270.
- ⁶⁴⁸. Chellaney, "Indian Scientists Exploring U Enrichment, Advanced Technologies," *op. cit.*
- ⁶⁴⁹. Ivan Fera and Kannan Srinivasan, "Keeping the Nuclear Option Open: What It Really Means," *Economic and Political Weekly*, Vol. 11, No. 49, 1986.
- ⁶⁵⁰. Mark Hibbs, "Second Indian Enrichment Facility Using Centrifuges Is Operational," *Nuclear Fuel*, *op. cit.*
- ⁶⁵¹. One other early consideration may have been to develop HEU based fission weapons, Raj Chengappa, *Weapons of Peace: The Secret Story of India's Quest to Be a Nuclear Power*, Harper Collins, New Delhi, 2000, p. 286. But there is no evidence that any have been tested.
- ⁶⁵². Vivek Raghuvanshi, "Indian Navy Reaches Nuclear Power Milestone," *Defense News*, *op. cit.*; Dinesh Kumar, "India Inching Towards Indigenously Build N-Powered Submarines," *The Times of India*, October 3 1998, A. Gopalakrishnan, "Undermining Nuclear Safety," *Frontline*, 24 June 2000.
- ⁶⁵³. Fera and Srinivasan, "Keeping the Nuclear Option Open: What It Really Means," *op. cit.*
- ⁶⁵⁴. Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, 1997, *op. cit.*, p. 270.
- ⁶⁵⁵. Albright and Basu "collected almost two hundred ... advertisements that were posted in the [Indian newspaper] *Times of India* from 1984 through 2005," *India's Gas Centrifuge Program: Stopping Illicit Procurement and the Leakage of Technical Centrifuge Know-How*, ISIS, 2006.
- ⁶⁵⁶. Srikumar Banerjee, "Founder's Day 2008 Address," Bhabha Atomic Research Centre, www.barc.ernet.in/talks/fddir08.html.

- ⁶⁵⁷ This phase reportedly involved “several hundred operating centrifuges made of domestically-produced maraging steel” with “a likely design throughput of under three separative work units (SWU) per machine per year” Hibbs, “Second Indian Enrichment Facility Using Centrifuges Is Operational,” *op. cit.*
- ⁶⁵⁸ This is based on interpreting “under 3 SWU/yr” to mean 1.5 to 2.5 SWU/yr and several hundred to mean over 300 and up to 800 machines. In March 1992, the head of the DAE said in an interview that at that time there were no plans to start serial production of centrifuges and that the purpose of the centrifuge plant is to develop centrifuge technology further, Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, 1997, *op. cit.*, p. 270. It is therefore assumed that this capacity stayed fixed till the DAE developed more advanced centrifuges.
- ⁶⁵⁹ Mark Hibbs, “India to Equip Centrifuge Plant with Improved Rotor Assemblies,” *Nuclear Fuel*, *op. cit.*, 1997.
- ⁶⁶⁰ During the period between 1997 and 1999, there was reportedly a “sudden increase in procurements of centrifuge-related items in almost identical quantities.” See *India’s Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, ISIS, 2007. The estimate here assumes that the improved designs have an output of about 5 to 6 SWU/yr and 300 to 800 machines were installed. As in the previous case, it is assumed that once these improved designs were installed, there was no increase in capacity till the next design was inducted.
- ⁶⁶¹ The advertisements collected by ISIS suggest that, in 2005, the DAE solicited “2,000 rotors and bellows made from 350-grade maraging steel” with specifications that suggest that these had outputs of 5–6 SWU/yr, *India’s Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, *op. cit.* This might result in an installed capacity of 9000 to 12,000 SWU/yr, assuming a centrifuge failure rate of 0 to 10%. A 10% rate of failure implies that installed capacity falls to about a third of the original value over a decade, and to about 12 percent of the original value over 20 years. Urenco’s centrifuges are said to have a 20-year lifetime. The zero percent failure rate corresponds to the situation with a sufficient number of spares to promptly replace all failed centrifuges.
- ⁶⁶² This corresponds to the installation of 1000 centrifuges with an output of 7.5 to 12.5 SWU/yr. The range is based on the BARC director’s comment and is just five times 1.5 to 2.5 SWU/yr for the first generation design. A 0–10% failure rate is assumed. The number of centrifuges is based on an advertisement that called for “1000 ... maraging steel rotors” with a “diameter of 190 millimeters and a finished length of 1,500 millimeters”, *India’s Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, *op. cit.* These dimensions may be compared to those of other centrifuge types in other countries, see Alexander Glaser, “Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation,” *Science & Global Security*, Vol. 16, No. 1, 2008.
- ⁶⁶³ M. V. Ramana, “An Estimate of India’s Uranium Enrichment Capacity,” *Science & Global Security*, Vol. 12, 2004.
- ⁶⁶⁴ It is of course possible that the necessary enriched uranium was produced much earlier. But the reports that the Rattehalli facility was not working well suggest that the necessary enriched uranium would have likely been produced only close to the time the reactor began to be tested.
- ⁶⁶⁵ This is consistent with the figures for submarine displacement and maximum speed if one assumes a drag coefficient of 0.035 (somewhat typical for a submarine design that is not highly streamlined), and an efficiency of conversion of reactor power to submarine propulsion power of 15 to 20%.
- ⁶⁶⁶ This assumes that the submarine core lifetime is 10 years and it operates on average for 100 hours/year at full speed and 5000 hours/year at half speed (or one-eighth power). The uranium requirement for each hour of operation is calculated by scaling from the Russian Sevморput KLR40 reactor, which has a power rating of 135 MWt, a design operating period of 10,000 equivalent full-power hours, and uses 150.7 kg of U-235 in its core, Anatoli C. Diakov et al., “Feasibility of Converting Russian Icebreaker Reactors from HEU to LEU Fuel,” *Science & Global Security*, Vol. 14, No. 1, 2006, p. 34. This translates to 2.7 g-U-235/MWt-day output required in the core.
- ⁶⁶⁷ There is no official information on the ATV and different media sources mention different figures for most of these quantities. The numbers mentioned here should, therefore, be treated as uncertain. However, since these numbers are merely used to set one constraint on the enrichment capacity, the implications of these uncertainties are not further explored here.
- ⁶⁶⁸ Manu Pubby, “India in N-Sub Club, Arihant to Be Inducted in Next Two Years,” *Indian Express*, 27 July 2009 and “No worry over China’s N-submarine: Roy,” *Zee TV News*, 11 September 2009, www.zeenews.com/news562592.html.

- ⁶⁶⁹. That is, 60 SWU per kilogram of 30% U, and 92 SWU per kilogram of 45% U.
- ⁶⁷⁰. This is the result of minimizing the total enrichment capacity at the beginning of 2000 subject to the constraint that the total enrichment work done is 13,000 SWU.
- ⁶⁷¹. This was first pointed out by ISIS, isis-online.org/isis-reports/detail/india-expanding-military-nuclear-site.
- ⁶⁷². www.isis-online.org/publications/iran/natanz03_02.html.
- ⁶⁷³. Robert S. Norris and Hans M. Kristensen, "Indian Nuclear Forces, 2008," *Bulletin of the Atomic Scientists*, November/December 2008.
- ⁶⁷⁴. Rahul Bedi, "India Launches First Indigenously Built Nuclear Submarine," *Jane's Navy International*, 29 July 2009.
- ⁶⁷⁵. The only reactor currently operating in India that uses HEU is Apsara, a 1 MWt research reactor that was commissioned in 1955. The HEU fuel used in this reactor was supplied by the United Kingdom and France. So far it has utilized two cores from the United Kingdom, containing 4.7 kg and 4.38 kg of U-235, and the spent fuel has been shipped back in 1966 and 1990, *50 Glorious Years of Apsara*, Bhabha Atomic Research Centre, 2006. The third core containing 4.5 kg of U-235 was obtained from France in 1983. As part of the US-India nuclear deal, the Indian government agreed that the reactor will be shut down by December 2010 and its core will be stored off-site, PTI, "Research Reactor at BARC to be shut down by December 2010," *Daily News and Analysis*, 15 November 2009. The reactor will be refurbished and will use indigenous low enriched uranium (19.75% U-235) with a power rating of 1-2 MWt, V. K. Raina et al., "Multi Purpose Research Reactor," *Nuclear Engineering and Design*, Vol. 236, No. 7-8, 2006. See also www-pub.iaea.org/MTCD/publications/PDF/P1360_ICRR_2007_CD/Papers/D.K.%20Shukla.pdf which suggests that the new power rating will be 2 MWt. The new reactor is expected to become operational by 2012. Fueling this would require under 500 SWU/y of capacity.
- ⁶⁷⁶. The 20 MWt reactor is designed to use LEU (19.75% U-235), Raina et al., "Multi Purpose Research Reactor," *op. cit.* The equilibrium core will have about 6 kg of U-235 and require about 115 kg of LEU every year. Fueling this reactor would require about 4300 SWU/y of enrichment capacity.
- ⁶⁷⁷. The DAE has also produced and tested fuel for PHWRs made of slightly enriched uranium (SEU), with an enrichment level of up to 2% uranium-235, and is studying the consequent improvement of uranium utilization. In 2009, 51 fuel bundles made of SEU were manufactured and are now undergoing experimental irradiation studies, *Annual Report 2009-2010*, Department of Atomic Energy, 2010. A typical PHWR fuel bundle contains 13.4 kg of uranium. Assuming this to be the case with SEU as well, these bundles should contain roughly 683 kg of SEU, and correspond to a total enrichment work of 1200 SWU. However, in the future, the DAE hopes that such SEU will be available from reprocessing the spent fuel of Light Water Reactors. So this use is not expected to pose any significant demand for separative work.
- ⁶⁷⁸. The traditional AHWR design uses a mixture of two fuels—PuO₂-ThO₂ and ThO₂-²³³UO₂, with about 200 kg of plutonium in the core and producing about 60% of its energy from U-233, R. K. Sinha and A. Kakodkar, "Design and Development of the AHWR—the Indian Thorium Fuelled Innovative Nuclear Reactor," *Nuclear Engineering and Design*, Vol. 236, No. 7-8, 2006. In 2009, the head of the DAE announced that India had made an export version of this design called the AHWR-LEU, which will dispense with any plutonium use as input. The brochure on the Advanced Heavy Water Reactor with LEU-Th MOX fuel is available at www.dae.gov.in/gc/ahwr-leu-broc.pdf. About 39% of the power will come from thorium through in-situ conversion to U-233.
- ⁶⁷⁹. "Thorium-Fuelled Exports Coming from India," *World Nuclear News*, 17 September 2009.
- ⁶⁸⁰. T. S. Subramanian, "In the event of a nuclear incident, victims must get prompt compensation," *The Hindu*, 6 September 2010. The location of the new facility is likely to be a town called Chellakere in the Chitradurga district in the state of Karnataka, "N-reactor, top secret Army facility at state R&D hub," *Deccan Chronicle*, 10 January 2010.

Chapter 10. Pakistan

- ⁶⁸¹. This chapter is drawn from Zia Mian, A.H. Nayyar, R. Rajaraman, "Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan," *Science & Global Security*, 17 (2), 2009, pp. 77-108.
- ⁶⁸². Mohamad Ashraf, "Uranium Prospecting in Pakistan," *The Nucleus*, Vol. 1, No. 4, 1964, pp. 28-30.

- ⁶⁸³. Muhammad Mansoor, "Nuclear Minerals in Pakistan," *The Nucleus*, Vol. 42, No. 1–2, 2005, pp. 73–83.
- ⁶⁸⁴. Purchases of mining equipment including "loaders, cranes and mining machines" were made between 1980 and 1985 "Dera Ghazi Khan: Irregularities in PAEC's project alleged," *Dawn*, 27 March 1998.
- ⁶⁸⁵. Shahid-ur-Rehman, "Pakistanis tell of Indigeneous U mining and Milling Effort," *Nuclear Fuel*, 1 December 1986.
- ⁶⁸⁶. "Pakistan," in *Country Nuclear Fuel Cycle Profiles, Second Edition*, IAEA Technical Reports Series No. 425, International Atomic Energy Agency, Vienna, 2005. www-pub.iaea.org/MTCD/publications/PDF/TRS425_web.pdf.
- ⁶⁸⁷. "Dera Ghazi Khan: Irregularities in PAEC's Project Alleged," *Dawn*, 27 March 1998.
- ⁶⁸⁸. The site was closed on 30 November 1999. Amir Mir, "DG Khan Uranium Mine was Closed 10 years Ago: Officials," *The News*, 21 May 2009. Nadeem Saeed, "Villagers' Fears of Nuclear Waste," *BBC*, 28 April 2006, news.bbc.co.uk/2/hi/south_asia/4954730.stm.
- ⁶⁸⁹. Muhammad Mansoor, *op. cit.*
- ⁶⁹⁰. C. Ganguly, "Uranium Exploration," International Atomic Energy Agency *Fuel Cycle and Waste Newsletter*, Volume 2, No. 1, April 2006, p. 5. www-pub.iaea.org/MTCD/publications/PDF/Newsletters/NEFW-02-01.pdf. Most uranium mining today involves average ore grades greater than 0.1% uranium. "Uranium Mining," World Nuclear Association, www.world-nuclear.org/education/mining.htm.
- ⁶⁹¹. International Atomic Energy Agency, World Distribution of Uranium Deposits (UDEPO) Database.
- ⁶⁹². The Table uses the annual estimates for uranium production in Pakistan reported in 1990, 1997, 1999, 2005, 2007 and 2009 issues of *Uranium: Resources Production and Demand*, OECD Publishing, Vienna, also known as the "Red Book." These estimates were retrospectively increased without explanation in 2006 to include production of 30 tons of uranium per year from 1971 to 1980 and continuing at this higher rate until 1991. *Forty Years of Uranium Resources, Production and Demand in Perspective: The Red Book Retrospective*, OECD, 2006, Appendix 7.1, pp. 256–257. This increase is inconsistent, however, with reports including from the Pakistan Atomic Energy Commission, that there was exploration and development but not large scale uranium mining in Pakistan between 1971 and 1980. See e.g., Muhammad Mansoor, *op. cit.* The 2009 Redbook estimated total production to 2009 as 1159 tons, and expected production in 2009 of 40 tons.
- ⁶⁹³. Ihtasham ul Haque, "\$600m plan to explore and mine uranium," *Dawn*, 1 March 2007.
- ⁶⁹⁴. "Uranium Mining in Pakistan," 29 August 2009, www.rupeenews.com/2009/08/29/uranium-mining-in-pakistan. The IAEA UDEPO database reports the Shanawa deposit having 2500–5000 tons of uranium at a grade of 0.03–0.05%.
- ⁶⁹⁵. *Text of the Agreement of 2 March 1977 between the Agency and Pakistan for the application of Safeguards in Connection with the supply of Uranium Concentrate*, IAEA INFCIRC/248, 7 July 1977.
- ⁶⁹⁶. "If the devil asks (me) to sell him Uranium, today, I'll sell it to him." *Nuclear Fuel*, 27 April 1981. Other reports suggest Pakistan imported 110 tons of uranium from Niger in 1979, and that this material was safeguarded. *Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise of Proliferation Networks*, International Institute for Strategic Studies, London, 2007, p. 26.
- ⁶⁹⁷. S.M.N. Zaidi, "Making of N-Power Fuel in Pakistan," *The Nation*, 21 September 1990.
- ⁶⁹⁸. This assumes a fuel burn-up of 7400 MWd/t and thermal efficiency of 0.32. The IAEA Power Reactor Information System (PRIS) database gives KANUPP's lifetime generation as 11226 GWeh, including 2009, and 8432 GWeh since Canada ended the fuel supply in 1980. KANUPP's original design equilibrium core average discharge burnup was initially calculated as 8650 MWd/t, but was recalculated in 1995 using modern reactor physics codes as 7400 MWd/t. Iqbal Ahmed, Waqar Butt, Zia ul Hasan Siddiqi, Javed Iqleem, "Plant Life Extension at Kanupp: An Update," *Nuclear Engineering International*, June 1997, pp. 18–20.
- ⁶⁹⁹. A. Q. Khan claims that, in 1982, Pakistan received 10 tons of uranium in un-enriched uranium hexafluoride and 5 tons enriched to 3% along with 50 kg of weapon-grade HEU. Simon Henderson, "Nuclear Scandal-Dr. Abul Qadeer Khan," *The Sunday Times*, 20 September 2009; R. Jeffrey Smith and Joby Warrick, "A Nuclear Power's Act of Proliferation," *Washington Post*, 13 November 2009.
- ⁷⁰⁰. Samar Mubarakmand, in *Munir Ahmad Khan Memorial Reference*, Islamabad, 28 April 2007. www.pakdef.info/pakmilitary/army/nuclear/memorial_munrahmed.html.

701. Shahid-ur Rehman, *Long Road to Chagai*, Printwise Publications, Islamabad, 1999, p. 50.
702. "German Firm Cited in Case Involving Sale of Fluoride Conversion Plant to Pakistan," *Nuclear Fuel*, 20 July 1981.
703. R. Jeffrey Smith and Joby Warrick, "A Nuclear Power's Act of Proliferation," *Washington Post*, 13 November 2009. A.Q. Khan claimed the uranium hexafluoride produced in the Pakistani plant was "impure." *Long Road to Chagai*, *op. cit.*, p. 73.
704. *Long Road to Chagai*, *op. cit.*, p. 59.
705. "Qadeer terms acquiring of nuclear technology a miracle," *Dawn*, 27 May 2001.
706. "N-capability acquired in 1983, says Qadeer," *Dawn*, 30 May 1999; Rauf Siddiqi, "Khan boasts Pakistan Mastered Uranium Enrichment by 1982," *Nucleonics Week*, 20 May 1999.
707. "The Pakistan Nuclear Program", Declassified US State department briefing paper, www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB6/ipn22_1.htm. The term "significant quantity" for HEU normally refers to the IAEA standard of 25 kg of U-235 in highly-enriched uranium, the amount required for a simple first generation implosion fission weapon, but the term may not have been used in this technical sense in the report.
708. Anwar Iqbal, "Pakistan can explode H-bomb: A Q Khan", *The News*, 30 May 1998; "Nuclear tests ensured country's impregnable defense: Qadeer," *The News International*, 27 May 2001.
709. "A Bomb Ticks in Pakistan", *New York Times Magazine*, 6 March 1988.
710. S. Levine, "Bhutto says Pakistan can Build Nuclear Weapons," *The Guardian*, 2 September 1991.
711. R. Jeffrey Smith, "Pakistan Official Affirms Capacity For Nuclear Device; Foreign Minister Vows to Contain Technology," *The Washington Post*, 7 February 1992.
712. In an interview with *BBC Hard Talk Pakistan* on February 10, 2004, Pakistan Army chief General Mirza Aslam Beg is reported as saying that "We brought it down from 95 per cent and above, which is weapons grade enrichment, to 5 per cent and below ... which is commercial grade enrichment ... And if you know how the centrifuge works, if you want to go up to 95 per cent, you have to keep the machine running for another two weeks and you'll have all the material you want." Cited in "Pak Army Never Controlled Nuclear Programme: Mirza Aslam Beg," in rediff.com/news/2004/feb/10pak2.htm.
713. Mark Hibbs, "U.S. Now Believes Pakistan to Use Khushab Plutonium in Bomb Program," *Nucleonics Week*, 16 July 1998. David Albright states that "As of early 1998, Pakistan is not known to have resumed the production of HEU." *Fact Sheet: India and Pakistan—Current and Potential Nuclear Arsenals*, 13 May 1998, www.globalsecurity.org/wmd/library/news/pakistan/1998/980513-isis1.htm.
714. The case for a HEU production moratorium from 1991–1998 is considered in Zia Mian, A.H. Nayyar, R. Rajaraman, "Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan," *Science & Global Security*, Volume 17, 2009, pp. 77–108.
715. The total amount of HEU produced with a given enrichment (and tails) depends only on the SWU capacity used and not on whether the enrichment was done in stages. See the formula for SWU capacity given in Appendix B.
716. This site has been identified as the Kahuta "South production area." *Nuclear Black Markets 2007*, *op. cit.*, p. 20.
717. Mark Hibbs, "China Said Aiding Kahuta Project," *Nucleonics Week*, 8 February 1996.
718. In 1998, the U.S. Department of Commerce listed "ultracentrifuge" facilities at Golra and Sihala, and an "enrichment plant" at Gadwal as subject to export restrictions. U.S. Department of Commerce, Bureau of Industry and Security, 15 CFR Part 742 and 744, *Federal Register*, Volume 63. No. 223, 19 November 1998. www.bis.doc.gov/pdf/india-pakistanentities-nov98.pdf.
719. "Summary of Substantial Facts," *Charge Sheet, The State versus Daniel Geiges and Gerhard Wisser*, High Court of South Africa, Transvaal Provincial Division, 2006, Sections 6.19 and 6.20.
720. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, p. 275. See also Mark Hibbs, "India and Pakistan fail to include new SWU plants on exchanged lists," *Nuclear Fuel*, 30 March 1992.
721. Mark Hibbs, "Khan Network sought CNOR bearings long after KRL gave up centrifuge," *Nuclear Fuel*, 26 September 2005.

- ⁷²² P-3 and P-4 centrifuges may resemble Urenco's 12 SWU 4-M and 20 SWU TC-10 machines respectively. Mark Hibbs, "Pakistan Developed More Powerful Centrifuges", *Nuclear Fuel*, 29 January 2007; Mark Hibbs, "P-4 Centrifuge Raised Intelligence Concerns about Post-1975 Data Theft," *Nucleonics Week*, 15 February 2007.
- ⁷²³ A Kahuta promotional video is said to show a cascade of 8000 to 10,000 P2 machines, David Albright, *Libya: A Major Sale at Last*, ISIS, 1 December 2010. This suggests a capacity of 40,000–50,000 SWU per year.
- ⁷²⁴ The Gadwal uranium enrichment plant is described as the site where "the final enrichment of uranium weapons fuel is thought to take place." Jonathan Landay, "Despite Taliban Turmoil, Pakistan Expands Nuke Plants," *McClatchy Newspapers*, 1 May 2009, www.mcclatchydc.com/world/story/67379.html.
- ⁷²⁵ PARR-1, a 5 MWt HEU (93% enriched) swimming pool reactor supplied by the United States in 1962 was converted in 1992 to 20% enriched fuel and its power increased to 9 MWt, with the power increased further to 10 MWt in 1999. The fuel is supplied by China. PARR-II is a 27 KW HEU fueled reactor supplied by China – China also provided the enriched fuel for its lifetime core (about 1 kg of 90% enriched HEU). The reactor is apparently to be converted to 12% enriched LEU. Tayyab Mahmood, Showket Pervez, Masood Iqbal, "Neutronic analysis for core conversion (HEU–LEU) of Pakistan research reactor-2 (PARR-2)," *Annals of Nuclear Energy*, Volume 35, 2008, pp. 1440–1446.
- ⁷²⁶ Simon Henderson, "Nuclear Scandal-Dr. Abul Qadeer Khan," *Sunday Times*, 20 September 2009, and R. Jeffrey Smith and Joby Warrick, "A Nuclear Powers Act of Proliferation," *Washington Post*, 13 November 2009.
- ⁷²⁷ The International Atomic Energy Agency considers that 8 kg of plutonium and 25 kg of uranium-235 in HEU are sufficient to produce first generation implosion weapons, including production losses. The Nagasaki bomb, an implosion weapon, contained 6 kg of plutonium, suggesting that a similar HEU implosion weapon may contain about 18 kg of HEU. More advanced weapon designs, of the kind in use today, contain 4 kg of plutonium in a fission primary, suggesting that comparable HEU fission weapons may contain about 12 kg of material.
- ⁷²⁸ Mark Hibbs, "After 30 Years, PAEC Fulfills Munir Khan's Plutonium Ambition," *Nucleonics Week*, 15 June 2000. Some early reports claimed Khushab was 70 MW. Mark Hibbs, "Bhutto May Finish Plutonium Reactor Without Agreement on Fissile Stocks," *Nucleonics Week*, 6 October 1994.
- ⁷²⁹ "Pakistan's Indigenous Nuclear Reactor Starts Up," *The Nation*, Lahore, 13 April 1998.
- ⁷³⁰ Mark Hibbs, "Bhutto May Finish Plutonium Reactor Without Agreement on Fissile Stocks," *Nucleonics Week*, 6 October 1994.
- ⁷³¹ "Nuclear programme top priority: Gilani," *Daily Times*, 21 February 2010, www.dailytimes.com.pk, mirrored at www.ipfmlibrary.org/day10.pdf. Satellite imagery from 31 December 2009 showed steam in some of the cooling towers of the Khushab-II reactor, see Paul Brannan, *Steam Emitted from Second Khushab Reactor Cooling Towers; Pakistan May Be Operating Second Reactor*, ISIS, 24 March 2010.
- ⁷³² David Albright and Paul Brannan, *Pakistan Appears to be Building a Third Plutonium Production Reactor at Khushab Nuclear Site*, ISIS, 21 June 2007.
- ⁷³³ Paul Brannan, *Construction of Third Heavy Water Reactor at Khushab Nuclear Site in Pakistan Progressing*, ISIS, 5 October 2010.
- ⁷³⁴ The U.S. officials are cited in William J. Broad and David E. Sanger, "U.S. Disputes Report on New Pakistan Reactor," *New York Times*, 3 August 2006.
- ⁷³⁵ Milton Benjamin, "Pakistan Building Secret Nuclear Plant," *Washington Post*, 23 September 1980.
- ⁷³⁶ "Pakistan is Reprocessing Fuel Rods to Create Plutonium Nuclear Weapons," *CBS News Transcripts* (6:30 PM ET), 16 March 2000. For details, see Z. Mian and A. H. Nayyar, "An Initial Analysis of ⁸⁵Kr Production and Dispersion from Reprocessing in India and Pakistan," *Science & Global Security*, Volume 10, 2002, pp. 151–179.
- ⁷³⁷ David Albright and Paul Brannan, *Pakistan Expanding Plutonium Separation Facility Near Rawalpindi*, ISIS, May 2009.
- ⁷³⁸ David Albright and Paul Brannan, *Chashma Nuclear Site in Pakistan with Possible Reprocessing Plant*, ISIS, 18 January 2007.
- ⁷³⁹ The production rate for plutonium containing 93.8% plutonium-239, i.e., weapon-grade, for a heavy-water moderated reactor is 0.78 g of plutonium per megawatt (thermal) day, at a burn-up of 1200 MWd/t. A value of 0.9 g per megawatt (thermal) day at a burnup of 1000 MWd/t is assumed by Albright, Berkout, and Walker, *op. cit.*, p. 462.

- ⁷⁴⁰. India's production reactors CIRUS and Dhruva may have had capacity factors as low as 50%. See Chapter 9.
- ⁷⁴¹. Pakistan may have been blocking the start of negotiations on a Fissile Material Cutoff Treaty at the United Nations Conference on Disarmament in part because it seeks to take advantage of the investment it has made in the second and the third Khushab production reactors. Zia Mian and A.H. Nayyar, "Playing the Nuclear Game: Pakistan and the Fissile Material Cutoff Treaty," *Arms Control Today*, April 2010, pp. 17–24.
- ⁷⁴². Pakistan would have accumulated depleted uranium tails from its enrichment activity. Since at least 2001, some of this material has been used to produce two kinds of depleted uranium armor-piercing ammunition at the Pakistan Ordnance Factories. "Pakistan joins DU producer nations," *Jane's International Defense Review*, 1 May 2001. The rate of production of this ammunition is unknown. Pakistan could produce about 200 depleted uranium shells per ton of depleted uranium tails, assuming that a typical depleted uranium munition may contain 5 kg of uranium. Steve Fetter and Frank von Hippel, "The Hazard Posed by Depleted Uranium Munitions," *Science & Global Security*, Volume 8, 2000, pp. 125–161.

Chapter 11. The Non-weapon States

- ⁷⁴³. The IAEA defines a "significant quantity ... the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded", as HEU containing 25 kg of U-235, *IAEA Safeguards Glossary*, 2001 Edition, p. 23.
- ⁷⁴⁴. Japan also has imported separated plutonium from France for breeder reactor R&D. In 1992, France shipped 1.5 tons of plutonium to Japan in the form of oxide powder for Japan's breeder-reactor program. Because of the shutdown of *Monju*, Japan's prototype breeder reactor, by a sodium fire in 1995, only 30 kg of that plutonium had been used as of May 2009, "Stop MOX shipment background," Citizens Nuclear Information Center, 6 March 2009, cnic.jp/english/topics/cycle/MOX/shipment/shipmentbg.html; and "MOX Fuel Ships Arrive in Japan Amidst Citizen Protest," May/June 2009, www.cnic.jp/english/newsletter/nit130.
- ⁷⁴⁵. Canada operated a pilot reprocessing plant at Chalk River during 1949–54, *Eurochemic*, OECD Nuclear Energy Agency, 1996, p. 43. Belgium hosted an experimental reprocessing plant, Eurochemic, that recovered a total of 0.65 tons of plutonium from power and research reactor spent fuel during 1965–1975, *Eurochemic, op. cit.*, p. 311, and operated a MOX-fuel-fabrication plant at Dessel from 1986 to 2006, Ann MacLachlan, "BN's MOX fuel plant at Dessel to close up shop this month," *Nuclear Fuel*, 3 July 2006. Germany operated a pilot-scale reprocessing plant at Karlsruhe from 1971 to 1990, www.euronuclear.org/info/encyclopedia/r/reprocessing-plant-karlsruhe.htm; a pilot MOX fuel-fabrication plant at Hanau from 1972 to 1992, and built a full-scale MOX-fuel-fabrication plant at Hanau that never operated, "The MOX Fabrication Plant at Hanau," WISE-Paris briefing, 9 March 2001, www.wise-paris.org/english/ourbriefings_pdf/010309BriefHAN1v1_en.pdf and Mark Hibbs, "Package deal allows Hanau SNM to be reprocessed in France," *Nuclear Fuel*, 5 July 2004. Italy operated two pilot reprocessing plants: EUREX reprocessed research-reactor fuel from 1970 to 1974 and CANDU fuel from 1980 to 1983; and ITREC reprocessed uranium-thorium fuel from the U.S. Elk River reactor "in the seventies." Italy also operated a pilot MOX fuel fabrication plant from 1968 to the "early eighties", *Radioactive Waste Management Programmes in OECD/NEA Member Countries: Italy*, www.nea.fr/rwm/profiles/Italy_profile_web.pdf, accessed 17 July 2010.
- ⁷⁴⁶. According to the annual declarations made by France and United Kingdom to the IAEA under the Plutonium Management Guidelines (INFCIRC/549).
- ⁷⁴⁷. Japan Atomic Energy Commission, www.aec.go.jp/jicst/NC/iinkai/teirei/siry02010/siry048/siry05-pdf (in Japanese). Fissile plutonium has been multiplied by 1.5 to get estimates of total plutonium.
- ⁷⁴⁸. In France, as of the end of 2008, all Belgian, German, and Japanese spent power-reactor fuel had been reprocessed and only 0.15 tons of Swiss fuel remained to be reprocessed. About half a ton of German, less than 0.05 tons of Belgian and no Swiss separated plutonium remained at the reprocessing plant. Virtually all the foreign separated plutonium held at the reprocessing plant was Japanese (14.3 tons) and Italian (4.2 tons), *Traitement des combustibles usés provenant de l'étranger dans les installations AREVA NC de La Hague*, Areva, 2008. See also Ann MacLachlan, "Foreigners own little spent fuel, more waste and Pu at La Hague," *Nuclear Fuel*, 27 July 2009.
- ⁷⁴⁹. Citizen's Nuclear Information Tokyo, personal communication, 1 July 2010.
- ⁷⁵⁰. Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, IPFM Research Report No. 6, International Panel on Fissile Materials, 2008, www.ipfmlibrary.org/rr06.pdf.

- ⁷⁵¹. Tatsujiro Suzuki, "Japan's Plutonium Breeder Reactor and its Fuel Cycle" in *Fast Breeder Reactor Programs: History and Status*, IPFM Research Report No. 8, 2010, Table 4.1. www.ipfmlibrary.org/r08.pdf.
- ⁷⁵². For shipment dates to France, *Traitement des combustibles usés provenant de l'étranger dans les installations AREVA NC de La Hague*, Areva, 2008, p. 21. The last shipment of light-water-reactor fuel to the UK was also in 1998, Philip White, Citizens Nuclear Information Center, Tokyo, personal communication, 6 September 2010.
- ⁷⁵³. Mark Hibbs and Margaret L. Ryan, "With Only Fuel Pools Done, JNFL Says Rokkasho Reprocessing Still on Target," *Nuclear Fuel*, 2 June 1997.
- ⁷⁵⁴. "Completion of nuclear reprocessing plant likely pushed back by 2 years," *Japan Today*, 2 September 2010.
- ⁷⁵⁵. M. Kato et al., "Activities Related to Safety Regulations of Spent Fuel Interim Storage at Japan," International Conference on Management of Spent Fuel from Nuclear Power Reactors, IAEA, Vienna, 31 May–4 June 2010, www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.htm.
- ⁷⁵⁶. Frank von Hippel, "South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime," *Arms Control Today*, March 2010, p. 22.
- ⁷⁵⁷. China has exported about 1 kg of HEU fuel each to Ghana, Iran, Nigeria, and Syria in the long-lived cores of Miniature Neutron Source Reactors. France exported small quantities of HEU to Chile and Iraq (now both cleaned out) and the United Kingdom to Australia (also cleaned out) and Japan, IAEA, *Nuclear Research Reactors in the World*, 2000, Table 9 and other sources.
- ⁷⁵⁸. BN-350 nuclear material protection. This activity provides safe and secure long-term storage of approximately 3000 kilograms of weapon-grade plutonium and 10,000 kilograms of HEU in spent fuel from the shutdown BN-350 fast breeder reactor in Kazakhstan, U.S. Department of Energy. *FY 2011 Congressional Budget Request*, Vol. 1, p. 437.
- ⁷⁵⁹. The IAEA reports quantities of HEU in spent fuel based on the original enrichment.
- ⁷⁶⁰. In contrast to its practice with plutonium, where separated plutonium and plutonium in irradiated fuel are reported separately, the IAEA reports separated HEU and HEU in irradiated fuel in a single total. The IAEA stopped reporting total tonnage of HEU in the non-weapon states in 2007. Its 2007 and 2008 annual reports only report "significant quantities" of HEU measured in units of 25 kg of contained U-235.
- ⁷⁶¹. Charles Messick, U.S. DOE Program Manager for Foreign Research Reactor Spent Nuclear Fuel, Office of Global Threat Reduction, National Nuclear Security Administration, Savannah River Site Office, personal communication, 25 June 2010.
- ⁷⁶². Dates when countries first acquired HEU are based on date of first criticality of HEU-fueled research reactors in each country although some were initially fueled with LEU. Does not include India, Israel, North Korea and Pakistan, all of which received HEU fuel before they became weapon states. Their HEU-fueled research reactors did not, however, play an important role in their weapon programs.
- ⁷⁶³. "NNSA Announces Removal of More than 73 Kilograms of Highly Enriched Uranium from Kazakhstan," 19 May 2009, www.nnsa.energy.gov/mediaroom/pressreleases/05.19.09.
- ⁷⁶⁴. Between May 1996 and May 2010, Japan shipped back to the United States 656 kg of HEU originally containing 354 kg of U-235, Charles Messick, personal communication, 22 June 2010. Japan received HEU from the United Kingdom as well as the United States.
- ⁷⁶⁵. Between May 1996 and May 2010, Germany shipped back to the United States 187 kg of HEU originally containing 149 kg of U-235, Charles Messick, personal communication, 22 June 2010. East Germany also received HEU from the Soviet Union, some of which has been returned to Russia. "Almost 600 Pounds of Highly Enriched Uranium Returned to Russia," NNSA Press Release, 18 December 2006, 268 kg of fresh HEU from Rossendorf.
- ⁷⁶⁶. "DOE Announces Successful Removal of Nuclear Material from Poland," NNSA Press Release, 10 August 2006, 40 kg of unirradiated HEU fuel from Maria research reactor, www.nnsa.energy.gov/mediaroom/pressreleases/doe-announces-successful-removal-nuclear-material-poland. Additional shipments of 9, 187, and 44 kg occurred in 2007, 2009, and 2010, respectively.
- ⁷⁶⁷. "NNSA Removes Highly Enriched Uranium From Czech Republic," NNSA Press Release, 11 December 2007, 80 kg of Russian-origin HEU in spent fuel, www.nnsa.energy.gov/mediaroom/pressreleases/nnsa-removes-highly-enriched-uranium-czech-republic; "Highly Enriched Uranium Recovered from Czech Technical University," 14 kg from critical facility, NNSA Press Release, 27 September 2005, www.nnsa.energy.gov/mediaroom/pressreleases/highly-enriched-uranium-recovered-czech.

technical-university; "Highly Enriched Uranium Repatriated from the Czech Republic," 22 December 2004, 6 kg of fresh HEU, www.energy.gov/news/archives/1562.htm. An additional shipment of 12 kg occurred in 2010.

- ⁷⁶⁸. 48 kg returned to Russia in 2002, www.nti.org/db/heu/pastpresent.html.
- ⁷⁶⁹. "Secret Mission to Recover Highly Enriched Uranium in Uzbekistan Successful," NNSA Press Release, 13 September 2004, 3 kg of fresh HEU fuel plus 8 kg of LEU fuel, www.energy.gov/news/archives/1497.htm; and "Secret Mission to Remove Highly Enriched Uranium Spent Nuclear Fuel from Uzbekistan Successfully Completed," NNSA Press Release, 20 April 2006, 63 kg.
- ⁷⁷⁰. Between May 1996 and May 2010, Argentina shipped back to the United States 45 kg of irradiated HEU originally containing 40 kg of U-235 and unirradiated fuel containing 4 kg of weapon-grade HEU, Charles Messick, personal communication, 22 June 2010.
- ⁷⁷¹. "NNSA Completes Conversion of the Budapest Research Reactor and Removal of All Fresh HEU [18 kg] in Hungary," NNSA Press Release, 15 September 2009, www.nnsa.energy.gov/mediaroom/pressreleases/09.15.09; "Highly Enriched Uranium Removed from Hungary," NNSA Press Release, 23 October 2008, 154.5 kg in spent fuel, www.nnsa.energy.gov/mediaroom/pressreleases/highly-enriched-uranium-removed-hungary.
- ⁷⁷². It is not clear which category Norway is in. The U.S. Nuclear Regulatory Commission reported in 1993 that 5 kg of U.S.-origin HEU had been retransferred to Norway, *Report to Congress on U.S. Exports of Highly Enriched Uranium*, 22 January 1993. Reportedly, Norway imported a total of nine kg of HEU. The purpose is not clear. It is believed that most was blended down but the government is still trying to clarify the situation, Ole Reistad, Norwegian Radiation Protection Authority, personal communication, 3 October 2010.
- ⁷⁷³. "Reactor Converted and Nuclear Material Removed in Vietnam," NNSA Press Release, 17 September 2007, "approximately 10 pounds" of HEU in fresh fuel, www.nnsa.energy.gov/mediaroom/pressreleases/reactor-converted-and-nuclear-material-removed-vietnam.
- ⁷⁷⁴. Ghana, Nigeria, and Syria each only have one Chinese-provided Miniature Neutron Source Reactor and Jamaica a Canadian Slowpoke reactor. These reactors each have long-lived cores containing about one kilogram of weapon-grade HEU.
- ⁷⁷⁵. U.S. HEU returns, May 1996 through May 2001, Charles Messick, personal communication, June 2010.
- ⁷⁷⁶. Between May 1996 and May 2010, Chile shipped back to the United States 12 kg of HEU originally containing 9.5 kg of U-235, Charles Messick, personal communication, 22 June 2010. However, this total does not appear to include a 2010 shipment containing 13.6 kg of U.S. HEU from the La Reina Nuclear Center and 4.6 kg of French HEU from Lo Aguirre Nuclear Center, "Ahead of Nuclear Security Summit, NNSA Announces Removal of All Highly Enriched Uranium from Chile," NNSA Press Release, 8 April 2010, nnsa.energy.gov/mediaroom/pressreleases/04.08.10.
- ⁷⁷⁷. "All Highly Enriched Uranium Removed from Bulgaria," 16.9 kg in fresh and 6.3 kg in spent fuel, NNSA Press Release, 17 July 2008, www.nnsa.energy.gov/mediaroom/pressreleases/07.17.08; "U.S. Nonproliferation Efforts Continue as Nuclear Material is Removed from Bulgaria," NNSA Press Release, 24 December 2003, 17 kg fresh HEU fuel, www.nnsa.energy.gov/mediaroom/pressreleases/u.s.-nonproliferation-efforts-continue-nuclear-material-removed-bulgaria.
- ⁷⁷⁸. The material was shipped in 1998, in Operation Auburn Endeavor, to the UK reprocessing plant for research-reactor fuel at Dounreay, "Removing Material From Vulnerable Sites," Nuclear Threat Initiative, www.nti.org/e_research/cnm/securing/vulnerable.asp.
- ⁷⁷⁹. Fourth consolidated report of the Director General of the International Atomic Energy Agency under paragraph 16 of Security Council resolution 1051 (1996), S/1997/779, 6 October 1997, www.iaea.org/OurWork/SV/Invo/reports/s_1997_779.pdf, p. 52, Table 1.3.
- ⁷⁸⁰. "Last of uranium removed from Latvia," *Baltic Times*, 23 May 2008, 14.4 kg in spent fuel, www.baltictimes.com/news/articles/20536/; "Highly Enriched Uranium Repatriated from Latvia," NNSA Press Release, 25 May 2005, 3 kg of fresh HEU, www.nnsa.energy.gov/mediaroom/pressreleases/highly-enriched-uranium-repatriated-latvia.
- ⁷⁸¹. 17 kg in 2004 and 3 kg 2006, all unirradiated, "HEU Removed from Poland, Libya," *Arms Control Today*, September 2006. An additional 5.2 kg in irradiated fuel was returned to Russia in 2009.

- ^{782.} 30 kg of fresh HEU from Pitesti and 23.7 kg of HEU in spent fuel from Magurele, all Russian origin, “NNSA Announces Removal of Last Highly Enriched Uranium from Romania; Air Shipment of Russian-Origin Spent Fuel,” NNSA Press Release, 30 June 2009, www.nnsa.energy.gov/mediaroom/pressreleases/06.30.09. Previously, in 2003, 14 kg of HEU was shipped back to Russia.
- ^{783.} The construction of this table started from the table, “Highly enriched uranium: Who has what?” www.nti.org/db/heu/HEU_Who_Has_What.pdf. That table in turn may have been based on a map in Alexander Glaser and Frank von Hippel, “Global Cleanout: Reducing the threat of HEU-fueled nuclear terrorism,” *Arms Control Today*, January/February 2006, p. 18.
- ^{784.} Reduced Enrichment Research and Test Reactor Program, www.rertr.anl.gov. An important stimulus for this program was provided by the 1977–79 International Fuel Cycle Evaluation (INFCE) finding that it “would seem feasible for the great majority of [research] reactors ... in the longer term [to use] less than 20% enriched fuel,” *INFCE Summary Volume*, IAEA, 1980, p. 40.
- ^{785.} Iraq had, at the end of 1990, in *unirradiated fuel* 0.4 kg HEU enriched to 93%; 13.7 kg to 80%; and 3.5 kg to 36% for a subtotal of 17.7 kg with an average enrichment of 72%; and in *irradiated fuel* (original content) 11.9 kg of HEU enriched to 93%; 19.2 kg to 80%; and 1.0 kg to 36% for a subtotal of 32.1 kg with an average enrichment of 84%, *Fourth consolidated report of the Director General of the International Atomic Energy Agency under paragraph 16 of Security Council resolution 1051 (1996), S/1997/779*, 6 October 1997, www.iaea.org/OurWork/SV/Invo/reports/s_1997_779.pdf, pp. 48–52.
- ^{786.} Energy Policy Act of 1992, Section 903, www.rertr.anl.gov/REFDOCS/EPACT92.html; statement by Representative Charles Schumer, *Congressional Record*, 5 October 1992, p. H11440.
- ^{787.} *Highly Enriched Uranium: Striking a Balance*, U.S. Department of Energy, 2001, pp. 96–100.
- ^{788.} The United States also exported a comparable amount of HEU to the United Kingdom and France for naval-reactor fuel, see Chapter 2.
- ^{789.} *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, p. 68.
- ^{790.} Alan Kuperman, personal communication, 30 May 2010, assuming that exports after 1997 were all 93.5% enriched. Kuperman notes that the exports for the years 2002–2004 and 2007–2008 are approximate. See also *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, Figure 6-3 for HEU exports for the period 1957–1994.
- ^{791.} In addition, nine tons, containing seven tons of U-235, was shipped to France and the United Kingdom. Israel and Pakistan received 19 and 6 kg of HEU respectively, *ibid*, Table 6-8. Israeli agents are believed also to have stolen during the 1960s up to 300 kg of weapon-grade uranium from a U.S. naval-fuel fabrication plant, Victor Gilinsky & Roger Mattson, “Revisiting the NUMEC affair,” *Bulletin of the Atomic Scientists*, March/April 2010, p. 61.
- ^{792.} To make a fast-neutron spherical critical mass inside a 5-cm-thick beryllium neutron “reflector,” the following quantities of U-235 are required in HEU of different enrichments: about 20 kg in 93.5%, 25 kg in 70%, 36 kg in 45%, 50 kg in 30%, and 80 kg in 20%, *Global Fissile Material Report 2009*, Figure A.4.
- ^{793.} C. E. Messick, “Foreign Research Reactor (FRR) Spent Nuclear Fuel (SNF) Acceptance Program” in *Return of Research Reactor Spent Fuel to the Country of Origin: Requirements for Technical and Administrative Preparations and National Experiences*, Proceedings of a technical meeting held in Vienna, August 28–31, 2006 (IAEA-TECDOC-1593, 2008), p. 7. The two types of fuel are aluminum-matrix fuel, which is received at the DOE’s Savannah River and zirconium-matrix (Triga) fuel, which is stored at the DOE’s Idaho National Laboratory.
- ^{794.} Original destinations from *Highly Enriched Uranium: Striking a Balance*, *op. cit.*, Tables 6-7, 6-8.
- ^{795.} Retransfers and returns prior to 1993, *Report to Congress on U.S. Exports of Highly Enriched Uranium*, U.S. Nuclear Regulatory Commission, 22 January 1993 (U-235 content not given).
- ^{796.} Returns, May 1996 – May 2010, Charles Messick, personal communication, 22 June 2010. Where not known, it has been assumed that all exports during 1998–2008 were weapon-grade (93.5% enriched). Applications from the U.S. Department of Energy to ship 15.5, 15.5, and 17.5 kg weapon-grade uranium to Canada for use as neutron targets for making medical isotopes in the NRU reactor were approved by the U.S. Nuclear Regulatory Commission on 14 April 2006 (application number XSNM03427), 19 October 2007 (docket number 11005701), and 4 November 2008 (docket number 11005747), respectively. There were also shipments to Canada in 2004 and 2005 for the same purpose under application/license number XSNM 03171, Alan Kuperman, personal communication, 20 June 2010. An application to export 85.5 kg of 93.5% enriched HEU to Belgium was approved by the NRC, 3 May 2006 (export license XSNM03404).

- ⁷⁹⁷. U.S. Government Accountability Office, *DOE Needs to Consider Options to Accelerate the Return of Weapons-Usable Uranium from Other Countries to the United States and Russia*, GAO-05-57, 2004, pp. 10–11; and Nuclear Research Reactors in the World, 2000, Table 9.
- ⁷⁹⁸. Nuclear Threat Initiative, “Past and Current Efforts to Reduce Civilian HEU Use,” www.nti.org/db/heu/pastpresent.html.
- ⁷⁹⁹. *Traitement des combustibles usés provenant de l'étranger dans les installations AREVA NC de La Hague*, Areva, 2008, p. 22. Belgium’s high-powered research reactor, the 100-MWt BR-2, is HEU fueled as was Australia’s 10-MWt HIFAR reactor until it was shut down in 2007. See also Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France*, International Panel on Fissile Materials, 2008, Table 5 and Ann MacLachlan, “Cogema sees [Research and Test Reactor] fuel reprocessing as small but attractive business,” *Nuclear Fuel*, 4 July 2005.
- ⁸⁰⁰. Some HEU-containing research-reactor fuel was reprocessed in Belgium during 1967–74 and 1.36 tons of HEU were recovered and recycled, *Eurochemic, op. cit.*, p. 311; The UK Dounreay reprocessing plant reportedly reprocessed research reactor fuel from “England, Denmark, Germany, Japan, Sweden, France and South Africa,” www.dounreay.com/decommissioning/fuel-cycle-area/research-reactor-fuel-reprocessing-plant.
- ⁸⁰¹. “Russian high enriched uranium for France,” WISE, 21 June 1996, www10.antenna.nl/wise/index.html?www10.antenna.nl/wise/454/4490.html; Apparently, this deal was not renewed, Pavel Podvig, “U.S. to supply HEU for the High Flux Reactor in France,” www.fissilematerials.org/blog/2010/03/us_to_supply_heu_for_the_.html. For technical information on the FRM-II reactor, see Alexander Glaser, “The Conversion of Research Reactors to Low-Enriched Fuel and the Case of the FRM-II,” *Science & Global Security*, Vol. 9, 2002, p. 61.
- ⁸⁰². Mark Hibbs, “EURATOM, Again, Accepts Russian Consent for HEU Transfer to FRM-2,” *Nuclear Fuel*, 9 March 1998; “Munich University Defiant on FRM-2 Conversion to LEU,” *Nuclear Fuel*, 8 February 1999; and “Green-Led Foreign Ministry Wants Russian-German HEU Deal Canceled,” *Nuclear Fuel*, 9 June 2003.
- ⁸⁰³. Among the non-weapon states, only Germany reports its inventory of HEU publicly to the IAEA along with its annual INFCIRC/549 declarations of its plutonium stocks. These declarations are published by the IAEA on its website as Information Circulars (INFCIRCS).
- ⁸⁰⁴. Germany returned 149 kg of HEU to the United States in 1236 fuel assemblies during the period 1996–2008. 754 of those fuel assemblies were shipped during the period 2000–2008, Charles Messick, personal communication, June 2010.
- ⁸⁰⁵. U.S. take-back requires that an HEU-fueled reactor have started up before May 1996, C. E. Messick, “Foreign Research Reactor (FRR) Spent Nuclear Fuel (SNF) Acceptance Program,” *op. cit.*
- ⁸⁰⁶. Defending the FRM-II’s use of HEU has been a high priority of Bavaria’s political leadership. Recently, the President of Bavaria announced that the deadline for converting the FRM-II from 90 percent to 50 percent enrichment is to be postponed from 2010 until at least 2018 because the required higher density fuel is not yet available, Christiane Funke, “Reaktor läuft länger mit waffenfähigem Uran” (“Reactor will run longer with weapon-grade uranium”) *Süddeutsche Zeitung*, 26 July 2010, www.sueddeutsche.de/muenchen/muenchen/politik/seehofer-in-garching-reaktor-laeuft-laenger-mit-waffenfaehigem-uran-1.979950.
- ⁸⁰⁷. “FRM-2 can’t run on low-enriched fuel, Munich experts calculate,” *Nuclear Fuel*, 23 May 2005.
- ⁸⁰⁸. In 2005, the Nuclear Threat Initiative and Kazakhstan announced the completion of the blend-down of 2900 kg of HEU in unused breeder-reactor fuel that “could have been used to make up to two dozen bombs.” The press release says that the enrichment was “up to 26%,” NTI Press Release, “Government of Kazakhstan and NTI Mark Success of HEU Blend-Down Project,” 8 October 2005.
- ⁸⁰⁹. The concern is that, in Austria’s anti-nuclear environment, submitting a license for conversion to LEU fuel could trigger a demand that the reactor be shutdown.
- ⁸¹⁰. “Trilateral Announcement Between Mexico, the United States, and Canada on Nuclear Security,” White House Press Release, 13 April 2010, www.whitehouse.gov/the-press-office/trilateral-announcement-between-mexico-united-states-and-canada-nuclear-security.
- ⁸¹¹. “Joint Statement by President Obama and President Yanukovich,” White House Press Release, 12 April 2010, www.whitehouse.gov/the-press-office/joint-statement-president-obama-and-president-yanukovich.

- ^{812.} “Conversion to LEU-Based Production of Molybdenum-99: Prospects and Feasibility,” chapter 10 in *Medical Isotope Production Without Highly Enriched Uranium*, U.S. National Academy Press, 2009.
- ^{813.} “South Africa’s NTP eyes US isotope market,” *World Nuclear News*, 14 April 2010.
- ^{814.} In 2005, Congress mandated that, if adequate supplies of Mo-99 made without using HEU did not become not available within six years, the Secretary of Energy should report on the feasibility of developing domestic sources for producing Mo-99 without the use of HEU, *Energy Policy Act of 2005*, Section 630, “Medical Isotope Production.” BWXT, has designed a reactor in which the LEU fuel would be in solution and also serve as target material. The University of Missouri has a 10-MWt research reactor that it is interested in using with LEU targets, *Medical Isotope Production Without Highly Enriched Uranium*, *op. cit.*, p. 45. In January 2010, GE-Hitachi signed a contract with the U.S. Department of Energy to develop a production approach that involves neutron capture in stable Mo-98, GE-Hitachi press release, “GE Hitachi Nuclear Energy to Deliver Life-Saving Medical Isotope Molybdenum-99 Using Alternative to Highly Enriched Uranium,” 25 January 2010.
- ^{815.} According to the operators’ most recent report to the IAEA, the reactor is used 60 hours per year, nucleus.iaea.org/RRDB/RR/Utilization.aspx?RIId=226, accessed 17 July 2010.
- ^{816.} *Medical Isotope Production Without Highly Enriched Uranium*, *op. cit.*, p. 13.
- ^{817.} *Government of Canada Response to the Report of the Expert Review Panel on Medical Isotope Production*, 31 March 2010, www.nrcan.gc.ca/eneene/sources/uranuc/pdf/isotopes-gc-re-eng.pdf. Canada’s two new Maple isotope-production reactors, which were to succeed the NRU as dedicated Mo-99 producers, have serious safety design problems and have been deemed to not be economic in any case.
- ^{818.} Derek Andersen, “Canada’s Nordion to Certify Rosatom Isotope,” *Moscow Times*, 28 Sept. 2010.
- ^{819.} Canada, Office of the Prime Minister, “PM announces a nuclear cooperation project with the United States to further secure inventories of spent highly enriched uranium,” 12 April 2010, news.gc.ca/web/article-eng.do?m=/index&nid=524699.
- ^{820.} “Fast Critical Assembly at JAERI (FCA),” U.S. Government, undated.
- ^{821.} In any case, the average enrichment of an HEU fast-reactor core of the size that the FCA is designed to model is 20-30 percent. Therefore there is no need for 93% enriched weapon-grade uranium. Russia fuels its demonstration fast-neutron reactors with HEU enriched to about 20 percent. In Russia’s counterpart fast-critical facility to the FCA, disks of weapon-grade uranium are mixed with disks of depleted and 36% enriched uranium to simulate the 20% enriched uranium, but the director of the facility has agreed that its weapon-grade uranium could be replaced by low-enriched, natural and depleted uranium, Frank von Hippel, “Future Needs for HEU-Fueled Critical Assemblies,” International Meeting on Reduced-enrichment Research and Test Reactors, Boston, 6–10 November 2005.
- ^{822.} Tatsujiro Suzuki, Japan Atomic Energy Commission, personal communication, 19 July 2010.
- ^{823.} The IAEA counts the HEU and U-235 in spent fuel as the original amount, not taking into account fission, personal communication, IAEA safeguards division, 22 June 2010. The BN-350 was fueled with enriched uranium in three enrichment zones with initial enrichments of 17%, 21% and 26%, IAEA, *Fast Reactor Database*, www.iaea.org/inis/nkm/nkm/aws/frdb/fulltext/02_coreAndBlanketLayoutOrGeometry.pdf. These enrichments would have decreased with irradiation.
- ^{824.} *Breakout of GTRI Reactor Conversion Expansion*, National Nuclear Security Administration, November 2009.
- ^{825.} Ole Reistad and Styrkaar Hustveit, “HEU Fuel Cycle Inventories and Progress on Global Minimization,” *Nonproliferation Review*, 15 (2), 2008, p. 265.

Appendix A. Fissile Materials and Nuclear Weapons

- ^{826.} *Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China*, also known as the “Cox Report,” U.S. House of Representatives, 3 January 1999, www.house.gov/coxreport/pdf/ch2.pdf, p.78. Original image credit: U.S. News and World Report, 1995, www.usnews.com.
- ^{827.} *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, U.S. Department of Energy, DOE/NN-0007, Washington, DC, January 1997, www.ipfmlibrary.org/doe97.pdf, Box 3-1 (pp. 37–39).

Appendix B. Production of Highly Enriched Uranium and Plutonium for Weapons

- ⁸²⁸. As an example of an online SWU calculator, see www.fissilematerials.org/swucalc.html.
- ⁸²⁹. Table adapted from A. Glaser, "Isotopic Signatures of Weapon-grade Plutonium from Dedicated Natural-uranium-fueled Production Reactors and Their Relevance for Nuclear Forensic Analysis," *Nuclear Science & Engineering*, Vol. 163 (2009), pp. 26–33.
- ⁸³⁰. With the exception of EL-102/Dimona, the following brief reactor descriptions are partially based on: A. Glaser, "Isotopic Signatures of Weapon-grade Plutonium from Dedicated Natural-uranium-fueled Production Reactors and Their Relevance for Nuclear Forensic Analysis," *Nuclear Science & Engineering*, 163 (1), September 2009.
- ⁸³¹. For example, the power levels of the B, D, and F Reactors were increased from 250 MW to eventually more than 2,000 MW thermal.
- ⁸³². B. D. Murphy, *ORIGEN-ARP Cross-Section Libraries for Magnox, Advanced Gas-Cooled, and VVER Reactor Designs*, Oak Ridge National Laboratory, ORNL/TM-2003/263, February 2004. For additional information, see also David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, pp. 59–66.
- ⁸³³. D. Albright and K. O'Neill (eds.), *Solving the North Korean Puzzle*, ISIS, Washington, DC, 2000, Table VIII.4, pp. 161–162.
- ⁸³⁴. E. A. G. Larson, *A General Description of the NRX Reactor*, CRIO-1043 (AECL-1377), Chalk River, Ontario, July 1961, www.ipfmlibrary.org/lar61.pdf, p. 1.
- ⁸³⁵. R. D. Sage, D. D. Stewart, H. B. Prasad, and H. N. Sethna, *Canada-India Reactor*, A/CONF. 15/P/1704 (AECL-729), Papers presented by Canada-India to the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, September 1–13, 1958, Atomic Energy of Canada Limited, Chalk River, Ontario, May 1959, www.ipfmlibrary.org/sag59.pdf.
- ⁸³⁶. See Chapter 10. Khushab II and III may be heavy-water moderated and cooled to increase plutonium production.
- ⁸³⁷. Pierre Péan, *Les Deux Bombes: Comment la France a «Donné» la Bombe à Israël et à l'Irak*, Fayard, Paris, 1982.
- ⁸³⁸. France later developed a so-called "snowflake" fuel that was used (or considered for use) in EL3 since 1963. E. Abillon and J. P. Genthon, *Physical Study of the "Snow Flake" Version of the Reactor EL3*, CEA-R-2344, 1963, www.ipfmlibrary.org/abi63.pdf.
- ⁸³⁹. In addition to Canada (18 operational), these are: India (18), South Korea (4), China (2), Argentina (2), Romania (2), and Pakistan (1). Information on number of operational reactors from www.iaea.org/programmes/a2, retrieved 7 September 2010. See also the CANDU Owners Group (COG, www.candu.org) for more details.
- ⁸⁴⁰. Zhiwen Xu, *Design Strategies for Optimizing High Burnup Fuel in Pressurized Water Reactors*, Ph.D. thesis, Massachusetts Institute of Technology, January 2003; and Z. Xu, P. Hejzlar, M. J. Driscoll, and M. S. Kazimi, *An Improved MCNP-ORIGEN Depletion Program (MCODE) and its Verification for High Burnup Applications*, PHYSOR, Seoul, October 7–10, 2002. MCODE is used with the kind permission of its author.
- ⁸⁴¹. *MCNP—A General Monte Carlo N-Particle Transport Code, Version 5*, LA-UR-03-1987, X-5 Monte Carlo Team, Los Alamos National Laboratory, April 2003, revised March 2005; A. G. Croff, *A User's Manual for the ORIGEN2 Computer Code*, ORNL/TM7175, Oak Ridge National Laboratory, July 1980; and S. Ludwig, Revision to ORIGEN2, Version 2.2, Transmittal Memo, 23 May 2002.
- ⁸⁴². Note that this ratio is taken for the actual (not the initial) mass of uranium present in the fuel for any given burnup level.

IPFM Members and Other Contributors to this Report

IPFM Members

Program on Science and Global Security – Princeton University

Harold Feiveson is a Senior Research Scientist and Lecturer in Princeton University's Woodrow Wilson School of Public and International Affairs. He has a Ph.D. in public affairs from Princeton University (1972). Feiveson is the editor of the journal *Science & Global Security*. His research focus has been on nuclear arms control and nuclear weapons proliferation. With Frank von Hippel, he co-founded and co-directed the Program on Science and Global Security until July 2006. He was a lead author of the overview chapter.

Alexander Glaser is an Assistant Professor jointly in the Woodrow Wilson School of Public and International Affairs and in the Department of Mechanical and Aerospace Engineering (MAE) at Princeton University. He directs the Nuclear Futures Laboratory in MAE. Glaser received his Ph.D. in physics (2005) from Darmstadt University of Technology in Germany. He is on the Science and Security Board of the *Bulletin of the Atomic Scientists* and an Associate Editor of *Science & Global Security*. He was a lead author of the chapters on stocks, France, and the United Kingdom, the lead author of Appendix B, and contributed to the chapter on Israel.

Zia Mian is a Research Scientist in Princeton University's Program on Science and Global Security and directs its Project on Peace and Security in South Asia. He has a Ph.D. in physics (1991) from the University of Newcastle upon Tyne. His research interests are in nuclear-weapon and nuclear-energy policy in South Asia. He is an Associate Editor of *Science & Global Security*. He was a lead author of the overview chapter and the chapters on stocks and Pakistan.

Pavel Podvig (representing Russia on the IPFM with Anatoli Diakov) works part-time for Princeton managing the IPFM blog "Fissile Materials." He is currently an independent analyst based in Geneva also running his own project, "Russian Nuclear Forces." During 2004–10, Podvig was at the Center for International Security and Cooperation at Stanford University. Previously, he was a visiting researcher at Princeton and a Senior Researcher at the Center for Arms Control Studies (CACs) at the Moscow Institute of Physics and Technology. He led the CACS project that produced the book, *Russian Strategic Nuclear Forces* (MIT Press, 2001). He was the lead author of the chapter on Russia's highly enriched uranium.

M.V. Ramana (representing India on the IPFM with R. Rajaraman) is currently a Research Scholar jointly with Princeton University's Program on Science and Global Security and the Nuclear Futures Laboratory. He has a Ph.D. in physics (1994) from Boston University; has held research positions at the University of Toronto, Massachusetts Institute of Technology, and Princeton University; and has taught at Boston University, Princeton University, and Yale University. His research has focused on India's nuclear energy and weapon programs. He was the lead author of the chapter on India.

Frank von Hippel (IPFM Co-Chair) is Professor of Public and International Affairs at Princeton University's Woodrow Wilson School of Public and International Affairs. He has a Ph.D. in nuclear physics (1962) from Oxford University. He co-founded Princeton's Program on Science and Global Security with Feiveson. He has worked on fissile material policy issues for the past 35 years, including contributing to: ending the U.S. program to foster the commercialization of plutonium breeder reactors; convincing the U.S. and Soviet Union to embrace the idea of a Fissile Material Production Cutoff Treaty; launching the U.S.-Russian cooperative nuclear materials protection, control and accounting program; and broadening efforts to eliminate the use of HEU in civilian nuclear reactors worldwide. He was a lead author of the overview chapter and the lead author of the chapters on the United States and the non-weapon states.

International Participants

James Acton (United Kingdom) is an associate in the Nonproliferation Program at the Carnegie Endowment for International Peace. He co-authored the Adelphi Paper, *Abolishing Nuclear Weapons*, and co-edited the follow-up book, *Abolishing Nuclear Weapons: A Debate* (both with George Perkovich). Prior to joining the Carnegie Endowment in October 2008, Acton was a lecturer at the Centre for Science and Security Studies in the Department of War Studies at King's College London and was the science and technology researcher at the Verification Research, Training and Information Centre (VERTIC), where he was a participant in the UK-Norway dialogue on verifying the dismantlement of warheads. He holds a Ph.D. in theoretical physics from the University of Cambridge. He was a lead author of the chapter on the United Kingdom.

Anatoli Diakov (Moscow, Russia, shared membership with Podvig) is a Professor of Physics at the Moscow Institute of Physics and Technology (Ph.D. in 1975) and, since 1991, the Director of its Center for Arms Control Studies. Diakov has written papers on nuclear arms reductions, the history of Russia's plutonium production, disposition options for excess plutonium, and the feasibility of converting Russia's icebreaker reactors from HEU to LEU as well as on many other topics relating to nuclear arms control and disarmament. He was the lead author of the chapter on Russia's plutonium.

Jean du Preez (South Africa) is Chief, External Relations and International Cooperation of the Comprehensive Nuclear-Test-Ban Treaty Organization in Vienna. Previously, he was Director of the International Organizations and Non-proliferation Program of the Monterey Institute for International Studies' Center for Non-proliferation Studies and, before that, served for 17 years in the South African Ministry of Foreign Affairs, including as Deputy-Director for non-proliferation and disarmament and as a Senior Political Counselor for Disarmament Affairs at South Africa's Permanent Mission to the United Nations. During that time, he represented his country at several international negotiating meetings, including the 1995 and 2000 NPT Review Conferences.

José Goldemberg (São Paulo, Brazil) has a Ph.D. in nuclear physics (1954). He was Rector of the University of São Paulo (1986–90), Federal Minister of Science and Technology (1990–91), Federal Minister of Education (1991–92) and Minister of Environment of São Paulo (2002–2006). He was the first IPFM co-chair with von Hippel, stepping down in 2007. While Brazil's Minister of Science and Technology, he persuaded President Collor de Mello to end Brazil's nuclear-weapon program, which led Argentina to shut its program down as well, with monitoring by a joint Argentine-Brazil inspectorate. Goldemberg is best known for his work on global energy and environmental issues. He was a co-recipient of Sweden's Volvo Environmental Prize in 2000, the recipient of the Blue Planet Prize of Japan in 2008, and the winner of the Trieste Science Prize in 2010.

Pervez Hoodbhoy (Islamabad, Pakistan, shared membership with Nayyar) in 2010 became emeritus Professor of Physics at Quaid-e-Azam University, Islamabad. He holds a Ph.D. in nuclear physics (1978) from MIT and is the recipient of the Abdus Salam Prize for Mathematics, the Baker Award for Electronics, Faiz Ahmad Faiz Prize for contributions to education in Pakistan, and the UNESCO Kalinga Prize for the popularization of science. He has been a Visiting Professor at MIT, Carnegie Mellon University, the University of Maryland, and the Stanford Linear Accelerator. He is a member of the Pugwash Council, and a sponsor of *The Bulletin of the Atomic Scientists*.

Martin B. Kalinowski (Hamburg, Germany, shared membership with Schaper) is a Professor and Director of the Carl-Friedrich von Weizsäcker Center for Science and Peace Research at the University of Hamburg, Germany. He holds a Ph.D. in nuclear physics (1997) from Darmstadt University of Technology, Germany, and was a member of the Interdisciplinary Research Group on Science, Technology, and Security (IANUS) at that University. He served in the Provisional Technical Secretariat of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization in Vienna, Austria (1998–2004). His research agenda deals with novel measurement technologies as well as nuclear and meteorological modeling of atmospheric radioactivity as a means to detect clandestine nuclear activities such as plutonium separation and nuclear testing.

Jungmin Kang (Seoul, South Korea) has a Ph.D. in Nuclear Engineering from Tokyo University (1999) and is currently a visitor with the Korea Studies program at the Paul H. Nitze School of Advanced International Studies, Johns Hopkins University. He was the lead South Korean analyst in the MacArthur-Foundation-funded East-Asia Science-and-Security Initiative. He served as an advisor to South Korea's National Security Council on North Korean nuclear issues during 2003 and on South Korea's Presidential Commission on Sustainable Development, where he advised on nuclear energy policy. Kang has co-authored articles on radioactive-waste management, spent-fuel storage, the proliferation-resistance of closed fuel cycles, plutonium disposition and the history of South Korea's explorations of a nuclear-weapon option.

Patricia Lewis (Ireland and United Kingdom) has a Ph.D. in nuclear physics (1981) and is the Deputy Director and Scientist-in-Residence of the James Martin Center for Nonproliferation Studies at the Monterey Institute of International Studies. Previously, she served as Director of the United Nations Institute for Disarmament Research (UNIDIR) and as founding Director of the Verification Technology and Information Centre (VERTIC) in London. Dr. Lewis was an Advisor to the International Commission on Nuclear Nonproliferation and Disarmament established by the governments of Australia and Japan (2008–09); a Commissioner on the Weapons of Mass Destruction Commission, chaired by Dr. Hans Blix (2004–06); and a Member of the Tokyo Forum for Nuclear Nonproliferation and Nuclear Disarmament (1998–99).

Li Bin (Beijing, China) is a Professor of International Studies and Director of the Arms Control Program in the Institute of International Studies of Tsinghua University. He received his Ph.D. from China's Academy of Engineering Physics (China's nuclear-weapon-theory and technical nuclear-arms-control institute). Within the Academy's Institute of Applied Physics and Computational Mathematics (IAPCM), he became in 1996 Director of the Arms Control Division and the Executive Deputy Director of the Program for Science and National Security Studies. He supported the Chinese team negotiating the Comprehensive Test Ban Treaty and attended the last round of negotiations as a technical advisor to the Chinese delegation.

Yves Maignac (Paris, France, shared membership with Schneider) is Executive Director of WISE-Paris, an energy-information agency, which he joined in 1997 after four years shared between academic research in Paris-XI University, applied studies in the French Atomic Energy Commission (CEA), and a position at the nuclear company STMI. In 1999–2000, he participated in the only independent economic evaluation of France's nuclear sector and its reprocessing policy. This study was commissioned by Prime Minister Jospin and resulted in what became known as the Charpin-Dessus-Pellat report. He also contributed to the 2001 report to the European Parliament's Scientific and Technological Option Assessment Panel on reprocessing plant discharges. In 2005–06, he was Scientific and Technical Advisor to the commission preparing France's public debate on the new European Power Reactor. He was a contributor to the chapter on France.

Miguel Marín Bosch (Mexico City, Mexico) had a long career in Mexico's Foreign Service, including serving as Deputy Minister for Asia, Africa, Europe and Multilateral Affairs. During the early 1990s, he was Mexico's Ambassador to the Conference on Disarmament and Chair of the Comprehensive Test Ban Negotiations during the first year of formal negotiations (1994). He also served as Chairman of the Group of Governmental Experts for the 2002 United Nations Study on Disarmament and Nonproliferation Education.

Arend J. Meerburg (Den Haag, the Netherlands) has an MSc in nuclear reactor physics (1964) and thereafter worked for some years in oceanography and meteorology (including in the Antarctic). He joined the Ministry of Foreign Affairs in 1970 and worked there until his retirement in 2004. During most of that period he was involved in multilateral arms control matters, including the final negotiations in Geneva of the Chemical Weapons Convention and the Comprehensive Nuclear-Test-Ban treaty. He was involved in the International Nuclear Fuel Cycle Evaluation, discussions of an International Plutonium Storage regime, and the Nuclear Suppliers Group. He served as Ambassador to Yemen (1996–2000). He was a member of the IAEA expert-group on Multilateral Nuclear Approaches to the Nuclear Fuel Cycle (2004–05).

Abdul H. Nayyar (Lahore, Pakistan, shared membership with Hoodbhoy) has a Ph.D. in physics (1973) from Imperial College, London, retired from the faculty of Quaid-e-Azam University in 2005 and is Director of the Ali Institute of Education, Lahore, a college for educating teachers for Pakistan's public school system. He has been active in Pakistan's nuclear debate since the 1980s and a regular summer visitor with Princeton's Program on Science and Global Security since 1998. He is President of Pakistan's Peace Coalition and the Co-Convener of Pugwash, Pakistan. He has worked on a range of issues relating to nuclear weapons and nuclear energy in South Asia, including reactor safety, fissile-material production, the consequences of regional nuclear war, and the feasibility of remote monitoring of a moratorium on plutonium separation. He was a lead author of the chapter on Pakistan.

R. Rajaraman (IPFM Co-Chair, New Delhi, India, shared membership with Ramana) is Emeritus Professor of theoretical physics in the School of Physical Sciences, Jawaharlal Nehru University. He is a Fellow of the Indian Academy of Science and Vice President of the Indian National Science Academy. He has a Ph.D. in theoretical physics from Cornell University (with Hans Bethe, 1963). He has been contributing articles to India's nuclear-weapon debate since 1970 and has been a regular summer visitor with Princeton's Program on Science and Global Security since 2000. He has written on the dangers of accidental nuclear war and the limitations of civil defense. In recent years his focus has been on capping South Asia's nuclear arsenals.

Ole Reistad (Oslo, Norway) is a Research Scientist with a joint appointment at the University of Oslo and the Norwegian Radiation Protection Authority. He has a Ph.D. in physics (2008) from the Norwegian University of Science and Technology. His work has focused primarily on highly enriched uranium issues and the security and safety of the naval spent nuclear fuel on Russia's Kola Peninsula. He is a co-organizer of the Norway-UK cooperative study on the verification of nuclear-warhead dismantlement.

Henrik Salander (Stockholm, Sweden) chairs the Middle Powers Initiative, a non-governmental organization that is dedicated to worldwide reduction and elimination of nuclear weapons. Previously, he headed the Department for Disarmament and Non-Proliferation in Sweden's Ministry for Foreign Affairs. During 2004–06, he was Secretary-General of the WMD Commission chaired by Hans Blix. He led Sweden's delegation to the 2000 NPT Review Conference where Sweden, along with the six other members of the New Agenda Coalition (Brazil, Egypt, Ireland, Mexico, New Zealand and South Africa), extracted from the NPT weapon states 13 specific commitments to steps toward ending the nuclear arms race, reducing their nuclear arsenals and the danger of nuclear use, and establishing a framework for irreversible disarmament. Salander was Sweden's Ambassador to the Geneva Conference on Disarmament (1999–2003) where he authored the 2002 "Five Ambassadors" Compromise Proposal to start negotiations on an FM(C)T and other treaties. He also chaired the 2002 session of the Preparatory Committee for the 2005 NPT Review Conference.

Annette Schaper (Frankfurt, Germany, shared membership with Kalinowski) is a Senior Research Associate at the Peace Research Institute in Frankfurt. Her Ph.D. (1987) is in experimental physics from Düsseldorf University. She co-founded the Interdisciplinary Research Group in Science, Technology, and Security at the Institute of Nuclear Physics at the Darmstadt University of Technology. She was a part-time member of the German delegation to the negotiations on the Comprehensive Test Ban Treaty and a member of the German delegation at the 1995 NPT Review and Extension Conference. Her research covers nuclear arms control and its technical aspects, including the test ban, a fissile material cut-off and verification of nuclear disarmament.

Mycale Schneider (Paris, France, shared membership with Marignac) is an independent nuclear and energy consultant. He founded the energy information agency WISE-Paris in 1983 and directed it until 2003. Since 1997 he has provided information and consulting services to many European governments, NGOs and think tanks. Since 2004 he also has been in charge of the Environment and Energy Strategies lecture series for the International MSc in Project Management for Environmental and Energy Engineering Program at the French Ecole des Mines in Nantes. In 1997, along with Japan's Jinzaburo Takagi, he received Sweden's Right Livelihood Award "for serving to alert the world to the unparalleled dangers of plutonium to human life." He was a lead author of the chapter on France.

Shen Dingli (Shanghai, China) stepped down from IPFM in 2010. He is Professor of International Relations at Fudan University, the Executive Dean of the University's Institute of International Studies and Director of its Center for American Studies. He co-founded China's first non-government-based Program on Arms Control and Regional Security at Fudan University. He received his Ph.D. in physics (1989) from Fudan University and did post-doctoral work in arms control at Princeton University. His research areas cover the China-U.S. security relationship, regional security and nonproliferation issues, and China's foreign and defense policies.

Tatsujiro Suzuki (Tokyo, Japan) stepped down from IPFM in 2009 upon being appointed the Vice-Chairman of the Japan Atomic Energy Commission. For the past 20 years, Suzuki has been deeply involved in providing technical and policy assessments of the international implications of Japan's plutonium fuel-cycle policies and in examining the feasibility of interim spent-fuel storage as an alternative. He has a Ph.D. in nuclear engineering from Tokyo University (1988).

William Walker (Edinburg, United Kingdom) stepped down from IPFM in 2010. He is a Professor of International Relations at the University of St. Andrews. He co-authored *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (SIPRI/Oxford University Press, 1997) and authored *Nuclear Entrapment: THORP and the Politics of Commitment* (Institute for Public Policy Research, London, 1999) and *Weapons of Mass Destruction and International Order* (Adelphi Paper, 2004).

Other Contributors to Global Fissile Material Report 2010

Robert Alvarez served as senior policy advisor to the U.S. Secretary of Energy between 1993–1999. Both before and after this period he worked as an independent analyst focusing on energy issues, including the environmental impacts of nuclear energy. He is now a Senior Scholar at the Institute for Policy Studies in Washington, DC. He was the lead author of the appendix on plutonium-bearing wastes to the United States chapter.

Marvin Miller was a member of the MIT Department of Nuclear Science and Engineering (NSE) from 1976 until his retirement in 1996. Previously, he was on the faculty of the Department of Electrical Engineering at Purdue University, working on laser theory and applications including isotope separation which was the bridge to his research on nuclear non-proliferation. He is now a Research Associate in the Science, Technology, and Society Program at MIT, where he continues his research on nuclear power and nuclear proliferation. He was the lead author of the chapter on Israel.

Hui Zhang is a Research Associate at the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government. He leads a research initiative on China's nuclear policies and his work includes verification techniques for nuclear arms control, the control of fissile material, nuclear terrorism, nuclear safeguards and non-proliferation, and the nuclear fuel cycle. He was a post-doctoral fellow at the Center for Energy and Environmental Studies, Princeton University from 1997–1999. He received his Ph.D. in nuclear physics in Beijing. He was the lead author of the chapter on China.

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. These measures also would be an important step on the path to achieving and sustaining a world free of nuclear weapons.

The mission of the IPFM is to advance the technical basis for cooperative international policy initiatives to achieve these goals. This report provides revised estimates of fissile material production and stocks worldwide.

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