IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2009

A Path to Nuclear Disarmament

Fourth 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 in nuclear weapon states.
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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 stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium is used in civilian reactor fuel in more than one hundred locations. The total amount used for this purpose is sufficient to make about one thousand Hiroshima-type bombs, a design 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. Professor José Goldemberg of Brazil stepped down as co-chair of IPFM on July 1, 2007. He continues as a member of IPFM. Short biographies of the panel members can be found at the end of this report.

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

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Foreword

Over the past year, the importance of charting a new common ground for reducing and eliminating stockpiles of the key nuclear weapon materials—plutonium and highly enriched uranium—has grown. It is not merely that the Fissile Material Cutoff Treaty, which would stop all production of fissile materials for weapons, has returned to the top of the international nuclear disarmament agenda, with the United Nations Conference on Disarmament agreeing this year to begin talks on such a treaty. More important, the entire project of nuclear disarmament has undergone a renaissance. Notably, President Barak Obama called in his speech in Prague on April 5, 2009 for a world without nuclear weapons. The idea of not merely reducing the number of nuclear weapons but of eliminating them entirely is getting more serious consideration than at any time since President Truman proposed the Baruch Plan to the UN to achieve this end in 1946.

It is in this new context, which is the focus of the present report, that the work of the International Panel on Fissile Materials is playing an indispensable role. Suddenly, people in government, in academia, and in society at large are asking, in more detail than ever before, what a world with very few or no nuclear weapons might actually look like. The difficult and still-important question of how to get to such a world is now accompanied by the perhaps even more difficult and even more important question of what precisely the arrangements in such a world would be and how these would work. The process of getting rid of nuclear weapons (if it really happens), after all, will take only a limited time; but the nuclear-weapon-free world will have to last forever. Harder than getting to zero will be staying there.

The number of nuclear weapons in the world has declined from a peak of more than 60,000 at the height of the Cold War to about a third of that today. If current talks between the Obama administration and the Russian government are successful, these numbers will decline further over the next few years, to about ten thousand operational warheads, including short-range and reserve warheads, plus perhaps another thousand in the arsenals of the world's other seven nuclear powers, with further reductions to follow. As the number of *weapons* declines, the importance of *materials* increases, especially if governments are taking the new goal of zero weapons seriously. In such a world, the immediate fear of nuclear war wanes, and the fear of the return of nuclear weapons takes its place. Attention turns away from warheads and ballistic missiles and toward uranium enrichment and plutonium separation facilities, plutonium and tritium production reactors, highly enriched uranium stockpiles for naval reactors, civilian stockpiles of plutonium and the like.

The *2009 Global Fissile Material Report*, in conjunction with its predecessors, places discussion of these matters, more comprehensively and in greater depth than anywhere else, on a solid technical foundation. It moves the debate out of the realm of slogan and heartfelt wish into the cool light of scientific reality. We come to understand that underlying the weapons systems is the more fundamental fact of nuclear technology and that underlying *that* is the root of the whole dilemma, the scientific knowledge that makes the weapons and materials alike possible. Since the fundamental knowledge is destined to survive even the abolition of the weapons, it is necessary to ask, as the experts who have written this report do in myriad ways, how, over the long run, we can live with it.

The questions that then move to the fore are such matters as: By what exact routes might a cheater on an abolition agreement proceed to rebuild nuclear weapons? What safeguards might the world deploy to protect itself against such a cheater? What measures of verification can give warning of such an attempt? Which nuclear-power technologies lend themselves to cheating, and how might they be circumscribed or eliminated? We are invited to school ourselves in "nuclear archeology" (the history of nuclear production facilities, fathomed through isotopic analysis and other means), in the possible "mining" of nuclear wastes (the danger that a nation will process these wastes to obtain plutonium), and in the "stuffing" or crushing of the plutonium pits at the heart of nuclear weapons to disable them while they await dismantlement.

Of course, acquiring control over fissile materials—by stopping their production for military purposes, by producing a detailed inventory (now woefully incomplete) of their existence, by inspecting that inventory—is not useful solely for abolition. It is also immediately useful for nuclear arms reduction and for reining in nuclear proliferation. If the world's grip on its fissile materials and technology were ever to become fully secure, then nuclear proliferation, especially to sub-national groups, would almost be a dead letter. There is no conflict here between the long and the short run. The information and recommendations presented in this report are therefore as immediately urgent as they are fundamental in the larger scheme of things. They are the guts of nuclear disarmament—a goal that this report represents with new clarity and brings closer to achievement.

Jonathan Schell

New York, September 2009

Overview

The goal of complete elimination of nuclear weapons has returned to the center of international debate. It is a goal as old as the nuclear age. The first resolution of the United Nations General Assembly in 1946 called for plans "for the elimination from national armaments of atomic weapons and of all other major weapons adaptable to mass destruction." It was already understood that central to the challenge would be the control of highly enriched uranium (HEU) and plutonium, the fissile materials that had been used respectively in the bombs that had destroyed the Japanese cities of Hiroshima and Nagasaki five months earlier.

The focus of *Global Fissile Material Report 2009* is on nuclear disarmament as seen through the lens of fissile material policy. If nuclear weapons are to be eliminated, the plutonium and HEU in the nuclear-weapon complexes, the HEU used to fuel the nuclear reactors that power over a hundred ships and submarines and over a hundred nuclear research reactors around the world, and the stock of civilian plutonium separated from nuclear-power-reactor spent fuel will have to be secured, placed under international monitoring and, to the extent possible, eliminated. The following chapters therefore discuss the fissile-material dimension of achieving and sustaining a world free of nuclear weapons.

Chapter 1, IPFM's annual review of global stockpiles, production and elimination, provides the context. Put simply, ending the threat from nuclear weapons will involve securing, safeguarding and eliminating the current worldwide stockpile of about 1600 tons of highly enriched uranium and 500 tons of separated plutonium. Large steps in that direction also will be required to support the deep cuts in nuclear arsenals that will be part of the nearer-term nuclear-disarmament process.

As part of this assessment, for the first time we include an appendix (at the end of this volume) listing sites worldwide where there is reason to believe that nuclear weapons probably are deployed or stored, and those where weapons and their components are designed, fabricated and assembled, or dismantled.

Chapter 2 surveys some of the challenges to eliminating nuclear weapons in a world where nine states have nuclear weapons and increasing numbers of others are acquiring the capability to produce them. A central issue is whether nuclear disarmament is to be pursued through a series of agreed steps laid out in advance in some kind of framework treaty or by continuing the step-by-step approach that emerged during the Cold War and continues today. There is also inevitably the question of reversibility.

Former nuclear weapon states will have legacy fissile materials and weapons-design, production and delivery capabilities not available to non-nuclear-weapon states. These legacy fissile material stocks and production capabilities will have to be subject to international control and used for peaceful purposes or eliminated.

Declaring fissile material and nuclear warhead stocks and production. Non-weapon states routinely provide detailed information on their nuclear-material stocks and activities to the International Atomic Energy Agency (IAEA). In the 1990s, the United States and United Kingdom produced reports on their fissile material stocks and the history of their production and consumption. To provide a basis for very deep cuts in the U.S. and Russian arsenals, detailed declarations may be required from Russia as well. Eventually, all weapon states will have to make such declarations as they join the effort to eliminate nuclear weapons.

Chapter 3 discusses how warhead and fissile-material declarations could be organized, and the challenges, more than six decades into the nuclear era, of producing comprehensive historical declarations. At some point in the disarmament process, all nuclear warheads, weapon components, and containers of fissile material will have to be declared, identified and tagged, and thereafter subject to international monitoring until they are eliminated. National and facility-level production and disposition records will have to be made available for verification. An appendix to Chapter 3 describes the origin, evolution, and capabilities of the Nuclear Materials Management and Safeguards System (NMMSS), which was used to generate the U.S. declarations of plutonium and HEU production, acquisition and utilization from the beginning to the mid-1990s.

Nuclear archaeology. After South Africa decided to eliminate its nuclear weapons and join the Nonproliferation Treaty as a non-weapon state, the IAEA conducted a long investigation to determine that South Africa's HEU declaration was consistent with the physical evidence remaining at its uranium enrichment plants. More recently, as part of an agreement to end North Korea's nuclear weapon program, the United States proposed to check North Korea's plutonium declaration with a detailed study of the available physical evidence in its plutonium-production complex. The same type of investigation will have to be done in the fissile-material production complexes of each of today's nuclear-weapon states. The sooner all weapon states make such declarations and the investigations begin, the more physical evidence of past production activities there will be to examine.

This type of investigation has been dubbed "nuclear archaeology" and is the subject of Chapter 4. One powerful tool that has already been developed is the graphite isotope-ratio method to determine cumulative production of plutonium in graphite-moderated production reactors (reactors used for producing weapons plutonium by the United States, the United Kingdom, Russia, France, China and North Korea). Studies should be mounted to see whether a similar approach could be developed to estimate past plutonium production in heavy-water-moderated reactors, in use by India, Israel and Pakistan even today. Checking declarations of HEU production would require measurements of the isotopic composition of samples of the HEU as well as the depleted uranium waste from the enrichment process. In some weapon states, uranium was used first in reactors to produce plutonium and then enriched to make HEU. The processing of materials at the various facilities left isotopic traces in the material that could be used to make consistency checks between plutonium and HEU production declarations.

Verified warhead dismantlement. A critical verification challenge will be to ensure that, once a state has declared its nuclear-weapon and component stockpiles, none of their contained fissile materials go astray before the fissile materials are converted to unclassified forms and placed under international monitoring pending disposition.

Chapter 5 reviews and builds on a 1990s U.S.-Russian "lab-to-lab" project that attempted to devise minimally intrusive approaches to verifying warhead dismantlement. A key addition is the early selection by international inspectors at deployment and storage areas of a random sample of warheads and components of each declared type as templates to provide radiation "fingerprints" for comparison with warheads and components declared later to be of the same types. This allows warheads to be identified without revealing detailed nuclear weapon design information. The chapter also finds that the verification of nuclear-weapon dismantlement could be greatly simplified if the quantities and isotopic compositions of the plutonium and HEU in each type of nuclear warhead were declassified.

Disposition of HEU and plutonium stocks. Nuclear disarmament would release about 900 tons of HEU and 150 tons of plutonium currently in nuclear warheads and the associated production complexes. If the United States, Russia and the United Kingdom were to follow France's example and convert their naval-propulsion reactors to low-enriched uranium fuel, an additional 200 tons of HEU in naval reserves—enough to make 8,000 nuclear weapons—could also be eliminated. Chapter 6 discusses the challenge of doing so.

There is ample precedent for the disposition of HEU from weapons. In the 1990s Russia and the U.S. together declared excess for military purposes about 700 tons of HEU. Almost 500 tons of this excess HEU, mostly Russian, has been down-blended to make low-enriched uranium (LEU) to fuel nuclear power reactors and the rest will be. In contrast, none of the about 90 tons of weapon-grade plutonium declared excess by Russia and the United States has yet been eliminated. Plans to use this plutonium to fabricate mixed plutonium-uranium oxide (MOX) for reactor fuel have made little progress while costs have dramatically increased in both states. It is time to suspend this effort and to consider alternative disposition options that would cover both current and future plutonium declared excess. In the meantime, all excess HEU and weapons plutonium stocks and associated disposition facilities should to be put under IAEA monitoring. This would establish a basis for arrangements that could apply to other weapon states when they declare fissile material excess and dispose of it.

Two hundred and fifty tons of separated civilian—but still weapon-usable—plutonium also have to be disposed of to make nuclear disarmament more irreversible. The United Kingdom, which owns about one third of this separated civilian plutonium, has just begun to discuss how to dispose of it. The United Kingdom should end efforts to get its troubled reprocessing plant back into operation since success would only make its plutonium disposition problem larger.

Verification of a ban on the production of fissile material for weapons. A verifiable Fissile Material Cutoff Treaty (FMCT) that ends all production of fissile material for weapons would be an essential building block for a nuclear-disarmament regime and is likely to be the first international agreement along that path. A detailed discussion of both the scope and verification of a Fissile Material Cutoff Treaty was the centerpiece of *Global Fissile Material Report 2008*, with the main ideas of that report summarized here in Chapter 7.

Effective verification of an FMCT will, at the least, require international monitoring of all reprocessing and enrichment plants, and also universal adherence to the Additional Protocol to the safeguards agreements with the IAEA that many non-weapon states have agreed to. The Additional Protocol requires states to declare all their nuclear-energy-related activities and gives the IAEA increased authority to look for undeclared activities related to nuclear-material production.

Nuclear energy and nuclear disarmament. In a nuclear weapon-free world, the major threat of breakout would be associated with the fuel-cycle facilities and fuels associated with nuclear power reactors. It is clear that controls on such facilities would have to apply equally to all countries.

If countries are allowed to separate plutonium from spent power-reactor fuel—as is done today in France, India, Japan, Russia, and the United Kingdom—they could use this plutonium to make nuclear weapons within weeks. Countries with large national enrichment plants could similarly quickly begin to make large quantities of HEU for weapons.

The breakout times would be longer in a world without reprocessing and where states lacked national enrichment plants. But a state with nuclear reactors still could build a “quick and dirty” reprocessing plant and recover plutonium from spent power reactor fuel within six months to a year. This would still be true if a state abandoned nuclear power but retained spent fuel under national control in long-term storage or in a geological repository.

Of course, with enough effort, even states without any nuclear-power infrastructure or legacy could develop nuclear weapons. The United States managed to develop nuclear weapons starting with no nuclear infrastructure in three years (1942–1945). A difference between a warning time of years or weeks could be critical, however, to the ability of the international community—or in some cases, a country’s internal political processes—to deal with the threat.

Societal verification. In a nuclear-weapon-free world, a robust international verification system based on safeguards and other technical measures would be necessary but not sufficient. Such traditional verification would have to be complemented by a system where individuals with knowledge of suspicious activities in their countries could and would alert the international community. The final chapter in this report discusses the elements of such a system of “societal verification.” Most of the international community would welcome such citizen reporting today in states aspiring to nuclear weapons. But citizens are unlikely to turn against their own government if it is simply trying to develop the same capabilities that nuclear-weapon states already have and claim as vital to their national security. It therefore is reasonable to expect that, only when all states have convincingly committed to nuclear disarmament, will the citizens of states engaged in clandestine nuclear activities be willing to “blow the whistle” on their own governments.

1 Nuclear Weapon and Fissile Material Stocks and Production

In mid-2009, the global stockpile of highly enriched uranium (HEU) was about 1600 ± 300 tons,* enough for more than 60,000 nuclear weapons. The large uncertainty is due to Russia not declaring how much HEU it produced before it ended production in the late 1980s. The United States, which ended production in 1992, and has the second largest HEU stockpile, has made public the history of its HEU production and utilization.

The nuclear weapon states as a whole account for over 99 percent of the global HEU inventory. The HEU held by non-weapon states, only ten tons today—but still enough to make hundreds of nuclear weapons—is falling because of an international effort to return the HEU to the United States or Russia as civilian research reactors shut down or are converted to LEU fuel. So far, sixty-eight reactors have been converted, with 40 more planned for conversion in the next five years.

There are currently uranium enrichment plants operating, under construction or planned in twelve states. Pakistan and India, however, are today the only states that continue to produce HEU for weapons and naval fuel, respectively. The enrichment plants in other countries are producing low-enriched uranium for power-reactor fuel.

The global stockpile of HEU is being reduced because Russia and the United States are down-blending HEU at a greater rate than Pakistan and India are producing. Most of the down-blending is taking place in Russia of HEU from excess Cold War weapons.

In 2009, the global stockpile of separated plutonium was about 500 ± 25 tons, roughly half produced for weapons and half produced in civilian nuclear power programs. Thus, there is about one third as much plutonium as there is HEU. Since the critical mass of plutonium is about one third that of HEU, however, the global stockpile of plutonium also is sufficient for more than 60,000 first-generation nuclear weapons.

Russia and the United States together hold most of the weapons plutonium. The main uncertainty here also is because Russia has not declared its plutonium stockpile. Only ten other countries hold stocks of separated plutonium, three of them non-weapon states. The four largest stockpiles of civilian plutonium are held by three weapon states (the United Kingdom, France and Russia) and Japan.

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* Throughout this report, tons refer to metric tons. One metric ton corresponds to 1000 kg or about 2205 lb. A glossary of technical terms used in this report is available at www.ipfmlibrary.org/glossary.

North Korea announced in April 2009 that it had ended the suspension of its plutonium production that it had agreed to in 2007 and had resumed reprocessing. India and Pakistan continue to produce plutonium for weapons and Israel may be producing as well. Pakistan is building two new plutonium production reactors in addition to the one that it currently has in operation and has been expanding its reprocessing capacity to be able to recover the plutonium from their fuel.

On the civilian side, China began testing a new pilot-scale reprocessing plant in 2009, but civilian plutonium programs in Japan and the United Kingdom encountered problems. Japan delayed startup of its Rokkasho commercial reprocessing plant and does not expect commercial operations to begin till late 2010 at the earliest. In June 2009, the United Kingdom's troubled THORP reprocessing plant was shut down by equipment problems again till at least the end of the year.

The goal of nuclear disarmament was given renewed prominence in 2009 by the incoming Obama administration in the United States. The United States and Russia agreed to negotiate by the end of 2009 a reduction to 1500–1675 deployed strategic warheads each, and to discuss still further cuts thereafter. They currently have total stockpiles, including warheads awaiting dismantlement, of about 10,000 warheads each. Whether the fissile material in the weapons to be withdrawn from the Russian and U.S. arsenals will be added to that material previously declared excess has not been announced. Britain and France, which have also announced cuts in arsenals in recent years, have not revealed whether they plan to declare excess the fissile materials in the weapons they have taken out of service.

Two new nuclear-weapon-free zones came into force in 2009, covering Central Asia and Africa, and including a total of 57 countries. All of the countries in the southern hemisphere are now in nuclear-weapon-free zones.

The following provides more detail on the changes in the world's nuclear-warhead and fissile material stocks.

Nuclear Weapon Stocks

Nine states currently have nuclear weapons. These are, in historical order: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan and North Korea. Estimates of their current nuclear-weapon stockpiles are shown in Table 1.1.

Country	Nuclear Warheads
United States	9400, of which 4200 are awaiting dismantlement
Russia	10,000, with a large fraction awaiting dismantlement
France	fewer than 300
United Kingdom	185
China	about 240
Israel	100 – 200
Pakistan	70 – 90
India	60 – 70
North Korea	fewer than 5

Table 1.1. Estimated total nuclear-weapon stockpiles, 2009.[1] *Source: FAS/NRDC.*

United States. In July 2009, the U.S. Department of States declared that, "as of May 2009, the United States had cut its number of operationally deployed strategic nuclear warheads to 2126, which meets the limits set by the [2002 Moscow] Treaty for 2012."[2] In addition, the United States currently has an estimated 500 non-strategic weapons and more than 6500 inactive weapons in reserve or awaiting dismantlement, bringing the total U.S. inventory to about 9400 warheads.

Russia. Russia continues to reduce the number of its nuclear warheads to meet its Moscow Treaty obligations. It is estimated to have less than 2800 operationally deployed strategic warheads.[3] The large uncertainty in the total number of Russia's warheads is due to a lack of information on the number of its tactical nuclear weapons and the number of excess warheads that still await dismantlement.

Russia and the United States. In July 2009, Russia and the United States agreed to negotiate by the end of the year a follow-on to the 2004 Strategic Arms Reduction Treaty, which will expire in 2009. They have announced that the objective is to agree before the end of 2009 to a reduction to 1500–1675 deployed strategic warheads each, with the cuts to be completed by 2016.[4] Beginning in 2010, there may be negotiations on further reductions—perhaps including non-deployed and non-strategic warheads.[5]

The United States is estimated to be dismantling about 350 warheads per year.[6] The current net dismantlement rate in Russia is estimated as perhaps 200–300 warheads a year.[7] At these rates, it would take decades for the United States and Russia to dismantle to about 1000 total warheads each, approximately the total possessed by all the other nuclear-weapon states. Both countries achieved much higher dismantlement rates in the 1990s when the United States was dismantling warheads at an average rate of about 1300 per year[8] and Russia was estimated to be dismantling about 2000 per year.[9]

United Kingdom. In March 2009, UK Prime Minister Gordon Brown announced that "Britain has cut the number of its nuclear warheads by 50% since 1997" and noted further that "our operationally available warheads now number fewer than 160."[10] The United Kingdom has 50 U.S.-supplied Trident missiles, currently deployed with up to three warheads each. There may be a relatively small number of reserve warheads. The United Kingdom has declared as excess less than ten percent of its weapon-grade plutonium. Its weapon-grade uranium is apparently kept in reserve for future use as nuclear-submarine fuel.

The United Kingdom is currently debating a decision to replace the four nuclear submarines that carry the Trident missiles, which are the country's only remaining nuclear-weapon delivery system.[11] It may reduce its future fleet to three submarines.[12]

France. France is reducing the number of nuclear weapons in its arsenal to meet the target set by President Nicolas Sarkozy in 2008, who announced that, after the planned reduction, "our arsenal will include fewer than 300 nuclear warheads."[13] At the same occasion, President Sarkozy also revealed that France "has no other weapons beside those in its operational stockpile." France has not indicated its plans for the disposition of the fissile materials contained in the roughly 300 warheads it has removed from service.

China. Over the past year, there appear to have been no significant changes in China's nuclear arsenal or major announcements of policy. The 2009 edition of the U.S. Department of Defense report *Military Power of the People's Republic of China* suggests a continuing effort to move towards more mobile and survivable delivery systems, including transitioning from liquid-fuel to solid-fuel road-mobile missiles and to submarine launched ballistic missiles.[14]

Nuclear-weapon and component sites

Nuclear weapons can be found at a large number of sites around the world. It is estimated there may be a total of 111 nuclear warhead storage sites, with 105 of these sites in nuclear weapon states. The United States currently maintains six sites in non-weapon states—with one site each in Belgium, Germany, the Netherlands and Turkey and two sites in Italy.[15] In the past, the United States stationed nuclear weapons in as many as 23 foreign countries.[16] Table 1.2 gives the total number of warhead and nuclear-component storage sites currently estimated in each country. Appendix B to this report gives a preliminary listing of these sites for each country.

Country	Warhead storage sites
China	14
France	7
India	5
Israel	4
Pakistan	8
Russia	48
United Kingdom	4
United States (domestic)	15
United States (in five foreign countries)	6
Total	**111**

Table 1.2. Estimated number of nuclear warhead storage sites by country. There are currently an estimated 111 warhead storage sites worldwide, in at least 13 countries, not including North Korea. In some cases sites are counted twice, when there are warheads deployed on missiles and spare warheads at nearby storage areas. *Source: Hans Kristensen and Robert S. Norris, FAS/NRDC.*

Russia accounts for almost half of all the nuclear warhead storage sites worldwide. This is in part due to Russia's large number of tactical nuclear warheads, which are ordinarily at a small number of national-level storage sites but for which storage areas are held ready at a much larger number of air and naval bases. The United States has withdrawn all but 500 tactical weapons from operational service and has mostly dismantled the retired weapons.

Nuclear Weapon Free Zones. In March 2009, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan established the Central Asian Nuclear Weapon Free Zone.[17] It is the first nuclear-weapon free zone in the Northern Hemisphere and breaks new ground by requiring its parties to accept an Additional Protocol agreement with the International Atomic Energy Agency (IAEA) and to become parties of the Comprehensive Nuclear Test-Ban Treaty.

In July 2009, the African Nuclear-Weapon-Free Zone Treaty (Treaty of Pelindaba), signed by 52 countries, came into force after it was ratified by Burundi, meeting the requirement for 28 parties to do so.[18] Among its novel provisions, the treaty prohibits attacks on nuclear facilities in the zone. The new treaties join those of Tlatelolco, Rarotonga, Bangkok, and Antarctica (Figure 1.1). All countries in the southern hemisphere are now in nuclear-weapon free zones.

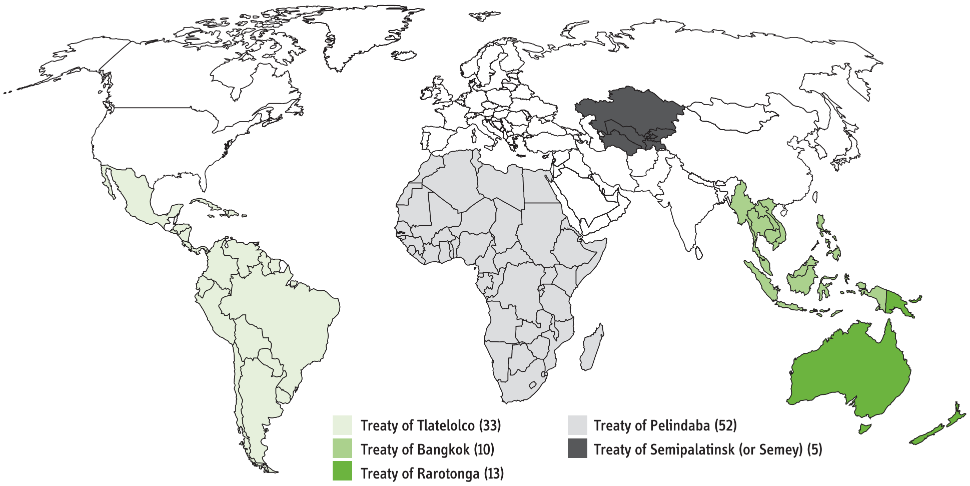


Figure 1.1. Nuclear-Weapon-Free Zones, 2009. There are now five nuclear weapons free zones, covering over 110 countries, including all the countries in the Southern hemisphere.

Highly Enriched Uranium Stocks

Figure 1.2 shows that more than 99 percent of the global stock of highly enriched uranium is in the nuclear-weapon states. Only the United Kingdom and the United States have made public the total sizes of their stocks of HEU.[19] Estimates of the remaining national holdings are generally quite uncertain. According to these estimates, despite the elimination of almost 500 tons of Russian and U.S. HEU by down-blending to low-enriched uranium, the global inventory still totals 1610 ± 300 tons—rounded to 1600 tons elsewhere in this report.

The main uncertainty in estimating the global total is due to a lack of information on Russia's stockpile, which may have been as large as 1500 tons in the 1990s. A 20% uncertainty is assumed in the figures for total stocks in China and Pakistan, and for the military stockpile in France, and 50% for India.

Russia. Our central estimate of Russia's stockpile continues to be based on a statement in 1993 by then Minister of Atomic Energy Viktor Mikhailov that "the 500 metric tons of HEU that is up for sale represents somewhere around 40 percent of all reserves that we [Russia] possess."[20] This implies a 1993 total stockpile of about 1250 tons of HEU, which is somewhat higher than what U.S. government and non-government experts had previously assumed, but consistent with publicly available information on Russia's fissile material production complex. As of June 2009, Russia had eliminated 367 out of 500 tons of weapon-grade HEU as part of its 1993 HEU deal with the United States, which is to be completed in 2013.[21]

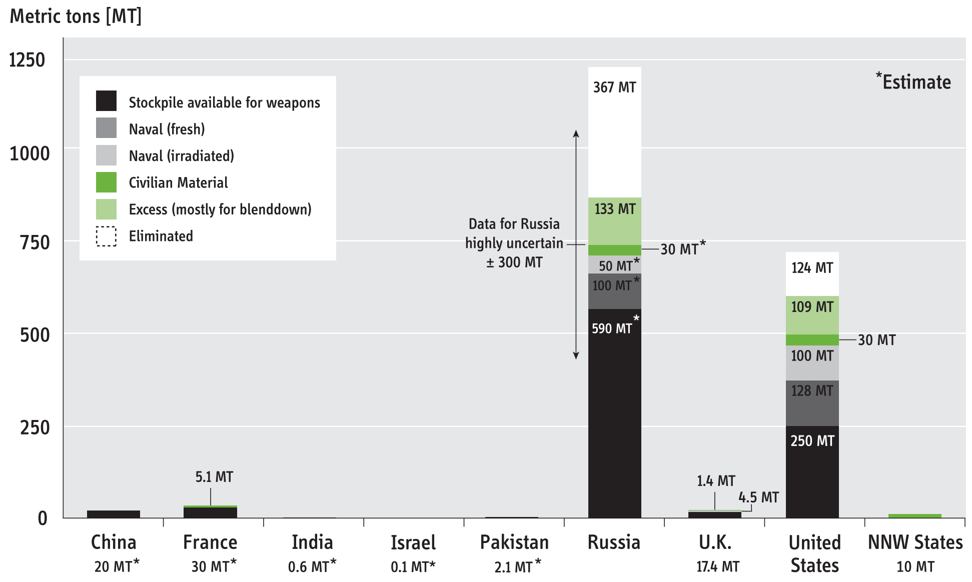


Figure 1.2. National stocks of highly enriched uranium as of mid-2009. The numbers for the United Kingdom and United States are based on their publications. The civilian HEU stocks of France, the United Kingdom are based on their public declarations to the IAEA. Numbers with asterisks are non-governmental estimates, often with large uncertainties.[22] Numbers for Russian and U.S. excess HEU are for June 2009. HEU in non-nuclear weapon (NNW) states is under IAEA safeguards. A 20% uncertainty is assumed in the figures for total stocks in China, Pakistan and Russia, and for the military stockpile in France, and 50% for India.

United States. As of mid-2009, the United States had down-blended cumulatively about 124 tons of highly enriched uranium[23]—mostly less than weapon-grade. Based on the declared total inventory of 741 tons from September 1996, this leaves 109 tons of excess HEU (mostly for blend-down), about 30 tons of civilian HEU (fresh and irradiated), about 100 tons of HEU in spent naval reactor fuel, which is to be disposed of as radioactive waste, and about 380 tons of unirradiated HEU in the military stockpile. This military total includes about 250 tons available for weapons and 128 tons of fresh HEU reserved for naval propulsion.[24]

Pakistan. Pakistan may be the only country producing HEU for weapons today. It is believed to have first achieved the capacity to produce a significant quantity of HEU in the early 1980s and to have built up its enrichment capacity using P-2 centrifuges and later more advanced P-3 and P-4 designs.[25] There have been claims that, along with its Kahuta enrichment facility, Pakistan may have an enrichment plant at Gadwal.[26] Reportedly near Wah, about 30 kilometers from Islamabad, Gadwal was described recently as a facility where already enriched uranium (presumably from Kahuta) is enriched further to weapon-grade.[27]

Pakistan's annual HEU production capacity is constrained by its limited domestic production of natural uranium and the need also to fuel its Khushab-I plutonium production reactor. To address this problem, Pakistan may have started to use reprocessed uranium recovered from Khushab spent fuel as feed for its uranium-enrichment program. We estimate Pakistan's enrichment capacity to be on the order of 30,000

Separative Work Units (SWU) per year today, which is equivalent to a production rate of 150 kg of weapon-grade HEU per year. By the end of 2008, Pakistan's total cumulative production of HEU would have been about 2.4 tons, but 200–400 kg may have been consumed in the 1998 nuclear weapons tests. Our central estimate for Pakistan's current stockpile of HEU is about 2.1 tons.[28]

India. India produces HEU for its naval propulsion program. It began testing a land-based prototype naval reactor in 2000–2001 and in July 2009 launched its first nuclear submarine for sea trials.[29] The submarine is described as being powered by an 85 megawatt (thermal) (MWt) reactor.[30] Two more submarines are under construction, with their hull sections already having been built. Completion of the submarines will take at least another five years.[31] There is some uncertainty about the level of enrichment of the fuel, with suggestions that it is be enriched to 30–45% uranium-235.

Estimates of India's HEU production depend on assumptions about its uranium enrichment capacity and whether it also produces HEU for weapons. In order to produce enough HEU by the end of 1999 to fabricate fuel for the land-based prototype submarine reactor core, India would have to have had a total enrichment capacity of at least 3000 SWU/yr by then.[32] A 2007 estimate, citing Indian purchases of a large number of centrifuge components, suggested that India could have an enrichment capacity of about 20,000 to 30,000 SWU/yr.[33] This capacity would be sufficient to produce 200–300 kg per year of HEU at 45% enrichment, or half this amount of 90% enriched HEU per year. This would give India enough separative capacity to produce HEU for four submarine cores by 2010.

North Korea. In early September 2009, Korea News Service reported that the permanent representative of the DPRK to the United Nations had submitted a letter to the president of the UN Security Council in late August 2009, noting that—among other things—"experimental uranium enrichment has successfully been conducted to enter into completion phase."[34]

Israel. We continue to assign to Israel an inventory of 100 kg of HEU, which may have been acquired covertly from the United States before 1966.[35] Israel also may have produced enriched uranium with laser or centrifuge technology, but information on this program is very limited and it may have ended.

South Africa. South Africa has a legacy stockpile of 400–450 kg of HEU that was part of its weapons program and is currently under IAEA safeguards.[36] This is what remains from an original stock of over 800 kg of HEU with an average enrichment of about 80%. Since its research reactor has been converted to low-enriched uranium fuel,[37] South Africa only uses HEU for a target material to produce molybdenum-99 for medical-isotope use. This use too could be converted to low-enriched uranium.[38]

Civilian Use of HEU. Since 1978, an international effort has been directed at converting HEU-fueled reactors to low-enriched fuel in the Reduced Enrichment for Research and Test Reactor (RERTR) program. Almost all new reactors designed since that time use LEU fuel. By 30 September 2009, the RERTR program intended to have converted or partially converted 68 research reactors and plans to convert another 40 reactors by 2014.[39] There are many reactors whose conversion has not been seriously discussed, however—notably in Russia, which has yet to begin shutdown or conversion of almost 70 of its own HEU-fueled research reactors, most of them little used.[40] There are also reactors in the West that may resist conversion.[41] The world's remaining research reactors consume about 800 kilograms of HEU per year—a significant reduction from more than

1400 kg that were used annually in the early 1980s. We continue to assign about 70 tons of HEU to the civilian research reactor fuel cycle, which includes about 10 tons (6.7 tons of ^{235}U in HEU) that are under IAEA safeguards in NPT non-weapon states and at least 1.3 tons under voluntary offer agreements in weapon states.[42]

Civilian uranium enrichment plants. There are currently civilian uranium enrichment plants operating, under construction or planned in ten states. These enrichment plants are intended to produce LEU for nuclear power reactor fuel, but could in principle quickly be turned to producing HEU for weapons. Appendix 1A lists all enrichment plants and whether they are under or have been offered for International Atomic Energy Agency (IAEA) safeguards. About half are under safeguards.

The two new enrichment plants to begin initial testing and operation in 2009 were Areva's George Besse II centrifuge enrichment plant, located at the Tricastin Site in France, and Urenco's Eunice plant in the United States.[43] Two additional new large-scale centrifuge enrichment plants are at various stages of development in the United States and could be completed over the next decade.[44] Also, in July 2009, Global Laser Enrichment (GLE) filed a U.S. license application for a large laser-enrichment plant to begin commercial operation in 2012.[45] There were significant capacity increases at the Urenco enrichment plants in Germany, the Netherlands, and the United Kingdom, which together delivered an additional 1300 tSWU in 2008 compared to 2007.[46] Russia also has been increasing the capacity at its domestic enrichment plants,[47] as well as at the centrifuge plant it supplied to China. In March 2009, Russia announced plans with Toshiba to build an enrichment plant in Japan.[48]

Separated Plutonium

Since 1944, more than 60 dedicated reactors have been used by the nine weapon states to produce plutonium for weapons purposes (IPFM estimate). As of 2009, nearly all of these reactors have been closed-down or dismantled and only India, Pakistan and perhaps Israel continue to produce plutonium for weapons. In addition, six countries reprocess their commercial spent fuel today: France, India, Japan, and Russia are deeply committed to reprocessing; China is testing a pilot reprocessing plant and is contemplating commercial reprocessing; and the United Kingdom is on the verge of abandoning reprocessing.

The global stockpile of separated plutonium is about 500 tons. It is divided almost equally between civilian and military stocks—the latter including material declared excess but not yet disposed (Figure 1.3). Separated plutonium exists mostly in nuclear-weapon states, but Japan and Germany also have significant stocks. The buildup of civilian stockpiles has slowed down with a dozen countries not renewing their contracts to have their spent fuel reprocessed by France, Russia and/or the UK and both the United Kingdom and Japan having to shut down their reprocessing plants because of equipment problems.

Weapons plutonium. Russia and the United States possess by far the largest stocks of military plutonium: 120–170 and 92 tons, respectively. Russia has declared 34 tons of its weapon-grade plutonium excess for military purposes.[49] The United States has declared excess 54 tons of separated government-owned plutonium, which includes 9 additional tons of weapon-grade plutonium added in September 2007.[50] In 1998, the United Kingdom declared excess 0.3 tons of its 3.5-ton stockpile of weapon-grade plutonium.[51]

India. India continues to produce weapons plutonium in its two production reactors, *Cirus* and *Dhruva*, at a combined rate of about 30 kilograms per year. We estimate India's stockpile of weapons plutonium produced in these two reactors to be about 700 kg. It separates much more plutonium from the spent fuel of its unsafeguarded pressurized heavy water power reactors (PHWRs), eight of which will remain outside IAEA safeguards under the U.S.-India deal.[52]

Israel. Assuming that its power is approximately 70 MWt, the Dimona reactor could produce plutonium at a rate of up to 15–18 kg/yr.[53] The reactor may have operated at this power level since the mid-1980s, when it was reportedly uprated from its initial 26 MWt.[54] On this basis, Israel could have produced 600–740 kg of weapon-grade plutonium by 2009 or enough for more than 100 nuclear warheads. Even if the Dimona reactor is used today only for tritium production,[55] Israel could still be separating plutonium from its spent fuel.

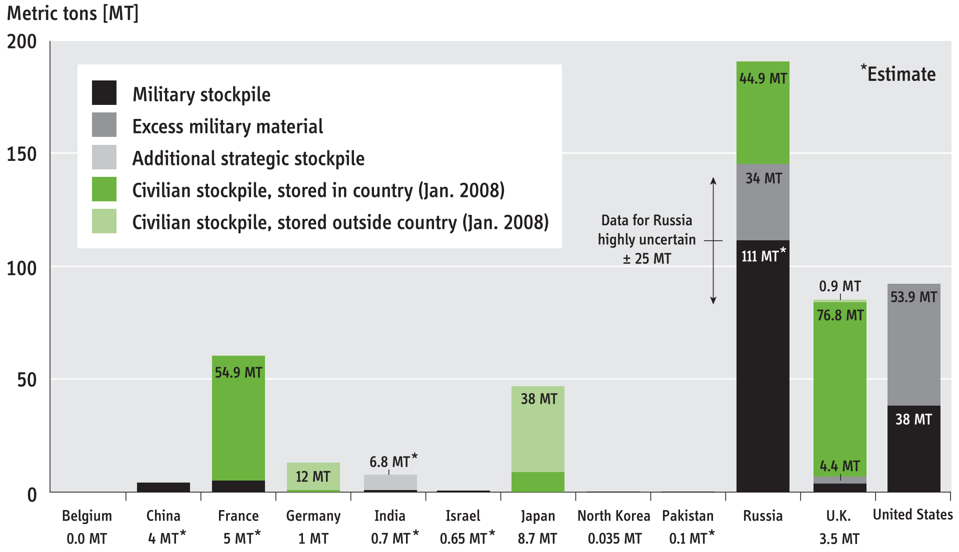


Figure 1.3. National stocks of separated plutonium. Civilian stocks are based on the most recent INFCIRC/549 declarations for January 2008 and are listed by ownership, not by current location. Weapon stocks are based on non-governmental estimates except for the United States and United Kingdom whose governments have made declarations. Uncertainties of the military stockpiles for China, France, India, Israel, Pakistan, and Russia are on the order of 20%. 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. Belgium holds 1.4 tons of foreign-owned plutonium, but has no stockpile of its own (Appendix 1C).

Pakistan. Pakistan continues to produce 10–12 kg per year of plutonium for weapons at its Khushab-I production reactor,[56] which has been in operation since 1998 (Figure 1.4 right) and produced about 100 kg of plutonium since then. Pakistan also is building two new production reactors at the same site (Figure 1.4, left).[57] The construction of Khushab-II appears from satellite imagery to have started in 2001–2002, while work on Khushab-III started in 2005 or 2006. Imagery from September 2008 has been interpreted as suggesting that the Khushab-II reactor may be completed late in 2009.[58] The two new reactor buildings appear to be identical to each other but different from

Khushab-I (Figure 1.4, right), which is reported to be a heavy-water-moderated natural-uranium-fueled reactor with a capacity of about 50 MWt.[59] U.S. government sources have indicated that “the emerging reactor [Khushab-II] appeared to be roughly the same size as the small one Pakistan currently uses to make plutonium for its nuclear program.”[60]

Pakistan is believed to reprocess spent fuel from Khushab-I at its New Labs facility near Rawalpindi. Satellite imagery suggests that Pakistan may have built a second reprocessing plant at New Labs to handle the additional spent fuel.[61] There are also indications that between 2002 and 2006 Pakistan may have resumed work on a large reprocessing plant at Chashma.[62] This facility was to have been built by France in the mid-1970s to handle 100 tons of spent fuel per year, but the deal was cancelled at an early stage of construction.

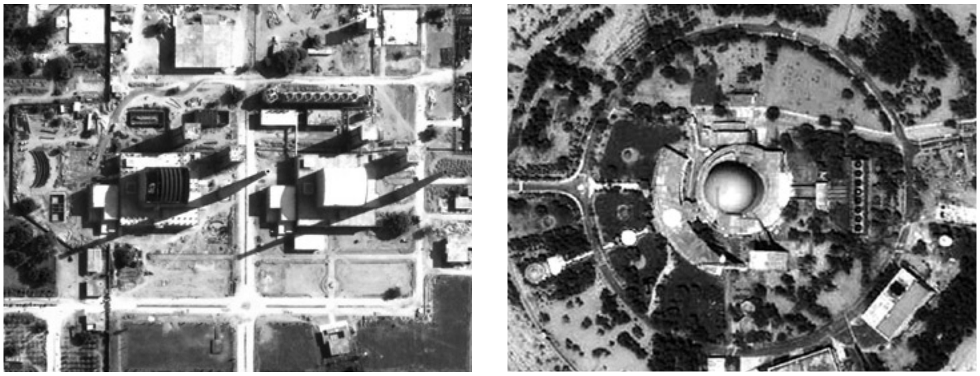


Figure 1.4. Khushab-II and Khushab-III reactors under construction, as of January 2009 (left). The image on the right shows the Khushab-I reactor, which features a similar number of cooling towers indicating a similar power. *Imagery of the new Khushab reactors (at 32.009 N, 72.172 E) courtesy Digital Globe. Imagery of Khushab-I (at 32.020 N, 72.208 E) courtesy of GeoEye.*

North Korea. North Korea is reported to have declared in June 2008 that they had separated 31 kg of plutonium before using 2 kg in its sub-kiloton October 2006 nuclear test.[63] On 25 May 2009, North Korea conducted a second nuclear test apparently with a yield of a few kilotons.[64] We assume that 5 kg of plutonium were consumed in this second test (the amount contained in the Nagasaki bomb). In June 2009, North Korea announced a resumption of reprocessing at its Yongbyon facility, ending an agreed suspension in place since February 2007. Independent analysts estimate that, operating the reprocessing plant at maximum capacity, North Korea could have reprocessed all of its remaining spent fuel and have produced another 8–12 kilograms of separated plutonium by September 2009.[65] We estimate, therefore, a value of about 34 kg for North Korea’s current stockpile of plutonium.

Civilian Plutonium. The production of separated plutonium for weapons—in India, Israel, North Korea and Pakistan—is taking place at much a lower rate than production in civilian programs. Today, China, France, Japan, Russia, and the United Kingdom operate plants for commercial purposes; while the United States continues to operate a small reprocessing plant for extraction of HEU for blend-down from unstable spent fuel and other materials (Chapter 6). Appendix 1B lists all operational reprocessing plants, including type, status, and capacity.

China. The only new reprocessing plant to become operational over the past year is in China. A pilot reprocessing plant of 50 tHM/yr (capable of expansion to 100 t/yr) has been undergoing commissioning.[66] "Cold" tests with uranium solutions reportedly were complete as of June 2009. "Hot" tests with spent fuel are planned.[67] China is considering building with France's help a commercial reprocessing plant with a capacity of 800 tHM/year by 2025.

France. The government-owned nuclear company Areva operates France's reprocessing plant—the world's largest—at La Hague. Areva recently made public the amounts of separated plutonium held at the reprocessing plant as of the end of 2008 (Table 1.3).[68] A stockpile of almost 18 tons of Japanese plutonium is the major foreign contribution to the total of 62 tons at the plant. Although all the spent fuel Japan sent to France has been reprocessed and Japan's reprocessing contract has not been renewed, most of its separated plutonium remains in France (and the United Kingdom) because of delays in the licensing of Japan's power reactors to use mixed uranium-plutonium oxide (MOX) fuel. A stockpile of about 5 tons of Italian plutonium remains at La Hague, presumably for eventual use in a French reactor, since Italy shut down all of its nuclear power plants after the 1986 Chernobyl accident. The Netherlands plutonium is also recycled in French reactors. Germany stopped sending fuel for reprocessing in April 2005, and all of its spent fuel has been reprocessed and the recovered plutonium sent to the MELOX MOX fabrication plant. Belgium and Switzerland also did not renew their reprocessing contracts and their separated plutonium also all has been recycled.[69]

Country	Plutonium Inventory
France	37. 8 tons
Germany	0.7 tons
Italy	5.3 tons
Japan	17.9 tons
Netherlands	0.3 tons
TOTAL	62.0 tons

Table 1.3. Plutonium inventory at La Hague reprocessing plant, as of 31 December 2008.[70] Small stockpiles (less than 62 kg) belonging to Australia and Australia are not listed here. The total inventory of foreign-owned plutonium stored in France is larger because a significant fraction is held at the MOX fabrication facility (MELOX). Note that this data is more recent than the data shown in Figure 1.3.

Germany. The plutonium declarations made by Germany to the IAEA are only partially useful. The cover letter attached to the most recent declaration points out that data "regarding any material that has been shipped abroad, especially for reprocessing … are not available on the German side."[71] Germany's remaining stockpile of separated plutonium can be determined indirectly, however, by adding foreign-owned material in Belgium, France and the United Kingdom, and subtracting the known amounts held in those countries by Italy, Japan, and the Netherlands.[72] Using this information, we estimate a stockpile of about 12 tons stored outside the country (mostly at MELOX, France). As of January 2008, assuming that about one ton of plutonium might be in Germany at any given time in preparation of a reactor reload, Germany's plutonium stockpile could be on the order of 13 tons. This estimate is consistent with data provided by the German utilities (Figure 1.5).[73]

India. As of mid-2009, we estimate that India has separated about 6.8 tons of unsafeguarded plutonium from the spent fuel of its heavy-water-moderated power reactors. India intends to use this plutonium as start-up fuel for a planned fleet of breeder reactors.

Japan. Commercial operation of the Rokkasho reprocessing plant has been delayed for at least another year following leaks of high-level radioactive waste.[74] It was expected to begin commercial operation in August 2009, after completing active testing. The plant was originally expected to be operating by December 1997. It may face further delays—perhaps for several years—because of problems with its vitrification process, which mixes the liquid highly radioactive reprocessing waste into glass for long-term storage.[75] Japan's Tokai reprocessing plant remains closed since an accident in May 2007.

Japan plans to start construction of a 130 tons/year MOX fuel plant in November 2009, two years behind schedule, and expects it to begin operation in 2015.[76] Its plan to have 16–18 nuclear reactors using MOX fuel by 2010 is now delayed by at least five years.[77] Three Japanese reactors, however, are scheduled in 2010 to begin using MOX fuel fabricated in France.[78]

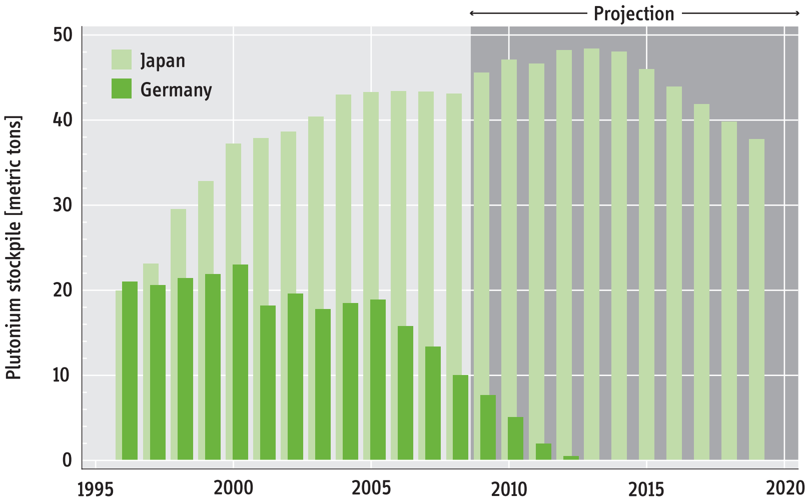


Figure 1.5. Stockpiles of separated civilian plutonium owned by Germany and Japan. Germany stopped shipping spent fuel for reprocessing (in France and the United Kingdom) in 2005. Since then, it has been able to gradually reduce its stockpile of separated plutonium from almost 20 tons to about 13 tons in 2008, and plans to consume the remaining material by the end of 2014. In contrast, if Japan's Rokkasho reprocessing plant operated at full capacity sometime, its plutonium stockpile would increase until the Rokkasho MOX fuel plant is completed.[79] Japan's reprocessing and MOX plants are both years behind schedule, however.

United Kingdom. The UK's Thermal Oxide Reprocessing Plant (THORP), which was built to reprocessing foreign light-water reactor fuel and UK Advance Gas Reactor fuel had resumed operation in late 2007 following a two-year shutdown after a major accident in 2005 involving a large and initially undetected leak of radioactive waste. It is now shutdown again, however, for at least seven months to carry out maintenance on one of its three high-level radioactive waste evaporators.[80] Reprocessing of the 7000 tons of spent fuel covered by the “baseload” contracts that were used to finance the construction of THORP of fuel was to have been completed in 2003 but only a little over 5000 tons had been reprocessed as of the end of 2008.[81]

Breeder Reactors. The original rationale for civilian reprocessing in France, Japan and the United Kingdom was to provide startup fuel for commercial plutonium breeder reactors that were to start coming on line in the 1990s. This rationale has now faded. In March 2009, France announced the end of normal operations at the Phénix fast breeder reactor, pending its final shutdown at the end of the year.[82] There are now no operating fast breeder reactors in Western Europe. In Japan, the experimental 140 MWt Joyo reactor continues to operate but the 280 MWe Monju reactor has been shut down since a sodium fire in 1995.

Russia continues to operate its 600-MWe BN-600 breeder reactor, which is fueled, however, with HEU, not plutonium, and is building a BN-800. India’s 500 MWe Prototype Fast Breeder Reactor (PFBR) is facing a delay and cost overrun of over 40 percent.[83] China expects to commission its 65 MWt Experimental Fast Reactor in 2009.[84] Past experience with fast breeder reactors suggests the programs in Japan, Russia, India and China will continue to face further operating, safety and cost problems.[85]

Appendix 1A. Uranium Enrichment Plants

Facility	Type	Operational Status	Safeguards Status	Capacity [tSWU/yr]
Brazil				
Resende	Civilian	Under construction	yes	120
China				
Shaanxi	Civilian	Operating	(yes)	500–1000
Lanzhou II	Civilian	Operating	offered	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	20–30
Iran				
Natanz	Civilian	Under construction	yes	120
Qom	?	Under construction	?	?
Japan				
Rokkasho	Civilian	Operating	yes	< 1050
Netherlands				
Almelo	Civilian	Operating	yes	3800
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	unconfirmed	11300
Piketon, Ohio	Civilian	Under construction	offered	3800
Eunice, NM	Civilian	Under construction	offered	3300–5900
Areva Eagle Rock, Idaho	Civilian	Under construction	(offered)	3300–6600
GLE, Wilmington, NC	Civilian	Planned	?	3500–6000

Uranium enrichment plants in operation, under construction, and planned, 2009. Capacity ranges account for ongoing or planned expansions. Only two gaseous diffusion plants remain today: George Besse I in France and the Paducah Plant, Kentucky. Both will shut down once new centrifuge capacities come online. In July 2009, a private consortium filed a U.S. license application for a large laser-enrichment plant in Wilmington, North Carolina.

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	Operating	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

Operational reprocessing plants worldwide. Capacities are shown in units of tons of heavy metal (almost entirely uranium) per year. Nine states operate plutonium separation (reprocessing) plants. China is starting up a new pilot plant. Only one of these states (Japan) is a non-weapon state. Among the weapon states, only India, Israel, North Korea and Pakistan continue to produce plutonium for weapons.

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

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

Since 1996, nine countries (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and United States) declare publicly their stocks of civilian plutonium annually to the IAEA (INFCIRC/549). Some countries now add civilian HEU to these declarations. The declarations by China are always zero. Switzerland declares material when fresh MOX happens to be in the country, but not yet loaded into its reactors. Germany's declarations are only partially useful, and not included here. Russia does not include in its declaration excess weapons plutonium, whereas the United States does.

The annual inventories (as of December 31) 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.

2 Fissile Materials and Nuclear Disarmament

The recognition of the need for nuclear disarmament and the question of how to achieve it are as old as the nuclear age. In June 1945, before the first nuclear weapon had been built, in what became known as the Franck Report, a group of scientists working on the U.S. atomic bomb program warned that:

> "The development of nuclear power is fraught with infinitely greater dangers than were all the inventions of the past. […] In the past, science has often been able to provide adequate protection against new weapons it has given into the hands of an aggressor, but it cannot promise such efficient protection against the destructive use of nuclear power. […] In the absence of an international authority which would make all resort to force in international conflicts impossible, nations could still be diverted from a path which must lead to total mutual destruction, by a specific international agreement barring a nuclear armaments race."[86]

In its first resolution, the United Nations General Assembly established a Commission and tasked it to draw up plans "for the elimination from national armaments of atomic weapons and of all other major weapons adaptable to mass destruction."[87] The Acheson-Lilienthal Report, authored largely by Robert Oppenheimer, and the official U.S. and Soviet proposals to the United Nations (the Baruch and Gromyko Plans respectively) of 1946 were the most prominent attempts to realize this goal.[88] The Gromyko Plan included the first proposed text for a nuclear disarmament treaty in the form of a *Draft International Convention to Prohibit the Production and Employment of Weapons Based on the Use of Atomic Energy for the Purpose of Mass Destruction.*[89]

In this chapter, we review briefly the effort to secure nuclear disarmament over the past six decades, the renewal of the nuclear debate over the past few years, and some of the major issues this effort will need to address today.

In succeeding chapters, we discuss in more detail some of these issues and the options for accounting for and eliminating nuclear weapons and the fissile materials that make them possible.

Early efforts

In 1946, the elimination of nuclear weapons seemed a comparatively simple task. There was just one nuclear-weapon state, with an arsenal of about ten Nagasaki-type nuclear bombs.[90] Long-range missiles had not been developed, civil applications of nuclear energy lay in the future, and the bureaucratic, military, industrial and doctrinal complexes and many of the rationales and justifications that would be erected around nuclear weapons during the Cold War had yet to come into being. The early hopes for nuclear disarmament were frustrated, however, by the onset of the Cold War and the nuclear arms race between the United States and Soviet Union.

Many states, organizations, civil society groups, and individuals including prominent scientists, held fast to the goal of nuclear disarmament (Figure 2.1). They could not achieve their ultimate goal but did help bring about agreements to limit nuclear weapons testing and restrain the arms race.[91] The first diplomatic success was the 1963 partial Test Ban Treaty, which aimed to end nuclear weapons testing in the atmosphere, under water and in outer space (Figure 2.2). Unfortunately, it lifted the public pressure on governments to end explosive testing which continued unabated underground.

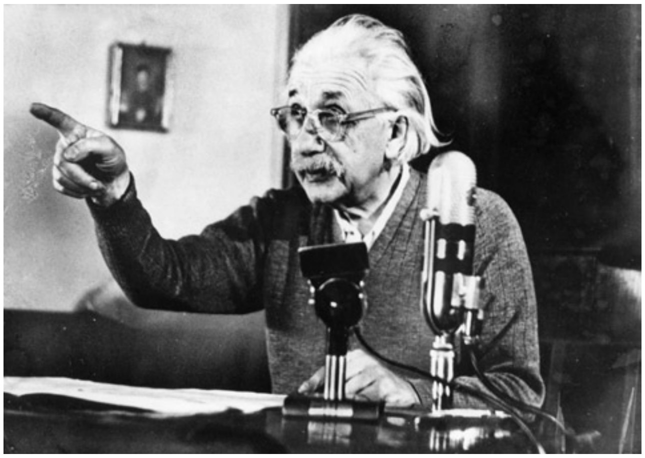


Figure 2.1. Albert Einstein declares his opposition to the atomic bomb and to the arms race between the United States and the Soviet Union in a press conference in Princeton (10 February 1950). *Credit: National Archives and Records Administration, courtesy AIP Emilio Segrè Visual Archives.*

Figure 2.2. Linus Pauling outside the White House, Washington, DC, protesting against nuclear weapons testing (28 April 1962). The following day, Pauling joined other Nobel Prize Winners at a White House meeting called by President Kennedy to honor them. *Credit: National Archives and Records Administration, courtesy AIP Emilio Segrè Visual Archives.*

The number of nuclear weapon states steadily increased, however, with Britain, France and China developing nuclear weapons by the late 1960s. In an effort to curb the further spread of nuclear weapons, the United States and the Soviet Union, now nuclear "superpowers," and the United Kingdom negotiated the 1970 nuclear Non-Proliferation Treaty (NPT) with a group of non-weapon states and agreed in Article VI "to pursue negotiations in good faith on effective measures relating to the cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a Treaty on general and complete disarmament under strict and effective international control." A number of countries abandoned incipient nuclear weapons programs over the next two decades, but Israel, India and Pakistan stayed outside the Treaty and developed nuclear weapons, as did North Korea, which joined the NPT but later withdrew (Table 2.1).

Country	Date of first nuclear test	Date of accession to NPT
United States	July 16, 1945	1970
Russia	August 29, 1949	1970
United Kingdom	October 3, 1952	1970
France	February 13, 1960	1992
China	October 16, 1964	1992
India	May 18, 1974	–
Israel	?[92]	–
Pakistan	May 28, 1998	–
North Korea	October 9, 2006	1985 (withdrew 2004)

Table 2.1. First nuclear weapons tests by current nuclear weapon states, 1945–2009.

During this period, there were occasional dramatic proposals for eliminating nuclear weapons. In 1986, Soviet leader Mikhail Gorbachev outlined a three-stage plan for nuclear disarmament within fifteen years.[93] Indian Prime Minister Rajiv Gandhi proposed a similar time-bound program in 1988, envisaging the abolition of all nuclear weapons by 2010.[94]

In the aftermath of the Cold War, as part of the preparations for the 1995 Review and Extension Conference of the NPT, which was to decide whether and for how long to extend the Treaty, there were many studies on and reports and statements supporting nuclear disarmament by political leaders and groups of eminent former policy makers and officials. A prominent example was the Canberra Commission of 1996.[95] The final agreement on indefinite extension of the NPT included a consensus decision on "principles and objectives for nuclear non-proliferation and disarmament" which contained the beginnings of a program of action. This decision included a commitment to "the determined pursuit by the nuclear-weapon States of systematic and progressive efforts to reduce nuclear weapons globally, with the ultimate goals of eliminating those weapons."[96]

In 1996, responding to a request from the United Nations General Assembly, the International Court of Justice, the highest court in the United Nations system, issued a unanimous advisory opinion ruling that Article VI of the NPT required nuclear-weapon state parties to the Treaty "to bring to a conclusion negotiations leading to nuclear disarmament."[97] At the April 2000 Review Conference of the NPT, the weapons states agreed in the final document to an "unequivocal undertaking … to accomplish the total elimination of their nuclear arsenals."[98] There have been continuing reductions in the sizes of the Russian and U.S. nuclear arsenals, but they each still contain thousands of nuclear warheads and there is no program yet to achieve complete nuclear disarmament.

The Nuclear Disarmament Debate Renewed

The complete elimination of nuclear weapons is being discussed again today, however, with some seriousness. This is most evident in the prominence recently given to the goal of a nuclear-weapon-free world by President Barack Obama of the United States and Prime Minister Gordon Brown of the United Kingdom.[99] Russian President Medvedev joined President Obama in an April 2009 statement declaring "we committed our two countries to achieving a nuclear free world."[100] At the July 2009 L'Aquila G-8 Summit, the leaders of France, the United States, the United Kingdom, and Russia declared that "we are all committed to seeking a safer world for all and to creating the conditions for a world without nuclear weapons."[101] A unanimous September 2009 Security Council resolution extended this commitment to include China.[102] There also have been a series of op-ed articles by former leaders and officials from a number of countries over the past two years supporting the elimination of nuclear weapons.[103]

Charting a path to elimination today is a more difficult challenge than six decades ago.[104] There are now nine nuclear armed-states and, in the case of the United States, military alliance commitments to about 30 non-weapon states that include the possibility of using U.S. nuclear weapons in their defense.[105] In the transition to a nuclear-weapon-free world, at least a few of these countries will want their security concerns to be recognized and addressed. Some states will be concerned about the conventional military power projection capabilities of the great powers. Some also will seek to maintain by other means the status and standing in the international system that they currently have by virtue of their nuclear weapons.[106] These concerns will shape the scope of a nuclear weapons ban and decisions such as on whether to eliminate long-range ballistic missiles along with nuclear weapons, and political issues such as whether to re-structure the powers and membership rights of the United Nations Security Council.[107]

The past several decades have shown, however, that successful wars of conquest and occupation have become near impossible even for great powers.[108] And countries do not need nuclear weapons to remind each other that their modern societies are vulnerable to long-range attack. Since September 11, 2001, industrialized countries have become acutely aware that nuclear-power and chemical plants as well as skyscrapers could be attacked with catastrophic results. As wealth becomes based more and more on knowledge and integration into the global economy, and if competition for land and natural resources can be held in check, fears of wars of conquest may recede further.

At the same time, more than 60 years of nonuse despite innumerable wars show that policy makers and the militaries of nuclear-armed states have come to understand that nuclear weapons are unusable in war.[109] A recent examination of the attitudes toward nuclear weapons in the U.S. Department of Defense (DoD) reported that, since the end of the Cold War, a "lack of interest in and attention to the nuclear mission and nuclear deterrence [has become] widespread throughout DoD."[110] This was exemplified in an August 2007 incident in which six nuclear armed cruise missiles were transported between the Minot and Barksdale U.S. Air Force bases without authorization and without the knowledge of those involved, and for 36 hours remained unaccounted for (Figure 2.3).[111] Since this incident came to light, the U.S. Air Force has been trying to re-organize its nuclear weapon management.

Figure 2.3. An Advanced Cruise Missile is loaded onto the wing of a B-52 at Minot Air Force Base (North Dakota). In August 2007, six nuclear-armed Advanced Cruise Missiles were inadvertently loaded onto a B-52 bomber and flown to Barksdale Air Force Base (Louisiana). The transfer remained unaccounted for at both bases and by the crew until discovered 36 hours later. *Source: Jocelyn Rich, U.S. Air Force, picture available on wikipedia.org.*

Resistance to nuclear disarmament today comes primarily from policy makers, former officials and intellectuals who have come to embrace nuclear deterrence and from the nuclear-weapon-complex, which relies on these weapons for its existence. Public sentiment world-wide largely is in favor of nuclear abolition, with polls showing overwhelming majorities even in the nuclear weapons states (except Pakistan, where margins are much smaller) in favor of an international verified agreement to eliminate nuclear weapons.[112] The issue is not, however, keenly felt and public opinion is not mobilized into an anti-nuclear movement on the scale that has been able in the past to impact policy.

Disarmament Challenges

There are several challenges facing the transition to a nuclear weapon free world and to assuring its security and stability. These include the mechanism or process shaping the disarmament trajectory, the issue of reversibility, the management and elimination of fissile material stocks, and the risks of nuclear weapon reconstitution or proliferation using material and capabilities in civilian nuclear energy programs.

Overall agreement or step-by-step? One of the overarching issues is whether countries commit to the explicit goal and an agreed framework for achieving nuclear disarmament, or whether they continue with an ad hoc approach of nuclear reduction and nonproliferation steps.[113]

Both approaches have been and likely will continue to be used. As part of the 2000 NPT Review Conference, the nuclear-weapon states party to the Treaty agreed to a program of thirteen steps towards the goal of meeting their obligations under Article VI. These steps included meeting specific targets and set timelines.[114] There have, as yet, been no formal talks among the five nuclear weapon states that are Parties to the NPT on achieving these obligations but their year-2000 agreement has helped frame the subsequent debate. At the same time, the United States and Russia, which account for more than 90 percent of the world's nuclear weaponry, have engaged in a fitful step-by-step bilateral process of arms control and reductions that has yielded significant reductions in their nuclear arsenals.

The balance between an agreed plan for disarmament and a step-by-step approach will have a bearing on declarations of stocks of fissile material. It would be natural in an overall plan for the nuclear-weapon states to commit to prepare and declare a complete inventory of their fissile material holdings early in the process, even if verification were to come later. In a step-by-step approach, declarations might be limited to material “excess to military requirements” as and when states chose to so decide.

Irreversibility. In the transition to zero—and for some time even in a disarmed world — a considerable degree of reversibility would be inevitable. As states give up nuclear weapons, they will have stockpiles of fissile material freed up by dismantling their weapons and a cohort of weapons design and engineering experts. They also will retain legacy production plants and former nuclear warhead R&D, production and maintenance facilities, all of which will require monitoring until they are decommissioned or converted to civilian purposes.

In 1984, disarmament advocate Jonathan Schell argued that the possibility of nuclear rearmament could actually help secure abolition, since in a world free of nuclear weapons “the knowledge of how to rebuild the weapons … would keep deterrence in force.”[115] A state considering possible nuclear breakout would be restrained by the prospect that others could quickly follow suit. Schell has also observed, however, that the impulse for breakout and the need to prepare to deter it would wane with time, since the political, legal, and moral pressures that have prevented nuclear weapons use since 1945 would be strengthened in the transition to a nuclear-weapon-free world.[116]

The issue of reversibility has been recognized and addressed more recently by nuclear-weapon states and non-weapon states as part of the NPT. The NPT thirteen steps, agreed in 2000, included a commitment for “the principle of irreversibility to apply to nuclear disarmament, nuclear and other related arms control and reduction measures.” Some states have adopted this approach. France, when it ratified the Comprehensive Nuclear Test Ban Treaty (CTBT), shut down and decommissioned its nuclear test site in the South Pacific, after a controversial series of tests in 1996. Also, after it decided to end its production of fissile material for nuclear weapons, it shut down and decommissioned its military HEU and plutonium-production facilities at Pierrelatte and Marcoule respectively.

In a world in which states agree not to commit resources to acquire or maintain nuclear weapons, theoretical knowledge of nuclear weapons would survive but capacities to make them would atrophy. As sociologist Donald MacKenzie has noted:

> “Outside of the human, intellectual, and material networks that give them life and force, technologies cease to exist. We cannot reverse the invention of the motorcar, perhaps, but imagine a world in which there were no car factories … where no one alive had ever driven, and there was satisfaction with whatever alternative forms of transportation existed. The libraries might still contain pictures of automobiles and texts on motor mechanics, but there would be a sense in which that was a world in which the motor car had been uninvented.”[117]

Fissile material controls. If nuclear weapons are to be eliminated, the plutonium and highly enriched uranium (HEU) that are at their cores will have to be eliminated. Also, stocks of these materials produced to fuel nuclear reactors, but which could be used to make nuclear weapons, will have to be minimized and the remainder heavily safeguarded. The importance of controlling fissile materials as a means of achieving and securing nuclear disarmament was advocated in the 1945 Franck Report, which discussed both rationing access to uranium and "book-keeping on the fate of each pound of uranium mined," and in the 1946 Acheson-Lilienthal Report, which proposed placing under international ownership and operational control all uranium mining as well as uranium enrichment and plutonium separation facilities.[118]

Such improvements in international fissile-material controls are merited even if nuclear disarmament turns out to be unachievable in the near future. With or without complete nuclear disarmament, deep cuts in fissile-material stocks and strengthened controls are required to support deep cuts of nuclear weaponry, bolster the nonproliferation regime, and prevent nuclear terrorism.

Today disarmers are faced with ten thousand warheads in service, a similar number awaiting dismantlement, and materials and components from tens of thousands more. There are also more than a hundred HEU-powered ships and submarines and over a hundred research reactors fueled with HEU mostly weapon-grade. More than 90 percent of the weapons, components and materials are concentrated, however, in Russia and the United States. The magnitude of the disarmament challenge in the remaining seven states is much less.

There also are thirty states with nuclear power plants that produce spent fuel containing plutonium as part of their normal operation and enough already-separated civilian plutonium to produce at least 30,000 nuclear warheads. Once again, however, most nuclear fuel cycle facilities and the separated plutonium are concentrated in a relatively small number of states.

Also, a great deal of experience has been accumulated in exercising national and international control over nuclear materials and technology. Fissile material accountancy and monitoring lie at the heart of the system of IAEA safeguards required by the NPT to verify that non-weapon states are abiding by their commitments not to divert fissile material to nuclear-weapon production.

The importance of including reduction of fissile material stocks in the nuclear-disarmament agenda is widely understood. Russia and the United States are eliminating significant fractions of the fissile material recovered from their excess Cold War warheads and, in 2009, the United Nations Conference on Disarmament agreed to begin talks on a treaty banning the production of new fissile material for nuclear weapons.[119] The talks may begin in 2010.

Securing nuclear-weapon elimination will require the international community to develop structures and confidence to respond to non-compliance immediately and effectively. One option to increase confidence in the likelihood of enforcement might be to place all nuclear material under international ownership and make national appropriation of nuclear material an offense under international law.

Even a robust verification system could not assure, however, that all fissile materials had been accounted for in a world in which enough fissile material has been produced to make more than 100,000 nuclear warheads. Measurement errors and material lost irretrievably in wastes and during testing by the United States and Russia in particular, will make it impossible to verify to a level of 99 percent (i.e. to within the equivalent of 1000 warheads) that all fissile material has been disposed of or placed under international monitoring. It is worth noting, however, that the uncertainty will be concentrated in the United States and Russia, which produced by far the largest amounts of fissile material and numbers of nuclear weapons, and carried out the most nuclear weapons tests. Assessing the adequacy of technical verification and the significance of uncertainty will be a political judgment.

Ultimately, the international verification system will have to be complemented by societal verification in which a large enough fraction of citizens are committed to maintaining a nuclear-weapon-free world that they can be depended to "blow the whistle" when they become aware of clandestine nuclear-weapon stockpiles and activities.

Nuclear power and nuclear disarmament. The organization of nuclear energy will be one of the more important technical factors shaping the possibility and difficulty of nuclear-weapon reconstitution or proliferation (Chapter 8). At one extreme would be a world with reprocessing and enrichment plants in many countries, with huge stocks and flows of separated weapon-useable plutonium and HEU in nuclear fuel cycles that could facilitate rapid rearmament. This world could have the civilian and naval fuel cycles in some weapon states today replicated in many countries: reprocessing and plutonium recycle as in France, naval reactors fueled by HEU as in the United States, fleets of HEU-fueled research reactors as in Russia, civilian national enrichment facilities as in the United States, Russia, Japan, etc. In this world, the technical barriers to nuclear rearmament would be at their lowest.

A world with higher technical barriers to nuclear rearmament would be one where separated weapon-useable fissile material would be very scarce. Spent-fuel reprocessing would have been abandoned in favor of interim storage—as has already occurred in most countries with nuclear power plants. HEU-fueled nuclear ships and submarines would have either been replaced by LEU-fueled vessels, as has been happening in France, or phased out.[120] Stocks of HEU would have been blended down and plutonium disposed of. And all uranium enrichment would occur at facilities owned by companies from more than one country and operated by multinational teams.

The most substantial technical obstacles to any nuclear rearmament would be in a world with no military or civilian nuclear activities whatsoever, except possibly those required to produce essential radioisotopes. Even then, however, there would be the enduring problem of some states having stored civilian spent nuclear fuel containing plutonium, and spent naval fuel containing highly enriched uranium, that could be accessed for weapons.

The debates today over the future role of nuclear energy and the proliferation and control of nuclear fuel cycle technology and the means to prevent its use for weapons mark only the beginning of a discussion that will become increasingly important as the world moves towards eliminating nuclear weapons.

3 Declarations of Fissile Material Stocks and Production

Several nuclear weapon states have already made public some quantitative information about their inventories of fissile materials and nuclear weapons. The United Kingdom has declared aggregate numbers of its military HEU and plutonium inventories. The United States also provided historical production by year and site, including selected isotopic characteristics of the materials produced. With regard to nuclear weapon-arsenals, all five NPT weapon states have declared or otherwise made public their stockpiles of total or deployed nuclear weapons: the United States specified the exact number of deployed strategic warheads, while China, France, and United Kingdom have given upper bounds of their stockpiles or made other statements that allow a good estimate of their total or deployed weapons.[121]

Declarations are valuable as confidence-building measures even without verification. Increasing amounts of background information and verification will be essential, however, if the declarations are to serve as a basis for deep cuts in nuclear arsenals. Chapter 4 discusses verification approaches to fissile material declarations in greater detail, while Chapter 5 lays out the concepts of verified warhead dismantlement. Here, we focus on some precedents, the desirable content of declarations, and the sequencing of information release.

Even without verification arrangements in place, declarations are useful. Experts from other governments and international agencies, and independent analysts will be able to assess the internal consistency of a declaration and cross-check it with intelligence or publicly available information. This is particularly true for declarations of historic fissile material production, which will be the main focus of this chapter.

Why Declarations Matter

In 1993, the United States Department of Energy made an initial declaration of the total quantity of HEU that the United States had produced. Several justifications for the declaration were offered including:[122]

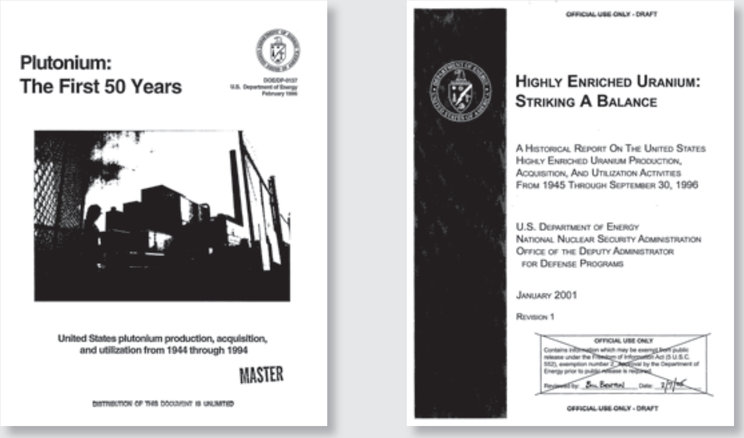
> “As a result of this declassification, the American public will have information that is important to the current debate over proper management and ultimate disposition of uranium. The release of this information should encourage other nations to declassify similar information.

> The quantities may aid in public discussions of issues related to uranium storage safety and security. […]
>
> [The data] could have valuable nonproliferation benefits by making potential International Atomic Energy Agency safeguards arrangements easier to implement.”

In its March 2006 public report on HEU, the United Kingdom made an explicit connection between its declaration and nuclear disarmament, stating that:[123]

> “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. This report is a contribution to building such confidence.”

Independent analysts have also emphasized the importance of declarations and the roles they can play in various arms-control contexts,[124] including in reducing the discriminatory nature of the nonproliferation regime, in which NPT weapon states are not legally required to report their nuclear material holdings to the International Atomic Energy Agency (IAEA). Preparing declarations and making them public would require nuclear weapon states to review their records and audit their inventories, and to be held accountable for how they manage their fissile material holdings. Extending declarations of fissile materials to all states would strengthen the nonproliferation regime and support efforts to assure the physical security of nuclear materials.



Plutonium:
The First 50 Years

DOE/DP-0137
U.S. Department of Energy
February 1996

United States plutonium production, acquisition, and utilization from 1944 through 1994

MASTER

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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

U.S. DEPARTMENT OF ENERGY
NATIONAL NUCLEAR SECURITY ADMINISTRATION
OFFICE OF THE DEPUTY ADMINISTRATOR
FOR DEFENSE PROGRAMS

JANUARY 2001

REVISION 1

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~~Reviewed by: Bill Bertram Date: 2/17/06~~

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Figure 3.1. The U.S. Plutonium and HEU Declarations of 1996 and 2001.[125] Both studies provide a rather detailed account of fissile material production and consumption by year and site. Appendix 3A discusses the methodology used to produce these studies and some of the difficulties encountered. The publication of the 2001 HEU report was delayed until 2006, apparently because of security concerns, and only released after a series of Freedom of Information Act appeals by the Federation of American Scientists.

Declarations of fissile material inventories or of the sizes and deployment of nuclear arsenals are—above all—a transparency measure. Perceived security risks would be the main concern put forward by nuclear weapon states to explain their opposition against making public declarations of their fissile material inventories or nuclear weapons holdings. In the present context, in which we consider deep cuts in the nuclear arsenals and a world preparing for nuclear disarmament however, the security benefits of declarations would by far outweigh the risks.

Declarations could both provide confidence in the disarmament process and eventually allow for more effective verification. A culture of regularly declaring both civilian and military fissile material stockpiles would also encourage states that have excess stocks to gradually dispose of them.

In many respects, declarations can therefore pave the way for nuclear disarmament, but making declarations early is equally important because it spotlights the importance of keeping good records. The UK Report on HEU offers a cautionary tale about the problems that its authors encountered in using old records:[126]

> "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. Average figures were used, or knowledge of the process used to assure that the material was indeed HEU."

In other words, even for the state itself, where access to information is not an issue, it may be difficult to compile accurate declarations of past production and use. Various types of irresolvable inconsistencies including "inventory differences" are to be expected. For example, in the case of the U.S. declarations, the inventory differences added up to 2.8 tons of plutonium and to 3.2 tons of uranium-235 in HEU.[127] This is up to a few percent of the total production, which appears reasonable, given the historic circumstances and practices. In absolute terms, however, these numbers combined are equivalent to an uncertainty of more than 1000 nuclear weapons, which will be a concern in a world considering deep cuts in the nuclear arsenals. Uncertainties in Russia's declarations would likely to be at least as significant.[128] This situation can only get worse with time.

The weapon states therefore should start the process of preparing for declarations now, even if they do not plan to share the information at this point. States need to establish good accounting systems for their fissile material holdings for their own purposes and the data should be selected and archived in a way that facilitates independent verification at a later date. Appendix 3A describes the Nuclear Materials Management and Safeguards System in use by the United States.

Content of Declarations and Sequencing of Information Release

At a minimum, a national accounting system for fissile materials would have to track national plutonium and HEU inventories. The U.S. system tracks 17 categories of nuclear materials today, including depleted, natural, and enriched uranium in different enrichment ranges; plutonium (weapon-grade and lesser grades); other fissile isotopes including uranium-233, neptunium-237 and americium-241; and additional materials such as tritium and thorium. Based on such a system, a phased series of declarations of fissile materials of increasing detail could be extracted.

Initial Declarations. As a first step, declarations could be made of total holdings of plutonium and highly enriched uranium. In its most basic form, such a declaration would essentially consist of two numbers and could be made in a single sentence. This is the approach taken by the United Kingdom in 1998.[129] Better, however, would be to include in initial declarations the total quantities of HEU and plutonium in:

1. Warheads, warhead components and associated working stocks in the warhead-production complexes overall and at individual sites;

2. Material that has been determined excess for military purposes but is still in weapons or weapon components;

3. Reserves for naval and other military-reactor use and in the naval fuel cycle (not including in spent fuel), divided into quantities in classified and unclassified forms;

4. Spent military-reactor fuel; and

5. Civilian stocks, divided into unirradiated and minimally irradiated forms (including in critical assemblies and pulsed reactor cores), and irradiated material in reactor cores and spent fuel.

Declarations organized along these lines would not go much beyond information that the United States has already made public. As one example of a declaration, Figure 3.2 shows the history of U.S plutonium production by year and site published in the 1996 plutonium declaration. Since virtually no plutonium has been disposed off or otherwise removed from the U.S. inventory since 1994, the total U.S. stockpile of separated plutomium remains at 92 tons today. It falls in two categories: 38 tons in the weapons complex and 54 tons declared excess for weapon purposes.

Similarly, the 2001 U.S. HEU declaration provides detailed information about production, acquisition, and utilization of HEU as of September 1996. In addition to historic data, listed by year, enrichment level, and production site, the report lists storage locations of the material through September 1996 (Figure 3.3). The total HEU inventory of 741 tons can be used as a baseline to determine the subsequent evolution and structure of the U.S. stockpile. In 1994, the United States declared 174 tons of its HEU inventory to be excess to military needs. In late 2005, the United States declared an additional 200 tons of excess HEU excess for weapons—of which 128 tons, however, will be reserved for HEU-fueled naval reactors.[130] Also, the United States regularly reports on progress made with blend-down efforts. Combined, this information allows for a rather detailed reconstruction of the evolution of the current U.S. stockpile (Figure 3.4).

The information is of such generality that it could not be directly verified. But it is—and has been—useful for preliminary review and consistency checks by other states, international bodies and independent analysts.

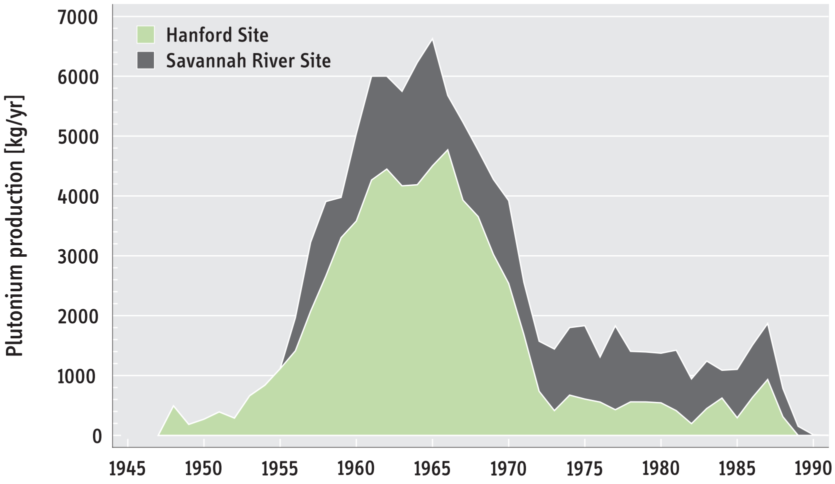


Figure 3.2. History of U.S. plutonium production by year and site from the 1996 declaration. The Hanford reservation on the Columbia River in Washington State is the site where the U.S. built its first plutonium-production reactors during World War II and produced the plutonium for the Trinity bomb test on July 16, 1945 and for the Nagasaki bomb. Ultimately, nine reactors were built there, all graphite moderated. The Savannah River site is near Columbia, South Carolina. All the five reactors built here were heavy-water moderated and were used for tritium as well as plutonium production.

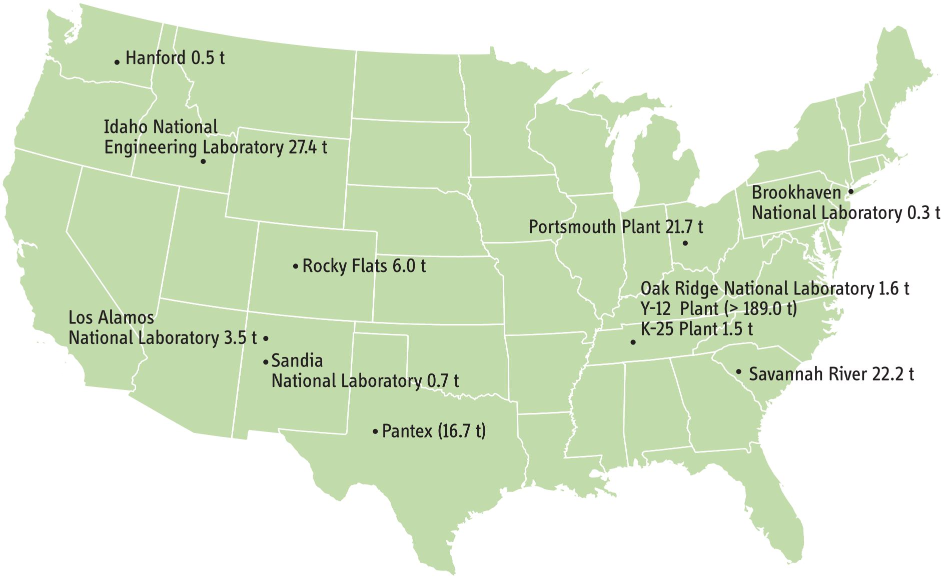


Figure 3.3. U.S. stocks of highly enriched uranium at Department of Energy sites as of 30 September 1996.[131] Miscellaneous sites held 3.7 tons of HEU, bringing the total inventory at DOE sites to about 290 tons. Based on the declared total U.S. inventory of 740.7 tons, this left more than 440 tons of HEU at Department of Defense sites.

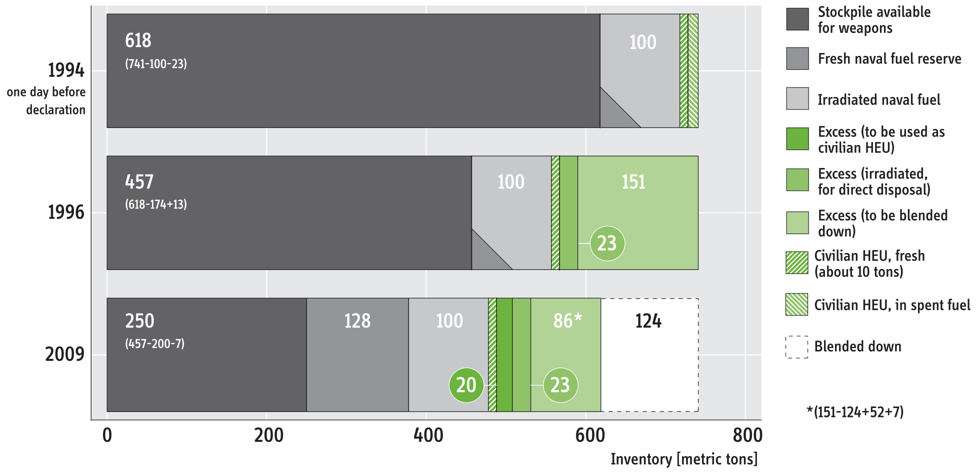


Figure 3.4. Evolution of the U.S. stockpile of HEU since production ended in 1992. Based on the 1996 HEU inventory and subsequent declarations of excess material, the structure of the U.S. HEU stockpile today can be estimated quite well. About 250 tons of HEU remain available for use in weapons—enough for 10,000 warheads.

Approaches to Verifying Historic Production of Fissile Materials

At the level of declarations of total fissile material production, other governments' experts, an international agency or independent analysts could compare declared material production to their own independent assessments. The United States and Russia each devoted substantial resources over the past decades to studying each other's and other countries nuclear complexes and would be able to make their own consistency checks on production-history declarations.

For example, during the Cold War, the United States and maybe other states monitored krypton-85 concentrations in the atmosphere as a way of estimating global plutonium production. Whenever irradiated spent fuel is dissolved in acid to recover plutonium, gaseous fission products are released from this fuel. Radioactive isotopes of the noble gases are emitted to the atmosphere because they pose little risk to the environment. Among these, krypton-85 is a particularly useful indicator for reprocessing because its concentration in the irradiated fuel scales directly with the amount of fission in the fuel. Also, due to its half-life of 10.8 years, krypton-85 gradually accumulates in the atmosphere (Figure 3.5). Another example is discussed in Appendix 3B, which presents an independent estimate of North Korea's plutonium production based on computer simulations. Such calculations can be further refined once more information about a weapons program become available.

While sizable uncertainties are likely, transparency in the process can yield verification confidence. Thus the declaration should include the methods used in arriving at the estimates of historical production, and, where possible, the original records used in this estimation. Outside experts then could repeat the analysis and perhaps find alternative means of cross-checking the results. For instance, while material shipment records at plutonium-production reactors can yield an estimate of the total plutonium separated from spent fuel, the power produced by the reactors can also be used to arrive at the same numbers. The more records that are made public as part of the initial declaration, the more cross-checking that is possible. Where multiple means of determining total production are possible, large uncertainties in a single estimate are less disconcerting.

If declarations are made early and new information as plants are cleaned out or new records are discovered is shared as well, this verification process could provide much more confidence than the large uncertainties in the declarations might at first suggest. Together with the knowledge gained concerning the material production complex, this initial verification stage will provide a firm basis of confidence upon which to build the next, more detailed stage of verification.

Once nuclear-weapon states release information on the production histories of materials by site and facility,[132] and are ready to provide adequate access to these sites and/or provide representative samples of the fissile materials themselves—a more rigorous verification approach could begin. The "nuclear archaeology" methods that could be used for this purpose are the subject of Chapter 4.

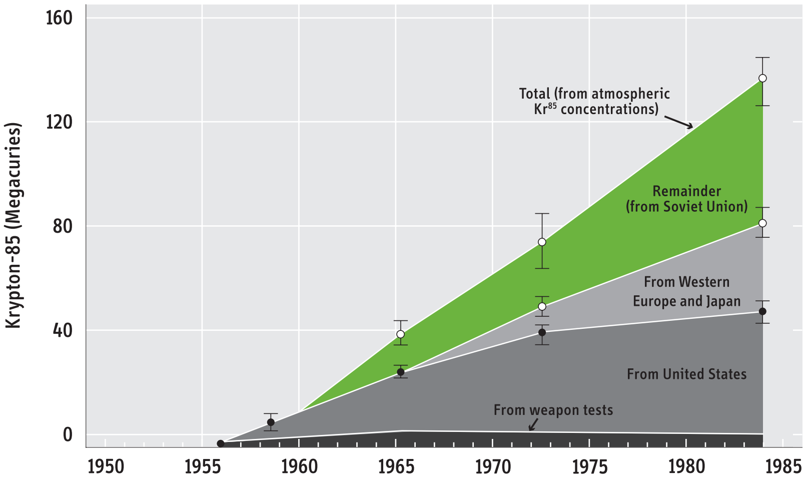


Figure 3.5. During the Cold War, the global inventory of atmospheric krypton-85 was known from measurements. Western analysts were able to estimate the amount of this krypton inventory associated with activities in the West, including reprocessing of military and civilian spent fuel. The size of the Soviet plutonium stockpile therefore could be estimated from the remaining krypton inventory in the atmosphere without any knowledge about the Russian production complex.[133]

Declarations: Fissile Materials versus Nuclear Weapons

At some stage, states will have to make public their nuclear weapons holdings and production history. Some states have already made a beginning. In a series of treaties beginning with the 1979 Strategic Arms Limitation Treaty (SALT), the United States and the Soviet Union agreed on numerical limits on their deployed nuclear forces, to disclose some information about their forces and accepted the need to facilitate verification.[134] As part of the 1987 Intermediate Nuclear Forces Treaty (INF), the United States and Soviet Union exchanged data on the number, characteristics, locations and production facilities of intermediate-range and shorter-range missiles and associated launchers and support structures.[135] There was an accompanying verification arrangement involving on-site inspections.[136] The 1991 START I treaty established limits on deployed U.S. and Soviet strategic weapons and created rules for counting these weapons and for verification (Chapter 5).[137]

The United States and Russia agreed in September 1994 to exchange detailed data on their nuclear arsenals, but this plan was not implemented. A 1997 U.S. National Academy of Sciences report on the future of U.S. nuclear weapons policy proposed that a data exchange between the United States and Russia about nuclear arsenals should include:[138]

- "the current location, type, and status of all nuclear explosive devices and the history of every nuclear explosive device manufactured, including the dates of assembly and dismantling or destruction in explosive tests;
- a description of facilities at which nuclear explosives have been designed, assembled, tested, stored, deployed, maintained, and dismantled, and which produced or fabricated key weapon components and nuclear materials; and
- the relevant operating records of these facilities."

As illustrated in Table 3.1, there is potentially a parallelism between declarations of fissile material holdings and declarations of nuclear weapons arsenals. It shows also how the level of detail could be incrementally increased from simple aggregated numbers to site- and facility-specific data and ultimately specify items by location, mass, and composition—possibly by "serial number" and deployment status in the case of nuclear warheads. This would be the equivalent of a "nuclear weapons register," first proposed in the 1990s.[139]

	Fissile Materials	Nuclear Weapons
Aggregate	Total inventory/Historical data on stocks, production, and consumption	Total stockpile/Historical data on stocks, assembly and disassembly
By Type and Characteristics	Detailed current and historical data on materials (isotopics, physical and chemical form) and their production	Detailed current and historical data on stockpiles of nuclear warheads (type and operational status)
By Site/Facility	Same by site/facility	Same by site/facility
By Item	Location, mass, composition of each item container	Serial number, location, status of each warhead

Table 3.1. Declarations of fissile material and nuclear weapons at increasing levels of detail.[140] Nuclear weapon states could declare their fissile material and nuclear weapon holdings in stages, with greater levels of specificity about the amounts, characteristics and locations of fissile material and nuclear weapons.

The most detailed declarations listed here have a precedent in the Chemical Weapons Convention (CWC), which requires parties to "specify the precise location, aggregate quantity and detailed inventory of chemical weapons it owns or possesses, or that are located in any place under its jurisdiction or control." A verification annex to the CWC specifies in detail what has to be declared. Parties are required to designate storage facilities and to ensure that "chemical weapons at its storage facilities are configured to allow ready access for verification."[141]

Israel and perhaps other countries might consider public declarations about the size of their nuclear arsenals much more problematic than declarations of their fissile-material holdings.[142] In such a situation, a country might declare only its fissile material stocks and assign some of the material to an ambiguous category, such as "other uses."[143]

Even without such concerns, it could be difficult to provide unambiguous numbers for nuclear-weapon stockpiles. At any given time, weapon states will have nuclear warheads at various stages of deployment, in storage, in transit, undergoing maintenance, being assembled and disassembled. During some of these activities, the warhead may or may not include all the fissile material components, as well as the high explosives, and electronic arming, fusing, firing and safety mechanisms (Figure 3.6).

Figure 3.6. Components of a U.S. B-61 thermonuclear weapon. A nuclear weapon is a complex mechanism, with the nuclear explosive or “physics package” (*) and its associated arming, fusing, firing and safety systems. The physics package is itself a composite, made up of a plutonium shell or pit surrounded by a high-explosive that when detonated compresses the pit into a super-critical mass able to undergo a fission chain-reaction, which in turn drives the explosion of a thermonuclear secondary. For more details see Appendix A. *Source: U.S. Department of Energy.*

Nuclear weapon states would have to agree at what stages in a nuclear warhead’s lifecycle, it may no longer be considered for accounting purposes a warhead. This would include identifying steps in the initial weapons assembly and final disassembly phase where it should be accounted for as an assembled weapon, weapons components or fissile materials. Prior to its assembly into a component and after its extraction, the fissile material could be assigned to a non-weapons category, where it could be made available to international inspectors for verification purposes.

It is worth noting that the distinction between declarations of fissile materials and of nuclear weapons will eventually become less relevant. Today, nuclear weapon states treat the quantities of fissile material in individual warheads as a secret but, once both fissile material inventories and nuclear weapon arsenals have been declared—and especially when relatively few weapon designs remain in the stockpile—more and more accurate estimates of the amount of fissile material per warhead will become possible.

Conclusions

Declarations of fissile material production and nuclear weapon holdings will be necessary for nuclear disarmament. These declarations must be followed by verification measures that give some confidence that the declaration is both complete and accurate.

Declarations of fissile material production histories can in principle be verified to a significant degree. Early preparation of such declarations, even if initially not shared, are extremely important because reconstruction of the history of fissile material production is often based on ephemeral and inadequate records, whose interpretation will require the assistance of workers who will inevitably become less available with time.

Given that the bulk of today's global fissile material inventory was produced decades ago, determining completeness will be an extraordinarily difficult task, even if a declaring state is fully cooperative. The task is made more complex by the fact nuclear-weapon states never expected that their nuclear-weapon activities would be subject to international review—let alone having international inspectors visit and examine related sites, materials, or documents.

Agreement that all nuclear weapons are to be eliminated should permit comprehensive and increasingly detailed declarations. Initial declarations for all weapons states could include aggregate numbers for the inventories of fissile materials and their production and disposition histories. The U.S. plutonium and HEU declarations suggest that site-by-site fissile material declarations are possible. Similarly, there is a precedent in U.S.-Russian arms control agreements for declarations of nuclear weapons by site. States may choose initially to make partial declarations for fissile material and nuclear weapons that cover only a single or a few sites.

The initial verification of declarations of fissile material production will depend on consistency checks within released records, while later, more detailed verification will come from actual measurements on available material and production facilities. These more intrusive verification methods, using techniques that have come to be known as nuclear archaeology, are further discussed in the following chapter. The verification of declared nuclear warheads and their dismantlement are discussed in Chapter 5.

Appendix 3A. The U.S. Plutonium and HEU Declarations

The U.S. Government's plutonium and highly enriched uranium (HEU) declarations *(Plutonium: The First 50 Years* and *Highly Enriched Uranium: Striking a Balance)* outlined the production, acquisition, and utilization of fissile materials from the mid 1940s to the mid 1990s.[144] These declarations were constructed from records dating back to the early 1940s and data collected regularly since the 1960s as part of the Nuclear Materials Management and Safeguards System (NMMSS). The origin, evolution and capabilities of NMMSS offer insights for other nuclear weapon states wishing to consider such a reporting system and in making such declarations for the purposes for furthering nuclear disarmament.

The U.S. Department of Energy:

- Declared the total U.S. plutonium and HEU inventories, including all materials held by the Department of Defense in nuclear warheads, military-reactor fuel, spent fuel, critical assemblies, and other military-use materials;

- Categorized plutonium and HEU either as "required" (i.e., in active use or planned future use in either weapons or non-weapons programs) or as "surplus" to defense needs; and

- Constructed a 50-year material balance account similar to a bank register, which compared an actual inventory against a calculated book inventory (based on total acquisitions minus total removals).

While other DOE reports had provided much of this information separately, these declarations combined previously released data with newly declassified information that allowed the United States to issue comprehensive reports for both plutonium and HEU.

Balancing the Books

The data for the declarations were available from at least one of three sources: (a) original site inventory and transaction journals, (b) site inventory and transaction data as reported to NMMSS, and (c) historical material control and accounting summary reports based on data submitted by facilities and compiled starting in the late 1940s by the Atomic Energy Commission (AEC). The reporting units in all three data sources for both plutonium and HEU were grams, subsequently summarized in kilograms for the purposes of simplifying the declarations.

The material balance at each site and nationally can be expressed using the following equation:

> Beginning inventory + receipts – shipments – measured discards or losses – ending inventory = material unaccounted

The production of plutonium in a uranium-fueled reactor is treated as a form of receipt, and the consumption (burnup) of U-235 in the same reactor as a form of removal or measured loss. Material unaccounted (i.e., the difference between the quantity of nuclear material held according to the accounting books and the quantity measured in a physical inventory) occurs primarily because the closed material balance is one in which all identified flows are measured. Therefore, material unaccounted outside of measurement error reflects either failure to measure all recognized material flows or failure to detect unrecognized material losses.

The total amount of nuclear material unaccounted during any time period is the sum of many smaller differences. Each difference arises for one or more of the following reasons: (a) difficulties with measuring plant holdup; (b) measurement uncertainties due to wide variations in the matrix containing the materials; (c) measurement uncertainties within statistical variations concerning the measurement itself; (d) inadequate, primitive measuring technologies, especially in the early years; (e) uncertain measurements for waste due to small quantities of materials; (f) operational losses, such as accidental spills in which accurate measurements had not been made before the spill; (g) corrections of human errors during input of accounting system data; and (h) rounding errors.

Each inventory difference is investigated by operating contractors and reviewed by DOE in order to assign a cause to any difference and to assure that no loss, diversion, theft or environmental contamination occurred.

The primary advantage of using data from closed material balances is in the rigor of each equation. Information not derived from closed material balances (e.g., management reports, historical memoranda, personal recollections) could be highly inaccurate and therefore must be corroborated with other, more reliable sources. A case in point was the quantity of United States produced HEU erroneously reported as 994 metric tons at the June 27, 1994 Secretary of Energy's Openness Press Conference and subsequently corrected to 1,045 metric tons by the 1996 HEU declaration. Several factors accounted for the 51 metric ton increase; most notably, the 1994 data relied exclusively on existing management reports that, upon closer examination, proved to be both incomplete and inaccurate.

A secondary advantage in using the closed material balance concept is that, since the late 1940s, all U.S. facilities have reported every element of the material balance equation to a centralized national system. By using the known beginning inventory (zero) and the known ending inventory of both plutonium and HEU, the task of solving for the closed material balance elements became manageable. Items of the closed material balance (including total receipts, total shipments, total measured discards or losses, and total material unaccounted on a national level) were researched and applied to the known aggregate national beginning and ending inventories.

Early NMMSS History

In the early 1940s, there was no U.S. government accounting standard related specifically to nuclear materials. During these formative years, manual records were kept in considerable detail but there was little standardization among facilities. In 1948, the first standardizing policies were established and those practices have served as a foundation for practices and procedures used today.

Early on, the AEC recognized the need for an accountability system for nuclear materials because virtually all work was performed in facilities owned or leased by the AEC and operated by contractors on a cost-plus basis. These AEC contractors had no direct financial incentive to control materials of unprecedented monetary and strategic value. To protect the interest of the government with respect to the proper use and stewardship of nuclear materials, including all plutonium and uranium of all enrichments, the AEC, after the enactment of the Atomic Energy Act of 1954, implemented a comprehensive set of accounting procedures. For the first time, facilities had a set of reporting requirements reflecting generally accepted principles of the accounting profession.

Due to the variability and complexity in the different nuclear fuel cycle facilities and processes, no particular accounting system was specified; however, requirements included double-entry bookkeeping and nuclear material transactions recording in order to track the status of any materials within a facility.

In the early 1960s, the AEC engaged the Stanford Research Institute (SRI) to perform a feasibility study on developing a headquarters management information system for nuclear materials. In 1963 the SRI study recommended that a national system be built and, in 1964, the project was begun in Oak Ridge, Tennessee. The NMMSS has been automated since 1965.

Union Carbide built the new system. Union Carbide seemed to be a logical choice because, at that time, it operated three nuclear plants in Oak Ridge (Y-12, X-10 and K-25) plus the uranium enrichment plant in Paducah, Kentucky and was well informed regarding the principles of nuclear materials accounting. In addition to the Union Carbide system, Oak Ridge continued to maintain the AEC mandated accounting records of nuclear materials in commercial facilities.

The first nuclear materials in NMMSS were of 12 types:

- Depleted uranium
- Enriched uranium (broken down into HEU ranges and LEU based on contained U-235)
- Plutonium (broken up into weapon-grade and lesser grades)
- Lithium enriched in Li-6
- Uranium-233
- Natural uranium
- Neptunium-237
- Plutonium-238
- Deuterium
- Tritium
- Thorium
- Uranium in cascades (i.e., unified uranium: depleted, normal, and enriched)

NMMSS began tracking helium-3 in 1969 and discontinued tracking it in July 1978. Normal and depleted lithium were reported by contractors beginning in 1971 and discontinued two years later. In 1974, six types of materials in the transuranium group were added and all but berkelium (removed in 2006) have remained in the system. These material types are as follows:

- Plutonium-242
- Americium-241
- Americium-243
- Curium
- Berkelium
- Californium

In the late 1940s, NMMSS was a manually-implemented central store of nuclear materials information—a set of account ledgers with amounts of nuclear materials as entries. AEC operations offices and headquarters staff prepared inventory, transaction, and material balance reports for the 12 original NMMSS material types based on feeder reports forwarded by AEC contractors and by Oak Ridge Operations Office for licensees.

These summary Oak Ridge material balance reports were an important source of information for creating the U.S. declarations; they chronicled U.S. nuclear activities on an annual basis in material-balance format from the mid-1940s through 1984. The material balance categories used in these early reports are still in use today and are the de facto basis for constructing overall historical material balances.

The trustworthiness of the quantities stated in the Oak Ridge summary reports was established by correlating and corroborating known elements from the material balance with data from other sources. For example, from 1945 through 1992, the U.S. conducted 1,054 nuclear tests and two wartime detonations. The quantities of nuclear materials expended in these activities were independently recalculated and compared with quantities stated annually in the summary reports. Similar correlations were possible with HEU produced in the Y-12 Plant calutrons from 1945 through 1947.

In addition to calculation reviews, site visits were conducted to examine primary source data documents. Many of these documents currently exist only in summary form, particularly for the period prior to 1969. Summarized data presented a major difficulty in the preparation of the HEU report as some of the site records failed to distinguish between HEU and LEU. Sites visited included Hanford, Savannah River, Portsmouth, and West Valley. Oak Ridge historical summary reports were then reviewed and compared for consistency with the various sites reports, original transfer journals, general ledgers, subsidiary ledgers or journals (designed to provide more information than was available in only the general ledger), and additional transaction and inventory records. The inaugural years' (1940s to early 1960s) data were generally easy to confirm because there was no commercial nuclear industry and very few facilities handled these important strategic materials.

Computer-based NMMSS began collecting inventory and material balance data in 1965. Transaction data was added to the system in 1967 and, in 1971, the system began processing data on a daily basis. In 1979 NMMSS completed a two-year project converting written documents into electronically retrievable records. This project consisted of data pertaining to U.S. international transactions. The task involved coding international transaction data from shipment files (in the form of NMMSS transactions) dating as far back as January 1950, and adding those international transactions to the NMMSS database. Exports, imports, and retransfers of nuclear materials data were included.

Thus, the international transaction data in NMMSS cover a longer historical period than domestic transactions. Even though there are some minor gaps in the data and even though comparison of the data (to records maintained by our foreign trading partners) is incomplete, the NMMSS database is a highly reliable source of information.

NMMSS Today

Today's NMMSS contains current and historical data on inventories and transactions involving source (natural and depleted uranium and thorium), special (plutonium and HEU), and other selected nuclear materials not only within the United States but also on all exports and imports of such material. Current NMMSS database records contain information on over 1,500 contractors, licensees, and international accounts dealing with selected nuclear materials. As the only source of truly reliable historical and current data regarding U.S. nuclear programs, NMMSS provides assistance in five critical areas: a) safeguards-like capability, b) international programs, c) materials management, d) program management, and e) financial management. NMMSS primarily serves Department of Energy (DOE), Nuclear Regulatory Commission (NRC), and other U.S. government entities. Additionally, NMMSS continues to serve site offices and individual nuclear facilities.

Database integrity is paramount to NMMSS operations; security mechanisms are designed to minimize threats common to most relational database management systems. System controls include server login monitoring, complex user/role access controls, and audit trail recording in order to monitor all changes made to NMMSS data. Subsequent to data entry, records become historical and can only be changed by a system administrator; however, changes to historical data are rare and additionally require written approval from the NMMSS software change control board. Because NMMSS is an historical data repository, legacy data is never discarded. Authorized changes, nonetheless, are required when moving to new database technologies or data formats.

Excess Determinations

An important component of the U.S. declarations was identified in the mid-1990s. Two hundred metric tons of surplus plutonium and HEU were withdrawn from national security needs. This U.S. Presidential directive permanently withdrew the identified material from any other defense related activity, including use of the HEU as naval-reactor fuel.

The declarations of excess nuclear materials were based solely on review of NMMSS summarized inventory records. This was appropriate because all U.S. government-owned nuclear materials in NMMSS are not only recorded by form and location, but are also are tagged by project numbers to identify both the program owner (e.g., Defense Programs or Environmental Management) and intended use (e.g., weapons stockpile or disposition). Using a centralized reporting system produced a reconciled declaration from summarized data; however, severe time constraints prevented consulting with DOE sites regarding their item-level inventory databases. Items are distinctive to site-specific material control and accounting systems; they have unique site identifiers that are traceable to inventory measurements or calculations. Items usually relate to site functions; therefore, at one site a fuel pin may be an item, while at a different site it may be a fuel assembly or a whole reactor core.

The excess declaration assumed nuclear weapons START I force structure, including all current and future national-security fissile-material requirements. National security requirements included: pit reuse/rebuild, enhanced surveillance, stockpile life extension program, tritium production, and naval and research reactors. Regardless of prior usage, all government-owned stocks of plutonium (i.e., both weapon-grade and non-weapon-grade) and HEU were included. Consequently, some of the material declared excess to national security had no actual nuclear weapon provenance.

A difficulty in using NMMSS for this type of exercise is that inventories are reported at an aggregate level (i.e., individual items are summarized based on a set of common identifiers). Therefore, one inventory line in NMMSS often represents tens or even hundreds of individual items. As a result, the initial declarations of excess were not item level based, but were instead based on aggregated data. Going forward, NMMSS has upgraded its database to accept item-level inventory information.

Summary

The significance of standard forms for the collection of material balance data cannot be overstated; it is the most important driver of a trustworthy national declaration. Item-level nuclear inventories with consistent data elements provide a useful, defensible status report for any nation/state and most importantly—one that is ultimately verifiable by outsiders. Preparing declarations requires a centralized accounting system to handle nuclear inventory, transaction, and material balance data in a uniform format. Reconciliation of site-submitted transactions with known inventory is a key component of NMMSS internal controls and is fundamental to sound business practices and generally accepted accounting principles.

Reconciliation offers effective self- and cross-check mechanisms to highlight differences and provide regulators with data necessary to investigate discrepancies. Without reconciliation, national-level historical closed material balance is extremely difficult to perform and even more difficult to verify.

The United States completed a task that many other weapon states consider to be daunting. Hundreds of facilities, with incomplete or missing records, going back dozens of years, added to the lack of any standardized central accounting systems are just a few of the immediate concerns that derail even the best of intentions. As a result, compiling an accurate and comprehensive declaration is extremely difficult, time consuming, and may well produce dubious results.

The material balance methodology used to prepare comprehensive U.S. declarations can also be applied at a single nuclear facility for a specified timeframe, thereby removing one of the barriers to engagement in nonproliferation initiatives. This can be accomplished by encouraging declarations at the single-site level. Nation states can publish their own comprehensive declaration, one year at one site at a time. Working at the site level in small time increments is not only manageable; it allows the use of nuclear archeology (forensics) to develop information confirmation strategies. Confirmation strategies could include looking at U-234 in tails at an enrichment plant or traces of plutonium and isotopic composition in high-level waste at a shutdown reprocessing plant. Initially, an agreed upon method is more important than the product.

The single-site approach offers partner nations a controllable task with nearly certain positive outcomes. The nature of the methodology offers minimal political risk, and should ultimately garner broad support by providing more insight into nuclear material holdings and disposition.

Appendix 3B.

Estimating Plutonium-Production in North Korea

In May 2008, the Democratic People's Republic of Korea (DPRK, or North Korea) provided the United States with about 18,000 pages of operating records that contain information on operation of its plutonium production reactor and the associated reprocessing facility since 1986.[145] A month later, North Korea submitted to China a declaration of its nuclear activities. This declaration is not available publicly, but reports suggest that North Korea claimed to possess 37 kilograms of plutonium,[146] and also that it had separated 30.8 kilograms of plutonium and had used 2 kilograms of this in its October 2006 nuclear weapons test.[147] The DPRK has since then conducted a second nuclear test, in 2009, and announced that it intends to separate the plutonium from its remaining spent fuel and to resume production activities at its nuclear facilities. Since the DPRK's declaration has not been made public, this appendix briefly describes North Korea's nuclear complex based on public information and provides an estimate of its plutonium production.

Status of the Major Plutonium Production Facilities in Yongbyon

Nuclear Fuel Fabrication Facility. The Yongbyon nuclear fuel fabrication facility refined U_3O_8 "yellowcake," produced uranium metal, and fabricated Magnox fuel rods for the 5-MWe reactor and partially fabricated fuel for the never-completed 50-MWe reactor.[148] The fuel-fabrication facility's capacity is reported to be about 100 metric tons of uranium fuel per year.[149]

Nuclear fuel fabrication was frozen under the 1994 Agreed Framework, which shut down operations at the Yongbyon Complex. No fresh fuel was fabricated, even after the DPRK restarted the 5-MWe reactor in 2003.[150] The February 13, 2007 Agreement shut down the nuclear fuel fabrication facility for disablement in mid-July 2007.[151] On April 14, 2009, however, after the U.N. Security Council condemned its April 5 rocket launch, the DPRK announced that it would restore the nuclear fuel fabrication facility and the 5-MWe reactor and reprocessing facility as well.[152]

5-Megawatt(electric) Reactor. The 5-MWe reactor is a carbon-dioxide gas-cooled graphite-moderated reactor fueled with natural-uranium metal that is clad in magnesium alloy ("Magnox").[153] It has a nominal thermal power of about 25 MWt[154] and is fueled with about 8,000 fuel rods containing about 50 tons of uranium. The fuel rods are placed in vertical channels in the graphite moderator and are cooled by CO_2 gas flowing through the channels.

The 5-MWe reactor operated from 1986 to April 1994.[155] Under the 1994 Agreed Framework, it was frozen from April 1994 till February 2003, when operation resumed after the Agreed Framework was abandoned. It was shut down to unload irradiated fuel in April 2005 and restarted in June 2005.[156] It was again shut down in mid-July 2007 for disablement.[157] However, as already noted, the DPRK announced on April 14, 2009 that it would be restored.

Reprocessing Facility. The Yongbyon reprocessing facility uses the PUREX process to extract plutonium from the reactor's spent fuel.[158] The nominal annual capacity of the reprocessing facility is approximately 110–125 metric tons of spent fuel in its one completed process line, assuming continuous operation for 300 days.[159] A second reprocessing line was scheduled for completion in 1996 but was frozen by the 1994 Agreed Framework.[160] If completed, it would have roughly the same capacity as the first process line.

Operation of the reprocessing facility started in 1989.[161] Under the Agreed Framework, it was frozen between 1994 and 2002. The DPRK restarted it in early 2003 after the Agreed Framework was abandoned. The DPRK claimed that, between January and June 2003, it reprocessed the 8,000 spent fuel rods containing 50 tons of uranium that had been stored since 1994.[162] Reprocessing restarted in June 2005.[163] The reprocessing facility was again shutdown in mid-July 2007 for disablement.[164] On 25 April 2009, however, the DPRK announced the restart of reprocessing of 8000 stored spent fuel rods from the 5-MWe reactor.[165]

Estimates of DPRK Plutonium Stocks

There have been at least three estimates of North Korea's plutonium production.

1. David Albright and Paul Brannan estimated that, prior to February 2007, the DPRK had separated 28–50 kilograms of plutonium, including up to 2 kilograms of plutonium produced in the IRT reactor prior to 1994.[166] They assumed that the DPRK used 5 kilograms of that amount in the October 2006 nuclear test. They also estimated that the unreprocessed fuel of the 5-MWe reactor when it shut down in July 2007 contained 10–13 kilograms of unseparated plutonium.

2. Siegfried Hecker estimated that the DPRK had separated 40 to 50 kilograms of plutonium by 2005 and that the reactor core contained roughly 8 kilograms of unseparated plutonium as of July 2007.[167]

3. An unclassified intelligence report to the U.S. Congress in 2007 estimated that the DPRK could have produced up to 50 kilograms of plutonium prior to the 2006 nuclear test with additional plutonium contained in unreprocessed fuel.[168]

As illustrated by the estimate below, such estimates are based on basic information about the characteristics of North Korea's 5 MWe reactor, and its operating history.

Plutonium and other transuranic elements are made by the neutron irradiation of uranium in a reactor. In the historical operating regime of the Yongbyon reactor, the concentration of plutonium produced in the uranium is almost linearly proportional to the "burnup" of the fuel, i.e. the energy produced per mass of fuel, measured in megawatt-days per metric ton of uranium in the fuel (MWt-day/tU):

$$\text{Plutonium concentration} = K \times \text{Burnup}$$
$$\text{Burnup} = (\text{reactor power}) \times (\text{reactor operation time}) / (\text{mass of fuel}).$$

The factor K between plutonium concentration and burnup depends on the reactor design and the fuel burnup. Table 3B.1 shows the physical characteristics of the 5-MWe reactor.

The average burnup of the spent fuel in 1994 was estimated at about 600–700 MWt-day/tU.[169] To get the core average burnup from subsequent operations, a reasonable assumption is that it operated at 20–25 MWt between 70 and 80 percent of the time. On this basis, the annual average burnup would be between 102 and 146 MWt-days per metric ton heavy metal (MWd/tHM). The estimated accumulated core average burnups of the 5-MWe reactor between February 2003 and April 2005 and between June 2005 and mid-July 2007 are about 220–320 MWd/tHM and 210–300 MWd/tHM, respectively.

Thermal power	20–25 MWt	Effective core diameter	643 cm
Electric power	5 MWe	Effective core height	592 cm
Specific power	0.5 MWth/tHM	Upper reflector	77.5 cm
Uranium loaded	50 tons	Bottom reflector	66.5 cm
Graphite-moderator	300 tons	Fuel composition	U (0.5%Al)
Graphite-reflector	300 tons	Uranium diameter, in fuel	2.9 cm
Number of channels	812–877	Uranium length in fuel	52 cm
Number of fuel channels	801	Length of fuel rod	60 cm
Number of control-rod channels	44	Uranium per fuel rod	6.242 kg
Number of fuel rods per channel	10	Fuel clad composition	Mg (1%Al)
Distance between channels	20 cm	Fuel clad thickness	0.05 cm
Diameter of channel	6.5 cm		

Table 3B.1. Physical characteristics of the 5-MWe reactor.[170]

The plutonium production as a function of burnup of the fuel can be estimated using the MCNPX Monte Carlo radiation transport depletion computer code.[171] This requires modeling the reactor core. This has been done for this estimate in an infinite core approximation. The geometry of a 3-dimensional pin-cell model is given in Figure 3B.1. It is composed of a fuel rod in a fuel channel that is surrounded by graphite moderator. The boundaries of the cell are assumed to be neutron reflecting because the cell is surrounded by identical cells that release as many neutrons into this cell as it releases into them. From these calculations, one gets the constant K relating plutonium production to burnup above as about 0.89 grams/MWt-day at a burnup of about 500 MWt-days/kgU.

Table 3B.2 gives the results of the calculations and the previous estimates by Albright and Brannan, and by Hecker.

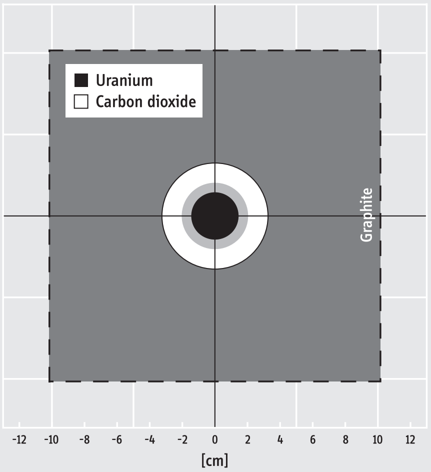


Figure 3B.1. Unit-cell of the three-dimensional pin-cell model of a fuel rod of the 5-MWe reactor (with neutron-reflecting boundaries).

Year of spent fuel discharge	Estimated average burnup of discharged spent fuel	Plutonium calculated in this study	Estimate by Albright and Brannan	Estimate by Hecker
Before 1994	N/A	N/A	1–10 kg*	8.6 kg*
1994	600–700 MWd/tHM	26.3–30.2 kg	27–29 kg	25 kg
2005	220–320 MWd/tHM	10.1–14.5 kg	13.5–17 kg	12 kg
2007	210–300 MWd/tHM	9.7–13.6 kg	6–7 kg	8 kg
Total		46–58 kg	48–63 kg	48–58 kg**

Table 3B.2. Estimated plutonium production from the 5-MWe reactor. *The 8.6 kilograms include up to 1-2 kilograms of plutonium produced in the IRT reactor prior to 1994.[172] **Hecker estimated that the DPRK produced an inventory of between 40 and 50 kilograms of plutonium by 2005, considering uncertainties.

Verifying the DPRK's past plutonium production is possible. In October 2008, the DPRK agreed on a number of verification measures, based on discussions between the United States and the DPRK, including access to all declared and undeclared sites, and the use of scientific procedures, including sampling and forensic activities (e.g., graphite samples from the 5-MWe reactor).[173] After the United States removed the DPRK from the State Sponsors of Terrorism List on 11 October 2008, however, the DPRK denied that it had agreed—particularly on the issue of taking samples from nuclear sites.[174] If samples were allowed, the graphite isotope ratio method (GIRM) could give an accurate estimate of the total plutonium production in the reactor without detailed information on the reactor's operating history.

4 Nuclear Archaeology

Verification of a nuclear weapon state's total production of plutonium and highly enriched uranium will help increase confidence that the state has accounted for and properly declared its stocks of fissile material. There is growing interest in a set of methods and tools that can be used to characterize past fissile material production activities, using measurements and sampling at production and storage sites and direct measurements of samples of fissile materials or related feed and waste materials. This field has been dubbed nuclear archaeology.[175]

As discussed in Chapter 3, states might make initial declarations of the total quantities of fissile materials they hold and provide information on historic production, consumption, and disposition of these materials. Such declarations would initially be reviewed by other countries, the IAEA, or another organization for internal consistency and consistency with available public information and intelligence.

More robust verification would include details of production processes by site and facility and measurements of selected characteristics of the materials involved. In the case of verifying plutonium production, for example, samples would be taken from the structural materials of shutdown production reactors. Similarly, for highly enriched uranium (HEU), the depleted uranium stored at the enrichment plants could be used to gain insights into past production.

	Graphite-moderated		Heavy-Water moderated	
	H_2O-cooled	Gas-cooled	H_2O-cooled	D_2O-cooled
United States	Hanford	–	–	–
Russia	"Tomsk-7"	–	–	–
United Kingdom	–	Calder Hall	–	–
France	–	G-Series	–	–
China	"Jiuquan"	–	–	–
Israel	–	–	–	Dimona
India	–	–	Cirus/NRX	Dhruva
Pakistan	–	–	Khushab	–
North Korea	–	Yongbyon	–	–

Table 4.1. Select natural-uranium fueled plutonium production reactors, by country.[176] 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.

Direct measurements of the fissile materials themselves could considerably enhance confidence in nuclear archaeology but would require countries to declassify isotopic information. Revealing such properties to international inspectors would be considered unacceptable by some nuclear weapon states today. Once countries are willing to declare their fissile-material stockpiles, however, the security impact of the additional information made available during the verification of those declarations would be relatively minor.

Verifying plutonium-production declarations

Only a few basic types of reactors have been used for the dedicated production of plutonium for weapons purposes. As shown in Table 4.1, natural-uranium-fueled reactors played a particularly important role.

The best-established example of nuclear archaeology relies on measurements of the buildup of transmutation products 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 (Figure 4.1).[177] Equivalent methods might be used with other types of reactors, especially with heavy-water-moderated reactors that have been used for military plutonium production.[178]

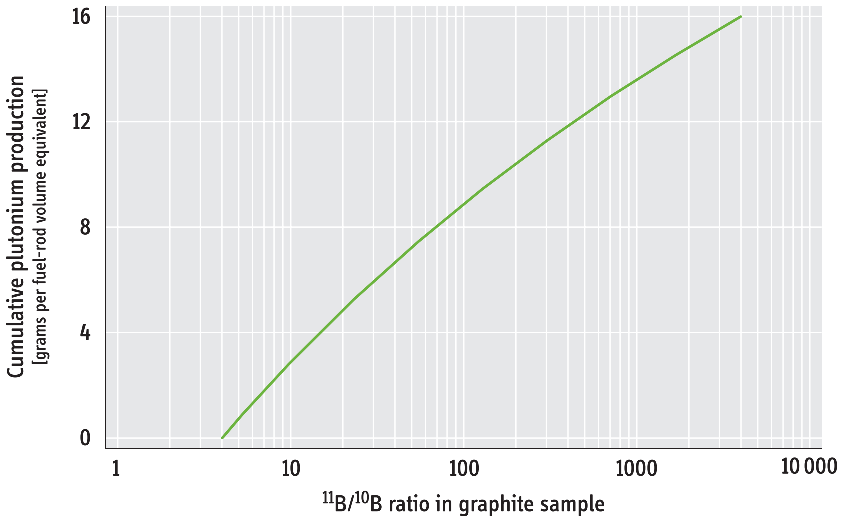


Figure 4.1. Nuclear archaeology in a graphite-moderated reactor. Even the high-purity graphite used as a neutron moderator in most plutonium-production reactors contains traces of many different elements, including boron. In natural boron, the isotope-ratio of $^{11}B/^{10}B$ is about 4:1, but ^{10}B nuclei have a much higher probability of absorbing neutrons and being transmuted than ^{11}B. Thus, over the life of the reactor, the $^{11}B/^{10}B$ ratio shifts to higher values while the absolute boron concentration decreases. Computer simulations for North Korea's Yongbyon reactor show how the boron isotope ratio can be correlated with the cumulative local plutonium production in a specified fuel channel in the 60-centimeter length occupied by a single fuel rod containing 6 kilograms of uranium. Using several tens of representative graphite samples, this data can be used to reconstruct the cumulative plutonium production in the entire reactor. *Simulations and results: Jungmin Kang.*[179]

Between 1992 and 1998, the U.S. Pacific Northwest National Laboratory (PNNL) conducted a research and development program to "evaluate and develop the technical basis for nuclear archaeological methods."[180] As part of this effort, graphite samples from various production reactors were analyzed to establish the applicability of the method. GIRM was tested at the Hanford plutonium-production reactors and, in the late 1990s, in U.S.-Russian lab-to-lab projects at three of Russia's production reactors at Seversk. Unfortunately, no quantitative results have been published from these tests. A full-scale exercise was carried out for the UK Trawsfynydd-II Magnox power reactor, whose fuel had been reprocessed to recover its plutonium.[181] The uncertainty of the GIRM analysis was estimated to be on the order of 5 percent but the difference between the estimated and recorded production was considerably less.[182]

Note that a nuclear archaeological analysis based on GIRM provides only an upper bound for the total amount of plutonium produced in a reactor, because losses on the order of 1–2% are typical during extraction of weapon-grade plutonium from the irradiated fuel.[183] The final estimate of cumulative plutonium production therefore has to combine the expected uncertainties of GIRM with estimated reprocessing losses. Overall, GIRM is expected to be accurate to within 3–7%, depending on the amount of information known about the reactor and its operating history.

As suggested by the 2008 U.S. verification proposal, GIRM could play a central role in verifying North Korea's 2008 plutonium declaration. This would require that the core of the Yongbyon reactor (Figure 4.2 and Appendix 3B), or at least significant samples from known locations within it, be preserved for analysis.

Figure 4.2. Inside North Korea's Yongbyon Reactor. In February 2008, the New York Philharmonic visited North Korea to perform in Pyongyang. A small group of Western journalists and media accompanied the orchestra and were allowed to visit the Yongbyon nuclear site the day before the concert. They were shown ongoing activities related to the disablement of the reactor. This openness by North Korea ended in April 2009. The banner reads: "Let's protect Dear General Kim Jong Il desperately!" *Source: CNN/Brian Rokus.*

At the most basic level, the analysis can be carried out with only minimal information: the fuel arrangement in the core and the total fuel volume, combined with 50–100 graphite samples taken from strategic locations in the core.[184] GIRM becomes much more accurate, however, if additional information is available to enable detailed computer simulations of the reactor's production history. Comprehensive declarations should therefore include detailed design information for production reactors and, if available, original operating records. The latter could provide information on masses and enrichments of the fuel elements, their positions in the core, fuel loading and discharge schedules and the operator's estimates of the "burnup" of the discharged fuel, i.e., the grams of fuel fissioned per kilogram of uranium loaded.

In anticipation of the need to verify national fissile material production as part of a nuclear-disarmament process, the core structures of decommissioned production reactors should be preserved until application of GIRM (and related methods for heavy-water-moderated production reactors) can be carried out by international teams. Fortunately, the neutron activation of these structures provides an incentive to delay dismantling them until their shorter-lived radioactive isotopes have an opportunity to decay away.[185] Several former Soviet and U.S. graphite-moderated production reactors have been encased in concrete to isolate them from the human environment during this period.[186]

Verifying HEU-production declarations

In contrast to GIRM, there is no obvious evidence available in the structure of enrichment plants that is unambiguously correlated with cumulative HEU production. Also confounding attempts to measure past HEU production is the fact that, once military HEU production stopped, many enrichment plants were converted to the production of LEU fuel for civilian power reactors. Apart from environmental sampling techniques that could confirm that HEU has been produced at such a plant at some point in the past, information gathered from processing equipment at enrichment plants would contribute little toward verification of a declaration of cumulative HEU production.

Estimating historic HEU production is possible, however, by measurements on the uranium that was processed. The most accessible and voluminous stream of such material would be the depleted uranium "tails," which often are stored for decades in cylinders next to enrichment plants (Figure 4.3).

The information that can be gleaned from the uranium tails derives from the fact that more than two isotopes naturally occur in uranium: in addition to uranium-238 (99.3%) and uranium-235 (0.7%), there are traces of uranium-234 (about 0.0055%).[187] In the enrichment process, U-234 and U-235 are both enriched in the HEU and reduced in the depleted uranium relative to U-238 and their enrichments and depletions are correlated with each other. As a result, if the composition of the feed material is known, the concentration of U-234 in the depleted uranium is correlated through the physics of the enrichment process with the U-235 enrichment of the associated enriched product (Figure 4.4).

In some cases, the uncertainties may be such that an analysis of the tails to determine the enrichment of the product could remain inconclusive. However, in most cases a sample of tails produced by the plant at a given time can be used to determine whether the plant's product at that time was LEU or HEU. Because decay products of the uranium-234 can be used to determine the date at which uranium was produced or purified,[188] a complete history of LEU versus HEU production can in principle be reconstructed from the plant's waste. Furthermore, if additional information about the production process were available (e.g. the rate at which natural uranium was fed into an enrichment plant), then it would be possible to make more accurate and detailed estimates of how much HEU was produced by a given enrichment plant.[189]

If inspectors were permitted to sample depleted uranium, a state trying to conceal some of its past production of HEU would need to hide the associated tails and hide or forge documents related to the acquisition and introduction of feed material and the operation of the plant during the relevant period.

Figure 4.3. Cylinders of depleted uranium at the storage area at the K-25 site, Oak Ridge, Tennessee, in 2001. The site held over 6000 cylinders containing depleted uranium "tails" produced as waste by the gaseous diffusion enrichment plant, which was closed in 1964 and is now being demolished. Beginning in 2002, these particular cylinders were shipped to Portsmouth, Ohio. A nuclear-archaeological analysis could determine if such cylinders are associated with former HEU production and help estimate the amount of HEU that was produced from the original feed material. *Source: U.S. Department of Energy.*

For small enrichment programs of simple design involving a single plant and no recycling of process materials and where the depleted uranium is still all available (as in the case of South Africa's HEU production), sampling of the tails could permit fairly detailed verification of past HEU production. The analysis would become more difficult, however, if a significant fraction of the depleted uranium were removed from the enrichment plant even without intention of evasion—for example, for depleted uranium munitions or for stripping of additional uranium-235 during a period of natural-uranium shortage.

The massive fissile material production programs mounted by the United States and the Soviet Union during the Cold War probably pose the greatest verification challenges. Multiple enrichment plants and plutonium-production reactors often were exchanging large quantities of nuclear material between them. Analysis of these programs therefore requires a more comprehensive and integrated approach.

Integrated Assessments of Historical Fissile Material Production

To overcome perceived uranium shortages and make the most efficient use of their resources, the Soviet Union, the United States and perhaps other nuclear weapon states did not produce their plutonium and HEU independently. Instead, natural uranium was first used to fuel a plutonium production reactor. After separation from the plutonium and fission products, the reprocessed uranium (still containing about 0.6% uranium-235 compared to 0.7% in natural uranium) was then recycled, either into new fuel to be used again in a production reactor or by feeding it into an enriching plant to produce HEU. In the United States, at least, low-enriched product from one enrichment plant was introduced as feed into different plants (Figure 4.5).

The interconnections among the various production facilities and the recycling of both tails and product from some of the plants make the verification of a declaration from this kind of program a much more challenging and complex task. On the other hand, the interconnections among the various facilities leave traces in the plutonium and the enriched and depleted uranium, offering the possibility of checking for consistency among plutonium and HEU declarations. Such cross-checks of declarations from different facilities would make it more difficult for a state to provide false or even incomplete declarations because the quantities and isotopics of materials at each site must remain consistent with all of the others. Diverting material would require successful deception across the entire production complex, instead of just within a single site.

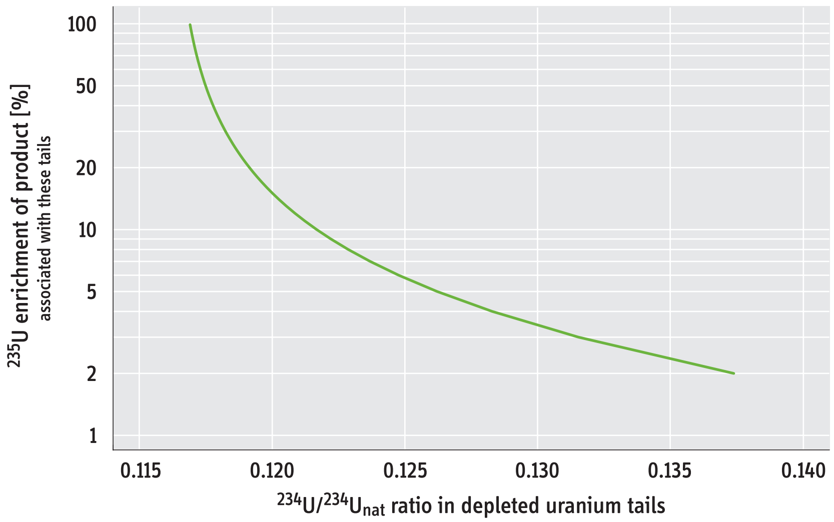


Figure 4.4. Nuclear archaeology on the depleted uranium tails from uranium enrichment.[190] If the composition of the feed material (e.g. natural uranium) is known, then the concentration of trace-isotope uranium-234 in the depleted uranium can be used to estimate the enrichment level of the uranium-235 in the associated enriched product. The fact that the content of uranium-234 in natural uranium can vary from mine to mine creates uncertainty,[191] but cylinders with tails from LEU and HEU production can be distinguished with high confidence. The graph shown here is for a uranium-235 tails concentration of 0.2%. *Simulations and results: Matthew Sharp, Harvard University.*

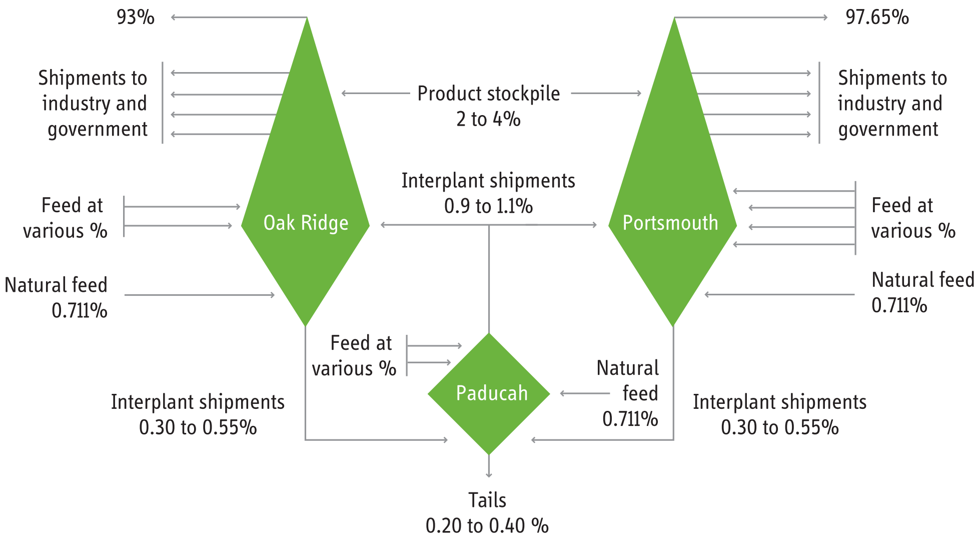


Figure 4.5. Integrated operation of the U.S. gaseous diffusion plants.[192] The United States used its Paducah plant to extract more uranium-235 out of the depleted uranium produced as waste by the other two (Oak Ridge and Portsmouth), and the enriched uranium from Paducah was then fed back to them as slightly enriched uranium. The reprocessed uranium feed from the Hanford or other production reactors is not shown in this figure.

Plutonium isotopics. The first plutonium isotope that is produced after a neutron is captured by a uranium-238 nucleus is plutonium-239. The longer uranium fuel is left in a reactor, however, the higher the probability that the plutonium will absorb another neutron and either fission or be converted into plutonium-240. The result is a shift of the isotopics of plutonium toward heavier isotopes. The ^{240}Pu/^{239}Pu ratio in plutonium is therefore a robust indicator of both the burnup of the uranium fuel and the amount of uranium needed to produce a given quantity of this plutonium.

Similarly, an elevated plutonium-238 content in plutonium is a clear indicator that the production reactor was fueled with recycled uranium containing uranium-236 (Figure 4.6)[193] Alternatively, if reprocessed uranium is fed into enrichment plants to make HEU, the isotopics of the fissile materials produced with this strategy (first plutonium, then HEU) allows consistency checks between declarations of the two materials.

Uranium isotopics: Reprocessed uranium contains two artificial uranium isotopes: the already mentioned uranium-236, which is produced by neutron capture on uranium-235, and trace quantities of uranium-232 produced by neutron capture on a decay product of uranium-235.[194] When an enrichment cascade is fed with uranium that has been recovered from spent fuel from a plutonium production reactor, uranium-232 and uranium-236 find their way into the enriched and depleted uranium along with the natural uranium isotopes. The concentration of these isotopes in HEU and depleted uranium depends on:

- The isotopic makeup of the reprocessed uranium;
- The fraction of reprocessed uranium in the enrichment plant feed;
- The enrichment of the product and depleted uranium produced by the plant; and

- The type of enrichment technology deployed in the plant, i.e., gaseous diffusion or gas centrifuge.[195]

If all this information is declared, the uranium-232 and uranium-236 contents of the HEU and depleted uranium can be computed and checked against measurements of samples.

In this way, declarations of cross-fed material link the plutonium and HEU declarations and isotopics. The information needed to support nuclear archaeology therefore should be included in future declarations by weapon states. The United States has already made this kind of information public.[196]

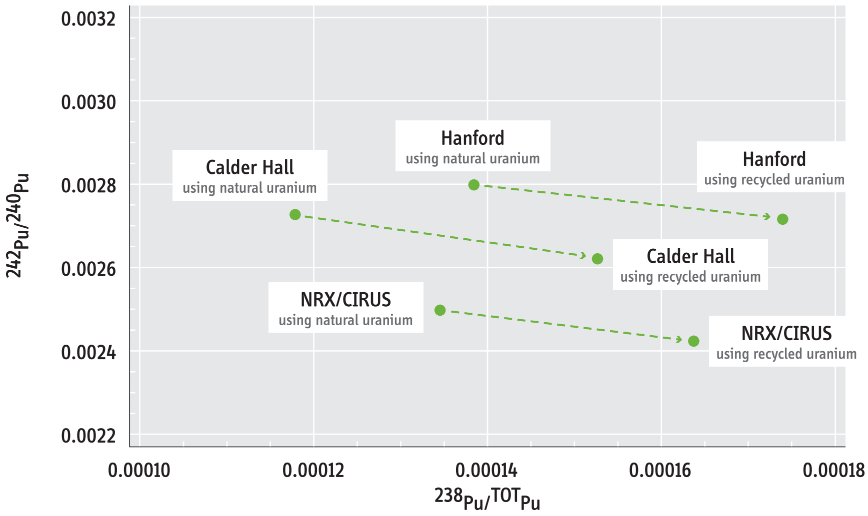


Figure 4.6. The impact of using natural versus recycled uranium fuel on the isotopics of plutonium from various types of production reactors. An elevated plutonium-238 fraction is an indicator that recycled uranium was used. The extra plutonium is produced from uranium-236 in the recycled uranium. Uranium-236, an artificial isotope, is absent in natural uranium but is produced by neutron absorption in uranium-235 during plutonium production.[197]

Examples of isotopic indicators of the production history of HEU and/or plutonium are shown in Figure 4.7 for four different fissile material production strategies. Each can be distinguished with high confidence based on the isotopics or other forensic signatures of sampled materials. For a case where reprocessed uranium is enriched to HEU, for example (the third-level down in the figure), there would be uranium-236 in the HEU and the associated depleted uranium.

The figure also shows how fissile materials are linked and how much natural and depleted uranium is associated with the production of a relatively small amount of HEU or plutonium. In the same third-level-down case, the existence of 320 kg of HEU containing the reactor-made isotope U-236 implies the existence of 70 kg of plutonium and almost 100 tons of U-236 containing depleted uranium tails. Also associated with the production of these materials would have been 100 tons of natural uranium and perhaps 100,000 tons of uranium mill tailings, the residue of the ore from which the uranium was extracted. Making all of this evidence disappear could be quite difficult to do—especially since the need to do was not considered when production originally took place.

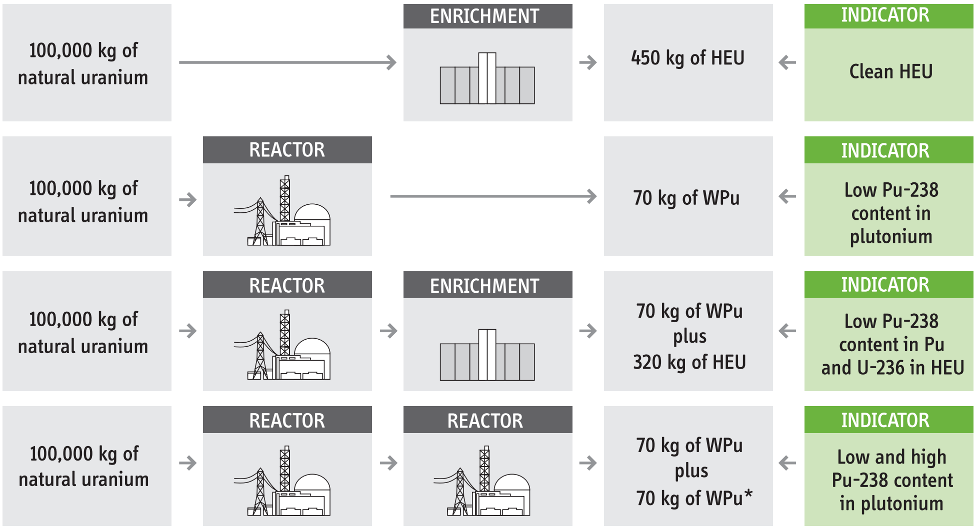


Figure 4.7. Fissile material production modes and their indicators. Various strategies can be pursued to produce plutonium, highly enriched uranium or both from a given amount of natural uranium. Based on an isotopic analysis of the fissile materials, the production mode can be identified with high confidence. The verification of a declaration benefits from the fact that large amounts of waste, including depleted uranium, are generated per kilogram of fissile material produced.[198] Note that the isotopics of plutonium produced from recycled uranium (WPu*) are different from the isotopics of plutonium produced from natural uranium (WPu). See also Figure 4.6.

This kind of integrated assessment of the fissile material production process would depend upon a (partial) forensic analysis of representative samples of the fissile materials themselves.

Other Forensic Signatures. Other forensic signatures also could be useful for a verification of declarations. Perhaps most important, the age and therefore the production date of nuclear material can be determined with remarkable accuracy based on the concentrations of decay products.[199] In the case of weapons materials that have been purified during the weapon production process, the decay products may have been removed. Even then, however, age-dating is possible based on selected isotope ratios, though with somewhat greater uncertainties.[200]

Applications of Nuclear Archeology

Nuclear archaeology as a verification tool has been evaluated in several exercises, where the results could be validated or compared against reference data provided by the operator. In addition to these test cases, nuclear archaeology has been applied to South Africa's nuclear-weapons program. Its application has been proposed to North Korea's nuclear program. And the United States has examined what could be learned if nuclear archeology were applied in the gaseous diffusion plants that produced HEU for U.S. nuclear weapons and naval reactors during the Cold War.

South Africa. In 1991, South Africa gave up its nuclear weapon program, dismantled its nuclear weapons, submitted the recovered fissile material to IAEA safeguards, and provided a report of the historical flows and balances, production, and transfers of fissile material in its weapons program. To verify this declaration, the IAEA audited the historical operating and accounting records of South Africa's nuclear production facilities, visited them and related facilities, took environmental samples and made a "large number of non-destructive and destructive measurements … on various types of material."[201] On this basis, and given the demonstrated willingness of the South African nuclear-program personnel to cooperate with the verification process, the IAEA concluded that it had "found no evidence that the inventory of nuclear material included in the Initial Report was incomplete."[202]

North Korea. In 2008, the United States submitted a detailed proposal for verifying the elimination of nuclear weapons and related fissile material programs by North Korea (Appendix 4A). This would be part of the implementation process of the 2005 Six-Party agreement between North Korea and the United States, Russia, China, Japan and South Korea, under which North Korea was to abandon all nuclear weapons and nuclear weapon programs. The U.S. proposal included in particular a call for:

- "Full access to all materials at any place on a site, facility or location where nuclear material, in any form, is or has been located"—including to sites that have not been declared;

- "Full access to records (fully preserved and maintained), including originals, and information systems […] documenting nuclear material production, handling, and disposition";

- "At any site, facility, or location, experts will be permitted to interview personnel, including scientists, technicians and facility managers"; and

- Photography, radiation detection equipment, and sample acquisition for forensic analysis in reactors, product materials, and process wastes.

The authors of the U.S. proposal concluded that "these measures provide a means to address all elements of a nuclear program, to include plutonium production, uranium enrichment, weapons, weapons production and testing, and proliferation activities."

U.S. HEU Production.[203] In the mid-1990s, U.S. experts carried out a "counterforensic investigation" at the U.S. Portsmouth and Paducah gaseous diffusion plants (GDPs). They collected samples and subjected a selection of them to a full radiochemical analysis to determine what information could in principle be learned by outside inspectors. Among many other results, the analysis found:

- *Uranium-236.* Detection of particles containing uranium-236 provides unambiguous evidence that at least some of the feed material had been previously irradiated in a nuclear reactor.

- *Absence of HEU.* No HEU was detected in the five samples that were analyzed, even though three of the five samples were taken at the Portsmouth GDP, which had been producing up to 97%-enriched uranium until 1992, only a few years before the exercise took place.[204]

- *Traces of plutonium.* Remarkably, traces of plutonium were detectable in these samples taken at uranium enrichment plants. They apparently arrived as impurities in reprocessed uranium. The amounts were sufficient to allow the isotopic composition of the material to be measured. The results not only showed that the plutonium was weapon-grade (6–7% $^{240}\text{Pu}/^{239}\text{Pu}$), but also provided some evidence about the type of reactor, in which the material was produced. The analysts concluded that the plutonium was produced in a natural-uranium fueled reactor.[205]

- *Traces of neptunium.* Radioactivity from neptunium-237 decay in the samples provided information about the reprocessing process originally used to separate uranium and plutonium from the fission products and minor transuranics, including neptunium. In this case, PUREX was seen as the most likely candidate because this process leaves the neptunium largely mixed with the uranium.

These results suggest that nuclear forensic analysis for nuclear archaeology can provide means to reconstruct in some details the production history of a weapons program, *even if not carried out at all sites*, especially where plants have been exchanging nuclear materials as part of an integrated national fissile material production complex. Apparently, the United States considered the types and the level of detail of information gathered during this exercise to be very sensitive. In a disarming world, however, where nuclear weapon states have made detailed declarations of their fissile material inventories, verification of these declarations would be considered of mutual interest.

In sum, national declarations of fissile material production can in principle be verified to a significant degree once detailed information by site and facility are shared. To enable rigorous verification of declarations, however, nuclear weapon states would have to provide the necessary access to former fissile material production sites and associated process materials, possibly including the fissile materials. Nuclear archaeology would play a key role in verifying nuclear disarmament, not only through the quantitative results it can provide, but also through the cooperative approach it requires.

Appendix 4A.

U.S. Proposal for Verification of North Korea's Denuclearization

The following text is a reproduction of an undated U.S. Government memo outlining the proposed approach to verify North Korea's declaration from 26 June 2008. The *Washington Post* posted the original document on its website in September 2008. It is also available at www.ncnk.org and www.ipfmlibrary.org/gov08.pdf.

VERIFICATION MEASURES DISCUSSION PAPER

Below is a list of measures that would be applied to undertake verification activities. These measures will form the basis for development of a verification implementation plan that assigns specific responsibilities and requirements. These measures provide a means to address all elements of a nuclear program, to include plutonium production, uranium enrichment, weapons, weapons production and testing, and proliferation activities.

The verification regime consists of experts of the six parties and is responsible to the Working Group on Denuclearization of the Korean Peninsula.

- Six Party Experts will be determined by their national governments, and will coordinate their actions in order to implement the agreed verification plan.

- Experts will be permitted to bring, utilize, and remove their own equipment in the course of exercising their responsibilities, to include measurement devices, radiation detection equipment, sampling materials and equipment, and GPS receivers.

- Experts will be permitted to use their own interpreters and translators.

- Experts will be allowed free communications, including attended and unattended transmission of information generated by containment and/or surveillance or measurement devices.

- Experts will be permitted to make use of internationally established systems of direct communications, including satellite systems and other forms of telecommunication.

- Experts will be given visas in a timely manner in order to conduct/support verification activities.

- If, in the course of implementing this plan, questions arise requiring resolution, either the expert of his/her designated representative may request a meeting to consult and clarify promptly. Should such a meeting not result in resolution of questions, any of the relevant parties may call for a meeting of the relevant parties to address the questions.

- Verification activities involving weaponization-related activities, information, facilities of material, will be conducted by experts from the Nuclear Weapons States as defined by the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Specifically, experts from the Nuclear Weapons States will:

  - conduct all verification activities relating to nuclear weaponization, including verification of all related information, personnel, facilities or materials; and

  - conduct sampling and forensic analysis and interviews of personnel as necessary to accomplish these verification activities.

- Information about weapons activities would be shared with the Six Party experts who are not from Nuclear Weapon States to the extent consistent with the NPT.

- Information sharing with the IAEA and IAEA access in these cases would be limited to select inspectors from Nuclear Weapons States, and granted to the extent necessary for the IAEA to carry out its safeguards and verification responsibilities.

<u>The verification measures of the verification regime include visits to facilities, review of documents, interviews with technical personnel and other measures unanimously agreed among the relevant parties.</u>

<u>Visits</u>: Experts must be allowed the following access in a prompt manner:

- Full access to all materials at any place on a site, facility or location where nuclear material, in any form, is or has been located, to include past and present facilities.

- Full access to any site, facility or location that does not contain nuclear material but is related to elements of nuclear program as declared or as determined by the relevant parties.

- Full access upon request to any site, facility or location in a declaration and any site, facility or location not contained in the declaration, for verification of the completeness and correctness of the declaration of nuclear program and to confirm the absence of undeclared nuclear material, equipment, and related activities.

<u>Review of Documents</u>: Experts will be given:

- Full access to records (fully preserved and maintained), including originals, and information systems (experts will have the right to make and remove from that Party copies or electronic media forms of copies) documenting nuclear material production, handling, and disposition, as well as other nuclear-related activities, to include:

  - the nuclear material control and accounting system;

  - records and reports showing inventories or nuclear material and changes in inventories, including receipts into and transfers out of the accounting system;

  - facility operations and design information, including facility modification and upgrade information;

  - data on the types, quantities and characteristics of declared nuclear material;

  - inventories, operating and production records, reports, logbooks or other records of any and all other facilities association with the design, development, or testing of elements of the nuclear program;

  - a general description of any site, facility or location, including its use and content;

  - transfer and receipt records of nuclear material, equipment, storage, containers, vehicles, and personnel; and

  - records of all imports or exports of nuclear materials and nuclear-related equipment.

  - <u>Interviews with Technical Personnel</u>: At any site, facility, or location, experts will be permitted to interview personnel, including scientists, technicians and facility managers.

<u>Other Measures</u>: At any site, facility, or location, experts will be permitted to undertake verification activities, including to:

- conduct and record visual observations, including by photographic and video-recording methods;

- utilize radiation detection equipment and other measurement devices;

- apply containment and surveillance systems and seals and other identifying and tamper indicating devices;

- conduct item-counting of nuclear materials;

- conduct forensic measurements of nuclear materials and equipment;

- collect and remove from that Party samples of nuclear materials, samples of equipment, environmental samples, and samples of nuclear waste in a manner consistent with denuclearization activities;

- record observations in personal notebooks; and

  - remain on site for the period deemed necessary and re-visit any facilities, sites, or locations to check data and resolve any questions or discrepancies that arise during the verification process.

  - as relates to a graphite-moderated reactor, collect, and remove from the Party physical samples of the graphite moderator after the core has been de-fueled.

  - As relates to a research reactor, collect and remove from the Party samples of the aluminum core support structure, and from the reactor reflector elements.

  - As relates to all nuclear materials, wastes, equipment, and facilities (fully preserved apart from denuclearization's activities) collect and remove from the Party samples and forensics measurements.

- The relevant parties may agree to additional measures to facilitate the verification process, including additional measures to help confirm the absence of undeclared nuclear material, equipment and related activities.

When necessary, the verification regime can welcome the IAEA to provide consultancy and assistance for relevant verification.

- The IAEA will apply safeguards measures appropriate to non-nuclear-weapons states in accordance with IAEA standards, principals, and practices to all nuclear material, nuclear fuel cycle, and nuclear fuel cycle-related facilities declared. Specifically, the Agency will:
  - establish material accountancy and control for all declared nuclear material pending its removal;
  - monitor the declared nuclear fuel cycle and nuclear fuel cycle-related facilities and nuclear material to provide a level of assurance that all nuclear activities have ceased and nuclear material or other items have not been tampered with;
  - undertake sampling and forensic analysis and interviews of personnel.
- The IAEA will share all data related to its safeguards activities and its evaluation of the declaration with all relevant parties, consistent with their respective international obligations, to support independent assessments by the relevant parties on the completeness and correctness of any declaration.

5 Verified Warhead Dismantlement

The nine nuclear weapon states today maintain over 20,000 nuclear warheads in total, including over 5000 deployed warheads, and components for many more. It will be necessary as early as possible in the disarmament process to account for these weapons and components and verify their dismantlement. Tracking warheads from deployment or storage areas through a dismantlement facility and monitoring of the recovered components and their final disposition can help provide assurance that no nuclear weapons or components are being hidden.

This chapter discusses how warhead dismantlement could be verified in the case of Russia and the United States, which between them still possess about 98 percent of the world's nuclear weapons and components (Chapter 1). As U.S. and Russian arsenals fall to much smaller numbers, verified warhead dismantlement will need to include other weapon states and similar procedures would apply. Only in the case of very small stockpiles—North Korea today and South Africa two decades ago—are the techniques of nuclear forensics and nuclear archeology likely to be accurate enough so that tracking warhead dismantlement becomes dispensable.

During the second half of the 1990s, Russia and the United States had a "lab-to-lab" research program to work on how warhead dismantlement could be verified with minimal intrusiveness; perhaps the best available summary is in a 1997 U.S. Department of Energy report.[206] The lab-to-lab studies examined verification of the stages of warhead dismantlement and emphasized that confidence in the authenticity of the warheads would depend greatly on being able to track the movement of warheads and components in sealed containers from the deployment or storage areas to the dismantlement facilities (Figure 5.1).

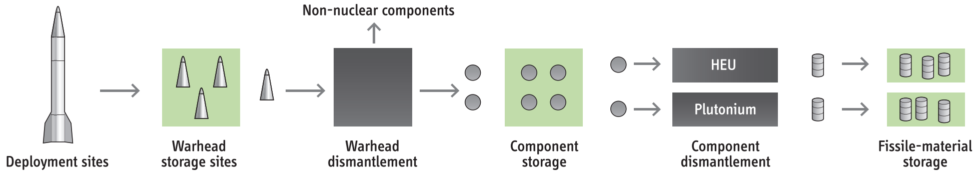


Figure 5.1. Nuclear warhead dismantlement starts with removal of warheads from deployment sites to storage sites. The warheads then go to dismantlement facilities where the fissile material components are removed and shipped to storage and then for further dismantlement. Ultimately, plutonium and highly enriched uranium emerge from the system in unclassified form and are stored for final disposition.

The various aspects of verified warhead dismantlement are discussed below, including:

- The initial declaration of warheads and components by location, type and the quantities of fissile material inside each warhead and component;
- Non-intrusive methods for identifying warhead and component types; and
- Dismantlement that permits verification of the amount of fissile material in each warhead.

Figure 5.2 shows the basic components of a modern thermonuclear weapon. At a warhead dismantlement facility, the 'primary' and 'secondary' are separated, and the chemical explosive is removed from the primary. At a later stage, the fissile-material components within the primary and secondary are themselves dismantled.

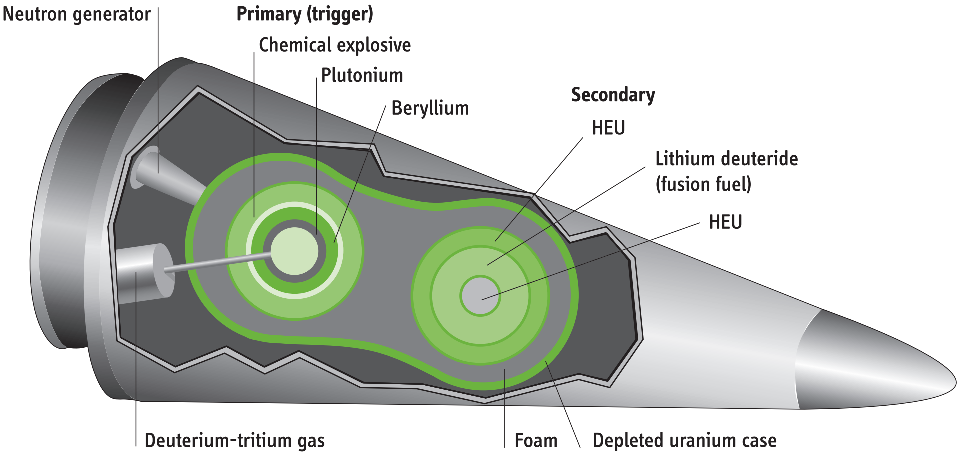


Figure 5.2. A nuclear warhead contains electronics and the nuclear explosive, often referred to as the "physics package." A modern physics package typically contains a fission "primary," a hollow plutonium shell or "pit." Just before its implosion into a supercritical mass by the surrounding chemical explosive, deuterium-tritium (D-T) gas would be injected into the pit. When the fission heat raised this gas to fusion temperature, it would produce a burst of neutrons that would cause additional fissions, "boosting" the fission energy release ten-fold. The explosion of the primary compresses and heats a fission-fusion "secondary" containing both highly enriched uranium and the fusion fuel lithium-deuteride. See Appendix A to this report for more information on fissile materials and nuclear weapons.[207]

Following warhead dismantlement, it would be necessary to monitor weapon component dismantlement. During the period 1996–2002, Russian and U.S. weapons scientists worked with the International Atomic Energy Agency (IAEA) to see whether it would be possible to have the IAEA monitor warhead components containing fissile material before they were dismantled.[208]

After the fissile material is converted to unclassified form, in which the mass, shape, alloying agents and isotopics have been changed to conceal weapon-design information, it can be subjected to the full panoply of measures developed for the IAEA to verify declarations of, and maintain containment and surveillance over, fissile materials in non-weapon states. Ultimately, there will need to be verified disposition of the fissile material recovered from weapon components (Chapter 6).

The initial declaration

Following the discussion in Chapter 3, we assume that in a verified nuclear-disarmament process states will declare their holdings of nuclear weapons and components both as countable warheads and components in containers, and amounts of fissile material in containers. In order to conceal the existence of some weapons or fissile material, a state would have to falsify declarations of both warheads and fissile material in a consistent manner in all records and physical evidence (Chapter 4).

At the time of the initial declarations, warheads would be in all stages of deployment, storage, maintenance and dismantlement, with their status changing as they moved between these stages. A state's declaration would therefore include all the locations among which its warheads move and the numbers of warheads and components at each location. Table 5.1 shows the locations of U.S. nuclear-weapon sites, grouped by mission. Appendix B gives weapons-storage locations worldwide.

	Locations**	Warheads (estimates)
With Delivery Vehicles*		
450 Minuteman III ICBM silos	Malstrom, MT; Minot, ND; and Warren, WY air bases	550
12 operational Trident submarines with 288 D5 SLBMs	Bangor, WA; and Kings Bay, GA naval bases and at sea	1152
44 operational and 49 reserve B-52H ALCM-armed bombers	Barksdale, LA and Minot, ND air bases	350
16 operational and 4 reserve B-2 bombers with nuclear bombs	Whiteman air base	150
F15E fighter-bombers	Seymour-Johnson, NC air base	≈ 50
NATO fighter-bomber bases in Europe with U.S. nuclear bombs	Belgium: Kleine Brogel; Germany: Büchel; Italy: Aviano & Ghedi Torre; Netherlands Volkel; and Turkey: Incirlik	200
In storage		
SLCMs for 12 attack submarines	Bangor, WA & Kings Bay, GA storage sites	100
In reserve or awaiting dismantlement	Mostly in Kirtland, NM, Nellis, NV, Bangor, WA, and Kings Bay, GA storage sites	≈ 7000
Being maintained, inspected and dismantled		
	Pantex, TX	≈ 500/year
Fissile component production, refurbishment and dismantlement		
Plutonium-containing "pit" production and inspection	Technical Area-55, Los Alamos, NM	≈ 20/year
HEU-containing secondary component production, inspection and dismantlement	Y-12 facility,[209] Oak Ridge, TN	≈ 450/year
Component storage		
Plutonium-containing pits	Pantex, TX	> 14,000
HEU-containing secondaries	Y-12 facility, Oak Ridge, TN	≈ 10,000

Table 5.1. Locations of U.S. warheads and fissile components.[210] *Missile types are intercontinental ballistic missiles (ICBM), submarine-launched ballistic missiles (SLBM), air-launched cruise missiles (ACLM), and sea-launched cruise missiles (SLCM); **U.S. States are Georgia (GA), Louisiana (LA), Montana (MT), North Carolina (NC), North Dakota (ND), New Mexico (NM), Nevada (NV), Tennessee (TN), Texas (TX), Washington State (WA), and Wyoming (WY).

The numbers of warheads and components shown for each group of deployment sites are estimates by non-governmental analysts, but the sites are public knowledge and there is no obvious security reason why the numbers of warheads could not be declared by the owning governments.

Verification of declarations

Initial verification of a national declaration would be limited to random checks that objects declared to be warheads and fissile components are present in the declared numbers at the declared locations. A basis would need to be laid, however, for later measures that could increase confidence that the objects are what they are claimed to be and ultimately that all the fissile material in the warheads and components have been placed under international safeguards.

Deployed warheads. The 1991 START Treaty contains important precedents for the types of inspections that could be initially used for verifying warhead declarations. The treaty requires that the United States and Russia notify each other of the number of deployed warheads on each strategic ballistic missile, with updates every six months and notifications of planned changes thirty days in advance.[211] Under the Treaty, each state can count the cone-shaped reentry vehicles on top of the missiles that house the nuclear warheads, i.e., each party has "the right to conduct reentry vehicle inspections of deployed [Intercontinental and Submarine Launched Ballistic Missiles] to confirm that such ballistic missiles contain no more reentry vehicles than the number of warheads attributed to them."[212] Inspections are permitted on up to ten ballistic missiles per year.[213] A radiation detector can be used in reentry-vehicle inspections to distinguish real nuclear warheads from objects that look like reentry vehicles but do not contain plutonium.[214]

The Treaty also provides "the right to inspect all weapon storage areas … to confirm the absence of long-range nuclear ALCMs [air-launched cruise missiles] at bases for heavy bombers declared not to be equipped for nuclear ALCMs."[215] Such inspections include the right to use "radiation detection equipment" to help distinguish nuclear from non-nuclear ALCMs.[216]

START does not require the declaration of numbers of nuclear ALCMs at bases of bombers declared to be equipped for carrying them or the numbers of nuclear bombs deployed at bases for long-range bombers. The number of nuclear-armed ALCMs and nuclear bombs in each storage bunker on a base could easily be declared, however. An agreed number of short-notice random inspections each year could check those declarations. A quota of challenge inspections could serve to check for the presence of nuclear weapons at sites not declared to contain nuclear weapons. The inspections could distinguish between nuclear and non-nuclear weapons with the same radiation-detection equipment used for reentry vehicle and ALCM inspections.

START does not require countries to declare warhead types, for example, whether a Trident II missile carries high-yield W88 or lower-yield W76 warheads or a mix. But warhead types could be declared. For cases where the "physics package" containing the fissile materials is identical between two different warhead types, that fact could be declared as well.

How could one increase confidence that the objects being counted are real nuclear warheads and bombs? One option would be for inspectors to be allowed early on to choose at random a small number of deployed warheads of each operational type and place them in sealed and tagged containers at a base in the owning country. Using agreed methods, these sample warheads could later be used as templates for checking the authenticity of other warheads declared to be of the same type. As discussed below, this comparison could be done in a way that would verify only whether two warheads were of the same type or of different types without revealing design information about either warhead.

Stored warheads. The United States and Russia have thousands of stored warheads, many awaiting dismantlement. Stored warheads could be declared and the declarations verified in the same way as deployed warheads. To prevent warheads from being removed or exchanged, the inspectors could apply unique tags and seals to each warhead or its container.

Stored components. Stored weapon components that contain fissile material, i.e., plutonium pits and secondaries, could be declared by type and tagged by inspectors. As with warheads, states could label containers by component type for possible later comparison with components from sample warheads declared to hold the same component type (Figure5.3).

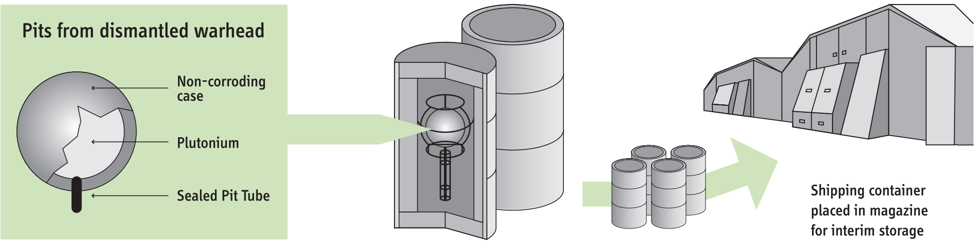


Figure 5.3. Storage arrangements for U.S. plutonium warhead "pits" at the Pantex warhead dismantlement facility in Amarillo, Texas.[217]

It would make a great deal of sense early in the dismantlement process to make the retirement of warheads and stored components irreversible. One idea is "pit stuffing," in which a material would be stuffed into the interior of the hollow plutonium pit in the primary using the tube through which deuterium-tritium "boost" gas would be introduced in an explosion.[218] This would make it impossible for the pit to be imploded into a supercritical mass.

Pit stuffing was originally developed at the U.S. Los Alamos nuclear-weapon laboratory to assure that warheads that been determined to be unsafe would not detonate accidentally. It could be carried out years before the warhead was dismantled and made difficult to reverse without making the pit unusable.

After warheads are dismantled, there would be more options. For example, a U.S. National Academy of Science study suggested that excess pits could be sealed in ductile metal "envelopes," to prevent oxidization of the plutonium if the pit cladding were cracked, and then flattened in a press.[219] Turning the plutonium back into a usable pit would require complete remanufacture.

Quantities of fissile materials in each warhead type. The verification of nuclear-weapon dismantlement would be much simplified if the quantities and isotopic compositions of the plutonium and HEU in each type of nuclear warhead and component were declassified at the outset.

Despite the recommendations of the U.S. Department of Energy's 1997 Fundamental Classification Policy Review,[220] however, these quantities are still classified in the United States.[221] Russia is even more sensitive in this regard. Before being willing to put the weapons plutonium that it has declared excess into a high-security storage facility built with U.S. funds, Russia has been converting it from pit form into standard 2-kilogram metal spheres.[222] Also, in the Russian-U.S. agreement on the disposition of excess weapons plutonium, Russia insisted on blending weapons plutonium with non-weapons plutonium, to conceal the isotopics of the weapons plutonium.[223] Russia's secrecy may seem excessive but the fact that it could be accommodated without compromising verification makes clear that such information can be protected if deemed essential.

The remainder of this chapter discusses the main elements of arrangements for assuring non-diversion of fissile material from the warhead dismantlement process, based largely on the approaches developed in the 1990s Russian-U.S. lab-to-lab project. These arrangements include:

1. Warhead and component "fingerprints," i.e., indicators that can be used to identify the type of nuclear explosive "physics package" that a warhead or component contains; and

2. Non-intrusive surveillance of the warhead-dismantlement process to ensure that no fissile material is removed.

Warhead and component "fingerprints"

The United States deploys eleven types of warheads (Table 5.2). Reportedly, they contain only six different "physics packages," i.e., six different configurations of fissile materials and implosion systems.[224]

Weapon system	Warhead designation
ICBM warheads	W78 and W87
SLBM warheads	W76 and W88
Air-launched cruise missile warheads	W80-1
Strategic bombs	B61-7, B61-11 and B-83
Tactical bombs	B61-3 and B61-4
Submarine-launched cruise missiles	W80-0

Table 5.2. U.S. operational nuclear-warhead types.[225]

Since different types of physics packages contain different quantities of fissile materials, it would be important to be able to distinguish them from each other. To do this, the lab-to-lab studies of the late 1990s explored the idea of "radiation fingerprints."[226] The U.S. labs built on methods already in use to check the integrity of U.S. nuclear weapons and components when they are returned to the Department of Energy for dismantlement or refurbishment: the Gamma Radiation Signature and the Nuclear Weapon Identification System.

Gamma Radiation Signature. The fissile materials in nuclear warheads naturally emit gamma rays with characteristic energies.[227] In 1989, as a part of a demonstration of the detectability of nuclear warheads, President Mikhail Gorbachev allowed a group of U.S. scientists to measure the energy spectrum of the gamma rays emitted by a Soviet cruise-missile warhead. It is shown in Figure 5.4 and is the only warhead spectrum ever published.[228]

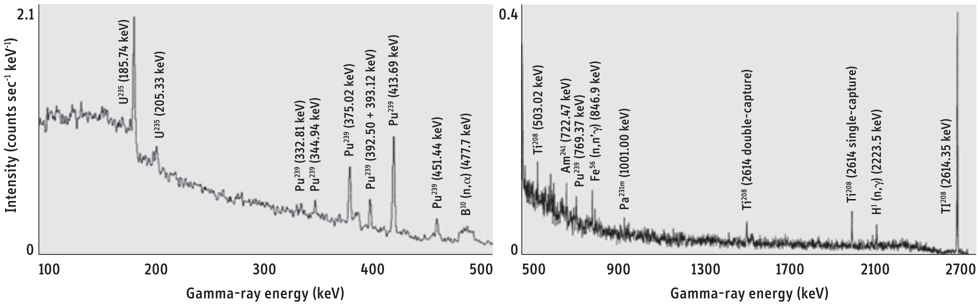


Figure 5.4. Gamma ray energy spectrum from a Soviet warhead. Peaks are apparent at the characteristic energies of gamma rays emitted by various plutonium and uranium isotopes and some of their decay products (e.g. thallium-208, Tl-208) as well as some nuclei transmuted by neutrons emitted by the warhead and some background radioactive isotopes. The spectrum on the right is a continuation of the one on the left with a five fold increase in the vertical scale.

The gamma radiation spectrum is specific to warhead types. In an experiment at the U.S. Pantex warhead assembly and dismantlement facility in Texas, warheads were wheeled past a low-energy-resolution gamma-ray detector.[229] It was found that spectra from warheads of the same type were similar and distinguishable from the spectra of other warheads types.[230]

Nuclear Weapons Identification System. The Nuclear Weapons Identification System (NWIS) uses an external source of neutrons to cause a small number of fissions in a warhead (or warhead component) and measures the timing of the penetrating neutrons and high-energy gamma rays that are released as a result (Figure 5.5).[231] It is used to check the integrity of the HEU-containing thermonuclear "secondary" components that are returned from Pantex to the Y-12 facility in Oak Ridge, Tennessee, for dismantlement or refurbishment.[232] Based on a limited number of samples, the signal patterns were distinguishable for each type of secondary.

Direct access to this radiation data by experienced nuclear-weapon designers might reveal design information.[233] The ratio of the radiation fingerprints from two warheads, one of which could have been randomly selected from a deployment or storage site in a way that maximized the probability of its authenticity, would contain less design information. If the warheads were identical as claimed, then the ratio would be unity to within statistical error.[234] All that would be revealed would be the degree of design difference between the warheads and the statistical error in the measurements.[235] The measurements and analysis on actual warheads and components would be done behind an "information barrier" that limited the information communicated to the inspectors.[236]

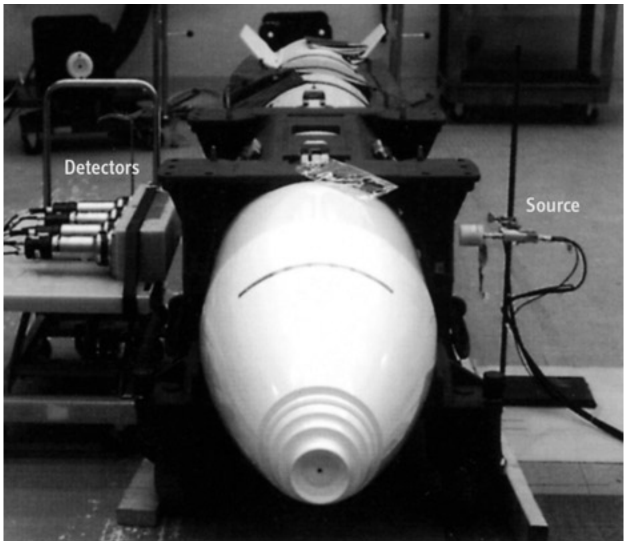


Figure 5.5. Nuclear-Weapons Identification System. To the right of the bomb is a Californium-252 source that sprays the bomb with penetrating neutrons. When neutrons strike fissile material, they cause fissions. To the left are four scintillation counters that measure the the numbers and timing of the secondary gamma rays and neutrons from the induced fissions. The counting pattern from an intact "template" warhead may therefore be compared with that from a warhead declared to be identical to see whether or not there are differences.[237]

Verifying fissile-material content. Once it is possible to distinguish different types of physics packages, the declarations of the fissile-material contents of each type could be checked. This could be done by processing some of the sample warheads of each type through a stringent version of the contained dismantlement process to be discussed below to determine how much plutonium and HEU each warhead and component of a specified type contains. The warheads and components subsequently declared to be of that type would then be expected to yield the same quantities of fissile materials.

Containment and surveillance of dismantlement

Warheads and components could be tracked through the dismantlement process to verify that no fissile material is diverted and to establish the radiation signatures of components and assays of fissile materials associated with specific warhead types. Later on, the process could be simplified by checking that the radiation signatures of the components and the assays of the fissile material emerging from the process corresponded to the numbers and types of warheads being dismantled.[238]

The general approach developed in the U.S. Department of Energy studies would involve the movement of warheads and components in sealed containers between a sequence of storage and dismantlement facilities. The United States studies focused primarily on how verification of U.S. warhead dismantlement could be implemented at the Pantex facility outside Amarillo, Texas, where U.S. warheads are assembled, inspected, refurbished and dismantled, but the same procedures could be applied "downstream" when the components are dismantled. Four options were considered.

- The least intrusive would only verify that tagged warheads were delivered to the gate of the dismantlement facility and that component containers coming out were also tagged.

- The two intermediate options would fence off four dismantlement cells and eleven dismantlement bays at Pantex and dedicate them to the verified dismantlement of warheads (see Figure 5.6).[239] Inspectors would thoroughly examine the cells and bays before a dismantlement campaign began to verify that there were no unmonitored openings in the walls that could be used to bypass the inspection system. The inspectors would check again after dismantlement was completed and the components had been shipped to storage in tagged and sealed containers to make sure that no undeclared weapon components or fissile material remained.

During a dismantlement campaign, the inspectors would monitor the boundaries of the dedicated dismantlement area with video cameras and check packages entering and leaving to verify that no fissile materials entered or left except in tagged, sealed containers. In the more intrusive of the intermediate options, the inspectors would also check packages entering and leaving individual cells and bays.

- The most intrusive option considered would have inspectors or their remotely operated cameras actually in the dismantlement cells and bays, but shielded from viewing the components.

A problem noted with the first option was that it would require monitoring of all the items entering and leaving the gates, including warheads that were only being sent for inspection or refurbishment or components that were being sent for reassembly. The problem with the fourth option was that it would maximize the danger that sensitive design information might be revealed. So the middle options were favored.

Regardless, much of the verification could be done remotely, via video cameras with the signals transmitted to inspectors at a nearby site. For the option involving monitoring of deliveries to and exports from the cells and bays, for example, their entrances would be monitored remotely by cameras and inspectors could be present when seals were removed from warhead containers and applied or removed from component containers.

Figure 5.6. Section of the U.S. Department of Energy's (DOE) Pantex facility outside Amarillo, Texas, proposed for verified warhead dismantlement in a 1997 DOE study. Warheads in tagged and sealed containers would be delivered from Department of Defense sites to a bunker in Zone 4 (above left). From there they would be transported into Zone 12 (foreground) and then into a fenced off section with eleven bays and four cells where the work of dismantling the warhead is carried out. After they have been put into their own containers, the pits are returned to Zone 4 for long-term storage. The secondaries are shipped to the DOE's Y-12 facility in Oak Ridge, Tennessee, for storage and dismantlement. *Picture courtesy of Los Alamos Study Group.*[240]

There has been considerable skepticism about the ability of inspectors to be able to detect whether seals have been opened between the cells.[241] For the purpose of this project, a seal was developed that could be continuously remotely monitored using a built-in infrared illuminator and night-vision camera (Figure 5.7).[242] Its signal could be monitored by a computer that would alert inspectors if there was any movement within the camera's field of view and record the images during that period for their review.

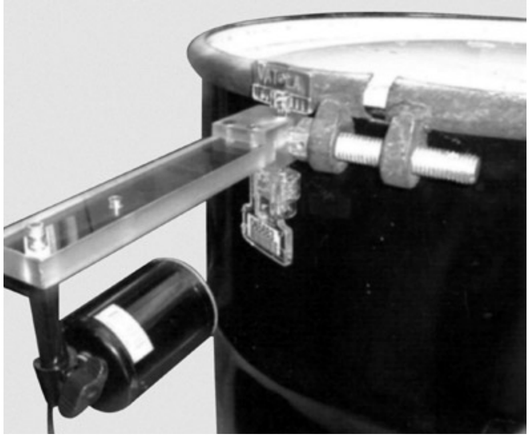


Figure 5.7. Seal with integrated identity tag and small battery-operated electronic camera that transmits the image continuously.[243] *Source: U.S. Department of Energy.*

The containers emerging from the dismantlement cell would have to be tagged and later screened to sort out the containers containing fissile material or they could be screened at the exit. The 1997 DOE study recommended that the destruction of non-nuclear warhead components be verified. Such destruction today includes burning of the high explosive and shredding plastic and metal parts. The verified disposition of the recovered fissile materials is discussed in the following chapter.

From bilateral to trilateral to multilateral verification

Responsibility for the warhead-dismantlement inspection regime might evolve with time. The initial focus would be on verifying reductions of today's Russian and U.S. stockpiles down to perhaps one thousand total warhead equivalents each (including components), and Russia and the United States would most likely insist on bilateral verification.[244] The IAEA could provide a second, international level of monitoring, however, by tagging and sealing warhead and component containers at storage sites and assaying fissile materials when they are finally in unclassified form. After this stage, other weapon states might be willing to join a verified dismantlement process.

It is not obvious who would do the inspections when verified warhead dismantlement becomes a multinational activity. The inspection activities that have been discussed above would not be inappropriate for IAEA inspectors from non-weapon states to carry out. Weapon states might be concerned, however, about the information that non-weapon-state inspectors might pick up at nuclear-weapon sites.[245] The IAEA could, however, recruit weapon experts from the weapon states to carry out verification tasks within weapon and component dismantlement facilities with IAEA inspectors from non-weapon states responsible for other parts of the verification system. The IAEA already does this when it encounters issues relating to nuclear-weapon design.

6

Disposition of Plutonium and Highly Enriched Uranium

As nuclear arsenals are reduced and weapons dismantled, the fissile material that is recovered needs to be verifiably rendered less accessible, by physically transforming it into a form from which it would be difficult and costly to recover for use in weapons. In a world moving toward eliminating all nuclear weapons, other stocks of potentially weapon-usable material that also will need to be made less accessible include excess highly enriched uranium (HEU) from naval stockpiles, as well as civilian HEU and separated plutonium. Disposition of fissile materials is therefore one of the central tasks on the nuclear disarmament agenda.

As reported in Chapter 1, the global stockpiles of fissile materials today are roughly 1600 tons of HEU and 500 tons of separated plutonium. Virtually all of this material is in the weapon states and mostly in Russia and the United States.

Russia and the United States together declared excess for military purposes, mostly in the mid-1990s, about 700 tons of HEU. Most of that HEU has already been blended down to low-enriched uranium (LEU) to make power-reactor fuel. Given the decisions that both countries have made on further reduction in their weapon stockpiles, it is clearly time for them to declare more weapons HEU excess. The United Kingdom and France have also reduced their arsenals to about half their Cold War peaks and could declare as excess for weapons purposes the HEU from their eliminated weapons. As other weapon states join the disarmament process, they could make similar arrangements.

The United States and Russia also between them declared about 90 tons plutonium excess in the 1990s. Plans were made to mix most of the current excess plutonium with uranium and turn it into mixed-oxide (MOX) reactor fuel and irradiate it, but there has been much confusion, and little momentum has developed toward real disposition. It is time to suspend these costly efforts and review and consider alternatives. Also, it is time to begin to live up to the commitments made by the two countries in the 1990s to subject fissile material stocks declared excess for military purposes to monitoring by the International Atomic Energy Agency (IAEA).

Finally, civilian reprocessing has resulted in the accumulation of large stockpiles of separated power-reactor plutonium in France, India, Japan, Russia and the United Kingdom. There are plans to recycle much of this material into reactor fuel in France, India, Japan and Russia. Except in the case of France, however, these programs have suffered prolonged delays. In the case of the UK stockpile, about 100 tons, discussions of disposition are just beginning.

Below, the ongoing efforts in Russia and the United States to dispose of highly enriched uranium are discussed first before turning to the issues associated with disposing of excess separated plutonium in the United States, Russia and the United Kingdom. This chapter is an update to the more extensive discussions of HEU and plutonium disposition in *Global Fissile Material Report 2007*. The reader is referred there for more details and references not provided here.

Highly Enriched Uranium

As of the middle of 2009, the estimated global stockpile of HEU was 1600 ± 300 tons, virtually all in the weapon states and mostly in Russia and the United States. This total includes HEU in weapons and components, stocks reserved for use as naval and research reactor fuel, and HEU in active and spent naval and research-reactor fuel.

Blend-down to low-enriched uranium is the main approach that is being pursued for disposing of unirradiated HEU. For HEU in spent fuel, two approaches are being pursued:

- Reprocessing to recover the HEU, which is then blended down to LEU

- Direct disposal in a geological repository alongside power-reactor spent fuel.

Below, we discuss each of these three disposition paths.

Blend-down of unirradiated HEU. Most of the weapon-grade HEU that has been blended down thus far is Russian: 367 tons between 1995 and mid-2009.[246] Russia is believed to have produced more HEU during the Cold War than the United States and, in the early 1990's decided that it could blend down 500 tons of this HEU to provide work and income for its nuclear complex. The U.S. Enrichment Corporation (USEC) contracted to buy the LEU for resale primarily in the United States as power-reactor fuel.[247]

Currently, USEC is purchasing annually LEU from 30 tons of blended-down Russian weapon-grade HEU (at least 90-percent enriched). Figure 6.1 provides a schematic of the blend-down process. The result of the blend-down of 30 tons of weapon-grade uranium is about 900 tons of LEU, enough to provide the annual fuel requirements for 45,000 Megawatts electric (45 GWe) of light-water reactor capacity. This is equivalent to about 45% of U.S. nuclear capacity or 12 percent of global capacity. The U.S.-Russian blend-down contract is on schedule to be completed at the end of 2013. Partly in anticipation of the end of the blend-down, there have been concerns about the possibility of a global shortage of LEU for reactor fuel and prices of uranium and enrichment work have increased dramatically.[248]

The U.S. Department of Energy also has a small "Materials Consolidation and Conversion" (MCC) program that buys and blends down excess HEU from Russia's civilian nuclear research institutes. As of the end of September 2008, the MCC program had blended down 10.7 tons of HEU and was planning to continue to buy and blend down HEU at a rate of about one metric ton per year.[249]

The United States for its part has declared 217 tons of HEU excess and available for blend-down and, as of mid-2009, had blended down 124 tons.[250] Unlike the Russian case, much of the HEU the United States has declared excess was not from weapons and most of it was less than weapon-grade, i.e., contained less than 90 percent U-235.[251] The reason is that most of the weapon-grade uranium that the United States has declared excess for weapons purposes has been allocated to a reserve for future use in naval reactor fuel (128 tons).

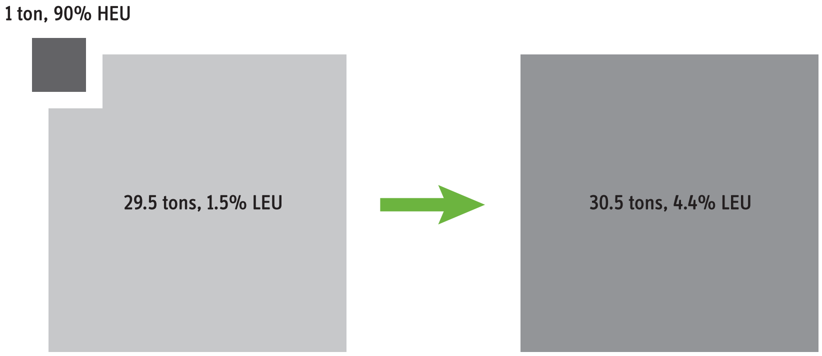


Figure 6.1. Blend-down of Russia HEU to LEU. One ton of excess Russian weapon-grade uranium, after mixing with 1.5-percent enriched blend-stock, produces enough low-enriched uranium to support a 1000-Megawatt (1-GWe) light-water nuclear power reactor for 1.5 years.

The United States has been blending down annually the equivalent of about 5 tons of weapon-grade HEU. That rate is currently projected to decline, however, to a rate of two tons a year with the result that disposition of the remaining 92 tons of U.S. excess HEU is not expected before 2050.[252] This slow disposition rate may be associated with a low U.S. rate of dismantlement of excess HEU-containing warhead components.[253]

After the disposition of the HEU they have thus far committed to blend down, both the United States and Russia still will have very large stocks of weapon HEU. To support a stockpile of 1000 nuclear weapons at 25 kg per warhead plus 20-percent working stocks, for example, would require only 30 tons of HEU for each country leaving a combined total of another 800 ± 300 tons of their weapons HEU excess.[254]

In addition, if Russia, the United Kingdom and the United States were to shift their naval-propulsion and research reactors (and Russia its icebreaker reactors)[255] to low-enriched uranium fuel—as France already has done and as being done worldwide outside Russia for research reactors—on the order of an additional 250 tons of HEU would become excess. Figure 6.2 shows a recent estimate of the amount of HEU being used annually in HEU-fueled ship-propulsion reactors. The United States is the largest user of HEU for this purpose. At two tons per year, the 128 tons that the United States has reserved for naval-reactor fuel would be sufficient for 60 years.

Thus, if the United States and Russia decided to reduce to 1000 warheads each and converted to LEU-fueled propulsion and research reactors over a period of about 20 years,[256] they could dispose of perhaps 360 tons and 700 tons weapon-grade uranium respectively.

How fast could Russia's excess HEU be blended down? In 2008, the private Washington-based Nuclear Threat Initiative released the results of a study on this question.[257] Scenarios were considered in which up to 42.5 tons of 90-percent HEU would be blended down per year. At this blend-down rate, it would take Russia 16 years to blend down 700 tons of excess HEU. For the United States to blend down 360 tons of excess weapon-grade HEU in the same period would require a blend-down rate of about 20 tons/year. The combined blend-down rates would be enough to support about 78 GWe of light-water reactor capacity or about 21 percent of the 2008 global capacity.[258]

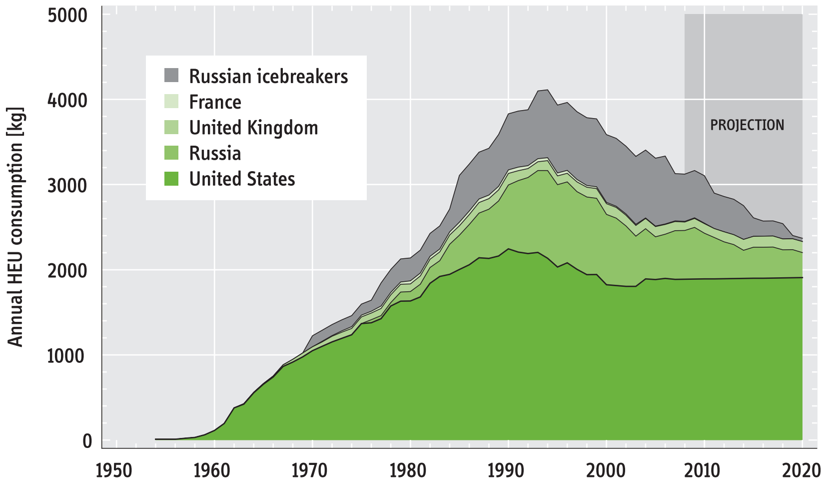


Figure 6.2. Estimated and projected HEU use for naval-propulsion reactors. The United States dominates because of its large fleet of nuclear-powered submarines and aircraft carriers. All U.S. and UK naval reactors use weapon-grade uranium. Russia is believed to use mostly less than weapon-grade (about 40-percent enriched) HEU in its submarine and icebreaker reactor cores. It is assumed that Russia will not replace its fleet of nuclear-power icebreakers and that its fleet of nuclear-powered submarines will continue to shrink. France has converted is submarine reactors to low-enriched uranium.[259] India launched its first nuclear-powered submarine in 2009. It is believed to use HEU fuel.

Current plans do not anticipate such a blend-down rate, however. The current U.S. expectation is that the blend-down of the remaining U.S. excess HEU will soon slow to a rate of about 2 tons per year. And, despite incentives provided by the U.S. Congress,[260] the Russian Government has no apparent interest in blending-down any more excess HEU beyond the 500 tons contracted for in 1993 for sale to the United States. The reason usually given is that the remaining stocks of HEU are needed as a reserve for Russia’s ambitious domestic nuclear-power expansion plans and foreign reactor and fuel sales. Since these reactors will be fueled with LEU, Russia could, however, blend down its stockpile to LEU in advance.

Thus, while the HEU that Russia and United States have declared excess has mostly been blended down, each should declare hundreds of tons more excess and commit to blend the material down at the maximum feasible rate.

Reprocessing of HEU spent fuel followed by blend-down. In Russia, spent HEU fuel from naval propulsion and research reactors is reprocessed and the recovered HEU blended down to LEU with uranium recovered from spent LWR power-reactor fuel. France also reprocesses and blends down the HEU from small quantities of research reactor fuel at its La Hague reprocessing plant.

The U.S. Department of Energy (DOE) has proposed that 21 tons of HEU in aluminum-based spent research-reactor fuel and other materials be separated in the H-canyon of the Savannah River reprocessing plant, where HEU spent fuel from tritium and plutonium production reactors was reprocessed during the Cold War. DOE recently estimated a cost of about $4.5 billion to reprocess this material—about ten times the value of the LEU that would be produced. The U.S. Government Accountability Office believes that the operation may be made even more costly by limitations of the waste-processing capacity at the site.[261]

The great cost of this proposed program is that it would be the primary reason for continuing to operate the H-canyon reprocessing plant until 2019.[262] This also appears to be the reason why advocates of this proposal within DOE and at the Savannah River site are so committed to the proposal: they do not want to see the last operating U.S. reprocessing plant shut down. Alternative approaches have been considered in the past that could cost considerably less and generate much less waste.[263] These alternatives should be considered again in an objective independent analysis.

Direct disposal of HEU spent fuel. During the Cold War, U.S. naval-reactor fuel was reprocessed to recover HEU to fuel the Savannah River plutonium and tritium-production reactors. Naval fuel reprocessing was ended in 1992, however, and U.S. spent naval fuel is currently slated for disposition in a geological repository. Some difficult-to-reprocess zirconium-based HEU research reactor fuel also is to be disposed with the naval reactor fuel. Altogether, more than 100 tons of HEU is involved. The United Kingdom also currently stores its spent naval HEU fuel.

Excess weapons plutonium

The global stockpile of separated plutonium is about 500 tons—about half civilian and half produced for weapons. Most of the weapon-grade plutonium is held by Russia and the United States In 2000, the two countries each committed to dispose of at least 34 tons of weapon-grade plutonium "withdrawn from nuclear weapon programs."[264] The United States has declared excess an additional 20 tons of separated plutonium but Russia has declined to match this additional plutonium because the U.S. material is either not weapon-grade or is mixed with waste. Three tons of the plutonium that is mixed with waste is being buried in the Department of Energy's Waste Isolation Pilot Plant in New Mexico. Another four tons of unirradiated plutonium is reserved for nuclear-energy R&D.[265] This leaves the disposition of 13 tons of the unmatched U.S. excess plutonium to be determined.

Among the other nuclear weapon states, only the United Kingdom has declared any plutonium excess: 0.3 tons or a little less than 10 percent of its stockpile of military plutonium.[266] This plutonium may by now have been blended into the United Kingdom's stock of separated reactor-grade plutonium.

Options for weapons plutonium disposition have been discussed for more than 15 years.[267] In the United States, an authoritative report was produced under the auspices of the National Academy of Sciences, which considered a large range of options and focused on two as being the most feasible in the near term:[268]

- "fabrication and use as fuel, without reprocessing, in existing or modified nuclear reactors;" or

- "vitrification [i.e., mixing into glass] in combination with high-level radioactive waste."

Until one or both of these strategies could be implemented, the study urged that “an agreed and stringent standard of security and accounting must be maintained … approximating as closely as practicable the security and accounting applied to intact nuclear weapons.”[269]

In the Russian-U.S. agreement, Russia chose the first option for disposition of its plutonium and, at Russian insistence, the United States committed to dispose of at least 25 tons of its excess weapon-grade plutonium in the same manner (Figure 6.3).[270]

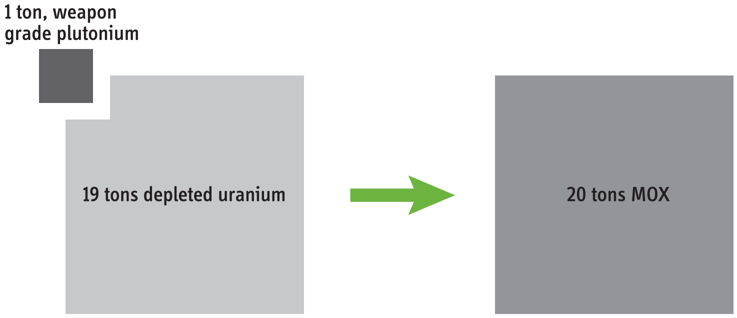


Figure 6.3. Separated plutonium can be mixed with depleted uranium to produce mixed-oxide (MOX) fuel for light-water reactors. Unlike the case of HEU blend-down, it is relatively easy to recover the plutonium from the fresh fuel by chemical extraction. Also MOX-fuel fabrication is not easy. The very high cancer risk from inhaled plutonium requires that the process be carried out in glove boxes. The large amounts of plutonium involved also require stringent safeguards and physical security. As a result, the cost of fabricating MOX fuel is higher than the cost of the LEU fuel that it replaces.

The MOX approach to plutonium disposition has encountered serious problems in the United States and Russia, however, and alternative approaches should still be seriously considered. The state of the policy discussions and IPFM recommendations in each case are discussed below.

United States. The U.S. Department of Energy (DOE) has contracted for the construction of a Mixed-oxide Fuel Fabrication Facility (MFFF) with a consortium led by France’s government-owned company Areva (Figure 6.4). The facility would use excess U.S. plutonium to produce MOX fuel for light-water reactors at a rate of up to 3.5 tons per year. Completion of the facility is currently projected for 2016.

The project has suffered long delays and huge cost escalation, however. In 2002, the DOE estimate was that the MFFF would cost $1 billion and start operations in 2007.[271] In 2009, the capital cost estimate of the MFFF and an associated Waste Solidification Building was $5.2 billion, the projected completion date was in 2016, and the estimated cost of operating the two facilities for 13 years was $2.9 billion.[272]

Figure 6.4. The Mixed-Oxide (MOX) Fuel Fabrication Facility, under construction at the U.S. Department of Energy's Savannah River Site, South Carolina, 28 September 2008.[273] *Source: U.S. Department of Energy*

Even if the MFFF project were completed on the current schedule, however, its operation would be delayed further because the multi-billion dollar Pit Disassembly and Conversion Facility (PDCF) facility that was to recover plutonium from excess U.S. nuclear-weapon pits and convert it into oxide form to feed into the MFFF has been put on hold. In January 2009, concerned that several technologies to be used in the PDCF were "not fully mature," DOE halted design work on the PDCF. Reportedly, DOE is considering whether it might wish to pursue an alternative strategy.[274]

A second issue is that, despite a DOE commitment in the year-2000 U.S.-Russian plutonium disposition agreement (Article VII.3) that it would work with the IAEA to establish arrangements to monitor its plutonium disposition process, it has not yet engaged the IAEA in the discussions of how to arrange for safeguards in the MOX Fuel Fabrication Facility or invited the IAEA to review the facility's design.[275]

Given this situation, the DOE should pause both to establish better management control over its plutonium-disposition program and to consider alternatives to MOX.[276]

In fact, the DOE plutonium-disposition strategy originally had two tracks: a MOX track for pure metal plutonium and an "immobilization" track for impure plutonium and plutonium in oxide form.[277] The immobilization strategy would have first embedded the plutonium in ceramic cylinders, then placed these cylinders on a rack inside a large canister and finally filled the canister with molten glass containing high-level waste to provide a radiation barrier similar to that provided by the fission products in spent fuel.

In 2002, however, DOE decided that the two-track route was too expensive, cancelled the "can-in-canister" immobilization track and decided to do a new study on what to do with its impure and oxide plutonium. In 2006, the study report came back with four options. Three were immobilization options using the high-level reprocessing waste at the Savannah River Site to provide a radiation barrier. Two of these were variations of the cancelled can-in-canister approach and the third would mix plutonium directly into the high-level-waste glass. Two of the options also would use the H-canyon reprocessing plant to dissolve the impure and oxide plutonium and clean up at least some of it to the point where it could be used in the MOX plant.

Of those options, the study found the cancelled can-in-canister approach to be the best. There was concern that keeping the reprocessing plant open would be too costly and that putting too much plutonium into the high-level waste might cause criticality problems.

The vitrification operations at the Savannah River Site are scheduled to be completed by 2019.[278] If this schedule were achieved, the time window for immobilization would be only open until 2019, which would limit how much plutonium could be immobilized. Immobilization of the high-level waste at Savannah River has been repeatedly delayed, however. It was originally supposed to start in 1992,[279] but, as of 2006, "high-capacity" processing was not scheduled to begin before 2011.[280] Also, as of 2009, construction of a vitrification plant at the DOE's Hanford site was underway with the ambition of vitrifying all of Hanford's waste within 25 to 35 years.[281] The immobilization option with high-level waste therefore will continue to be available for some time.

Other immobilization options also exist and should be considered. One proposal would immobilize the plutonium in a ceramic matrix and then dispose of it with spent power-reactor fuel.[282] There is even the question of whether options without a radiation barrier should be considered. Plutonium being disposed in the U.S. Waste Isolation Pilot Plant (WIPP) is not mixed with fission products. Since the radiation barrier decays with the 30-year half-life of the fission product cesium-137, the long-term security of the plutonium would in any case depend upon deep burial and international control of activities around the burial site.

Russia. Russia originally considered building a duplicate of the U.S. MOX plant and recycling its 34 tons of excess weapon-grade plutonium in the fuel of Russian light-water reactors (LWRs). Much of Russia's nuclear-energy establishment wanted instead to use the plutonium to start up a fleet of fast-neutron plutonium-breeder demonstration reactors. Its acquiescence to the LWR plan therefore was contingent on full foreign funding for all the costs of the program, including construction and operation of the MOX plant and conversion of the Russian LWRs to allow the use of MOX fuel. The estimated cost of the program grew in parallel with that of the U.S. plutonium-disposition program to $4.1 billion in 2006.[283]

The U.S. Congress initially supported construction of a MOX-fuel fabrication facility for plutonium irradiation in Russia's LWRs and allocated funds for that purpose. After Russia decided to switch to irradiation in breeder reactors, however, Congress rescinded its previous appropriations.[284] One concern was that the operation of breeder reactors would cause increases in the quantities of plutonium separated and recycle. The spirit of the Russian program therefore was fundamentally at odds with the U.S. objective of reducing stockpiles of separated plutonium. The Obama Administration's proposed budget for Fiscal Year 2010 requested no funding for Russia's MOX-fuel fabrication facility.[285] The future of Russia's plutonium disposition program is therefore uncertain.

In the meantime, the U.S. excess plutonium in pits is in storage at the Pantex plant, where construction of a high-security underground bunker has been proposed to store them,[286] and non-pit excess plutonium has largely been consolidated in an old production-reactor building at the Savannah River site.[287] In Russia, 25 tons of excess plutonium from pits is being emplaced in a high-security bunker built with U.S. assistance at the Mayak reprocessing facility and the remainder of the weapon-grade plutonium that Russia declared excess for weapons is being consolidated in underground storage at another former plutonium-production site at Zheleznogorsk in Siberia.[288]

Given the problems with both U.S. and Russian weapons plutonium disposition programs and that the plutonium is relatively secure, it would be useful for the two states to begin a new process to consider disposition options that would cover both current and future plutonium declared excess.

Civilian Plutonium

The global stock of civilian plutonium, about 250 tons, is mostly located at reprocessing plants in France, India, Japan, Russia and the United Kingdom (Chapter 1). Separation of the civilian plutonium was originally launched in the expectation that it would be used to start up plutonium breeder reactors. That continues to be the expectation in Russia and India. In France, the separated plutonium is being recycled into MOX fuel for its light-water reactors. Japan is starting to do the same with its plutonium that has been separated in France and the United Kingdom, and plans to do so also with the plutonium separated at its new Rokkasho reprocessing plant.

United Kingdom. The situation in the United Kingdom is different, however. 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 not yet developed plans for its separated plutonium.[289] Recently, however, the UK Government has begun a discussion of its plutonium-disposition options.[290] A perspective on this discussion may be found on the IPFM website.[291]

The United Kingdom currently has the world's largest national stockpile of separated civilian plutonium at its Sellafield reprocessing plants. Unless it halts reprocessing of its own spent fuel before it fulfills its existing contracts, its stockpile of separated civilian plutonium will increase from 82 tons of domestic and 27 tons of foreign plutonium at the end of 2008[292] to about 97–120 tons of separated domestic civilian and 34 tons of foreign plutonium.[293]

The United Kingdom has two reprocessing plants at Sellafield. The B-205 plant reprocesses metal natural-uranium fuel from first-generation "Magnox" reactors, the last of which is to be shut down in 2010.[294] The reprocessing of the Magnox fuel will probably have to be completed because the fuel is low "burnup" and therefore much more voluminous per unit of electricity generated than LWR oxide fuel. It also corrodes easily and therefore is relatively more costly to store.[295]

But spent uranium-oxide fuel from light-water reactors and the UK's Advanced Gas-cooled Reactors (AGRs) can be stored for much less ($100–200/kg) than it costs to reprocess it in an already built operating reprocessing plant (about $900/kg).[296] Reprocessing is much more costly in the UK's Thermal Oxide Reprocessing Plant (THORP), which has been mostly shut down since April 2005.[297]

The United Kingdom could save the cost of refurbishing and operating the troubled THORP plant and the cost of disposing of the additional plutonium to be separated there if it did not reprocess the approximately 3000 tons of AGR spent fuel containing about 27 tons of plutonium and 750 tons of foreign light-water reactor fuel containing 7.5 tons of plutonium that remain to be reprocessed under its existing contracts.

With regard to the reprocessing of foreign spent fuel, the contracts specify that the United Kingdom will return to the owning country the resulting solidified high-level radioactive waste and separated plutonium—the latter either in the form of MOX fuel or in the form of plutonium oxide delivered to another fabricator of MOX fuel.

One way for the United Kingdom to proceed, therefore, might be to exchange its own already separated plutonium and vitrified high-level waste for that which would have been produced by reprocessing the spent foreign fuel. Such "virtual reprocessing" was suggested in 1993 by President Clinton's Science Advisor to his UK counterpart as a much more economical alternative to operating the THORP plant.[298]

In 2007, the NDA received permission from the UK Government to substitute UK plutonium for foreign plutonium that had not yet been separated in order to fulfill requirements for MOX fuel fabrication for its foreign customers.[299] Nevertheless, the Government rejected suggestions that this approach be used as an alternative to reprocessing the remaining foreign spent fuel.[300]

Conclusion

The disposal of much of the HEU recovered from dismantled excess Cold War warheads is well underway. But much more could be declared excess and stocks reserved for naval-reactor fuel could be declared excess as well if the United States, Russia and the United Kingdom followed France's example and designed their future naval reactors to use LEU fuel. This would allow roughly two-thirds of the current global HEU stockpile to be available for blenddown. The United States and Russia together could plausibly blenddown this much HEU in about 15 years. HEU in irradiated spent fuel that is not scheduled for reprocessing and blend down should be securely stored and placed in secure geological repositories once they become available.

There has not been much progress yet in disposition of excess weapons plutonium. There exist plans to do so in Russia and the United States, principally by irradiating MOX in plutonium breeder reactors and light-water power reactors, respectively. Given the great costs and continuing delay of these options, and the fact that breeder reactors would create a demand for continued civilian reprocessing, the alternative of immobilization—with or without high-level waste—should be seriously reconsidered by both countries. The United Kingdom would reduce its plutonium disposition problem if it gave up trying to complete its foreign reprocessing contracts and opted instead for "virtual reprocessing," in which it fulfills those contracts by exchanging already separated UK plutonium and high-level waste for foreign spent fuel.

In the absence of an end to reprocessing, there will continue to be large stockpiles of civilian plutonium. France is recycling about 10 tons per year; after more than a decade of delay Japan is launching its own plutonium-recycle program; and China has similar plans, although perhaps two decades in the future. In that time frame, Russia and India each could be recycling a few tons per year in breeders. With several years of material in the pipeline, it would be difficult even with the best intentions to get below a global inventory of civilian plutonium on the order of 100 tons—enough to make more than 10,000 warheads. If disarmament proceeds, these stockpiles would become of increasing concern.

7

Verified Cutoff of Fissile Material Production for Weapons

Setting up arrangements to verify a ban on the production of fissile materials for weapons is a part of the nuclear disarmament agenda that hopefully will soon be under negotiation at the UN Conference on Disarmament (CD) in Geneva. On 29 May 2009 the CD agreed to begin negotiations on "a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."[301] The proposed treaty is often referred to as the Fissile Material Cutoff Treaty (FMCT) and by the IPFM as the FM(C)T.[302] Verification of an FM(C)T was discussed at length in *Global Fissile Material Report 2008*. This chapter provides an overview and places it in the context of the nuclear disarmament agenda. For details, the reader is referred to the 2008 report.

Under a nuclear disarmament regime, the distinction between weapon and non-weapon states would disappear, and all fissile material would be under international safeguards. The question is how large a step in that direction will be taken under an FM(C)T. Specifically, negotiation of an FM(C)T will have to address two fundamental issues:

1. Whether and to what extent a treaty banning any new unsafeguarded production of fissile materials should also subject pre-existing non-weapons stocks of fissile material to international monitoring to verify that they are not converted to weapons use, and

2. How such a treaty should be verified, including the extent to which safeguards obligations in the nuclear weapon states and non-nuclear weapon states will converge.

An incomplete moratorium

Four of the five weapon states that are Parties to the Non-Proliferation Treaty—the United States, Russia, the United Kingdom and France—declared in the late 1980s and early 1990s that they had permanently ended production of fissile materials for nuclear weapons. China's government did not make such a public declaration but has let it be known unofficially since the early 1990s that it has suspended production and will only feel compelled to resume if it feels that the effectiveness and/or survivability of its deterrent is being eroded by a buildup of U.S. missile-defenses and/or long-range precision-guided weapons.[303]

In South Asia, production of fissile materials is accelerating as India builds a "minimum deterrent" of unspecified size and Pakistan races to build up its fissile-material production capacity (Chapter 1). Israel's policy of "opacity," i.e., not talking about its nuclear-weapon-related activities, has left unclear whether it is continuing to produce weapon-grade plutonium at its Dimona nuclear complex but, most likely it is, if only as a byproduct of its tritium production.[304] Finally, on 24 September 2008, North Korea announced that it would resume separation of plutonium for weapons and, on 13 June 2009, announced that it was launching a program to enrich uranium for weapons as well.[305]

As the world moves toward complete nuclear disarmament, however, all the nuclear weapon states will have to halt production of fissile material for weapons and accept effective arrangements to verify this.

Verification of a ban on production of fissile material for weapons

Verification of a ban on the production of fissile materials for weapons will require determinations that:

1. Production facilities that have been declared shut down are indeed shut down and remain so;

2. All plutonium separated and HEU produced at declared production facilities after the ban comes into force are placed under IAEA safeguards and remain under safeguards; and

3. There are no undeclared enrichment or reprocessing facilities.

Shutdown production facilities. Under an FM(C)T, countries would either convert production facilities (reprocessing plants, plutonium-production reactors, and enrichment plants) to safeguarded civilian use or shut them down and decommission them.

Reprocessing plants. In practice, the facilities used to recover weapon-grade plutonium from the low-burnup[306] magnesium or aluminum-clad uranium metal used in production reactors are so different from those used to reprocess the high-burnup zirconium-clad uranium-oxide fuel used in most power reactors that no military reprocessing plant has been converted to civilian use. A few plutonium-production reactors have been operated as dual-purpose reactors, producing electricity as well as weapon-grade plutonium, but operating them for electricity production alone has been uneconomic and all such dual-purpose reactors have been decommissioned or soon will be.[307]

Enrichment plants. In the United States, military gaseous diffusion enrichment plants were converted to civilian use but two out of the three have now been shut down and replacement capacity for the third is under construction. In China, it is believed that the two gaseous diffusion plants used to produce HEU for weapons have been shutdown. LEU for China's power reactors is produced by centrifuge enrichment plants. In France, the Pierrelatte gaseous enrichment plant that produced France's HEU is being decommissioned. In Russia, three large centrifuge plants that produced HEU for weapons have been converted to producing low-enriched uranium for nuclear power plants.[308] The UK's centrifuge enrichment plant that produced some of its HEU has similarly been converted.

Most facilities for producing fissile materials for weapons in the five NPT weapon states are therefore shut down and, in some cases, are in the process of being decommissioned.

The verification challenge at these sites will be minimal. It will only be necessary to confirm that key equipment necessary to the operation of the facility has been disabled or removed. Seals could be applied to assure that spent fuel is not introduced into reprocessing plants or uranium feedstock into enrichment plants and remotely monitored electronic cameras and other sensors could be set up to monitor any activity in key areas of the plants with periodic random unannounced on-site checks to make sure that the seals are intact and monitoring systems are functioning properly. Facilities for which there are no conversion plans should be decommissioned as quickly as possible to make their shutdown irreversible.

Operating reprocessing and enrichment plants. The second element of verifying an FMCT would be to assure that any plutonium, HEU or other fissile material[309] produced in a declared reprocessing plant or enrichment plant after the treaty comes into force for a Party, is placed under IAEA safeguards.

Reprocessing. Some weapon states (China, France, India, Russia and the United Kingdom) and one non-weapon state (Japan) are separating large quantities of weapon-usable plutonium from spent power-reactor fuel for civilian purposes. The original rationale was to provide startup fuel for plutonium-breeder reactors. When those reactors were not commercialized, Belgium, France, Germany and Switzerland began to recycle their separated plutonium in light-water-reactor fuel.[310] Japan and China intend to do the same while India and Russia are still moving ahead with their breeder programs, although at a glacial pace. The United Kingdom is winding down its reprocessing and is beginning to consider options for disposing of approximately 100 tons of separated power-reactor plutonium that it has accumulated (Chapter 6).

Reprocessing and plutonium recycle are not economic, nor are plutonium breeder reactors. Nor do they simplify the problem of spent fuel disposal.[311] Furthermore, the spread of reprocessing has been closely associated with the spread of nuclear-weapons programs. Today, only one non-weapon state, Japan, reprocesses and twelve non-weapon states that in the past sent their spent fuel to France, Russia and the United Kingdom to be reprocessed have not renewed their contracts. For them, reprocessing, simply exchanged the problem of storing and disposing of spent fuel for the equally politically challenging problem of storing and disposing of the solidified high-level reprocessing waste that the reprocessing countries insist on sending back to their foreign customers. Countries that have reprocessing plants have the political advantage that it does provide a single central location to which their nuclear power plants can ship their spent fuel.[312]

Modern civilian reprocessing plants are designed to separate annually 7–17 tons of plutonium—enough to make a thousand nuclear weapons or more.[313] Since plutonium is a directly weapon-usable material, this puts a tremendous burden on safeguards. Even with input and output measurement errors of plutonium from reprocessing and mixed-oxide (uranium-plutonium) fuel fabrication plants as low as one percent, it would be impossible to prove by mass balance checks alone that plutonium, sufficient to make tens of weapons had not been diverted. The IAEA, therefore, adds layers of expensive monitoring, containment and surveillance to increase its confidence that no significant diversions are occurring at Japan's reprocessing plants, especially at the large, recently completed plant at Rokkasho. This reprocessing plant plus a smaller pilot plant, the only reprocessing facilities in a non-weapon state, account for about 20 percent of the IAEA's total safeguards budget.[314]

Enrichment and reprocessing facilities worldwide

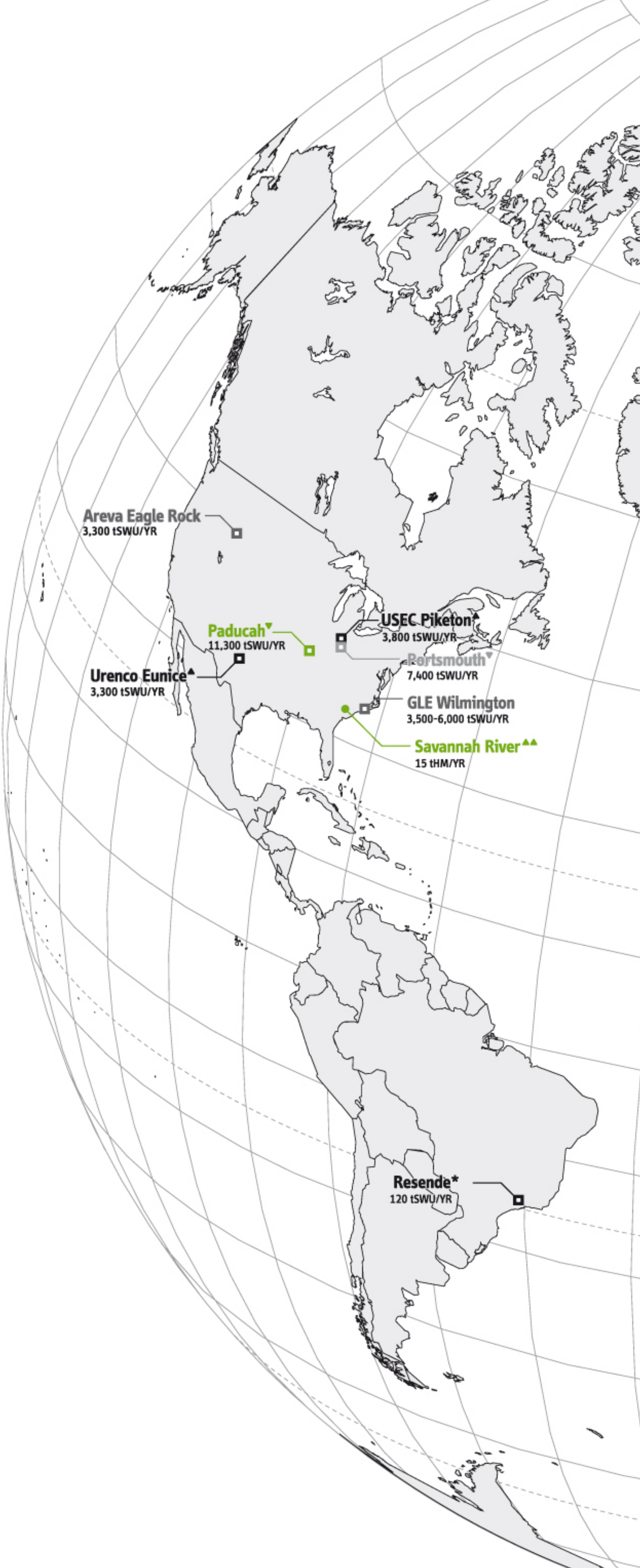
▣ Enrichment Facility
● Reprocessing Facility

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

Operational
Under Construction
Planned
Future uncertain

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

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



IPFM graphics redrawn from *Bulletin of the Atomic Scientists*

Ten states operate a total of 18 reprocessing plants. This includes two plants (in Japan and China) still undergoing testing prior to operation and three scheduled to be shutdown (two in Russia and one in the United Kingdom). Pakistan is building possibly one additional reprocessing plant, which is also included here. Only India, Israel, North Korea and Pakistan are believed to be producing plutonium for weapons.

Twelve states have 23 operating, under construction or planned uranium enrichment plants. This does not include North Korea, which in 2009 claimed to have successfully enriched uranium. All of these are centrifuge plants, except for two gaseous diffusion plants (in France and the United States) that are to be replaced with centrifuge plants currently under construction or planned, and a laser enrichment plant under development in the United States. There are possibly only three military plants producing HEU today (two in Pakistan and one in India). The map does not include all R&D and pilot scale plants.


BNFL Magnox**▼
1,500 tHM/YR
BNFL Thorp**▼
1,200 tHM/YR
Urenco Nederland*
3,800 tSWU/YR
Urenco Capenhurst**
5,000 tSWU/YR
Urenco Deutschland*
2,200 tSWU/YR
La Hague UP2**
1,000 tHM/YR
La Hague UP3**
1,000 tHM/YR
Georges Besse II▲
7,500 tSWU/YR
Eurodif/Georges Besse**▼
10,800 tSWU/YR
Novouralsk▲▲
13,300 tSWU/YR
Seversk▲▲
3,800 tSWU/YR
Seversk▲▲▼
6,000 tHM/YR
Zelenogorsk▲▲
7,900 tSWU/YR
Zheleznogorsk▲▲▼
3,500 tHM/YR
Angarsk▲
2,200 tSWU/YR
Mayak RT-1▲▲
400 tHM/YR
Rokkasho*
800 tHM/YR
Rokkasho*
1,050 tSWU/YR
Yongbyon▲▲▼
100–150 tHM/YR
Yumenzhen
50–100 tHM/YR
JNC Tokai*
200 tHM/YR
Gadwal▲▲
TBD
Lanzhou 2▲
500 tSWU/YR
Shaanxi**
500–1,000 tSWU/YR
Qom*
TBD
Kahuta▲▲
20–30 tSWU/YR
Nilore▲▲
20–40 tHM/YR
Chashma
50–100 tHM/YR
Natanz*
120 tSWU/YR
Dimona▲▲
40–100 tHM/YR
Tarapur▲▲
100 tHM/YR
Trombay▲▲
50 tHM/YR
Kalpakkam▲▲
100 tHM/YR
Rattehalli▲▲
20–30 tSWU/YR

At Rokkasho, the IAEA was able to verify the design of the reprocessing plant and installed independent measuring instrumentation before some areas of the plant were embedded in concrete or became contaminated. For pre-existing plants, the IAEA would not have this luxury. Nevertheless, it should be possible to design safeguards procedures, including the use of short-notice random inspections that would make it difficult to operate the plant improperly and make it possible to detect a diversion of plutonium larger than the measurement errors in the plant plutonium throughput.[315]

It would be better for verification of an FM(C)T, however, if reprocessing was phased out altogether. This would also have the advantage of allowing attention to be focused on the elimination of the existing large stockpiles of civilian and excess weapons plutonium. Given that civilian spent-fuel reprocessing is neither economic nor necessary to nuclear power for the foreseeable future, such a phase-out does not appear an unreasonable goal (Chapter 8).

Enrichment. Only one country, India, is known to be producing HEU for non-weapon purposes today. India is building naval reactors that reportedly are fueled with HEU enriched to between 20 and 40 percent uranium-235.[316] Other countries (the United States, Russia and the United Kingdom) are known to use HEU in naval-reactor fuel but their requirements could be satisfied for many decades using excess Cold War weapons HEU. France has already shifted its naval reactors to LEU. HEU is also used as a research reactor fuel but, outside Russia at least, it is being replaced by LEU.

Thus the major challenge in the near term would be to verify that all operating enrichment plants except India's are indeed not producing HEU. In principle, the enrichment of the uranium in the key collector or "header" pipes in the enrichment plants could be monitored. This may be impractical in Russia's huge enrichment plants, however, because they have hundreds of thousands of relatively low-capacity centrifuges and complex piping arrangements (Figure 7.1).

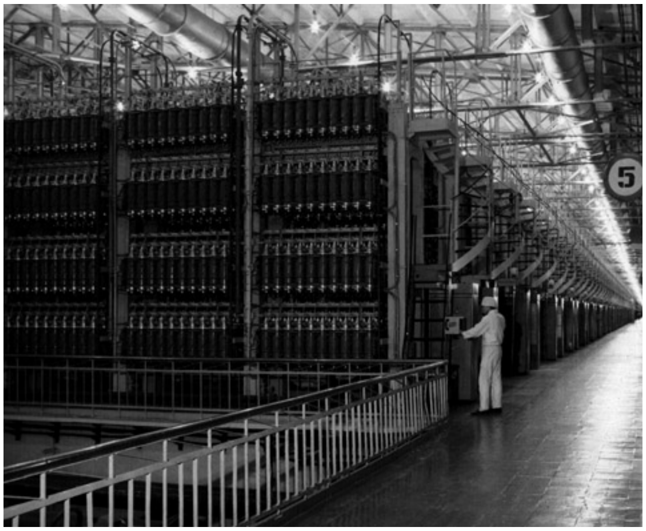


Figure 7.1. Interior of Russia's Novouralsk gas centrifuge enrichment plant. This facility has a capacity of over 10 million SWU/yr.[317] *Source: U.S. Department of Energy*

A supplementary approach to detect clandestine HEU production in a large enrichment plant would be to look for traces of leaked HEU. The IAEA has used this technique with remarkable effect in Iran and elsewhere. It involves taking "swipes" of surfaces inside a facility and then inspecting the dust picked up by the swipe for particles of uranium.

When such particles are identified, they can be bombarded by a beam of atoms that will knock off uranium ions that can be passed through a mass spectrometer to determine the percentages of uranium-235 and uranium-238. Figure 7.2 shows an example of a pair of images of a 0.15-mm (150-micron) square that are formed by ions knocked off uranium particles deposited on the surface of a planchet. The relative brightness of the particles in the images depends upon the percentages of uranium-235 or uranium-238 atoms in a given particle.

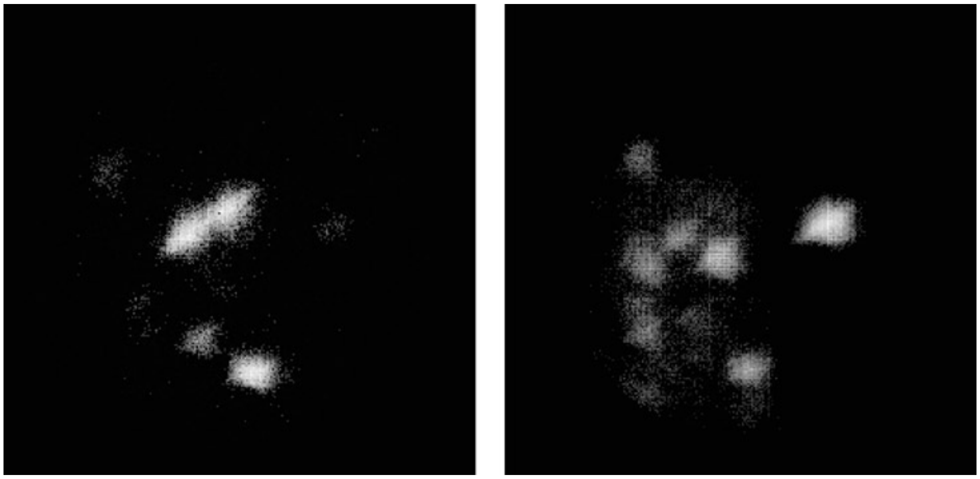


Figure 7.2. Images of micron-sized particles of uranium from swipes. The images were obtained by scanning the particles with an ion beam and using a mass spectrometer to separate the different-mass uranium ions that were knocked off. Particles that are bright in the U-235 image (left) are HEU. Those that are bright in the U-238 image (right) are low-enriched or natural uranium.[318] *Source: IAEA*

The complication for the case of Russia's centrifuge enrichment facilities is that there could be old particles of HEU dating back to when Russia was producing HEU before 1989. These particles would have to be distinguished from possible new particles of HEU. One approach, age dating the particles using the in-built clock associated with the decay of uranium-234 into thorium-230 is discussed in *Global Fissile Material Report 2008*, Chapter 4.[319]

India may continue producing HEU but its enrichment plant is small enough so that its output of HEU could be accurately monitored.

Non-weapon use of fissile materials. Once HEU or plutonium is under safeguards, it must be carefully monitored until, in the case of HEU, it is down-blended to low-enriched uranium, and, in the case of plutonium, it is embedded in a radioactive matrix equivalent to the plutonium in spent power reactor fuel.[320] In most cases, effective approaches for doing this have been worked out for NPT safeguards in non-weapon states.

A new safeguards issue for the weapon states, however, will be the fact that many of them have HEU-fueled military reactors. Most of these are naval reactors but Russia, for example, also uses HEU-fueled reactors to produce tritium for its nuclear weapons.[321]

Any new production of HEU for reactor fuel would have to be safeguarded under an FM(C)T and, depending upon the scope of the FM(C)T, some pre-existing stocks of HEU also could come under safeguards. The quantity of HEU in military-reactor fuel cycles is substantial. The United States, for example, uses an average of about 2000 kg of weapon-grade uranium annually to fuel the reactors that propel its submarines and aircraft carriers. If converted to first-generation Nagasaki-type implosion weapons at 25 kg per weapon, that would be enough to produce 80 nuclear weapons a year.

The non-weapon use of HEU produced or reserved for naval and tritium-production reactor fuel could be verified by measuring the quantity of HEU produced or withdrawn from stocks to make HEU fuel and then confirming that it was actually put into a reactor. Verification procedures that have been developed for HEU-fueled research reactors might have to be altered if, as appears likely, some of the weapon states will consider the designs of their military reactors and their fuel to be sensitive information. The IPFM has been exploring various technical approaches that could help, but the IAEA and the weapon states would have to work out compromises under which the most sensitive design and operating information would be concealed while still enabling the IAEA to obtain enough information to verify that no significant amount of HEU was being diverted. The best solution, however, would be for the weapon states to switch to LEU-fueled reactors. The international community then would not have to worry about possible diversions of HEU from the naval fuel cycles and the nuclear navies could preserve military secrets.

Clandestine production. Finally, there is the challenge of detecting clandestine reprocessing or enrichment activities. This is a challenge that is already faced in non-weapon states that are parties to the NPT. Iraq mounted a clandestine enrichment program as did Libya and Iran. In all three cases, the programs were discovered before they went into operation. For Iraq, the discovery was as a result of that country having to accept intrusive inspections after its defeat in the 1991 Gulf War. This helped lay the basis for the Additional Protocol under which non-weapon states commit to declare to the IAEA all significant nuclear-related activities and allow the IAEA to check those declarations.[322] Iran voluntarily complied with the Additional Protocol for two and a half years between 2003 and 2006. During that period, the IAEA was able to visit suspect sites and detected undeclared enrichment-related activities.

The Additional Protocol also creates the possibility that the IAEA, if authorized by the IAEA Board, could carry out wide-area environmental monitoring to detect evidence of clandestine reprocessing or enrichment. There is a long Cold War history of atmospheric measurements of the concentration of the 11-year half-life fission product krypton-85 to detect foreign reprocessing activities.[323] Recently, published analyses have begun to appear. Figure 7.3 shows the detection of krypton-85 at a site 60 kilometers away from a Japanese pilot reprocessing plant. Krypton-85 releases were detected with at least 50-percent probability down to levels corresponding to the separation of about 2 kg of weapon-grade plutonium per week, i.e., about one bomb equivalent per month.

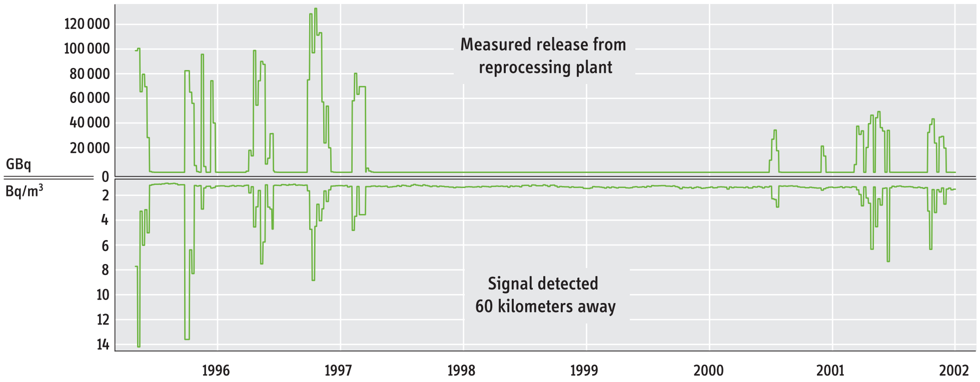


Figure 7.3. Releases of the radioactive gas krypton-85 make it possible to detect a reprocessing plant at some distance downwind. The figure shows the correlation between measurements of Kr-85 concentrations (inverted below the axis) 60 km from the Tokai, Japan experimental reprocessing plant compared to the measured releases from the plant (above the axis).[324]

The gaseous releases from centrifuge enrichment plants are very small. The uranium hexafluoride (UF_6) gas in the system is at less than atmospheric pressure with the result that leakage is generally of air into the system rather than UF_6 outward except when natural-uranium feed and enriched-uranium product cylinders are detached from the system. Air filtration systems are also standard equipment. Still, the degradation products of UF_6 in the environment, molecules containing both uranium and fluorine, do not occur naturally. It is therefore worthwhile to determine if extremely sensitive detection techniques could be developed for such molecules. Furthermore, if tight controls could be established on UF_6 at declared production plants, then a clandestine enrichment plant would require a clandestine UF_6 production plant. Such plants produce the UF_6 at above atmospheric pressure and therefore leak more UF_6 than centrifuge enrichment plants.[325]

When there is an indication of possible clandestine reprocessing or enrichment activity, the IAEA has the right to request an inspection. In a non-weapon state—and presumably in a nuclear-weapon-free world—inspectors would be free to take and analyze swipes. During the transition, at military nuclear sites in a weapon state, however, swipes could reveal information that a state considers sensitive: the isotopic makeup of or alloying material used in its weapon-grade plutonium, for example.

This is a familiar situation for the verification of the Chemical Weapons Convention (CWC) since chemical manufacturers wish to protect proprietary processes. Nevertheless, the Organization for the Prohibition of Chemical Weapons (OPCW), which is responsible for the verification of the CWC, uses sensitive instruments, notably gas-chromatograph mass spectrometers (GCMS) that are capable of identifying millions of chemical species and could be used for industrial espionage. For purposes of verifying the CWC, however, the chemical manufacturers and the OPCW have devised a “managed access” approach under which the library of chemical signatures inside the GCMS memory is purged of all information other than that relating to chemical-weapon agents, their precursors and degradation products.

The IAEA could similarly use instruments that have been rendered incapable of detecting anything beyond information required by the inspectors. Figure 7.4 shows, for example, a technique that could be used as a substitute for swipe samples. Laser breakdown spectroscopy could be used to turn particles on a surface into ionized plasma that would emit light with wavelengths characteristic of the particles' constituent atoms. If spectral lines characteristic of uranium and fluorine were found together, that would be an indicator of gas centrifuge enrichment. The lines of all other elements could be blocked.

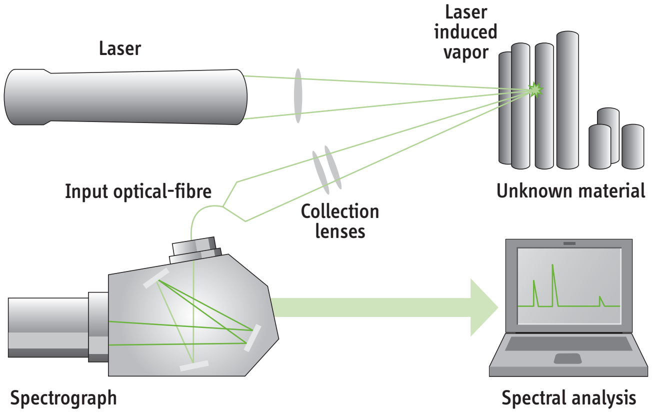


Figure 7.4. Laser breakdown spectroscopy. A laser is used to vaporize a microscopic amount of material on a surface. The light emitted by the resulting incandescent vapor is analyzed by a spectrometer. An indicator of gas-centrifuge uranium enrichment having taken place in the facility would be the presence together of spectral lines of uranium and fluorine. The computer could block the detection of lines associated with other elements. *Graphics adapted from the Canadian IAEA Safeguards Support Program.*

Thus, under an FM(C)T, the safeguards obligations of the nuclear weapon states and the non-weapon states would begin to converge, with the IAEA having the responsibility of verifying non-production of fissile materials for weapons at both declared and suspect nuclear sites in all states. The authority of the IAEA to check for undeclared nuclear activities has been strengthened and codified in the Additional Protocol. It will be critical to the verifiability of nuclear disarmament that both weapon and non-weapon states ratify this Protocol.

In a nuclear-weapon-free world, several of the verification problems that will have to be dealt with today under a fissile cutoff treaty would be considerably eased. For one, there would be no stocks of fissile material not under international safeguards. Secondly, all states, including the nuclear weapon states, would have to adhere to a strict and strengthened Additional Protocol. Finally, managed access procedures could be greatly simplified because the nuclear-weapon states would no longer need to protect nuclear weapon-design information.

Appendix 7A.

Verification of a Ban on Tritium Production for Weapons

Tritium (T), the super-heavy artificial isotope of hydrogen, is thought to be used by all the NPT nuclear weapon states in most of their nuclear warheads. India, Israel, and Pakistan also are suspected to be using tritium in their weapon programs. It is used to increase ("boost") the amount of fission and hence explosive yield of a nuclear weapon by generating additional neutrons through the fusion reaction with deuterium (D), the heavy form of hydrogen that constitutes 0.015 percent of hydrogen in nature:

$$\text{deuterium} + \text{tritium} \rightarrow \text{helium-4} + \text{neutron}$$

Boosting has made possible the high-yield, compact nuclear warheads that characterize the arsenals of the NPT weapon states. Removing the D-T boost gas would reduce the yields of most of these warheads into the sub-kiloton range.[326] It is estimated that 2–3 grams of tritium are used for each warhead.

Due to its short half-life of 12.3 years, tritium has to be replenished on a regular basis. It can be produced in nuclear reactors, mostly by neutron capture in lithium-6, via the reaction:

$$\text{lithium-6} + \text{neutron} \rightarrow \text{helium-4} + \text{tritium}$$

This reaction process is similar to the production of plutonium by neutron capture on uranium-238. The same production reactors therefore can be used for both plutonium and tritium production. In heavy-water-moderated reactors, deuterium captures a neutron, generating tritium:

$$\text{deuterium} + \text{neutron} \rightarrow \text{tritium}$$

Thus, tritium is unavoidably produced in the moderator and can be extracted with a detritiation facility.

Tritium is gaining significance within the nuclear proliferation process. This is exemplified by the successful attempts of India and Pakistan to acquire tritium-production technology from the West. Banning the production of tritium for weapons could also be a part of a broader nuclear disarmament process.

Production of tritium today

In 2009 there are about 10 production reactors remaining that are used for tritium generation or are available for that purpose (Table 7A.1). Few if any of these are dedicated to tritium production; some probably are primarily for plutonium production; two produce radioisotopes for sale; and one is a commercial power reactor.

Production of tritium in the United States was interrupted with the shutdown of the K-Reactor at Savannah River Site in 1988. In 2003, the capability to produce tritium for U.S. weapons was re-established using the pressurized water reactors operated by the Tennessee Valley Authority at Watts Bar. Irradiated lithium-6 targets are transported to a tritium-extraction facility at the Savannah River Site that became operational in

2007.[327] Russia continues to produce tritium as needed in two HEU-fueled reactors at its complex near Ozersk in the Urals.[328] The Indian reactors Cirus and Dhruva are known to produce plutonium and tritium in lithium-6 targets. In addition, tritium is gained by detritiating the heavy water. Pakistan can produce tritium both in the core of the unsafeguarded Khushab reactor as well as in the moderator. The Kanupp reactor is under safeguards, but the IAEA has no mandate to inspect the detritiation of its heavy water.

State of tritium controls

Three levels of control can be distinguished: facility, national, and international. Measures taken at a higher level generally have effects at the lower levels. In all countries, some sort of tritium control is obligatory at the facility level for radiation-protection purposes. Most countries also have national-control systems that become effective above a certain threshold inventory of tritium.

International tritium control is still in its infancy. The IAEA has no mandate for tritium control because it is not a fissile material and, during negotiations of the 1968 NPT, it was decided not to include tritium in the definition of "special nuclear materials" and not to place it under international nuclear safeguards.[329]

Country	Facility	Start up	Tritium prod. capacity by capture of neutrons in deuterium of heavy water	Tritium prod. capacity by irradiation of lithium-6 targets	Actual usage for tritium (T), plutonium (Pu) prod. or other purposes
China	Second Ministry of Machine Building Industry	1968	–	?	only T
France	Celestin I/II, 250 MWt heavy-water reactors	1967/68	2 × 17 g/yr	2 × 150 g/yr	Pu (ended) and T
India	Cirus 40 MWt & Dhruva, 100 MWt heavy water reactors, Bhabha Atomic Research Center	1960 and 1988	3 and 7 g/yr	24 and 60 g/yr	Pu and T
Israel	Negev Nuclear Research Center Dimona, IRR-2, 70 MWt	1963	5 g/yr	40 g/yr	Pu and T
Pakistan	Kanupp 125 MWe & Khushab 50 MWt heavy water reactors	1971 and 1998	9 and 3 g/yr	0 and 30 g/yr	Kanupp: T, electric power generation Khushab: Pu and T
Russia	Ozersk (former Chelyabinsk-65) Ruslan and Lyudmila LWRs ~1000 MWt each	1979 and 1988	–	4000 g/yr	T, ^{238}Pu and other commercial radioisotopes
USA	Watts Bar, pressurized water reactor, ~1200 MWe	2003	–	3000 g/yr	T, electric power generation

Table 7A.1. Operating reactors available for tritium production, 2009.[330] India has 13 operating unsafeguarded heavy-water power reactors that produce tritium in their moderator.

In September 1990, the 4th review conference of the parties to the NPT recognized that tritium is—although not identified in NPT Article III.2—relevant to the proliferation of nuclear weapons. The conference therefore called for "early consultations among states to ensure that their supply and export controls are appropriately coordinated."[331] No subsequent activities were initiated within the NPT framework, but, as a consequence of this resolution, international coordination of export controls was strengthened.

The Coordinating Committee for Multilateral Export Control (CoCom) was the first institution that coordinated national export controls of tritium. According to CoCom regulations, licenses were required for exports of tritium and of equipment specifically designed for the production or recovery of tritium. But CoCom regulations did not require any verification provisions, and not many countries adhered to the regime.

The Wassenaar Arrangement resulted in a new control body and partly liberalized export controls. In 1992, the Nuclear Suppliers Group (NSG) adopted "Guidelines for Transfers of Nuclear-Related Dual-Use Equipment, Material and Related Technology." The dual-use list covers not only tritium, tritium compounds and mixtures but also raw materials for the breeding of tritium and tritium facilities or components. The NSG guidelines are not legally binding, however, and do not include verification provisions. Tritium control for nonproliferation purposes at the international level is therefore still limited. A trilateral tritium control agreement on European tritium handling research facilities that receive tritium from Canada may provide the basis for a stronger regime.

Tritium control between Canada and Europe

In May 1991, EURATOM and Canada, the world's largest producer of tritium for civilian use, extended their 1959 agreement for cooperation in the peaceful uses of atomic energy.[332] The agreement covers fusion-energy as well as fission research and development. Tritium is used as fuel in fusion reactors. The parties agreed that EURATOM would establish control procedures for tritium shipments from Canada to EURATOM member states: "EURATOM shall apply to tritium items appropriate recording, accounting and inventory procedures." EURATOM verifies the inventory at the receiving facility as long as the tritium remains there and makes sure that the tritium is neither removed without authorization nor used for purposes other than fusion research, nor re-transferred beyond the territories of EURATOM member states without prior written consent of the Government of Canada.

EURATOM's control system relies on two different procedures:

- Operators submit monthly declarations to the EU-Commission's Directorate General for Energy and Transport, Direction H (DG TREN-H), providing information such as the amount of tritium stored, and whether removals or additions have taken place. These declarations are regularly analyzed by EURATOM and compared to data provided by Canadian suppliers.

- Annual inspections of tritium facilities are conducted by EURATOM. These inspections review and evaluate the operators' tritium bookkeeping and physically verify their tritium holdings using an approved measuring method.

Thus far, only two facilities (Tritium Laboratory Karlsruhe and the Joint European Torus) have been subject to such supranational tritium control while hundreds of facilities world-wide contain quantities exceeding one gram of tritium.[333] These include several detritiation facilities that are used for the extraction of tritium from heavy water used in reactors.

The fusion research facility ITER in Cadarache, France, will receive its first tritium supply at the earliest in 2016. The amounts of tritium located and produced in this place will be unprecedented. The operational inventory will be 2–5 kg; on-site stocks could be more than 20 kg; and annual production is likely to be close to 300 kg. This will raise the importance for tritium control for nonproliferation but creates significant challenges for EURATOM's accountancy and inventory verification.[334]

International tritium controls for nonproliferation

Tritium control on the international level could have two objectives:

- To prevent diversion of tritium from civilian facilities to be used for weapon purposes. This is the same nonproliferation objective as international controls on fissile materials.

- To reduce the amount of tritium available for nuclear weapon states by stopping its production. Decay then would gradually reduce the stockpile. This objective has not yet been embraced by the nuclear weapon states.

An International Tritium Control System (ITCS) has been proposed for the purpose of preventing diversion of civilian tritium to weapons use.[335] Its four rules would be:

- No tritium produced in civilian facilities would be made available for any nuclear explosion purpose.

- No tritium would be exported to states not party to the treaty.

- States party to the treaty could acquire tritium by import or indigenous production for civilian purposes, provided they carried out accountancy measures, reported the resulting data to a supervising international agency, and accepted agency inspections of all their tritium facilities and stocks.

- If the accumulated amount or throughput of tritium (including imports and indigenous production) in a state party to the treaty exceeded a "significant quantity" (SQ, of, for example, one gram), it would be subject to inspection, including verification of the end-use of any exported tritium.

For nuclear-weapon-state parties to the ITCS, these obligations would apply only to their civilian facilities and materials. Nuclear-weapon uses of tritium produced in military production facilities in nuclear weapon states would remain uncontrolled.

Since the verification tasks of the ITCS are comparable to those carried out by the IAEA for plutonium and HEU, it would be worthwhile to consider giving the IAEA a mandate to verify the non-weapon use of civilian tritium. The IAEA is the main international organization within the nuclear nonproliferation regime that carries out verification tasks worldwide. The verification tasks regarding tritium are compatible with the principles and norms of the IAEA Statute. According to Article III.5 of the IAEA Statute, the Agency is authorized "to establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment, facilities, and information made available by the Agency … are not used in such a way as to further any military purpose." Such controls could be implemented at the request of the parties to any bilateral or multilateral arrangement in the field of nuclear energy.[336] The procedures and measurement technologies applied for nuclear safeguards related to fissile materials can easily be adapted to the additional task of detecting clandestine tritium production. This as well as tritium accountancy and inventory verification can be implemented at reasonable cost.[337]

Integrating tritium controls into a Fissile Material (Cutoff) Treaty

Tritium controls could reinforce nuclear disarmament if a cutoff of the production of tritium for nuclear weapons were integrated into a fissile material (cutoff) treaty or FM(C)T.[338] The goal of such an Integrated Cutoff (ICO) would be to end tritium supplies for nuclear weapons program on the way to complete nuclear disarmament. The four tritium-related key rules of this ICO would be the following:

- No tritium production for nuclear weapons purposes.

- All military facilities for the production of tritium in weapon states would be converted to civilian use or shut down.

- No new facilities for the production of tritium for weapons would be constructed, including using new tritium production technologies such as particle accelerators.

- No civilian facilities would be converted into military facilities or made use of for military purposes, and no tritium produced in civilian facilities would be transferred to military uses.

The reinforcement of disarmament by the decay of the military inventory of tritium with a half-life of 12.3 years could be accelerated by simply removing tritium from nuclear warheads and placing it under IAEA safeguards.[339] Assuming that most nuclear weapons rely on tritium for boosting their yield, they would have a greatly reduced catastrophic potential as soon as the tritium was removed. The precondition for such a qualitative nuclear disarmament would be a decision to abandon high-yield nuclear weapons. This could be an attractive first quick step after a decision for global and complete nuclear disarmament.

Complete and non-discriminatory international control of tritium would be achieved by a combination of these two proposed agreements. Implementation of the ITCS without the ICO would lead to further discrimination against the non-nuclear weapon states, because they would have to fulfill more obligations than the nuclear weapon states. On the other hand, the ICO alone does not address the tritium control in the civilian sector and therefore could not assure that no tritium is transferred from civilian to military use. Both ICO and ITCS are verifiable with similar technical means at reasonable cost.

One advantage of an ICO would be that it would simplify FM(C)T verification. This is because the same facilities can be used for the production of plutonium and tritium. In the absence of an ICO, non-intrusive FM(C)T inspection would be required of tritium-production targets to verify that they did not include fertile material for producing plutonium or some other fissile material.

Under the draft FM(C)T of the International Panel on Fissile Materials, a state party to a FM(C)T could “reserve HEU to fuel reactors for other military purposes that are not banned by the treaty, such as producing tritium for nuclear weapons.”[340] Russia does, in fact, produce tritium in reactors fuelled with HEU. Safeguarding the HEU might require new methods if there are sensitivities, for example, about revealing the operating level of the reactors. The “zero” approach, where no military production reactors or reprocessing plants are allowed to operate, would be easier to verify.

Since physical barriers can never be completely tight, the most efficient way to prevent the diversion of tritium for military purposes, besides binding and verified political commitments, is to minimize any production and application. Possible future civilian uses of tritium for fusion power, however, would thwart this goal.

Summary

The agreement between Canada and Euratom to assure the civilian use of tritium supplied by Canada for Europe’s fusion research and development programs provides a prototype for an International Tritium Control System that would complement the Non-Proliferation Treaty with a ban on the diversion of civilian tritium to nuclear-weapon use.

As part of a nuclear disarmament agreement, a Fissile Material Cutoff Treaty could be broadened to ban the production of tritium for weapons. As a result of tritium decay, a cutoff of fresh tritium would, on a timescale of a decade or so, transform boosted fission and thermonuclear weapons into low-yield fission weapons.

The verification arrangements for these regimes have been scoped and it appears that the costs would not be prohibitive.

8 Nuclear Power and Nuclear Disarmament

A civilian nuclear power program provides a state a foundation to produce fissile materials for nuclear weapons. It allows a country to train scientists and engineers, to build research facilities, to construct and operate nuclear reactors, and possibly also to learn techniques of reprocessing and enrichment that could later be turned to producing weapons materials. Even small civilian nuclear energy programs can involve large stocks and flows of nuclear-weapon-usable materials.

The authors of the 1945 Franck Report, an early effort to anticipate the political and social problems created by nuclear technology for the post-war world, raised the possibility of "conversion of a peacetime nucleonics industry to military production."[341] The 1946 Acheson-Lilienthal Report, the first comprehensive plan to control nuclear energy, recognized that a system of inspections alone might not suffice to constrain the "latent proliferation" capabilities of civilian nuclear power in a nuclear-weapon-free world.[342]

> "We have concluded unanimously that there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled only by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are not merely technical, but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations each free to develop atomic energy but only pledged not to use it for bombs. National rivalries in the development of atomic energy readily convertible to destructive purposes are the heart of the difficulty."

A civilian program could carry a country along a path of latent proliferation, in which the country moves closer to nuclear weapons without actually having to make an explicit decision to acquire them.[343] Barriers to the use of nuclear power for weapons are a central part of international nonproliferation policy today and will need to be strengthened further in a disarming world.

In a disarmed world, the existence of a nuclear-power infrastructure would shorten the time for states, especially former nuclear weapon states, to acquire nuclear weapons. This has led some analysts to conclude that reliance on nuclear power will not be tolerable in a nuclear-weapon-free world.[344]

On the other hand, some argue that the breakout capability inherent in civilian nuclear power could help stabilize the transition to a disarmed world by reassuring countries that they could respond in kind if others sought to break out of any disarmament agreement.[345] States would, in effect, move to non-weaponized deterrence ("virtual arsenals") based on civilian nuclear energy programs able to produce in a relatively short time fissile materials for a few or many nuclear weapons. As states gain confidence that a disarmed world is robust and will endure, the need for such a potential breakout capability could vanish over time.

The purpose of a breakout would be to obtain a military advantage or respond to some sudden perceived security threat. In a disarmed world, motivations of prestige or status, which may drive some countries today to acquire nuclear weapons, would be offset by the stigma associated with such weapons.

It is prudent to assume that almost any state could construct a nuclear device if it obtained the requisite amounts of highly enriched uranium or separated plutonium. A 1988 paper co-authored by Carson Mark, who had been for 25 years head of the Theoretical Division at the Los Alamos National Laboratory (LANL), and four of his LANL colleagues, including the well-known weapons designer, Theodore Taylor, concluded:

> "Crude nuclear weapons (similar to the Hiroshima gun-type and Nagasaki implosion-type weapons) could be constructed by a group not previously engaged in designing or building nuclear weapons provided that they have the technical knowledge, experience, and skills in relevant areas, e.g., the physical, chemical, metallurgical and nuclear properties of the various materials to be used, as well as the characteristics affecting their fabrication, and the technology of high explosives and/or chemical propellants."[346]

In the remainder of this chapter, we examine how fissile material could be acquired, either overtly and clandestinely, for different nuclear power infrastructures, ranging from a world without any significant nuclear power to a world in which many nations have their own enrichment and reprocessing plants. We then consider what constraints might be imposed on nuclear power to help stabilize a nuclear-weapon-free world.

A World without Nuclear Energy

In a world without civilian nuclear power there would be only a few internationally-shared research reactors used for scientific, industrial, medical, and other civilian purposes. But there would remain a widespread reservoir of knowledge of nuclear engineering. In such a world, a country wishing to obtain nuclear explosive materials could proceed in two ways:

1. Construct an enrichment plant to produce highly enriched uranium (HEU); or

2. Construct a dedicated production reactor and reprocessing plant to obtain plutonium.

These are, in fact, the two paths that the United States pursued in parallel to acquire nuclear weapons during World War II. Both routes produced enough fissile material for a bomb in August 1945, a little more than two and a half years after Enrico Fermi and his colleagues produced the first sustained fission chain reaction in December 1942.

The United States deployed huge resources and hundreds of thousands of people in this effort. But a much smaller effort would have sufficed. At their design power, the three plutonium production reactors built during World War II were able to produce together by late 1945 the six kilograms of plutonium required to make a Nagasaki-type bomb every two weeks.[347] The K-25 gaseous diffusion enrichment plant built at Oak Ridge, Tennessee during World War II had a similarly large capacity, producing about one bomb's worth (25 kg) of weapon-grade uranium a week by 1947.[348] The project was secret at the time, but would be discovered without much delay in the modern world constantly overflown by imaging satellites.

Today, if a state wanted to develop a clandestine nuclear-weapon capability, it would probably choose gas-centrifuge enrichment technology, which can be deployed on a small scale.[349] Centrifuge plants need little electricity and have few emissions or other characteristic signatures, thus making detection extremely difficult (Appendix A).[350] Historically, for a state without centrifuge technology, developing this capability on a near-commercial scale has taken upwards of a decade (Figure 8.1). It may take significantly less time, however, if a program sought only to make simple centrifuges, without aiming for the high separation efficiency, throughput and durability associated with current commercial requirements.[351]

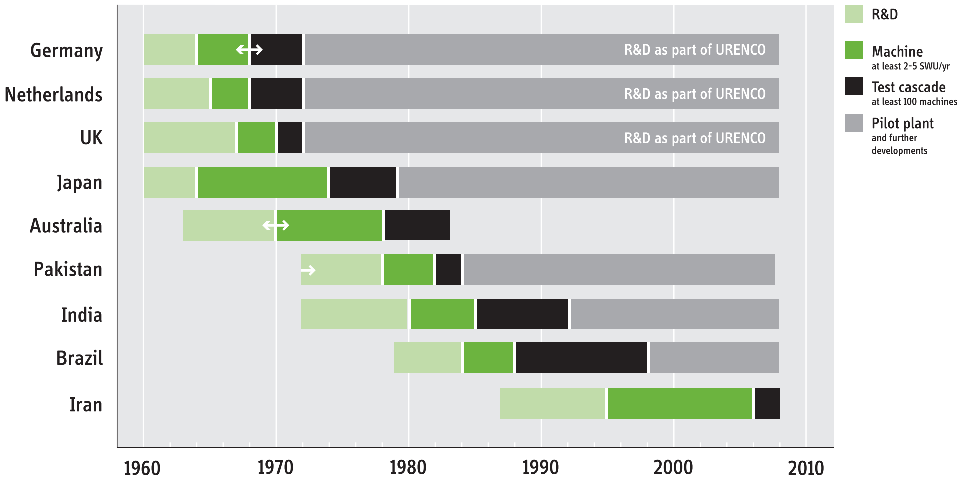


Figure 8.1. Timeline of selected centrifuge development programs from the R&D stage to operation of a pilot facility. Studies of national centrifuge development programs suggest it takes about 10–20 years to develop the basic technology. The time required to develop such basic first generation centrifuges is being reduced as key technologies for producing precision components are increasingly available worldwide and are being integrated into computer-controlled machine-tools.[352]

Laser-isotope separation (LIS), which also has low energy requirements but much higher separation factor and unit throughput, could potentially pose an even more severe problem than centrifuge technology. LIS was pursued in the 1970s and 1980s but gas-centrifuge technology became commercially competitive first. In 2006, however, General Electric and Hitachi acquired an Australian laser-enrichment process, SILEX, and are planning to build a large (3.5–6.0 million SWU/yr) enrichment plant based on this process in the United States.[353] If this effort succeeds, other states may pursue laser enrichment programs.

Although we are assuming a world with no nuclear power, some states would have spent fuel from past nuclear activities. Such countries could, in principle, mine this legacy material for plutonium. The IAEA estimated that, as of 2005, there were about 165,000 tons of power reactor spent fuel stored worldwide, and projected that there might be 280,000 tons of power reactor spent fuel stored by 2015.[354] Today, this spent fuel is stored on the surface. In a future world without nuclear power, it might be stored in underground repositories. IAEA policy is to continue safeguarding spent fuel even after repository closure.[355] The breakout should therefore be detected at the latest when a country starts mining operations. Conceivably, significant quantities of spent fuel could be recovered within months from a buried repository.[356]

Spent fuel from a commercial light-water reactor typically contains about one percent plutonium. Enough plutonium to make a first-generation Nagasaki-type bomb could therefore be recovered from a single ton of spent fuel.[357] To separate this plutonium, a country would have to reprocess the spent fuel (Figure 8.2).

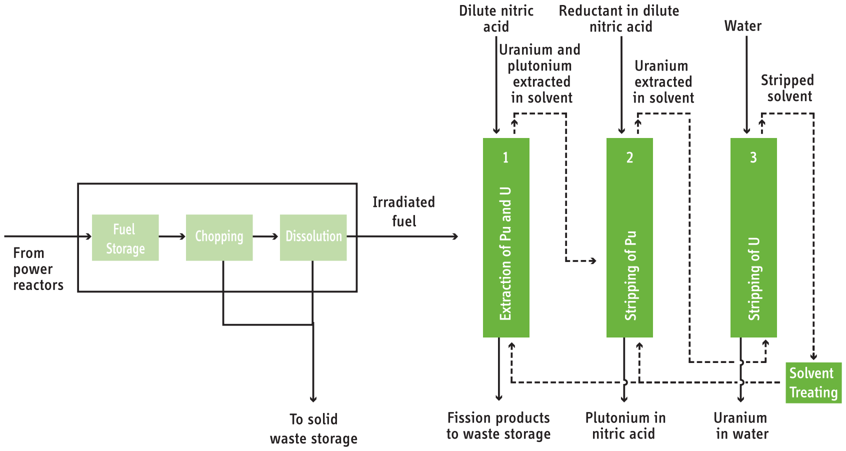


Figure 8.2. The key steps in a basic reprocessing plant. With the current PUREX technology, the spent fuel is chopped into small pieces and dissolved in hot nitric acid. The plutonium is extracted in an organic solvent that is mixed with the nitric acid using blenders and pulse columns, and then separated with centrifuge extractors.

A state with access to spent fuel could construct in advance a "quick and dirty" reprocessing plant with minimal and rudimentary arrangements for worker radiation protection and radioactive waste management. This might be accomplished in a year or less. A relatively small reprocessing plant with a capacity of 50 tons heavy-metal per year could separate up to 500 kilograms of plutonium annually, or enough for a single bomb in a week or less.[358]

Thus, even in a world without nuclear energy, states with spent-fuel repositories could try to secretly position themselves to be only months or less away from a nuclear-weapon capability. The key question would be whether, in a nuclear-weapon-free world, repugnance of nuclear weapons would be so pervasive and societal verification sufficiently well organized and effective, that it would be impossible to keep such a project secret (Chapter 9).

A World with Nuclear Energy

Today, thirty-one nations have nuclear power plants (Figure 8.3).[359] Seven of these states have nuclear weapons: the United States, Russia, United Kingdom, France, China, India and Pakistan.[360] Two states, Israel and North Korea, have nuclear weapons but do not have civil nuclear energy programs. At least six states with nuclear energy programs have had nuclear-weapon programs in the past: Argentina, Brazil, South Africa, South Korea, Sweden and Taiwan. About 30 countries have expressed interest in launching nuclear energy programs.[361] Among these, 20 countries have announced plans to build power reactors by 2020.

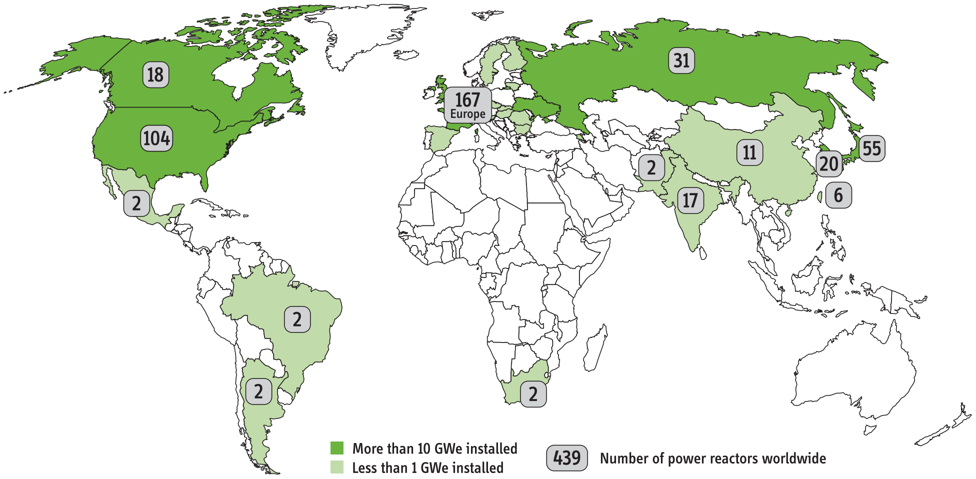


Figure 8.3. Global distribution of operating nuclear power reactors, 2009. There are 31 states with nuclear powers plants, 19 of these are in Europe (including Russia and the Ukraine), 6 in Asia (including Taiwan), 5 in the Americas, and one in Africa. Since 2006, about 20 countries that have no nuclear power plants today have announced plans to build one or more reactors by 2020: they include Algeria, Australia, Bangladesh, Egypt, Indonesia, Israel, Jordan, Libya, Morocco, Nigeria, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates, Vietnam, and Yemen.

There are many ways to deploy and use nuclear energy, which differ with regard to the nuclear fuel cycle, ownership and management. Today, although it is a subject of debate, every country is allowed to deploy its preferred fuel cycle and all relevant facilities are under national control. This means that the host state is in a position to take them over quickly and operate them successfully. The length of time it would take country to acquire nuclear weapons would therefore depend upon what nuclear facilities it has to begin with. Below, three classes of countries are considered:

- Countries with reprocessing plants;
- Countries without reprocessing plants or separated plutonium, i.e. operating their reactors on a "once-through" fuel cycle, but with national uranium-enrichment plants; and
- Countries operating on a once-through fuel cycle and without national uranium-enrichment plants.

Countries with reprocessing. Countries that operate reprocessing plants or have plutonium separated from fission products from the reprocessing of their spent fuel in other countries can obtain plutonium for weapons almost immediately, though it might still take days or weeks to process the plutonium into weapons.

The reactor-grade plutonium typically discharged from today's commercial light-water power reactors can be used to make nuclear weapons. A 1997 U.S. Department of Energy Report restated a U.S. position that dated back at least to 1977: "Virtually any combination of plutonium isotopes … can be used to make a nuclear weapon. […] reactor-grade plutonium is weapon-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states."[362]

If it is available, nuclear-weapon designers prefer "weapon-grade" plutonium (more than 90% Pu-239), however. This could be obtained by any country with a power reactor by withdrawing a batch of fuel after it had reached only about 5 percent of its design burnup. At this point, the 20-ton load of fuel typically discharged annually from a light-water reactor would contain about 40 kg of weapon-grade plutonium.[363] This fuel could be reprocessed without much delay due to its low radiation level.

Some advocates of reprocessing have recognized this problem and suggested alternative reprocessing technologies in which pure plutonium would not be separated out.[364] But none of the proposed technologies would significantly increase the time required for a country to obtain weapon-usable plutonium from the mixes containing the recycled plutonium. Perhaps most importantly, the gamma radiation fields around all such mixes are orders of magnitude lower than the gamma radiation field around spent fuel (Figure 8.4). It therefore would be far less hazardous than spent fuel to handle and less demanding to reprocess.

The proliferation risks associated with reprocessing and the recycling of plutonium are seen as high in today's world. In a nuclear-weapon-free world, fuel cycles involving separated plutonium might be considered intolerable.

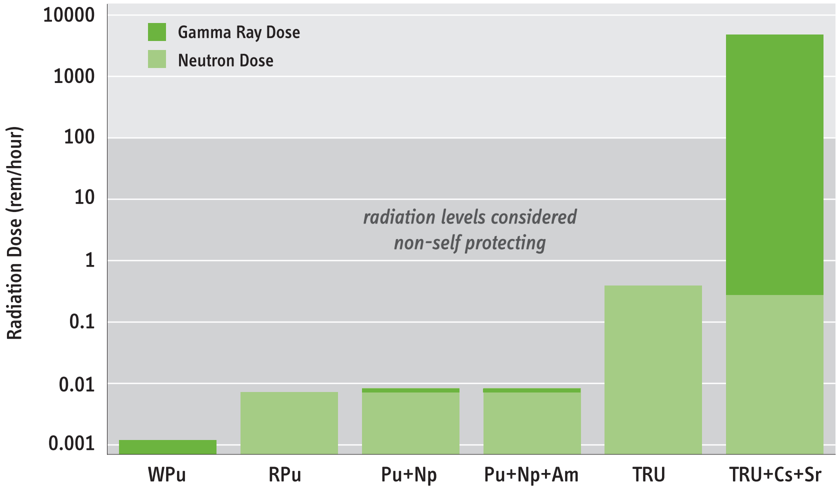


Figure 8.4. Radiation dose levels one meter away from 4 kilograms of plutonium. Even with different admixtures of transuranic elements (TRU), the dose rates are all hundreds of times lower than the level that the IAEA considers self protecting and thousands of times lower than is provided by the cesium and strontium in spent fuel (right bar).[365] WPu stands for weapon-grade plutonium; RPu for reactor-grade plutonium; TRU stands for all the transuranics in the spent fuel.

Countries with once-through nuclear fuel cycles and uranium-enrichment plants. Light-water reactors (LWRs) are likely to continue to dominate nuclear power worldwide for the next several decades. Such reactors operate most economically on a once-through fuel cycle. In such a fuel cycle, reactors are fueled with low-enriched uranium and the fuel that is discharged is stored and there is no plutonium separation. LWRs depend upon uranium enrichment, however, and today's gas-centrifuge enrichment plants can be used to produce weapon-grade uranium as well as low-enriched uranium.[366]

There are twelve states today with uranium enrichment plants (Figure 8.5). Of these, India and Pakistan operate only military enrichment plants. Iran's enrichment program has focused attention, however, on the fact that an increasing number of countries are pursuing enrichment programs—or might decide do so in the future. The Director General of the International Atomic Energy Agency has suggested that "we are going in the next 10 or 20 years to have 30 or 40 countries, in my estimation, who are virtual nuclear weapon states." because they will have uranium enrichment.[367]

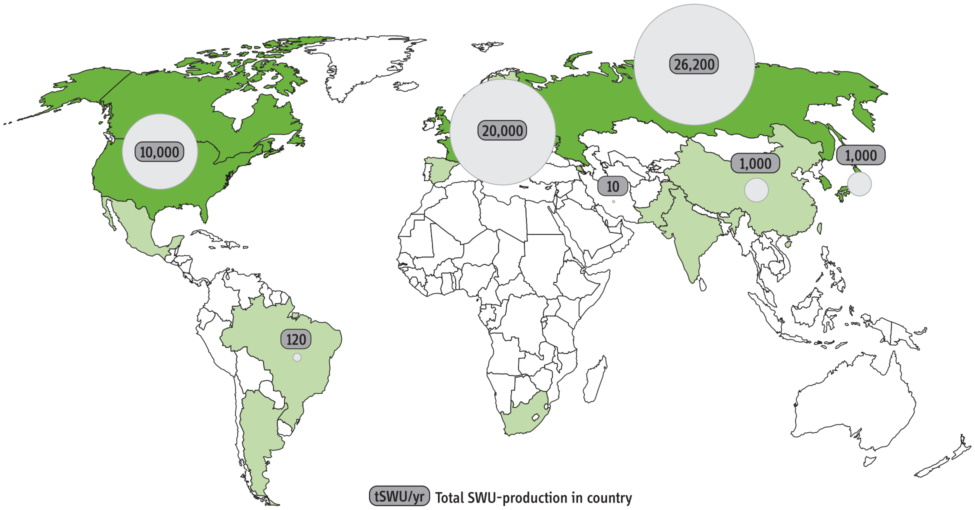


Figure 8.5. Global distribution of civilian uranium enrichment capacity, 2009. There are today 17 plants in 12 countries (France, Germany, the Netherlands and United Kingdom in Europe), including possibly three military enrichment plants in South Asia.

Centrifuge plants are organized into cascades designed to convert natural uranium into low-enriched uranium (LEU). A commercial plant typically has many such cascades operating in parallel. The quickest path to produce weapon-grade uranium at a centrifuge facility designed to produce low-enriched uranium could be through "batch" recycling with no reconfiguration of the cascade piping. The product of some cascades would be fed into other cascades instead of natural uranium and the output of that second set of cascades would be fed into a third set. In this manner, it would be possible within days to begin the production of weapon-grade uranium (Figure 8.6).

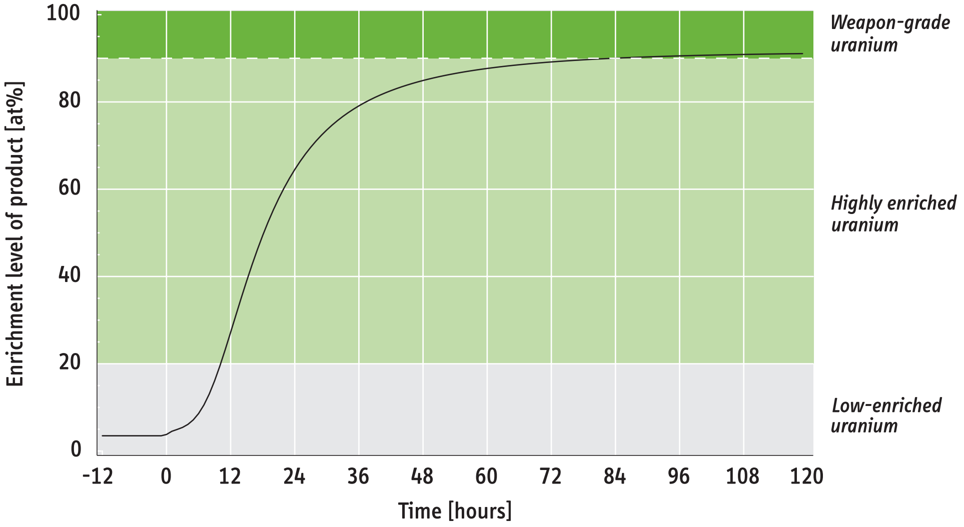


Figure 8.6. Enrichment level of the product recovered from a centrifuge cascade after two batch-recycling steps. In this simulation, at time zero, low-enriched uranium (3.5%) is fed into three cascades connected in parallel. The output of these cascades reaches an enrichment level of 16.3%. This product is fed into a fourth cascade, which delivers weapon-grade uranium after about 3.5 days.[368]

For a small national enrichment facility sized to fuel a one GWe LWR, the time to produce HEU sufficient for a few weapons would be on the order of a few weeks. Commercial centrifuge plants in operation today are typically very much larger, however, sized to fuel tens of power reactors. A facility sized to support about ten reactors would be capable of providing enough HEU for several weapons per week.

Countries that have national enrichment plants therefore have near nuclear-weapon-state status. In a nuclear-weapon-free world, it might be required to put these plants under some sort of multinational or international control and site them in countries that would not have the military forces or the expertise to seize and operate them in the face of international opposition.

Countries with once-through nuclear fuel cycles and no reprocessing or enrichment plants. Countries with no reprocessing or enrichment plants would still have spent nuclear fuel. If it were possible to build a clandestine "quick and dirty" reprocessing plant undetected, a country could begin to produce plutonium for weapons within weeks.

In summary, therefore, countries with reprocessing or enrichment plants could produce fissile materials for several weapons within days or weeks. Countries with nuclear-power reactors could do so within months, if they were able to clandestinely build a quick and dirty reprocessing plant in advance without detection. If they were unable to do so—perhaps due to effective societal verification (Chapter 9)—then they might be on the order of a year from having nuclear weapons materials. Finally, in a world without nuclear power and with all spent fuel in monitored underground repositories, the world would have at least a few more months to respond to a country breaking out by using a repository as a plutonium mine.

Figure 8.7 offers some notional timelines for the different fissile material production scenarios, which summarize the relative "breakout-resistance" of the different nuclear-power situations discussed above. It is assumed states would choose a breakout option that would minimize the time available for the international community to intervene and prevent the production of a few nuclear weapons.

States that have never had a nuclear energy program would take the longest time to break out. For them to break out with a clandestinely built enrichment plant could take perhaps a decade. A reprocessing route would be quicker, but lacking spent fuel, along with the reprocessing plant they would need also to build a production reactor, which could most likely not be concealed. The time to build the two facilities and irradiate and reprocess the fuel would be a few years. States with greater fuel cycle expertise and capabilities—and more developed domestic markets for specialized components and materials normally associated with enrichment and reprocessing programs—would take correspondingly less time to build either a small enrichment or small reprocessing plant. A state with a domestic enrichment industry could build a clandestine facility within a year or so, or within a few weeks convert a civilian enrichment plant to produce HEU. A state with already separated civilian plutonium stockpiled at a domestic reprocessing plant under national control would be able to obtain weapon-usable material immediately. The IAEA assumes that plutonium or HEU could be converted into weapons components within 1 to 3 weeks.[369]

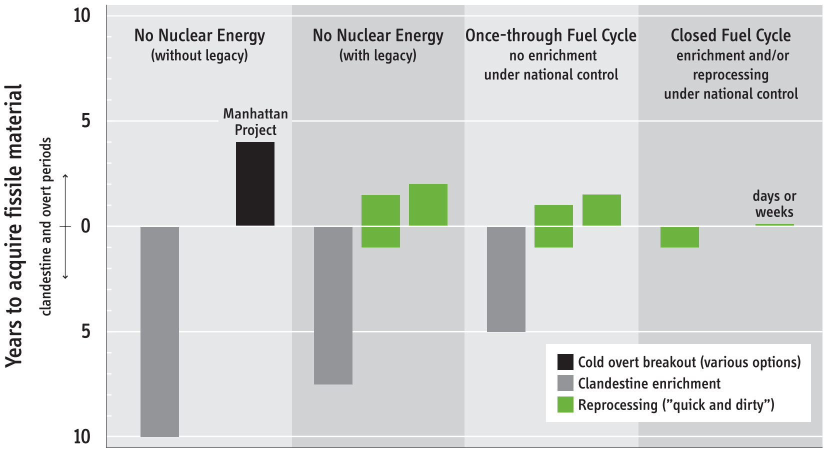


Figure 8.7. Notional times to produce fissile material for a small number of nuclear weapons for states with different nuclear energy capabilities. The four scenarios, from left to right, correspond to states that have never had nuclear energy programs (far left); states that have ended their nuclear programs and retain only legacy spent fuel in a geological repository and some prior nuclear expertise; states with an active nuclear energy program based on a once-through nuclear fuel cycle and no national enrichment or reprocessing plants; and states with operating enrichment and reprocessing plants (far right). The total height of a bar represents the time to produce fissile materials. The time during which the program would be overt is the upper half of the figure and the covert period in the lower half. The breakout options include building a clandestine centrifuge enrichment plant (dark grey bars) and building a "quick and dirty" reprocessing plant either covertly or more quickly in an overt crash-program (green).

Transition Period

The discussion so far has focused on a nuclear-weapon-free world. But such a world will likely take a long time to achieve, and it is important to ask what would be the impact of nuclear power on stability during the transition period, which would be characterized by relatively small nuclear arsenals with tens to hundreds of warheads.

During the transition, the current nuclear weapon states would have access to large amounts of fissile materials recovered from dismantled nuclear weapons. These stockpiles might be placed under some type of international monitoring to await disposition, but could be removed suddenly from monitoring if the host state decided to do so. During this period, therefore, former weapons material would provide a quicker route to rearmament than the domestic civilian nuclear energy sector.

For non-weapon states with a civilian nuclear power and fuel cycle infrastructure, nothing much would be changed by the disarmament process in the weapon states. They would retain the option of diverting materials from their civilian programs to weapons if the disarmament process somehow fell apart.

A key question for the achievement of a weapon-free world is whether, during the transition, reliance on civilian nuclear power increases in states that have it today and expands to new states. If the expansion includes a proliferation of fuel-cycle facilities to countries that today have no or only a negligible amount of nuclear power, then as the world moves toward nuclear disarmament, there would be additional countries with either stockpiles of nuclear weapon-usable material or facilities to produce such material. It is therefore not too early to think about and to begin to organize institutional arrangements that would minimize the destabilizing impact of nuclear power in a nuclear-weapon-free world.

Institutions and Safeguards for a Nuclear-Weapon-Free World

The essential challenge of safeguarding nuclear power in a nuclear-weapon-free world is to lengthen the period between the start of any effort by a country to acquire nuclear weapons and its fruition, during which time the international community could develop an effective response.

At a minimum, all nuclear facilities would be placed under international safeguards, such as now implemented by the International Atomic Energy Agency (IAEA) in non-weapon states. Such safeguards would include inspections at declared nuclear facilities and the universal implementation of the Additional Protocol, with perhaps strengthened authorities for the IAEA to look for undeclared, clandestine nuclear facilities.

Important additional measures would be regional, multinational and international arrangements to discourage national fuel cycle facilities, such as reprocessing and enrichment plants.[370] International spent fuel storage sites and repositories, where states collectively own and operate sites, could offer a greater degree of oversight and security against plutonium mining. The transition from today's national fuel-cycle facilities to multinational facilities would take time but, at the least, it could be required that any new facilities be multinational.

This raises questions about where such facilities would be built and by whom and what sort of multinational management structure provides effective control over the use of such a facility.[371] Collective ownership works to create a potential political barrier to the host state seizing the plant for weapons purposes. In the longer run, the establishment of an international authority to oversee and manage all the sensitive parts of the fuel cycle for all countries—notably enrichment and reprocessing—may be necessary.[372]

Conclusion

Possession of civilian nuclear power would shorten the time required for a state to break out of a disarmament agreement and produce nuclear weapons. By the same token, such possession also would allow a more rapid deployment or redeployment of nuclear weapons by states wishing to match such a breakout. The existence of a civilian nuclear program would probably also make more possible, though still difficult, a clandestine program by a state to produce fissile material for weapons, which if successful could reduce the time available for the international community to react against the country.

If civilian nuclear power were phased out in parallel with nuclear weapons disarmament and before a possible expansion spread nuclear power to many more countries, it would have some security advantages in making it more difficult and time-consuming for the scores of countries without any nuclear infrastructure today to launch nuclear-weapon programs from scratch.

If civilian nuclear power is not phased out, it is important to limit to the extent possible national nuclear fuel cycle facilities. Reprocessing plants, by producing nuclear weapon material directly or nearly directly, present the greatest dangers in a nuclear-weapon-free world. They provide the most plausible route to get weapon-usable material, and they shorten the time for a breakout to days or weeks. Other countries with similar plants could respond by a similar breakout also in a short time. The speed of such breakouts would give little time for collective responses under the United Nations Charter, including international sanctions and other actions. Given this situation, serious consideration should be given to the possibility of phasing out reprocessing plants altogether. In principle, this should not be a difficult decision, since reprocessing will not be necessary or economic for the foreseeable future. In practice, however, the powerful reprocessing and breeder reactor establishments in a number of countries would put up strong political resistance.

How important would it be to give the international community a few more weeks or months or even years to respond to a breakout? The answers depend upon political considerations beyond the issues of civilian nuclear power and fissile materials, and include: how a state might use a fleeting nuclear-weapons monopoly; whether the state in question is powerful enough militarily and economically to resist a non-nuclear response; and what enforcement mechanisms could be built into a disarmament treaty.
In any case, as an adjunct to any nuclear disarmament treaty, it would be essential to create international institutions to operate and safeguard both enrichment and reprocessing plants (if they cannot be eliminated altogether) and spent fuel storage sites. Such a system should be established during the lengthy transition period to disarmament by moving as many parts of the fuel cycle as possible from national to multinational and preferably international control.

Even with stringent and equitable new rules to govern nuclear power, its continued operation and certainly any global expansion will impose serious proliferation risks in the transition to nuclear disarmament. A phase-out of civilian nuclear energy would provide the most effective and enduring constraint on proliferation risks in a nuclear-weapon-free world. The costs and benefits of such a phase-out, however, would require a broader discussion of global energy policy.

9 Societal Verification

The concept of societal verification, the reporting of possible violations of international nuclear-disarmament agreements both by ordinary citizens and those such as nuclear scientists with direct knowledge of such violations was apparently first introduced by Leo Szilard, a physicist best known for his contributions to the making of the atomic bomb, and later for his advocacy that it not be used against Japan. The idea was eventually taken up by others, including Joseph Rotblat, a Manhattan Project scientist and founder of the Pugwash movement, who emphasized both its pivotal role in verifying a nuclear-weapon-free world and the difficulty of persuading scientists and technologists to act as whistle-blowers in a world of competing nation-states and strong traditions of patriotism.

In this chapter, we briefly summarize the history of societal verification and discuss the actions of the most prominent modern whistle-blower, the Israeli nuclear technician, Mordechai Vanunu.

Although a nuclear-weapon-free world may be some time away, there is already an agreement in the nuclear domain where societal verification could be usefully applied, the Nuclear Non-proliferation Treaty (NPT). Since the discovery of a covert nuclear program in Iraq, the International Atomic Energy Agency (IAEA) has begun to complement its traditional safeguards with the analysis of public information and information provided by the intelligence communities of member states. To date, however, the IAEA hasn't provided a formal channel for non-governmental organizations or individual scientists and technologists to reveal possible violations of the NPT. A better understanding of the potential and challenges involved in the use of information from such non-traditional sources as a means of detecting clandestine nuclear activities is emerging. But a strong and demonstrable commitment to nuclear disarmament by the nuclear weapon states may be required to create social legitimacy for such whistle-blowing.

Szilard's proposal

During World War II, as Manhattan Project scientists and engineers raced to build facilities to make highly enriched uranium and plutonium and to design the bomb, in 1944, Leo Szilard shifted his attention from advancing the project to the need for a system of international controls to prevent a post-war nuclear arms race between the United States and the Soviet Union.[373] In March 1945, Szilard drafted a memo, "Atomic Bombs and the Postwar Position of the United States" for transmission to President Roosevelt.[374] Szilard argued that, given the significant overlap in the technologies for peaceful applications of nuclear energy and for making bombs, a very tight system of controls would be required including unrestricted access by international inspectors to the territory of all states to detect possible misuse of the peaceful atom as well as possible clandestine nuclear activities dedicated to making nuclear bombs. In the memo, Szilard argued:

> "That there may be dangerous loopholes in control systems which might be set up is illustrated by events that took place after the First World War. At that time there were many Germans who were willing to give information to the Inter-allied Commission about violations of the control regulations, but those who actually did so were publicly tried under the German Espionage Law and were given heavy sentences. The Treaty of Versailles did not stipulate that the German Espionage Law must be revoked.
>
> Clearly, it would be desirable to create a situation, which would permit us to appeal in various ways to physicists and engineers everywhere for information that would uncover violations of the controls. This would give us additional assurance that such violations would be detected, but it presupposes that we succeed in creating conditions that would enable us to guarantee the personal safety of their families."

These comments allude to the two potential modalities for societal verification, "citizens reporting," also known as "inspection by the people," and "whistle-blowing" by those who have direct knowledge of violations of international treaties or agreements, in particular, scientists and technologists who are employed by relevant laboratories and industries. Szilard notes that societal verification requires legal sanction and, especially in the case of whistle-blowers, who often are sworn to secrecy as a condition of their employment, the assurance of physical protection for both them and their families. This would be especially important if they resided in states where the punishment for whistle-blowing is likely to be severe.

Figure 9.1. Leo Szilard (1898–1964), the scientist who introduced the concept of societal verification in the nuclear age, here in September 1949 reading of the onset of the U.S.-Soviet nuclear arms race, which he anticipated and warned against. *Credit: Argonne National Laboratory, courtesy AIP Emilio Segrè Visual Archives.*

After the war, Szilard and others elaborated on these ideas, specifically in the context of detecting violations of treaties and agreements in the area of nuclear weapons such as a ban on nuclear testing or a ban of nuclear weapons altogether.

Obviously, societal verification, including whistle-blowing, can be and has been applied in monitoring agreements and reporting violations in many other contexts, e.g., human rights, humanitarian assistance, and environmental protection. Although a detailed discussion of these other areas would carry us too far afield, we mention them briefly below in those cases where the experience gained might provide useful lessons for the application of societal verification in the nuclear area.

An International Duty?

The most vigorous proponent of societal verification in recent years, particularly in the context of verifying a nuclear-weapon-free world, was the late Joseph Rotblat. A paper he wrote in 1993 provides a useful summary of previous work in this area, mostly dating from the 1950s and 1960s, as well as his own views about the role of societal verification in a nuclear-weapon-free world and the importance of and obstacles involved in enlisting ordinary citizens as well as scientists and technologists.[375]

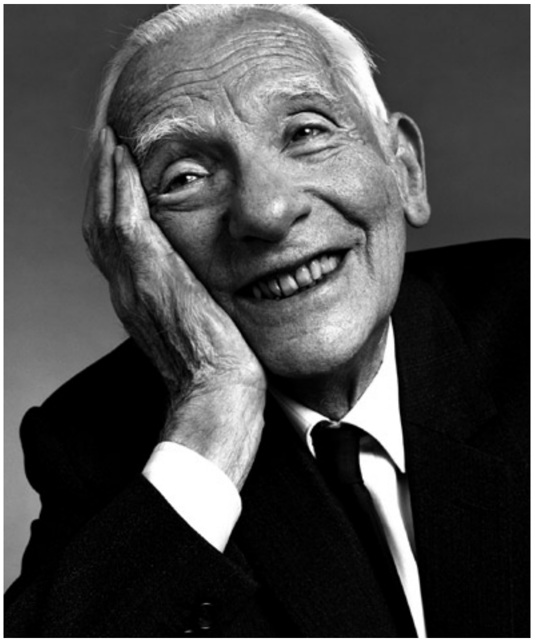


Figure 9.2. Sir Joseph Rotblat (1908–2005), a Manhattan Project scientist, one of the founders of the scientists' Pugwash movement, and a strong advocate of societal verification. Rotblat, a Nobel Laureate, was a leading supporter of Israeli whistle-blower Mordechai Vanunu, arguing that Vanunu's exposure of Israel's nuclear weapon program was an act of conscience. *Credit: Peter Hönnemann.*

With regard to its role in a nuclear-weapon-free world, Rotblat agrees with the prevailing view that, while there is considerable room for improvement in technical verification methods such as physical inspection, instrumental detection and aerial reconnaissance, such methods cannot be relied on to provide complete assurance that all nuclear weapons had been eliminated or weren't being secretly produced. Since the possession of a even few weapons might give a transgressing state the capability to exert political blackmail, a complementary societal verification system needs to be developed and used alongside technical verification means to provide the requisite assurance that violations of a treaty banning nuclear weapons would be detected in a timely manner. Others, including both proponents and opponents of abolition, share Rotblat's view that technical verification means do not suffice, but are skeptical of the efficacy or are unfamiliar with the potential of societal verification.

The skepticism about societal verification is based primarily on doubts about the willingness of citizens, including scientists, to report violations of international treaties and agreements by their country, especially in non-democratic states, and the impact of false alarms on the verification system. Following earlier proposals, Rotblat, counters that, for societal verification to be effective, such reporting must be generally recognized to be the right and duty of all citizens and that, to this end, the international treaty or agreement, specifically one that establishes a nuclear-weapon-free world, must contain a clause requiring that national laws be enacted that guarantee the right and require the duty.[376]

As to the presumed ineffectiveness of citizens reporting in non-democratic states, Rotblat notes that the refusal of a state to sign the treaty would amount to a declaration that it intended to acquire nuclear weapons, while acceding to the treaty with the intention of cheating would be difficult because the international control agency would have the right to monitor for violations using both technical and societal means. For example, the probability of detecting a small, clandestine centrifuge plant by wide-area environmental sampling would be greatly enhanced if the agency had information about where such a plant might be located.

Rotblat was apparently the only scientist to leave the Manhattan Project when it became clear in late 1944 that Germany didn't have a viable nuclear weapons program; and given this background, it isn't surprising that he emphasized the important role of scientists and technologists as potential whistle-blowers, a role that is to a degree supported by the openness of international science.

Rotblat recognized that one of the most difficult aspects of societal verification is the taint of disloyalty, the stigma of spying on colleagues or fellow-citizens, and he issued a clarion call for a new mindset involving a loyalty to mankind instead of individual nations:[377]

> "At present, loyalty to one's nation is supreme, generally overriding the loyalty to any of the subgroups. Patriotism is the dogma; 'my country right or wrong' the motto. And in case these slogans are not obeyed, loyalty is enforced by codes of national criminal laws. Any transgression is punished by the force of law: attempts by individuals to exercise their conscience by putting humanitarian needs above those dictated by national laws are denounced by labeling those individuals as dissidents, traitors or spies. They are often severely punished by exile (Sakharov), long-term prison sentences (Vanunu), or even execution (the Rosenbergs).
>
> The time has now come to develop, and recognize consciously, loyalty to a much larger group, loyalty to mankind. […] Among scientists the feeling of belonging to mankind is already well developed. Science has always been cosmopolitan in nature; its methods and ethics are universal, transcending geographical frontiers and political barrier. Because of this, scientists have developed the sense of belonging to the world community, of being citizens of the world. […] This new loyalty is necessary for the protection of the human species, whether nuclear weapons are eliminated or not. But the recognition of the necessity of this loyalty, and the education of the general public about this need, would be of momentous importance in ensuring compliance with a treaty to eliminate nuclear weapons."

The historical record with regard to scientists acting as citizens of the world and not of individual states, especially with regard to the development of weapons of mass destruction, is not encouraging, however.[378] The involvement in work on chemical weapons by the eminent German physical chemist, Fritz Haber; the work on nuclear weapons by Soviet scientist and later human-rights activist, Andrei Sakharov; and the work on Soviet biological weapons by Ken Alibek offer important examples.

During World War I, the Jewish-born Haber, who would win the Nobel Prize in chemistry in 1918 for the discovery of a process for the synthesis of ammonia, headed the effort to develop chemical weapons for Germany. He pursued the task with strong purpose and great energy and never tried to minimize his role or expressed any moral misgivings even after the war. In this respect, he remained a German patriot to the end, which came in 1933 with the rise of Hitler when he had to resign as director of the Kaiser Wilhelm Institute for Physical Chemistry. Still, in his farewell letter to his Institute colleagues, he could say: "*Im Frieden der Menschheit, im Kriege dem Vaterlande!*" (In peace for mankind, in war for the fatherland!)[379]

Unlike Haber, Sakharov, a leading Soviet nuclear weapon designer, acknowledged the terrible nature of the weapons he and his colleagues built after World War II. But they were also convinced that the effort to keep pace with the United States in the nuclear domain was essential, and the dedication and energy they brought to their work was characteristic of "a true war psychology."[380] The Soviet Government rewarded them amply for their successful efforts, and it was only later, after nuclear parity with the United States had been achieved, that Sakharov began to speak out publicly about the dangers of the nuclear arms race. His behavior was hardly unique: like their fellow citizens, many scientists become convinced of their patriotic duty to aid their country when its national security is threatened by external powers, and only have second thoughts later, if at all.

Moreover, when Haber and Sakharov were engaged in the development of chemical and nuclear weapons, respectively, there were no international treaties or agreements prohibiting such work. This was not true in the case of Ken Alibek, however, who was informed after joining Biopreparat, the principal Soviet agency for R&D in biological weapons, in 1975, that the work he would be engaged in violated the 1972 Biological and Toxins Weapons Convention, of which the Soviet Union was a signatory. He was also told that the United States had a secret biological weapons program, however, and on this basis had no difficulty in engaging in his assigned tasks, which had the added attraction of involving significant technical challenges. Alibek later left the Soviet Union and revealed the details of the Soviet biological weapons program.[381]

In Alibek's case, there was a legal basis for blowing the whistle, even if it was not acted on, but what of situations where there is no such basis, i.e., the activity in question isn't prohibited by international treaty or agreement? An interesting case in point is that of Mordechai Vanunu, who worked as a technician in the secret Dimona nuclear weapons facility in Israel from 1976 to 1985. During this time, Vanunu surreptitiously took photographs of the parts of the facility to which he had access. He subsequently shared these photos, along with his notes about the operation of the facility, with reporters for the *Sunday Times*. A front-page story, based on this information, was published by the *Times* on 5 October 1986. By that time, however, 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 for violating the secrecy oath that he took at the time of his employ.[382] Vanunu was released in 2004, but has been denied permission to leave Israel where he is almost universally viewed as a traitor.

Figure 9.3. Two of the pictures taken by Vanunu inside Dimona in or before 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, however, 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.

A small group of individuals, including Joseph Rotblat, supported Vanunu through his arrest, trial and punishment on the grounds that, on the one hand, the existence of a nuclear arsenal in Israel was already well-known and, on the other, that Vanunu acted out of a genuine concern that this secret, advanced nuclear arsenal was a threat to world peace. Thus, while he may have committed a crime in the sense of violating the Israeli Official Secrets Act—which Vanunu claims he signed before being informed that he would be working on nuclear weapons—Rotblat and others considered Vanunu to be a *bona fide* whistle-blower and a true prisoner of conscience, whose punishment, which included being kept in solitary confinement for ten years, was unduly harsh.[383]

Vanunu revealed new, concrete evidence of a large and sophisticated nuclear arsenal, and, in so doing, raised troubling questions about Israeli nuclear policy. However, since Israel is not a signatory of the NPT, its acquisition of nuclear weapons, which it has decided not to publicly acknowledge, does not violate international agreements. The issue then is the tension between a country's desire to keep secret certain information about its activities, especially relating to national security, and the right of insiders to blow the whistle, even if they violate security regulations in doing so.

Lessons for the Nuclear Domain?

There is a growing effort to better understand the opportunities and challenges of using whistle-blowing and other sources of information to uncover nuclear programs. In an important analysis, Ronald Mitchell examined how non-governmental "actors," and non-governmental organizations (NGOs) in particular, could help in identifying undeclared nuclear facilities.[384] Such groups have shown themselves capable and willing to assist international regimes in contexts such as human rights, humanitarian assistance, and environmental protection by accurately and honestly monitoring and reporting violations of international treaties and agreements in these areas. Mitchell describes such actions as a "fire alarm" system and contrasts it to traditional safeguards procedures of the International Atomic Energy Agency, which he refers to as a "police patrol" system.

The limitations of the safeguards system came to prominence as a result of the failure of the IAEA to detect nuclear facilities in Iraq prior to the conclusion of the 1991 Gulf War — and remain a major concern for non-proliferation policy. While subsequent efforts to address this problem by increasing the IAEA's authority to conduct more intrusive and unannounced inspections on the one hand, and to utilize intelligence information supplied by member states on the other, are both useful they have basic limitations. The Iraqi experience has not eliminated most states' resistance to such inspections. Moreover, the resources that the IAEA can devote to such activities are limited. While "fire alarms" by member states related to clandestine activities can be very valuable, the IAEA has to very cautious in using such information as the states ringing the alarm often have their "own axes to grind," and also may demand unacceptable *quid pro quos*.

Mitchell concludes that there is a potentially useful role for a "fire alarm" system to detect undeclared nuclear activities utilizing information supplied by civil society groups, but only if several conditions are satisfied. In particular:

1. These groups have the capability to detect and report on suspect nuclear-related activities;

2. The balance of incentives and disincentives to do so must favor the former; and

3. The IAEA has the resources and political authority required to process this information and to discriminate between false and true alarms, and use it.

We discuss these requirements in turn in the following.

With reference to both (1) and (2), Mitchell makes the useful distinction between actors who are nationals of the government they are reporting on and those who are not. While the threat of retaliation for insiders is likely to be much greater than for outsiders, the access of insiders to relevant information is also likely to be greater. Moreover, they also may have strong incentives to reveal such information because they oppose the acquisition of nuclear weapons on various grounds or as a way of embarrassing and bringing external political pressure on a government that they want removed for other reasons.

An example often cited to illustrate the latter motive is the revelation in 2002 by the Iranian opposition group Mojahedin-e Khalq of the existence of a centrifuge facility at Natanz in Iran. Given that this group has its headquarters in Iraq, thus protecting it from retaliation by the Iranian government, it probably is more accurately characterized as an insider/outsider organization. In addition, there is credible evidence in this instance that it served as a convenient conduit for the release of information acquired by a foreign government opposed to Iran's nuclear activities. However, to the extent that such cooperation makes fire alarms more effective politically, they probably should be (discreetly) encouraged.

Also, while outsider NGOs in general have neither the financial resources nor the technological capabilities available to government intelligence organizations, some NGOs involved in monitoring non-nuclear activities have demonstrated impressive capabilities as well as considerable zeal in pursuing their objectives.

In the nuclear area, there exists a legion of local community-based anti-nuclear groups, especially around nuclear sites, including nuclear weapons facilities. They are particularly visible in the United States and United Kingdom, but have also emerged elsewhere.[385] Over time, some of these groups become very expert in understanding the activities at the site they contest, and develop some prominence as principled critics. There are now also NGOs that exist as vehicles to expose wrong-doing by government programs—a leading U.S. example is the Project on Government Oversight.[386] Both kinds of groups have served to attract whistle-blowers seeking to reveal problems at nuclear facilities where they work.

While NGOs operating in the nuclear domain currently don't have great technical skills, some, e.g., Greenpeace, the National Resources Defense Council and the Institute for Science and International Security, have demonstrated the capacity to monitor radiation levels or interpret commercial satellite imagery (Figure 9.4), while others, such as the Stockholm International Peace Research Institute and the Monterey Institute for International Studies have compiled impressive data bases based on open source information. Moreover, technological developments may significantly increase these capabilities. The cost of satellite imagery, for example, has declined considerably in recent years while its spatial resolution has increased.

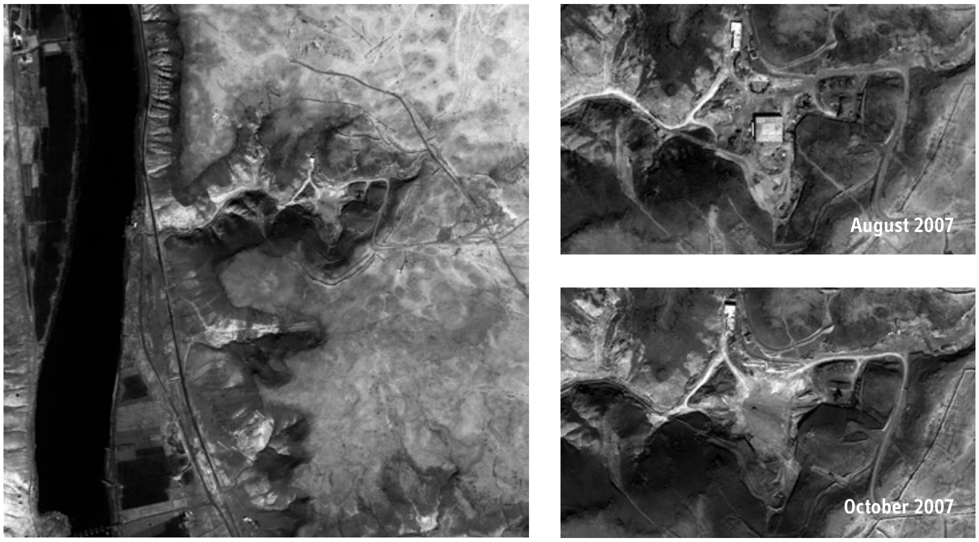


Figure 9.4. The Al Kibar site in Syria in August and October 2007. On 6 September 2007, Israel attacked a target inside Syria. Analysts with the Institute for Science and International Security (ISIS), a Washington-based group, acquired commercial satellite imagery taken before and after the raid and were able to pinpoint the site of the attack (35.708 N, 39.833 E). A box-shaped building had disappeared and efforts were underway to clean-up the site. In May 2008, the IAEA informed Syria that it intended to send a team of inspectors to Syria to "review all available information and to visit the Dair Alzour [Al Kibar] site and three other locations alleged by some Member States to be of relevance."[387] *Credit: Google Earth (August 2007) and Digital Globe/ISIS (October 2007).*

Understandably, states that provide intelligence information must protect their sources. This requires that the IAEA to be very cautious in evaluating and acting on such information, however, since accusations that prove to be false alarms entail significant political costs. Accepting information from non-state actors could considerably increase the difficulty of distinguishing false from true alarms. Even assuming that most outsider NGOs have strong incentives to accurately report their findings, the information provided by insiders is potentially much more valuable, while also generally being more difficult to verify.

The larger political problem is that while some countries welcome the opportunity to provide select information to the IAEA about illicit nuclear activities in states they consider to be "rogues," they are much less enthusiastic about empowering non-state actors to do the same because of concerns that the latter might blow the whistle on questionable activities within their own borders, particularly with regard to matters related to national security.

For their part, many insiders will only provide information if they can do so without revealing their identities. Here, technology may be coming to the rescue. Various potential methods have recently been described that use proxy computers in countries that don't censor the internet to assist people to communicate their information untraceably.[388]

In sum, the information provided by non-state actors, both insiders and outsiders, might significantly assist the IAEA in detecting undeclared nuclear activities. But this will require the creation of a system for collecting and evaluating the information, and developing procedures for how to respond. This will be even more important in verifying a nuclear-weapon-free world.

There is, in fact, already a precedent in the field of human rights. The International Criminal Court, charged with prosecuting cases of genocide, provides in its founding treaty, the Rome Statute, that individuals or organizations may submit information on crimes within the jurisdiction of the Court and that "witnesses" must be protected. Such information from a non-state party is called a "communication."[389]

The ICC procedure is clearly defined:

> "when the Prosecutor receives a communication, … the Prosecutor shall not seek to initiate an investigation unless he first concludes that there is a reasonable basis to proceed. Once a decision to initiate an investigation is taken, senders of related communications are promptly informed of the decision, with reasons for the decision."
>
> "The Statute does not specify what the communication should contain. The Office analyses all communications received and the extent of the analysis is affected by the detail and substantive nature of the information available. If the available information does not provide sufficient guidance for an analysis that could lead to a determination that there is a reasonable basis to proceed, the analysis is concluded and the sender informed. This decision is provisional and may be revised in the event that new information is forthcoming."

The obligation to protect witnesses (Article 43.6 of the Rome Treaty) states that

> "the Registrar shall set up a Victims and Witnesses Unit within the Registry. This Unit shall provide, in consultation with the Office of the Prosecutor, protective measures and security arrangements, counselling and other appropriate assistance for witnesses, victims who appear before the Court, and others who are at risk on account of testimony given by such witnesses."

It is possible to imagine similar whistle-blowing and witness-protection provisions in a treaty that eliminates and prohibits nuclear weapons.

Conclusion

The greatest obstacle to establishing a credible system for verifying global nuclear disarmament, including the use of societal means, is that the existing nuclear weapons states don't want to give up their weapons. This resistance links the problems of global disarmament and a credible verification system, of which societal verification would be an essential component, and suggests they are two sides of a coin: one cannot have disarmament without effective verification or effective verification without disarmament.

Regarding the need of societal verification for disarmament, there is no doubt that advances in technology can make traditional verification means more sensitive, hence less ambiguous, as well as less intrusive and more cost effective. A system for sounding the alarm on suspicious activities will still be needed, however, as a complement to traditional verification.

Regarding the need of disarmament to make societal verification possible, despite considerable support in the nonproliferation community for universal implementation of the Additional Protocol to IAEA Safeguards, including the possibility of extending its current reach via, e.g., wide area environmental sampling, there is also significant resistance to such initiatives without a concomitant commitment on the part of the weapons states to disarmament. The need for such a *quid pro quo* will also be true in the case of societal verification. For example, Rotblat's vision of changing the mindset of scientists from citizens of a particular country to "citizens of the world" cannot be realized selectively. It is reasonable to expect that only when scientists in nuclear weapon states stop work on such weapons will their peers in other countries refuse to participate in such programs and blow the whistle on those who do.

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.

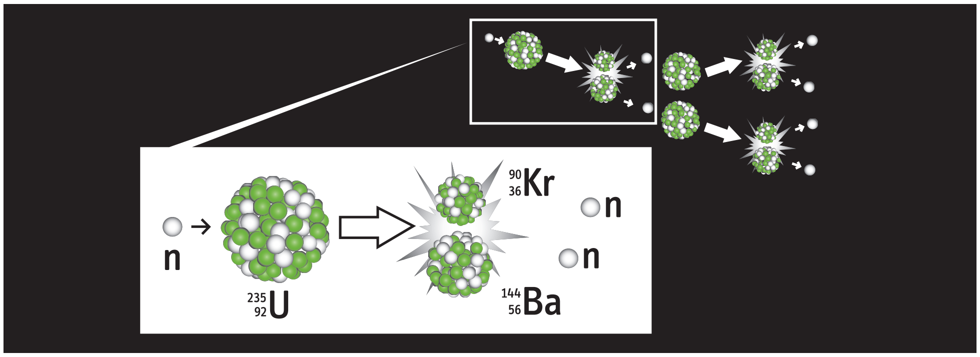


Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission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

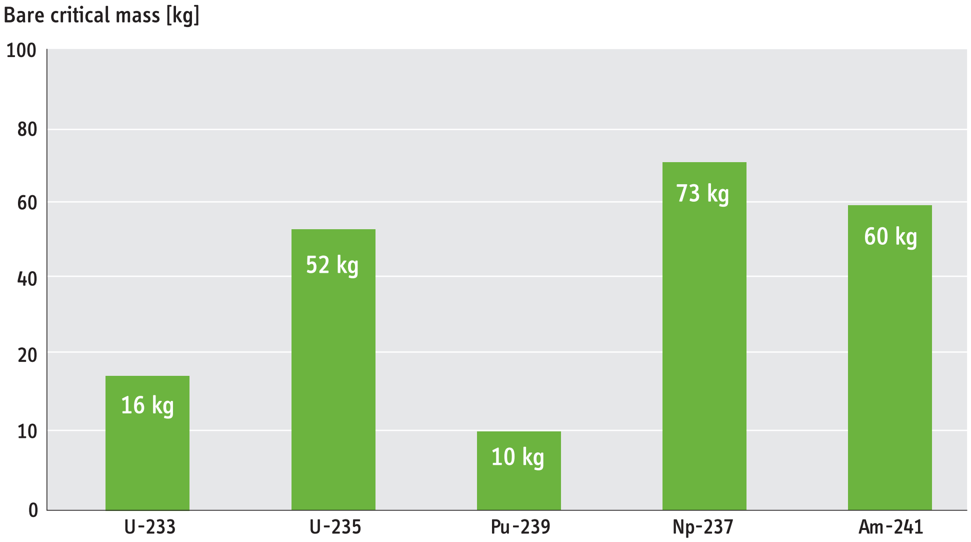


Figure A.2. Bare critical masses for some key fissile isotopes. A bare critical mass is the spherical mass of fissile metal barely large enough to sustain a fission chain reaction in the absence of any material around it. Uranium-235 and plutonium-239 are the key chain-reacting isotopes in highly enriched 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).

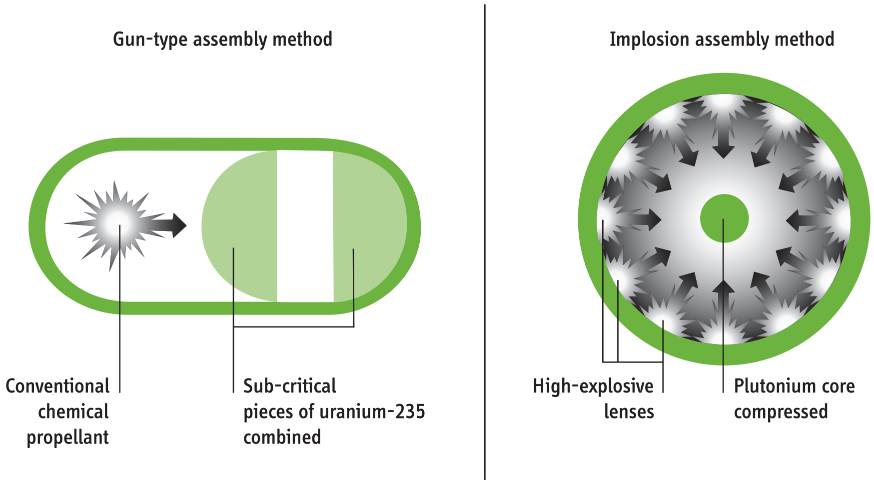


Figure A.3. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated "gun-type" method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow. 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 at the moment a chain reaction in the fissile mass 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.

In modern nuclear weapons, the yield of the fission explosion is typically "boosted" by a factor of ten by introducing a mixed gas of two heavy isotopes of hydrogen, deuterium and tritium, into a hollow shell of fissile material (the "pit") just before it is imploded. When the temperature of the fissioning material inside the pit reaches about 100 million degrees, it ignites the fusion of tritium with deuterium, which produces a burst of neutrons that 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 5.2 in Chapter 5). The tritium in the secondary is made during the explosion by neutrons splitting lithium-6 into tritium and helium.

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

Because both implosion and neutron-reflecting material around it can transform a subcritical into a supercritical mass, the actual amounts of fissile material in the pits of modern implosion-type nuclear weapons are considerably smaller than 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 U-235 contained in HEU. The United States has declassified the fact that 4 kg of plutonium is sufficient to make a nuclear explosive device.

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

Production of Fissile Materials

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

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

To minimize their masses, however, actual weapons typically use uranium enriched to 90-percent U-235 or higher. Such uranium is sometimes defined as "weapon-grade." Figure A.4 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.

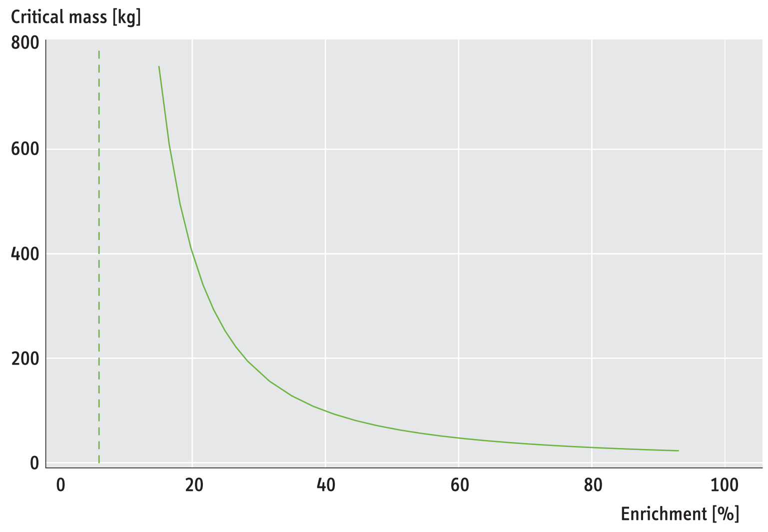


Figure A.4. The fast-neutron critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data in the figure is for a uranium metal sphere enclosed in a 5-cm-thick beryllium neutron "reflector" that would reflect about half the neutrons back into the fissioning mass.

Gas centrifuges spin uranium hexafluoride (UF_6) gas at enormous speeds, so that the uranium is pressed against the wall with more than 100,000 times the force of gravity. The molecules containing the heavier U-238 atoms concentrate slightly more toward the wall relative to the molecules containing the lighter U-235. This effect can be exploited to separate the two isotopes. An axial circulation of the UF_6 is induced within the centrifuge, which multiplies this separation along the length of the centrifuge, and increases the overall efficiency of the machine significantly (see Figure A.5 for an illustration).

Plutonium. Plutonium is an artificial isotope produced in nuclear reactors when uranium-238 (U-238) absorbs a neutron creating U-239 (see Figure A.6). 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.1). 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.

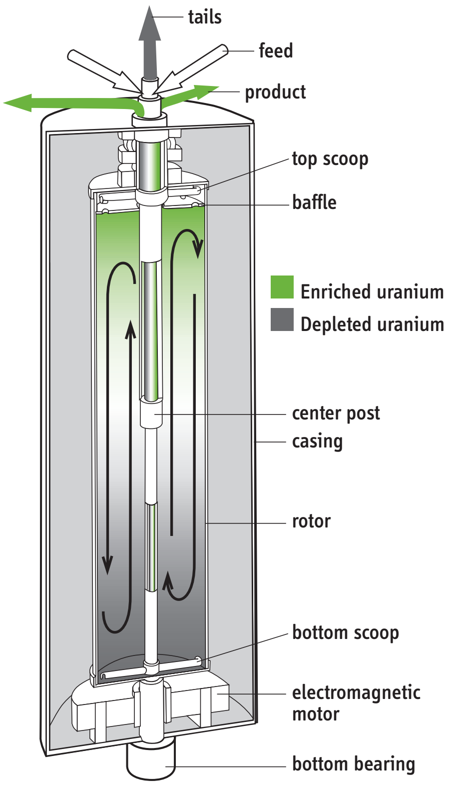


Figure A.5. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small 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.

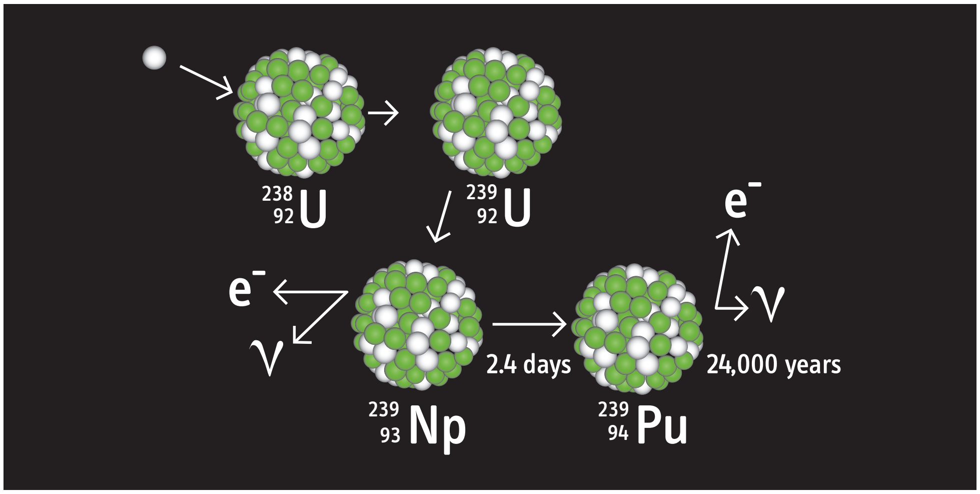


Figure A.6. Making plutonium in a nuclear reactor. A neutron released by the fissioning of a chain-reacting U-235 nucleus is absorbed by the nucleus of a U-238 atom. The resulting U-239 nucleus decays with a half-life of 24 minutes into neptunium, which in turn decays into Pu-239. Each decay is accompanied by the emission of an electron to balance the increase in charge of the nucleus and a neutrino.

Isotope	Critical Mass [kg]	Half Life [years]	Decay Heat [watts/kg]	Neutron Generation [neutrons/g-sec]
Pu-238	10	88	560	2600
Pu-239	10	24,000	1.9	0.02
Pu-240	40	6,600	6.8	900
Pu-241	13	14	4.2	0.05
Pu-242	80	380,000	0.1	1700
Am-241	60	430	110	1.2
WPu (94% Pu-239)	10.7		2.3	50
RPu (55% Pu-239)	14.4		20	460

Table A.1. Key properties of plutonium isotopes and Am-241 into which Pu-241 decays. Data from: U.S. Department of Energy, "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems," in Technological Opportunities to Increase the Proliferation Resistance of Global Nuclear Power Systems, TOPS, Washington, 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.

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.

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 … reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states …"
>
> "At the lowest level of sophistication, a potential proliferating state or sub-national group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At

> the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium."

For use in a nuclear weapon, the plutonium must be separated from the spent fuel and the highly radioactive fission products that the fuel also contains. Separation of the plutonium is done in a "reprocessing" operation. With the current PUREX technology, the spent fuel is chopped into small pieces and dissolved in hot nitric acid. The plutonium is extracted in an organic solvent 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 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.

Appendix B

Worldwide Locations of Nuclear Weapons, 2009

This list of nuclear weapons locations includes sites where there is reason to believe that: 1) nuclear weapons probably are deployed or stored; and 2) nuclear weapons and their components are designed, fabricated and assembled, or dismantled. It is based on open sources.[390]

Country	Location/Name	Region/Province	Weapon System	Remarks
Belgium	Kleine Brogel Air Base	Limburg	B61-3/4	US bombs for delivery by Belgian F-16s of the 10th Wing
Subtotal	1			
China[391]	Baoji area	Shaanxi	Various	Regional warhead storage site
	Chinese Academy of Engineering Physics, Mianyang (Science City)	Sichuan	Various	Warhead design
	Danyang Air Base	Hubei	Bombs	Potential weapons storage facility for nuclear bombs, near H-6 bomber base[392]
	Huaihua region (55 Base)	Hunan	DF-4 SSM	Regional warhead storage site for 803, 805 and 814 Missile Brigades subordinate to 55 Base HQ
	Huangshan region (52 Base)	Anhui, Jiangxi	DF-3A/DF-21 SSM	Regional warhead storage site for 807, 811, 815 and 817 Missile Brigades subordinate to 52 Base HQ
	Kunming region (53 Base)	Yunnan	DF-3A/DF-21 SSM	Regional warhead storage site for 802 and 808 Missile Brigades subordinate to 53 Base HQ
	Jianggezhuang Naval Base	Shandong	JL-1 SLBM	Possible warhead storage
	Luoyang region (54 Base)	Henan	DF-4/DF-5A/DF-31 SSM	Regional warhead storage site for 801, 804 and 813 Missile Brigades subordinate to 54 Base HQ
	Pingtung area (Institute of Materials)	Sichuan	Various	Nuclear weapons fabrication, with possible underground warhead storage near Mianyang

Country	Location/Name	Region/Province	Weapon System	Remarks
China	Shenyang region (51 Base)	Liaoning, Jilin	DF-3A/DF-21 SSM	Regional storage site for 806, 810, 816, and 818 Missile Brigades subordinate to 51 Base HQ
	Xining region (56 Base)	Qinghai, Shaanxi	DF-3A/DF-4/DF-21 SSM	Regional storage site for 806, 809, 812 Missile Brigades subordinate to 56 Base HQ
	Yidu area	Shandong	DF-21 SSM	Possible warhead storage
	Yulin Naval Base	Hainan	JL-2 SLBM	Possible warhead storage
	Zitong (Research and Design Academy of Nuclear Weapons)	Sichuan	Various	Warhead assembly, disassembly and dismantlement[393]
Subtotal	14			
France	Centre d'Etudes de Valduc	Bourgogne	TN75, TN81, TNA, TNO	Assembly, disassembly and dismantlement of nuclear warheads
	Ile Longue Naval Base	Bretagne	M45 (M51) SLBM	TN75 warheads on Triumphant-class SSBNs. From 2010 TNO warheads on M51 SLBM
	Istres Air Base	Provence	ASMP (ASMP-A)	TN81 warheads for ASMP for Mirage 2000N. From 2010 TNO warheads for ASMP-A
	Luxeuil-les-Bains Air Base	Franche-Comté	ASMP (ASMP-A)	TN81 warheads for ASMP for Mirage 2000N. From 2010 TNO warheads for ASMP-A
	Saint-Dizier Air Base	Champagne-Ardenne	ASMP-A	Deployment of ASMP-A for Rafale K3 begins in 2009
	South of Ile Longue	Bretagne	TN75 (TNO)	Warhead storage site for M45 SLBMs at nearby SSBN base. From 2010 also M51 SLBMs with TNO
	Toulon Naval Base, or vicinity[394]	Côte d'Azur	ASMP (ASMP-A)	TN81 warheads for ASMP for Super Étendard on Charles de Gaulle aircraft carrier. From 2011 TNA warheads on ASMP-A for Rafale MK3
Subtotal	7			
Germany	Büchel Air Base	Rheinland-Pfalz	B61-3/4	US bombs for delivery by German PA-200 Tornados of the 33rd Fighter-Bomber Wing
Subtotal	1			
India	Chandighar Plant	Punjab	Various	Possible production of nuclear weapons
	Jodhpur Storage Facility	Rajasthan	Prithvi/Agni SSM	Potential underground facility for Prithvi and/or Agni launchers
	Unknown facility (Air Force)	Unknown	Bombs	For possible use by Jaguar-IS at Gorakhpur and Lohegaon air bases, and Mirage 2000H at Ambala and Gwalior air bases

Country	Location/Name	Region/Province	Weapon System	Remarks
India	Unknown facility (Army)[395]	Unknown	Prithvi/ Agni SSM	For use by 222nd and 333rd Missile Groups (Prithvi), and 334th and 335th Missile Groups (Agni)
	Unknown facility (Navy)	Unknown	Dhanush SSM	For Dhanush ship-launched SSMs[396]
Subtotal	5			
Italy	Aviano Air Base	Friuli-Venezia Giulia	B61-3/4	US bombs for delivery by US F-16s of the 31st Fighter Wing
	Ghedi Torre Air Base	Lombardia	B61-3/4	US bombs for delivery by Italian PA-200 Tornados of the 6th Wing
Subtotal	2			
Israel[397]	Dimona (Negev Nuclear Research Center)	n.a.	Various	Plutonium, tritium, and warhead production complex
	Sdot Micha Base and/or Tirosh Depot	n.a.	Jericho II SSM	Warheads for approximately 50 MRBMs in caves
	Soreq Nuclear Research Center	n.a.	Various	Possible warhead design and fabrication
	Tel Nof Air Base	n.a.	Bombs	For F-16Is. Nuclear bombs possibly in adjacent WSAs near base
Subtotal	4			
Netherlands	Volkel Air Base	Noord-Brabant	B61-3/4	US bombs for delivery by Dutch F-16s of the 1st Wing
Subtotal	1			
North Korea[398]	?	?	?	It is unknown how North Korea has weaponized its nuclear capability
Subtotal	?			
Pakistan	Fatejhang National Defense Complex	Punjab	SSM	Missile development and potential warhead storage capability
	Masroor Weapons Depot	Sindh	Various	Potential storage of bombs for Mirage Vs at Masroor Air Base, and/or warheads
	Quetta Air Base	Balochistan	Bombs	Potential storage site with underground facilities in high-security weapons storage area near Quetta Air Base
	Sargodha Weapons Depot[399]	Punjab	Various	Potential storage site for bombs for F-16s at nearby Sargodha Air Base, and warheads for SSMs
	Shanka Dara Missile Complex	Punjab	SSM	Missile development and potential warhead storage capability

Country	Location/Name	Region/Province	Weapon System	Remarks
Pakistan	Unknown facility (Air Force)	?	Bombs	Central Air Force storage facility with bombs for F-16s at F-16s at Sargodha Air Base, and Mirage Vs at Kamra Air Base
	Unknown facility (Army)	?	SSM/GLCM	Central Army storage facility with warheads for SSMs and Babur cruise missiles
	Wah Ordnance Facility[400]	Punjab	Various	Possible warhead production, disassembly and dismantlement facility
Subtotal	8			
Russia[401]	Barnaul Missile Division	Altai Krai	SS-25 ICBM	Warheads on 36 ICBMs
	Belaya Air Base	Irkutsk	AS-4 ASM, bombs	For Tu-22M3 Backfire bombers. Weapons possibly stored in remote WSA
	Borisoglebsk (Voronezh-45)	Voronezh	Various	National level weapons storage site
	Chazma (Abrek) Bay SLBM Storage Facility	Primorsky	SLBM/SLCM/ASW	Possible storage of warheads for SLBMs and other naval weapons
	Chebsara (Vologda-20)	Vologda	Various	National level weapons storage site
	Dodonovo (Krasnoyarsk-26)	Krasnoyarsk	Various	National level weapons storage site
	Dombarovskiy-Yasnyy Missile Division	Orenburg	SS-18 ICBM	Warheads for 34 ICBMs
	Engels Air Base	Saratov	AS-15 ASM, bombs	For Tu-160 Blackjack and Tu-95 Bear bombers. Weapons probably stored in adjacent WSA
	Golovchino (Belgorod-22)	Belgorod	Various	National level weapons storage site
	Irkutsk Missile Division	Irkutsk	SS-25 ICBM	Warheads for 27 ICBMs
	Karabask (Chelyabinsk-115)	Chelyabinsk	Various	Possible national level storage facility for Chelyabinsk-70
	Korfovskiy (Khabarovsk-47)	Khabarovsk	Various	National level weapons storage site
	Korolev area	Moscow	Gazelle ABM	Warheads for 12 interceptors
	Kozelsk Missile Division	Kaluga	SS-19 ICBM	Warheads for 31 ICBMs
	Krasnoarmeyskoye (Saratov-63)	Saratov	Various	National level weapons storage site[402]
	Lakhta-Kholm Air Base	Arkhangelsk	AS-4 ASM, bombs	For Tu-22M3 Backfire bombers. Possible WSA near by

Country	Location/Name	Region/Province	Weapon System	Remarks
Russia	Lesnoy (Sverdlovsk-16/45)[403]	Sverdlovsk	Various	Warhead assembly plant and national level weapons storage site[404]
	Lytkarino area	Moscow	Gazelle ABM	Warheads for 16 interceptors
	Mongokhto (Alekseyevka) Air Base	Khabarovsk	AS-4, bombs	For Tu-22M3 Backfire bombers. Weapons possibly stored in WSA near base
	Mozhaysk-10	Moscow	Various	National level weapons storage site
	Nerpichya Weapons Storage Facility	Kola	Various	Potential storage facility for naval weapons, including for nearby Bolshaya Lopatka Naval Base
	Nizhniy Tagil Missile Division	Sverdlovsk	SS-25 ICBM	Warheads for 27 ICBMs
	Novosibirsk Missile Division	Novosibirsk	SS-25 ICBM	Warheads for 36 ICBMs
	Okolnaya SLBM Storage Facility	Kola	SLBM	Possibly storage of warheads for SLBMs and other naval weapons
	Olenegorsk Storage Facility	Kola	Various	National level nuclear weapons storage site (possibly two: Olenegorsk-2 near Ramozero and Olenegorsk-8 near Vysokiy)
	Rybachiy Naval Base	Kamchatka	SS-N-18 SLBM	Warheads on SS-N-18s onboard Delta III-class SSBNs
	Rzhanitsa (Bryansk-18)	Bryansk	Various	National level weapons storage site
	Sarov (Arzamas-16)[405]	Nizhni Novgorod	Various	Possibly limited storage
	Sebezh-5	Pskov	Various	National level weapons storage site
	Selikhino (Komsomolsk-31)	Khabarovsk	Various	National level weapons storage site
	Shaykovka Air Base	Kaluga	AS-4 ASM, bombs	For Tu-22M3 Backfire bombers. Weapons probably in remote WSA[406]
	Skhodnya area	Moscow	Gazelle ABM	Warheads for 16 interceptors
	Snezhinsk[407] (Chelyabinsk-70)	Chelyabinsk	Various	Nuclear warhead design laboratory and national level weapons storage site
	Sofrino area	Moscow	Gazelle ABM	Warheads for 12 interceptors
	Soltsy Air Base	Novgorod	AS-4 ASM, bombs	For Tu-22M3 Backfire bombers. Possible WSA near base
	Tatishchevo Missile Division	Saratov	SS-19, SS-27 ICBM	Warheads for 41 SS-29 and 50 SS-27 ICBMs

Country	Location/Name	Region/Province	Weapon System	Remarks
Russia	Teykovo Missile Division	Ivanovo	SS-25, SS-27 ICBM	Warheads for 9 SS-25 and 13 SS-27 ICBMs
	Trekhgorny[408] (Zlatoust-36)	Chelyabinsk	Various	Warhead assembly[409]
	Ukrainka Air Base	Amur	AS-15 ASM, bombs	For Tu-95 Bear bombers. Possible WSA near base
	Uzhur Missile Division	Krasnoyarsk	SS-18 ICBM	Warheads for 34 ICBMs
	Vidyaevo Naval Base	Kola	Various	Warheads for naval forces in central storage
	Vilyuchinsk SLBM Storage Facility	Kamchatka	SLBM	Warheads for SS-N-18 SLBMs, possibly also other naval weapons
	Vnukovo area	Moscow	Gazelle ABM	Warheads for 12 interceptors
	Vozdvizhenka Air Base	Primorsky	AS-4 ASM, bombs	For Tu-22M3 Backfire bombers. Possible WSA near base
	Vypolzovo Missile Division	Novogorod/Tver	SS-25 ICBM	Warheads for 18 ICBMs
	Yagelnaya Naval Base	Kola	SS-N-23 SLBM	Warheads on SLBMs on Delta IV-class SSBNs. Possible WSA near base. Might also store other naval weapons
	Yoshkar-Ola Missile Division	Mari El	SS-25 ICBM	Warheads for 27 ICBMs
	Zalari (Irkutsk-45)	Transbaikal	Various	National level warhead storage site
Subtotal	48[410]			
Turkey	Incirlik Air Base	Adana	B61-3/4	US bombs for delivery by F-16s from other US bases
Subtotal	1			
United Kingdom	Aldermaston Atomic Weapons Establishment	England	UK Trident System	Warhead design. Possibly a few warheads present
	Burgfield Atomic Weapons Establishment	England	UK Trident System	Warhead assembly, disassembly and dismantlement
	Coulport Royal Navy Ammunition Depot	Scotland	UK Trident System	National level warhead storage site
	Faslane Royal Navy Base	Scotland	Warheads and Trident II D5 SLBM	On deployed Vanguard-class SSBNs
Subtotal	4			
United States	Bangor (Kitsap) Naval Submarine Base	Washington	W76, W76-1, W88, Trident II D5 SLBM	On deployed Ohio-class SSBNs
	Barksdale Air Force Base	Louisiana	B61-7, B83-1, W80-1/ALCM	For B-52Hs of the 2nd BW
	Kings Bay Naval Submarine Base	Georgia	W76, W76-1, W88, Trident II D5 SLBM	On deployed Ohio-class SSBNs

Country	Location/Name	Region/Province	Weapon System	Remarks
United States	Kirtland Air Force Base	New Mexico	B61, W62, W80, B83, W78, W87[411]	National level Air Force warhead storage site
	Lawrence Livermore National Laboratory	California	W62, W83, W87	Warhead design. Fissile material to be cleaned out
	Los Alamos National Laboratory	New Mexico	B61, W76, W78, W80, W88	Warhead design, surveillance and maintenance
	Malmstrom Air Force Base and Missile Field	Montana	W62,[412] W78, W87	Warheads for 150 Minuteman III ICBMs
	Minot Air Force Base and Missile Field	North Dakota	B61-7, W62,[413] W78, B83-1, W87	Warheads for 150 Minuteman III ICBMs and bombs for B-52Hs of the 5th BW
	Nellis Air Force Base	Nevada	B61, W62, W80, B83, W78, W87[414]	National level Air Force warhead storage site
	Pantex Plant	Texas	Various	Warhead assembly, disassembly and dismantlement
	Seymour-Johnson Air Force Base	North Carolina	B61-3/4	For F-15Es of the 4th FW
	Strategic Weapons Facility Atlantic (Kings Bay)	Georgia	W80-0/TLAM-N, W76, W76-1, W88, Trident II D5 SLBM	National level Navy warhead storage site
	Strategic Weapons Facility Pacific (Bangor)	Washington	W80-0/TLAM-N, W76, W76-1, W88, Trident II D5 SLBM	National level Navy warhead storage site
	Warren Air Force Base and Missile Field	Colorado, Nebraska, Wyoming	W62,[415] W78, W87	Warheads for 150 Minuteman III ICBMs
	Whiteman Air Force Base	Missouri	B61-7/11, B83-1	For B-2s of the 509th BW
Subtotal	15			
Total	**111**			

Abbreviations: ABM = Anti-Ballistic Missile; ALCM = Air-Launched Cruise Missile; ASM = Air-to-Surface Missile; ASMP = Air-Sol Moyenne Portée; ASW = Anti-Submarine Warfare; BW = Bomb Wing; FW = Fighter Wing; GLCM = Ground-Launched Cruise Missile; HQ = Headquarters; ICBM = Intercontinental Ballistic Missile; SLBM = Submarine-Launched Ballistic Missile; SLCM = Sea-Launched Cruise Missile; SSBN = Nuclear Powered Ballistic Missile Submarine; SSM = Surface-to-Surface Missile; TLAM/N = Tomahawk Land-Attack Missile/Nuclear; WSA = Weapons Storage Area.

Endnotes

Chapter 1. Nuclear Weapon and Fissile Material Stocks and Production

[1] www.fas.org/programs/ssp/nukes/nuclearweapons/nukestatus.html

[2] "The Legacy of START and Related U.S. Policies," U.S. Department of State, Bureau of Verification, Compliance, and Implementation, Fact Sheet, 16 July 2009, www.state.gov, mirrored at www.ipfmlibrary.org/gov09.pdf.

[3] www.fas.org/blog/ssp/2009/07/start.php

[4] www.whitehouse.gov/the_press_office/The-Joint-Understanding-for-The-START-Follow-On-Treaty

[5] A long-standing proposal has been that the United States and Russia should agree to a ceiling of 1000 total warheads each, roughly equal to the *total* number of weapons held by all the other nuclear weapon states. One suggestion was for a nuclear force of 1000 weapons of which 500 are operationally deployed and another 500 in a reserve force that would take much longer to prepare for use; see S. D. Drell, and J. E.Goodby, "What are Nuclear Weapons For? Recommendations for Restructuring U.S. Strategic Nuclear Forces," *Arms Control Association*, April 2005. In 2009, arms control advocates in the United States and the Chairman of the U.S. Senate Foreign Relations Committee called for a goal of 1000 or fewer deployed weapons; see John F. Kerry, "New directions for foreign relations," Boston Globe, 13 January 2009. The proposal by U.S. arms control group for a U.S.-Russian agreement setting a ceiling of 1000 total warheads or fewer within five years is contained in a March 2009 letter to Secretary of State Clinton, www.fcnl.org/pdfs/nuclear/Clinton_START.pdf.

[6] www.fas.org/blog/ssp/2009/02/sort.php

[7] The United States is estimated to have dismantled 250 warheads in 2007, 300 warheads in 2008 and may dismantle 350 in 2009. Robert S. Norris and Hans Kristensen, "U.S. Nuclear Forces, 2009," *Bulletin of Atomic Scientists*, March/April 2009. The estimated Russian warhead dismantlement rate is sourced in *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf, Endnote 260.

[8] *FY 2000 Stockpile Stewardship Plan*, Office of Defense Programs, U.S. Department of Energy, 15 March 1999, Appendix E, p. E-2.

[9] *Management and Disposition of Excess Weapons Plutonium*, National Academies of Sciences, National Academy Press, Washington, DC, 1994, p. 104.

[10] www.number10.gov.uk/Page18631

[11] "Proliferation in Parliament," Summer 2009, www.acronym.org.uk/parliament/0907.htm.

[12] Speech by Prime Minister Gordon Brown, United Nations General Assembly, New York, 23 September 2009, www.number10.gov.uk/Page20719.

[13] Speech by President Nicolas Sarkozy, Presentation of SSBM Le Terrible in Cherbourg, 21 March 2008, www.ipfmlibrary.org/sar08.pdf.

[14] *Military Power of the People's Republic of China 2009*, U.S. Department of Defense Annual Report to Congress, www.defenselink.mil/pubs/pdfs/China_Military_Power_Report_2009.pdf.

[15] Amy F. Woolf, *Nonstrategic Nuclear Weapons*, Congressional Research Service, RL-32572, 28 January 2009, www.fas.org/sgp/crs/nuke/RL32572.pdf.

[16] Robert S. Norris, William M. Arkin and William Burr, "Where the Bombs Were" *Bulletin of Atomic Scientists*, November/December 1999, pp. 26–35; NRDC Nuclear Notebook, "Appendix B: Deployments by Country, 1951–1977," *Bulletin of Atomic Scientists,* November/December 1999, p. 66–67; and Robert S. Norris, William M. Arkin and William Burr, "Where they were: How much did Japan know," *Bulletin of Atomic Scientists*, November/December 1999, January/February 2000, pp. 11–13, 78–79.

[17] "Nuclear-Weapon Free Zone in Central Asia," www.iaea.org/NewsCenter/News/2009/canwfztreaty.html.

[18] "Africa Renounces Nukes," www.iaea.org/NewsCenter/News/2009/africarenounces.html.

[19] *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*, U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf; and UK Ministry of Defence, *Historical Accounting for UK Defence Highly Enriched Uranium*, March 2006, www.ipfmlibrary.org/mod06.pdf.

[20] Statement at the Annual Symposium of the Uranium Institute in London (now, the World Nuclear Association), reported in *NUKEM Market Report*, weekly report for the week ended Sept. 17, 1993. See also T. Cochran, Nuclear Warhead Destruction, Paper presented at the United Nations Symposium on Security, Disarmament, and Confidence Building in the CIS Context, Kiev, Ukraine, 29 September 1993, docs.nrdc.org.

[21] As of 30 June 2009, according to USEC, the U.S. company responsible for purchasing the Russian downblended uranium.www.usec.com/megatonstomegawatts.htm.

[22] Unless otherwise noted, updated data based on previous estimates from *Global Fissile Material Reports 2006* and *2007*, International Panel on Fissile Materials, www.ipfmlibrary.org/gfmr06.pdf and gfmr07.pdf.

[23] Robert M. George, "U.S. HEU Disposition Program," *50th INMM Annual Meeting*, Tucson, AZ, 13–19 July 2009.

[24] For a more detailed discussion on the structure of the U.S. stockpile, see *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf, Appendix 1A.

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

[26] An "enrichment plant" at Gadwal was listed by the U.S. Department of Commerce in 1998 as subject to export restrictions. U.S. Department of Commerce, Bureau of Industry and Security, 15 CFR Part 742 and 744, *Federal Register*, vol. 63. No. 223, 19 November 1998; www.bis.doc.gov/pdf/india-pakistanentities-nov98.pdf, mirrored at www.ipfmlibary.org/doc98.pdf.

[27] On Gadwal as the site for enrichment to weapon-grade uranium, see Jonathan Landay, "Despite Taliban Turmoil, Pakistan Expands Nuke Plants," *McClatchy Newspapers*, 1 May 2009, www.mcclatchydc.com/world/story/67379.html.

[28] Zia Mian, A. H. Nayyar and R. Rajaraman, "Uranium Resource Constraints on Fissile Material Production in Pakistan," *Science & Global Security*, in press.

[29] "India launches nuclear submarine," BBC, news.bbc.co.uk/2/hi/south_asia/8169360.stm.

[30] Press Trust of India, "India reaches milestone with launch of n-powered submarine," 26 July 2009.

[31] Sandeep Unnithan, "PM's wife to launch INS Arihant, India's first nuclear submarine," *India Today*, 16 July 2009.

[32] The enrichment capacity was estimated in M. V. Ramana, "An estimate of India's Uranium Enrichment Capacity," *Science & Global Security*, Vol. 12, 2004, pp. 115–124. The testing of the prototype naval reactor was reported in Vivek Raghuvanshi, "Indian Navy Reaches Nuclear Power Milestone," *Defense News*, 5 November 2001. See also Dinesh Kumar, "India Inching Towards Indigenously Build N-powered Submarines," *The Times of India*, 3 October 1998, and A. Gopalakrishnan, "Undermining Nuclear Safety," *Frontline*, 24 June 2000. One report claims that these tests are of a "scaled down reactor" but this has not been corroborated elsewhere. Even if true, it is still likely that the Rattehalli complex would have produced sufficient enriched uranium to fabricate the entire reactor core.

[33] David Albright and Susan Basu, *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, Institute for Science and International Security, 18 January 2007.

[34] "DPRK Permanent Representative Sends Letter to President of UNSC," Korea News Service, Tokyo, 4 September 2009, www.kcna.co.jp, mirrored at kns09.pdf; and "N. Korea Claims Progress in Enriching Uranium," *New York Times*, 3 September 2009.

[35] There have been several classified investigations of this case. Recent public statements by former government officials suggest that such a transfer did in fact occur. In October 2007, former Congressional staffer, Henry Myers wrote that "senior officials in the U.S. government concluded in the late 1960s that weapon-size quantities of HEU had probably been diverted from NUMEC [Nuclear Materials and Equipment Corporation] to Israel." Victor Gilinsky, a former U.S. Nuclear Regulatory Commissioner, pointed out that "the CIA believed that the nuclear explosives in Israel's first several bombs, about one hundred kilograms of bomb-grade uranium in all, came from material that was missing at a U.S. naval nuclear fuel plant." See: H. Myers, "The Real Source of Israel's First Fissile Material," *Arms Control Today*, October 2007, p. 56; and V. Gilinsky, "Israel's Bomb," *New York Review of Books*, Volume 51, Number 8, 13 May 2004, www.nybooks.com/articles/17104, and "Time for More NUMEC Information," *Arms Control Today*, June 2008.

[36] Jean Du Preez "South Africa" in *Country Perspectives on the Challenges to a Fissile Material (Cutoff) Treaty*, International Panel on Fissile Materials, 2008.

[37] Gavin Ball, "Conversion of Safari Research Reactor from HEU to LEU fuel," *Proceedings of the Annual Conference of the Institute of Nuclear Materials Management*, Tucson, Arizona, July 2009 and personal communication, 31 August 2009.

[38] *Medical Isotope Production Without Highly Enriched Uranium,* National Academy of Sciences, National Academy Press, 2009.

[39] *Fiscal Year 2010 Congressional Budget Request*, U.S. Department of Energy, Vol. 1, p. 447.

[40] Ole Reistad and Styrkaar Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *Nonproliferation Review,* Vol. 15, No. 2, 2008, p. 265.

[41] The most prominent and controversial exception is the research reactor FRM-II near Munich, Germany, which went into operation in 2004 and requires 35–40 kg of weapon-grade HEU per year. Enrichment reduction to 50% or less is currently planned, and should have been completed by 31 December 2010 according to an agreement between the German Federal Government and Bavarian State Government. The new Federal Government, elected in September 2009, might however not insist on the implementation of this agreement, which would be welcome by the operator of the reactor and by the Bavarian State Government.

[42] *IAEA Annual Report 2008*, GC(53)/7, International Atomic Energy Agency, Vienna, 2009, Table A4.

[43] *AREVA inaugurates the first cascade at its Georges Besse II plant*, Press Release, 18 May 2009, www.areva.com; "Inauguration ceremony at George Besse II," *World Nuclear News*, 18 May 2009, www.world-nuclear-news.org. The full capacity of 7.5 million SWU/yr will not be reached until 2016–18. Areva has the option to further expand the capacity of the plant to 11.0 million SWU/yr. The plant will be large enough to supply low-enriched uranium for France's entire fleet of nuclear reactors. Louisiana Energy Services (LES), a subsidiary of Urenco, is currently constructing the National Enrichment Plant near Eunice, New Mexico, with an initial capacity of 3.3 million SWU/yr (eventually expandable to 5.9 million SWU/yr). Initial operation is scheduled to begin by the end of 2009.

[44] The French company Areva is planning to build the Eagle Rock Enrichment Facility in Idaho Falls, Idaho. On 31 March 2009, Areva announced its intent to revise the license application for this centrifuge plant to obtain the option of expanding its capacity from 3.3 million SWU/yr by 2018 to 6.6 million SWU/yr by 2022. "Areva maps out Eagle Rock expansion," *World Nuclear News*, 22 April 2009. Construction of USEC's American Centrifuge Plant, however, is experiencing delays, and the December 2012 target for reaching design capacity of 3.8 million SWU per year is increasingly unlikely. In July 2009, the U.S. Department of Energy denied a loan guarantee for the USEC plant, but agreed to postpone a final decision until early 2010, "Second chance for USEC," *World Nuclear News*, 5 August 2009. U.S. Energy Secretary Steven Chu explained that "this agreement gives USEC the time it needs to more fully test its technology and develop additional financial support for the project." Department of Energy and USEC Announce Decision to Delay USEC Loan Guarantee Application Final Review," Press Release, U.S. Department of Energy, 4 August 2009, www.energy.gov/news2009/7742.htm.

[45] Global Laser Enrichment is owned by General Electric (51 percent), Hitachi (25 percent) and Cameco, a Canadian uranium producer (24 percent). Virtually nothing is known about the details of the laser enrichment process the plant will use. The U.S. Nuclear Regulatory Commission accepted the license application for review in August 2009.

[46] www.urenco.com/content/37/URENCO-Enrichment-Company-UEC.aspx, mirrored at www.ipfmlibrary.org/uec09.pdf.

[47] The installed capacity of the Russian enrichment industry increased from 25.1 million SWU/year by the end of 2006, to 26.2 million SWU/year by the end of 2007. *Russian Enrichment Industry State & Prospects of Development Annual Report 2007*, International Business Relations Corporation, Department of Nuclear Power Engineering & Nuclear Fuel Cycle, Moscow, 2008, www.ibr.ru/documents/Demo%20Eng.pdf. Rosatom, Russia's national nuclear corporation, plan for 2015-30 includes an increase in enrichment capacity to 54 million SWU per year. "Russia's Ambitious Plans for Enrichment," *Uranium Intelligence Weekly*, 27 July 2009.

[48] This cooperation between Russia and Japan would be a precedent of a non-weapon state receiving centrifuge technology, even though Japan has developed its own technology in the past. *About the cooperation of Atomenergoprom OJSC with Toshiba Corporation in the field of uranium enrichment*, Atomenergoprom OJSC Press Release, 18 May 2009, www.minatom.ru.

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

[50] *U.S. Removes Nine Metric Tons of Plutonium From Nuclear Weapons Stockpile*, U.S. Department of Energy, Press Release, 17 September 2007, www.ipfmlibrary.org/bod07.pdf.

[51] UK Ministry of Defence, *Strategic Defence Review*, 1998, Chapter 4.

[52] Eight of India's sixteen unsafeguarded power reactors have been declared civilian and are to be placed under IAEA safeguards in a phased process by 2014. The list of reactors is available in Zia Mian, A. H. Nayyar, Rajaraman and M. V. Ramana, *Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal*, Research Report #1, International Panel on Fissile Materials, 2006.

[53] Assuming 0.85 grams of plutonium produced per MWt-day and 250–300 effective full power days per year.

[54] As of August 2009, the 26 MWt rating was still listed in the IAEA research reactor database, which is based on government-provided information, www.iaea.org/worldatom/rrdb.

[55] Tritium (T) and deuterium (D) are used in nuclear weapons to "boost" the yield of fission energy with a burst of neutron-producing fusion reactions. Tritium has a 12-year half-life and therefore must be replenished.

[56] The natural uranium fueled reactor, based on the Canadian NRX reactor design (as is India's CIRUS reactor), is assumed to be 50 MWt and operating at 70% capacity, with a fuel burnup of 1000 MWd/t.

[57] *Update on Khushab Plutonium Production Reactor Construction Projects in Pakistan*, Institute for Science and International Security (ISIS), 23 April 2009. The second Khushab reactor was reported in July 2006, see David Albright and Paul Brannan, *Commercial Satellite Imagery Suggests Pakistan is Building a Second, Much Larger Plutonium Production Reactor: Is South Asia Headed for a Dramatic Buildup in Nuclear Arsenals?*, ISIS, 24 July 2006; and "US Disputes Report on New Pakistan Reactor," *New York Times*, 3 August 2006. Images of the third reactor were released in June 2007. David Albright and Paul Brannan, *Pakistan Appears to be Building a Third Plutonium Production Reactor at Khushab Nuclear Site*, ISIS, 21 June 2007.

[58] David Albright and Paul Brannan, *Second Khushab Plutonium Production Reactor Nears Completion*, ISIS, September 18, 2008.

[59] Mark Hibbs, "After 30 Years, PAEC Fulfills Munir Khan's Plutonium Ambition," *Nucleonics Week*, 15 June 2000.

[60] 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*, August 3, 2006.

[61] David Albright and Paul Brannan, "Pakistan Expanding Plutonium Separation Facility Near Rawalpindi," ISIS, 19 May 2009.

[62] This plant is located at 32.381 N, 71.440 E. David Albright and Paul Brannan, "Chashma Nuclear Site in Pakistan with Possible Reprocessing Plant," ISIS, January 18, 2007.

[63] "North Korea Declares 31 Kilograms of Plutonium," NTI, *Global Security Newswire,* October 24, 2008; According to Selig S. Harrison who visited Pyongyang in early January 2009, the DPRK said that it has weaponized almost 31 kilograms of plutonium. Choe Sang-Hun, "North Korea Says It Has 'Weaponized' Plutonium," *New York Times*, 18 January 2009, p. A8. The U.S. estimate had been that North Korea produced 40–50 kg of plutonium, including the amount used in its test, Helene Cooper, "In Disclosure, North Korea Contradicts U.S. Intelligence on Its Plutonium Program," *New York Times*, 31 May 2008.

[64] *Second nuclear test conducted by North Korea on 25 May 2009*, Fact Sheet, Carl Friedrich von Weizsäcker Center for Science and Peace Research (ZNF), University of Hamburg, 25 May 2009.

[65] Siegfried S. Hecker, " The risks of North Korea's nuclear restart," *Bulletin of Atomic Scientists*, 12 May 2009, Hui Zhang, "Is North Korea's reprocessing facility operating?" *Bulletin of Atomic Scientists*, 23 July 2009. See also Appendix 3B in this report.

[66] WNA, August 2009, www.world-nuclear.org/info/inf63.html.

[67] Zhongmao Gu, "Chinese Perspective: Securing Nuclear Fuel Cycle While Embracing Global Nuclear Renaissance," *3rd UC Forum on the Future of Nuclear Power: Emerging Non-Proliferation And Security Challenges In Nuclear Energy, Near And Long Term Solutions*, Berkeley Nuclear Research Center, 11–12 June 2009.

[68] *Traitement des combustibles usés provenant de l'étranger dans les installations AREVA NC de La Hague*, Rapport 2008, Areva, www.lahague.areva-nc.fr.

[69] See the 2008 declarations to the IAEA from Belgium and Switzerland available at www.iaea.org.

[70] *Traitement des combustibles*, Areva, *op. cit.*, p. 29.

[71] *Letter to the International Atomic Energy Agency from the Permanent Mission of the Federal Republic of Germany to the Office of the United Nations and to other International Organisations Vienna, 20 June 2008.* Appended to International Atomic Energy Agency INFCIRC/549/Add.2/11, 18 July 2008.

[72] Japan declares only the fissile component (^{239}Pu and ^{241}Pu) of this material, and we multiply by 1.5 to obtain an estimated total. Numbers for Italy and the Netherlands are for the La Hague plant only (Table 1.3). The result therefore provides an upper bound for Germany's inventory.

[73] An industry source specified 9.15 tons of fissile plutonium, i.e. Pu-239 and Pu-241, which corresponds to about 16 tons of total plutonium in January 2007. Scheduled loadings of plutonium in MOX fuel into German reactors are projected to be about 3 tons per year for the next few years, before slowing down in 2012 and 2013. The German stockpile of separated plutonium will have all been loaded by 2014; M. Weis, M. Flakowski, R. Haid, F. Plaputta, and F. Völker, "Plutonium-Verwertung: 40 Jahre MOX-Einsatz in Deutschen Kernkraftwerken" [Plutonium-Recycling: 40 Years of MOX-Use in German Nuclear Power Reactors], atw, Vol. 51, No. 12, 2006, pp. 793–796. One year later (January 2008), the stockpile therefore should be on the order of 13 tons of which 1 ton may be located in Germany at any given time as fresh MOX fuel for reactor reloads.

[74] "Test run of spent fuel reprocessing plant to be extended again," Japan Today, 29 August 2009, www.japantoday.com/category/technology/view/test-run-of-spent-fuel-reprocessing-plant-to-be-extended-again. In January 2009, 150 liters of high-level radioactive waste leaked in the vitrification building and, in June 2009, a worker was exposed to radiation while trying to repair equipment in the building. "Worker Radiation Exposure at Rokkasho Reprocessing Plant," Citizens' Nuclear Information Center, Nuke Info Tokyo No. 131, July/August 2009, www.cnic.jp/english.

[75] "Rokkasho Plant Faces Formidable Technical Hurdles to Operation," *Uranium Intelligence Weekly*, February 23, 2009.

[76] "November construction start for Japanese MOX plant," 27 April 2009, www.jaif.or.jp/english, mirrored at www.ipfmlibrary.org/jaif09.pdf.

[77] "Japan delays MOX nuclear fuel goal by 5 years," *Reuters*, 12 June 2009, www.reuters.com.

[78] www.cnic.jp/english/topics/cycle/MOX/pluthermplans.html.

[79] Estimates by Tadahiro Katsuta and Tatsujiro Suzuki, October 2009, updating data published in a report by the same authors, *Japan's Spent Fuel and Plutonium Management Challenge*, Research Report #2, International Panel on Fissile Materials, September 2006, www.ipfmlibrary.org/rr02.pdf.

[80] Martin Forwood, "Britain's reprocessing boondoggle," *Bulletin of Atomic Scientists*," 19 August 2009, www.thebulletin.org/web-edition/op-eds/britains-reprocessing-boondoggle.

[81] Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, Research Report #5, International Panel on Fissile Materials, 2008, pp. 9–10.

[82] Ann MacLachlan, "Phenix's end of regular operation also stops transmutation tests," *Nucleonics Week*, March 19, 2009.

[83] "India's fast nuclear reactor project costs rise 40 percent," *Calcutta News Net*, 14 August 2009, www.calcuttanews.net/story/530677.

[84] "Chinese fast reactor nears commissioning," *World Nuclear News*, 7 April 2009, www.world-nuclear-news.org.

[85] Thomas B. Cochran, Harold A Feiveson, Walt Patterson, Gennadi Pshakin, M. V. Ramana, Mycle Schneider, Tatsujiro Suzuki and Frank von Hippel, *Fast Breeder Reactor Programs History and Status"* Research Report #8, International Panel on Fissile Materials, *forthcoming.*

Chapter 2. Fissile Materials and Nuclear Disarmament

[86] *Report of the Committee on Political and Social Problems* (The Franck Report), Manhattan Project "Metallurgical Laboratory," University of Chicago, June 11, 1945, www.ipfmlibrary.org/fra45.pdf.

[87] UN General Assembly Resolution 1, 24 January 1946.

[88] For the Acheson-Lilienthal Report, see Chester I. Barnard, J. R. Oppenheimer, Charles A. Thomas, Harry A. Winne, and David E. Lilienthal, *A Report on the International Control of Atomic Energy,* Washington, DC, 1946, www.ipfmlibrary.org/ach46.pdf. The text of the Baruch and Gromyko plans are available respectively in *Documents on Disarmament* 1945–1959, Volume I (1945–1956), U.S. Department of State, Washington, DC, August 1960, pp. 7–16 and 17–24.

[89] The Draft Convention proposed by the Soviet Union in 1946 is available at www.ipfmlibrary.org/gro46b.pdf

[90] Natural Resources Defense Council, "Table of US Strategic Bomber Forces," www.nrdc.org/nuclear/nudb/datab7.asp.

[91] The history of the international peace movement and visionary leaders since 1945 to advance nuclear disarmament has been chronicled in Lawrence Wittner's three volume history, *The Struggle against the Bomb, Stanford University Press*. See also the summary volume, *Confronting the Bomb: A Short History of the World Nuclear Disarmament Movement*, Stanford University Press, 2009.

[92] This does not include the possible occurrence of an Israeli or joint Israeli-South African nuclear test or series of tests in 1979. See e.g. Seymour Hersh, *The Samson Option: Israel's Nuclear Arsenal and American Foreign Policy*, Random House, New York, 1991, pp. 271–272. A declassified 22 October 1979, U.S. National Security Council memo concludes that the U.S. intelligence community had "high confidence after intense technical scrutiny" that there had been a "low-yield atmospheric nuclear explosion" on 22 September 1979. *South Atlantic Nuclear Event*, National Security Council Memo for Secretary of State, Defense, Energy etc. www.ipfmlibrary.org/nsc79.pdf. After a high-level review, the Carter Administration decided that the evidence was not conclusive. The "Ad Hoc [White House Office of Science and Technology Policy] Panel Report on the September 22, 1979 event" was published in *Dimona: The Third Temple? The Story Behind the Vanunu Revelation* by Mark Gaffney, Amana Books, Brattleboro, VT, 1989, Appendix B.

[93] Statement by Soviet General Secretary Gorbachev, January 15, 1986, *Documents on Disarmament 1986*, U.S. Arms Control and Disarmament Agency, Washington, DC, July 1993, pp. 10–19.

[94] Prime Minister Rajiv Gandhi, "A World Free of Nuclear Weapons," Speech to United Nations General Assembly, New York, June 9, 1988. www.indianembassy.org/policy/Disarmament/disarm15.htm.

[95] *Report of the Canberra Commission on the Elimination of Nuclear Weapons*, August 1996, www.dfat.gov.au/cc, mirrored at www.ipfmlibrary.org/can96.pdf.

[96] 1995 Review and Extension Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, Final Document, Part I, Organization and work of the Conference, NPT/CONF.1995/32 (Part I), New York, 1995, www.un.org/Depts/ddar/nptconf/2142.htm.

[97] In full, the sentence reads, "There exists an obligation to pursue in good faith and bring to a conclusion negotiations leading to nuclear disarmament in all its aspects under strict and effective international control." *Legality of the Threat or Use of Nuclear Weapons*, Advisory Opinion, International Court of Justice, I.C.J. Reports 1996, p.267. www.icj-cij.org/docket/files/95/7495.pdf.

[98] Rebecca Johnson, "The 2000 NPT Review Conference: A Delicate, Hard-Won Compromise," *Disarmament Diplomacy*, No. 46, May 2000, p. 21.

[99] President Barack Obama outlined a goal "to seek the peace and security of a world without nuclear weapons" and observed that "This goal will not be reached quickly—perhaps not in my lifetime." He also committed that "As long as these weapons exist, the United States will maintain a safe, secure and effective arsenal." Speech at Hradcany Square, Prague, Czech Republic, 5 April 2009. Similarly, Prime Minister Gordon Brown argued for "the ultimate ambition of a world free from nuclear weapons," but that at the same time asserted that the United Kingdom was "committed to retaining the minimum force necessary to maintain effective deterrence," speech at Lancaster House, London, 17 March 2009.

[100] Joint Statement by President Dmitriy Medvedev of the Russian Federation and President Barack Obama of the United States of America, 1 April 2009.

[101] *L'Aquila Statement on Nonproliferation*, July 2009, www.g8italia2009.it/static/G8_Allegato/2._LAquila_Statent_on_Non_proliferation.pdf. A similar statement was not contained, however, in the 2008 G-8 Summit, held in Hokkaido, Japan. At the time, the LDP Government, since replaced by one more interested in nuclear disarmament, was expressing concern about the potential loss of the U.S. nuclear "umbrella" over Japan.

[102] United Nations Security Council Resolution, S/RS/1887, 24 September 2009, www.ipfmlibrary.org/unsc1887.pdf.

[103] From the United States, see George P. Shultz, William J. Perry, Henry A. Kissinger And Sam Nunn, "A World Free of Nuclear Weapons," *Wall Street Journal*, 4 January 2007; from the United Kingdom, Douglas Hurd, Malcolm Rifkind, David Owen and George Robertson, "Start worrying and learn to ditch the bomb: It won't be easy, but a world free of nuclear weapons is possible," *The Times*, 30 June 2008; from Italy, Massimo D'Alema, Gianfranco Fini, Giorgio La Malfa, Arturo Parisi and Francesco Calogero, "For A World Free Of Nuclear Weapons," *Corriere Della Sera*, 24 July 2008; from Germany, Helmut Schmidt, Richard von Weizsäcker, Egon Bahr and Hans-Dietrich Genscher, "Toward a Nuclear-free World: A German View," *International Herald Tribune*, 9 January 2009.

[104] A notable recent effort to outline the problems facing nuclear abolition is George Perkovich and James M. Acton, *Abolishing Nuclear Weapons*, Adelphi Paper 396, Routledge for the IISS, London, 2008, pp. 52–57, reprinted with perspectives from many nuclear armed states, in *Abolishing Nuclear Weapons: A Debate*, George Perkovich and James M. Acton eds. Carnegie Endowment for International Peace, Washington, DC, 2009. Concerns that may arise in China, France, Germany, India, Iran, Israel, Japan, North and South Korea, Pakistan, the United Kingdom and the United States about nuclear weapon reductions, conventional forces and constraints on nuclear energy, among other things are discussed in the IPFM report *Reducing and Eliminating Nuclear Weapons: Country Perspectives on Fissile Materials and Nuclear Disarmament.*

[105] There are 25 non-weapon state members of the North Atlantic Treaty Organization. The April 2009 meeting of NATO leaders affirmed that "deterrence, based on an appropriate mix of nuclear and conventional capabilities, remains a core element of our overall strategy," *Declaration on Alliance Security, Issued by the Heads of State and Government*, North Atlantic Council Meeting, Strasbourg/Kehl, 4 April 2009, www.nato.int/cps/en/natolive/news_52838.htm. The U.S. also has commitments to Australia, New Zealand, Japan, South Korea and Taiwan. The U.S. is apparently also considering a formal public "defense umbrella" guarantee that could include the possibility of nuclear use to Israel and perhaps Arab allies in the Middle East in response to concerns about Iran's nuclear program. Mark Landler and David E. Sanger, "Clinton Speaks of Shielding Mideast from Iran," *New York Times*, 22 July 2009.

[106] In 2006, President Jacques Chirac of France explained that "The creation of a national deterrence force was a challenge for France. […] Nuclear deterrence thus became the very image of what our country is capable of producing when it has set itself a task and holds to it." Speech by Jacques Chirac, President of the French Republic, Landivisiau/L'Ile Longue, January 19, 2006, www.acronym.org.uk/dd/dd82/82chirac.htm.

[107] The NPT preamble, for instance, cites the desire among the parties for "the cessation of the manufacture of nuclear weapons, the liquidation of all their existing stockpiles, and the elimination from national arsenals of nuclear weapons and the means of their delivery." The five permanent members of the Security Council, the United States, United Kingdom, Russia, France and China all have nuclear weapons.

[108] The United States was unable to pacify South Vietnam in the 1960s and early 1970s. The Soviet Union failed to subdue Afghanistan in the 1980s. The United States has had limited success in its wars in Afghanistan since 2001 or in Iraq since 2003. For an extended argument, see Jonathan Schell, *The Unconquerable World: Power, Nonviolence, and the Will of the People,* Metropolitan Books, New York, 2003.

[109] In 2007, former U.S. Secretaries of State, George Shultz and Henry Kissinger, Secretary of Defense, William Perry and former chairman of the Senate Armed Services Committee, Sam Nunn argued that "Deterrence continues to be a relevant consideration for many states with regard to threats from other states. But reliance on nuclear weapons for this purpose is becoming increasingly hazardous and decreasingly effective," George P. Shultz, William J. Perry, Henry A. Kissinger and Sam Nunn, "A world free of nuclear weapons," *Wall Street Journal*, January 4, 2007.

[110] *Report of the Secretary of Defense Task Force on DoD Nuclear Weapons Management, Phase II: Review of the DoD Nuclear Mission*, December 2008, Executive Summary, www.defenselink.mil/pubs/pdfs/PhaseIIReportFinal.pdf. This has been identified as part of a larger problem crisis of confidence across the U.S. nuclear weapons complex about the importance and future of nuclear weapons, *Nuclear Deterrence Skills*, Report of the Defense Science Board Task Force, Washington, DC, September 2008, www.acq.osd.mil/dsb/reports/2008-09-NDS.pdf.

[111] Michael Hoffman, "B-52 mistakenly flies with nukes aboard," MilitaryTimes.com, 10 September 2007, www.militarytimes.com/news/2007/09/marine_nuclear_B52_070904w. For an analysis of this incident and its implications see Hans M. Kristensen, "Nuclear Safety and the Saga About the Missing Bent Spear," Federation of American Scientists Strategic Security Blog, 22 February 2008, www.fas.org/blog/ssp/2008/02/nuclear_safety_and_the_saga_ab.php

[112] Global Zero, "Publics around the World Favor International Agreement to Eliminate All Nuclear Weapons," www.globalzerocampaign.org.

[113] The Global Zero campaign has proposed that states agree a nuclear weapons ban with a schedule for the verified, elimination of nuclear arsenals to be achieved by 2030.

[114] "13 practical steps for the systematic and progressive efforts to implement Article VI of the Treaty on the Non-Proliferation of Nuclear Weapons and paragraphs 3 and 4 (c) of the 1995 Decision on 'Principles and Objectives for Nuclear Non-Proliferation and Disarmament," Sixth NPT Review Conference, Briefing No 18, May 20, 2000, including the Conference Agreement on a Programme of Action (Next Steps) on Nuclear Disarmament, www.acronym.org.uk/npt/npt18.htm.

[115] Jonathan Schell, *The Abolition*, Alfred A. Knopf, New York, 2000, p.153. Michael Mazarr proposed a more formal arrangement of "virtual nuclear arsenals" in which the nuclear armed-states maintain infrastructures able to produce "a few dozen nuclear weapons within a period of a few days or weeks," Michael Mazarr, *Nuclear Weapons in a Transformed World*, St. Martin's Press, New York, 1997, p. 4.

[116] Jonathan Schell, "The Abolition of Nuclear Arms: An Idea Whose Time Has Come," Lecture at International Security Studies Program, Yale University, 25 March 2009.

[117] Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*, MIT Press, Cambridge, MA, 1990, p. 426. This argument is developed at greater length in Donald MacKenzie and Graham Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," American Journal of Sociology, Volume 101, Number 1, July 1995, pp. 44–99. George Perkovich and James Acton make a somewhat different argument: "It is sometimes said that nuclear weapons 'cannot be disinvented'. We recognise this, but believe that the point is made to deflect careful thinking rather than encourage it. No human creation can be disinvented. Civilization has nevertheless prohibited and dismantled artefacts deemed too dangerous, damaging or morally objectionable to continue living with. Mass-scale gas chambers such as those used by Nazi Germany have not been disinvented, but they are not tolerated. […] The issue is rather whether means could exist to verify that a rejected technology—nuclear weapons in this theoretical case—had been dismantled everywhere, and to minimise the risk of cheating." Perkovich and Acton, *Abolishing Nuclear Weapons*, 2009, op. cit., p. 17.

[118] *Report of the Committee on Political and Social Problems (The Franck Report), op. cit.*; and *A Report on the International Control of Atomic Energy, op. cit.*

[119] On 29 May 2009, the CD agreed on a plan of work for this year that included establishing a working group to negotiate a fissile material cut-off treaty, on the basis of the Shannon mandate for such talks agreed on 24 March 1995, www.reachingcriticalwill.org/political/cd/papers09/2session/CD1863.pdf. Implementation of the plan of work has been stalled by Pakistan, however, and the plan of work will need to be renewed in 2010.

[120] Both France and the United Kingdom have recently decided for cost reasons to use conventional power plants for their future aircraft carriers, www.naval-technology.com/projects/gaulle. France (for export), Germany and Sweden have all developed conventional submarines which, in addition to being able to operate under water on battery power, carry oxygen and fuel for "air-independent" steam-turbine, fuel cell and Stirling engines respectively, which allow them to operate for weeks at moderate speeds (circa 10 kilometers per hour) without snorkeling, en.wikipedia.org/wiki/Air-independent_propulsion. This is adequate for near-home missions. However, all French, UK and U.S., most Russian and some Chinese submarines are nuclear powered, as are all U.S. aircraft carriers. The United States is considering shifting medium surface combatant vessels such as cruisers to nuclear power, U.S. Department of Energy, *FY 2009 Congressional Budget Request, Volume 1, National Nuclear Security Administration*, pp. 547–548.

Chapter 3. Declarations of Fissile Material Stocks and Production

[121] These numbers and some related official statements are discussed in Chapter 1 (for France, the United States and the United Kingdom). China's Foreign Ministry declared in April 2004 that China "possesses the smallest nuclear arsenal" among the nuclear-weapon states of the NPT, which—at the time—was equivalent to less than 200 deployed Chinese nuclear weapons. Ministry of Foreign Affairs of the People's Republic of China, "Nuclear Disarmament and Reduction of" [sic], *Fact Sheet China*, 27 April 2004, www.fmprc.gov.cn, mirrored at www.ipfmlibrary. org/prc04.pdf.

[122] "Declassification of Today's Highly Enriched Uranium Inventories at Department of Energy Laboratories," U.S. Department of Energy, 27 June 1994, www.ipfmlibrary.org/doe06a.pdf.

[123] *Historical Accounting for UK Defence Highly Enriched Uranium*, UK Ministry of Defence, March 2006, www.ipfmlibrary.org/mod06.pdf.

[124] Harald Müller, *The Nuclear Weapons Register: A Good Idea Whose Time Has Come*, PRIF Report No. 51, Peace Research Institute Frankfurt, June 1998; or Nicholas Zarimpas, ed., *Transparency in Nuclear Warheads and Materials. The Political and Technical Dimensions*, SIPRI, Oxford University Press, 2003.

[125] *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; and *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*, Draft, Rev. 1., U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf.

[126] *Historical Accounting*, UK Ministry of Defence, *op. cit.*

[127] *Plutonium: The First 50 Years, op. cit.*, p. 52, and *Striking a Balance, op. cit.*, p. 104.

[128] In the planned Soviet economy, the need to meet quotas provided incentives for misrepresentation even within the government. These impediments make compiling a declaration difficult and make an unambiguous determination of the completeness of that declaration by an outside party nearly impossible.

[129] "We can also be more open about fissile materials. Our current defence stocks are 7.6 tonnes of plutonium, 21.9 tonnes of highly enriched uranium and 15,000 tonnes of other forms of uranium." *The Strategic Defence Review*, UK Ministry of Defence, Cm 3999, July 1998, §72, www.ipfmlibrary.org/mod98.pdf. The United Kingdom released more detailed declarations on historical plutonium and HEU accounting in 2000 and 2006 respectively, *Plutonium and Aldermaston—an historical account*; and *Historical Accounting for UK Defence Highly Enriched Uranium*.

[130] Of the remaining 72 tons, 52 will be blended down to LEU and 20 were reserved to fuel research and space reactors.

[131] *Striking a Balance, op. cit.*, p. 38 (Table 3-1). The Y-12 plant stores HEU from dismantled thermonuclear warhead second stages, as well as a large amount of in-process HEU in the forms of liquids, oxides residues, etc. In 1996, DOE reported that Y-12 held more than 189 tons and Pantex 16.7 tons of HEU. Savannah River has a stock of irradiated HEU fuel from plutonium-production reactors. A large part of the 23 metric tons of HEU listed at Portsmouth, in the form of uranium hexafluoride, was subsequently transferred to the Y-12 facility, U.S. Department of Energy, Highly Enriched Uranium Working Group Report, DOE/EH-0525, December 1996; and private communication with Robert Alvarez, 2 February 2006.

[132] The U.S. declarations *Plutonium: The First 50 Years* and *Highly Enriched Uranium: Striking a Balance* contain facility-specific data for R&D sites, but did not break down by material in weapons and weapon components.

[133] Frank von Hippel, David H. Albright and Barbara G. Levi, "Stopping the Production of Fissile Materials for Weapons," *Scientific American*, September 1985.

[134] Treaty Between The United States Of America And The Union Of Soviet Socialist Republics On The Limitation Of Strategic Offensive Arms, Together With Agreed Statements And Common Understandings Regarding The Treaty, June 1979, www.state.gov/www/global/arms/treaties/salt2-2.html.

[135] Memorandum of Understanding regarding the Establishment of the Data Base for the Treaty between the Union of Soviet Socialist Republics and the United States of America on the Elimination of their Intermediate-Range and Shorter-Range Missiles, www.state.gov/www/global/arms/treaties/infmou.html.

[136] Protocol Regarding Inspections Relating to the Treaty between the United States of America and the Union of Soviet Socialist Republics on the Elimination of their Intermediate-Range And Shorter-Range Missiles, www.state.gov/www/global/arms/treaties/inf5.html.

[137] Treaty between the United States of America and the Union Of Soviet Socialist Republics on the Reduction and Limitation of Strategic Offensive Arms, 31 July 1991, www.state.gov/www/global/arms/starthtm/start/start1.html.

[138] *The Future of U.S. Nuclear Weapons Policy*, National Academy of Sciences, Washington, DC, 1997, p. 61, www.nap.edu/openbook.php?record_id=5796.

[139] Müller, *The Nuclear Weapons Register*, 1998, *op. cit*.

[140] Adapted from S. Fetter, "Stockpile Declarations," pp. 129–150 in N. Zarimpas, *Transparency in Nuclear Warheads and Materials. The Political and Technical Dimensions*, SIPRI, Oxford University Press, 2003.

[141] Chemical Weapons Convention Verification Annex,
www.opcw.org/chemical-weapons-convention/verification-annex/part-iva.

[142] Israel has maintained its policy of "nuclear opacity" for decades and has pledged not to be first state to "introduce" nuclear weapons into the Middle East.

[143] Müller, *Nuclear Weapons Register*, 1998, *op. cit.*, Sections 6.1 (The "De-Facto-Nuclear Weapon State Problem") and Section 6.2 (Staging the Register), pp. 17–21.

[144] *Plutonium: The First 50 Years*, 1996, *op. cit.*, and *Highly Enriched Uranium: Striking a Balance, op.cit.*

[145] Peter Crail, "NK Delivers Plutonium Documentation," *Arms Control Today*, June 2008.

[146] Glenn Kessler, "Message to U.S. Preceded Nuclear Declaration by North Korea," *Washington Post*, 2 July 2008, p. A7.

[147] "North Korea Declares 31 Kilograms of Plutonium," *Global Security Newswire*, Nuclear Threat Initiative, 24 October 2008. According to Selig S. Harrison who visited Pyongyang in early January 2009, the DPRK said that it has weaponized almost 31 kilograms of plutonium. Choe Sang-Hun, "North Korea Says It Has 'Weaponized' Plutonium," *New York Times*, 18 January 2009, p. A8.

[148] Had they been completed, the plant also would have produced fuel for the DPRK's 50-MWe and likely also the 200-MWe reactor.

[149] *Solving the North Korean Nuclear Puzzle*, David Albright and Kevin O'Neill (eds.), Institute for Science and International Security, Washington, DC, 2000, p. 144.

[150] Siegfried Hecker, "Denuclearizing North Korea," *Bulletin of the Atomic Scientists*, May/June 2008.

[151] "N Korea closes more nuclear sites," *BBC News*, 18 July 2007.

[152] The disablement of the nuclear fuel fabrication facility began in early November 2007 and three out of four steps had been completed as of January 2009: removal and storage: of three uranium ore concentrate dissolver tanks; seven uranium-conversion furnaces, including storage of the refractory bricks from which they were made; both metal casting furnaces and the associated vacuum system; and eight machining lathes. One uncompleted step was destruction of the stockpile of fresh fuel rods, Mary Beth Nikitin, *North Korea's Nuclear Weapons*, Congressional Research Service, 12 February 2009. The DPRK has in storage about 2,400 fuel rods for the 5-MWe reactor and about 12,400 fuel rods without cladding for the 50 MWe reactor. These fuel rods were fabricated during 1991–1994. The total weight of the stored fuel rods is 101.9 tons of uranium, J. W. Shin, "Joon-Kuk Hwang confirmed about 14,800 fresh fuel rods," Newsis, 20 January 2009 (South Korean news media).

[153] The design of the UK's 50 MWe Calder Hall reactor apparently was the basis for that of the 5-MWe reactor, *Solving the North Korean Nuclear Puzzle, op. cit.*, p. 146.

[154] Although the nominal power of the 5-MWe reactor is about 25 MWt, it rarely exceeded 20 MWt, *Solving the North Korean Nuclear Puzzle, op. cit.*, p. 124.

[155] *Solving the North Korean Nuclear Puzzle,* 2000*, op. cit.*, pp. 113 and 117.

[156] David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007," Institute for Science and International Security, 20 February 2007.

[157] "IAEA Team Confirms Shutdown of DPRK Nuclear Facilities," *Press Release*, International Atomic Energy Agency, 18 July 2007. The disablement process of the 5-MWe reactor began in early November 2007 and one out of three steps had been completed as of January 2009: removal of reactor cooling loop and wooden cooling tower interior structure. The DPRK destroyed the cooling tower on 27 June 2008. Two uncompleted steps were discharge of 8,000 spent fuel rods to the spent fuel pool and removal of control rod drive mechanisms. About 6,100 spent fuel rods had been discharged from the reactor to the cooling pool as of February 2009, Mary Beth Nikitin, 2009, *op. cit.*

[158] PUREX stands for Plutonium and Uranium Recovery by EXtraction. The PUREX process is a liquid-liquid extraction method used to dissolve spent nuclear fuel and separate pure uranium and plutonium from fission products. The recovery rate of plutonium from the spent fuel varies from from 95 to 99 percent, Thomas W. Wood, et al., "Establishing Confident Accounting for Russian Weapons Plutonium," *Nonproliferation Review*, Summer 2002.

[159] *Solving the North Korean Nuclear Puzzle*, 2000, *op. cit.*, pp. 113, 149.

[160] *North Korea's Weapons Programmes: A Net Assessment, International Institute for Strategic Studies*, 2004, p. 36.

[161] *Solving the North Korean Nuclear Puzzle*, 2000, *op. cit.*, p.122.

[162] Mary Beth Nikitin, 2009, *op. cit.*

[163] David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007," Institute for Science and International Security, February 20, 2007, www.isis-online.org/publications/dprk/DPRKplutoniumFEB.pdf

[164] The disablement process of the reprocessing facility began in early November 2007 and four steps had been completed as of January 2009: cut cable and remove drive mechanism associated with the receiving hot-cell door; cut two of four steam lines into reprocessing facility; removal of drive mechanisms for the fuel cladding shearing and slitting machines; and removal of crane and door actuators that permit spent fuel rods to enter the reprocessing facility, Mary Beth Nikitin, 2009, *op. cit.*

[165] "N Korea says it has restarted nuclear facilities," *Associated Press*, April 25, 2009.

[166] "The North Korean Plutonium Stock, February 2007," *op. cit.*

[167] Siegfried Hecker, "Denuclearizing North Korea," *Bulletin of the Atomic Scientists*, May/June 2008; "I took the David Albright estimate of 8.6 kg produced before 1994 (both IRT and 5-MWe). Then I made a rough estimate of 25 kg from the 2003 reprocessing campaign and 12 kg from the 2005 reprocessing campaign—for a total of 45.6 kg. Because of the uncertainties, I called it 40 to 50 kg (again noting that this may be high). It does not include the roughly 8 kg of unseparated plutonium in the current load of fuel rods." Private communication with Siegfried Hecker, April 2009.

[168] *North Korea's Nuclear Weapons, op. cit.*

[169] David Albright and Kevin O'Neill Editors, *Solving the North Korean Nuclear Puzzle*, The Institute for Science and International Security, Washington, DC, p. 118, 2000.

[170] *Solving the North Korean Nuclear Puzzle, op. cit.*, p. 161; 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, p. 4; Personal communication with expert at Korean Atomic Energy Research Institute (KAERI), ROK, November 2008.

[171] MCNPX (MCNP eXtended) is a Monte Carlo radiation transport computer code that transports nearly all particles at nearly all energies, performing the depletion calculation of nuclear fuels. John S. Hendricks, et al., *MCNPX 2.6.0 Extensions*, LA-UR-08-2216, 11 April 2008.

[172] "The North Korean Plutonium Stock, February 2007," *op. cit.*

[173] "U.S.-North Korea Understandings on Verification," Fact Sheet, U.S. Department of State, 11 October 2008. The detailed verification proposal offered by the U.S. government to the DPRK in 2008 is reproduced in the Appendix to Chapter 4 of this report.

[174] Glenn Kessler, "N. Korea Doesn't Agree To Written Nuclear Pact," *Washington Post*, 12 December 2008, p. A22.

Chapter 4. Nuclear Archaeology

[175] S. Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile-Material Production," *Science & Global Security*, 3 (1993), pp. 237–259, www.ipfmlibrary.org/fet93.pdf.

[176] 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.

[177] For an excellent discussion and a review of several case studies, see: T. W. Wood, B. D. Reid, J. L. Smoot, and J. L. Fuller, "Establishing Confident Accounting for Russian Weapons Plutonium," *Nonproliferation Review*, 9(2), Summer 2002, pp. 126–137, available at www.cns.miis.edu/npr.

[178] In the case of reactors moderated by materials other than graphite, core support structures and other reactor components could be sampled. The 2008 U.S. Verification Measures Discussion Paper, reproduced in Appendix 4A, whose focus is the verification of North Korea's 2008 declaration, specifies in this regard: "As relates to a research reactor, collect and remove from the Party samples of the aluminum core support structure, and from the reactor reflector elements." One complication for the heavy-water production reactors at the U.S. Department of Energy's Savannah River site is that they were used for both plutonium and tritium production. This may also have been the case for some of France's graphite-moderated production reactors.

[179] The plot is adapted from data to be published in Jungmin Kang, "Using Graphite Isotope Ratio Method to Verify DPRK's Declaration of Plutonium Production," *submitted for publication*.

[180] Wood et al., 2002, *op. cit.*

[181] During 1965–69, some of this plutonium may have gone into the UK weapon stockpile, D. Albright, F. Berkhout and W. Walker, *Plutonium and Highly Enriched Uranium 1996,* Oxford University Press, 1967, p. 63.

[182] Actual and estimated production differed by only 0.3% (Wood et al., *op. cit.*), which is clearly better than what one can reasonably expect.

[183] Percentage losses during production of weapons plutonium can be expected to be larger than losses expected in commercial reprocessing plants due to the roughly ten times lower concentration of plutonium in the irradiated fuel. Also, in the early weapons programs, a sense of "urgency," less sophisticated technologies, and little environmental oversight may all have contributed to higher process losses.

[184] Reactors are typically cylindrical or cubical. For symmetry reasons, it is therefore sufficient to consider a small fraction of the core, for example, a 30-degree segment in the case of a cylinder, which would reduce the number of fuel channels to be analyzed by a factor of 12. For each fuel channel in this segment, a few axial samples are sufficient to characterize the average flux profile in the core. In total, less than 100 samples, taken from known locations in the core, should adequately describe the complete flux distribution in the reactor. In the case of the Trawsfynydd-II demonstration project in the United Kingdom, 90 samples were acquired and used for a nuclear-archaeological analysis, Wood et al., *op. cit.*, p. 130.

[185] For example, graphite of the French plutonium production reactors G1, G2, G3 will not be removed before 2030, in part to allow cobalt-60 levels to fall sufficiently, see *Inventaire national des matières et déchets radioactifs 2009, Catalogue descriptif des familles,* Agence Nationale Pour La Gestion Des Déchets Radioactifs (ANDRA), Châtenay-Malabry, June 2009, www.andra.fr. Apparently, this delay is meant to reduce exposure doses and to enable sending the metal waste to Soulaines for surface storage.

[186] In May 2009, however, it was reported that "the Department of Energy is considering tearing down Hanford's K Reactors that stand on the banks of the Columbia River rather than sealing them up for 75 years. If the plan goes forward, it could lead to tearing down eight of the nine plutonium production reactors along the river instead of leaving them "cocooned." Only B Reactor, which is expected to be preserved as a museum, would remain standing, Annette Cary, "Demolition being considered rather than sealing Hanford reactor sites," *TriCity Herald*, 12 May 2009.

[187] Uranium-234 is a decay product of uranium-238 and has a half-life much shorter than its parent. In equilibrium, the concentration of uranium-234 in natural uranium is determined by the ratio of the half-lives.

[188] Uranium-234 decays to Thorium-230, which has a 75,000-year half-life.

[189] S. Fetter, "Nuclear Archaeology", op. cit., p. 237; M. Sharp, "Applications and Limitations of Nuclear Archaeology," *submitted to Science & Global Security*.

[190] Matthew Sharp, Harvard University, *in preparation*.

[191] Uranium-238 decays to uranium-234 via thorium-234, whose half-life is 24 days. If water is flowing through a non-uniform or thin uranium deposit, the difference between the solubilities of uranium and thorium can result in some of the thorium being moved from a more concentrated to a less concentrated part of the uranium deposit or vice versa.

[192] *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*, Draft, Rev. 1., U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf, Figure 2-2 (p. 27).

[193] When uranium-235 absorbs a neutron in a reactor, there is a chance that it will not fission but instead become uraninum-236. The next neutron capture produces uranium-237, which quickly decays into neptunium-237. Another neutron capture in neptunium-237 produces neptunium-238, which decays into plutonium-238.

[194] U-235 decays slowly into to thorium-231, which decays in turn to protactinium-231 (Pa-231). Neutron capture on Pa-231 produces Pa-232, which decays with a 1.3-day half-life to U-232. U-232 has a half-life of 70 years.

[195] H. Wood and A. Glaser, "Computational Analysis of Signatures of Highly Enriched Uranium Produced by Centrifuge and Gaseous Diffusion," *INMM 49th Annual Meeting*, Nashville, TN, 13–17 July 2008.

[196] Examples are: R. F. Smith, *Historical Impact of Reactor Tails on the Paducah Cascade*, KY/L-1239, Paducah Gaseous Diffusion Plant, U.S. Department of Energy, March 1984, www.ipfmlibrary.org/smi84.pdf; and S. P. Gydesen, Selected Monthly Operating Data for B and T Plants, Redox and Purex (1944–1972), HW-89085, Hanford Atomic Products Operation, Richland, Washington, April 1992, www.ipfmlibrary.org/gyd92.pdf.

[197] Figure adapted from A. Glaser, "Isotopic Signatures", *op. cit*.

[198] In the case of uranium enrichment, about 200 kg of tails are left behind for every kilogram of weapon-grade HEU produced (assuming 0.2-percent U-235 remaining in the tails). Similarly, in the case of production of weapon-grade plutonium, about one thousand times as much reprocessed uranium and a large volume of the high-level radioactive waste are produced.

[199] K. J. Moody, I. D. Hutcheon, and P. M. Grant, *Nuclear Forensic Analysis*, Taylor & Francis, Boca Raton, FL, 2005, Chapter 6 (Chronometry), pp. 207–240.

[200] In the case of plutonium, for example, the americium-241 buildup from plutonium-241 decay provides the most accurate chronometer. Even if the americium is removed from the plutonium, however, the low plutonium-241/plutonium-239 ratio, compared to what would be consistent with production-reactor operations that would produce the measured Pu-240/Pu-239 and Pu-242/Pu-239 ratios, could be used to estimate the age of the material.

[201] Report on the Completeness of the Inventory of South Africa's Nuclear Installations and Material, International Atomic Energy Agency, GC(XXXV)/RES/567 4 September 1992, www.ipfmlibrary.org/iaea92.pdf.

[202] Report on the Completeness of the Inventory of South Africa's Nuclear Installations and Material, 1992, *op. cit.*, p. 10, §31.

[203] K. J. Moody, et al., *Nuclear Forensic Analysis, op. cit.*, Chapter 21 (Counterforensic Investigation of U.S. Enrichment Plants), pp. 421–445.

[204] Planning a swipe sampling campaign requires careful selection of the most appropriate sampling locations to maximize detection of nuclear signatures. In the plants investigated here, heavy contamination made sampling efforts more difficult because depleted, natural, or slightly enriched uranium are much more abundant. The analysts noted that, "although some swipe specimens were taken, the most useful sampling devices were spatulas and horseshoe magnets," Moody et al., 2005, *op. cit.*, p. 422.

[205] Moody et al., *op. cit.*, pp. 434–435. The United States produced about 64 percent of its weapon-grade plutonium in graphite-moderated natural/slightly-enriched uranium fueled reactors at the Hanford Site in Washington State. Almost all the remainder was produced in heavy-water-moderated reactors at the Savannah River Site in South Carolina. Post-1968, plutonium production at the Savannah River Site (accounting for about 20 percent of total U.S. weapon-grade plutonium) was done in depleted uranium targets with neutrons provided by HEU "driver fuel," U.S. Department of Energy, *Plutonium: The First 50 Years* (1996) and T. B. Cochran, W. M. Arkin, R. S. Norris and M. M. Hoenig, *U.S. Nuclear Warhead Facility Profiles*, Ballinger, 1987, p. 102.

Chapter 5. Verified Warhead Dismantlement

[206] *Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement*, Office of Arms Control and Nonproliferation, U.S. Department of Energy, 1997, www.ipfmlibrary.org/doe97c.pdf. Other studies include A. Bieniawski and P. Irwin, "Overview of the US-Russian Laboratory-to-Laboratory Warhead Dismantlement Transparency Program: A US Perspective," *Proceedings of the 41st Annual Meeting of the Institute of Nuclear Materials Management*, 2000; O. Bukharin, "Russian and US technology development in support of nuclear warhead and material transparency initiatives" in Nicholas Zarimpas, *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, Oxford University Press, 2003; and *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities*, U.S. National Academy of Sciences, National Academy Press, 2005.

[207] Adapted from *Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China*, 3 January 1999, also known as the "Cox Report," www.house.gov/coxreport/pdf/ch2.pdf, p.78. Original image credit: *US News and World Report*.

[208] *Global Fissile Material Report 2008*, Chapter 6.

[209] About 2000 W-76 warheads will go through life-extension programs between 2008-2021. This involves refurbishing the thermonuclear secondaries (officially referred to as "canned subassemblies"), U.S. Department of Energy, National Nuclear Security Administration, *Fiscal Year 2009 Congressional Budget Request*, Volume 1, pp. 101–102; Hans Kristensen, Federation of American Scientists, personal communication, 7 March 2009. We also assume that about 250 excess secondaries are dismantled per year to provide HEU for naval propulsion reactors and other purposes.

[210] Robert Norris and Hans Kristensen: "U.S. nuclear forces, 2009," *Bulletin of the Atomic Scientists*, March/April 2009, p. 59; "U.S. nuclear forces, 2008," *Bulletin of the Atomic Scientists*, March/April 2008, p. 50; "U.S. nuclear forces, 2007," *Bulletin of the Atomic Scientists*, January/February 2007, p. 79; "Where the weapons are, 2006," *Bulletin of the Atomic Scientists*, November/December 2006, p. 57; Hans Kristensen, "U.S. Nuclear Weapons Withdrawn From the United Kingdom," FAS Security Blog, 26 June 2008, and Hans Kristensen and Robert Alvarez personal communication.

[211] *START Treaty between the US and USSR on the Reduction and Limitation of Strategic Offensive Arms*, Protocol on Notifications, Article I.1-2, 4.

[212] A reentry vehicle is the cone-shaped cover that makes it possible for a strategic ballistic-missile warhead to survive its high-speed passage through the atmosphere on its way to its target. *START Treaty between the US and USSR on the Reduction and Limitation of Strategic Offensive Arms*, Article XI.6.

[213] *START Treaty*, Protocol on Inspections and Continuous Monitoring, Article IX.1.

[214] *Radiation Detection Equipment: An Arms Control Verification Tool*, Defense Threat Reduction Agency, Order No. 211P, 2006, pp. 8–12. Some plutonium isotopes fission spontaneously. As a result, a nuclear warhead with a plutonium pit continuously emits penetrating neutrons, making it easily detectable. See e.g. S. T. Belyaev et al., "The Use of Helicopter-Borne Neutron Detectors to Detect Nuclear Warheads in the USSR-US Black Sea Experiment," *Science & Global Security*, Vol. 1, 1990, p. 328.

[215] *START Treaty*, Protocol on Inspections and Continuous Monitoring, Article VII.14.f.

[216] *START Treaty*, Protocol on Inspections and Continuous Monitoring, Annex 4, "Procedures for Inspections of Heavy Bombers, Former Heavy Bombers, Long-range ALCMs, and their Facilities," Article IV.4.i. Each party has a right to conduct baseline data inspections and up to a total of fifteen update inspections each year at randomly selected facilities covered by the data exchange (Article VII.2).

[217] *Pantex Final Environmental Impact Statement for the Continued Operation of the Pantex Plant and Associated Storage of Nuclear Weapon Components*, U.S. Department of Energy, EIS-0225, 1996, Figure 1.2.2.1-1.

[218] Matthew Bunn, "'Pit-stuffing:' How to disable thousands of warheads and easily verify their dismantlement," and R. L. Garwin, "Comment on Matt Bunn's 'pit-stuffing' proposal," *Federation American Scientists Public Interest Report 51*, No. 2, March/April 1998.

[219] *Management and Disposition of Excess Weapons Plutonium*, U.S. National Academy of Sciences, National Academy Press, 1994, p. 119.

[220] The average quantities of fissile material in a warhead could be estimated simply by dividing the quantities of fissile material coming out of the dismantlement process by the numbers of warheads going in. The report of the U.S. Department of Energy's Fundamental Classification Policy Review found that "estimates made of special nuclear material in specific weapons based on plant averages and feed streams are of little consequence," *Report of the Fundamental Classification Policy Review Group*, Dr. Albert Narath, Chair, 15 January 1997, www.fas.org/sgp/library/repfcprg.html, Chapter 6.

[221] See, for example, *Restricted Data Declassification Decisions: 1946 to the Present* (RDD-8), U.S. Department of Energy, 1 January 2002, I.II.I.33.a, www.ipfmlibrary.org/rdd8.pdf. A separate note emphasizes: "The average masses of special nuclear materials in the U.S. nuclear weapons or special nuclear materials masses in any specific weapon type remain classified."

[222] *Global Fissile Material Report 2008*, p. 70. See also Matthew Bunn, *Monitoring Stockpiles: Mayak Storage Facility Transparency*, 2007, www.nti.org/e_research/cnwm/monitoring/mayak.asp.

[223] The Russian-U.S. agreement on verification the disposition of excess weapons plutonium specified that its isotopic content would not be measured until it had been mixed with up to 12 percent as much "blend-stock" plutonium whose isotopic makeup also would not be measured, *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, Article II.6, www.ipfmlibrary.org/gov00.pdf. Similarly, the 1996–2002 Trilateral (IAEA-Russia-U.S.) Initiative, which, if implemented, would have allowed the

IAEA to verify through an “information barrier” that the plutonium in a pit inside a container was “weapon-grade,” the IAEA would have been allowed to verify only that the Pu-240/Pu-239 ratio was less than 0.1, *Global Fissile Material Report 2008*, Chapter 6.

[224] The physics packages in the four B-61 warhead variants and the two cruise-missile warheads are reportedly all the same, Thomas Cochran, William Arkin and Milton Hoenig, *U.S. Nuclear Forces and Capabilities*, Ballinger, 1984, p. 80.

[225] “U.S. nuclear forces, 2009,” *op. cit.*

[226] *Transparency and Verification Options, op. cit.*, Appendix E: “Interim Technical Report on Radiation Signatures for Monitoring Nuclear Warhead Dismantlement.”

[227] Fissile isotopes undergo radioactive decay at different rates. Each isotope in the fissile material emits gamma rays with characteristic energies when it decays. Additional gamma rays are generated from the capture of neutrons emitted by the plutonium in warhead materials. The gamma energy spectrum coming from a warhead is further modified as the gamma rays pass through the surrounding materials because the ability of gamma rays to penetrate these materials depends upon their energy. Also, some gamma rays lose part of their energy as a result of scattering off electrons (Compton Scattering).

[228] Steve Fetter, Thomas B. Cochran, Lee Grodzins, Harvey L. Lynch and Martin S. Zucker, “Measurements of Gamma Rays from a Soviet Cruise Missile,“ *Science*, Vol. 248, 18 May 1990, p. 828.

[229] Some of the energy deposited in the crystal of a scintillation detector by a gamma ray is converted into light whose energy is measured by photomultipliers.

[230] Because of the relatively short (14-year) half-life of plutonium-241, account would have to be taken of the fact that the gamma signals from its decays and those of its decay product, americium-241, would respectively decline and grow with the age of the warhead.

[231] Californium-252, a 2.6-year half-life isotope that decays 3 percent of the time by spontaneous fission, is used as the neutron source. In NWIS, the Cf-252 is in an ionization chamber. The two medium-sized nuclei into which the Cf-252 splits (its “fission products”) separate with high energy because of their mutual repulsion and cause ionization in the gas of the chamber. These ions are attracted to wires by an electric field and thereby cause a signal. The neutron source is designed so that it sends a signal whenever a neutron is emitted. The distribution of delay times of the neutrons and gammas that are induced by fissions in the secondaries provides information about the material in the secondary.

[232] The Gamma Ray Signature method cannot be used for such a purpose because the low-energy gamma rays generated by HEU deep in the component do not escape and the presence or absence of this deep HEU is therefore not visible.

[233] Although it is not possible for non-weapon experts to reconstruct a warhead design from spontaneous or induced radiation patterns, experienced nuclear-weapon designers could calculate these patterns for various warhead designs and see whether one matches.

[234] In fact, it would not be unity because of variations in materials and measurements. For example, weapon-grade plutonium contains different percentages of 14-year half-life plutonium-241 depending upon its age.

[235] The statistical uncertainties in the raw data could be revealing because they would be proportional to the square root of the number of counts in a particular energy-time bin. Russian and U.S. weapons experts could agree on a weighted sum of the ratios of the counts in different energy and time bins that provides good differentiation between different types of warheads.

[236] See the discussion of the use of information barriers in the Trilateral Initiative, *Global Fissile Material Report 2008*, Chapter 6. A good technical description and discussion may be found in the joint IAEA-Russian-U.S. paper, Diana G. Langner et al., “Attribute Verification Systems with Information Barriers for Classified Forms of Plutonium in the Trilateral Initiative, IAEA Safeguards,” *Proceedings of the Symposium on International Safeguards Verification and Nuclear Material Security, 29 October–2 November 2001, Vienna,* IAEA-SM-367/17/02.

[237] *Arms Control and Nonproliferation Technologies: Technology R&D for Arms Control*, U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Spring 2001, www.ipfmlibrary.org/doe01b.pdf, p. 44.

[238] The authors of *Transparency and Verification Options, op. cit,* argued, however, that it would be critical to verify that no undeclared components or fissile material from previously dismantled warheads were introduced into the process to allow an intact warhead to be removed after it had been declared for a particular dismantlement campaign. This would require every warhead to be subject to contained dismantlement.

[239] Dismantlement cells, also known in the United States as "Gravel Gerties," are designed to contain the plutonium dust if sensitive chemical explosive were to accidentally detonate during its removal from the plutonium "pit." All other dismantlement operations—and even the removal of insensitive explosive from around pits—can be carried out in the more numerous "bays," which are ordinary rooms.

[240] Based on *Transparency and Verification Options*, p. 59.

[241] Roger G. Johnston, "Tamper-Indicating Seals for Nuclear Disarmament and Hazardous Waste Management, *Science & Global Security*, Volume 9, 2001, pp. 93–112.

[242] E. R. Gerdes, R. G. Johnston and J. E. Doyle, "A Proposed Approach for Monitoring Nuclear Warhead Dismantlement," *Science & Global Security,* Vol. 9, 2001, p. 113.

[243] J. E. Doyle, "Chain-of-custody monitoring of warhead dismantlement," in *Technology R&D for Arms Control, op. cit.*, p. 54.

[244] In 2003, it was projected that, as of the end of 2005, there would be over 14,000 plutonium pits from dismantled U.S. warheads in storage at the U.S. Pantex warhead assembly/disassembly facility, *Supplement Analysis for the Final Environmental Impact Statement for the Continued Operation of the Pantex Plant and Associated Storage of Nuclear Weapon Components*, U.S. Department of Energy, DOE/EIS-0225/SA-03, February 2003, Table 1-2.

[245] A famous example of how much information can be picked up by interacting on an unclassified basis with weapon-facility personnel was provided by Howard Morland, who wrote in the article, "The H-bomb secret" that "This description and the details that follow are the result of six months' investigation of the nuclear weapon production complex in the United States. It is a mosaic of bits and pieces taken from employee recruitment brochures, environmental impact statements, books, articles, personal interviews, and my own private speculation," *The Progressive*, November 1979, p. 14.

Chapter 6. Disposition of Plutonium and Highly Enriched Uranium

[246] www.usec.com/megatonstomegawatts.htm, accessed, 21 July 2009.

[247] The original framework "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons" was signed in Washington, DC, on 18 February 1993, www.ipfmlibrary.org/heu93.pdf. It took over a year to negotiate the remaining specifics of the deal, including arrangements for verification that the agreed amount of HEU was indeed being blended down and the price to be paid, see www.usec.com/megatonstomegawatts_history.htm. At the then prevailing prices for enrichment work, USEC found that it could make more profit by reselling the Russian LEU than by selling LEU produced in the U.S. energy-intensive legacy gaseous diffusion plants.

[248] "UxC Historical Ux Price Charts," www.uxc.com. There were other equally important reasons for the recent dramatic spike in natural-uranium prices, including the closure of mines, the anticipation of a nuclear-energy "renaissance," and the speculative activities of hedge funds.

[249] *Fiscal Year 2010 Congressional Budget Request*, U.S. Department of Energy, pp. 391, 397.

[250] Robert M. George, "U.S. HEU Disposition Program," *Annual Meeting of the Institute of Nuclear Materials Management*, Tucson, Arizona, 12–16 July 2009.

[251] *Global Fissile Material Report 2007*, Table 2.1. As of mid-2009, the United States had blended down 124 tons of HEU with an average enrichment of 55.9 percent equivalent in U-235 content to 77 tons of 90% enriched HEU, "U.S. HEU Disposition Program," *op. cit.*

[252] *FY 2010 Congressional Budget Request: National Nuclear Security Administration*, U.S. Department of Energy, Vol. 1, May 2009, p. 417.

[253] The United States would need to dismantle about 200 HEU weapon components per year for forty years to make available enough HEU both for the 128 tons reserved for naval fuel and the 92 tons to be blended down.

[254] The ±300 tons uncertainty reflects the uncertainty in published estimates of Russia's HEU stocks.

[255] Russia refuels its icebreakers and submarines approximately every 10 years and fuels them with HEU enriched to about 40 percent. It might be possible to replace this fuel with higher-uranium-density LEU fuel enriched to just less than 20 percent without requiring a new core design, Anatoli Diakov, et al., "Feasibility of Converting Russian Icebreaker Reactors from HEU to LEU Fuel," *Science & Global Security*, Vol. 14, 2006, p. 33. Russia has reportedly adapted an icebreaker reactor-core design to LEU fuel for a floating nuclear power plant that it hopes to produce for an export market, Nikolai Sokov, "Construction of Russia's First Floating Nuclear Power Plant Raises Potential Nonproliferation Issues, Opportunities," *WMD Insights*, September 2006; and "Russian floating nuclear plant builder Sevmash diverting cash to other projects," Bellona, July 8, 2008, www.bellona.org/articles/articles_2008/fnpp_sinking.

[256] New U.S. submarines and aircraft carriers have lifetime cores. There is therefore a declining requirement of HEU for refueling. Twenty years would be a reasonable length of time for the development of LEU-fueled reactors for new submarines and aircraft carriers. Lifetime reactor cores fueled with LEU might be up to three times larger or, if the same size as the weapon-grade uranium core, might require refueling once or twice during the submarine or aircraft carrier lifetimes, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, Director, Naval Nuclear Propulsion, U.S. Department of Energy, June, 1995, www.ipfmlibrary.org/onnp95.pdf. For another perspective, see Ma Chunyan and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors" *Nonproliferation Review*, Spring 2001, p. 86.

[257] Laura S. H. Holgate, "Expanding Russian HEU Blend Down;" Robert E. Schultz, "Cost and Schedule for Russian HEU Blend Down: Expansion Approaches;" and Kevin Alldred, "Russian HEU blend down technology and options for expansion," *Annual Meeting of the Institute for Nuclear Materials Management*, 13–17 July 2008.

[258] We assume blend down with natural uranium, which would result in 82 percent as much LEU as the current practice of blending down Russian HEU with 1.5-percent enriched LEU obtained by enriching depleted uranium. This current practice, which results in the use of about as much enrichment work as making the LEU from natural uranium, was a strategy to meet the 1996 ASTM limit on U-234 in LEU. In 2004, the ASTM raised this limit by 10 percent, however, and it should be achievable by blending with natural uranium, ASTM Standard C996, 2004, "Uranium Hexafluoride Enriched to Less than 5% ^{235}U." For a discussion of the amounts of minor isotopes in highly enriched uranium, see Houston G. Wood and Alexander Glaser, "Computational Analysis of Signatures of Highly Enriched Uranium Produced by Centrifuge and Gaseous Diffusion," *Proceedings of the Annual Meeting of the Institute for Nuclear Materials Management*," Nashville, Tennessee, 13–17 July 2008.

[259] Based on Ole Reistad and Styrkaar Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *Nonproliferation Review*, Vol. 15, No. 2, 2008, p. 265, Figure 5.

[260] H. R. 2638, *Consolidated Security, Disaster Assistance, and Continuing Appropriations Act*, 2009, Sec. 8118. "Incentives for Additional Down-blending of Highly Enriched Uranium by the Russian Federation," would increase the amount of low-enriched uranium of Russian origin that may be imported into the United States during the period 2014–20 if Russia blends down additional highly enriched uranium.

[261] *DOE Needs to Take Action to Reduce Risks Before Processing Additional Nuclear Material at the Savannah River Site's H-Canyon*, U.S. Government Accountability Office, GAO-08-840, 2008.

[262] Clean up some impure plutonium for disposal has been proposed as a second reason for operating the H plant.

[263] See e.g. *Report on the Savannah River Site Aluminum-based Spent Nuclear Fuel Alternatives Cost Study*, U.S. Department of Energy, Savannah River Operations Office, 1998; and H. B. Peacock et al, "Melt-Dilute Treatment of Spent Nuclear Fuel Assemblies from Research and Test Reactors," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR)*, Budapest, Hungary, 3–8 October 1999.

[264] *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, Article I, www.ipfmlibrary.org/gov00.pdf.

[265] These four tons of plutonium are in unirradiated fuel from the Idaho National Laboratory's Zero Power Plutonium Reactor (a critical facility). At the time this report went to press, the future of this plutonium was under review. The two options under consideration were disposal as MOX and shipment to the high-security Device Assembly Facility on the Nevada Test Site, to which the HEU and plutonium-containing critical facilities of Los Alamos National Laboratory have already been shipped, personal communication, Greg Bass, Department of Energy Idaho Office, 2 September 2009.

[266] UK Ministry of Defense, *Strategic Defence Review*, 1998, Chapter 4, para. 72; *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*, 2000, §10.

[267] See e.g. Frans Berkhout et al., "Disposition of separated plutonium," *Science & Global Security*, Vol. 3, 1993, p. 161.

[268] *Management and Disposition of Excess Weapons Plutonium*, National Academy of Sciences, National Academy Press, 1994, p. 2.

[269] *Ibid.*, p. 12.

[270] *Agreement Concerning the Management and Disposition of Plutonium, op. cit.*, "Annex on Quantities, Forms, Locations, And Methods Of Disposition." The Russian concern was that, unlike irradiation in reactor fuel, disposition with high-level waste would not alter the isotopic mix of plutonium, i.e., it would still be weapon grade. Therefore, if the U.S. recovered the plutonium at some future point, it could be used in existing weapon designs.

[271] *Status of the Mixed Oxide Fuel Fabrication Facility*, U.S. Department of Energy, Office of Inspector General, Office of Audit Services, Audit Report DOE/IG-0713, 2005, p. 1.

[272] *Fiscal Year 2010 Congressional Budget Request*, U.S. Department of Energy, Vol. 1, May 2009, pp. 413–442.

[273] www.moxproject.com/construction/aerials.shtml, accessed 26 July 2009.

[274] *Energy and Water Development Appropriations Bill*, 2010, U.S. House of Representatives Appropriations Committee, Report 111-203, 13 July 2009, p. 145.

[275] According to §3.28 of the IAEA Safeguards Glossary, for facilities that are to be subject to IAEA safeguards, "… the State is to provide preliminary information on any new nuclear facility as soon as the decision is taken to construct, or to authorize the construction of, the facility, and to provide further information on the safeguards relevant features of facility design early in the stages of project definition, preliminary design, construction and commissioning …"

[276] The economic value of the MOX fuel should be a relatively minor consideration for a $10-billion-dollar program. Assuming that the MOX contains 4.7 percent plutonium the 723 tons of MOX fuel that could be produced from 34 tons of plutonium would replace low-enriched uranium fuel worth about $2 billion today. To produce a kilogram of 4.4 percent enriched uranium with 0.25 percent U-235 left in the depleted uranium requires about 9 kilograms of natural uranium and 6.7 separative-work units (SWUs). For 15 years prior to 2004, the spot market price of uranium was less than $25/kg. Then it climbed to a peak of $350/kg in 2007. By 2009, it had fallen again to about $130/kg. The price of enrichment work climbed from a plateau of about $100/SWU prior to 2006 to $160/SWU in 2009. At 2009 prices, therefore, the cost of producing a kilogram of 4.4-percent enriched uranium would be $2200. Conversion and fabrication costs would bring the cost up to about $2600/kg. Uranium, SWU, and conversion prices from www.uxc.com.

[277] *Agreement Concerning the Management and Disposition of Plutonium*, "Annex on Quantities, Forms, Locations, And Methods Of Disposition," *op. cit.*

[278] *Plutonium Disposition Alternatives Study*, Savannah River Site, Y-AES-G-00001, Revision 0, May 2006.

[279] *Long-lived Legacy: Managing High-level and Transuranic Waste at the DOE Nuclear Weapons Complex*, U.S. Congress, Office of Technology Assessment, 1991, p. 27.

[280] *Tank Waste Retrieval, Processing, and On-site Disposal at Three Department of Energy Sites: Final Report*, National Academy of Sciences, National Academy Press, 2006, p. 53.

[281] *FY 2010 Congressional Budget Request*, U.S. Department of Energy, Volume 5, p. 224.

[282] J. M. Kang et al., "Storage MOX: A Third Way for Plutonium Disposal?" *Science & Global Security*, Vol. 10, 2002, p. 85.

[283] *Analysis of Russian-Proposed Unified Scenario for Disposition of 34 Metric Tons of Weapon-grade Plutonium*, Joint U.S.-Russian Working Group on Cost Analysis and Economics of Plutonium Disposition, U.S. Department of Energy, 2006.

[284] *Energy and Water Development Appropriations Bill, 2008,* U.S. House Appropriations Committee Report 110–185, 11 June 2007, p. 114; and *"Energy and Water Development Appropriations Bill, 2010,* U.S. Senate Appropriations Committee, 9 July 2009, p. 115.

[285] The budget proposal simply states that, "agreement with Russia on the Protocol [to the September 2000 U.S.-Russia Plutonium Management and Disposition Agreement] involves three key issues: $400 million U.S. contribution, use of Russian fast[-neutron breeder] reactors for plutonium disposition and monitoring and inspection programs," U.S. Department of Energy, *FY 2010 Congressional Budget Request: National Nuclear Security Administration*, Vol. 1, May 2009, pp. 414, 415.

[286] U.S. National Nuclear Security Administration, "Pantex Plant: Assembly/Disassembly And High Explosives (HE) Production & Machining, Complex Transformation. Preferred Alternative," October 2008.

[287] *Global Fissile Material Report 2007*, p. 52.

[288] Pavel Podvig, *Consolidating Fissile Material in Russia's Nuclear Complex*, Research Report #7, International Panel on Fissile Materials, May 2009, www.ipfmlibrary.org/rr07.pdf, p. 12.

[289] The United Kingdom has only one light-water power reactor. Its remaining power reactors use graphite for neutron moderation and carbon dioxide for cooling. This does not mean that the plutonium could not have been recycled in some of these reactors, however, especially the Advanced Gas Reactors, which, like LWRs, are fueled with low-enriched oxide fuel.

[290] *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.

[291] Christopher Watson, *UK Plutonium Disposition Options*, 2009, www.ipfmlibrary.org/wat09.pdf.

[292] *Communication Received from the United Kingdom … Concerning Its Policies Regarding the Management of Plutonium … and of High Enriched Uranium*, International Atomic Energy Agency, INFCIRC/549/Add.8/12, 15 September 2009.

[293] As of the April 2005 shutdown of the UK's Thermal Oxide Reprocessing Plant (THORP) by a large pipe break, 750 tons of overseas light-water reactor (LWR) spent fuel and 3100 tons of contracted UK Advanced Gas Cooled Reactor (AGR) fuel remained to be reprocessed there, Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, Research Report #6, International Panel on Fissile Materials, July 2008, www.ipfmlibrary.org/rr06.pdf, p. 11. The 3100 tons of AGR fuel included 2512 tons of post-base-load contracts, however, and the UK Nuclear Decommissioning Authority's commitment to reprocessing all of this AGR fuel is uncertain. After the accident, THORP operated only intermittently and, as of March 2009, only an additional 18 tons of LWR fuel and 33 tons of AGR fuel had been reprocessed. In addition, 29 tons of LWR fuel and 63 tons of AGR fuel had been

dissolved, leaving 753 tons of LWR fuel and 492–3004 tons of AGR fuel to be reprocessed, depending upon how much of the post-base-load fuel is reprocessed, Pearl Marshall, "Thorp expected to soon restart normal reprocessing operations," *Nuclear Fuel*, 9 March 2009. Assuming that AGR spent fuel with a burnup of 30 megawatt-days per kilogram contains on average 0.9% and that LWR fuel contains 1 percent plutonium, that would amount to 4–27 tons of domestic and 7.5 tons of foreign plutonium that remain to be separated from oxide fuel. Another 14 tons of plutonium remains to be separated from Magnox uranium-metal fuel (see below).

[294] The last two UK Magnox reactors (Wylfa site, 0.475 GWe each) will shut down in 2010, *Strategy*, UK Nuclear Decommissioning Authority, 2006, p. 45. 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, *The Legacy of Reprocessing in the United Kingdom, 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, David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996*, Oxford University Press, 1997, p. 480.

[295] Magnox fuel has a burnup of about 4 MWt-days/kgU compared to about 50 MWt-days for LWR low-enriched uranium fuel. 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.

[296] See e.g. *Economic Assessment of Used Nuclear Fuel Management in The United States*, Boston Consulting Group, 2006. Figure 7 shows interim storage costs as $150 per kilogram of original uranium in LWR spent fuel. Figure 9 shows the combined operating costs of France's La Hague reprocessing plants and the Melox MOX-fuel fabrication plant as $888 million/year. For the past decade, the throughput of the reprocessing plants at La Hague has been about 1000 tons/year.

[297] Martin Forwood, *The Legacy of Reprocessing, op. cit.*, p. 11.

[298] "Draft letter from Dr. Gibbons [President Clinton's Science Advisor] to William Waldegrave [UK Science Advisor] *re* Possible Alternative to Putting the Thermal Oxide Reprocessing Plant (THORP) into operation," 8 November 1993, www.ipfmlibrary.org/ostp93.pdf. The cover letter requests concurrence from the Departments of State, Defense and Energy, and National Security Council for sending the letter. The State Department did not concur. Gibbons therefore conveyed the suggestion in a phone conversation with Waldegrave. At the time, the UK foreign reprocessing contracts totaled 4547 tons for the partially pre-paid "base-load" contracts that paid for the construction of the plant and 787 tons of post-base-load contracts from Germany, which were later reduced to about 100 tons, *The Legacy of Reprocessing in the United Kingdom, op. cit.*, p. 9. Reprocessing this amount of foreign spent fuel would result in about 47 tons of separated plutonium. Had the virtual reprocessing proposal been adopted, the approximately 66 tons of Magnox plutonium in the current UK stockpile plus 14 tons to come would have been more than enough to exchange for the plutonium in the foreign spent fuel and the UK's separated-plutonium problem would be much smaller.

[299] Since the Sellafield MOX Plant (SMP) has operated at only one to two percent of its nominal capacity, the Nuclear Decommissioning Authority (NDA) has had to subcontract its MOX fuel fabrication contracts to France as they come due. SMP's design annual fabrication capacity is 120 tons of MOX fuel containing about ten tons of plutonium. The plant began operating in 2004 and, as of the end of 2008, had produced only about 6 tons of MOX fuel, *Sellafield MOX Plant (SMP). Stuck on the road to nowhere*, CORE Briefing, 18 February 2009. As of the end of 2008, the SMP had processed less than one half of a ton of plutonium into MOX fuel. As of May 2008, the NDA had subcontracted MOX fuel fabrication orders to France totaling an estimated 1.3 tons of contained plutonium, *4-Month Suspension of UK Spent Fuel Transports on Quality Assurance Issues, and the UK's First Plutonium Shipment to Europe*, CORE Briefing, 28 May 2008.

[300] The UK Government statement in response to the suggestion was that "It is intended that all the overseas spent fuel covered by existing overseas contracts will be reprocessed," *Advance Allocation: Proposal on how to manage overseas spent nuclear fuel awaiting processing at Sellafield,* Government Response to Consultation, Department for Business Enterprise & Regulatory Reform, November 2007, p. 4.

Chapter 7. Verified Cutoff of Fissile Material Production for Weapons

[301] "Decision for the establishment of a Programme of Work for the 2009 session," CD/1864, 29 May 2009 decides *inter alia* to "establish a Working Group under agenda Item 1 entitled 'Cessation of the nuclear arms race and nuclear disarmament' which shall negotiate a treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices, on the basis of the document CD/1299 of 24 March 1995 and the mandate contained therein." The quote characterizing the treaty is from CD/1299.

[302] Most non-weapon states and some weapon states would like to see the treaty capture under IAEA safeguards some pre-existing fissile materials as well. This could include plutonium and HEU used in the fuel of nuclear-power and civilian research reactors and fissile materials formerly in weapons that have been declared excess for weapons use. Advocates of such a broadened FMCT often characterize it as a Fissile Material Treaty. The IPFM has tried to capture both positions by calling it a Fissile Material (Cutoff) Treaty

[303] See e.g. the Chinese perspective in *Banning the Production of Fissile Materials for Nuclear Weapons: Country Perspectives on the Challenges to a Fissile Material (Cutoff) Treaty*, Companion Volume to the Global Fissile Material Report 2008, International Panel on Fissile Materials, October 2008, www.ipfmlibrary.org/gfmr08cv.pdf.

[304] Tritium is made by neutron capture in lithium-6 in reactors. But, the natural-uranium fuel of Israel's Dimona reactor contains 140 uranium-238 atoms for every chain-reacting uranium-235 atom. Many neutrons therefore would be captured in uranium-238 nuclei, converting them to uranium-239 nuclei that then decay into plutonium-239. Also, the fuel of the Dimona reactor, which was originally designed for plutonium production, is probably uranium metal clad with aluminum or magnesium alloy for ease of reprocessing. Such fuel, unlike the zirconium-clad uranium-oxide fuel used in power reactors cannot be easily stored for a long time in water and is therefore usually reprocessed. It is therefore likely that, even if Israel thinks that it has produced enough separated plutonium, it is probably still producing more as a byproduct of tritium production.

[305] "DPR Korea cuts off UN atomic watchdog agency's access to nuclear facilities," UN News Center, 24 September 2009; Blaine Harden, "North Korea Says It Will Start Enriching Uranium: Weapons Move Is 'Retaliation' for Sanctions," *Washington Post*, 14 June 2009.

[306] "Burnup" is a measure of the percentage of the fuel that has been fissioned. Most weapon-grade plutonium has been produced in graphite or heavy-water-moderated reactors by irradiating natural uranium to a level where roughly one gram of uranium-235 in a kilogram of natural uranium has been fissioned. This produces plutonium that is more than 90 percent plutonium-239. With further irradiation, neutron captures in the plutonium cause losses through fission and fissionless neutron capture increases the percentage of Pu-240, Pu-241, and Pu-242 in the plutonium. In light-water reactor fuel, today about 50 grams of uranium and plutonium are fissioned per kilogram of low-enriched uranium fuel.

[307] The ADE-2 reactor in the Siberian plutonium city of Zheleznogorsk near Krasnoyarsk is the last dual-purpose reactor. It is scheduled to be shutdown by the Summer of 2009 or 2010 when a replacement coal-fired plant is completed under a program financed by the U.S. As part of the financing agreement, Russia's Government agreed that the weapon-grade plutonium produced after 1994 by this reactor and two other dual-purpose production reactors that operated at a second plutonium city, Seversk, would not be used for nuclear weapons and would be subject to U.S. monitoring, www.ransac.org/new-web-site/related/agree/bilat/core-conv.html.

[308] One of these, the Novouralsk enrichment plant, is still licensed to produce uranium enriched up to 30 percent in U-235.

[309] Although there is no report that any fissile material other than plutonium or HEU is currently in use in nuclear weapons, in principle, uranium-233, neptunium-237, americium-241 and -243 and other fissile isotopes all could be so used. See Appendix, "Fissile Materials and Nuclear Weapons."

[310] Belgium and Germany both had their own pilot reprocessing plants but they were shut down in 1979 and 1991 respectively. Most of the plutonium that has been recycled in Belgium and Germany—and all of the plutonium recycled in Swiss reactors—was separated in French and UK commercial reprocessing plants.

[311] See e.g. Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France and Martin Forwood, The Legacy of Reprocessing in the United Kingdom*, IPFM Research Reports Nos. 4 and 5 respectively, 2008.

[312] Frank von Hippel, "Why reprocessing persists in some countries and not in others: The Costs and Benefits of Reprocessing," in Henry Sokolski, ed., *Expanding Nuclear Power: Weighing the Costs and Risks*, Non-proliferation Education Center, 2009, *forthcoming*.

[313] The modern reprocessing plants in France, Japan and the United Kingdom are licensed to annually reprocess 1700, 800 and 700 tons of spent fuel respectively. In actuality, today, after the loss of virtually all its foreign customers, France's plant is reprocessing 1000 tons annually, Japan's plant has not begun commercial operation because of a serious design problem, and the UK reprocessing plant has endured a series of prolonged shutdowns since 2005 because of equipment failures. Typically, spent light-water reactor fuel is about one percent plutonium, so roughly 17,000, 8000 and 7000 kg of plutonium would be recovered if the plants operated at full capacity. The Nagasaki bomb contained 6 kilograms of weapon-grade plutonium. Eight kilograms of power-reactor plutonium would have the same critical mass.

[314] In addition to the commercial Rokkasho reprocessing plant, Japan also operates the pilot-scale Tokai Reprocessing Plant, www.jaea.go.jp/english/04/tokai-cycle/02.htm.

[315] See Shirley Johnson, *Safeguards at Reprocessing Plants Under a Fissile Material Cutoff Treaty*, International Panel on Fissile Materials Research Report No. 6, 2009; and *Global Fissile Material Report 2008*, Chapter 5.

[316] "India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes," by David Albright and Susan Basu, Institute for Science and International Security (ISIS), 18 January 2007, p. 9, www.isis-online.org/publications/southasia/indiagrowingcapacity.pdf

[317] *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.

[318] Richard Stone, "Iran's Nuclear Program: State-of-the-Art Nuclear Sleuths," *Science*, 13 June 2003, p. 1643.

[319] Uranium-234 is a decay product of U-238.

[320] Spent fuel is monitored under the NPT to protect against the possibility of clandestine reprocessing. Under the FM(C)T, it would probably be sufficient—initially at least—to verify declarations of spent fuel with a small number of random spot checks.

[321] A gas of tritium (T), mixed with deuterium (D), is injected into the hollow plutonium "pit" of a modern nuclear weapon when the weapon is triggered. The energy released by the fission chain reactions in the plutonium heat the gas up to temperatures where the thermonuclear reaction, $D + T \rightarrow$ helium + neutron, takes place. The resulting burst of neutrons causes an additional burst of fissions that "boosts" the power of the explosion more than tenfold. The U.S. formerly produced tritium for its nuclear weapons using the HEU-fueled production reactors at the Department of Energy's Savannah River Site but has shifted to inserting lithium-6 "targets" in LEU-fueled power reactors.

[322] *Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application Of Safeguards*, International Atomic Energy Agecny, INFCIRC/540 (Corrected), September 1997.

[323] Some declassified documents relating to the U.S. program have been compiled by William Burr, *Documents on the U.S. Atomic Energy Detection System [AEDS]*, National Security Archive Electronic Briefing Book No. 7, www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB7/nsaebb7.htm.

[324] Adapted from R. Scott Kemp and C. Schlosser, "A performance estimate for the detection of undeclared nuclear-fuel reprocessing by atmospheric 85Kr," *Journal of Environmental Radioactivity 99* (2008) p. 1341–1348. Because of cost and reliability issues, Krypton-85 is not currently captured at reprocessing plants, but could be.

[325.] R. Scott Kemp, "Initial Analysis of the Detectability of UO2F2 Aerosols Produced by UF6 Released from Uranium Conversion Plants," *Science and Global Security*, 16 (2008), p. 115.

[326.] A kiloton is a measure of explosive power: the rough equivalent of one thousand tons of chemical high explosives.

[327.] *New tritium source on line at DOE´s Savannah River Site*, U.S. Department of Energy, Office of Public Affairs, Washington, DC, 2007.

[328.] P. Podvig, *Consolidating Fissile Materials in Russia's Nuclear Complex*, Research Report #7, International Panel on Fissile Materials, May 2009, www.ipfmlibrary.org/rr07.pdf.

[329.] L.C. Colschen and M.B. Kalinowski, "Can International Safeguards be Expanded to Cover Tritium?" *IAEA Symposium, International Nuclear Safeguards 1994: Vision for the Future*, IAEA-SM-333/27, Vienna, 14–18 March 1994, Proceedings Serial No. 945, Vol. 1, pp. 493–503.

[330.] M. B. Kalinowski, *Update of International Control of Tritium for Nuclear Nonproliferation and Disarmament*, CRC Press, London, 2004, Table 2.6. Estimates of production capacities by irradiation of lithium-6 targets in natural-uranium-fueled heavy-water reactors are based on calculations of the production of U-233 in such reactors, J. Kang and F. von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security*, Vol. 9, 2001, pp. 1–32.

[331.] *Report of Main Committee II of the 4th NPT Review Conference*, Document NPT/CONF.IV/MC.II/1, 10 September 1990.

[332.] "Exchange of Letters Between the Government of Canada and the European Atomic Energy Community (EURATOM) amending the Agreement for Co-operation in the Peaceful Uses of Atomic Energy of October 6, 1959," CST1991/23, Government of Canada (Brussels, Belgium), 15 July 1991, EL/CEEA/CDN/GE, reproduced in *Official Journal of the European Communities*, No. C 215/5, 17 August 1991.

[333.] *International Control of Tritium for Nuclear Nonproliferation and Disarmament, op. cit.*

[334.] J. Reckers, *Tritiumbilanzierung im Fusionsreaktor ITER. Anwendung statistischer Testtheorie auf Inspektionsstrategien bei Messunsicherheit [Tritium accounting at the ITER fusion reactor: Application of statistical tests on inspection strategies with measurements uncertainties]*, Diploma thesis submitted to the University of Hamburg, September 2007, www.znf.uni-hamburg.de/diplomReckers.pdf.

[335.] M. B. Kalinowski and L. C. Colschen, "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," *Science & Global Security*, Vol. 5, 1995, p. 131.

[336.] IAEA Statute, Article III.A.5.

[337.] *International Control of Tritium for Nuclear Nonproliferation and Disarmament, op. cit.*

[338.] M. B. Kalinowski and L. C. Colschen, "International Control of Tritium," 1995, *op. cit.*

[339.] *International Control of Tritium for Nuclear Nonproliferation and Disarmament, op. cit.*

[340.] *A Fissile Material (Cut-off) Treaty: A Treaty Banning the Production of Fissile Materials for Nuclear Weapons or Other Nuclear Explosive Devices, Article-by article explanation*, International Panel on Fissile Materials, September 2009, www.ipfmlibrary.org/fmct-ipfm-sep2009.pdf.

Chapter 8. Nuclear Power and Nuclear Disarmament

[341.] James Franck (Chairman), Donald J. Hughes, J. J. Nickson, Eugene Rabinowitch, Glenn T. Seaborg, J. C. Stearns and Leo Szilard, *Report of the Committee on Political and Social Problems Manhattan Project, "Metallurgical Laboratory"* University of Chicago, June 11, 1945 (The Franck Report), www.ipfmlibrary.org/fra45.pdf.

[342.] C. I. Barnard, J. R. Oppenheimer, C. A. Thomas, H. A. Winne, and D. E. Lilienthal, *A Report on the International Control of Atomic Energy*, Washington, DC, 1946, www.ipfmlibrary.org/ach46.pdf.

[343] H. A. Feiveson, *Latent Proliferation: The International Security Implications of Civilian Nuclear Power*, PhD Thesis, Princeton University, 1972.

[344] T. B. Taylor, "Nuclear Power and Nuclear Weapons," July 1996, originally published by the Nuclear Age Peace Foundation, and reprinted in *Science & Global Security*, Vol. 13, 2005.

[345] J. Schell, *The Abolition*, Alfred A. Knopf, New York, 1984.

[346] J. Carson Mark, Theodore Taylor, Eugene Eyster, William Maraman, and Jacob Wechsler, "Can Terrorists Build Nuclear Weapons?" in Paul Leventhal and Yonah Alexander, eds., *Preventing Nuclear Terrorism: Report and Papers of the International Task Force on Preventing Nuclear Terrorism*, Rowan & Littlefield, Lanham, MD, 1987.

[347] The three reactors produced an average of 170 kg of plutonium a year during 1945–47, US Department of Energy, *Plutonium: The First 50 Years: United States Plutonium Production, Acquisition, and Utilization from 1944 through 1994* (1996) Table 2. The initial design thermal power of the Hanford B reactor, 250 megawatts, was achieved in February 1945. At this power level, it would take the first three reactors about a week to produce enough plutonium for a Nagasaki-type bomb. By late 1956, the B-reactor power level reached 800 MWt and, by January 1961, it was over 2000 MWt. *B Reactor Museum Association, History of 100-B/C Reactor Operations, Hanford Site*, www.b-reactor.org/hist1-4.htm.

[348] The K-25 gaseous diffusion plant produced 1529 kg of 26% enriched uranium in 1945 and 2889 kg of 29% enriched uranium in 1946 for enrichment to weapon-grade by the electromagnetic isotope separation plant. In 1947, however, it produced 1264 kg of 93% enriched uranium, US Department of Energy, *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 1996,* U.S. Department of Energy, 2001, Table 5.3.

[349] An enrichment plant with 5000 first generation centrifuges, of the kind built by Pakistan in the late 1970s and early 1980s and that Iran is currently installing and operating, could make enough HEU for one bomb a year. It would require a floor area approximately 50 meters on a side, easily able to fit in a small building or underground, and would consume only about 100 kilowatts of electrical power, which could be provided by a diesel generator.

[350] *Global Fissile Material Report 2007*, Chapter 9. R. S. Kemp and A. Glaser, "The Gas Centrifuge and the Nonproliferation of Nuclear Weapons," pp. 88–95 in Shi Zeng (ed.), *Proceedings of the Ninth International Workshop on Separation Phenomena in Liquids and Gases (SPLG)*, 18–21 September 2006, Beijing, China, Tsinghua University Press, 2007.

[351] R. Scott Kemp, PhD thesis, Woodrow Wilson School, Princeton University, *forthcoming.*

[352] Based on estimates by Alexander Glaser, IPFM.

[353] "GEH selects site for potential Silex enrichment plant," *World Nuclear News*, 1 May 2008, www.world-nuclear-news.org.

[354] *Multilateral Approaches To The Nuclear Fuel Cycle: Expert Group Report To The Director General Of The International Atomic Energy Agency*, International Atomic Energy Agency, Vienna, 2005, p. 109.

[355] Gordon Linsley and Abdul Fattah, "The Interface Between Nuclear Safeguards and Radioactive Waste Disposal: Emerging Issues," *IAEA Bulletin*, 21, 1994, pp. 22–26.

[356] Edwin S. Lyman and Harold A. Feiveson, "The Proliferation Risks of Plutonium Mines," *Science & Global Security*, Vol. 7, 1998, pp. 119–128.

[357] The Nagasaki bomb contained 6.1 kilograms of weapon-grade plutonium, Major General Leslie R. Groves, "Memorandum for the Secretary of War, " 18 July 1945, reprinted in Martin J. Sherwin, *A World Destroyed*, Alfred A. Knopf, (New York, 1975, Appendix P. The corresponding critical mass of the "reactor-grade plutonium" in spent light-water-reactor fuel would be about 8 kg.

[358] The possibility of the quick construction of a reprocessing plant was raised during the Carter Administration's debate over changing U.S. policy on reprocessing in a 1977 study by a group of technical experts at the Oak Ridge National Laboratory who presented the design of such a plant together

with a flow sheet and an equipment list. The study sought to make the case that a country with a minimal industrial base could quickly and secretly build such a plant and that therefore a U.S. policy to oppose civilian reprocessing would not have a significant anti-proliferation effect. See: D. E. Ferguson to F. L. Culler, *Simple, Quick Processing Plant*, Intra-Laboratory Correspondence, Oak Ridge National Laboratory, August 30, 1977; and: *Quick and Secret Construction of Plutonium Reprocessing Plants: A Way to Nuclear Weapons Proliferation?*, Report to the Comptroller General of the United States, EMD-78-104, October 6, 1978. Similar conclusions have been reached in subsequent U.S. assessments; see J. P. Hinton et al., *Proliferation Resistance of Fissile Material Disposition Program Plutonium Disposition Alternatives: Report of the Proliferation Vulnerability Red Team*, Sandia National Laboratory, SAND97-8201, October 1996. See also, Victor Gilinsky, Marvin Miller, and Harmon W. Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors*, The Nonproliferation Policy Education Center, Washington, DC, September 2004, Appendix 2.

[359] IAEA, Power Reactor Information System, 7 September 2009, www.iaea.org/programmes/a2/

[360] Israel and North Korea have nuclear weapons but no civil nuclear-energy programs, although North Korea's Yongbyon plutonium-production reactor generated 5 Megawatts of electrical power.

[361] The World Nuclear Association, a nuclear industry group, claims over thirty states are "actively considering" starting nuclear energy programs. It lists them by region. In Europe: Italy, Albania, Portugal, Norway, Poland, Belarus, Estonia, Latvia, Ireland, Turkey; in the Middle East and North Africa: Iran, Gulf states, Yemen, Israel, Syria, Jordan, Egypt, Tunisia, Libya, Algeria, Morocco; in Central and Southern Africa: Nigeria, Ghana, Namibia, Uganda; in South America: Chile, Ecuador, Venezuela; in Central and Southern Asia: Azerbaijan, Georgia, Kazakhstan, Mongolia, Bangladesh; and in Southeast Asia: Indonesia, Philippines, Vietnam, Thailand, Malaysia, Australia, New Zealand. World Nuclear Association, "Emerging Nuclear Energy Countries," 26 August 2009, www.world-nuclear.org/info/inf102.html.

[362] Livermore National Laboratory weapons designer, Robert Seldon, briefed the leaders of the French and Japanese reprocessing establishments on this fact during 1976. Robert Seldon, "All Plutonium can be used Directly in Nuclear Explosives," briefing slides, 1976. They continued to argue for many years, however, that plutonium generated in commercial reactors could not be used for weapons since this grade plutonium has a relatively high fraction of the isotope Pu-240. The U.S. Department of Energy statement says: "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 weapons-grade plutonium. Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton-range possible with a simple, first-generation nuclear device." *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, Box 3–1 (pp. 37–39), www.ipfmlibary.org/doe97.pdf.

[363] A. 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*, Vol. 163, No. 1, September 2009, pp. 26–33.

[364] Alternative reprocessing technologies include aqueous processes, in which uranium would be precipitated out with the plutonium, and pyroprocessing technology, an electro-refining procedure that would keep some of the higher transuranics and rare-earth (lanthanide) fission products with the plutonium.

[365] Based on R. Hill, "Advanced Fuel Cycle Systems: Recycle/Refabrication Technology Status," September 7, 2005. See also Jungmin Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel," *Science & Global Security*, Vol. 13, 2005, p. 169.

[366] H. Wood, A. Glaser, and R. S. Kemp, "The Gas Centrifuge and Nuclear Weapons Proliferation," *Physics Today*, September 2008, pp. 40–45.

[367] Interview with Mohamed Elbaradei, CNN Late Edition with Wolf Blitzer, 8 May 2005.

[368] A. Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and their Relevance for Nuclear Weapon Proliferation," *Science & Global Security*, Vol. 16, Nos. 1–2, 2008.

[369] *IAEA Safeguards Glossary 2001 Edition*, International Nuclear Verification Series, No. 3, International Atomic Energy Agency, Vienna, 2002, §3.13, www.ipfmlibrary.org/iaeaglossary.pdf.

[370] Y. Yudin, *Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals*, UNIDIR/2009/4, United Nations Institute for Disarmament Research, New York and Geneva, 2009, www.unidir.ch, and: A. Glaser, Internationalization of the Nuclear Fuel Cycle, *International Commission on Nuclear Non-proliferation and Disarmament*, ICNND Research Paper No. 9, February 2009, www.icnnd.org.

[371] Germany has proposed a Multilateral Enrichment Sanctuary Project, a scheme that envisages a host state offering its territory to a separate set of countries to build and operate an enrichment plant on that site. Ideally, the host would have no experience with uranium enrichment and a hypothetical takeover of the plant would be less of a concern. "Communication received from the Resident Representative of Germany to the IAEA with regard to the German proposal on the Multilateralization of the Nuclear Fuel Cycle," International Atomic Energy Agency INFCIRC/704, 4 May 2007. It was later amended in INFCIRC/727, 30 May 2008 and INFCIRC/735, 25 September 2008. For a discussion, see A. Glaser, *Internationalization of the Nuclear Fuel Cycle, op. cit.*

[372] This was proposed in the 1946 Acheson-Lilienthal proposal. Similar ideas were discussed in the 1970s when the creation of an International Nuclear Fuel Authority (INFA) was considered by the United States. More recently, some analysts have picked up the INFA concept as a strategy to resolve the crisis surrounding Iran's enrichment program: T. B. Cochran and C. E. Paine, "International Management of Uranium Enrichment," presentation, *International Meeting on Nuclear Energy and Proliferation in the Middle East*, Amman, Jordan, 22–24 June 2009.

Chapter 9. Societal Verification

[373] For more details, see the excellent biography by William Lanouette, *Genius in the Shadows*, Charles Scribner's Sons, New York, 1992.

[374] The memo is reproduced in Spencer Weart and Gertrud Weiss Szilard (eds.), *Leo Szilard: His Version of the Facts*, MIT Press, 1978, pp. 196–204. President Roosevelt died before the memo could be delivered.

[375] Joseph Rotblat, "Societal Verification," in Joseph Rotblat, Jack Steinberger, and Bhalchandra Udgaonkar, eds., *A Nuclear-Weapon-Free World*, Westview Press, Boulder, 1993, pp. 103–118.

[376] For earlier suggestions in this direction, see Grenville Clark and Louis B. Sohn, *World Peace Through World Law*, Second Edition, Harvard University Press, 1960, p. 267, and Lewis Bohn, "Non-Physical Inspection Techniques", in D.G. Brennan, ed., *Arms Control, Disarmament, and National Security, Braziller*, New York, 1961.

[377] Joseph Rotblat, *op. cit.*, pp. 115–116.

[378] Marvin Miller, *Acquisition of Weapons of Mass Destruction: The Role of Scientists*, June 1999, www.ipfmlibrary.org/mil99.pdf.

[379] Quoted by Herbert Mehrtens, "Mathematics and War: Germany, 1900–1945," in Paul Forman and Jose M. Sanchez-Ron, eds., *National Military Establishments and the Advancement of Science and Technology*, Klumer Academic, 1996, pp. 89, 126; see also Marvin Miller, *op. cit.*, p. 5.

[380] Andrei Sakharov, *Memoirs*, Knopf, 1990, pp. 96–98; see also Marvin Miller, *op. cit.*, p. 5.

[381] Ken Alibek, *Biohazard,* Random House, 1999.

[382] See, e.g., Frank Barnaby, *The Invisible Bomb*, I.B. Tauris & Co. Ltd., London, 1989.

[383] A collection of papers by a diverse group of Vanunu's supporters presented at an international conference held in Tel-Aviv, Israel in October 1997, chaired by Rotblat, was published in London in 1997. Jane Shallice and Peter Hounam, eds., *Voices for Vanunu*, Campaign to Free Vanunu, London, 1997.

[384] Ronald P. Mitchell, “Identifying Undeclared Nuclear Sites: Contributions from Nontraditional Sources”, pp. 43–58 in *Proceedings of Second Workshop on Science and Modern Technology for Safeguards*, Albuquerque, NM, 21–24 September 1998, www.ipfmlibrary.org/mit98.pdf.

[385] Examples include the Los Alamos Study Group (www.lasg.org), which acts as a watchdog over the activity of the Los Alamos National Laboratory. More broadly, there is the Alliance for Nuclear Accountability, a network that brings together many anti-nuclear groups based in communities around nuclear sites, www.ananuclear.org.

[386] Project on Government Oversight, Washington, DC, www.pogo.org.

[387] Report by the Director General, Implementation of the NPT *Safeguards Agreement in the Syrian Arab Republic,* GOV/2008/60, International Atomic Energy Agency, 19 November 2008.

[388] David Talbot, “Dissent Made Safer”, *Technology Review*, Vol. 112, No. 3, MIT, Cambridge, MA, 2009, pp. 60–65.

[389] www.icc-cpi.int/Menus/ICC/Situations+and+Cases/Referals+and+communications

Appendix B. Worldwide Locations of Nuclear Weapons, 2009

[390] Most nuclear states do not release information about locations of nuclear weapons or components.

[391] Locations listed here for Chinese land-based missiles forces are mainly based on Thomas C. Reed and Danny B. Stillman, T*he Nuclear Express: A Political History of the Bomb and Its Proliferation*, Zenith Press, Minneapolis, NM, 2009, pp. 84–113, 220–234, 354–363; Bates Gill, et al., *The Chinese Second Artillery Corps: Transition to Credible Deterrence*, in James C. Mulvenon and Andrew N. D. Yang, eds., *The People’s Liberation Army as Organization: Reference Volume v. 1.0*, RAND, CF-182, 2002; Mark A. Stokes, *China’s Military Modernization: Implications for the United States*, Strategic Studies Institute, U.S. Army War College, September 1999; William M. Arkin, et al., *Taking Stock: Worldwide Nuclear Deployments 1998*, Natural Resources Defense Council, 1998, pp. 45–48, 89; Robert S. Norris, et al., *Nuclear Weapons Databook Volume V: British, French, and Chinese Nuclear Weapons*, Westview Press, Boulder, CO, 1994.

[392] China also deploys about 120 H-6 bombers at Anqing Air Base, Leiyang Air Base, Nanjing Air Base, as well as Qili Air Base and Xian Air Base. Any of these bases could potentially have a secondary nuclear mission, but Danyang is the only air base with an external igloo-type storage facility near by. Anqing and Leiyang both have underground facilities that potentially could store nuclear bombs, and several of the bases are undergoing modernizations that might be associated with adding cruise missile capability to some of the H-6 bombers.

[393] This might be the nuclear weapon production and storage facility reported by Thomas C. Reed and Danny B. Stillman as located a two-and-a-half-hour driver north of Mianyang near the city of Pingtung. See: Thomas C. Reed and Danny B. Stillman, *The Nuclear Express: A Political History of the Bomb and Its Proliferation*, Zenith Press, Minneapolis, NM, 2009, p. 358.

[394] An alternative location might be Istres Air Base.

[395] Locations of nuclear Prithvi/Agni garrisons are not known. Potential Prithvi candidates include Bhatinda and Jullundapur in Punjab. A potential new (but unconfirmed) Prithvi and/or Agni underground storage facility might be located near Daijar north of Jodhpur in Rajasthan. The facility includes a dozen tunnels with what appear to be roll-out-and-launch pads and missile handling buildings.

[396] The Indian Navy is also developing a submarine-launched ballistic missile and possibly a cruise missile, and design of warheads for these systems is probably underway.

[397] Claims of a nuclear capability for Harpoon or Popeye cruise missiles on Dolphin-class submarines remain ambiguous.

[398] A recent U.S. Air Force survey does not credit any of North Korea's ballistic missiles with nuclear capability. U.S. Air Force, National Air and Space Intelligence Center, *Ballistic and Cruise Missile Threat*, NASIC 1031-0985-09, June 2009, available online at www.fas.org/blog/ssp/2009/06/nasic09.php.

[399] In response to reports about terrorist attacks on suspected nuclear facilities, including Sargodha Depot, Pakistani military spokesman Maj. Gen. Athar Abbas stated: "These are nowhere close to any nuclear facility." Ishtiaq Mahsud, Pakistani officials: Militant clashes kill about 70," *Associated Press*, 12 August 2009.

[400] *Ibid*.

[401] Locations listed here are based on Charles L. Thornton, *U.S. Efforts to Secure Russia's Nuclear Warheads: Background and Issues*, Center for International & Security Studies, School of Public Affairs, University of Maryland, Presentation to: Russian American Nuclear Security Advisory Council, 2 December 2003 (listed with permission from the author); Oleg Bukharin, et al., *New Perspectives in Russia's Ten Secret Cites*, Natural Resources Defense Council, October 1999; Joshua Handler, *Russian Nuclear Warhead Dismantlement Rates and Storage Site Capacity: Implications for the Implementation of START II and De-alerting Initiatives*, Woodrow Wilson School, Princeton University, February 1999; William M. Arkin, et al., Taking Stock: *Worldwide Nuclear Deployments 1998*, Natural Resources Defense Council, 1998, pp. 26–38, 81–87; Thomas B. Cochran, et al., *Nuclear Weapons Databook Volume IV: Soviet Nuclear Weapons*, Harper & Row, New York, 1989. Other valuable resources include U.S. Department of Defense, *Cooperative Threat Reduction Program Annual Report to Congress Fiscal Year 2009* (and previous years); Matthew Bunn, *Securing the Bomb 2008*, Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, November 2008, pp. 47–49, 93-95; Gunnar Arbman and Charles Thornton, *Russia's Tactical Nuclear Weapons Part II: Technical Issues and Policy Recommendations*, Swedish Defence Research Agency (FOA), FOI-R-1588-SE, February 2005. We are grateful for edits provided by Pavel Podvig at CISAC, Stanford University; Pavel Podvig, ed., *Russian Nuclear Forces*, MIT Press, Cambridge, MA, 2001.

[402] General Eugene Habiger, the former commander of U.S. Strategic Command, visited the national storage site in 1998, and later described being shown strategic and tactical nuclear weapons: "We went to Saratov, a national nuclear weapons storage site, where I saw not only strategic weapons, but tactical weapons ... there were five nuclear weapon storage bays," General Eugene Habiger, Commander of U.S. Strategic Command, U.S. Department of Defense News Briefing, The Pentagon, Tuesday, 16 June 1998.

[403] Lesnoy is located near Nizhnyaya Tura.

[404] Sverdlovsk-45 is one of two Russian warhead assembly plant (the other being Zlatoust-36). Sverdlovsk-16 is a national level storage facility about eight kilometers west of the plant.

[405] Warhead assembly and dismantlement at Sarov reportedly ended in 2003.

[406] The safety perimeter of the high-security WSA appears to have been upgraded sometime prior to May 2007.

[407] Located near Voskresenskoye.

[408] Located near Yuryuzan.

[409] Zlatoust-36 is one of Russia's two warhead production plants (the other being Sverdlovsk-45).

[410] In addition to these permanent storage locations, there are a significant number of temporary storage sites including railhead and transfer stations. Nuclear-capable bases where weapons have been moved to central storage include Air Force bases with Su-24 Fencer bombers (Chernyakhovsk, Dzhida, Eysk, Khurba, Lebyazhye, Morozovsk, Pereyaslavka, Siverskiy, Smuravyevo, Voronezh, and Voszhaevka), naval bases with Tu-22M Backfire bombers and Il-28 ASW aircraft, and air defense bases with nuclear-capable SA-10 Grumble surface-to-air missiles. U.S. government lists tend to have a higher number for Russian nuclear weapons storage locations, apparently because they include many temporary sites, particularly Navy sites, and sometimes also count individual fenced sites within larger facilities. In a recent example of this, one NNSA publication listed 73 Russian nuclear warhead "sites" as including 25 SRF "sites," while another NNSA publication identified that the 25

SRF "sites" were at 11 bases. In other words, individual named storage locations can contain multiple sites. See: U.S. Department of Energy, National Security Administration, "NNSA: Working To Prevent Nuclear Terrorism," Fact Sheet, September 2009, p. 1; U.S. Department of Energy, National Nuclear Security Administration, *FY 2010 Congressional Budget Request*, May 2009, pp. 390, 391.

[411.] The underground weapons storages facility at Kirtland AFB might also store some naval warheads.

[412.] The W62 is scheduled to be retired in 2009.

[413.] *Ibid*.

[414.] Nellis Air Force Base might also store some naval warheads.

[415.] The W62 is scheduled to be retired in 2009.

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Over the past six decades, our understanding of the nuclear danger has expanded from the threat posed by the vast nuclear arsenals created by the superpowers in the Cold War to encompass the proliferation of nuclear weapons to additional states and now also to terrorist groups. To reduce this danger, it is essential to secure and to sharply reduce all stocks of highly enriched uranium and separated plutonium,the key materials in nuclear weapons, and to limit any further production. 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.

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