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

Global Fissile Material Report 2006

First report of the International Panel on Fissile Materials

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

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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 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 weapons disarmament, to halting the proliferation of nuclear weapons, and to ensuring that terrorists do not acquire nuclear weapons.

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

The Panel is co-chaired by Professor José Goldemberg of the University of São Paulo, Brazil and Professor Frank von Hippel of Princeton University. Its founding members include nuclear experts from fifteen countries: Brazil, China, Germany, India, Japan, South Korea, Mexico, Netherlands, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom and the United States. This group of countries includes six nuclear weapon states and nine non-weapon states. Short biographies of the panel members can be found in the Appendix.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. It has full panel meetings twice a year in capitols 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 make presentations.

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Summary

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 these dangers it is essential to secure and to sharply reduce all stocks of highly enriched uranium and separated plutonium, the key materials in nuclear weapons, and to limit any further production.

The current global stockpiles of fissile materials are huge: 1400-2000 metric tons* of highly enriched uranium (HEU) and about 500 tons of plutonium – enough for several tens of thousands of nuclear weapons. It is urgent to reduce these stocks to very low levels at a very limited number of locations.

Chapters 1–3 in Part I of this report explain what fissile materials are, their use in nuclear weapons, how they are produced and disposed, and provide estimates of current national stockpiles and production rates. Chapter 4 provides a brief overview of the agreements and institutions that have been set up to control the production and use of fissile materials.

Part II (chapters 5-8) describes four goals toward which we believe significant progress can be made in the near future:

- A cutoff on production of fissile materials for weapons, and placement under international safeguards of all civil stocks of fissile material, and stocks that are excess to military requirements;

- Declarations by Russia and the United States (and eventually by the other nuclear weapon states) of their total fissile-material stockpiles;

- Measures to limit the proliferation of national uranium centrifuge enrichment and reprocessing plants; and

- Total or near-total elimination of the use of highly enriched uranium as a civilian reactor fuel.

A Fissile Material Cutoff Treaty (FMCT) would impose upon the nuclear weapon states (including India, Pakistan, Israel, and North Korea) the obligation not to produce fissile materials for weapons. This obligation has already been accepted by the non-nuclear weapon states, and would help to ensure that reductions in the nuclear weapons arsenals are irreversible. Declarations – or at least an exchange of information between Russia and the United States on their overall fissile-material stockpiles – would provide a basis for further balanced reductions in their nuclear

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* In this report, tons should be understood to refer to metric tons.

arsenals. Containing the proliferation of national fissile material production facilities would reduce concerns about an increasing number of countries obtaining a nuclear-weapon option along with such facilities. Finally, eliminating HEU in civilian-reactor fuel would greatly reduce the danger of HEU falling into the hands of potential nuclear terrorists.

Fissile Material Cutoff Treaty

Negotiations on an FMCT have been blocked in the Conference on Disarmament (CD) for a decade by a lack of agreement on whether or not the negotiations will proceed in parallel with discussions of possible treaties to bar nuclear threats against non-nuclear states, to prevent an arms race in outer space, and to achieve nuclear disarmament. The United States opposes such linkages and the rules require that the CD can proceed only by consensus.

If this problem can be overcome – either in the CD or by creating another negotiating forum – the negotiators will have to deal with, among other issues, the scope of the treaty and how it would be verified.

The weapon states would like to see the scope confined to a ban on the future production of fissile materials for weapons. Many non-weapon states would also like to include a ban on the use for weapons of materials that have been produced for civilian use or have been declared excess for military use.

The issue of verification has been complicated by the Bush Administration's 2004 decision to oppose international verification of an FMCT. Effective verification is politically and technically feasible, however, and would be valuable. If previously produced civilian materials and materials declared excess for military use were included within the scope of an FMCT, then the verification arrangements for the civilian nuclear activities in the nuclear weapon states could be the same as in the non-weapon states. Verification that known uranium-enrichment and reprocessing facilities had been either shut down or converted to weapon use would also be straightforward. Verification of the absence of fissile materials production at other sites could be done using "managed access" procedures similar to those that have already been accepted under the Chemical Weapons Convention (CWC), which allows ad hoc arrangements to protect unrelated sensitive information when international inspectors check on concerns that a facility might be housing illicit chemical-weapons production. We also discuss, in a preliminary way, possible arrangements to provide international assurance that HEU declared for naval-reactor fuel use was not being diverted to weapon use.

Stockpile declarations

Russia and the United States have reduced the number of weapons in their nuclear arsenals to about one-third of their Cold-War peaks, and they have declared substantial amounts of HEU and plutonium excess to their military needs. But they still retain hundreds of tons more fissile materials in their weapons stockpiles than they need and cannot credibly call on other states to make reductions until they have made deeper cuts themselves.

Such reductions are unlikely, however, unless the United States and Russia have better knowledge of the sizes of each others' fissile materials stockpiles. Russia and the United States should therefore declare their total stocks of fissile materials and separately, the total quantities of fissile materials not inside warheads and warhead components. We review various ways in which they could join in non-intrusive cooperate efforts to strengthen each other's confidence in the accuracy of these declarations.

Limiting the proliferation of fuel cycle facilities

The crisis over Iran's gas-centrifuge uranium enrichment program has focused the international community on the fact that, if a country broke its Nonproliferation Treaty (NPT) commitments, it could quickly convert a centrifuge enrichment plant designed to produce low enriched uranium for power-reactor fuel to the production of highly enriched uranium for weapons. Alternatively, a country that has mastered centrifuge technology could build in parallel, a small, difficult to detect, clandestine centrifuge plant.

Proposals to limit the proliferation of enrichment plants raise concerns about discrimination. However, there might be objective criteria on which there could be broad international agreement. For example, it might be agreed that the possession of national enrichment facilities is not economically justified until a country or a group of countries operating a multinational enrichment plant acquires a nuclear generating capacity equivalent to at least that of ten large nuclear reactors. It would also make sense for countries to acquire advanced centrifuges from Urenco (the multinational operation owned by the United Kingdom, Germany, and the Netherlands), as France and the United States are doing, or from Russia, as China is doing, rather than spending billions of dollars developing the technology for themselves.

The spread of reprocessing plants represents a different sort of problem. The reprocessing of civilian spent nuclear fuel has generated a global stockpile of separated weapon-usable civil plutonium that will soon be larger than that of weapons plutonium. It is widely agreed that there is currently no economic justification for plutonium separation and recycle. Nevertheless, Japan has begun large-scale reprocessing at its new Rokkasho plant; and the United States, under a newly announced Global Nuclear Energy Partnership (GNEP), has begun to talk of future reprocessing. Reprocessing is being carried out in France and Japan and is being considered in the United States largely because they are meeting resistance to siting either interim spent-fuel storage facilities or long-term geological repositories. Reprocessing offers host communities many more jobs and much larger tax revenues, and thereby facilitates acceptance by these communities of interim storage of the resulting high-level waste and plutonium. On-site storage of spent fuel in dry casks next to the nuclear-power reactors has been adopted as a short term alternative by nuclear power operators in the United States, Germany and elsewhere. Such storage appears safe for extended periods of time, and certainly for as long as the reactors continue to operate. Over time, dry-cask storage could be centralized.

Eliminating the use of HEU fuel

There is an urgent need to improve the security of military and civilian facilities that store or use fissile materials. This is especially critical for highly enriched uranium (HEU), which, if obtained by terrorist groups, could be fabricated into nuclear weapons much more easily than could plutonium. The more than 100 civilian research reactors fueled with HEU and their associated fuel development and fabrication facilities are of particular concern. The operators of these facilities cannot afford military-style security. Many of the reactors are obsolete and should be decommissioned. As many as possible of those that are still needed should be converted to use low enriched uranium fuel. Civilian research involving the use of HEU should be confined to a few well-secured and internationally-shared facilities.

U.S., Russian and U.K. naval reactors use HEU fuel and hundreds of tons of excess weapons uranium have been set aside for their future use. While some of these reactors have lifetime cores and cannot be converted, future naval reactors also should be designed to use low enriched uranium.

I Background

Introduction

The first four chapters of this report provide essential background for understanding the fissile material problem. As Chapter 1 explains, less than 8 kilograms of plutonium or 25 kilograms of weapon-grade uranium are sufficient to create an explosive nuclear chain reaction that could destroy a substantial part of a modern city and kill hundreds of thousands. All grades of HEU and virtually all mixes of plutonium isotopes are weapon-usable.

Chapters 2 and 3 describe the current national and global stocks of fissile materials (both military and civilian), and their current rates of production and disposition. Most of the existing stocks derive from the Cold War weapons programs of the United States and the Soviet Union, and to a lesser extent, from the programs of the other nuclear weapon states. However, civilian facilities capable of producing fissile materials are of increasing concern – notably centrifuge plants for producing enriched uranium and reprocessing plants for separating plutonium from spent nuclear power-reactor fuel. Additional concerns relate to stocks of highly enriched uranium used as fuel in research and propulsion reactors.

Chapter 4 describes some of the important achievements of the international community in its attempts to control fissile materials, including the Nonproliferation Treaty (NPT) and safeguards applied by the International Atomic Energy Agency (IAEA).

Part II, Chapters 5-8 highlight various possibilities for further progress in limiting and reducing fissile-materials stocks.

1 Fissile Materials and Nuclear Weapons

Fissile materials are materials that can sustain an explosive fission chain reaction.* They are essential in all nuclear explosives, from first-generation fission weapons to advanced thermonuclear weapons. The most common fissile materials in use are uranium highly enriched in the isotope U-235, and plutonium. Lack of access to these materials is the main technical barrier to the acquisition of nuclear weapons.

Explosive fission chain reaction

When the nucleus of a fissile atom – say U-235 or Pu-239 – 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 a chain reaction in a "critical mass" of fissile materials (Figure 1.1). Each fission of an atomic nucleus releases one hundred million times the energy released per atom in 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. The fission of one kilogram of fissile materials – the approximate amount that 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.

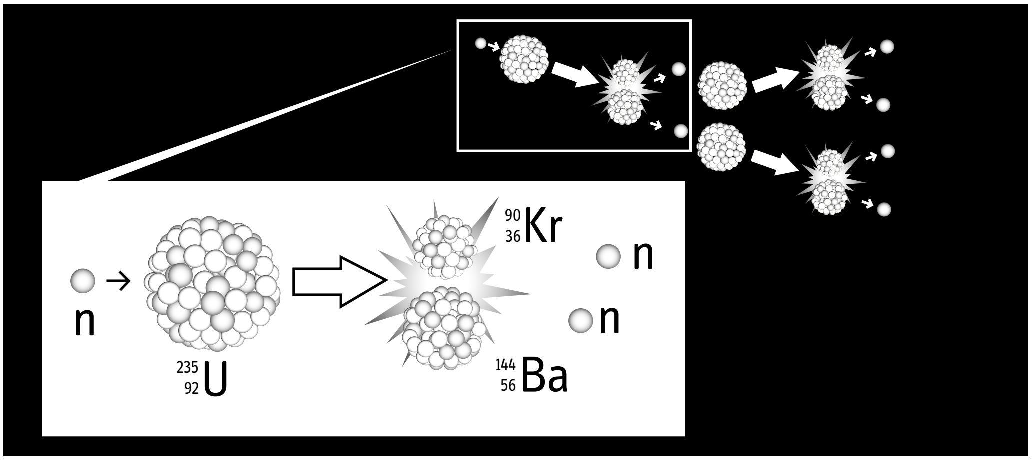

Figure 1.1 - An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. A neutron is absorbed by the nucleus of a fissile atom (uranium-235 in this example), which splits into two fission products (barium and krypton in this example). Additional neutrons are released in the process, which can set off a chain reaction in a critical mass of fissile materials. The energy set free is carried mainly by the fission products, which separate at high velocities. The chain reaction proceeds extremely fast; in a millionth of a second there can be 80 doublings of the neutron population, fissioning one kilogram of material and releasing an energy equivalent to 18,000 tons of high explosive (TNT).

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* See Glossary for definitions of unfamiliar terms used in this report.

The minimum amount of material needed for a chain reaction to be sustained is defined as the critical mass of the fissile material. A "sub-critical" mass will not sustain a chain reaction, because too large a fraction of the neutrons escape from the surface before being absorbed by a fissile nucleus.

Fission weapon design

Nuclear weapons are either pure fission explosives, such as the Hiroshima and Nagasaki bombs, or two-stage, thermonuclear weapons.

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 sub-critical piece of HEU was fired into another to make a super-critical mass (see Figure 1.2, left). The Nagasaki bomb operated using implosion, which has been incorporated into most modern weapons. Chemical explosives implode a sub-critical mass of material to a higher density. This reduces the spaces between the atomic nuclei and results in less leakage of neutrons out of the mass, with the result that it becomes "super-critical" (see Figure 1.2, right). For either design, the maximum yield is achieved when the chain reaction is initiated at the moment the weapon assembly is most supercritical.

HEU can be used in either gun-type or implosion weapons. As is explained below, plutonium cannot be used to achieve a high-yield explosion in a gun-type device.

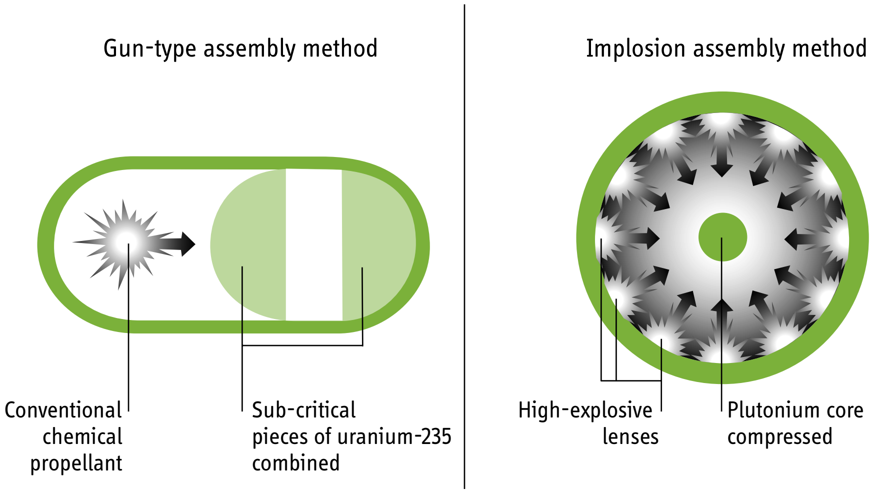

Figure 1.2 - Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated "gun-type" method used in the Hiroshima bomb (left), a sub-critical projectile of HEU is propelled towards a sub-critical target of HEU. Only HEU can be used with this design because the assembly process is relatively slow. For plutonium, the "implosion-type" method used in the Nagasaki bomb has to be mastered. This requires rapid spherical implosion of a plutonium (or uranium) sphere or shell. 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.

Gun-type weapons are simple devices and do not require testing.[1] They therefore could be built and stockpiled clandestinely by a technically unsophisticated state. This is what South Africa did during the Apartheid regime. Gun-type designs are also well within the reach of subnational groups. 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 device in the short time before guards could intervene.[2]

In advanced implosion weapons, the yield is typically "boosted" by up to an order of magnitude by introducing a mixed gas of deuterium and tritium, heavy forms of hydrogen, into the hollow shell of the fissile materials or "pit" of the weapon just before it is imploded.[3] When the temperature of the fissioning materials inside the pit reaches about 100 million degrees, it can ignite the fusion of tritium with deuterium, which produces a burst of neutrons that "boost" the fraction of fissile materials fissioned and thereby the power of the explosion.

In a thermonuclear weapon, a 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. The tritium in the secondary is made during the explosion by neutrons splitting lithium-6 into tritium and helium (see Figure 1.3).

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 used in the secondary stage of thermonuclear weapons to provide the same yield in a more compact design.[4]

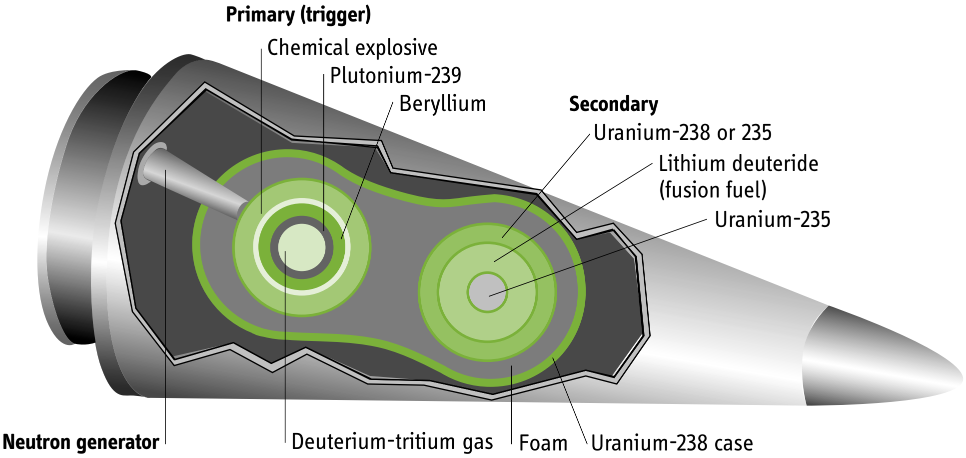

Figure 1.3 – A modern thermonuclear weapon usually contains both plutonium and highly-enriched uranium. Typically, these warheads have a mass of about 200-300 kg and a yield of several hundred kilotons, which corresponds to about one kilogram per kiloton of explosive yield. For comparison, the nuclear weapons that destroyed Hiroshima and Nagasaki weighed 300 kg per kiloton.[5]

Typical quantities of fissile materials in nuclear weapons

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 'reflect' neutrons back into the core.[6] Without neutron reflection, the bare critical masses for Pu-239 and U-235 metal are about 10 kg and 52 kg respectively. The actual amounts of fissile material in the pits of modern implosion-type nuclear weapons are considerably smaller.

The IAEA defines a "significant quantity" of fissile material to be the amount required to make a first-generation implosion bomb of the Nagasaki-type (see Figure 1.2, right), including production losses. The significant quantities are 8 kg for plutonium[7] and 25 kg of U-235 contained in HEU.[8]

The United States has declassified the fact that 4 kg of plutonium is sufficient to make a nuclear explosive device.[9] Based on the critical mass ratios, about three times that amount (about 12 kg) of HEU would be sufficient for a similarly designed fission weapon. A rough estimate of *average* plutonium and HEU in deployed thermonuclear weapons can be obtained by dividing the estimated total stock of weapons 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 3 kg of plutonium and 25 kg of HEU.

Highly enriched uranium (HEU)

U-235, in nature, 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 U-235 enrichment of 6 percent could, in principle, sustain an explosive chain reaction, uranium enriched to above 20 percent U-235, defined as "highly enriched uranium," is generally taken to be required for a weapon of practical size. The IAEA therefore considers HEU a "direct use" weapon-material.

Actual weapons use higher enrichment, however, as reflected by the definition of "weapon-grade" uranium as enriched to over 90-percent in U-235. Figure 1.4 shows the critical mass of uranium as a function of enrichment. To enrich uranium in U-235 requires sophisticated isotope separation technology. Isotope separation on the scale required to produce nuclear weapons is still within the reach of only government and nuclear-industry sponsored programs.

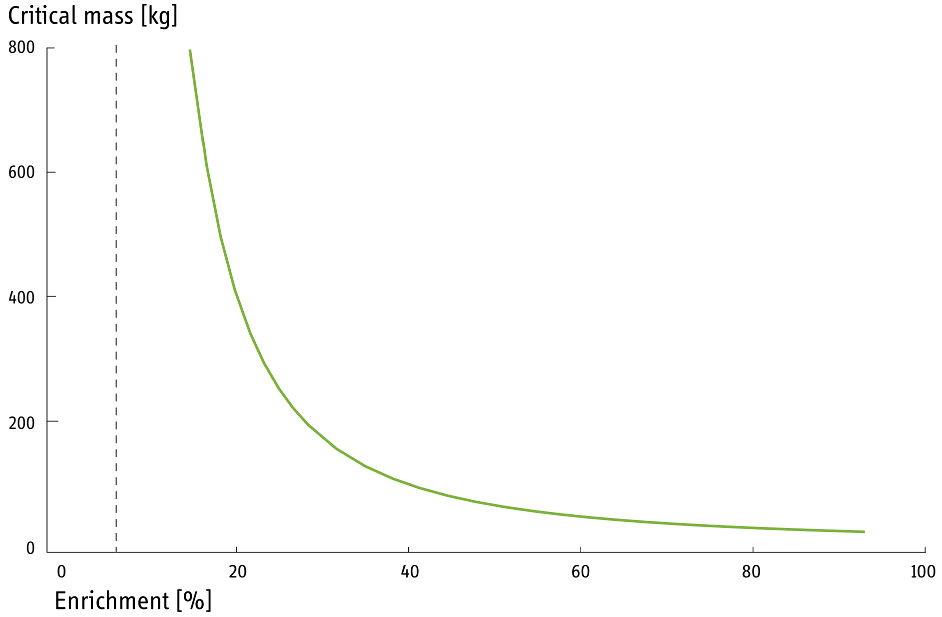

Figure 1.4 - The fast critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data in the figure is for a uranium sphere enclosed in a 5-cm beryllium reflector.[10]

Plutonium

Plutonium is produced in a nuclear reactor when U-238 absorbs a neutron creating U-239, which 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 a third or fourth and become Pu-241 or Pu-242. Plutonium therefore comes in a variety of isotopic mixtures. 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. Weapon-grade plutonium contains more than 90 percent of the isotope Pu-239. The plutonium in typical power-reactor spent fuel (reactor-grade plutonium) contains between 50 and 60 percent Pu-239, and about 25 percent Pu-240, and has a critical mass about one third larger than weapon-grade plutonium.

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, thus increasing the probability a neutron would initiate a chain reaction before the bomb assembly reaches its maximum super-critical 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 higher neutron production rate from reactor-grade plutonium similarly reduces the probable yield of first-generation implosion design – but only by ten-fold, because of the much shorter time for the assembly of a supercritical mass. In the Nagasaki design, even for the earliest possible pre-initiation of the chain reaction, the yield would not be reduced below about 1000 tons TNT equivalent.[11] That would still be a devastating weapon.

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

> "[V]irtually any combination of plutonium isotope … 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."[12]

Other fissile materials

In addition to plutonium, other weapon-usable fissile materials can be produced by irradiating different target materials in nuclear reactors or by the decay of certain isotopes of plutonium. Among these are uranium-233, neptunium-237, and americium-241. The bare critical masses of these alternative fissile materials, along with those of Pu-239 and U-235, are shown in Figure 1.5.

While Pu-239 and U-235 are the only fissile materials known to be used in deployed nuclear weapons, the United States has tested designs containing U-233[13] and France may have experimented with neptunium-237 in nuclear tests.[14]

We are unaware of any public report of weapons experiments involving americium, but U.S. weapons designers have concluded that "designs using americium as a nuclear weapon fuel could be made to work."[15]

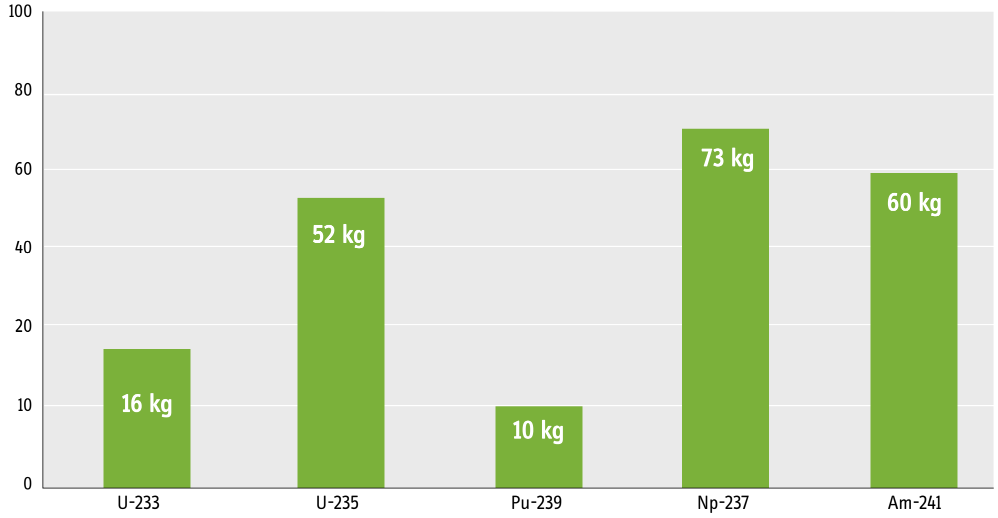

Figure 1.5 – Bare critical masses for various fissile materials.[16]

2 Nuclear-Weapon and Fissile-Materials Stocks

Almost the entire global stockpile of HEU was produced for nuclear-weapons and naval propulsion reactors – mostly during the Cold War by the Soviet Union and the United States. About half of the global stockpile of separated plutonium was similarly produced for weapons during the Cold War. The other half was produced by reprocessing civilian spent power reactor fuel.

Nuclear weapons arsenals

Nine states are thought to have nuclear weapons. These are, in historical order, the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan and North Korea. The first five are parties to the Nonproliferation Treaty (NPT). All but North Korea, and possibly Israel, have tested nuclear weapons. Israel has maintained public ambiguity about its nuclear-weapon status.[17] North Korea has stated that it has nuclear weapons.[18]

Figure 2.1, based on estimates by the Natural Resources Defense Council (NRDC), shows the huge scale of U.S. and Soviet nuclear-weapons-production during the Cold War.

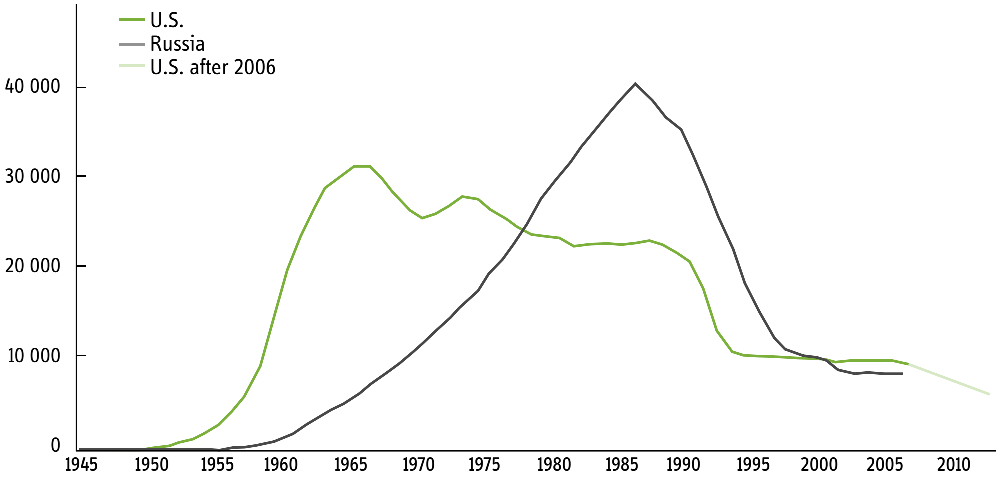

Figure 2.1 – Rise and fall of the U.S. and Russian nuclear weapon stockpiles. Natural Resources Defense Council (NRDC) estimates suggest the number of U.S. warheads peaked at about 30,000 in the mid-1960s, and the Soviet/Russian warheads at 40,000 in the 1980s. Since then, the nuclear arsenals of both countries have dropped sharply. The United States and Russia are each committed to reducing their number of *deployed strategic* warheads to 1700-2200 by 2012. The NRDC estimates that the number of total *operational* warheads in the U.S. arsenal by that date will be about 6000, with the Russian operational arsenal likely to be no larger. However, both countries may still have many thousands of additional warheads and components in the dismantlement queue.[19]

In June 2003, the U.S.-Russia Strategic Offensive Reduction Treaty (SORT) entered into force. Under SORT, the United States and Russia are committed to reduce their deployed strategic arsenals to 1700-2200 warheads each by the end of 2012.[20] Although the treaty does not require the elimination of warheads removed from deployment, it appears likely that the United States and Russia will reduce their total stockpiles of nuclear warheads substantially. In mid-2004, the United States announced that, by 2012, it would shift almost half of the current U.S. nuclear-warhead stockpile into the queue for dismantlement.

Non-governmental analysts have estimated that, after the reductions, about 6000 warheads will remain in the U.S. stockpile, including non-strategic and reserve warheads.[24] The number of operational nuclear warheads in the Russian arsenal could also fall to 6000 or lower by 2012.[21]

By comparison, the remaining nuclear weapon states are estimated to possess a combined total on the order of 1000 warheads (Table 2.1).

Country	Nuclear Warheads
U.S.	10,000
Russia	10,000
U.K.	200
France	350
China	200
India	40-50
Pakistan	<50
Israel	75-200
North Korea	<15

Table 2.1 - U.S. and Russian nuclear warhead totals dwarf those of other countries. They could be reduced ten-fold and still be equal to the sum of the stocks of the other nuclear weapon states. The totals for U.S. and Russia do not include warheads awaiting dismantlement. These numbers are approximate.[22]

Non-weapon uses of fissile materials

Most of the global fissile material stockpile has been produced for nuclear-weapon purposes. HEU and plutonium are also used to fuel some reactors.

HEU use in naval and other reactor fuels. Russia, the United Kingdom and the United States each use HEU to fuel their submarine and (in the case of the United States) aircraft carrier propulsion reactors. France is shifting from HEU to LEU fuel for its nuclear submarines. During the Cold War, United States produced an average of six metric tons of HEU per year for this purpose.[23] Today, the United States uses about two tons per year of weapon-grade uranium, and Russia, about one ton of weapon-grade equivalent.[24]

HEU is also used to fuel military and civilian research reactors and Russia's fleet of seven nuclear-powered ice-breakers. The United States and the Soviet Union/Russia used and also supplied HEU to many countries for civilian research reactors and medical-isotope production as part of their Atoms for Peace programs. Most of this material is in the weapon states but more than 10 metric tons are in non-nuclear weapon states.[25] Very roughly, 50 tons of the HEU shown in Figure 2.2 (and in Table 2.A.1 in the appendix to this chapter) is in the fuel cycles of research reactors worldwide and in Russia's nuclear-powered icebreakers.[26] Even though this material currently represents only a few percent of the global total, it would be sufficient for about 1000 gun-type weapons and is located at more than 100 sites – many inherently difficult to secure. This HEU is currently the object of a global "clean-out" campaign (see discussion in Chapter 8).

The United States and Russia have also used HEU to fuel plutonium and tritium production reactors.

Civilian separated plutonium. In a few countries, large quantities of plutonium have been separated in reprocessing plants from civilian spent fuel. Some of this plutonium has been mixed with uranium, fabricated into "mixed-oxide" fuel, and recycled into fuel for light-water power reactors. But most remains stockpiled at the reprocessing plants where it was separated in France, the United Kingdom, and Russia. The total amount of separated civilian plutonium is about 250 metric tons – and growing. At 8 kg per warhead, this would be enough for more than 30,000 warheads.

Global stocks and national holdings of fissile materials

All five NPT nuclear weapon states have declared (China informally) that they have ended or suspended their production of fissile materials for weapons.[27] Both the United Kingdom and the United States have published the totals for their stocks of plutonium and HEU. The countries holding most of the world's civilian plutonium annually submit information on the sizes of their stockpiles to the IAEA for publication on its website. A few of these countries also submit numbers for their civilian stocks of HEU. The IAEA has exact information on the fissile holdings of the non-weapon states but publishes only global totals. Published estimates of the remaining stocks of weapon materials are by non-governmental analysts and have substantial uncertainties.

The most complete compilation of publicly available data and estimates of global production and consumption of fissile materials – unfortunately, now a decade old – can be found in the book, *Plutonium and Highly Enriched Uranium 1996*, by Albright, Berkhout and Walker.[28] Albright and collaborators have updated this information on the website of the Institute for Science and International Security.[29] Where countries have not published their stocks, the numbers below are largely based on this work.

Highly enriched uranium. As shown in Figure 2.2, as of mid-2006, the global stockpiles of HEU totaled very roughly 1400 tons plus about 325 tons of excess weapons uranium that is to be blended down to low enriched uranium (see also Table 2.A.1). More than 99 percent of this material is in the possession of the nuclear weapon states.

The only states believed currently to be producing HEU are Pakistan (for weapons) and India (for naval-reactor fuel). Their estimated production rates are each on the order of a hundred kilograms per year. While significant in terms of weapon-equivalents, this production has an insignificant impact on the total global stock.

In fact, the total amount of HEU in the world is shrinking. In 1993, Russia contracted 500 tons of 90-percent enriched uranium in redundant Cold War warheads to be blended down to 4-5 percent U-235 to be sold to the United States for use as power-reactor fuel. As of mid-2006, 275 tons had been blended down – the equivalent of about 11,000 nuclear bombs.[30] In 1994, the United States similarly declared 174 tons of its weapon HEU excess (this was revised to 178 tons in 2001)[31] and began to blend down most of it to low-enrichment for use in U.S. power reactor fuel. By the end of 2005, about 60 tons had been blended down.[32]

In late 2005, the United States declared an additional 200 tons of HEU excess for weapons purposes. However, only 20 tons of this material will be blended down to low-enriched uranium. Of the remainder, 160 tons of weapon-grade uranium will be reserved for U.S. and U.K. naval-reactor fuel and 20 tons for space reactors and research reactors.[33] We assume that Russia has similarly reserved the equivalent of

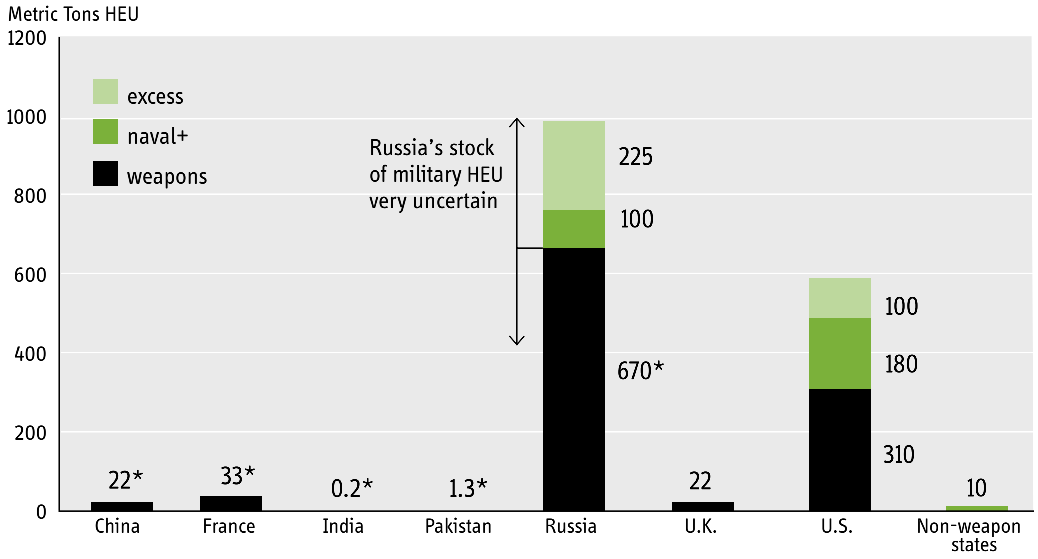

Figure 2.2 – National Stocks of Highly-Enriched Uranium as of mid-2006 (93% enriched equivalent, see Table 2.A.1 for uncertainties). The quantity of weapon-grade uranium in the world is overwhelmingly a consequence of the U.S-Soviet nuclear arms race. The two countries account for over 95 percent of the total world stockpile. However, with the Cold War ended, Russia declared 500 tons of its HEU excess, and the United States similarly 198 tons (about 145 tons 93% equivalent); and both countries have begun to eliminate this HEU. As of mid-2006, Russia had blended down about 275 tons and the United States about 60 tons to non-weapon-usable low enriched uranium for reactor fuel. The United States has reserved 180 tons of HEU for naval and other reactor fuel. Russia is assumed here to have reserved 100 tons for such purposes.
*Numbers of military stocks are estimates.

100 tons of weapon-grade uranium for future naval-reactor use. This would leave 400-1000 tons of HEU in Russia's weapons stockpile and 310 tons in the U.S. weapons stockpile.

The recent U.S. designation of 160 tons of weapon-grade uranium for future use in naval reactors highlights naval reactor use as a second military challenge to reducing global stocks of HEU. At 25 kg per warhead, the U.S. stockpile of weapon-grade uranium reserved for naval reactor fuel would be comparable to the amount of HEU in the U.S. stockpile of 6000 operational warheads projected for 2012.

If Russia and the United States reduced to 1000 nuclear warheads each – as many analysts believe they could before expecting that other countries join them in similar disarmament measures – they would require only about 25 tons of HEU each for weapons.[34]

On this scale, the 300 or so tons of HEU which the United States and Russia have so far kept in reserve for naval and other reactors are huge (see Figure 2.3). This suggests that the question of HEU-fueled reactors might have to be dealt with before such deep cuts in the stockpiles of weapon HEU become politically feasible.

Separated plutonium. As shown in Figures 2.4 and 2.5, the global stockpile of separated plutonium is about 500 tons – approximately equally divided between weapon and civilian stocks – but all weapon-usable. It is mostly in the nuclear weapon states, but Japan and a few non-weapon states in Europe also have significant stockpiles of civilian plutonium (see also Table 2.A.2 in the appendix to this chapter).

The United States, Russia, the United Kingdom, France and reportedly China have stopped producing plutonium for weapons.

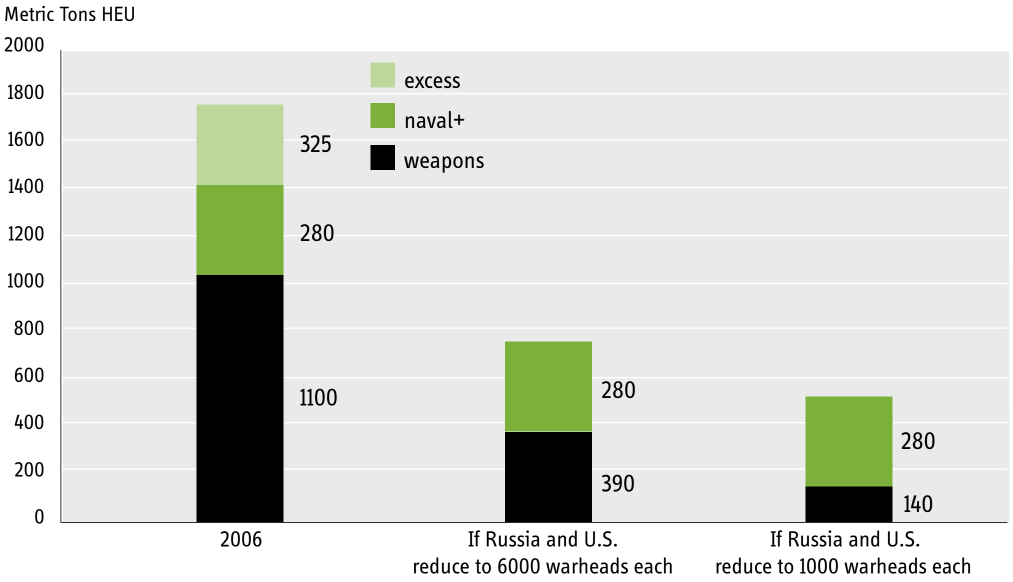

Figure 2.3 – Global HEU Stockpiles – Potential for Reductions (metric tons). Global stockpiles of HEU could shrink dramatically in the future if the United States and Russia continue to reduce their nuclear-weapons arsenals and continue to blend-down HEU recovered from dismantled warheads. If future naval and other reactors were to use LEU fuel, the stockpiles of HEU could be still further reduced. The equivalent weapons stockpile numbers assume 25 kg of HEU per warhead. We assume that the total HEU holdings of all countries other than the United States and Russia stay constant at approximately 90 tons.

There is no indication that Israel, India, Pakistan or North Korea have halted their production of plutonium for weapons. Once again, however, the quantities that they may be producing, while significant in weapons equivalents, do not significantly increase the total global stock.

In 2000, the United States and Russia agreed to each dispose of, in parallel and irreversibly, 34 metric tons of their excess weapon plutonium.[35] But there has been little progress so far.

As shown in Figure 2.5, by the end of 2004, about as much plutonium had been separated from civilian spent fuel as had been produced for weapons. Most of this material is now stockpiled at the reprocessing plants at La Hague, France; Sellafield, United Kingdom; and Ozersk (Mayak), Russia.

Assuming 4 kilograms of plutonium in the average Russian or U.S. warhead, each country would require only about 24 tons of weapon-grade plutonium to support the roughly 6,000 warheads that they are each expected to retain in 2012. The United States and Russia therefore could declare excess, about half, and more than three quarters of their respective remaining stockpiles. If they reduced the number of their nuclear weapons to 1000 each, Russia and the United States would require only 4 tons of weapon-grade plutonium each.

Figure 2.5 shows the global stockpile of weapon plutonium today and for the above hypothetical Russian and U.S. reductions. The 2004 global stockpile of separated civilian plutonium shown in the future scenarios is assumed to be the same size as today – an optimistic projection since civilian separated plutonium stocks are still growing. The present civilian stockpile already dwarfs the amount of plutonium required to support even 12,000 Russian and U.S. warheads. Here too, therefore, the use of fissile materials in reactor fuel could complicate the problem of nuclear arms reductions.

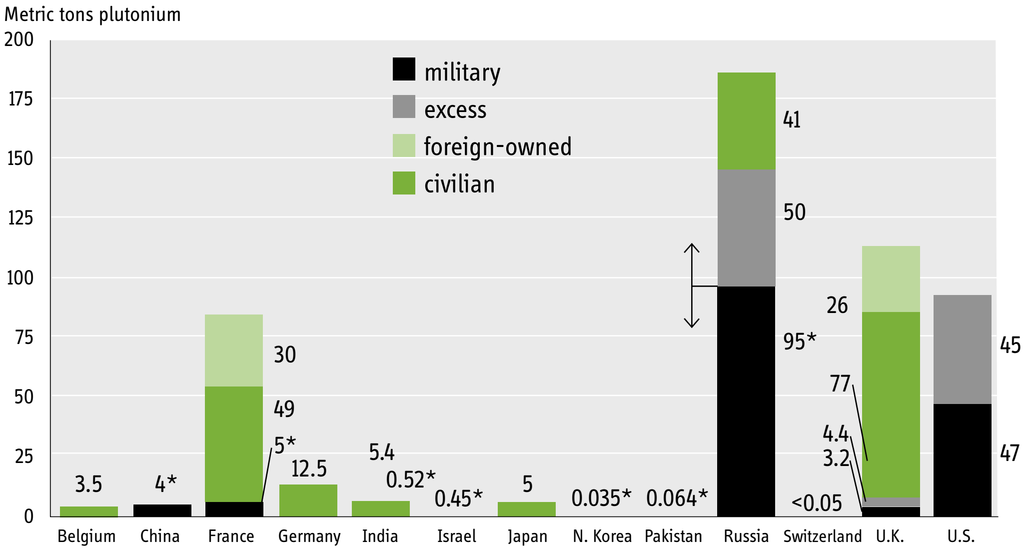

Figure 2.4 - National Stocks of Weapons and Separated Civilian Plutonium. By the end of 2004, the global stockpile of separated plutonium was about 500 tons. This was divided approximately equally between weapons and civilian stocks. Virtually all the weapons plutonium is owned by the United States and Russia. But the United Kingdom, France, Germany, and Japan, along with Russia, also own substantial quantities of separated civilian plutonium, largely the result of the reprocessing of civilian spent fuel in the United Kingdom, France, and Russia. A total of about 100 tons of U.S., Russian, and U.K. weapons plutonium has been declared excess by those countries, but none of this has yet been disposed. India's stock includes both civilian and military; North Korean, Pakistani, and Israeli stocks are military only; Belgian, German and Swiss are civilian only. See Table 2.A.2.
*Numbers of military stocks are estimates.

Alternative fissile materials. Among the exotic fissile materials, U-233 has been produced in the largest quantities: "The U.S. has investigated using U-233 in nuclear weapons, in reactors, and for other purposes. The United States and several other countries have significant quantities of separated U-233. Somewhat [less than] 2 metric tons of separated U-233 containing uranium are in the U.S. inventory. Half of this material is considered high-quality … with few isotopic impurities."[36] U-233 is made by neutron capture in thorium-232. The global U-233 stockpile may grow substantially in the future, if thorium-based fuels start to play a more prominent role in the nuclear fuel cycle as envisioned especially in India.[37]

Spent nuclear fuel contains weapon-usable neptunium-237 and americium-241 as well as plutonium.[38] The global stock of neptunium-237 in spent fuel is estimated to be 60 tons. Some has been separated for targets, that when irradiated in reactors, produce Pu-238. The radioactive decay heat from this 88-year half-life isotope is used to power long-lived thermoelectric generators for spacecraft sent to explore the outer planets, where solar cells are considered impractical. Americium stocks in spent fuel are estimated to be about 90 tons.[39] Small amounts (on the order of several kg/year) have been separated. One use of americium-241 is in smoke detectors.

The IAEA does not consider either neptunium-237 or americium as "direct use material," and does not safeguard them. However, in 1999, the IAEA Board of Governors called on "all States to protect and control these materials" and is monitoring their production in and transfers to non-nuclear weapon states under a voluntary arrangement.[40] In its 2004 Safeguards Statement, the IAEA reported that it "continues to experience difficulties in obtaining information from States … regarding neptunium and americium."[41]

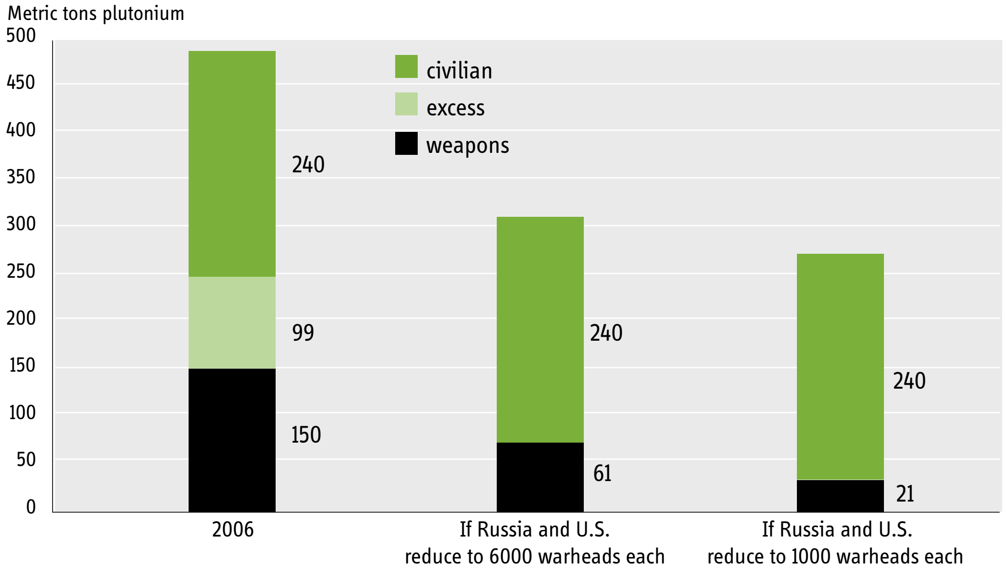

Figure 2.5 – Global Plutonium Stockpiles – Potential for Reductions (metric tons). Global stockpiles of plutonium could shrink substantially if the United States and Russia reduced further their nuclear weapons arsenals and disposed of weapons plutonium made excess by the reductions. It is assumed here that the combined weapons stockpiles of other nations stay constant at about 13 tons. The shrinking of plutonium stocks could still be more dramatic if all of the separated civilian plutonium were disposed. The stockpiles of separated civilian plutonium shown here are assumed not to increase from today. If reprocessing of civilian spent fuel continues at its present rate and the recycling of the separated plutonium in light water reactors remains limited, however, civilian plutonium stocks will continue to rise.

Appendix 2.A Global Fissile Material Stocks

Table 2.A.1 – Global Stocks of Highly Enriched Uranium
(93 percent enriched equivalent, metric tons)

Country	National stockpile (mid 2006)	Production Status [b]	Comments
China	22 ± 25%[a]	Stopped in 1987-1989	
France	33 ± 20%[a]	Stopped in 1996	
India	0.2 ± 50%[a]	Continuing	
Pakistan[c]	1.3 ± 15%[a]	Continuing	
Russia[d]	770 ± 300 tons[a]	Stopped in 1987-1988	Includes 100 tons assumed to be reserved for naval and other reactor fuel. Does not include 225 tons to be blended down.
U.K.	22 (declared)	Stopped in 1963	
U.S.[e]	490 (declared)	Stopped in 1992	Includes 180 tons reserved for naval and other reactor fuel. Does not include 100 tons to be blended down or otherwise disposed.
Non-weapon states[f]	10		
Total (approximate)	1350 ± 300 tons		Does not include 325 tons to be blended down.

Table 2.A.1 - Notes:

[a] Institute for Science and International Security, *Global Stocks of Nuclear Explosive Materials*: Chapter 7, Table 1, "Estimated Military and Excess Stocks of Highly Enriched Uranium in the Acknowledged Nuclear Weapon States, End 2003," "Plutonium and HEU Holdings by Country, End 2003, in Tonnes," revised, 30 June 2005; Chapter 11, "Estimates of Unirradiated Fissile Material in de Facto Nuclear Weapon States, Produced in Nuclear Weapon Programs," revised 30 June 2005; and Chapter 1, Table 1, "Plutonium and HEU Holdings by Country, End 2003," revised 7 September 2005. These estimates are for the end of 2003. We have taken into account subsequent blend-down of Russian excess weapons HEU.

[b] Albright, Berkhout and Walker, *Plutonium and Highly Enriched Uranium 1996*, p.80, Table 4.1.

[c] Assuming production at a rate of 0.1 ton/yr between 2003 and 2005.

[d] U.S. Enrichment Corporation (USEC) reports that, as of 28 June 2006, 275 metric tons of bomb-grade HEU had been blended down: "USEC, Megatons to Megawatts," www.usec.com. The HEU shown as a Russian reserve for naval reactors is a guess, not based on any public information.

[e] As of 30 September 1996, the United States had an inventory of 740.7 tons of HEU containing 620.3 tons of U-235 and had declared 177.8 tons containing 122 tons of U-235 excess, *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, 2001, www.ipfmlibrary.org/doe01.pdf. An additional 20 tons were declared excess in 2005 (we assume the same average enrichment as the material previously declared excess). This would leave a residual stockpile equivalent (in terms of U-235 content) of 517 tons of 93-percent enriched HEU. We assume that, during the subsequent decade, approximately 20 tons were consumed for naval reactor fuel and 5 tons for research-reactor fuel. As of 31 December 2005, the United States had down-blended about 60 metric tons of HEU with average enrichment levels between 40 and 75 percent U-235: USEC, Megatons to Megawatts, www.usec.com. We approximate the remaining HEU to be blended down or otherwise disposed as 100 tons of 93% equivalent.

[f] *IAEA Annual Report 2004,* not including HEU originally enriched to 20-26% in spent fast-reactor fuel in Kazakhstan.

Appendix 2.A

Table 2.A.2 – Global Stocks of Separated Plutonium
(metric tons)

Country	Military stocks[a] (end of 2005)	Military production[b]	Civilian stocks end of 2004[c]
Belgium	0		3.5 (2003) (+0.4 tons abroad)
China	4 ± 50%[a]	stopped in 1991	0
France	5 ± 25%[a]	stopped in 1994	79 (30 tons foreign owned)
Germany	0		12.5 (+13.5 tons in France & U.K.)
India[d]	0.52	continuing	5.4 (2005)
Israel	0.45 ± 25%[a]	continuing	0
Japan	0		5 (+37 tons in France & U.K.)
N. Korea[e]	0.035 ± 50%	continuing	0
Pakistan	0.064	continuing	0
Russia	145 ± 25 tons[a] (34-50 tons declared excess)	effectively stopped in 1997	41 (2005)
Switzerland	0		up to 3 tons in France and U.K.
U.K.	7.6 (4.4 tons declared excess)	stopped in 1989	103 (26 foreign owned, plus 1 ton abroad)
U.S.	92 (45 tons declared excess)	stopped in 1988	0
Totals (approximate)	254 ± 25 tons (up to 100 tons declared excess)		240 tons

Table 2.A.2 - Notes:

[a] Institute for Science and International Security, *Global Stocks of Nuclear Explosive Materials [for 2003],* (Chapter 2, Table 1, revised 30 June 2005 and Chapter 11, revised 30 June 2005. The weapons plutonium holdings of the NPT nuclear weapon states were unchanged between 2003 and 2005 except for Russia, which is producing a total of about 1.2 tons of weapon-grade plutonium annually in three production reactors that continue to operate because they also produce heat and electricity for nearby populations, Russia has committed not to use this material for weapons, however, "Agreement between the Government of the United States of America and the Government of the Russian Federation concerning cooperation regarding plutonium production reactors," 23 September 1997, www.ipfmlibrary.org/ransac97.pdf, Article IV

[b] Albright, Berkhout and Walker, *Plutonium and Highly Enriched Uranium 1996*, 1906; China, p.76; France, p. 68; U.K., p. 63; and U.S., p.38.

[c] Civilian stocks from INFCIRC/549 declarations to the IAEA, except for India, which is from *Global Stocks of Nuclear Explosive Materials*, Chapter 4, Table 2, revised 8 July 2005. In its INFCIRC/549 statement of 4 November 2005, the United States declared, as civilian stocks, a total of 45 tons, described as plutonium contained in unirradiated MOX fuel or other forms, and unirradiated separated plutonium held elsewhere.

[d] Following the 2005 proposal by U.S. President Bush and India's Prime Minister Singh for India to separate its military and civilian nuclear activities and submit India's civilian activities to IAEA monitoring in exchange for access to civilian safeguarded materials and technology in the international market, India has proposed to include in the military sector much of the plutonium from India's power reactors labeled "civilian" here.

[e] North Korea estimate from David Albright and Paul Brannan, "The North Korean Plutonium Stock Mid-2006," Institute for Science and International Security, 26 June 2006.

3 Production and Disposition of Fissile Materials

Although the first uranium-enrichment plants were built to produce HEU and the first reactors were built to produce plutonium – both for weapons – globally, the civilian nuclear sector today vastly exceeds the nuclear-weapon sector in terms of the numbers of fuel cycle facilities and fissile-material production capabilities.

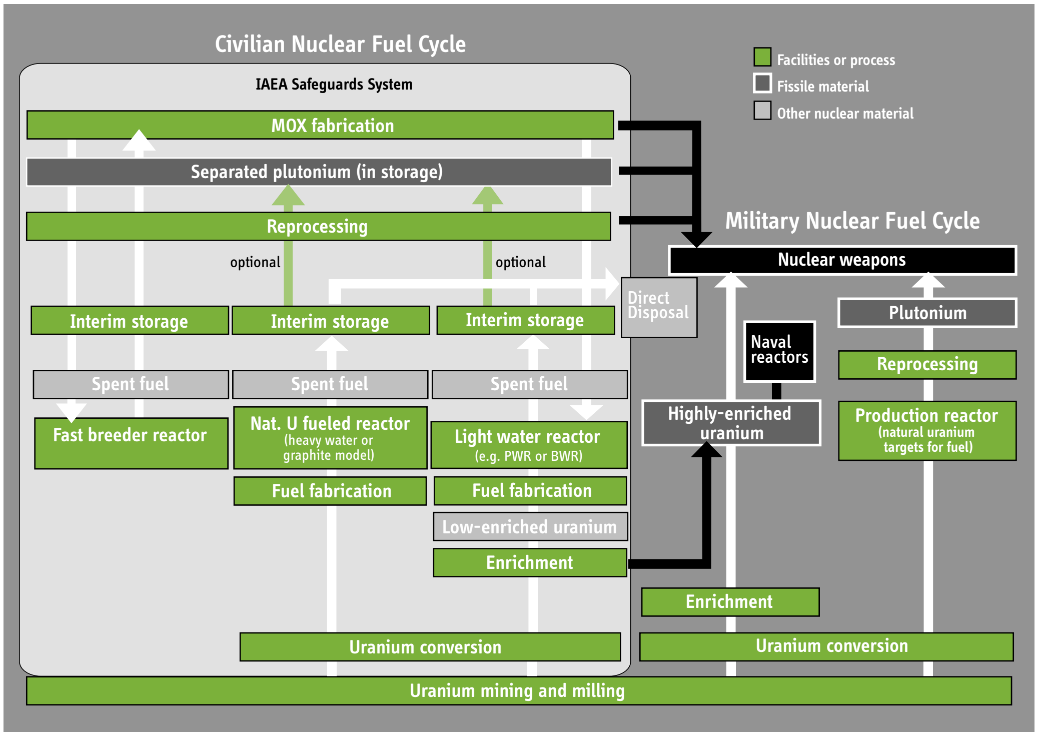

Figure 3.1 - Fissile-material production in civilian and military nuclear fuel cycles. The civil and military nuclear fuel cycles have many materials and processes and products in common. This raises the possibility of the diversion of materials from civil to military programs and of covert production of weapon-usable materials. The purpose of IAEA safeguards is to detect any such misuse of civilian nuclear material.

A capability to produce HEU and plutonium for weapons is inherent in the civilian nuclear fuel cycle (Figure 3.1). In 1946, Robert Oppenheimer observed that, if there were a convention banning nuclear weapons:

> "We know very well what we would do if we signed such a convention: We would not make atomic weapons, at least not to start with, but we would build enormous plants, and we would design these plants in such a way that they could be converted with the maximum ease and the minimum time delay to the production of atomic weapons saying, this is just in case somebody two-times us; we would stockpile uranium; we would keep as many of our developments secret as possible; we would locate our plants, not where they would do the most good for the production of power, but where they would do the most good for protection against enemy attack."[42]

Production of Fissile Materials

All nuclear fuel cycles start today with uranium. Uranium ore is mined and milled to extract the uranium.

Natural uranium, which only contains 0.7 percent of U-235, is used directly as a fuel in a small fraction of the world's power reactors. These are the heavy water reactors (HWRs or CANDUs), developed by Canada but used today also in Argentina, China, South Korea, India, Pakistan and Romania. The heavy water slows or 'moderates' the neutrons without absorbing them. Slow neutrons are preferentially absorbed on U-235 (250 times relative to U-238).[43] As a result, it is possible to sustain a slow-neutron chain reaction in natural uranium despite the fact that only one atom in 140 is U-235. Very pure graphite was used to slow neutrons in the first plutonium-production reactors. The U.K.'s Magnox and AGR reactors, which use graphite as a moderator, are descended from its plutonium-production reactors.

Uranium can also be enriched in the fraction of the chain-reacting isotope U-235. Most nuclear power reactors today are light water reactors (LWRs) that use ordinary water as both moderator and coolant. Because ordinary water absorbs more neutrons than heavy water, LWRs require fuel enriched to 3-5% U-235. The potential dual use of enrichment facilities manifests itself in the fact that they can be adapted to produce HEU for nuclear weapons.

In a reactor, neutrons captured on U-238 in the fuel produce plutonium. By the time the fuel is discharged, about one percent of the spent LWR fuel is plutonium.

After the fuel is discharged from a reactor, it is cooled in on-site pools for at least several years. The spent fuel can then either continue to be stored on site or elsewhere, or be reprocessed to recover the plutonium and uranium, with the fission products and other materials stored in tanks and then solidified as high-level waste. Ultimately, the spent fuel or high-level waste is to be stored in geological repositories. No repository is yet licensed or in operation but candidate sites are under development in the United States, Finland, and Sweden.[44]

The separation of plutonium for civilian use was originally seen as a way to increase the energy that could be recovered from natural uranium, specifically from the U-238 isotope that makes up 99.3 percent of natural uranium. Conventional reactors are efficient only in fissioning U-235.

The plan in most industrialized countries in the 1970s was that plutonium recovered from their spent LWR fuel would be used to provide the initial fuel for breeder reactors that would then produce more plutonium from U-238 than they consumed, thus in effect, turning U-238 into their fuel. Breeder reactors have not matured as a safe and economic technology, however. As a result, some countries that reprocess spent fuel are storing their separated civilian plutonium, while others recycle it as fuel for LWRs. As noted earlier, almost any mixture of plutonium isotopes can be used in a nuclear weapon. Reprocessing therefore is also a dual-use technology.

Uranium isotope separation

The isotopes U-235 and U-238 are chemically virtually identical, differing in weight by only one percent. They are therefore very difficult to separate either chemically or physically. The ability to do so on a scale sufficient to make nuclear weapons or LWR fuel is found in only a relatively small number of nations.

In any 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. The work of isotope separation is measured in "separative work units" (SWUs). Likewise, the capacity of enrichment facilities is commonly described in SWU/yr. [45]

To produce one kilogram of low-enriched uranium, with 4% U-235 for LWR fuel takes about 7.5 kilograms of natural uranium feed and 6.5 SWU, if 0.2% U-235 is left in the depleted tails. To produce one kilogram of weapon-grade uranium (93% U-235) takes about 230 kilograms of natural uranium feed and 200 SWU, at a tails assay of 0.3%. Therefore, producing a kilogram of weapon-grade uranium requires about thirty times as much enrichment work as is required to produce a kilogram of LWR fuel. However, it takes about 20,000 kg a year of the low enriched uranium to fuel a typical 1000-Megawatt power reactor, as compared to the 25 kg of weapon-grade uranium to produce a nuclear weapon.

Therefore, even a small enrichment plant, such as the one that Iran proposes to build at Natanz, which is sized to fuel only a single power reactor, could make enough HEU for tens of bombs a year – or if 20 tons of 4% LEU were fed into it, could produce enough weapon-grade uranium for four bombs in a little more than a week (see Table 3.1).

Feed	Time	Product	Depleted Tails
150 metric tons natural uranium	1 year	20,000 kg LEU (4%)	0.2% U-235
150 metric tons natural uranium	1 year	654 kg HEU (93%) (26 bombs)	0.31%
150 metric tons natural uranium	40 days	100 kg HEU (93%) (4 bombs)	0.65%
20,000 kg 4% LEU	8 days	100 kg HEU (93%) (4 bombs)	3.55%

Table 3.1 - A 130,000 SWU/year enrichment plant could either supply a single 1000-MWe reactor or make weapon-grade uranium sufficient for many bombs. About 130,000 SWU are needed to produce the annual reloading of LEU fuel for a 1,000 MWe reactor. The same enrichment capacity could produce enough weapon-grade uranium for 26 nuclear weapons per year (assuming 25 kg of 93%-enriched uranium per weapon) or four weapons in 40 days. If the 20,000 kg of 4-percent enriched LEU produced for an annual reactor reload were instead recycled through the enrichment plant, it could be turned into enough HEU for 4 weapons in *8 days.*

Today, two enrichment technologies are used on a commercial scale: gaseous diffusion and centrifuges. Gaseous diffusion plants remain operational in the United States and France, but both countries plan to switch to more economical gas centrifuge enrichment technology. For the same reason, all countries which have built new enrichment plants during the past three decades have chosen centrifuge technology. Table 3.2 shows enrichment facilities currently operational or planned worldwide.

Country	Name/Location	Type	Status	Process	Capacity 1000's of SWUs/year
Brazil	Resende Enrichment	Civilian	Under construction	GC	120
China	Lanzhou 2	Civilian	Under construction	GC	500
	Shaanxi Enrichment Plant	Civilian	In operation	GC	500
France	Eurodif (Georges Besse)	Civilian	In operation	GD	10800
	Georges Besse II	Civilian	Planned	GC	500
Germany	Urenco Deutschland[a]	Civilian	In operation	GC	1800 (4500)
India	Rattehalli[b]	Military	In operation	GC	4-10
Iran	Natanz[c]	Civilian	Under construction	GC	100-250
Japan	Rokkasho Enrichment Plant	Civilian	In operation	GC	1050
Netherlands	Urenco Nederland[a]	Civilian	In operation	GC	2500 (3500)
Pakistan	Kahuta[b]	Military	In operation	GC	15-20
Russia[d]	Angarsk	Civilian	In operation	GC	1600
	Novouralsk (Sverdlovsk-44)	Civilian	In operation	GC	9800
	Zelenogorsk (Krasnoyarsk-45)	Civilian	In operation	GC	5800
	Seversk (Tomsk-7)	Civilian	In operation	GC	2800
U.K.	Capenhurst	Civilian	In operation	GC	4000
U.S.	Paducah Gaseous Diffusion	Civilian	In operation	GD	11000
	Portsmouth	Civilian	Standby	GD	7400
	Piketon, Ohio (USEC/DOE)[e]	Civilian	Planned	GC	3500
	Eunice, NM (LES/Urenco)[e]	Civilian	Planned	GC	3000

Table 3.2 - Large enrichment facilities, operational, under construction, and planned. Apart from some laboratory-scale facilities, all enrichment facilities today use either the gaseous diffusion (GD) or the gas centrifuge (GC) process. Since the large U.S. gaseous diffusion facility in Portsmouth, Ohio was shutdown in 2001, centrifuge facilities have accounted for more than half of global SWU production. Unless otherwise noted, enrichment capacities are based on the IAEA's Nuclear Fuel Cycle Information System (NFCIS, data retrieved in February 2006).

Notes: a) Entries in parentheses for Urenco facilities are capacities after planned expansions are complete; b) Estimates for India from: M.V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security*, Vol. 12, 2004; and for Pakistan from: D. Albright et al., *Plutonium and Highly Enriched Uranium, 1996;* c) Entry for Iran assumes 50,000 machines with a capacity of 2-5 SWU/yr each, from: Mark Hibbs, "Current Capacity at Natanz Plant about 2,500 SWU/yr, Data Suggest," *Nuclear Fuels*, 31 January 2005; d) Estimates for Russia are from: Oleg Bukharin, "Understanding Russia's Enrichment Complex," *Science & Global Security*, Vol. 12, 2004; e) Information on planned U.S. facilities from U.S. Nuclear Regulatory Commission, www.nrc.gov/materials/fuel-cycle-fac/gas-centrifuge.html.

Modern 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. Combined with an axial countercurrent circulation of the UF_6 in the machine, this effect can be exploited to separate the two isotopes (see Figure 3.2 for an illustration).

Both throughput and enrichment achieved with a single machine are very small. The process is therefore repeated in a "cascade" of of ten or more stages to produce uranium enriched to the 3-5 percent level used in most nuclear-power reactors. If the cascade is extended to three times as many stages or the uranium is recycled through the cascade three or four times, weapon-grade uranium can be produced (see Figure 3.3).

1 Uranium hexafluoride (UF6) is injected into the centrifuge and spun at very high speeds.

2 Due to the enormous centrifugal force, the heavier uranium-238 isotope has a tendency to be closer to the rotor wall.

3 U-235 concentration increases in the rising and decreases in the descending streams, which are extracted at the top and bottom respectively.

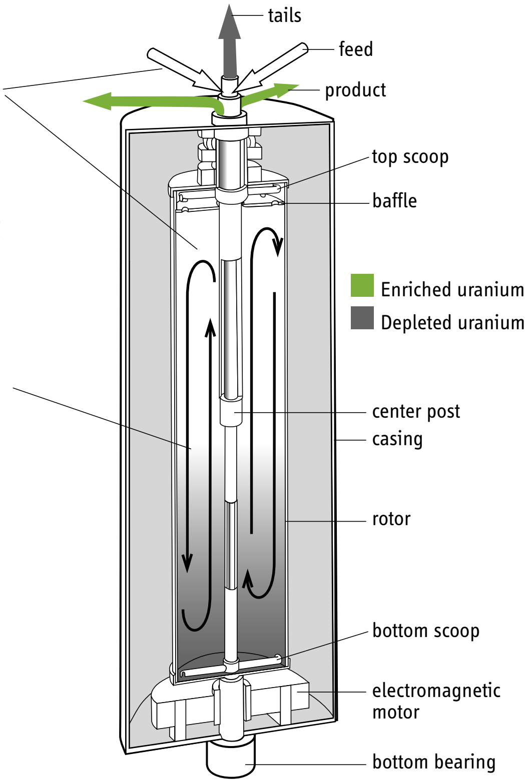

Figure 3.2 - The gas centrifuge for uranium enrichment and its large-scale use in an enrichment facility. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other 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.[46]

From a nonproliferation perspective, centrifuge technology has two major disadvantages relative to gaseous diffusion technology. First, the number of stages is much smaller (ten in the example given in Figure 3.3 versus a thousand) and so the uranium moves through the cascade very quickly. Second, the inventory held up in a typical cascade is more than a thousand metric tons in a gaseous diffusion plant as compared to a few kilograms in a centrifuge plant.[47] This means that it could take only days to flush the uranium out of a centrifuge cascade and re-configure it for HEU production. This makes possible a "breakout" scenario, where peaceful technology is quickly converted to weapon use.

Second, clandestine centrifuge facilities are virtually impossible to detect with remote- sensing techniques. A centrifuge plant with a capacity to make HEU sufficient for a bomb or two per year could be small and indistinguishable from many other industrial buildings. Due to its low power consumption, there are no unusual thermal signatures as compared to other types of factories with comparable floor areas. Leakage of UF_6 to the atmosphere from centrifuge facilities is also minimal because the gas in the pipes is below atmospheric pressure. Air therefore leaks into the centrifuges rather than the UF_6 leaking out. The challenge of detecting gas-centrifuge enrichment plants is discussed further in Chapter 7.

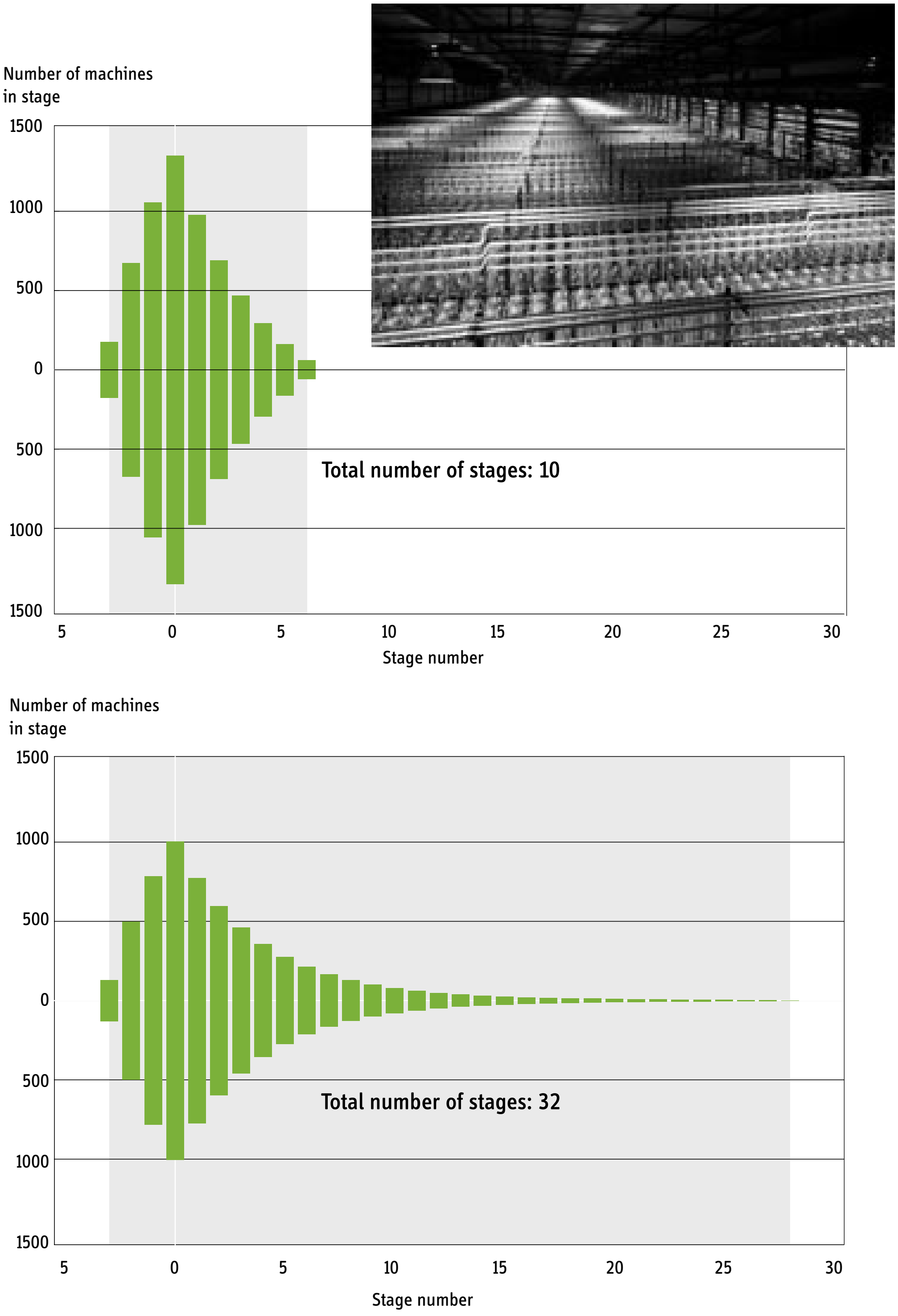

Figure 3.3 – Typical cascades for LEU and HEU production. The LEU cascade (top) produces uranium enriched to 4%, U-235 in 10 stages (seven processing enriched uranium and three depleted uranium); the HEU cascade (bottom) produces uranium enriched above 90% in 32 stages. Tails are 0.3% in both cases and the enrichment factor per stage is 1.3. The number of machines in both cascades is identical, but the HEU cascade produces much less product.

Figure 3.4 - Inset photo. Cascade hall in Urenco's plant at Gronau, Germany, seen from above (courtesy Urenco).

Plutonium production and separation

The weapon that destroyed Nagasaki contained six kilograms of plutonium. Plutonium does not occur naturally. It is produced in nuclear reactors when a U-238 nucleus absorbs a neutron creating short-lived U-239, which subsequently decays to neptunium and, ultimately, to plutonium (see Figure 3.5).

Almost all reactors dedicated to the production of plutonium for weapons have been fueled with natural uranium. To avoid the buildup of unwanted heavier plutonium-isotopes, (Pu-240, Pu-241, etc.) only about one seventh of the 0.7 percent U-235 in the fuel is fissioned.[48] In such reactors, about 0.9 grams of plutonium are produced per gram of U-235 fissioned or, equivalently, per thermal megawatt day. For example, India's CIRUS research reactor, which has a thermal power of 40 megawatts, would, at a 70% capacity factor, discharge annually about 10.2 tons of spent fuel containing about 9.2 kg of weapon grade plutonium.

Plutonium is also produced in civilian power reactors. In LWRs, the net plutonium production is only 0.2-0.3 grams of plutonium per thermal megawatt-day because about two thirds of the plutonium is fissioned in place during the long residency of the fuel in the reactor core. A 1000 MWe (3000 megawatt-thermal) LWR, operating at a 90-percent capacity factor produces about 250 kilograms of plutonium per year. Because the burn-up of the fuel is much higher than in production reactors, the fraction of heavier plutonium isotopes is more than 40 percent.

In the heavy-water-moderated CANDU power reactor, plutonium production per megawatt-day is about twice as high as in LWRs and the fraction in the heavier plutonium isotopes is smaller – about 25 percent. CANDU reactors are continuously refueled instead of once every one or two years for LWRs, thus making international monitoring of the fuel more costly.

Several countries have pursued the development of fast-neutron or "plutonium-breeder" reactors. In breeder reactors, the reactor core is surrounded by a "blanket" of natural or depleted uranium that captures the neutrons escaping the core to make more plutonium. The plutonium that builds up in the blanket is weapon-grade.

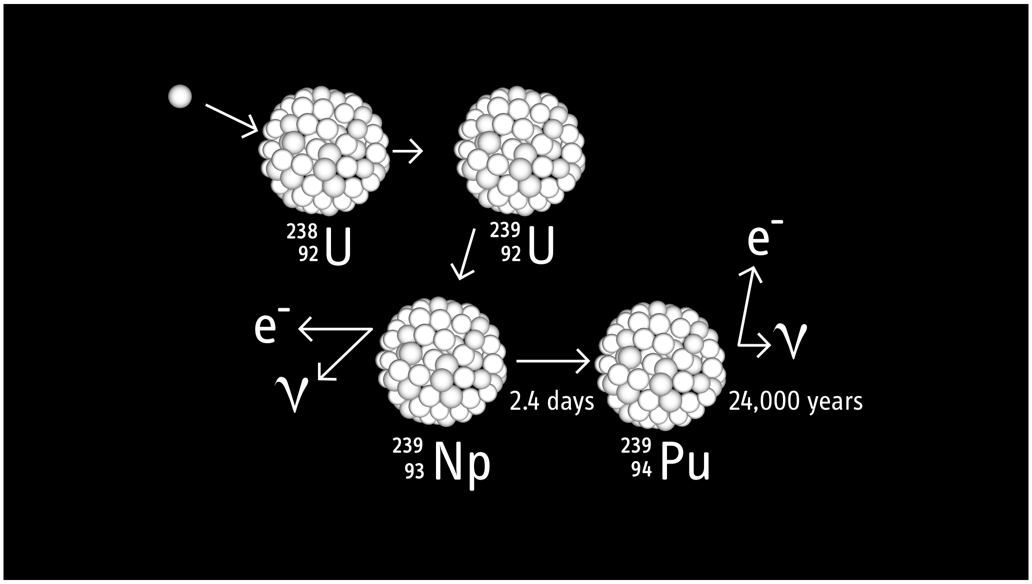

Figure 3.5 - Making plutonium in a nuclear reactor. A neutron released by the fissioning of a chain-reacting U-235 nucleus is absorbed by the nucleus of a U-238 atom. The resulting U-239 nucleus decays with a half-life of 24 minutes into neptunium, which in turn decays into Pu-239. Each decay is accompanied by the emission of an electron (e^-) and a neutrino (ν).

Thus, uranium-based spent fuel from all types of reactors will contain substantial amounts of plutonium. However, as long as the plutonium remains embedded in the spent fuel along with the highly radioactive fission products, it is relatively inaccessible. Spent fuel can only be handled remotely due to the very intense radiation field, which makes its diversion or theft a rather unrealistic scenario.[49] Therefore, separating the plutonium from the fission products and uranium makes diversion or theft a much greater concern. Separated plutonium can be handled without radiation shielding. It is dangerous primarily when inhaled or ingested.

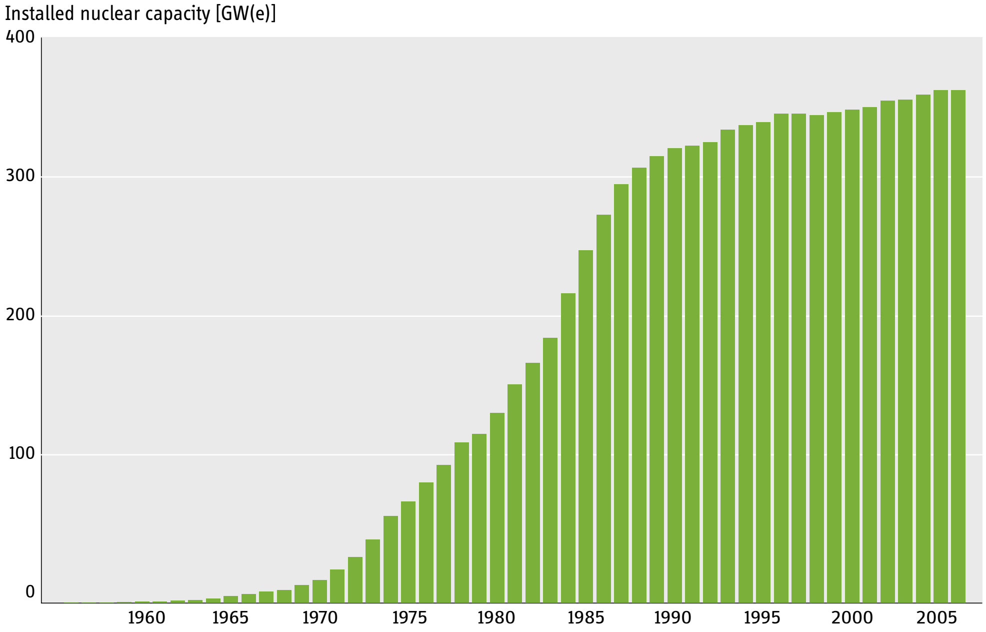

Figure 3.6 - Nuclear power capacity, historically. Global nuclear capacity grew rapidly during the 1970s and 1980s. Public opposition, high costs, unresolved waste issues, and the accidents at Three-Mile-Island and Chernobyl in 1979 and 1986 led to a sharp decline of new orders of nuclear power plants worldwide. In 2006, there were 440 power reactors with an installed capacity of about 370 GW(e). Due to the shutdown of aging reactors, this capacity will decline during the next few decades unless the rate of ordering new nuclear power plants rises above an average of about ten per year.

Separation of the plutonium is done in a "reprocessing" operation. With the current PUREX technology, the spent fuel is chopped into small pieces, and dissolved in hot nitric acid. The plutonium is extracted in an organic solvent which is mixed with the nitric acid using blenders and pulse columns, and then separated with centrifuge extractors. Because all of this has to be done behind heavy shielding and with remote handling, reprocessing requires both resources and technical experience. However, detailed descriptions of the process have been available in technical literature since the 1950s.

Military reprocessing. All of the nuclear weapon states have produced plutonium through reprocessing. As indicated in the previous chapter, the United States, United Kingdom, France, and China have stopped producing plutonium for weapons. Russia continues to produce about 1.2 tons of separated plutonium a year as an unwanted byproduct of the continued operation of three of its plutonium-production reactors. Israel, India, Pakistan, and North Korea have not indicated that they have stopped plutonium production for weapons.

Country	Name/location	Type	Status	Design capacity [tHM/yr]
France	La Hague - UP2	Civilian	In operation	1000
	La Hague - UP3	Civilian	In operation	1000
India[a] (heavy-water reactor [HWR] fuel)	Trombay	Military	In operation	50
	Tarapur	(unclear)	In operation	100
	Kalpakkam	(unclear)	In operation	100
Israel[b] (HWR fuel)	Dimona	Military	In operation	40-100
Japan	JNC Tokai Reprocessing Plant	Civilian	In operation	210
	Rokkasho Reprocessing Plant	Civilian	Under construction	800
Pakistan[a] (HWR fuel)	Nilore	Military	In operation	10-20
Russia	RT-1 Ozersk (Mayak or Chelyabinsk-65)	Civilian	In operation	400
	RT-2, Zheleznogorsk (Krasnoyarsk-26)	Civilian	Deferred	800
	Seversk (Tomsk -7)[c]	Military	In operation	6000
	Zheleznogorsk (Krasnoyarsk-26)[c]	Military	In operation	3500
U.K.	BNFL B205 Magnox Reprocessing (graphite-moderated reactor fuel)	Civilian	In operation	1500
	BNFL Thorp	Civilian	Operation currently suspended	900

Table 3.3 - Reprocessing facilities worldwide, operational and under construction. As listed by the IAEA's Nuclear Fuel Cycle Information System (NFCIS, data retrieved in February 2006), except where indicated. Actual throughput in reprocessing plants is often a small fraction of their design capacity.

Notes: a) Estimates for India and Pakistan are from: Z. Mian and A.H. Nayyar, "An Initial Analysis of Kr-85 Production and Dispersion from Reprocessing in India and Pakistan," *Science & Global Security*, Vol. 10, No. 3, 2002; b) the estimate for Israel is inferred from: Albright, Berkhout and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 259-261; c) estimates for Seversk and Zheleznogorsk derived from peak annual plutonium production given by Thomas Cochran, Robert S. Norris ad Oleg A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview, 1995, p. 280 and 291, and plutonium concentration in spent fuel given by D.F. Newman, C.J. Gesh, E.F. Love and S.L. Harms, *Summary of Near-term Options for Russian Plutonium Production Reactors*, Pacific Northwest National Laboratory, PNL-9982, July 1994, p. 9.

Plutonium produced in commercial reactors. Figure 3.6 shows the growth of nuclear power worldwide. At present, world nuclear generating capacity stands at about 370 gigawatts-electric (GWe), approximately 87 percent of which is in LWRs.[50] The total spent fuel generated annually is approximately 7000 metric tons, containing about 70 metric tons of plutonium. The cumulative total of plutonium still in spent fuel worldwide at the end of 2005 was approximately 1450 metric tons.[51] Roughly one-third of the spent fuel generated each year is reprocessed; most of the remainder is being stored at reactor sites. Reprocessing of civilian spent fuel is being done at present in the United Kingdom, France, Russia, India, and Japan (see Table 3.3). This civilian separation of plutonium stemmed originally from the interest of some industrialized countries in commercializing plutonium-breeder reactors. This interest, which peaked in the 1970s, was driven by an expectation that the world's nuclear generating capacity would grow to thousands of gigawatts by the year 2000 and approach 10,000 GWe in 2020.[52] Such a huge capacity could not have been supported by known reserves of high-grade uranium ore.

Efforts to commercialize plutonium breeder reactors have largely failed because of their poor economics and technical difficulties. A few countries in Western Europe are using their separated plutonium to make mixed-oxide (MOX, uranium-plutonium) fuel for conventional light-water reactors as a substitute for standard LEU fuel. The United Kingdom and Russia are simply storing their separated plutonium and Japan has not yet overcome local opposition to MOX fuel. As a result, the global stockpile of separated civilian plutonium has been growing steadily for decades. Figure 3.7 illustrates this trend, going back to 1996, when all countries with stocks of civilian separated plutonium except India started to publicly declare their civilian plutonium holdings to the IAEA. With Japan's new reprocessing plant going into operation in 2006, the growth of the global stockpile of separated civilian plutonium will continue for some time, even if the United Kingdom ends its reprocessing operations by 2012, as currently planned.[53]

The United States abandoned reprocessing in the late 1970s for nonproliferation and economic reasons. Recently, however, the Bush Administration embraced reprocessing as part of its proposed Global Nuclear Energy Partnership (GNEP). This proposal is discussed further in Chapter 7.

Disposition of fissile materials

From a technical perspective, the disposition of HEU is simple and straightforward. It can be down-blended to low enrichment by mixing with depleted, natural, or slightly-enriched uranium. This process cannot be reversed without re-enrichment. It is also economically attractive since the LEU product can be sold for use as commercial reactor fuel at a price several times higher than the cost of the blend down process.

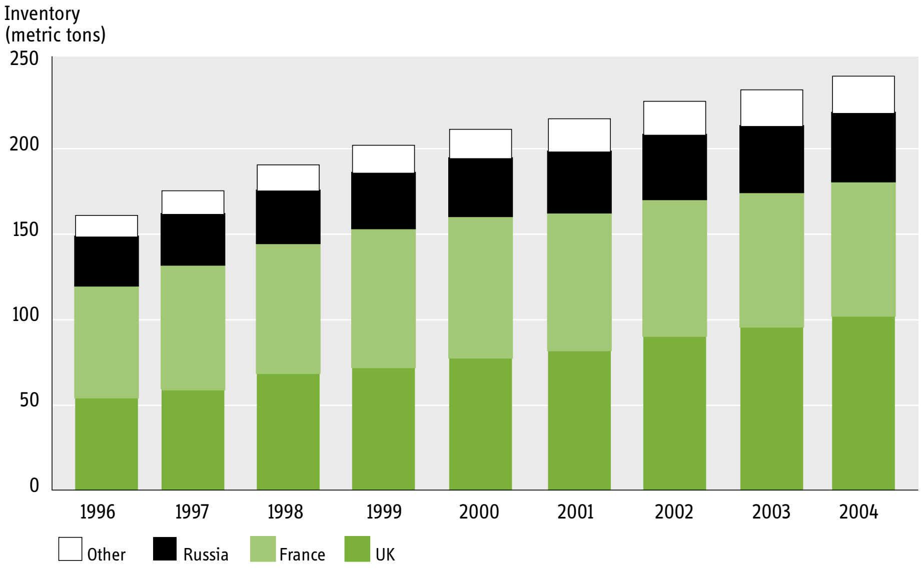

Figure 3.7 - Stockpiles of civilian separated plutonium are growing. Since 1996, the civilian plutonium stockpile has increased by more than 80 metric tons and exceeded 240 metric tons at the end of 2004. This total does not include the nearly 100 tons of weapon-grade plutonium declared excess by the United States, Russia. and the U.K. Japan, Germany and some smaller West European countries store their plutonium at the French and U.K. reprocessing plants until it can be used. This practice increases the inventories attributed here to France and the U.K. (see Table 2.A.2). The civilian stockpile of separated plutonium is likely to continue to grow rapidly because of Japan's large new reprocessing plant at Rokkasho, which became operational in 2006, although Japan has not yet been able to recycle any of the more than 40 tons of separated plutonium that it has already accumulated. Data from IAEA INFCIRC/549 declarations.

Russia agreed to sell 500 tons of its excess weapon-grade HEU, after down-blending to LEU, to the United States in a groundbreaking 1993 bilateral agreement. The rate of blend down is limited to 30 tons per year, however, so as not to disrupt the uranium and enrichment markets. The United States is similarly down-blending most of the 198 tons of HEU that it has declared excess for military purposes.

Plutonium. The debate on the management of separated plutonium inventories has been primarily focused on the weapon plutonium declared excess by the United States and Russia.[54] Most of the considerations are equally applicable, however, to the disposition of civilian stocks of separated plutonium that are accumulating in Europe, Russia – and soon – Japan.

Two approaches are currently being pursued:

1. Consolidating and storing excess inventories indefinitely in high-security facilities such as that built at Mayak for excess Russian weapon plutonium, with U.S. funds.[55] This approach is only as effective as the institution responsible for security.

2. Mixing the plutonium with fission products – either through irradiation or directly – so as to recreate the radiation barrier that was eliminated when the plutonium was separated. This concept is sometimes measured by the "spent fuel standard," which was defined in the National Academy studies as the objective of making excess plutonium "roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in spent fuel."[56] One way to do this is by mixing the plutonium with uranium to make mixed oxide fuel and then irradiating the fuel in power reactors. MOX fuel containing about four percent weapon-grade plutonium mixed with depleted uranium can be used as an alternative to LEU fuel in LWR. In a second approach, the plutonium would be mixed with already existing fission products in highly radioactive reprocessing waste – or with spent fuel, to create a radiological barrier.[57]

In the long term (after a century or so of cooling), the gamma-radiation field around spent fuel will die down to levels that are no longer considered adequate for self protection and additional barriers such as deep safeguarded underground storage would be required.

Russia and the United States agreed in 2000 to eliminate 34 tons of weapon plutonium each. Russia agreed, however, only on the conditions that its plutonium and most of the U.S. plutonium be disposed of in MOX and that other governments fund the building and operation of the necessary infrastructure in Russia. Progress has been stalled for years by disagreements between the United States and Russia with regard to immunity from liability of U.S. contractors in Russia. The G-7 governments have committed $800 million, but that is nowhere near enough to cover both construction and operation of a MOX-fuel fabrication plant. The estimated cost of constructing the U.S. MOX facility increased from less than $1 billion to $3.5 billion between 2002 and 2005.[58] In any case, Russia would prefer to use the assistance to help it build a plutonium breeder reactor to irradiate the plutonium.[59] In 2006, the U.S. Congress began to reassess this program, including considering decoupling the U.S. and Russian plutonium disposition programs and shifting the focus of the U.S. plutonium-disposition program to the less costly option of immobilizing the plutonium with fission products.[60]

Currently, neither Russia nor the United Kingdom has definite plans for how to dispose of their excess stocks of civilian plutonium. Japan plans to dispose of its stock via recycle in MOX in light water reactors but has not yet begun because of public opposition.

4 Agreements and Institutions to Control Fissile Materials

There are many overlapping bilateral, multilateral and international agreements in place to control the production and use of fissile materials and a diverse array of institutions that have emerged to monitor them. In the past, almost all of these efforts focused on preventing proliferation activities in non-nuclear weapon states. Since September 2001, however, they have focused as well on the physical protection of fissile materials against possible threats from sub-national groups.

Efforts to control access to nuclear-weapon materials predate the bombing of Hiroshima. Even as work on the first nuclear weapon was going on, General Leslie Groves, who was in charge of the effort, the "Manhattan Project," proposed that the United States try to acquire total control of the world's uranium supplies in order to stop any other state from having access to the raw material from which fissile materials can be produced.[61] But it was clear, even then, that uranium is available virtually everywhere, even if not in concentrations of interest to commercial producers.

In the aftermath of the destruction of Hiroshima and Nagasaki, the newly founded United Nations, on January 24, 1946, in its first General Assembly resolution, established an Atomic Energy Commission "to deal with the problems raised by the discovery of atomic energy." The Commission was given a mandate to make proposals for: sharing the basic science of atomic energy, instituting a system of safeguards to ensure that the uses of the new science were peaceful, and eliminating atomic weapons and all other weapons of mass destruction.[62]

On March 16, 1946, the United States published a *Report on the International Control of Atomic Energy* (the so-called Acheson-Lilienthal Report) which presented the U.S. Government's first public thoughts on the management of atomic energy. In June 1946, the United States presented to the United Nations a modified version of this proposal, known as the Baruch Plan.[63] While the plan failed to gain approval, it informed the Atomic Energy Commission's first annual report to the U.N. Security Council in December 1946. The Commission proposed a treaty to establish an international agency and "for the control of atomic energy to the extent necessary to insure its use only for peaceful purposes." It argued that:

> "Effective control of atomic energy depends upon effective control of the production and use of uranium, thorium, and their nuclear fuel derivatives. Appropriate mechanisms of control to prevent their unauthorized diversion or clandestine production and use and to reduce the dangers of seizure – including one or more of the following types of safeguards: accounting, inspection, supervision management, and licensing – must be applied through the various stages of the processes

> from the time the uranium and thorium ores are severed from the ground to the time they become nuclear fuels and are used."[64]

Largely because of the Cold War, there was little immediate progress in this direction. In the struggle for allies in this contest, the United States, in 1953, launched its "Atoms for Peace" program to share nuclear technology with other states for peaceful purposes.[65] The Soviet Union launched a similar program. The outcome was the start of nuclear research and energy programs in many more countries, some of which subsequently were used as the basis for nuclear-weapon programs.

In the absence of international safeguards, systems of bilateral safeguards were established whereby nuclear suppliers could be assured of the peaceful use of nuclear facilities and materials that they supplied. These arrangements, established most extensively by the United States, required recipient states to provide reports on the use of U.S.-supplied reactors and materials and to permit U.S. inspectors to visit facilities. The United States had negotiated 20 such agreements by the year the International Atomic Energy Agency was established in 1957.[66]

International Atomic Energy Agency (IAEA)

The United Nations established the International Atomic Energy Agency (IAEA) "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" and to do so in a way that "assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose." Specifically, the IAEA was charged:

> "To establish and administer safeguards designed to ensure that special fissionable and other materials, services, equipment,facilities, and inormation made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose; and to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement, or at the request of a State, to any of that State's activities in the field of atomic energy."[67]

According to its founding statute, the IAEA is required to both promote and regulate nuclear power. This double role is seen by some to be problematic.[68]

Nuclear Nonproliferation Treaty (NPT) and its safeguards system

The 1970 Nuclear Nonproliferation Treaty (NPT) commits signatories which had tested nuclear weapons before 1967 (United States, Russia, United Kingdom, France and China) to eliminate their nuclear weapons (but not by any specified date) and requires all other signatory states not to acquire such weapons. It also assures non-nuclear weapon states access to the peaceful use of nuclear technology under a system of inspections by the IAEA.

With regard to safeguards, non-nuclear weapon states agree to subject all their "source or special fissionable material" to IAEA safeguards.[69] The generic IAEA safeguards agreement, INFCIRC/153, requires non-nuclear weapon states who that are parties to the NPT to declare all nuclear facilities containing source or special fissionable materials, to report all activities involving significant quantities of such materials, and to allow IAEA inspections of such facilities and activities. The requirement that all of a country's peaceful activities be put under safeguards is referred to as "full-scope" or "comprehensive" safeguards.[70]

The goal of these safeguards is to be able to detect in a timely fashion, and hence deter, possible diversion or production of a significant quantity of fissile material. A significant quantity is defined as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded," taking into account possible losses due to conversion and manufacturing processes (see Table 4.1). Timeliness of detection is determined by comparison with the estimated time that it would take to extract or produce metallic fissile materials from the diverted material and convert it into a nuclear weapon component (see Table 4.2).

Table 4.1 - IAEA 'Significant Quantities' of Nuclear Materials[71]

Fissile Materials	Significant Quantity
Plutonium containing less than 80% Pu-238	8 kg
U-233	8 kg
HEU (uranium containing more than 20% U-235)	25 kg of contained U-235
Materials from which fissile material could be produced	
LEU (containing less than 20% U-235),	75 kg of contained U-235
Natural uranium	10 tons
Depleted uranium or thorium	20 tons

Table 4.2 - Estimated times for producing finished weapon-usable metal components[72]

Beginning material form	Conversion time
Pu, HEU or U-233 metal	7–10 days
Pure Pu compounds such as PuO_2	1–3 weeks
HEU, U-233 and plutonium in other forms, including in irradiated fuel	1–3 months
LEU and thorium	3–12 months

In addition to the comprehensive safeguards embodied in INFCIRC/153, the IAEA has concluded INFCIRC/66 safeguards agreements on specific facilities in India, Pakistan and Israel, which remain outside the NPT.

Since the late 1970s, in response to charges of discrimination, the five NPT nuclear weapon states have negotiated individual "voluntary offer" agreements with the IAEA whereby the Agency can monitor and inspect materials at facilities placed on a "facilities list" by the host state.[73] All of these states reserve the right to remove facilities from the list. In the United States, about 250 facilities have been offered for safeguards.[74] But, because of the IAEA's limited resources, only four containing large amounts of HEU or plutonium are actually being safeguarded and are being inspected monthly.[75]

The most recent IAEA report, for 2004, shows that the Agency had safeguards agreements in force with 144 States. These covered 923 facilities and locations, and about 164,000 tons of nuclear material, including 32 tons of HEU and 89 tons of separated plutonium. During 2004, there were 2302 safeguards inspections at 598 facilities and locations.[76]

In 2004, the IAEA's safeguards budget was $104.9 million, with an additional $16.3 million in voluntary contributions from member states for equipment, services and staff training.[77] The total IAEA budget for 2004 was $268.5 million.

After the Gulf War of 1991 revealed that Iraq, a party to the NPT, had been pursuing a covert nuclear weapon program, the IAEA's authority was extended to allow it to look for undeclared activities as well as monitor declared activities. The interpretation of the IAEA's rights under INFCIRC/153 were therefore strengthened. An Additional Protocol (INFCIRC/540) was concluded in 1997, allowing the Agency to require: more comprehensive information about nuclear-related activities, increased access to sites, and authorization to employ environmental sampling and other means to look for undeclared activities.

As of December 13, 2005, 107 countries had signed the Additional Protocol, and 71 of those had ratified it. Several non-nuclear weapon states with active nuclear programs have not yet signed, including Argentina, Brazil, Egypt and South Korea. Iran has signed but not yet ratified. All of the original five weapon states have signed the Protocol as a supplement to their voluntary offer agreements, but it has not yet come into force for the United States and Russia.[78] Even after full ratification, however, implementation of the Additional Protocol in the nuclear weapon states will be limited, with the weapon states allowed to keep facilities out of bounds to the IAEA under national security exceptions.[79]

Regional initiatives

Some groupings of states have established regional and national mechanisms that complement IAEA safeguards. Two of these are Euratom and the Argentine-Brazil Agency for Accounting and Control (ABACC). These have generally worked well but not without controversy because of disputes over their authority relative to that of the IAEA and the issue of "self-policing."[80] Also, large groups of non-weapon states have joined regionally to reinforce the Nonproliferation Treaty by declaring their regions to be nuclear-weapon-free zones.

Euratom. France and the United Kingdom are NPT nuclear weapon states and therefore exempt from compulsory IAEA safeguards, except to the extent that these safeguards follow nuclear materials from non-weapon states. Because they are members of Euratom, however, under the terms of the Euratom Treaty of 1957, all materials in France and the United Kingdom that are declared to be civilian have to be placed under Euratom safeguards. Under this treaty, the European Commission can send inspectors to any place in the EU where declared nuclear materials are located. Safeguards agreements between the EU, the IAEA and the EU member states lay out the arrangements whereby the IAEA can oversee and complement Commission controls of nuclear materials. The United Kingdom and France report civil nuclear material stocks and activities to both Euratom and the IAEA in the same detail as do non-weapon-state members. The IAEA and the Commission both perform inspections in the non-nuclear members of the EU; but only Commission inspectors do so for U.K. and French civilian nuclear materials.[81]

ABACC. In 1991, Argentina and Brazil signed a bilateral agreement to use nuclear energy for peaceful purposes only, and to prohibit and prevent the acquisition or testing of nuclear weapons. In this way they formally ended the secret nuclear weapon programs that had been underway in both states since the late 1970s. To monitor the agreement, they established the Argentine Brazil Agency for Accounting and Control of Nuclear Materials (ABACC). Subsequently, both countries joined the NPT – Argentina in 1995 and Brazil in 1998.[82] Under ABACC, Argentine and Brazilian inspectors regularly visit facilities in the other country. And, as with Euratom, the IAEA oversees and complements the ABACC safeguards arrangements.[83]

The model adopted in Europe and Latin America of regional confidence building in tandem with broader international oversight has proven to be quite effective and might be appropriate in other regions such as the Middle East and South Asia.

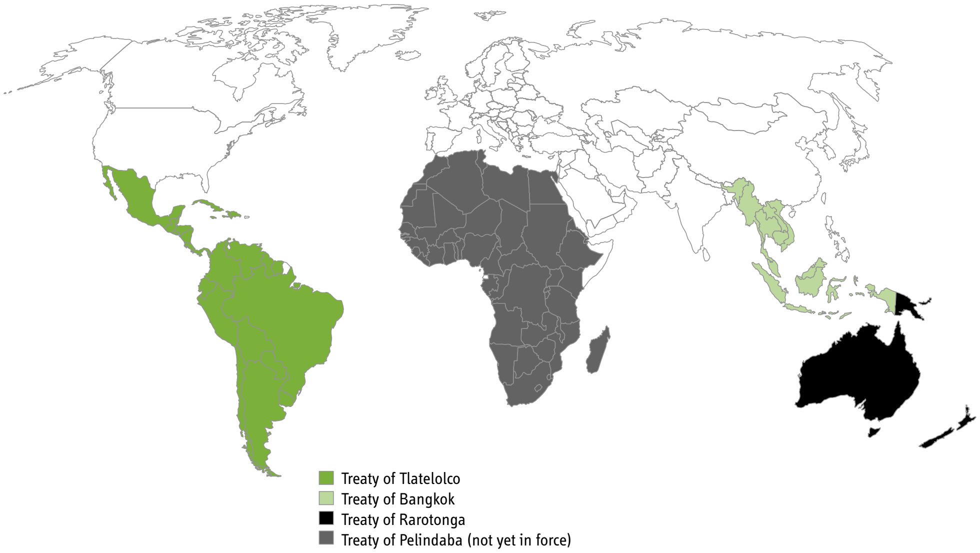

Figure 4.1 – Since 1967 many states have joined their neighbors in creating regional Nuclear Weapon Free Zones. The map shows these states up to 2005, but does not include the associated ocean areas that are also covered.

Nuclear-weapon-free zones. Nuclear weapon free zones forbid the manufacture, production, acquisition, testing and stationing of nuclear weapons in their regions. These zones now include Latin America (the Treaty of Tlatelolco, 1967), the South Pacific (the Treaty of Rarotonga, 1985), South-east Asia (the Treaty of Bangkok, 1995), and Africa (the Treaty of Pelindaba, 1996, which has not yet entered into force). In 2005, the Central Asian states agreed on the text of the Central Asian Nuclear Weapons Free Zone Treaty. A number of other zones have been proposed, including for the Middle East and South Asia. Figure 4.1 above shows the existing zones.

Conditions and constraints imposed by nuclear suppliers

Bilateral safeguards. The IAEA has taken over most of the verification responsibilities associated with bilateral safeguards.[84] However, the constraints included in the bilateral arrangements continue to condition the supply and uses of facilities, equipment, technology and materials. These conditions have extensive coverage, in large part because of the United States use of such agreements, and in particular, the 'consent rights' it attached to uranium that it has supplied or enriched or that has passed through a reactor using U.S. licensed technology. By one estimate, the United States has consent rights on over 80% of the non-Russian origin fuel currently in the civil nuclear sector worldwide.[85]

Canada and Australia have also applied bilateral safeguards patterned on those developed by the United States. These are significant because Canada and Australia are responsible for 65% of the world's uranium supply. Australia, for example, requires that its bilateral safeguards will be applied if, for any reason, IAEA safeguards cease to apply.[86]

Nuclear Suppliers Groups. Groups of states exporting nuclear material and equipment have agreed on guidelines for these exports. The first was the Nuclear Exporters Committee, known as the Zangger Committee, established in 1971.[87] The Nuclear Supplier Group (NSG) established in 1977, has now largely superseded the Zangger Committee. It includes 45 nuclear suppliers[88] and plays a major role in managing international trade in nuclear technology. The NSG agreed on a set of guidelines for nuclear transfers in 1978 that includes a list of items that suppliers agree to export to non-nuclear weapon states only when the receiving state has brought into force an agreement with the IAEA for full-scope safeguards on all its current and future nuclear activities. Suppliers have also agreed to exercise restraint on the transfer of sensitive technologies, such as reprocessing and enrichment facilities. In practice, since the NSG was founded, its members have exported enrichment or reprocessing technology to only one non-nuclear weapon state, Japan.

Physical protection of nuclear material and nuclear facilities

Convention on the Physical Protection of Nuclear Material. To counter the risk of theft of fissile materials, a Convention on the Physical Protection of Nuclear Material was signed in March 1980 to set security standards on international transport of nuclear materials and cooperation among states for the protection, recovery, and return of stolen nuclear materials.[89] In July 2005, the Convention was renamed the Convention on Physical Protection of Nuclear Material and Nuclear Facilities and amended to legally require signatories to protect nuclear facilities and nuclear materials in peaceful domestic use and storage as well as in international transport.[90] The amendments will take effect once they have been ratified by two-thirds of the signatories of the Convention.

U.N. Security Council Resolution 1540. In April 2004, the U.N. Security Council passed Resolution 1540 requiring all states to "adopt and enforce appropriate effective laws which prohibit any non-State actor to manufacture, acquire, possess, develop, transport, transfer or use nuclear, chemical or biological weapons and their means of delivery."[91] States are also required "to develop and maintain appropriate effective measures to account for and secure" nuclear, chemical, or biological weapons and materials, including putting in place physical protection measures, border controls, law enforcement efforts to prevent illicit trafficking, and export and trans-shipment controls.

The resolution required each state to submit, within six months, a report on what measures it had taken to comply. A "1540 Committee" was set to oversee implementation of the resolution.[92] The chair of the 1540 Committee reported in December 2005 that 124 States had submitted reports and that 60 or so states had not yet reported.[93] The 1540 Committee's original mandate was to expire in April 2006 but has been extended until April 2008.

II New Initiatives to Control Fissile Materials

Introduction

If there is to be progress in nuclear disarmament and nonproliferation and in countering the risk of nuclear terrorism, new initiatives will be required to stem the production of fissile materials, reduce stocks and locations, and constrain the spread of the means of their production.

The following four chapters therefore examine technical and policy issues relating to:

- Verification of an agreement to prevent the further production of fissile material for weapons,
- Sharing between countries information about the sizes of the existing stockpiles of fissile materials – starting with Russia and the United States,
- Limiting the spread of enrichment and reprocessing facilities, and
- Drastically reducing the use of highly enriched uranium as a reactor fuel.

These initiatives could represent important elements of a strengthened fissile material control regime.

5 A Fissile Material Cutoff Treaty

Advocates of nuclear reductions have sought, since the 1950s, a Fissile Material Cutoff Treaty (FMCT) that would cap the amount of fissile material available for nuclear weapons and lay a basis for irreversible reductions. With the end of the Cold War, both the Soviet Union/Russia and the United States decided to support an FMCT and, in 1993, the U.N. General Assembly passed, by consensus, a resolution calling for the negotiation of:

> "a non-discriminatory, multilateral and international and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."[94]

Under the Nuclear Nonproliferation Treaty (NPT), the non-weapon states have already committed not to produce fissile material for weapons and are subject to stringent verification by the IAEA. Therefore, the FMCT would impose new limitations only on the five countries that have joined the NPT as weapon states (the United States, Russia, United Kingdom, France and China) and the four countries that are not parties to the NPT (Israel, India, Pakistan – and North Korea, if it does not rejoin the NPT as a non-weapon state).

All five NPT nuclear weapon states made known in the early 1990s (China informally) that they had ended or suspended their production of fissile material for weapons.[95] An FMCT would turn this informal production moratorium into a binding commitment. If they became parties to the treaty, an FMCT also would cap the stockpiles of the four non-NPT countries, all of which may still be producing fissile materials for weapons.

The 1995 and 2000 NPT Review Conferences reaffirmed the importance of achieving an FMCT and, in 2000, the Review Conference specifically called upon the U.N. Conference on Disarmament in Geneva to commence negotiations immediately and conclude them within five years.

Initiation of negotiations on an FMCT in the U.N.'s Conference on Disarmament in Geneva (CD) has been blocked for a decade however, by disagreements over proposals to link the negotiations to parallel negotiations on other issues. The most recent attempt to break this impasse was made in 2003 by five CD Ambassadors who proposed that negotiations on an FMCT proceed in parallel with negotiations on a treaty to bar nuclear threats against non-nuclear weapon states and separate discussions (but not negotiations) on possible treaties on nuclear disarmament and on arrangements to prevent an arms race in outer space.[96] This compromise has wide support in the CD but not by the consensus that is required to proceed.[97]

The impasse on issues of linkage may reflect the reality that none of the NPT weapon states currently gives a high priority to pursuit of an FMCT. The Bush Administration recently showed some interest and tabled a draft FMCT at the CD on May 18, 2006.[98] Reportedly, it sees negotiation of an FMCT as helpful in reducing opposition in the Nuclear Suppliers Group and the U.S. Congress to the proposed U.S.-India nuclear deal.[99] In the absence of an FMCT, this deal would allow India to accelerate the buildup of its stockpile of fissile material for weapons.[100] India formally supports negotiations on a cutoff but sees it in the distant future and expects to produce more fissile material for weapons in the interim, as does Pakistan. Israel is unenthusiastic about a cutoff, in part at least because it produces tritium with its plutonium-production reactor at Dimona and is loath to accept intrusive verification there.

Even if the logjam at the CD could be broken and negotiations on an FMCT finally launched, there would be a number of contentious issues to deal with. These include the definition of fissile materials, the treatment of pre-existing stocks of materials, the production of fissile materials for civilian purposes, the manner of verification of the treaty, and its duration. Each of these issues is discussed in turn below.

Definition of fissile material

The definition of fissile material in the U.S. draft FMCT is close to the definition adopted by the IAEA for weapon-usable or “direct-use” material: uranium enriched to more than 20% in U-235 or U-233 and plutonium containing less than 80% Pu-238.[101]

Russia proposed an alternative definition in 2005 that would ban only the production for weapons of “weapon-grade” plutonium and uranium containing more than about 90 percent of the isotopes Pu-239 and U-235 respectively.[102] Such a narrow definition has not received support from other members of the CD. While the Russian definition specifies materials that are optimal for weapon use, lesser-quality materials could be used for weapons. The uranium in the Hiroshima bomb, for example, was enriched to about 80% U-235. Also, “reactor-grade” plutonium in the spent fuel of power reactors is now widely understood to be weapon-usable.[112] Its isotopic fraction of Pu-239 is typically about 60 percent.[103]

In addition to the materials designated by the IAEA as direct-use, two other reactor-produced fissile materials are also potentially weapon-usable and are defined by the IAEA as “alternative nuclear materials:” neptunium-237 and americium.[104] Neptunium-237, in particular, has nuclear characteristics quite similar to those of U-235.[105] Small but significant quantities of these materials have been separated for various purposes. The definition of fissile materials in the FMCT therefore should allow for the future inclusion of such materials.

Tritium, a heavy form of hydrogen with a half-life of 12 years, is widely used in nuclear weapons but it is not a fissile material. It is made in nuclear reactors and is used to “boost” the power of the fission triggers in modern nuclear weapons. Because of its relatively short half-life, most of the nuclear weapon states will eventually seek to produce tritium unless they reduce their weapon stockpiles at a rate faster than tritium decays. Therefore, any attempt to include it in an FMCT would likely encounter strong resistance from most of the weapon states. In any case, nuclear weapons can be made without tritium but no nuclear weapon has ever been made without fissile material.

The question of pre-existing stocks

The U.N. General Assembly resolution that called for an FMCT does not refer to fissile-material stocks acquired before the treaty comes into force. Most of the nuclear weapon states support this exclusion, and the draft FMCT tabled by the United

States at the CD in May 2006 explicitly leaves the use of previously-produced fissile material unconstrained:

> "No Party shall, after the entry into force of the Treaty for that Party, produce fissile material for use in nuclear weapons or other explosive devices" [Article I]
>
> "The term 'produce fissile material' does not include activities involving fissile material produced prior to entry into force of the Treaty, provided that such activities do not increase the total quantity of plutonium, uranium-233, or uranium-235 in such fissile material." [Article II.3]

Many non-weapon states have strongly argued however, that the use of pre-existing stocks of fissile materials should be constrained and the "Shannon mandate," adopted by the CD as a basis for FMCT negotiations in 1995, explicitly does "not preclude any delegation from raising for consideration … past production [or] the management of such material."[106]

In fact, a ban might be considered on the weapon use of three categories of pre-existing fissile materials not currently dedicated to weapons:

- Materials in civilian use,
- Materials from dismantled weapons that have been declared excess for future military use, and
- Highly-enriched uranium that has been reserved for future use in naval reactors.

Such bans also might be negotiated separately from an FMCT.

Should the production of civilian fissile materials also be banned?

The use of fissile materials for civilian purposes has been controversial since at least 1974, when India used the first plutonium that it had separated for nominally peaceful purposes to make a "peaceful nuclear explosion." The Ford Administration reversed the previous U.S. policy of promoting plutonium as the nuclear fuel of the future and both the United States and Soviet Union launched programs to reduce the use of HEU as a civilian reactor fuel. The question therefore naturally arises as to whether an FMCT should ban the production of fissile material for any purpose, not just explosive purposes.

The effort to eliminate HEU as a civilian reactor fuel is currently receiving broad international support because of concerns about the possibility that terrorists might use stolen HEU to make simple gun-type nuclear explosives (see Chapter 8). It is therefore conceivable that a fissile cutoff could be broadened to include production of HEU for civilian use. If such a ban were broadened further to end HEU production for naval-reactor use, however, other nations with nuclear-powered submarines and ships would be forced to follow France's example and design their future naval reactors to use LEU. Today, such a proposal would likely be opposed by at least the United States – and probably the United Kingdom and Russia as well.

Any effort to ban the separation of plutonium for recycle as a civilian fuel could attract the opposition of at least those countries currently engaged in civilian reprocessing and that expect to continue to do so: France, India, Japan and Russia. The Bush Administration has proposed to reverse the U.S. anti-reprocessing policy but opposes the separation of pure plutonium (see Chapter 7).

Verification

The critical verification issues to be resolved are:

1. Activities to be monitored,

2. Measures to look for undeclared fissile material production, and

3. Means to verify the non-weapon use of pre-existing stocks of fissile materials, to the extent that limitations on such stocks are included in the FMCT.

Scope of Verification. The 1993 U.N. General Assembly consensus resolution called for an "effectively verifiable" FMCT. In July 2004, however, the Bush Administration announced that, while the United States still supported an FMCT, it would oppose international verification arrangements. In a "white paper" submitted along with the draft FMCT treaty to the Conference on Disarmament on May 18, 2006, the Bush Administration argued that:

> "'Effective verification' of an FMCT cannot be achieved … even with … verification mechanisms and provisions … so extensive that they could compromise the core national security interests of key signatories, and so costly that many countries will be hesitant to accept them … mechanisms and provisions that provide the *appearance* of effective verification without supplying its *reality* … could provide a false sense of security" [emphasis in original]."[107]

The U.S. draft FMCT therefore would limit verification to "national means and methods" and accordingly, the United States submitted a proposal to the CD to revise the 1993 U.N. mandate for FMCT negotiations by removing the phrase "effectively verifiable." This reversed the previous (Clinton Administration) position, which had emphasized the importance of international verification.[108]

If there is international verification at all, then there are differing views on the scope of verification appropriate for an FMCT. The non-weapon states tend to argue for a universal, "comprehensive" approach while most of the weapon states favor a partial, "focused" approach."[109] In either case, it would be necessary for the IAEA to confirm the status of shutdown enrichment and reprocessing facilities.

In a comprehensive approach, the entire civilian fuel cycles of the nuclear weapon states would be put under the same type of safeguards required by the NPT in the non-weapon states. Thus, IAEA safeguards in the nuclear-weapon and non-weapon states would be identical, except inside the nuclear weapon complexes, where previously produced fissile materials could be stored and recycled into new nuclear weapons. IAEA monitoring could also be excluded from the naval-fuel-cycle to the extent that previously produced fissile material was being used for fuel.

In a focused approach, safeguards would be applied only on enrichment and reprocessing facilities, and on any new fissile material produced in these facilities. This approach would monitor all the inputs and outputs of declared reprocessing facilities and down-stream mixed-oxide (MOX, i.e. plutonium-uranium) fuel-fabrication plants, and follow the MOX fuel until it is loaded into a reactor. It would also verify that uranium-enrichment plants are not producing HEU or, if they are, that its use is monitored. However, safeguards would not be applied to natural-uranium or low-enriched uranium fuel, or to any type of spent fuel. Low-enriched uranium is monitored in non-weapon states to safeguard against the possibility of its diversion to a clandestine enrichment facility for further enrichment. Spent fuel is monitored to safeguard against the possibility of a clandestine reprocessing plant.

The principal argument for a focused approach to verification is that it would be less costly. Also, it would allow countries to exclude IAEA monitoring from any facility where newly produced fissile material was not present. The principal argument for a comprehensive approach is that it would remove discrimination in the current nonproliferation regime with regard to safeguards on civilian nuclear activities.

Any comparison of the two approaches to verification should take into account the fact that many nuclear facilities in the NPT nuclear weapon states are already under international safeguards or have been offered to be placed under safeguards:

- Following their decisions to end their production fissile materials for weapons, France and the United Kingdom declared all their operating enrichment and reprocessing facilities to be civilian. In conformity with the requirements of the Euratom Treaty, these facilities became subject to Euratom safeguards.

- As a result of the 1983 Hexapartite Agreement on Safeguards on gas-centrifuge enrichment plants, the centrifuge enrichment plants in the United Kingdom are under IAEA safeguards and the centrifuge enrichment plants being built in France and the United States will be as well.[110] The U.S. and French gaseous-diffusion enrichment plants will be shut down as the operating capacities of the replacement gas-centrifuge plants increase.

- China's two centrifuge-enrichment plants, which were provided by Russia, have been offered for IAEA safeguards, and safeguards have been implemented in one.[111]

- In the non-NPT states, the IAEA safeguards six power reactors (including two under construction) and a reprocessing plant in India; two power and two research reactors in Pakistan; and a research reactor in Israel.[112] Under the proposed U.S.-India nuclear deal, India has offered to place eight more reactors under safeguards.[113]

All NPT nuclear weapon states also have volunteered to allow the IAEA to apply safeguards on additional civilian nuclear facilities. The United States has offered to accept "safeguards … on all source or special fissionable materials in all facilities within the United States, excluding only those facilities associated with activities of direct national security significance to the United States." The United Kingdom and France have made similar commitments, while Russia and China have offered safeguards on a very limited list of facilities.[114] Given the limited budget it has been given by member countries, however, the IAEA inspects only a few of these volunteered facilities, giving priority instead to verifying nonproliferation in the non-weapon states.

Cost of FMCT verification. In 1995, the IAEA estimated that applying the same measures that it applies in non-weapon states to all the civilian nuclear facilities and materials in nuclear weapon states (i.e., the comprehensive approach to verification) would cost $140 million a year.[115] In comparison, in 1995 the total IAEA safeguards budget was $87 million.[116]

The results of the 1995 IAEA study may not be a good basis, however, for estimates of the costs of expanding safeguards to the nuclear weapon states today. The IAEA published neither the methodology that it used nor the list of facilities that it assumed would be covered. We have examined, however, a similar study published in 1996 by Brookhaven National Laboratory, a U.S. laboratory that provides technical support to the IAEA safeguards.[117]

A widely used measure of verification effort is "person days of inspection effort (PDI)." The Brookhaven study estimated that implementing comprehensive safeguards in the nuclear weapon states would require annually, 35,000 PDIs. The corresponding estimate in the IAEA study was about 25,000. The Brookhaven study also estimated that almost 60 percent of the IAEA's verification effort in the nuclear weapon states would be expended on 23 operating reprocessing plants.

Most of the military reprocessing plants in the NPT nuclear weapon states have been shut down, however. Today, by our count (see Table 3.3 in Chapter 3), there are 13 operating reprocessing plants in the nuclear weapon states, of which four are scheduled to be shutdown, and at least three more would likely be shut down under an FMCT.[118] As a result, even if China and the United States go forward with proposed reprocessing plants, the number of operating reprocessing plants to be monitored in the nuclear weapon states would be about one third of the number assumed in the Brookhaven report.

Also, as we pointed out above, a significant number of reprocessing, enrichment, and associated facilities in the nuclear weapon states already are subject to international safeguards. This would further reduce the *additional* monitoring requirements of an FMCT.

With regard to the comparison of the costs of the comprehensive and focused verification approaches, the critical point to keep in mind is that reprocessing, enrichment and MOX fuel-fabrication plants would be monitored in any case, and require far more intensive efforts to safeguard than do reactors fueled by low-enriched uranium. Indeed, it takes about the same number of person-days of inspector effort to monitor operations at one large reprocessing plant as it does to safeguard 100 LEU-fueled reactors. Therefore, not only would the cost of verifying an FMCT be less than sometimes imagined, but so also would be the cost difference between comprehensive and focused safeguards.

Verification that no clandestine enrichment or reprocessing is taking place. After the establishment of either comprehensive or focused monitoring at declared civilian nuclear facilities, the next challenge to both NPT and FMCT verification is to assure that there are no clandestine enrichment or reprocessing activities.

Once a suspect site has been identified, a general approach has been developed that would be applicable in nuclear-weapon as well as non-weapon states. This general approach involves what is called "managed access" in the Chemical Weapons Convention, i.e. arrangements for the inspectors to resolve the treaty-related concerns of the inspecting agency without acquiring unrelated national-security or proprietary information of the host state.

The IAEA's Information Circular (INFCIRC) 153, which controls NPT verification in non-weapon states, allows the IAEA to make "special inspections" at suspect sites not declared to have nuclear activities or materials.[119] The Additional Protocol to INFCIRC/153, which is voluntary, but which countries are under considerable international pressure to ratify, allows the IAEA to request access to "[a]ny location specified by the Agency … to carry out *location-specific environmental sampling* … for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities at the specified location" [emphasis in the original].[120]

Questions raised by detection of particles of enriched uranium at various Iranian sites resulted in Iran revealing to the IAEA more information about its enrichment activities than it had originally provided (see Figure 5.1).[121] In a nuclear-weapon facility, particles of enriched uranium might be associated with weapon-manufacturing activities, but if they contained degradation products of enriched uranium

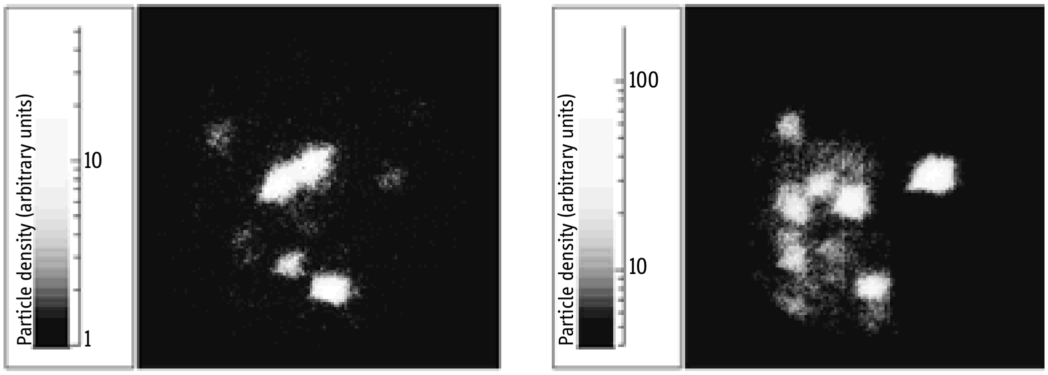

Figure 5.1 - Images of micron-sized particles of uranium oxide made with a Secondary Ion Mass Spectrometer. A beam of ions scans the particle, knocking out ions whose masses are then measured in a mass spectrometer. The images on the left and right show respectively the U-235 and U-238 concentrations on the particle surface. Particles that are brighter on the left-side image carry highly enriched uranium.[122]

hexafluoride, one possible explanation could be the presence of a centrifuge cascade. Other indicators, such as electromagnetic radiation associated with the high-frequency electrical motors that spin the centrifuges, then could be sought.

A clandestine reprocessing facility could similarly be identified by the detection of radionuclides from reprocessed spent fuel or targets. Such contamination can be dated using the mix of different half-life radionuclides present. It was such an analysis of swipe samples from North Korea's reprocessing plant by the IAEA that undercut North Korea's claim that it had reprocessed only one batch of spent fuel there.[123]

A reprocessing plant can also be detected from a considerable distance through its releases of the radioactive gas, krypton-85. Kr-85 is difficult to contain because it is chemically non-reactive like helium. It is generally released during reprocessing when the spent fuel is chopped up and dissolved. Therefore, locally increased concentrations are an indicator of possible reprocessing activities (see Figure 5.2.).

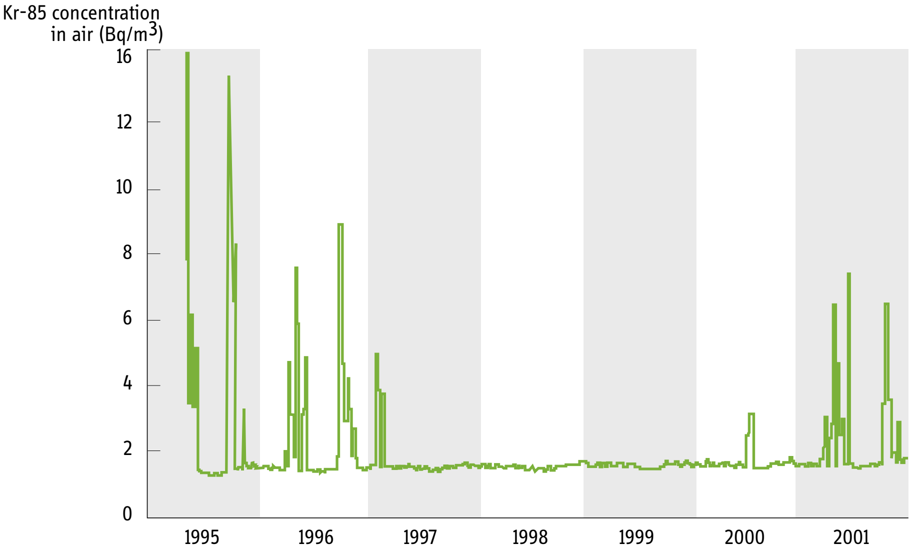

Figure 5.2 - One-week average atmospheric Kr-85 concentrations measured at Tsukuba Japan, 1995-2001. Unless extraordinary precautions are taken, the reprocessing of spent fuel will release the radioactive gas, krypton-85, to the atmosphere. The spikes in the figure show the detection of krypton-85 released from Japan's Tokai pilot reprocessing plant 80 kilometers upwind. No spikes are seen between April 1997 and July 2000 or from August to December 2000, periods during which the Tokai Mura plant was closed down. Original data courtesy of C. Schlosser and H. Sartorius, German Federal Office for Radiation Protection (BfS) Freiburg, private communication, May 2006.[124]

Both INFCIRC/153 and the Additional Protocol allow a state to refuse access to a site if it is concerned about revealing sensitive proprietary or national-security information. INFCIRC/153 requires, however, that if "unusual circumstances require extended limitations on access by the Agency, the State and the Agency shall promptly make arrangements with a view to enabling the Agency to discharge its safeguards responsibilities in the light of these limitations."[125] The Additional Protocol similarly requires that the host country "shall make every reasonable effort to satisfy Agency requirements without delay, at adjacent locations or through other means."[126]

All the NPT nuclear weapon states have signed the Additional Protocol, and for three, (China, France and the United Kingdom) the Additional Protocol is in force.[127] However, the information and access that are to be provided to the IAEA are much more limited than required under the Additional Protocols for non-weapon states. Under an FMCT, the Additional Protocols in the nuclear weapon states would have to be amended to allow inspectors to look for clandestine enrichment or reprocessing plants, as they already may in non-weapon states.

Before it ratified the Chemical Weapons Convention (CWC) in 1997, the United States assured itself that managed access sufficient to satisfy the Convention-related concerns of the inspectors of the Organization for the Prohibition of Chemical Weapons could be arranged at all its major nuclear facilities without revealing sensitive information.[128] During the Clinton Administration, the State Department official responsible for coordinating the U.S. negotiating position on the FMCT, suggested that similar arrangements should make it possible to determine, without revealing sensitive information, whether or not a nuclear facility harbors enrichment or reprocessing activities.[129]

Verification of pre-existing stocks. As noted above, some possible versions of an FMCT might subject certain pre-existing stocks of fissile materials to international monitoring: civilian fissile materials, weapon materials declared excess to military purposes, and/or HEU reserved for naval reactor fuel. Declarations of these stocks are discussed separately in Chapter 6. In the following, we present a brief summary of how such declarations could be verified.

As discussed in Chapter 2, the global stockpile of civilian fissile material is currently dominated by separated reactor-grade plutonium. It seems unlikely that any of the countries owning this material would wish to convert it to weapon use. Nine countries that own almost all of this material (Belgium, Canada, France, Germany, Japan, Russia, Switzerland, and the United Kingdom) have declared it to be civilian in the IAEA information circular INFCIRC/549. Most of the plutonium is stored in the United Kingdom and France and is subject to Euratom safeguards, and a significant amount belongs to non-weapon states and is therefore already subject to IAEA safeguards. Under any approach to verification, the reprocessing plants, MOX-fuel-fabrication facilities and associated transportation links and storage facilities would be subject to IAEA safeguards for plutonium separated after the FMCT comes into force. It therefore would be straightforward – and indeed a simplification – to extend the safeguards to cover pre-existing separated civilian plutonium as well.

Among the non-NPT states, India has a stockpile of reactor-grade plutonium that is being separated to provide startup fuel for its prototype breeder reactor. Whether India would wish to declare it irreversibly civilian under an FMCT, however, is uncertain. In connection with the proposed U.S.-India nuclear deal, India plans to exempt this plutonium from IAEA safeguards.

The NPT nuclear weapon states also have some tens of tons of HEU in the cores and fuel cycles of their research reactors and of Russia's nuclear-powered icebreakers. There is currently a global effort to replace much of this HEU with LEU because of concerns about the potential for nuclear terrorism (see Chapter 8). Under the comprehensive approach to FMCT safeguards, the research-reactor fuel could be declared to be civilian and subjected to IAEA monitoring in the same way as HEU in the corresponding facilities in Japan and other non-weapon states. Such arrangements also could be extended to plutonium in civilian nuclear-reactor R&D facilities.

The United States and Russia have already agreed in principle to work out verification arrangements for the plutonium and HEU that they have declared irreversibly excess to weapons. As discussed in Chapter 6, the blend down of most excess Russian and U.S. weapon uranium is already being verified.

But some of the fissile materials that Russia and the United States have declared excess could remain in weapons components for decades. In addition, since Russia considers the exact isotopic make up of its weapon-grade plutonium classified, that material will not be accessible to international inspectors until after it is blended with reactor-grade plutonium to produce an unclassified mix.

Figure 5.3 - The U.S. Nuclear Materials Identification System can measure the quantity and enrichment of HEU in a container or warhead. A weak source of neutrons on the right (one microgram or less of californium-252) irradiates the interior of an object – in this case a nuclear bomb – causing fissions in the HEU. The transmission of the source neutrons and the timing and intensity of gamma-rays and neutrons from the fissions are measured by detectors on the other side of the object. For FMCT verification, the data would be filtered through an information barrier so that the inspectors verify only agreed attributes.[130]

In 1996, Russia, the United States and the IAEA launched a "Trilateral Initiative" to develop equipment that would allow IAEA inspectors to verify some unclassified attributes of stored weapons components and materials by measuring the gamma and neutron radiation coming out of their containers. The working group devised one such approach for plutonium still in a weapon "pit" and demonstrated it with an actual U.S. pit in August 2000.[131] The attributes verified included that the container held at least two kilograms of weapon-grade plutonium metal in an axially symmetric form. A computer analyzed the data and passed the results through an "information barrier" that filtered out information such as the size and shape of the pit and the exact amount of plutonium that it contained. Systems that have been developed to determine that a warhead or a container contains HEU could similarly be adapted for IAEA use (see Figure 5.3 above).

Although the United States and Russia lost interest in the Trilateral Initiative after 2002, if the parties agreed to an FMCT, the techniques developed in the Trilateral Initiative could be implemented to verify excess stocks.

In most nuclear weapon states, the challenge of verifying that HEU newly produced for naval-reactor fuel has not been diverted might not arise for many decades. The issue might arise first with India, which is reportedly developing a HEU-fueled naval reactor.[132] France is phasing out HEU use in its naval reactors and China is believed to use fuel enriched to about 20 percent – the boundary between LEU and HEU.[133] Russia, the United Kingdom and the United States, which use HEU fuel in their naval reactors, all have access to large stockpiles of excess weapons HEU.

Indeed, as already noted in Chapter 2, the United States has set aside 160 tons of excess weapon-grade uranium for future use in naval-reactor fuel. Using the standard estimate of 25 kilograms of weapon-grade uranium per warhead, the 160-ton U.S. naval stockpile would be enough to make 6400 warheads. In a future world with much smaller numbers of nuclear weapons, the possibility that such a huge stockpile could be converted back to weapon use would surely raise concern and possibly prevent deeper cuts in the nuclear arsenals.

To eliminate the rationale for these HEU stockpiles, the United States and other states with naval-propulsion reactors could follow the example of France and design their next-generation naval reactors to be fueled with LEU.[134] In the meantime, verification arrangements could be devised to assure that HEU stockpiles committed to naval use are not diverted to weapon use.[135]

For example, all the stocks of HEU reserved for naval-reactor fuel could be declared and placed in containers subject to IAEA monitoring. Inspectors could then verify any withdrawal and verify nonintrusively that the fabricated fuel contained the amount of HEU withdrawn from the monitored. It might also be possible to devise arrangements whereby they could verify that the fuel had been loaded into the reactor. The reactor could be sealed just as the IAEA seals light-water power reactors in non-weapon states between each re-fueling. After the fuel is irradiated, diversion would have to include reprocessing to separate the HEU from the fission products.

When spent naval-reactor fuel is discharged from the reactor, it could be assayed again and placed in monitored storage.[136]

Duration of an FMCT

The U.S. draft FMCT treaty includes a provision that the treaty "shall remain in force for a period of 15 years from the date of its entry into force" and that the treaty could be extended by consensus. This means, however, that any party could veto its extension.

This provision appears provocative and unwise. The United States and other nuclear weapon states expended considerable effort in 1995 to persuade the non-weapon states to make the NPT permanent. They would court derision from the non-weapon states if, in their turn, they were willing only to sign onto a 15-year FMCT. In any case, the U.S. draft FMCT contains the standard withdrawal clause that "each party shall, in exercising its national sovereignty, have the right to withdraw from the Treaty if it decides that extraordinary events, related to the subject matter of this Treaty, have jeopardized its supreme interests."

A step-by-step approach?

At the moment, there is little prospect that negotiations on an FMCT will begin soon or, if negotiations began, that they would not be long and tortuous. Given this situation, an *ad hoc* step-by-step approach toward realizing the objective of an FMCT could be considered:

1. Additional nuclear weapon states could join in the production moratoria that have been formally announced by four of the five NPT weapon states and informally by China.

2. After an enrichment or reprocessing plant is shut down, the nuclear weapon states could allow the IAEA to verify that fact. The United States and Russia are already verifying the shutdown of each other's plutonium production reactors.

3. When they are not producing HEU at their enrichment plants, the nuclear weapon states could allow the IAEA to verify that fact. The United Kingdom and China have opened their centrifuge enrichment plants to such monitoring and France and the United States intend to do so once their new plants are completed.

4. More nuclear weapon states could offer their operating reprocessing plants and the plutonium that they separate for international monitoring. France and the United Kingdom already accept Euratom and IAEA safeguards at their reprocessing plants and on the plutonium that they separate.

5. U.S., Russian, and U.K. weapons materials declared excess for military use could be put under IAEA safeguards, using procedures such as those worked out under the Trilateral Initiative.

6. Experts from a group of nuclear weapon states could form a study group to devise managed-access arrangements that would allow IAEA inspectors to determine whether or not there are undeclared enrichment or reprocessing activities at their nuclear-weapon or naval-reactor fuel cycle sites. A relevant precedent is a joint study by U.S. and Russian nuclear-weapon experts that devised procedures by which the two countries could verify the dismantlement of each other's nuclear weapons without acquiring weapon-design information.

7. A similar group of experts could work out arrangements with the IAEA to verify that HEU committed for naval-reactor use is not being diverted to weapon use.

8. An additional source of funding could be devised for the IAEA to ensure that it could take full advantage of such opportunities.

6 Declarations of Fissile Material Stocks

The NPT requires non-weapon states to declare to the IAEA, and update regularly, information on the locations and quantities of all fissile materials on their territories, but not to make this information available to other governments or the public. It requires no disclosures whatsoever by the nuclear weapon states party to the Treaty.

Despite this, the NPT nuclear weapon states have made public, some information on their production and holdings of fissile material. Further declarations could be an essential prerequisite to deeper irreversible cuts in nuclear weapons. In its March 2006 public *Report on HEU*, the United Kingdom stated that:

> "The U.K. 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 stock-piles of fissile material are consistent with past acquisition and use. This report is a contribution to building such confidence."[137]

All countries should prepare such declarations for themselves, as soon as possible, because reconstruction of the history of their fissile-material production may be based on ephemeral and inadequate records whose interpretation will require the assistance of workers who will inevitably become less available with time. The U.K. *Report on HEU* offers a cautionary tale about the problems that its authors encountered with production records:

> "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."

The content of initial declarations

If nuclear disarmament is to be carried to completion, the nuclear weapon states eventually will have to declare to the IAEA or some similar international institution their entire stocks of fissile material by amount, form and location. As a first step, declarations could be made of total HEU and plutonium holdings and also total quantities in nuclear weapons and associated stocks, weapons materials declared excess, naval fuel cycles, and civilian use. Some nuclear weapon states have already made significant declarations along these lines.

Declarations and transparency to date

In 1993, the United States Department of Energy (DOE) made public the total quantity of HEU that it had produced. The declaration did not give a breakdown by enrichment or how much HEU had been used in nuclear-reactor fuel and in nuclear tests. The DOE also made public the quantities of HEU at all Department of Energy sites other than the Pantex warhead assembly/disassembly facility in Amarillo, Texas.

The justifications given for making the information public were so that:

> "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 will be of some aid to regulators who will oversee environmental, health and safety conditions at the national laboratories [and] have valuable non-proliferation benefits by making potential International Atomic Energy Agency safeguards easier to implement."[138]

In 1996, the United States updated these data (see Figure 6.1).

A much fuller history of U.S. HEU production and disposition was completed in January 2001 but only released by the Bush Administration five years later as a result of a series of Freedom of Information Act appeals by the Federation of American Scientists.[139] This provided an accounting of total production, with annual production data for each enrichment facility organized into four enrichment ranges (20-70%, 70-90%, 90-96% and over 96%), along with annual transfers of civilian HEU from and to other states. The amount of HEU consumed in plutonium and tritium production reactors, down blended for research reactor fuel and disposal, and transmuted into uranium-236 is reported. The use of HEU in nuclear tests and in naval reactors is reported in one total rather than separately "for national security reasons."

The report declared that, as of September 30, 1996, the United States had an inventory of 740.7 tons of HEU (containing 620.3 tons of uranium-235) and an overall inventory shortfall of 3.2 tons of HEU.[140]

The U.S. Department of Energy had already published, in 1996, the size of its total plutonium stockpile as of the end of September 1994 (99.5 tons). It also reported that approximately two-thirds of this material (66 tons) was in weapons or in weapon components at the Pantex warhead assembly/disassembly plant and gave thequantities of plutonium at the other DOE sites.[141]

In 1998, the United Kingdom similarly declared its full HEU and plutonium stockpiles, both civilian and military.[142] And, as already noted, in 2006, the United Kingdom gave a somewhat more detailed accounting of its HEU stocks, as of March 2002.[143]

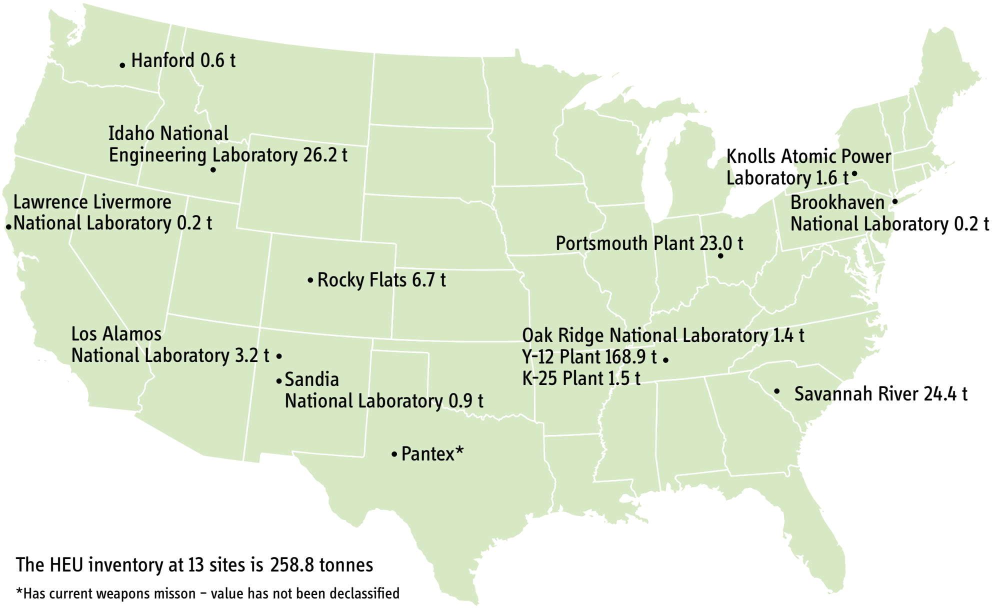

Figure 6.1 - U.S. stocks of highly enriched uranium at Department of Energy sites as of 31 December 1993, not including at the Pantex warhead assembly-disassembly facility.[144]

These precedents show that it is possible to make substantial declarations without the sky falling. To date, however, none of the other nuclear weapon states have made comparable declarations.

Materials declared excess for military use

HEU. In 1993, in an agreement with the United States, Russia declared 500 metric tons of HEU excess to its military requirements and committed to convert this HEU to low-enriched uranium (LEU) to be sold to the United States for civilian reactor fuel.

In 1994, the United States declared 174.3 metric tons of HEU excess to its military requirements, and undertook to blend down most of this HEU to LEU.[145] In 1996, the United States released information on the locations of this HEU.[146] The 2001 report revised the HEU content in the excess material to be 177.8 metric tons as of September 1996.[147] An additional 200 metric tons were declared excess for weapon use in 2006, but only 20 of the 200 tons are to be blended down to LEU. The remainder is reserved for naval and other HEU-fueled reactors.[148]

At the end of 2005, about half of the 500 metric tons of Russian HEU had been blended down, as well as about one-third of the 178 tons of U.S. HEU. The quantities of HEU blended down are regularly reported publicly.[149]

Russia's HEU blend-down process is being monitored by the United States under a bilateral agreement. The United States checks periodically that the HEU is coming from weapon-grade uranium metal and U.S. instruments continuously monitor enrichments and flows at the piping T-junctions where the HEU in the form of UF_6 gas is blended with slightly (1.5-percent) enriched uranium to produce LEU.[150]

The IAEA has monitored the blend-down of 60 tons of the U.S. excess HEU.[151] An additional 15-17.4 tons will be blended-down under IAEA monitoring. Thirty-nine tons of HEU is being blended down by Nuclear Fuel Services for use in Tennessee Valley Authority power reactors, but not, to our knowledge, under IAEA monitoring.[152]

Plutonium. In 1996, President Clinton identified as excess 38.2 tons of weapon-grade plutonium, including 21.3 tons in weapon components at the Pantex warhead assembly/disassembly plant and in weapons in the dismantlement queue.[153] In 1998, Presidents Clinton and Yeltsin agreed that Russia and the United States would each remove up to 50 tons of plutonium from their nuclear-weapons programs.[154] In 2000, the United States and Russia each agreed to dispose in parallel and irreversibly 34 metric tons of excess weapon plutonium.[155] This agreement called for both bilateral monitoring and IAEA verification of the disposition. In its annual INFCIRC/549 declarations to the IAEA of its civilian plutonium stocks, the United States has identified an additional 11 metric tons of separated plutonium as excess to its weapons requirements.[156] The United Kingdom has similarly declared 4.4 metric tons of plutonium as excess.

Thus far, none of the plutonium declared excess by the United States, Russia, and the United Kingdom has been disposed of or subjected to verification. And no other nuclear weapon state has declared weapon plutonium or HEU excess.

HEU in stocks committed to naval reactors. In 2005, the United States declared excess to weapon purposes, an additional 200 metric tons of HEU, of which 160 metric tons will be reserved for naval reactors.[157] No other country with naval-propulsion reactors (Russia, the United Kingdom, France, China – or India, which has a land-based prototype) has declared a specific HEU reserve for naval-propulsion reactors.[158]

Civil Stocks. Fissile materials in non-weapon states are subject to IAEA safeguards. The Euratom agreement requires its members, including the nuclear weapon states, France and the United Kingdom, to place all of their civil facilities and stocks of HEU and plutonium under Euratom safeguards. This means that their civil stocks have been declared to both Euratom and the IAEA.

In addition, in 1997, nine countries with civilian plutonium activities (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom and the United States) began to declare publicly their stocks of civilian plutonium annually to the IAEA “with a view to increasing the transparency and public understanding of the management of plutonium.” These declarations are publicly available at the IAEA web site as addenda to the March 16, 1998 communication from these countries to the IAEA concerning their policies regarding the management of plutonium (INFCIRC/549). Three of these countries, which belong to the European Union (France, Germany and the United Kingdom) have, in addition to reporting to Euratom, voluntarily begun to make similar declarations of their stocks of civilian HEU. All the INFCIRC/549 declarations give subtotals of the fissile stocks at reprocessing plants, fuel-fabrication plants, reactors, and elsewhere, divided into non-irradiated forms and irradiated fuel.

Future Declarations and Transparency

Declarations of fissile material stocks are valuable as confidence-building measures even without verification. However, increasing amounts of background information and verification will be essential if the declarations are to serve as a basis for deep cuts in nuclear arsenals.

The United States and Russia, in particular, could begin to provide more transparency regarding their past production and allow some level of international monitoring of the fissile materials that they have declared excess to weapon needs and the HEU stocks they intend to reserve for future use in naval-reactor fuel.

Perhaps the most feasible approach in the near term would be for the nuclear weapon states, starting with Russia and the United States, to declare regularly their total stocks of plutonium and uranium-235 in HEU and also the total quantities of each in the following subcategories:[159]

1. In warheads, warhead components and associated working stocks in their warhead-production complexes;

2. Materials that have been declared excess for weapon purposes but are still in weapons or weapon components;

3. HEU reserves for naval-reactor use that are in unclassified form;

4. HEU in spent military reactor fuel; and

5. Civilian material, divided into material that is unirradiated and in spent fuel.

These declarations would not go much beyond information that the United States and the United Kingdom have already made public.

Declarations of this generality alone could not be directly verified. However, if the nuclear weapon states also released information on the production history of their fissile accumulations, some rough consistency checks would be possible with other available information. The U.S. declaration of its plutonium production already includes, for example, a table of production by year and site (see Figure 6.2). Similarly, its declaration of its HEU production provides annual data by facility in four different enrichment ranges (see Figure 6.3).

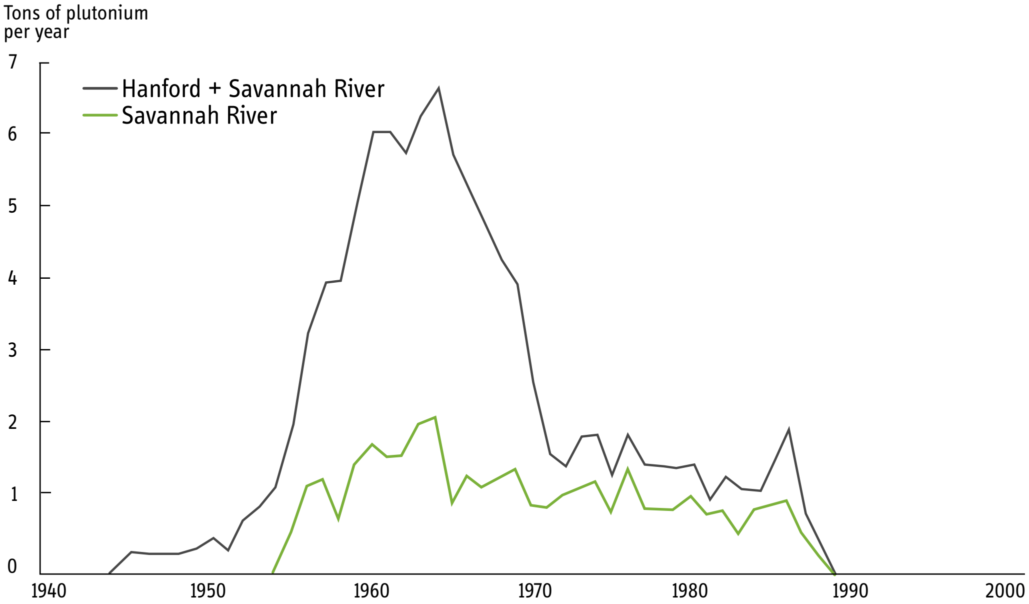

Figure 6.2 - History of U.S. plutonium production by site. The Hanford reservation on the Columbia River in Washington State is the site where the U.S. built its first plutonium-production reactors during World War II and produced the plutonium for the Trinity bomb test on July 16, 1945 and for the Nagasaki 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. They were used for tritium as well as plutonium production. The United States did not produce tritium after it shut down its last production reactors in 1988. It is currently preparing to resume production in lithium-6 targets inserted into civilian power reactors. The data for 1945-7 is a 3-year average. In addition, the United States acquired 5.7 tons of foreign plutonium (almost all from the United Kingdom), 1.7 tons from U.S. civilian reactors, and 0.6 tons from other government reactors for a total of 111.4 tons. However, these figures are approximate: U.S. production records show 2.8 tons more plutonium production than are currently in the inventory, corrected for recorded uses and losses.[160]

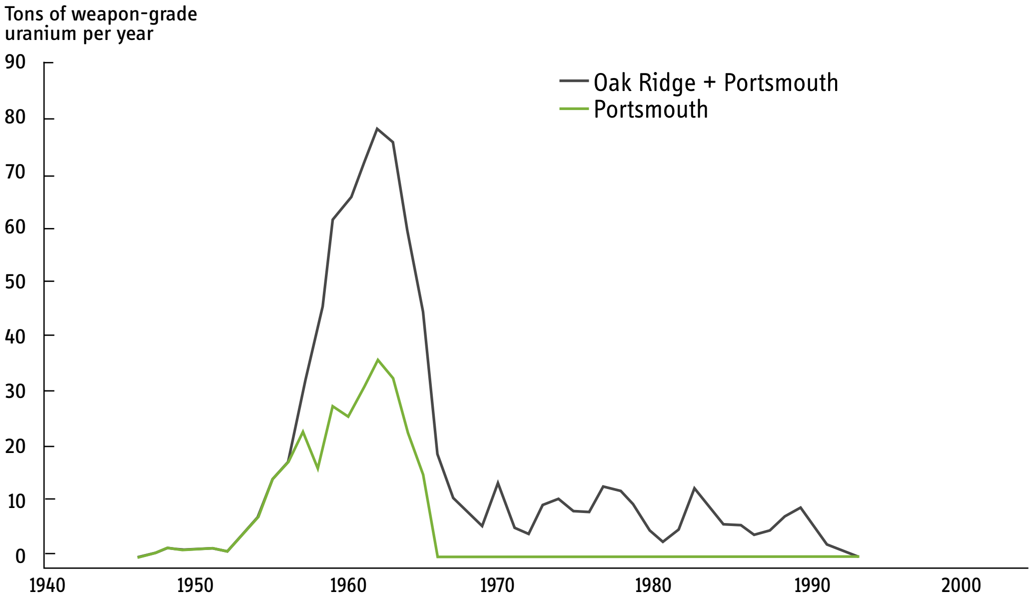

Figure 6.3 - History of U.S. production of weapon-grade uranium by site. The United States produced a total of 802 tons of uranium enriched to 90% or more. Most of the material produced after 1964 was enriched to 96 percent or greater for use as naval-reactor fuel. In addition, the United States produced 219 tons of HEU enriched to between 20 and 70 percent (average 38%) and 24 tons enriched to between 70 and 90 percent. The material produced in 1945 is included in the total for 1946. The first U.S. HEU production took place at the Oak Ridge, Tennessee site and included the HEU for the Hiroshima bomb. All of the Oak Ridge material produced during 1945 and 1946 and some produced during 1947 was enriched to weapon grade using calutrons. Otherwise all enrichment was by the gaseous diffusion process. The gaseous diffusion plant (GDP) in Paducah, Kentucky produced low-enriched uranium, which was further enriched by the Oak Ridge and Portsmouth, Ohio GDPs.[161]

The United States and Russia, each of which over the past decades devoted substantial resources studying each other's nuclear complexes, could probably each verify roughly such production-history declarations. The amount of krypton-85 that the Soviet Union released annually from its reprocessing plants has been deduced, for example, from measurements of the rising inventory of this gas in the earth's atmosphere and information on releases from other large sources.[162] The declaring countries could further strengthen confidence in their declarations by making available to the IAEA copies of their detailed production records.

Further checks on the accuracy of the production histories presented could be provided in the future by on-site measurements at the production sites. One well-established example of such "nuclear archaeology" is the use of measurements of the degree of transmutation of trace elements in the graphite moderator of plutonium-production reactors to estimate the cumulative neutron flow through the graphite and thereby their cumulative plutonium production.[163]

In sum, future deep cuts in the existing stocks of fissile materials for weapons will not be feasible, unless countries reveal much more information about the history of their production and use of these materials. The earlier such information is compiled and released, the more accurate and useful it is likely to be.

7 Limiting National Fissile-Material Production Capabilities

The crisis over Iran's uranium enrichment program and the controversy over Japan's new commercial reprocessing plant have each underscored the fact that the Nuclear Nonproliferation Treaty permits non-nuclear weapon state parties to the treaty to deploy national uranium enrichment or reprocessing facilities and build up stockpiles of fissile materials. NPT Article IV.1 states that

> "Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II of this Treaty."

As weapon states reduce their stockpiles, similar concerns could arise about the military potential of their enrichment and reprocessing facilities.

The debate therefore revolves around a Party's intentions, i.e. whether non-weapon states intend to conform permanently with their nonproliferation commitments under Articles I and II and whether weapon states intend to live up to their disarmament commitments under Article VI. In the case of stockpiles of fissile material, it also revolves around concerns about the possibility of theft.

As shown in Figure 7.1, eleven countries today have civilian enrichment and/or reprocessing plants in operation or under construction. Six of the eleven countries are nuclear weapon states. The non-weapon states that have operating facilities are Brazil, Germany, Japan and the Netherlands.[164] Iran is doing research and development with a small centrifuge cascade at Natanz and is planning to build and operate a much larger facility there.[165]

Five non-weapon states that had operational pilot-scale facilities: Argentina and South Africa (enrichment), and Belgium, Germany and Italy (reprocessing) have suspended or terminated their programs.

Germany and the Netherlands are members of a multinational enrichment consortium, Urenco. This leaves Brazil, Iran and Japan as the only non-nuclear weapon states with purely national fuel-cycle facilities. See also Tables 3.2 and 3.3.

There are a number of critical differences between uranium enrichment and reprocessing. One is that reprocessing is not currently an essential part of the fuel cycle of the light-water reactors that now dominate civilian nuclear power. It can be postponed indefinitely by storing the spent fuel.

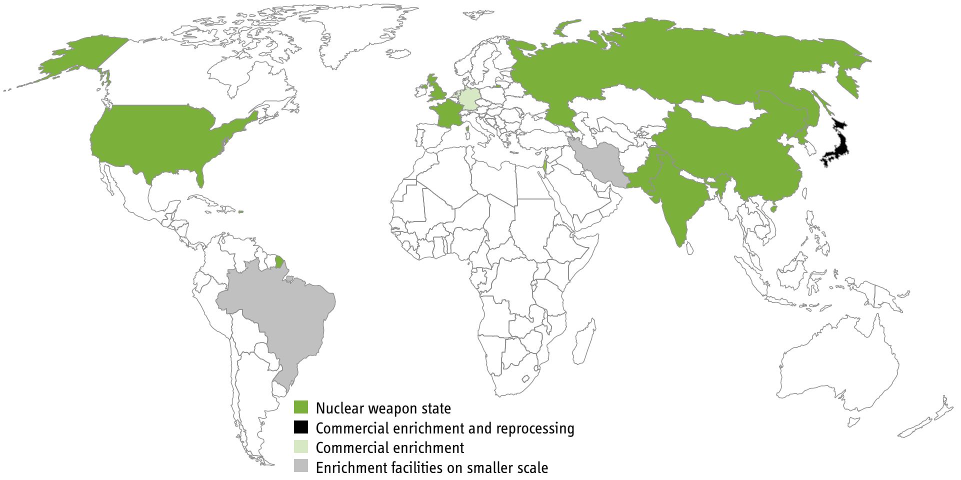

Figure 7.1 – Civilian enrichment and reprocessing plants worldwide. At present, Brazil, Iran, and Japan are the only non-weapon states with purely national fuel-cycle facilities. Germany and the Netherlands have enrichment plants but these are part of a multinational consortium.

Uranium enrichment, however, is needed to supply the fuel for the reactors. The need for security of supply therefore provides a plausible reason for countries to build national enrichment plants. This was the justification offered by Japan, Brazil and Iran. France and the United States too are insisting on building new domestic enrichment plants designed by Urenco and using Urenco centrifuges, even though they could equally well invest in expanding the capacity of Urenco's existing enrichment plants.

Proliferation dangers associated with gas-centrifuge enrichment

Centrifuges currently have decisively superior economics to other uranium enrichment technologies. They account for half of the world's enrichment capacity, and will account for all of it after France and the United States complete their current programs to replace their gaseous diffusion plants with centrifuge plants. Therefore, there is every reason for a country wishing to acquire an enrichment plant to choose centrifuge technology.

Gas-centrifuge enrichment technology creates special proliferation concerns, however. First, because of its small inventory of uranium-hexafluoride, a centrifuge plant can convert rapidly from producing low-enriched uranium for power-reactor fuel to producing highly enriched uranium for weapons. Second, if a country wished to build a small clandestine centrifuge plant, it would be difficult to detect. A centrifuge plant uses relatively little power and leaks almost no gas to the atmosphere. This contrasts dramatically with the first uranium enrichment plants in the declared nuclear weapon states, which were gas-diffusion plants with huge inventories and power requirements.

Figure 7.2 shows France's Eurodif gas-diffusion plant at the back right with a capacity of 8.5 million SWU/yr. In the foreground are four full-sized 915 MWe nuclear power reactors, more than half of whose combined output is required to power the enrichment plant when it is operating at full capacity. The energy intensity of the plant is also dramatized by the enormous cooling towers required to remove the heat generated by the compressors that force uranium hexafluoride gas through thousands of diffusion barriers.

For contrast, Figure 7.3 gives a view of Urenco's centrifuge enrichment plant in the Netherlands (3.5 million SWUs/yr). The capacity is about half as large as that of the Eurodif plant but, because centrifuge enrichment requires only a few percent as much energy per separative-work unit (SWU), it requires neither a nearby power plant nor cooling towers to remove waste heat from the plant.[166] From the air or space, the centrifuge plant is not obviously distinguishable from any other factory.

For a small enrichment plant, the situation is much much worse. It only requires an enrichment capacity of about 5000 SWUs/year – about 0.15 percent of the capacity of the Almelo plant – to produce enough weapon-grade uranium annually to make 25 kilograms of weapon-grade uranium – enough for an implosion bomb. A gas-centrifuge plant of this size could be hidden relatively easily in a small, anonymous building – or even underground. The floor area required could be contained in a square approximately 25 meters on a side.[167] Such a plant would consume only about 100 kilowatts of electrical power, which could be provided by a portable diesel generator.[168]

Figure 7.2 - France's Eurodif gas-diffusion uranium enrichment plant (large-area buildings in back) requires so much electrical power that it is co-located with a four-unit nuclear power plant.[169]

Figure 7.3 - Urenco's Almelo centrifuge enrichment plant has no associated power plants or cooling towers.[170]

Thus, once a country mastered the technology, it could, in principle, build a clandestine centrifuge-enrichment facility – one of the possibilities driving concerns about Iran's centrifuge program.

Economic competitiveness, however, is a moving target. As a cumulative result of Urenco's long-term research and development program, each generation of its machines has had dramatically improved capacity and performance (see Figure 7.4). Urenco designs have made all other designs noncompetitive except for those fabricated in Russia, which adopted a different approach based on stacks of ever faster-spinning short centrifuges, while Urenco built each generation of centrifuges taller as well as faster.

There is therefore an economic incentive for even advanced countries to acquire centrifuge plants from Urenco or Russia. This is why both France and the United States are acquiring Urenco centrifuge plants. China has similarly built two centrifuge-enrichment plants using centrifuges supplied by Russia. The U.S. Enrichment Corporation hopes to leapfrog this competition by building a plant based on huge and costly centrifuges with enrichment capacities of 300-400 SWU/yr using technology developed by a $3 billion U.S. Department of Energy program. There is some skepticism, however, about its prospects for success.[171]

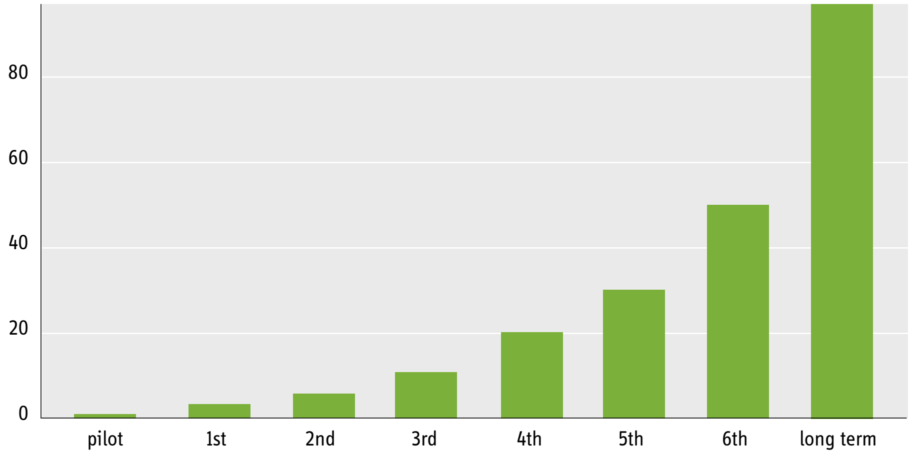

Figure 7.4 - The capacity of modern centrifuges is increasing. As shown here, Urenco has been able to improve the performance and increase the capacity of its machines dramatically. Such advanced machines could not be produced independently without a similarly dedicated long-term research and development effort. Building and successfully operating a first-generation machine, however, has become easier due to availability of high-precision tools and equipment.[172]

Reprocessing

Whereas enrichment is essential to supply fuel for light-water reactors, reprocessing of spent fuel can be postponed indefinitely. Indeed, it is generally accepted today that, for the foreseeable future, reprocessing and plutonium recycle will be less economic than purchasing fresh low-enriched uranium fuel and storing the spent fuel. This is true, even in France, the country that is generally viewed as having the most successful reprocessing and plutonium recycle program. In 2000, the French government concluded that, even with its reprocessing and MOX-fuel fabrication plants paid for, France would save $4 to $5 billion over the remaining lifetime of its current fleet of power reactors if it stopped reprocessing in 2010.[173]

Originally, interest in civilian reprocessing stemmed from programs in the industrialized countries to commercialize plutonium-breeder reactors. These reactors were to be fueled by the plutonium produced by neutron capture on the uranium isotope uranium-238. U-238 is 140 times more abundant than U-235, the primary fuel of current-generation reactors.

To provide plutonium for the initial cores of their planned breeder reactors, the major industrialized countries launched programs to harvest the plutonium contained in the light-water reactor spent fuel. The plutonium makes up about 1 percent of the spent fuel. Britain and France used the expertise that they had developed in their weapons programs to build large-scale commercial reprocessing plants financed by pre-paid reprocessing contracts from foreign utilities.

The breeder dream soon collapsed, however. The United States and Germany abandoned demonstration breeder reactor projects before they were completed. France, Japan and the United Kingdom completed demonstration reactors, but they proved very costly and troublesome to operate. France shut down its 1200-MWe demonstration breeder reactor in 1998 after it had operated at an average six-percent capacity over 13 years.[174] Japan's 280-MWe demonstration breeder reactor first went critical in 1994 but was shut down by a sodium fire in 1995 and has not yet been brought back into operation.[175] Russia's 600 MWe BN-600 demonstration reactor, in contrast, has been kept on line with an average capacity factor of about 74 percent since 1980 but has suffered 15 sodium fires in 23 years.[176] A follow-on demonstration reactor, the BN-800, has been intermittently under construction since 1986 and is currently again a high-priority project for Russia's nuclear establishment.[177] India has begun to build a demonstration breeder reactor and China a pilot scale plant.[178] But, despite a worldwide expenditure of perhaps $100 billion in current dollars thus far on developing and demonstrating breeder reactors with a total thermal capacity of about 9 GWt, no country has yet succeeded in commercializing them.[179]

Commercial reprocessing has continued, however. Today civilian reprocessing on a large scale is underway in Britain, France, India and Russia and, in 2006, a large new reprocessing plant began operating in Japan.

Reprocessing has continued primarily because of a combination of local political pressures to do something about the problem of spent fuel accumulating at power-reactor sites and not-in-my-backyard political opposition elsewhere to geological repositories and central interim storage facilities for spent fuel. Indeed, Germany and Japan largely financed the French and U.K. multi-billion-dollar commercial reprocessing facilities as a way to export their spent-fuel storage problems.

The respite was only temporary. After their reprocessing plants went into operation, Britain and France began to ship the solidified reprocessing waste back to the countries of origin – reopening the issue of where to store it. Germany's utilities finally decided to stop reprocessing, store newly generated spent fuel on site, and phase out nuclear power. Japan's nuclear utilities went a different route. They persuaded the relatively poor rural prefecture of Aomori to store for 50 years the radioactive waste being returned from Europe in exchange for a large reprocessing plant and large tax payments to the local government.

Some countries – notably France and Germany – are recycling their separated plutonium in the form of mixed-oxide fuel (MOX) back into the reactors from whose spent fuel it was extracted. Japan plans to do the same but local government opposition has delayed this program for about a decade.[180] The United Kingdom has been simply stockpiling its own separated civilian plutonium. Russia has been stockpiling the separated plutonium that it has recovered from the spent fuel of its own first-generation power reactors and those of Eastern Europe. As a result of these growing national stockpiles, the total global stock of separated civilian plutonium is about 250 tons (see Chapter 2).

The Bush Administration's Global Nuclear Energy Partnership

U.S. nuclear utilities too have been unable to ship their accumulating spent fuel off their reactor sites. The reason is delays in the licensing of the U.S. Department of Energy's (DOE) proposed Yucca Mountain, Nevada, geological repository that was supposed to have begun operations in 1998. The utilities have therefore been suing the DOE for the costs of building additional on-site dry-cask storage.

If the Yucca Mountain repository is licensed, the U.S. Department of Energy estimates its physical capacity as 105,000-200,000 tons.[181] A recent study by the Electric Power Research Institute (EPRI) concludes that the capacity could be still higher – from 260,000-570,000 tons.[182] Current law, however, limits the quantity of spent fuel that can be stored there to 63,000 tons "until such a time as a second repository is in operation."[183] U.S. reactors will have discharged this amount of spent fuel by 2008. In the spring of 2006, the DOE submitted legislation to Congress that would lift this legislated limit on the capacity of Yucca Mountain.[184]

As an alternative option, in 2005, the U.S. Congress asked the Department of Energy to develop a plan for centralized interim storage and reprocessing of U.S. spent fuel.[185] In May 2006, the DOE responded with a plan for a "Global Nuclear Energy Partnership" (GNEP). It envisioned building reprocessing plants that would separate spent light-water-reactor fuel into four streams (see Figure 7.5): uranium; plutonium mixed with the other transuranic elements, neptunium, americum and curium; the 30-year-half-life fission products, strontium-90 and cesium-137; and other fission products.

The strontium-90 and cesium-137 would be resolidified and placed into interim surface storage for some hundreds of years. The transuranic elements would be recycled in fast-neutron reactors until they were fissioned. These are the same sodium-cooled reactors that previously were to be commercialized as plutonium breeder reactors. With the removal of the plutonium breeding uranium blankets around their cores, they now would be transuranic *burner* reactors. It was proposed that demonstration reprocessing and fast-neutron reactor plants be built and put into operation by 2020.[186]

The purpose of this effort would be to drastically reduce the fraction of the long-lived radionuclides in the spent fuel going into the Yucca Mountain repository. This would decrease the long-term temperature increase of the rock around the disposal tunnels per ton of spent fuel and increase by up to one-hundredfold the amount of spent fuel that could be discharged from U.S. nuclear reactors before a new repository would have to be sited.[187]

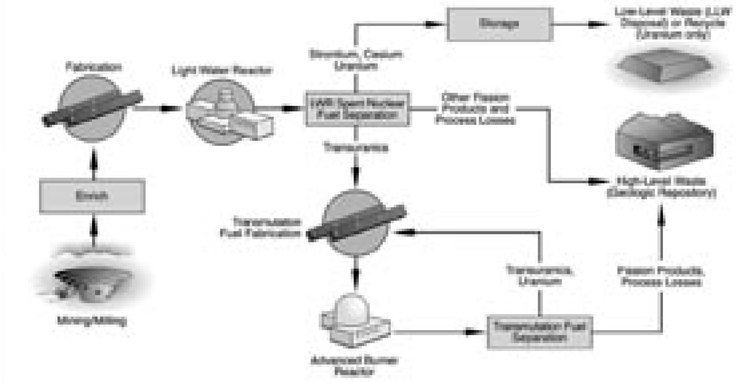

Figure 7.5 - Diagram showing a Department of Energy proposal for reprocessing U.S. spent fuel and fissioning the transuranics with fast-neutron reactors, shown here as "Advanced Burner Reactors." After reprocessing, the 30-year half-life isotopes, cesium-137 and strontium-90, which dominate the radiological hazard until they decay away, would be placed in interim surface storage for some hundreds of years. This raises the question as to why the spent fuel should not be placed in such interim storage until the long-term future of nuclear power is clarified instead of rushing into a reprocessing and transmutation program that would ultimately cost about $100 billion dollars to process just the existing U.S. spent fuel.[188]

GNEP is controversial for two reasons: its cost and its impact on nonproliferation policy.

Cost. A 1996 U.S. National Academy of Sciences study estimated the extra cost of a separations and transmutation program for the first 62,000 tons of U.S. spent fuel, relative to the cost of simply storing the spent fuel in a repository, as "likely to be no less than $50 billion and easily could be over $100 billion."[189] U.S. utilities, which have been paying the U.S. Government 0.1 cent per kilowatt-hour of nuclear-generated electricity for spent-fuel disposal services, have made clear that they will not pay for the extra cost of building a reprocessing plant or fast-neutron reactors.[190]

The great cost of the DOE's proposed program and the fact that it proposes to store the most dangerous isotopes in the spent fuel[191] on the surface for hundreds of years may eventually increase the appeal to the U.S. Congress of interim storage without reprocessing.[192]

Impact on nonproliferation policy. Following India's 1974 nuclear explosion, which used civilian plutonium separated with U.S. assistance, the United States reversed its policy of encouraging reprocessing and plutonium recycle worldwide. During the Carter Administration, the U.S. policy became, in effect, "We don't reprocess and you don't need to either." Partly as a result, since 1974, only two additional countries have begun to reprocess, North Korea and Pakistan, both for weapons purposes. During the same period, Argentina, Belgium, Brazil, Germany and Italy, shut down their pilot reprocessing plants, and South Korea and Taiwan abandoned their laboratory-scale reprocessing efforts.

The Department of Energy has responded in two ways to concerns that a new U.S. reprocessing initiative would undermine nonproliferation efforts:

1. By developing reprocessing technologies that would not separate out pure plutonium. The proliferation-resistance of these technologies has been challenged, however, and the Argonne National Laboratory, which provides the technical analysis for DOE policy in this area, has responded by proposing ever more complex versions of its UREX+ fuel cycle.[193]

2. By citing the Bush Administration's proposal that enrichment and reprocessing be confined to "countries that already have substantial, well-established fuel cycles."[194]

Indeed, the DOE named its proposed reprocessing and reycle program the Global Nuclear Energy Partnership to convey the idea that the United States and other countries with large nuclear programs would provide reprocessing services to other countries.

France, the United Kingdom and Russia have been doing this already but France and the United Kingdom have recently lost all of their foreign customers. Russia has kept a few because, unlike France and the United Kingdom, it is willing to keep other countries' plutonium and radioactive waste. In effect, it is providing permanent storage for foreign spent fuel – although with the fuel separated into three components: uranium, plutonium and high-level waste. Its customers are happy, however, for Russia to take their spent fuel, whether it reprocesses it or not. While the spent fuel from some first-generation VVER-440 reactors in Eastern Europe, Russia and Ukraine is reprocessed at the Mayak combine in the Urals, the spent fuel from their VVER-1000 reactors is stored in a pool associated with an uncompleted reprocessing plant near Krasnoyarsk. Russia's Federal Atomic Energy Agency (Rosatom) has indicated an interest in reprocessing – or storing – spent fuel from other countries as well.[195] Recently, the Bush Administration has indicated its support for such a venture.[196]

On August 7, 2006, however, the DOE reversed course and announced that, given that the technology for recycling all of the long-lived transuranic elements in spent fuel was not available, it was considering building a 2000-3000 ton per year reprocessing plant based on the existing technology being used in France, and a 2000 MWt (thermal) fast neutron reactor of the French Supérphenix design. The fast reactor would be fueled initially by "conventional fast reactor fuel," i.e., a mix of plutonium and uranium produced by the reprocessing plant.[197] Even the 2500 MWt Supérphenix, operating at its design 70 percent capacity factor on a once-through fuel cycle, however, could only annually irradiate 1.5 tons of plutonium in this way,[198] while reprocessing 2000-3000 tons of light water reactor spent fuel would separate 20-30 tons of plutonium per year. In effect, therefore, the DOE proposes to spend tens of billions of dollars to transform the spent fuel accumulations at many U.S. nuclear-power-reactor sites into separated plutonium and high-level waste accumulating at a single reprocessing site.

One can only assume that the compelling reason for the DOE initiative is to use the reprocessing plant as a magnet to get spent fuel moved away from reactor sites. But it is difficult to understand the urgency. On-site storage of spent fuel in dry casks has been widely adopted by nuclear power operators in the United States, Germany, and elsewhere. The U.S. Nuclear Regulatory Commission has declared such storage to be "safe and environmentally acceptable" for at least 100 years.[199] All studies of which we are aware find little difference in the cost of on-site and centralized dry-cask storage.[200]

Efforts to limit the proliferation of national fuel-cycle plants

Proposals to limit the proliferation of enrichment and reprocessing plants have been made periodically since the beginning of the nuclear era. The 1946 Acheson-Lillienthal report urged that such "sensitive facilities" should be placed under international ownership.[201] After India used civilian plutonium to make a nuclear explosive device in 1974, there was a second wave of interest in limiting national ownership of reprocessing facilities, with studies launched in 1975, 1977, 1978, 1980, and 1987.[202]

During the Cold War, the combination of the advanced nuclear states refusing to export fuel cycle facilities and the ability of the United States and Soviet Union to press their allied states not to develop such capabilities on their own was relatively effective. With the end of the Cold War, however, it became more difficult for Washington and Moscow to enforce nuclear abstinence. Also, over the past three decades a black-market developed for centrifuge plant designs and components. Efforts are therefore being made to strengthen control over technology exports and renewed proposals are being made for at least multinational – if not international control of fuel-cycle facilities.

Strengthened technology export controls. In his talk at the National Defense University on February 11, 2004, President Bush called upon the Nuclear Suppliers Group to deny enrichment and reprocessing technologies "to any state that does not already possess full-scale, functioning enrichment and reprocessing plants," and, in compensation, ensure that states that do not have such plants have reliable access to enrichment and reprocessing services.[203] No member of the Nuclear Suppliers Group has contracted to export either type of plant to a non-weapon state other than Japan since the 1970s. However, there has been resistance to the proposal within the G-8 group of countries, which has been willing to support a formal moratorium on exports only on a year-by-year basis.

To deal with the problem of illicit technology exports exemplified by the A.Q. Khan network, the Bush Administration launched the Proliferation Security Initiative under which many countries have agreed to cooperate to intercept illicit shipments of dual-capable technologies such as gas centrifuges.[204] Indeed, the interception of centrifuge components being shipped to Libya by the A.Q. Khan network is often cited as a model for the type of operation envisioned in the Proliferation Security Initiative.

The U.N. Security Council also passed in April 2004 UNSC resolution 1540, which requires all U.N. members to set up legal and regulatory systems to assure that "all States shall take and enforce effective measures to establish domestic controls to prevent the proliferation of nuclear, chemical, or biological weapons and their means of delivery."[205]

Multinational control of fuel-cycle facilities. In his November 2003 speech to the United Nations General Assembly, IAEA Director General El Baradei proposed that enrichment and reprocessing be restricted "exclusively to facilities under multinational control."[206] The Nuclear Suppliers Group guidelines already state that suppliers should "encourage" recipients to "accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities."[207]

A subsequent study done for the IAEA by an expert group assessed a number of international and multinational approaches including the IAEA operating as "administrator of a fuel bank; promoting voluntary conversion of existing [fuel cycle] facilities to multinational nuclear arrangements … and creating … regional multinational nuclear arrangements for new facilities …" The panel observed, however, that "there is a consistent opposition by many [non-nuclear weapon states] to accept additional restrictions on their development of peaceful nuclear technology without equivalent progress on disarmament."[208] Japanese, U.S. and enrichment-industry officials also expressed skepticism.[209]

In January 2006, Russian President Putin suggested that Russia would be willing "to offer nuclear fuel cycle services, including enrichment under the control of the IAEA." The specifics of the proposal remain to be worked out.[210] Russia has also offered to let Iran invest in a Russian enrichment facility as an alternative to building its own.

Two other ideas might be worth considering: the establishment of objective criteria for the ownership of national fuel-cycle facilities, and a "black-box" approach to enrichment technology transfer:

Criteria for national ownership of fuel-cycle facilities. A criteria-based approach to national ownership of fuel-cycle facilities is apparently of interest to most of the members of the Nuclear Suppliers Group but is opposed by the United States. A Princeton University graduate workshop has proposed that the IAEA convene a conference to establish international agreement on objective criteria that would have to be met before a country could qualify for hosting an enrichment plant. As a possible standard, it has suggested that a country have at least ten Gigawatts (GWe) of light-water reactor generating capacity, the equivalent of about ten full-sized power reactors. Supplying this much capacity with LEU would require about one million SWUs of enrichment work per year, potentially enough to provide a domestic market for a Urenco-type enrichment plant large enough to be economically competitive with foreign enrichment services.[211]

Such a criterion would disqualify all but four (Germany, South Korea, Japan, and Ukraine) of the 25 non-nuclear weapon states with nuclear power reactors as well as several nuclear weapon states.[212] Two of the above-threshold non-nuclear weapon states, Germany and Japan, already have enrichment plants, as do two of the countries below the threshold (Brazil and the Netherlands). An argument might be made, however, to exempt the Netherlands because it is part of the EU and its enrichment plant is part of an EU multinational company.

Black box enrichment plants. Accepting the current technological dominance of two centrifuge-enrichment suppliers, Urenco and Russia, would be another way to limit the proliferation of centrifuge technology. The danger of centrifuge technology proliferation would be reduced to the extent that other countries chose to import centrifuges rather than develop their own.

As already noted, this is happening already. France and the United States are building plants using imported Urenco centrifuges; and China uses Russian centrifuges. The Urenco contracts involve the export of its centrifuge technology only on a "black box" basis. The centrifuges are to be manufactured in the Netherlands and assembled by Urenco technicians in the recipient countries.[213] Since the centrifuges are expected to operate for perhaps 20 years without maintenance, there is no need for the personnel of the host country to examine their interiors. Russia has made a similar black-box arrangement for the centrifuge plants that it has supplied to China. The fact that three weapon states are willing to acquire enrichment technology on a black-box basis should make such an approach appear less discriminatory to non-weapon states.

8 Global Cleanout of Highly Enriched Uranium

Major efforts are being made to upgrade the security of sites where fissile materials can be found. The United States, which has taken a leadership role in this respect, launched in 1993 a cooperative "materials, protection, control and accounting" program that is currently spending more than $400 million per year on security upgrades of sites with fissile material in the former Soviet Union (such as shown in Figure 8.1). The status and progress of the various efforts have been well summarized by the Project on Managing the Atom, at Harvard's Kennedy School, and by RANSAC.[214]

Increasing the security of fissile materials in storage is a vital undertaking. In the long run, however, the most effective approach to the risk of diversion or theft is to eliminate the material from as many locations as possible. This section discusses the feasibility of a global cleanout of civilian highly enriched uranium, still held at more than a hundred civilian sites worldwide – primarily in research-reactor fuel cycles.

Figure 8.1 - These cylinders in a Russian institute's storage facility contain in total ton quantities of plutonium and highly enriched uranium. The portability of the cylinders increases the risk of theft.[215]

During the 1950s and 1960s, as part of their competing Atoms for Peace programs, the United States and the Soviet Union built hundreds of research reactors domestically, and for export to more than 40 other countries. In response to demands for longer-lived fuel and maximum reactor performance, export restrictions on fissile materials were relaxed, and most of these reactors shifted to fuel containing weapon-grade HEU. As a result, HEU is still used today as a research-reactor fuel in about 140 civilian reactors worldwide. In addition, HEU remains at sites of many shut down, but not yet decommissioned reactors. Taken together, the global inventory of civilian HEU reactor fuel is very roughly 50 metric tons, widely distributed around the globe (see Figure 8.2). According to a 2004 U.S. Government study, there were 128 sites known around the world associated with research reactors with at least 20 kilograms of HEU.[216]

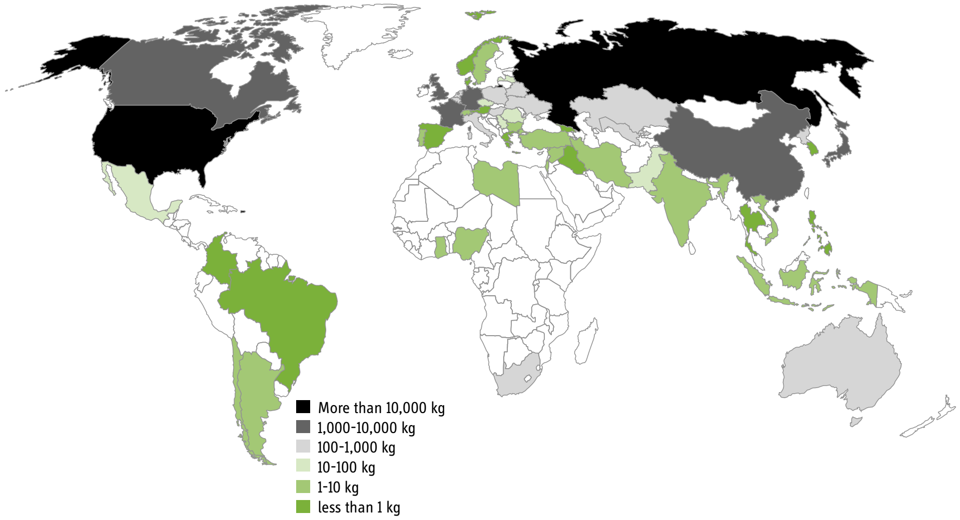

Figure 8.2 - Civilian HEU is still distributed around the globe in large quantities. International efforts to convert HEU-fueled research reactors to low-enriched uranium have reduced the annual demand of the material by about 250 kg of HEU per year. Yet, there are still more than 100 sites worldwide where the material can be found in significant quantities at operational or shut down but not yet decommissioned HEU-fueled reactors.

Reactor conversion to low-enriched fuel

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.[217] By the end of 2005, the RERTR program had converted or partially converted 42 research reactors.[218] The world's remaining research reactors consume about 1,000 kilograms of HEU per year – virtually all supplied by the United States and Russia. RERTR program analysts believe that 41 more reactors can be converted using existing LEU fuels.[219] Of the Western-designed reactors, about ten, which consume the bulk of the HEU, cannot be converted however, until advanced LEU fuels are developed. These research reactors have compact, high-powered cores designed to maximize neutron intensity for testing reactor fuels and materials to high irradiation levels, and for neutron-scattering measurements.

The primary approach of the RERTR program has been to develop 19.75-percent enriched LEU fuels (i.e., just below the 20-percent threshold that defines HEU) in which uranium-238 is added to dilute the U-235 in the fuel. As a result, the concentration of uranium in the nuclear fuel is increased approximately five-fold. Fortunately, the uranium densities in the HEU fuels that have to be replaced are mostly quite low: 3-6 percent of the density of solid uranium – or about 0.6-1.2 grams uranium per cubic centimeter (g/cc). The most advanced fuel commercialized thus far has an effective uranium density of 4.8 g/cc. Because of unexpected poor irradiation performance of a candidate fuel with a higher uranium density that was to be commercialized in 2006, the expected availability of fuels with the densities required to convert research reactors with compact, high-powered cores has slipped to around 2010. The most promising fuel currently under development, solid uranium alloyed with molybdenum,[220] has a uranium density of more than 16 g/cc and could be used to convert almost all remaining high-powered research reactors.[221] If these fuels can be successfully developed and qualified, the main technical obstacle for a global HEU cleanout would be removed.

Decommissioning unneeded HEU reactors

Most of the world's aging fleet of HEU-fueled reactors is no longer needed. The total number of these research reactors worldwide could be reduced, in principle, from hundreds to tens.[222] Just shutting down an HEU-fueled reactor is not sufficient, however. To complete the cleanout, the HEU fuel must be removed, i.e. the reactor must be "decommissioned."[223] To make a decommissioning program attractive in Russia and elsewhere, it may be necessary for concerned countries to invest in strengthening the surviving research-reactor centers. Such assistance should be conditioned, however, on the management being willing to allow research groups from decommissioned facilities to become "user groups" on a nondiscriminatory basis. Such arrangements are standard in the United States and Western Europe, but are still foreign to Russia where, if a group does not have its own reactor, it does not have an opportunity to do experiments. Russia accounts for about one third of the world's HEU-fueled reactors and probably over one half of the HEU associated with civilian HEU-fueled reactors.

Beyond RERTR: other types of HEU reactors

Conversion efforts have thus far been focused almost entirely on HEU-fueled reactors that are refueled regularly, and therefore, can be converted by refueling them with LEU instead of HEU fuel. This excludes critical assemblies and pulsed-power reactors that have lifetime cores that can contain huge quantities of barely-irradiated HEU (see Figure 8.3).

Figure 8.3 - The Russian critical assembly shown at the top has ton quantities of HEU and plutonium – mostly in the form of tens of thousands of small disks that are stacked up in columns to simulate fuel of different enrichments and mixes of uranium and plutonium. The shut down – but not decommissioned – U.S. critical assembly shown at the bottom similarly has ton inventories of plutonium and HEU associated with it that are loaded into drawers.[224]

There are about 45 HEU-fueled critical assemblies worldwide that are listed by the IAEA as "operating." In 2005, the IAEA hosted a consultation on the future need for critical assemblies. The consultation concluded that, given the greatly increased capabilities of computer simulations, and the large numbers of criticality "benchmark" experiments that have been performed, there should be joint workshops of reactor designers and critical- and sub-critical assembly experts to consider which existing facilities are no longer needed, and to modernize the facilities that are still needed.[225] Decommissioning the redundant critical assemblies would be much less costly than decommissioning other types of research reactors. Since their uranium fuel is barely irradiated, it is easily handled – which is also the reason it is of such proliferation concern.

There are also about 20 HEU-fueled pulsed reactors that similarly contain large inventories of barely irradiated HEU and could similarly be either decommissioned or converted to LEU. The All-Russian Institute of Experimental Physics (VNIIEF) in Sarov, Russia has proposed a feasibility study on the conversion of its BIGR pulsed reactor, which has an HEU inventory of 833 kilograms of weapon-grade uranium.[226]

Russia also uses HEU fuel in seven nuclear-powered icebreakers. LEU fuel has been developed for a proposed floating nuclear power plant that would be powered by a reactor derived from one of the reactor types (the KLT-40) used on the icebreakers. The privately funded Nuclear Threat Initiative has offered to support the adaptation of this fuel for the icebreakers.[227]

Converting HEU-fueled military propulsion reactors would further extend the scope of the global cleanout initiative discussed in this section. China is believed to use LEU – or HEU fuel barely above 20 percent enrichment – in its submarines, and France is shifting to LEU fuel.[228] U.S. and U.K. naval reactors are fueled with weapon-grade uranium but are unlikely to be converted since they mostly have lifetime cores. Future naval reactors could be designed to use LEU but, in 1995, the then director of the U.S. Naval Nuclear Propulsion program argued that LEU-fueled reactor cores using the same fuel technology would have to be three times larger in volume than cores fueled with weapon-grade uranium and that this would lead to a ten percent cost increase in the Navy's new Virginia-class attack submarines.[229]

Because of the highly classified nature of naval-reactor fuel design, it has been impossible for independent analysts to review this conclusion. However, approaches by which such cost increases could be mitigated have been proposed, including adopting a compact system design in which steam generators are inside the reactor pressure vessel.[230] This design has allowed France to deploy the world's smallest nuclear-powered attack submarines (the Rubis class). The impact of a larger reactor core should be relatively small on the cost of larger U.S. nuclear-powered ships, such as ballistic-missile submarines and aircraft carriers.

Russia's submarines, reportedly, use HEU fuel with enrichments ranging from 21 to 45 percent. This, along with the fact that Russia's submarines, like France's, are refueled at five to ten year intervals, should make it easier to convert them to LEU.[231]

Toward a comprehensive HEU "global cleanout" program

In 2004, the U.S. Department of Energy responded to Congressional concern about how slowly the HEU-cleanout programs were moving by combining its reactor-conversion and spent HEU-fuel take back efforts into a Global Threat Reduction Initiative (GTRI) program.[232]

This initiative would achieve complete elimination of HEU-fuel shipments to research reactors outside Russia by 2014. Critical assemblies and pulsed reactors containing huge quantities of barely irradiated uranium are not yet formally being targeted, however, and Russia has not yet agreed to convert or decommission its own HEU-fueled reactors.

What is needed is a broader international effort to: (1) decommission obsolete and redundant HEU-fueled research reactors; (2) accelerate the conversion of operating research reactors for which replacement LEU fuel is available; (3) assure that fuels are developed to convert all the remaining HEU-fueled research reactors; and 4) maximize the security and minimize inventories and enrichments of any HEU-fueled reactors that remain in operation.

Consideration also needs to be given to making more attractive the effort to decommission or shut down little-used HEU-fueled reactors by concentrating research-reactor or accelerator neutron services in regional centers of excellence, that are available on a nondiscriminatory basis, to user groups from institutes whose research reactors have been shutdown.

The key countries whose cooperation is required are those that have built and exported, or operate high power HEU-fueled research reactors, large critical assemblies, or pulsed reactors. The United States, Russia, United Kingdom, France, China, Germany and Japan account for more than 90 percent of the global civilian HEU inventory and demand. Their joint engagement in an accelerated conversion and clean-out effort would likely bring along the other countries that receive or have received fuel from the major HEU suppliers.

The reluctance of Russia's government to give this effort high priority domestically – at the same time that the leading Russian nuclear institutes have been asking for funding for projects to convert and decommission their HEU-fueled reactors – illustrates the importance of working directly with the institutes as well as on a government-to-government level. This "bottom-up" approach, in which Russian institutes help to get their government's approval, has been key to virtually all successful cooperative nuclear security initiatives. Unfortunately, Russia's security services have been increasingly blocking collaboration between Russia's nuclear institutes and U.S. Government programs working on HEU cleanout. This makes it even more important for other countries to become more seriously engaged with this agenda.

Endnotes

Chapter 1. Fissile Materials and Nuclear Weapons

[1] It should be noted that North Korea claims to have plutonium-based weapons that have not been tested.

[2] U.S. Department of Energy, Office of Security Affairs, Office of Safeguards and Security, *Manual for Protection and Control of Safeguards and Security Interests,* Chapter I, "Protection and Control Planning," Washington, DC, DOE, 15 July 1994, www.ipfmlibrary.org/doe94.pdf.

[3] Deuterium, a stable isotope of hydrogen with one neutron and one proton in the nucleus occurs naturally. Tritium, which has two neutrons and one proton, has a half-life of 12 years and is made in nuclear reactors when a lithium-6 atom absorbs a neuron and splits into tritium and helium.

[4] See, for instance, R. Alvarez and D. Sherman, "U.S. to Resume Uranium Production for Weapons," *Bulletin of the Atomic Scientists,* Vol. 41, No. 4, April 1985, pp. 28–30.

[5] Source: *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.*

[6] J. C. Mark, T. Taylor, E. Eyster, W. Maraman, and J. Wechsler, "Can Terrorists Build Nuclear Weapons?" in P. Leventhal, S. Tanzer, and S. Dolley, eds., *Nuclear Power and the Spread of Nuclear Weapons – Can We Have One without the Other?* Brassey's, Inc., Washington, DC, 2002, pp. 235-248.

[7] Plutonium of any composition, but less than 80% Pu-238. Plutonium containing more than 80 percent Pu-238 is considered unusable for nuclear weapons because of the large amount of heat generated by the relatively short-lived (88-year half-life) isotope.

[8] *Safeguards Glossary 2001 Edition, International Nuclear Verification Series,* No. 3, International Atomic Energy Agency, Vienna, 2002, §3.14, www.ipfmlibrary.org/iaeaglossary.pdf.

[9] U.S. Department of Energy, Office of Declassification, 1 January 2001 (RDD-7) states: "Hypothetically, a mass of 4 kilograms of plutonium or uranium-233 is sufficient for one nuclear explosive device," www.ipfmlibrary.org/rdd7.pdf.

[10] A. Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science & Global Security,* Vol. 14, No. 1, 2006, pp. 1-24, www.ipfmlibrary.org/sgs14glaser.pdf.

[11] J. C. Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science & Global Security,* Vol. 4, 1993, pp. 111-128, www.ipfmlibrary.org/sgs04mark.pdf.

[12] *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, pp. 37-39, www.ipfmlibrary.org/doe97.pdf.

[13] The 15 April 1955, 'MET' test in the 'Teapot' series used a composite plutonium and uranium-233 core, and had a yield of 22 kilotons, see www.nuclearweaponarchive.org. There may have been others; T. B. Cochran, W. Arkin, and M. M. Hoenig, "Nuclear Weapons Databook," Vol. 1, *U.S. Nuclear Forces and Capabilities,* Ballinger, Cambridge, 1984, p. 23.

[14] D. Albright and K. Kramer, "Neptunium 237 and Americium: World Inventories and Proliferation Concerns," 22 August 2005, www.isis-online.org.

[15] In 1999, the U.S. Department of Energy revealed that, as part of an exercise some years previously, four U.S. weapons design teams had independently come to this conclusion; see D. Albright and K. Kramer, "Neptunium 237 and Americium: World Inventories and Proliferation Concerns," *op. cit.*

[16] Values based on Monte Carlo simulations performed by Alexander Glaser using MCNP (Version 4C2) using cross-section data from ENDF/B-VI (Release 6). For uranium and neptunium, a density of 19.0 g/cc has been assumed, while the density of americium is only about 13.6 g/cc. Critical-mass values for these exotic fissile materials are less accurate than those for U-235 or plutonium due to less extensively validated cross-section libraries. In 2003, Los Alamos National Laboratory reported an experimentally determined critical mass of 57 kg, using neptunium-237, Mark Chadwick, "Neptunium Nuclear Data and Criticality," presentation at the 53rd Cross Section Evaluation Working Group Meeting and U.S. Nuclear Data Program Meeting, Brookhaven National Laboratory, 4-7 November 2003.

Chapter 2. Nuclear-Weapon and Fissile-Material Stocks

[17] Avner Cohen, *Israel and the Bomb*, Columbia University Press, New York, 1998, especially Chapter 16, "The battle over the NPT," The uncertainty as to whether or not Israel has conducted a nuclear test is related to the question of interpretation of a flash detected by a U.S. satellite over the South Indian Ocean on 22 September 1979. See e.g., S. Hersh, *The Samson Option,* Random House, New York, 1991, Chapter 20, "An Israeli Nuclear Test."

[18] North Korea's nuclear weapons are presumed to use plutonium extracted from the spent fuel of its small 5 MWe Yongbyon reactor; "North Korea Says Nuclear Fuel Rods Processed," *New York Times,* 2 October 2003; "North Koreans Say they Hold Nuclear Arms," *New York Times,* 10 February 2005.

[19] National Resource Defense Council (NRDC), Nuclear Data, www.nrdc.org/nuclear/; R. Norris and H. Kristensen, "NRDC: Nuclear Notebook: Russian Nuclear Forces," 2005, *Bulletin of the Atomic Scientists,* March/April 2005, pp. 70-72; U.S. Nuclear Forces, 2006, January/February 2006, pp. 68-71. For basis of the projection of U.S. nuclear stockpile to 2012, see R. Norris and H. Kristensen, "What's Behind Bush's Nuclear Cuts?" *Arms Control Today,* October 2004. The United States has an estimated 4,000-6,000 warheads in its dismantlement queue. The Bush Administration has made the dismantlement rate a secret but it is believed to have been running at only about one hundred warheads per year. Recently, under Congressional pressure, the Department of Energy agreed to increase the dismantlement rate by 50 percent, W. Pincus, "U.S. to Step up Disassembly of Older Nuclear Warheads," *Washington Post,* 4 May 2006.

[20] Text of the Strategic Offensive Reductions (SORT) Treaty, www.ipfmlibrary.org/sort.pdf.

[21] R. Norris and H. Kristensen, "U.S. Nuclear Reductions," NRDC Nuclear Notebook, *Bulletin of the Atomic Scientists,* September/October 2004, pp. 70-71; R. Norris and H. Kristensen, "What's Behind Bush's Nuclear Cuts?" *Arms Control Today*, October 2004.

[22] S. Kile and H. Kristensen, "World Nuclear Forces," *SIPRI Yearbook,* Oxford University Press, New York, 2005, p. 579; *NRDC Nuclear Notebook, Bulletin of the Atomic Scientists,* British Nuclear Forces, 2005, November/December 2005, pp. 77-79; French Nuclear Forces, 2005, July/August 2005, pp. 73-75; Chinese Nuclear Forces, 2006, May/June 2006, pp. 66-63; India's Nuclear Forces, 2005, September/October 2005, pp. 73-75; Pakistan's Nuclear Forces, 2001, January/February 2002, pp. 70-71; Israeli Nuclear Forces, 2002, September/October 2002, pp. 73-75; North Korea's Nuclear Program, 2005, May-June 2005, pp. 64-67.

[23] Based on U.S. production of HEU enriched to more than 96 percent, *Highly Enriched Uranium, Striking a Balance: A Historical Report of the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities, 1945 through Sept. 30, 1996,* U.S. Department of Energy, 2001 (revision 1, redacted for public release), www.ipfmlibrary.org/doe01.pdf, Table 5-1. See also David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996,* SIPRI, Oxford University Press, New York, 1996, pp. 88, 112.

[24] Most of Russia's nuclear submarines are believed to be fueled by 21-45 percent enriched uranium, Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review,* Vol. 8, 2001.

[25] The *IAEA Annual Report for 2004,* Table A18 shows 21.9 tons under IAEA safeguards in the non-weapon states. An unofficial breakdown by the Institute for Science and International Security shows about 11 tons of this material in Kazakhstan – mostly in fresh and spent fuel associated with the shutdown BN-350 fast-neutron power and desalination reactor whose fresh fuel was enriched to up to 26 percent, www.isis-online.org. In 2005, the Nuclear Threat Initiative announced that the

2.9 tons of unused BN-350 fresh fuel had been blended down, “Government of Kazakhstan and NTI Mark Success of HEU Blend-Down Project,” NTI press release, 8 October 2005, www.nti.org. The HEU in the spent fuel is probably mostly burned down to less than 20 percent enrichment.

[26] Alexander Glaser and Frank von Hippel, “Global Cleanout: Reducing the Threat of HEU-Fueled Nuclear Terrorism,” *Arms Control Today,* January/February 2006, pp. 18-23.

[27] *Plutonium and Highly Enriched Uranium 1996, op. cit.,* pp. 38, 68, 76, 80.

[28] *Plutonium and Highly Enriched Uranium 1996, op. cit.*

[29] Albright, et al., “Global Stocks of Nuclear Explosive Materials,” 2005, www.isis-online.org.

[30] U.S. Enrichment Corporation, *Progress Report, U.S.-Russian Megatons to Megawatts Program,* (as of 28 June 2006), www.usec.com.

[31] *Highly Enriched Uranium: Striking a Balance, op. cit.*

[32] U.S. Enrichment Corporation, Progress Report, *U.S.-Russian Megatons to Megawatts Program* (as of 31 December 2005), www.usec.com. The average enrichment of this HEU is about 60 percent. In Table 2.A.1, the quantity of HEU to be blended down has been converted to 93 percent enrichment equivalent. See footnote to Table 2.A.1.

[33] *Remarks prepared for Energy Secretary Sam Bodman,* 2005 Carnegie International Nonproliferation Conference, 7 November 2005.

[34] Harold Feiveson, ed., *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-Alerting of Nuclear Weapons,* Brookings, Washington, DC, 1999.

[35] *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, www.ipfmlibrary.org/doe00.pdf.

[36] D. R. Tousley, C. W. Forsberg, and A. M. Krichinsky, “Disposition of Uranium-233,” *International High-Level Radioactive Waste Management Conference,* American Nuclear Society, Las Vegas, Nevada, 11-14 May 1998. About 500 kg of uranium-233 is stored at Oak Ridge National Laboratory, in Building 3019, www.ipfmlibrary.org/ornl00.pdf and www.ipfmlibrary.org/bwxt00.pdf.

[37] R. Chidambaram and C. Ganguly, “Plutonium and Thorium in the Indian Nuclear Programme,” *Current Science,* Vol. 70, No. 1, 10 January 1996, pp. 21-35, www.ias.ac.in.

[38] David Albright and Kimberly Kramer, *Neptunium 237 and Americium: World Inventories and Proliferation Concerns,* 22 August 2005, estimated the global stock of neptunium-237 from civil power reactors to be 54 tons, in 2003, and a production rate of about 3 tons/year, which would suggest a current stock of about 60 tons; www.isis-online.org.

[39] *Ibid.,* estimate 87 tons of americium from civil reactors.

[40] *IAEA Annual Report,* 1999.

[41] *IAEA Safeguards Statement,* 2004.

Chapter 3. Production and Disposition of Fissile Materials

[42] J. Robert Oppenheimer, “Failure to Achieve International Control of Atomic Energy”, in Morton Grodzins and Eugene Rabinowitch, eds., *The Atomic Age,* Simon and Schuster, New York, 1963.

[43] In heavy water, most of the hydrogen is deuterium, a heavier isotope of hydrogen containing a neutron and a proton in its nucleus. Only about one in ten thousand hydrogen atoms in nature is deuterium.

[44] *Final Environmental Impact Statement for a Geological Repository for the Disposal of Spent Nuclear Fuel and High-level Radioactive Waste at Yucca Mountain, Nye County, Nevada,* DOE/EIS-0250, 2002, www.ocrwm.doe.gov; “Onkalo Underground Rock Characterization Facility at Olkiluoto, Eurajoki, Finland,” Posiva, www.ipfmlibrary.org/onkalo.pdf; “Deep Repository for Spent Nuclear Fuel [in Sweden],” SKB, www.ipfmlibrary.org/skb.pdf; and Mason Inman, “Rethinking Nuclear Power: Down to Earth: Lingering Nuclear Waste,” *Science,* 19 August 2005.

[45] We use SWU here as an abbreviation for the kilogram-SWU not the 1000-times larger ton-SWU.

[46] Source: R. Olander, "The Gas Centrifuge," *Scientific American,* Vol. 239, No. 2, August 1978.

[47] S. Krass, P. Boskma, B. Elzen, and W. A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation,* SIPRI, Taylor & Francis Ltd., London and New York, 1983. See Table 5.1, p. 113; Table 6.3, p. 188, and also p. 49, link to full text at www.ipfmlibrary.org/welcome/.

[48] The United States defines weapon-grade plutonium as plutonium containing less than 6 percent Pu-240. Plutonium-240 builds up to this level at about 700 MWt-days/ton in a graphite-moderated reactor and at 1400 MWt-days/ton in a heavy-water-moderated reactor, *Heavy-Element Concentrations in Power Reactors,* NUS Corporation, SND-120-2, 1977.

[49] For example, consider the dose rate from a pressurized water reactor (PWR) fuel assembly for an unshielded person at varying distances from the assembly. The mass of a typical PWR assembly is about 600 kg. The fuel has a burn up of up to 50,000 megawatt-days per ton, and contains about 5 kilograms of plutonium. For such an assembly, even after 15 years of cooling, a person 1 meter from the assembly would receive a lethal dose in a few minutes. Moving 5 meters away from such fuel would increase the time for a lethal dose to a couple of hours, W. R. Lloyd, M.K. Sheaffer and W.G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air,* Lawrence Livermore National Laboratory, Report UCRL-ID-115199, 1994. After the first decade following discharge from the reactor, the dose rate is dominated by cesium-137 and the dose rate declines with roughly that isotope's half-life of 30 years. The owning state would, of course have the equipment to divert spent fuel but detecting thefts of such large, highly radioactive objects is relatively easy.

[50] International Atomic Energy Agency, *Power Reactor Information System (PRIS) Database,* updated 5 January 2006, www.iaea.org.

[51] The amount of plutonium in power-reactor spent fuel at end of 2003 was about 1350 tons, D. Albright, *et. al*., "Global Stocks of Nuclear Explosive Materials: Summary Tables and Charts, Revised September 7, 2005," www.isis-online.org. This plutonium is growing at roughly 50 tons per year (0.2 tons/GWe-year for 350 GWe of capacity minus 20 tons/yr being separated at reprocessing plants).

[52] See e.g. the U.S. Atomic Energy Commission's *Proposed Environmental Statement on the Liquid Metal Fast Breeder Reactor Program,* Washington, DC, 1974.

[53] "Sellafield Shutdown Ends the Nuclear Dream," *The Guardian,* 26 August 2003; "Huge Radioactive Leak Closes THORP Nuclear Plant," *The Guardian,* 9 May 2005.

[54] F. Berkhout, A. Diakov, H. Feiveson, H. Hunt, E. Lyman, M. Miller, and F. von Hippel, "Disposition of Separated Plutonium," *Science & Global Security,* Vol. 3, 1993, pp. 161-213, www.ipfmlibrary.org/sgs03berkhout.pdf; *Management and Disposition of Excess Weapons Plutonium,* U.S. National Academy of Sciences, National Academy Press, Washington, DC, 1994; *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options,* National Academy of Sciences, National Academy Press, Washington, DC, 1995.

[55] See the discussion in Matthew Bunn and Anthony Weir, *Controlling Nuclear Warheads and Materials,* Harvard University, 2003, www.managingtheatom.org.

[56] U.S. National Academy of Sciences, 1994, op. cit., p. 34. The U.S. Department of Energy put the standard in slightly different but essentially equivalent words: "A concept to make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors," U.S. Department of Energy, Office of Fissile Material Disposition, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition,* 1996.

[57] For the option on disposing with spent fuel, see J. Kang, F. von Hippel, A. MacFarlane, and R. Nelson, "Storage MOX: A Third Way for Plutonium Disposal?" *Science & Global Security,* Vol. 10, 2002, p. 85, www.ipfmlibrary.org/sgs10kang.pdf.

[58] *Status of the Mixed Oxide Fuel Fabrication Facility,* U.S. Department of Energy, Office of the Inspector General, Office of Audit Services, Report DOE/IG-173, 2005, www.ipfmlibrary.org/doe05.pdf.

[59] "Russians, West Still at Standoff on Plutonium Disposition Financing," *Nuclear Fuel,* 13 March 2006; "U.S. Appears Ready to Drop Objections to Russian Fast-Reactor Pu Disposition," *Nuclear Fuel,* 10 April 2006.

[60] "House Appropriators Deliver Blow to DOE's GNEP, MOX Programs," *Nuclear Fuel,* 22 May 2006.

[61] Richard Rhodes, *The Making of the Atomic Bomb,* Simon and Schuster, New York, 1986, p. 500.

[62] UNGA Resolution 1.1, 24 January 1946, “Establishment of a Commission to Deal with the Problems Raised by the Discovery of Atomic Energy,” full text at www.ipfmlibrary.org/welcome/.

[63] Full text of the Acheson-Lilienthal proposal at www.ipfmlibrary.org/welcome/.

[64] General Findings and Recommendations Approved by the Atomic Energy Commission and Incorporated in its First Report to the Security Council, December 31, 1946(1), www.ipfmlibrary.org/unsc46.pdf.

[65] Dwight Eisenhower, “Atoms for Peace” Speech, December 1953, full text at www.ipfmlibrary.org/welcome/.

[66] John Carlson, “The Role of Bilateral Nuclear Safeguards Agreements,” *Trust and Verify,* No 122, October 2005-February 2006.

[67] IAEA statute is available at www.iaea.org.

[68] In 2006, nine former European Environment Ministers called for the IAEA to end its role in promoting nuclear energy and focus on its safeguards mission, www.greenpeace.org, the text is also available at www.ipfmlibrary.org/reform.pdf.

[69] The IAEA’s *Safeguards Glossary,* 2001, defines source material as natural or depleted uranium or thorium after extraction from ore. Special fissionable materials include enriched uranium, plutonium and neptunium-237, www.ipfmlibrary.org/iaeaglossary.pdf.

[70] IAEA Information Circulars, or INFCIRCs, are its standard record of agreements and other official information. The IAEA safeguards monitor activities at facilities including reactors, critical facilities, conversion, fabrication, enrichment and reprocessing plants, and storage sites, as well as places where nuclear material in amounts greater than one ‘effective kilogram’ is customarily used; INFCIRC/153 available at www.ipfmlibrary.org/inf153c.pdf.

[71] IAEA *Safeguards Glossary,* 2001, www.ipfmlibrary.org/iaeaglossary.pdf.

[72] IAEA *Safeguards Glossary,* 2001.

[73] Britain was the first nuclear weapon state to sign such an agreement (1978, INFCIRC/263). It was followed by the United States (1980, INFCIRC/288); France (1981, INFCIRC/290); Russia (1985, INFCIRC/327) and China (1989, INFCIRC/369).

[74] *The Cost of Implementing the Additional Protocol to the Treaty on the Non-Proliferation of Nuclear Weapons,* Congressional Budget Office, Washington, DC, 5 March 2004, www.ipfmlibrary.org/cbo04.pdf.

[75] HEU at Y-12 facility at Oak Ridge National Laboratory, Tennessee, and at a storage facility at Savannah River, South Carolina; plutonium at Pacific Northwest National Laboratory, Hanford, Washington; and HEU from Kazakhstan stored at BWX facility, Lynchburg, Virginia, US-IAEA safeguards Agreements, www.ipfmlibrary.org/dtirp.pdf. The United States submits to the IAEA an inventory-change report for each month and an annual material balance report, www.ipfmlibrary.org/nrc00.pdf.

[76] *IAEA Safeguards Report,* 2004.

[77] *IAEA Safeguards Statement,* 2004.

[78] Strengthened Safeguards System: Status of Additional Protocols, www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html.

[79] See, for example, INFCIRC/263/Add1, 24 February 2005, for the United Kingdom agreement, www.ipfmlibrary.org/inf263a1.pdf.

[80] David Fischer, *History of the International Atomic Energy Agency: The First Forty Years,* IAEA, New York, 1997, pp. 256-260, and Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order,* Resources for the Future, Washington, DC, October 1987, pp. 159-160. Euratom is controversial within the European Union for other reasons, too. In particular, Article 1 of the Euratom treaty calls for “creating the conditions necessary for the speedy establishment and growth

of nuclear industries." To this end, significant funding for nuclear research and low-interest loans are provided. Critics of the treaty argue that renewable energy sources do not receive comparable institutionalized benefits in the European Union today.

[81] Director-General for Energy and Transport, European Commission, "Nuclear Safeguards," undated, www.euratom.org. See also *INFCIRC/193: Agreement between Belgium, Denmark, the Federal Republic of Germany, Ireland, Italy, Luxembourg, the Netherlands, the European Atomic Energy Community and the Agency in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons,* 14 September 1973, www.ipfmlibrary.org/inf193.pdf.

[82] Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), www.abacc.org.

[83] *Agreement of 13 December 1991 between the Republic of Argentina, the Federative Republic of Brazil, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials and the International Atomic Energy Agency for the Application of Safeguards,* INFCIRC/435, March 1994; www.ipfmlibrary.org/inf435.pdf.

[84] These are now designated as IAEA INFCIRC/66 safeguards agreements and apply only to specified facilities and materials rather than the broad coverage of the 'full-scope' or 'comprehensive' INFCIRC/153. This includes the verification of facilities and materials provided to the non-NPT states under bilateral agreements. These are only the IAEA safeguards at present in these states.

[85] Cristina Chuen, "Russian Spent Nuclear Fuel," *NTI Issue Brief,* February 2003, www.nti.org.

[86] John Carlson, "The Role of Bilateral Nuclear Safeguards Agreements," *Trust and Verify,* No 122, October 2005-February 2006.

[87] The members of the Zangger Committee (www.zanggercommittee.org) are Argentina, Australia, Austria, Belgium, Bulgaria, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Republic of Korea, Luxemburg, the Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, the United Kingdom and the United States.

[88] Members of the Zangger Committee plus Belarus, Brazil, Croatia, Cyprus, Estonia, Kazakhstan, Latvia, Lithuania, Malta, and New Zealand, www.nuclearsuppliersgroup.org.

[89] *Convention on the Physical Protection of Nuclear Material,* www.ipfmlibrary.org/inf274r1.pdf.

[90] See www.iaea.org/About/Policy/GC/GC49/Documents/gc49inf-6.pdf.

[91] S/RES/1540 (2004), www.ipfmlibrary.org/unsc1540.pdf.

[92] UN 1540 Committee, disarmament2.un.org/Committee1540/.

[93] See www.ipfmlibrary.org/unsc8591pdf.

Chapter 5. A Fissile Material Cutoff Treaty

[94] UN General Assembly Resolution 48/75L, 1993.

[95] *Plutonium and Highly-Enriched Uranium 1996, op.cit.* Russia continues to produce weapon-grade plutonium in three production reactors but committed in 1997 that this plutonium will not be used in nuclear weapons, "Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors," 23 September 1997, Article IV, www.ransac.org, also at www.ipfmlibrary.org/ransac97.pdf.

[96] *Initiative of the Ambassadors Dembri, Lint, Reves, Salander and Vega,* CD/1693/Rev. 1, 5 September 2003, www.ipfmlibrary.org/cd1693.pdf.

[97] See e.g. the statement to the CD by Acting U.S. Assistant Secretary of State Rademaker, 18 May 2006, www.ipfmlibrary.org/rad06.pdf.

[98] "Draft Mandate Text" and draft "Treaty on the Cessation of Production of Fissile Material for Use in Nuclear Weapons or other Nuclear Explosive Devices," submitted by the United States to the U.N. Conference on Disarmament, available at www.ipfmlibrary.org/welcome/.

[99] Carol Giacomo, "U.S. to Propose Treaty on Nuclear Fuel Production," *Reuters,* 17 May 2006, www.washingtonpost.com.

[100] Zia Mian, A.H. Nayyar, R. Rajaraman and M.V. Ramana, Fissile Materials in *South Asia and the Implications of the U.S.-India Nuclear Deal,* IPFM Report, 2006, www.ipfmlibrary.org/southasia.pdf.

[101] *IAEA Safeguards Glossary,* 2001 edition, p. 23. The IAEA defines U-233 as a direct-use material. It is not, to our knowledge, actually used in nuclear weapons. The U.S. definition takes into account the fact that it can be isotopically denatured for weapons use by dilution with U-238. A mixture of 12% U-233 with U-238 has the same critical mass as uranium 20% enriched in U-235, see e.g., Jungmin Kang and Frank von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security,* Vol. 9, 2001, p. 1, www.ipfmlibrary.org/sgs09kang.pdf.

[102] "Statement by Ambassador Leonid Skotnikov at the Plenary meeting of the CD," 28 June 2005.

[103] See e.g., *Plutonium Fuel: An Assessment,* OECD, 1989, Table 9.

[104] *IAEA Safeguards Glossary, 2001 edition,* pp. 23, 32. Americium is a mix of Am-241 (432 year half-life) and Am-243 (7400 years). Neptunium-237 has a half-life of 2 million years. The radioactivity of a material varies inversely with its half-life. Plutonium-239 has a half-life of 24,000 years.

[105] See e.g., 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, Table 1, www.ipfmlibrary.org/sgs13kang.pdf.

[106] *Conference on Disarmament Report,* CD/1299, www.reachingcriticalwill.org/political/cd/shannon.html.

[107] See geneva.usmission.gov and www.ipfmlibrary.org/usm06.pdf.

[108] See e.g. "Fissile Material Cutoff Treaty Fact Sheet," Washington File, U.S. Department of State, 29 June 1999, www.ipfmlibrary.org/dos99.pdf

[109] See e.g. Victor Bragin, John Carlson, and John Hill, "Verifying a Fissile Material Production Cutoff Treaty," *Nonproliferation Review,* Fall 1998, pp 97-107.

[110] Mark Hibbs, "U.S. Pressing ElBaradei to Agree to Safeguard both new SWU Plants," *Nuclear Fuel,* Vol. 3, 30 January 2006.

[111] China's Shaanxi centrifuge enrichment plant, "Facilities Under Agency Safeguards or Containing Safeguarded Material on 31 December 2004," *IAEA Annual Report, 2004,* Table A-20, www.ipfmlibrary.org/iaea04.pdf.

[112] *Ibid.*

[113] *Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan,* 7 March 2006, www.ipfmlibrary.org/sep06.pdf.

[114] U.K., INFCIRC/263, 1978; U.S., INFCIRC/288, 1981; France, INFCIRC/290, 1981; China, INFCIRC/369; and USSR/Russia, INFCIRC/327, 1985. IAEA information circulars (INFCIRCs) are available on the IAEA website, www.iaea.org.

[115] "A Cut-Off Treaty and Associated Costs: IAEA Secretariat Working Paper on Different Alternatives for the Verification of a Fissile Material Production Cut-off Treaty and Preliminary Cost Estimates Required for the Verification of these Alternatives," presented at the Workshop on a Cut-Off Treaty, Toronto, Canada, 17-18 January 1995.

[116] *IAEA Annual Report, 1995,* p. 44. Including extra-budgetary resources spent on safeguard support and development would bring the total to $100 million.

[117] D. Dougherty, A. Fainberg, J. Sanborn, J. Allentuck, and C. Sun, *Routine Inspection Effort Required for Verification of a Nuclear Material Production Cutoff Convention,* Brookhaven National Laboratory, Report BNL-63744, SSN-96-14, 1996, www.ipfmlibrary.org/bnl96.pdf.

[118] British Nuclear Fuel Ltd's (BNFL's) B205 plant, which reprocesses Magnox (gas-cooled reactor) fuel, is to be shut down in 2012. BNFL's THORP plant for reprocessing light-water reactor fuel was shut down by a major leak that was detected in April 2005. If it is returned to operation, THORP could complete its reprocessing contracts in 2010, Strategy, U.K. Decommissioning Authority, April 2006, pp. 45-46, www.ipfmlibrary.org/nda06.pdf. No more reprocessing contracts are expected. Russia operates two reprocessing plants associated with plutonium-production reactors at Seversk and Zheleznogorsk. The reactors continue to operate because they supply heat to nearby populations. The

United States and other countries are financing the refurbishment and construction of coal-fired replacement plants. According to the current schedule, the two reactors at Seversk will be shutdown in 2008 and the one at Zheleznogorsk in 2011, "Elimination of Weapons Grade Plutonium," U.S. Department of Energy, www.ipfmlibrary.org/ewgpp.pdf. The military reprocessing plants in Israel, North Korea and Pakistan also would likely shut down under an FMCT.

[119] *The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons,* INFCIRC/153 (Corrected) June 1972, www.ipfmlibrary.org/inf153c.pdf, Sections 73-77.

[120] *Model Protocol Additional to the Agreement(s) Between States and the International Atomic Energy Agency for the Application of Safeguards,* INFCIRC/540 (Corrected), September 1997, www.ipfmlibrary.org/inf540c.pdf, Articles 5c and 18f.

[121] See for example, *Implementation of the NPT safeguards agreement in the Islamic Republic of Iran,* report of the Director General of the IAEA, GOV/2004/83, 15 November 2004, www.ipfmlibrary.org/gov04-83.pdf, paragraphs 36-41.

[122] Richard Stone, "Iran's Nuclear Program: State-of-the-Art Nuclear Sleuths," *Science,* 13 June 2003, p. 1643.

[123] "The DPRK's violation of its NPT Safeguards Agreement with the IAEA," excerpt from David Fischer, *History of the International Atomic Energy Agency,* IAEA, 1997, www.ipfmlibrary.org/iaea97.pdf.

[124] M. Hirota et al., "Spatial and Temporal Variations of Atmospheric ^{85}Kr Observed During 1995-2001 in Japan: Estimation of Atmospheric ^{85}Kr Inventory in the Northern Hemisphere," *J. Radiat. Res.,* Vol. 45, 2004, pp. 405-413.

[125] INFCIRC/153, para. 76d.

[126] *Model Additional Protocol, op. cit,* Article 5c.

[127] U.K. INFCIRC/263/Add.1, 2005; France, INFCIRC/290/Add.1, 2005; and China, INFCIRC/369/Add.1, 2002.

[128] However, the United States added a condition to its ratification of the CWC that samples taken by the Organization for Prohibition of Chemical Weapons could not be taken for analysis outside the U.S.

[129] Michael Guhin, *Remarks at the 7th Carnegie International Non-Proliferation Conference,* Washington, DC, 11-12 January, 1999, www.carnegieendowment.org and www.ipfmlibrary.org/guh99.pdf.

[130] *Fissile Material Transparency Technology Demonstration,* Los Alamos National Lab, www.lanl.gov and www.ipfmlibrary.org/fmtt.pdf.

[131] L.G. Chiang, J.K. Mattingly, J.A. Ramsey and J.T. Mihalczo, "Verification of Uranium Mass and Enrichments of Highly Enriched Uranium Using the Nuclear Materials Identification System (NMIS)," Oak Ridge Y-12 Plant Report No. Y/LB-16,056, 2000, www.ipfmlibrary.org/doe00a.pdf.

[132] M.V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security,* Vol. 12, 2004, p. 91, www.ipfmlibrary.org/sgs12ramana.pdf.

[133] Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review,* Spring 2001, p. 86.

[134] *Ibid.*

[135] A preliminary assessment may be found in, Morten Bremer Maerli, "Timely Options for Increased Transparency and Non-Intrusive Verification on Highly Enriched Uranium Naval Fuel," *Journal of Nuclear Material Management,* Vol. XXXI, No. 4, 2003.

[136] A system developed for assaying the uranium-235 in spent U.S. naval reactor fuel is described in Roddy Walton and Howard Menlove, "Nondestructive Assay for Nuclear Safeguards," *Los Alamos Science,* Summer 1980, p. 88. The fuel burnup could be assayed by measuring neutron emission from the transuranic isotopes and also from the intensity of the decay gamma rays from long-lived fission products, see e.g. H. Toubon, C. Riffard, M. Batifol and S. Pelletier, "Burn-Up Credit, Applications for UO2 and MOX Fuel Assemblies in AREVA/COGEMA," *Proceedings of the 7th International Conference on Nuclear Criticality Safety,* 20-24 October 2003, Tokai-mura, Japan, www.ipfmlibrary.org/tou03.pdf.

Chapter 6. Declarations of Fissile Material Stocks

[137] U.K. Ministry of Defence, *Historical Accounting for U.K. Defence Highly Enriched Uranium*, March 2006, www.ipfmlibrary.org/mod06.pdf.

[138] "Declassification of the United States Total Production of Highly Enriched Uranium," U.S. Department of Energy, 27 June 1994, and "Declassification of Today's Highly Enriched Uranium Inventories at Department of Energy Laboratories," 27 June 1994, www.ipfmlibrary.org/doe06a.pdf.

[139] *Highly Enriched Uranium: Striking a Balance, op. cit.,* www.ipfmlibrary.org/doe01.pdf.

[140] *Ibid.,* pp. 104-109.

[141] *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.

[142] INFCIRC/570, 21 September 1998.

[143] *Historical Accounting for U.K. Defence Highly Enriched Uranium, op. cit.*

[144] Source of redrawn DOE figure: *Plutonium and Highly Enriched Uranium 1996, op. cit.*, p. 82. 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 metric tons of HEU. The Savannah River plant was reported to hold 22 metric tons and Pantex, 16.7 metric tons. 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.

[145] USEC, *Megatons to Megawatts Program*, www.usec.com.

[146] U.S. Department of Energy press release, "DOE Declassifies Location and Forms of Weapon-Grade Plutonium and Highly-Enriched Uranium Inventory Excess to National Security Needs," 8 February 1996, www.ipfmlibrary.org/doe96a.pdf. See also "Initial Characterization of Excess Highly Enriched Uranium," July 1996, Figure 3.1, www.ipfmlibrary.org/doe96b.pdf. Eighteen tons of the HEU was in spent fuel and not expected to be recovered.

[147] *Highly Enriched Uranium: Striking a Balance, op. cit.,* Table 3.3 on p.45.

[148] *Remarks prepared for Energy Secretary Sam Bodman,* Carnegie International Nonproliferation Conference, 7 November 2005, www.carnegieendowment.org.

[149] USEC, *Megatons to Megawatts Program,* www.usec.com.

[150] *Status of Transparency Measures for U.S. Purchase of Russian Highly Enriched Uranium,* U.S. Government Accountability Office Report GAO/RCED-99-194, 1999; J.T. Mihalczo, "Blend-Down Monitoring System for HEU," and "Blend-Down Enrichment Monitoring System for HEU Transparency," Oak Ridge Y-12 Plant Report No. Y/LB-16,051, 2000.

[151] There are 14.2 tons (70 percent average enrichment) of HEU in the form of UF_6 at the U.S. gaseous-diffusion enrichment facility at Portsmouth, Ohio, "USEC-DOE Megatons to Megawatts Program," www.ipfmlibrary.org/usec06.pdf, and an additional 45.8 tons in metal and oxide form (43-percent average enrichment) at the BWXT facility in Lynchburg, Virginia, "Nuclear Products Division Passes IAEA Safeguards for 2002," in *Explore BWXT,* October 2003, p. 21, www.ipfmlibrary.org/bwxt03.pdf. See also Dan Horner, "Blend-Down of USEC HEU Near End, Others Gearing Up, DOE Official Says," *Nuclear Fuel,* 30 January 2006.

[152] Michael Knapik, "DOE has Limits on HEU Sales this Decade," *Nuclear Fuel,* 31 January 2005. The 15-17.4 tons of 60-75-percent enriched material replaces ten tons of U.S. excess weapon-grade HEU that was placed under IAEA safeguards in 1994.

[153] U.S. Department of Energy press release, "DOE Declassifies Location and Forms of Weapon-Grade Plutonium and Highly-Enriched Uranium Inventory Excess to National Security Needs," *op. cit.*

[154] "Joint Statement of Principles for Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes," 2 September 1998, www.nti.org.

[155] *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,* 1 September 2000, www.ipfmlibrary.org/doe00.pdf.

[156] These 11 tons of additional U.S. excess plutonium, which Russia did not wish to match with its own excess weapons plutonium, comprises 7.4 tons of non-weapon-grade plutonium and 3.6 tons of weapon-grade plutonium in scraps, residues and other forms. In addition, the United States declared excess 7.5 tons of plutonium in spent government-owned fuel, "U.S. Surplus Plutonium by Material Type and Disposition Pathway," Office of Fissile Materials Disposition, U.S. Department of Energy, undated.

[157] *Remarks prepared for Energy Secretary Sam Bodman,* Carnegie International Nonproliferation Conference, 7 November 2005.

[158] France's LEU-fueled naval reactors reportedly use LEU enriched to up to 10 percent, which is probably a higher enrichment than that produced by its gas diffusion plant or by the Urenco centrifuge plant that is being built in France. France therefore may be blending down some of its stockpile of HEU to make this LEU.

[159] Ideally, it would be desirable to declare the HEU by enrichment. However, if that is not possible, declaring the U-235 in the HEU is much better than declaring the total mass of the HEU as a way to measure the embedded enrichment work. The enrichment work per kilogram of contained U-235 (assuming 0.3 % depleted uranium) is 192 kilogram-separative-work-units (SWUs) for 20% enriched HEU and 214 for 90-percent enriched HEU.

[160] Based on *Plutonium: The First 50 Years, op. cit.,* Tables 2 and 3, www.ipfmlibrary.org/doe96.pdf.

[161] Based on *Highly Enriched Uranium – Striking a Balance, op. cit.,* Tables 5-1, 5-2 and 5-3.

[162] Frank von Hippel, D.A. Albright and Barbara G. Levi, "Stopping the Production of Fissile Material for Weapons," *Scientific American,* September 1985, pp. 40 47; and Frank von Hippel, D.A. Albright and Barbara G. Levi, *Quantities of Fissile Materials in US and Soviet Nuclear Weapons Arsenals,* Princeton University PU/CEES Report No. 168, 1986.

[163] Steve Fetter, "Nuclear Archeology: Verifying Declarations of Fissile-Material Production," *Science & Global Security,* Vol. 3, 1993, pp. 237-59, www.ipfmlibrary.org/sgs03fetter.pdf; Thomas W. Wood, Bruce D. Reed, John L. Smoot, and James L. Fuller, "Establishing Confident Accounting for Russian Weapons Plutonium," *Nonproliferation Review,* Summer 2002, p. 126.

Chapter 7. Limiting National Fissile-Material Production Capabilities

[164] Brazil announced the start of operations at its Resende centrifuge enrichment facility in May 2006, Steve Kingstone, "Brazil Joins World's Nuclear Club," *BBC,* 6 May 2006, www.ipfmlibrary.org/bbc06.pdf; and "Brazil Officially Starts First Uranium Enrichment Facility," *Environment News Service,* www.ipfmlibrary.org/ens06.pdf.

[165] Nazila Fathi, David E. Sanger and William J. Broad, "Iran Reports Big Advance in Enrichment of Uranium," *New York Times,* 12 April 2006.

[166] Urenco's plant at Capenhurst, U.K. consumed 90 kWh/SWU in 2004, a number that has been declining as later generation centrifuges are introduced, *Health, Safety and Environment,* Report of Urenco, Capenhurst, 2004, p. 24. The energy requirement of a gas-diffusion plant is about 2400 kWh/SWU, "Energy Analysis of Power Systems," *UIC Nuclear Issues Briefing Paper #57,* August 2005, www.ipfmlibrary.org/uip06.pdf.

[167] Assuming that the center-to-center spacing for the centrifuges is 0.5 meters and that each machine has a capacity of 5 SWU/year, 1000 machines could fit into an area of 250 square meters. If the centrifuge hall is 40 percent of the total plant area, the total plant could fit into an area of 625 square meters, Marvin Miller, "The Gas Centrifuge and Nuclear Prolifration," in Victor Gilinsky, Marvin Miller and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors,* Nonproliferation Policy Education Center, Washington, DC, 2004, Appendix I.

[168] Assuming a relatively inefficient 200 kwh/SWU.

[169] By permission, Areva, image 9582.

[170] By permission, Urenco.

[171] "Many Questions Remain about USEC's Centrifuge Performance," *Nuclear Fuel,* 26 April 2004; *Plutonium and Highly Enriched Uranium 1996, op. cit.,* p. 81. The U.S. machines, unlike the Urenco and Russian machines, would require an on-site repair facility.

[172] Figure adapted from P. Upson, *Centrifuge Technology: The Future for Enrichment,* World Nuclear Association Symposium, 5-7 September 2001, www.ipfmlibrary.org/ups01.pdf.

[173] J-M. Charpin, B. Dessus, and R. Pellat, "Economic Forecast Study of the Nuclear Power Option," Office of the Prime Minister, Paris, France, July 2000, www.ipfmlibrary.org/cha00.pdf.

[174] "Cresys-Malville-Superphenix," in Mary Byrd Davis, *Nuclear France: Materials and Sites,* www.ipfmlibrary.org/byrd01.pdf.

[175] "Fast Breeder Reactor," JAEA, Japan, www.ipfmlibrary.org/jnc03.pdf.

[176] N.N. Oshkanov, M.V. Bakanov, and O.A. Potapov, "Experience in Operating the BN-600 Unit at the Belyiyar Nuclear Power Plant," *Atomic Energy,* Vol. 96, No. 5, 2004, p. 315.

[177] "Overview of Fast Reactors in Russia and the Former Soviet Union," Argonne National Laboratory International Nuclear Safety Center, www.ipfmlibrary.org/insc.pdf; "Renaissance of Fast Reactors," RIA Novosti, 24 February 2006, www.ransac.org.

[178] "Construction Begun on Prototype Fast Breeder," *Nuclear News,* January 2005, p. 29.; Mark Hibbs, "Sino-Russian Pilot FBR to Begin Installing Equipment next March," Nuclear Fuel, 28 October 2002.

[179] For a list of the 18 experimental, prototype and commercial breeder reactors that had been built as of 1995, see *Plutonium and Highly Enriched Uranium 1996, op. cit.,* Table 7.1.

[180] Shaun Burnie and Aileen Mioko Smith, "Japan's Nuclear Twilight Zone" *Bulletin of the Atomic Scientists,* May/June 2001, p. 58.

[181] The Draft Environmental Impact Statement (EIS) for the repository found that the suitable area for a repository is at least 4200 acres, *Draft EIS for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada,* DOE/EIS-0250D, 1999, Appendix I, pp. I-26, I-88 to I-96, www.eh.doe.gov. The Final EIS considered loadings ranging from 25 to 56 tons per acre and includes a scenario in which all of the spent fuel projected to be discharged by the current generation of U.S. power reactors (105,000 tons) would be emplaced there. This amount of spent fuel would occupy the full 4200 acres at the 25 tons per acre loading. The same area could hold 235,000 tons at the higher loading, *Final EIS for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada,* DOE/EIS-0250, 2002, www.ocrwm.doe.gov, Table 2-2; Appendix A, Section A.1 and Table A-8; and Appendix I, Figure I-3.

[182] J. Kessler, "Program on Technology Innovation: Room at the Mountain," Electric Power Research Institute, Technical Update, May 2006; "Yucca Mt. Could Hold 570,000 mt, EPRI Says," *Nuclear Fuel,* 24 April 2006, p. 1.

[183] *Nuclear Waste Policy Act of 1982,* Section 114d.

[184] Proposed "Nuclear Fuel Management and Disposal Act," submitted to Congress, 5 April 2006, www.ipfmlibrary.org/bod06.pdf.

[185] *Conference Report on the Energy and Water Appropriations Act for Fiscal Year 2006,* Report 109-275, "Nuclear Energy Programs," pp. 141-142 and "Nuclear Waste Disposal," pp. 156-157.

[186] *Ibid,* Figure 1 and p. 2.

[187] Ronald Wigeland, Theodore Bauer, Thomas Fanning and Edgar Morris, "Separations and Transmutation Criteria to Improve Utilization of a Geological Repository," *Nuclear Technology,* April 2006, p. 95.

[188] *Report to Congress: Spent Nuclear Fuel Recycling Program Plan,* U.S. Department of Energy, May 2006, www.ipfmlibrary.org/doe06.pdf, Figure 3.

[189] *Nuclear Wastes: Technologies for Separations and Transmutation,* National Academy Press, Washington, DC, 1996, www.nap.edu, p. 7. Assuming that the average amount of fission energy released in the first 62,000 tons of U.S. spent fuel was 40,000 megawatt-days per ton and that the heat to electric energy conversion factor is one third, $100 billion would translate into 0.5 cents per kilowatt hour.

[190] Testimony of David J. Modeen, Vice President and Chief Nuclear Officer, Electric Power Research Institute, before the Energy Subcommittee of the Science Committee, U.S. House of Representa-

tives, 6 April 2006, www.ipfmlibrary.org/mod06a.pdf.

[191] The long-term evacuation caused by the Chernobyl accident is primarily due to land contamination by cesium-137, "Exposures and Effects of the Chernobyl Accident," *Sources and Effects of Ionizing Radiation,* United Nations Scientific Committee on the Effects of Atomic Radiation, UN, New York, 2000, Annex J, www.unscear.org.

[192] The leadership of the relevant House of Representatives committee is already unhappy that the Department of Energy has not heeded instructions to include interim storage in its spent fuel program, "House Appropriators Serious about Interim Storage of Utility Fuel," *Nuclear Fuel,* 22 May 2006, p. 1.

[193] The first version of UREX + would have left plutonium mixed with neptunium, see e.g. "Design and demonstration of the UREX+ process using spent nuclear fuel" by G.F. Vandegrift et al, presented at ATALANTE 2004 – Advances for future nuclear fuel cycles, Nimes, France, 21-24 June 2004. The May 2006 DOE version was to leave all of the minor transuranics, including americium and curium, mixed with the plutonium. However, the radiation dose from this mix would still be orders of magnitude below the IAEA's self-protection standard of one Sievert per hour at one meter, E.D. Collins," Closing the Fuel Cycle Can Extend the Lifetime of the High-Level-Waste Repository," Oak Ridge National Laboratory, American Nuclear Society 2005 Winter Meeting, 17 November 2005, Washington, DC, p. 13, www.ipfmlibrary.org/ornl05.pdf; and 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 pp. 169-181, www.ipfmlibrary.org/sgs13kang.pdf. Most recently, Argonne has proposed that the lanthanide fission products would remain in the transuranic mix until it was delivered to each fast-neutron reactor site. There the lanthanides would be separated out and the fuel fabricated, Phillip Finck, Deputy Associate Laboratory Director, "The Benefits of the Closed Nuclear Fuel Cycle," Applied Science and Technology and National Security, Argonne National Laboratory, briefing to U.S. House of Representatives staff, 10 March 2006, Slide 3.

[194] *Report to Congress: Spent Nuclear Fuel Recycling Program Plan, op. cit.,* p. 10.

[195] Paul Webster, "Minatom: The Grab for Trash," *Bulletin of the Atomic Scientists,* September-October 2002, p. 33.

[196] Peter Baker, "U.S. and Russia to Enter Civilian Nuclear Pact Bush Reverses Long-Standing Policy, Allows Agreement That May Provide Leverage on Iran," *Washington Post,* 8 July 2006.

[197] Office of Nuclear Energy, Department of Energy, "Notice of Request for Expressions of Interest in a Consolidated Fuel Treatment Center to Support the Global Nuclear Energy Partnership," and "Notice of Request for Expressions of Interest in an Advanced Burner Reactor to Support the Global Nuclear Energy Partnership," *Federal Register,* 71, #151, 7 August 2006, pp. 44673-44679.

[198] See *e.g. International Fuel Cycle Evaluation: Fast Breeders,* International Atomic Energy Agency, INFCE/PC/5, 1980, Table 1.

[199] U.S. Nuclear Regulatory Commission, "Waste Confidence Decision Review," *Federal Register,* 55, 1990, p. 38474-38514.

[200] See *e.g. U.S. Monitored Retrievable Storage Review Commission, Nuclear Waste: Is There a Need for Federal Interim*
Storage? 1989 and Allison Macfarlane, "Interim Storage of Spent Fuel in the United States," *Annual Review of Energy and Environment,* Vol. 26, 2001, p. 201.

[201] "The Acheson-Lilienthal Report on the International Control of Atomic Energy," *op.cit.*

[202] See *e.g.,* the discussions in the Summary and Working Group reports of the International Nuclear Fuel Cycle Evaluation, IAEA, 1980. See also Lawrence Scheinman, "The Nuclear Fuel Cycle: A Challenge for Nonproliferation," *Disarmament Diplomacy,* Issue No. 76, March/April 2004.

[203] The White House, "Fact Sheet: Strengthening International Efforts against WMD Proliferation," 11 February 2004, www.ipfmlibrary.org/usg04.pdf.

[204] "The Proliferation Security Initiative," U.S. State Department, www.ipfmlibrary.org/dos04.pdf, and "The Proliferation Security Initiative at a Glance," www.armscontrol.org.

[205] U.N. Security Council Resolution 1540, 28 April 2004, www.ipfmlibrary.org/unsc1540.pdf.

[206] Statement by the IAEA Director General, Dr. Mohammed El Baradei, to the 58th Regular Session of the U.N. General Assembly, 3 November 2003, www.ipfmlibrary.org/iaea03.pdf. See also, Dr.

Mohammed El Baradei, “Toward a Safer World,” *The Economist,* 16 October 2003, www.ipfmlibrary.org/iaea03a.pdf. These statements referred to facilities producing separated plutonium and highly enriched uranium. Subsequently, it became clear that El Baradei’s proposal covered all enrichment plants.

[207] Section 6 of the NSG Part I guidelines, published in IAEA INFCIRC/254/Rev.5/Part 1 (Corrected), “Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment, and Technology,” www.iaea.org and www.nuclearsuppliersgroup.org.

[208] *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the International Atomic Energy Agency,* IAEA, INFCIRC-640, 2005, www.ipfmlibrary.org/inf640.pdf, pp. 102-3, 19.

[209] “Skepticism of [Multinational Nuclear Arrangements],” *Nuclear Fuel,* 25 April 2005.

[210] “Putin Says Russia is Ready to Create International Fuel Cycle Center,” *Nuclear Fuel,* 30 January 2006; “Questions Abound on Proposals by Bush, Putin on Fuel Centers,” *Nuclear Fuel*, 13 March 2006.

[211] *Stemming the Spread of Enrichment Plants: Fuel-Supply Guarantees and the Development of Objective Criteria for Restricting Enrichment,* Princeton University, Woodrow Wilson School of Public and International Affairs, January 2006, www.ipfmlibrary.pdf/wws06.pdf, p. 23.

[212] The other 21 non-weapon states are: Argentina (0.9 GWe), Armenia (0.4), Belgium (5.8), Brazil (1.9), Bulgaria (2.7), Canada (has 12.3 GWe but natural-uranium fueled), Czech Republic (1.7), Finland (2.7), Hungary (1.7), Iran (1 nearly complete), Lithuania (1.3), Mexico (1.4), Netherlands (0.5), Romania (0.6), Slovak Republic (2.5), Slovenia (0.7), South Africa (1.8), Spain (7.6), Sweden (9.5), Switzerland (3.2), and Taiwan (4.9). The nuclear weapon states that have less than 10 GWe of nuclear power capacity are: China (6), India (3), Israel (0), North Korea (0.005), and Pakistan (0.5). The U.K. may also soon fall below the threshold, RWE Nukem Market Report, December 2005, p. 19.

[213] “French Centrifuge Plant Will be ‘Black Box’ Equipped with TC-21 Machine,” *Nuclear Fuel,* 19 December 2005.

Chapter8. Global Cleanout of Highly Enriched Uranium

[214] Matthew Bunn and Anthony Weir, *Securing the Bomb 2006,* Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University; commissioned by the Nuclear Threat Initiative, www.nti.org/cnwm; William Hoehn, “Update on Congressional Activity Affecting International Cooperative Nonproliferation Programs,” Russian-American Nuclear Security Advisory Council, 7 June 2006, www.ransac.org.

[215] *Strategic Plan 2006,* Office of International Material Protection and Cooperation, National Nuclear Security Administration, U.S. Department of Energy, 2005.

[216] *DOE Needs to Take Action to Further Reduce the Use of Weapons-Usable Uranium in Civilian Research Reactors,* U.S. Government Accountability Office, GAO-04-807, 2004, p. 28.

[217] The most prominent and controversial exception is the German research reactor FRM-II, which became operational in 2004. This facility requires more than 40 kg of HEU per year. If the reactor is not converted it will therefore discharge in its planned 40-year lifetime up to 1,600 kg of irradiated HEU fuel, still enriched to more than 88-percent.

[218] Status and progress of international RERTR activities are regularly summarized in overview papers presented at the annual RERTR conferences, www.rertr.anl.gov.

[219] Presentation by Andrew Bieniawski, Director of the U.S. Department of Energy’s Global Threat Reduction Initiative, International RERTR Conference, 7 November 2005.

[220] Pure uranium metal is not suitable as a research-reactor fuel because it swells seriously under irradiation at only a fraction of the desired fuel life.

[221] Uranium-molybdenum alloy fuel may not be suitable for research reactors that operate at the high temperatures associated with power reactors. Russia has a 100 MWt research reactor that operates at such temperatures and is building another. Both have associated HEU-fueled critical assemblies.

[222] Two IAEA research-reactor experts put it this way at the 2003 international Reduced Enrichment for Research and Test Reactors (RERTR) conference: “Only reactors with special attributes (such as

a high neutron flux, a cold [neutron] source, in-core loops to simulate power reactor conditions) or with commercial customers (such as radioisotope production or silicon doping) are adequately utilized."

[223] In 2000, the IAEA's International Nuclear Safety Advisory Group urged consideration of proper decommissioning of 258 shutdown research reactors worldwide. In a follow-up analysis, one reason cited for these reactors not being decommissioned was "the hope that the reactor will be returned to operation," F. Alcala-Ruiz et al, *Safety of Research Reactors,* IAEA, 2001 www.ipfmlibrary.org/iaea01.pdf.

[224] Picture of BFS2 from Institute of Physics and Power Engineering website. Picture of ZPPR reactor from Argonne National Laboratory website, www.ne.anl.gov.

[225] *The Future Use of Critical and Subcritical Assemblies,* report of a Consultation held at IAEA HQ, Vienna, 7-10 February 2005.

[226] *Using Low-Enrichment Uranium in VNIIEF Pulsed Nuclear Reactors,* International Science and Technology Center Proposal #3128.

[227] Laura Holgate, Nuclear Threat Initiative, personal communication, 14 December 2005.

[228] Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," Nonproliferation Review, Vol. 8, 2001, p. 86.

[229] *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion,* prepared by Director of Naval Nuclear Propulsion, June 1995.

[230] Thomas Ippolito Jr., *Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design,* M.S. dissertation, MIT, 1990, www.ipfmlibrary.org/ipp90.pdf.

[231] Chunyan Ma and Frank von Hippel, *op. cit.*

[232] *Remarks Prepared for Energy Secretary Spencer Abraham,* International Atomic Energy Agency, Vienna, 26 May 2004.

Glossary

Additional Protocol. The voluntary agreement between a state and the International Atomic Energy Agency to accept more stringent safeguards than those originally required to verify compliance with the Nonproliferation Treaty or other safeguards agreements. Devised in the 1990s following the discovery of Iraq's clandestine uranium-enrichment programs, it broadens the information on nuclear activities a state declares to the IAEA and provides additional rights for IAEA inspectors to verify this declaration, including taking swipe samples to check for possible undeclared nuclear activities in a country.

Americium-241. A fissile isotope with a half-life of 433 years produced from decay of plutonium-241. There is no public information that americium has ever been used to build a nuclear weapon but it is considered an "alternative nuclear material" by the IAEA.

Breeder reactor. A nuclear reactor that produces more fissile material than it consumes in "fertile" material (U-238 or thorium). Most R&D has been focused on fast-neutron reactors cooled with liquid sodium. Despite many attempts, breeder reactors have not been successfully commercialized.

Burn-up. A measure of the fission energy generated by a mass of fuel in a reactor usually given at the time of discharge from the reactor, measured in units of thermal megawatt-days per kilogram or thousand thermal megawatt-days per metric ton.

Cascade. The arrangement of isotope separation elements (for example, centrifuges) in a uranium enrichment facility. The cascade is organized as a series of "stages" in each of which separation elements operate in parallel. The stages are connected in series so that material from one stage is passed to another for further enrichment or depletion of the uranium in the isotope U-235. The final output streams when the feed is natural uranium are enriched and depleted uranium.

Centrifuge. A rapidly rotating cylinder used for the enrichment of uranium in which the heavier isotope (uranium-238) in uranium hexafluoride gas is forced to higher concentrations near the cylinder's walls, while the lighter isotope (uranium-235) concentrates towards the center of the cylinder.

Chain reaction. A continuing process of nuclear fissioning in which the neutrons that are released from one fission trigger other nuclear fissions. In a nuclear weapon, an extremely rapid, multiplying chain reaction causes an explosive release of energy. In a reactor operating at constant power, the chain reaction is controlled so that each fission causes on average exactly one fission.

Critical mass. The minimum amount of a fissile material required to sustain a chain reaction. The exact mass of material needed to sustain a chain reaction varies according to its geometry, the mixture of fissile isotopes and other elements it contains, its density (e.g. whether it is in metal or oxide form), and the neutron-reflecting properties and thickness of the surrounding materials.

Depleted uranium. Uranium having a smaller percentage of uranium-235 than the 0.7 percent found in natural uranium. It is a by-product of the uranium enrichment process.

Enrichment. The process of increasing the concentration of one isotope of a given element (in the case of uranium, increasing the concentration of uranium-235).

Fertile material. Nuclear isotopes that are transmuted by neutron absorption and radioactive decay into fissile materials. One such element is uranium-238, which, after it absorbs a neutron, decays in two steps into plutonium-239.

Fissile material. Material that can sustain an explosive fission chain reaction – notably plutonium of almost any isotopic composition and highly-enriched uranium.

Fission. The process by which a fissionable nucleus splits either after absorbing a neutron or, in some cases, spontaneously. During the process of nuclear fission, typically two or three high-speed neutrons also are emitted, along with gamma rays.

Fissionable material. A heavy isotope with an atomic nucleus that can be caused to undergo fission when struck by a neutron. Uranium-238 is a fissionable isotope, in that it can be fissioned by high-energy neutrons, although, unlike uranium-235, it cannot sustain a fission chain reaction.

Fizzle yield. The reduced explosive energy that is released by a nuclear weapon when the chain reaction is initiated at the first moment when the explosive assembly becomes critical. This is termed pre-initiation. In an implosion weapon using reactor-grade plutonium, a fizzle yield could be the equivalent to the explosion of one kiloton of TNT.

Gaseous diffusion. A method of isotope separation based on the fact that gas molecules carrying isotopes with different masses diffuse through a porous barrier (or membrane) at different rates. The method is used to separate uranium hexafluoride molecules containing uranium-235 from molecules containing uranium-238. It requires significant amounts of electric power to pump the gas through the membranes.

Half-life. The time required for one-half of the nuclei in a quantity of a specific radioactive isotope to decay.

Heavy metal. The uranium, thorium, and transuranic elements in reactor fuel, usually measured in metric tons.

Heavy-water reactor. A reactor that uses heavy water as a neutron “moderator,” i.e. to slow the neutrons between fissions. Most of the hydrogen in heavy water is deuterium, whose nucleus, unlike that of ordinary hydrogen, contains a neutron as well as a proton. Only about one in ten thousand hydrogen atoms in nature is deuterium. Heavy water is made by concentrating water molecules containing deuterium. Heavy water reactors typically use natural uranium as fuel. It is impossible to sustain a chain reaction in natural uranium in a reactor moderated by ordinary water because the “light” hydrogen in the water absorbs too many neutrons.

High-level waste. The radioactive waste containing fission products and non-plutonium "transuranic" elements (i.e. neptunium, americium and curium) resulting from the reprocessing of spent fuel.

Highly enriched uranium (HEU). Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to 20 percent or more. A large fraction of HEU is 90-percent enriched or higher because it was originally produced for weapons use.

International Atomic Energy Agency (IAEA). A separately funded organization, established in 1957 under the United Nations, that is responsible for promoting the peaceful use of nuclear technology and implementing "safeguards" agreements with non-weapon states under which it checks that fissile material is not diverted from peaceful uses and (for states that are members of the Nonproliferation Treaty) that no fissile material is made in undeclared facilities.

Isotope. A form of any element that is designated by the sum of the number of protons and neutrons that its nucleus contains (e.g. uranium-235 has 92 protons and 143 neutrons). Because all isotopes of an element have the same number of protons in the nucleus and therefore the same number of electrons, they have virtually the same chemical properties. But, because they have different numbers of neutrons in the nucleus, they have different atomic weights and nuclear properties. Uranium-235, for example, can sustain a fission chain reaction while uranium-238, whose nucleus contains three more neutrons, cannot.

Kiloton TNT (kt). A unit used to measure the energy of a nuclear explosion, roughly the energy released by the explosion of one thousand tons of TNT, by definition, equal to 10^{12} calories (4.184×10^{12} joules). The fission of 1 kilogram of fissile material releases about 18 kilotons of TNT equivalent.

Light water. Ordinary water (H_2O) as distinguished from heavy water (D_2O) that contains deuterium, a heavier isotope of hydrogen.

Light-water reactor. A reactor that uses ordinary water to cool the reactor and to "moderate" the speeds of neutrons between fissions and usually uses low-enriched uranium as fuel.

Low-enriched uranium (LEU). Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to less than 20 percent. The fuel of light-water reactors is usually enriched to 4-5 percent. Fuel rods containing low-enriched uranium can sustain a chain reaction when immersed in ordinary water.

Megawatt (MW). One million watts. Used to measure the rate of energy output of a nuclear power plant: 1 million watts of electricity (megawatts-electric, or MWe). Also used to measure the rate at which heat is released in research or plutonium-production reactors: 1 million watts of thermal energy (megawatts-thermal, or MWt). A typical light water power reactor today has a peak electricity generation capacity of approximately 1000 megawatts-electric – that is, 10^9 watts. Such a reactor would generate about 3000 megawatts-thermal.

Megawatt-day (MW-day). A unit of energy. The cumulative amount of heat that would be released in a day at a rate of one megawatt. The fission of one gram of uranium or plutonium releases approximately one megawatt-day of thermal energy.

Metric ton (sometimes tonne). One thousand kilograms. A metric weight equivalent to about 1.1 short tons. A short ton equals 2000 pounds.

Mixed-oxide fuels (MOX). Nuclear reactor fuel composed of a mixture of plutonium and natural or depleted uranium in oxide form, commonly referred to as MOX fuel. The plutonium replaces the uranium-235 in low-enriched uranium as the primary fissioning material in the fuel. MOX is used in Europe – and planned in India and Japan – to recycle plutonium recovered from spent fuel through reprocessing. The United States and Russia hope to dispose of some of their excess weapon plutonium in MOX fuel.

Natural uranium. Uranium as found in nature, containing 0.7 percent of uranium-235, 99.3 percent of uranium-238, and trace quantities of uranium-234 formed by the decay of U-238.

Neptunium-237. A 2-million-year half-life fissile isotope, produced in nuclear reactors by two successive neutron captures on uranium-235. There is no public information that neptunium-237 has actually ever been used in a nuclear weapon but its properties make it as suitable as U-235 and the IAEA considers it an "alternative nuclear material."

Neutron. An uncharged elementary particle with a mass slightly greater than that of a proton. Neutrons are found in the nuclei of every atom heavier than hydrogen. Neutrons provide the links in a fission chain reaction.

Nuclear fuel. Basic chain-reaction material, usually including both fissile and fertile materials. Commonly used nuclear fuels are natural uranium and low-enriched uranium. Highly enriched uranium and mixed-oxide fuel (see above) are also used to fuel some reactors.

Nuclear fuel cycle. The chemical and physical operations needed to prepare nuclear material for use in reactors and to dispose of or recycle the material after its removal from the reactor. Existing fuel cycles begin with the mining of uranium ore and produce fissile plutonium as a by-product by absorption of neutrons in uranium-238 while the fuel is in the reactor. Some proposed fuel cycles would use natural thorium as a fertile material to produce the fissile isotope uranium-233, which would then be recycled in reactor fuel. An "open" fuel cycle stores the spent fuel indefinitely. A "closed" fuel cycle reprocesses it and recycles the fissile and fertile material once or more and stores the fission products and other radioactive isotopes.

Nuclear reactor. An arrangement of nuclear and other materials designed to sustain a controlled nuclear chain reaction that releases heat, which can be used to generate electricity, or mechanical power to propel a ship. Since reactors can also produce fissile material (for example, plutonium) in the irradiated fuel, they may be used as a source of fissile material for weapons. Nuclear reactors fall into three general categories: power reactors, production reactors (for producing fissile materials such as plutonium and U233, and also radioactive isotopes used in medicine) and research reactors.

Nuclear Supplier Group (NSG). A group of nuclear technology and material supplier countries organized in 1977 which have agreed to guidelines for nuclear exports, currently including a "trigger list" of items that suppliers agree to export to non-nuclear weapon states only when the receiving state has brought into force an agreement with the IAEA that allows the Agency to safeguard all nuclear activities within the state.

Nuclear waste. The radioactive products formed by fission and neutron transmutation of materials in a reactor. Most nuclear waste is initially contained in spent fuel. If this material is reprocessed, new categories of waste result.

Nuclear Weapon Free Zone. A region of non-nuclear weapon states that have reaffirmed collectively through a treaty their decision not to manufacture, acquire, test, or possess nuclear weapons and their requirement that nuclear weapon states not store nuclear weapons there or threaten to use nuclear weapons against the signatories.

Plutonium-239. A fissile isotope produced when uranium-238 captures an extra neutron. The plutonium that has been used in the core of nuclear weapons typically contains more than 90 percent Pu-239. It has a half-life of about 24,000 years.

Plutonium-240. An isotope produced in reactors when a plutonium-239 atom absorbs a neutron instead of fissioning. Its concentration is limited in weapons plutonium because of its high rate of spontaneous fission. It has a half-life of 6600 years.

Plutonium-241. A fissile isotope produced in reactors by neutron absorption by plutonium-240. Pu-241 has a half-life of only 14 years and decays into americium-241.

Power reactor. A reactor designed to produce heat to generate electricity, as distinguished from reactors used primarily for research or for producing plutonium or other isotopes.

Production reactor. A reactor designed primarily for the large-scale production of plutonium for weapons and/or tritium.

Radioactivity. The spontaneous disintegration of an unstable atomic nucleus, resulting in the emission of electrons (beta decay), helium nuclei (alpha decay), and/or gamma rays (high-energy X-rays).

Reactor-Grade Plutonium. The United States defines reactor-grade plutonium as containing more than 18 percent plutonium-240 – much more than in weapon-grade plutonium. Reactor-grade plutonium can be used, however, to make a nuclear explosive.

Recycle. The reuse of the uranium and/or plutonium in spent fuel after separation from fission products by a reprocessing plant.

Reprocessing. The chemical treatment of spent reactor fuel to separate plutonium and uranium from fission products. Because of the intense radioactivity of the fission products, this has to be done remotely behind heavy shielding.

Research reactor. A reactor designed primarily to supply neutron irradiation for experimental purposes. It may also be used for training, the testing of materials, and the production of radioisotopes.

Safeguards. Measures aimed at detecting in timely fashion the diversion of significant quantities of fissile material from monitored peaceful nuclear activities. For non-nuclear weapon states that are parties to the Nonproliferation Treaty, the safeguards are implemented by the IAEA. See *Significant Quantity.*

Separative Work Unit (SWU). A measure of the work done by a machine or plant that separates uranium into streams with higher and lower fractions of U-235. Sometimes referred to as a kilogram-SWU to distinguish it from a ton-SWU (1000 SWUs).

Significant quantity (SQ). The IAEA defined amount of fissile material required to manufacture a first-generation nuclear explosive device: Plutonium containing less than 80% Pu-238 – 8 kg, Uranium-233 – 8 kg, and Uranium-235 (in HEU) – 25 kg.

Spent fuel. Fuel elements that have been removed from the reactor because the fissionable material they contain has been depleted to a level near where it can no longer sustain a chain reaction. The high concentration of radioactive fission products in spent power-reactor fuel creates a gamma-radiation field around it that makes light-water reactor fuel "self protecting" for about one hundred years. At a distance of a meter, the gamma field would be lethal in minutes a few years after discharge and in hours a century after discharge.

Strategic Offensive Reduction Treaty (SORT). An agreement between the United States and Russia that entered into force in June 2003 to reduce the number of their *operationally deployed* strategic nuclear warheads to 1700-2200 warheads each by the end of 2012.

Thermonuclear explosive. A type of nuclear weapon that produces much of its energy through nuclear fusion reactions of heavy hydrogen isotopes (also known as a hydrogen bomb). These fusion reactions only proceed at temperatures around one hundred million degrees that are created by a fission explosive "trigger." Thermonuclear weapons can have yields much larger than simple fission weapons.

Thorium-232. The naturally-occurring isotope of thorium that is "fertile" in that neutron absorption in it produces the fissile isotope Uranium-233.

Transuranic. Any element whose atomic number is higher than that of uranium. All transuranics are produced artificially and are radioactive. The most commonly produced transuranic isotopes, in order of increasing weight, are neptunium, plutonium, americium and curium.

Tritium. The heaviest hydrogen isotope, containing one proton and two neutrons in the nucleus, produced most effectively by bombarding lithium-6 with neutrons. In a fission weapon, the fusion of tritium with deuterium to make helium produces an extra neutron that can be used to cause additional fissions. Tritium-deuterium gas is used in modern fission weapons to produce extra neutrons in this way to "boost" the weapon's explosive power.

Uranium. A radioactive element with the atomic number 92. The two principal natural uranium isotopes are uranium-235 (0.7 percent of natural uranium), which is fissile, and uranium-238 (99.3 percent of natural uranium), which is not.

Uranium dioxide (UO_2). The chemical form of uranium used in heavy-water and light-water power reactor fuel. Produced as a powder, uranium dioxide is pressed and then sintered into ceramic fuel pellets.

Uranium hexaflouride (UF_6). A volatile compound of uranium and fluorine. UF_6 is a solid at atmospheric pressure and room temperature, but can be transformed into gas by heating. UF_6 gas is the feedstock in gas-centrifuge and gaseous-diffusion uranium enrichment processes.

Uranium oxide (U_3O_8). The most common oxide of uranium found in typical ores. Uranium oxide is extracted from the ore during the milling process. The ore may contain only 0.1 percent uranium oxide. Yellowcake, the product of the milling process, contains about 80 percent uranium oxide.

Uranium-233. A fissile isotope produced by neutron absorption in fertile thorium-232. Like HEU and plutonium, it is theoretically an excellent material for nuclear weapons. It has been used in at least one nuclear test but not in deployed nuclear weapons – perhaps because a small amount of U-232 is produced with it. A decay product of the U-232 produces gamma radiation at levels higher than the levels produced by weapon-grade plutonium. U-233 is also a potentially attractive reactor fuel for heavy and light-water moderated reactors because it releases more neutrons than U-235 per neutron absorbed.

Uranium-235. The only naturally occurring fissile isotope. Natural uranium contains 0.7 percent uranium-235; light-water reactors use fuel containing 4-5 percent; and weapon-grade highly enriched uranium normally contains at least 90 percent of this isotope.

Uranium-238. A fertile material. Natural uranium contains approximately 99.3 percent uranium-238.

Weapon-grade. Fissile material with the isotopic makeup typically used in fission explosives, that is, uranium enriched to over 90 percent uranium-235 or plutonium that is more than 90 percent plutonium-239. The HEU used in the Hiroshima weapon was enriched to about 80 percent. Uranium enriched to greater than 20 percent and plutonium containing less than 80 percent Pu-238 are considered weapon-usable, however.

Yellowcake. A uranium concentrate produced during the process of extracting uranium from ore (“milling”) that contains about 80 percent uranium oxide (U_3O_8). In preparation for uranium enrichment, the yellowcake is converted to uranium hexafluoride gas (UF_6). In the preparation of natural uranium heavy-water power reactor fuel, yellowcake is processed into purified uranium oxide.

Yield. The total energy released in a nuclear explosion – usually measured by the number of kilotons of TNT whose explosion would release the same amount of energy.

Appendix A

IPFM Members

Morten Bremer Mærli (Norway, shared membership with Reistad) a nuclear physicist by training, is a senior research fellow at the Norwegian Institute of International Affairs (NUPI), working on nuclear nonproliferation and the prevention of nuclear terrorism. His doctoral thesis, titled *Crude Nukes on the Loose? Preventing Nuclear Terrorism by Means of Optimum Nuclear Husbandry, Transparency, and Non-Intrusive Fissile Material Verification,* assesses the risk of nuclear terrorism. The best threat reducing strategy is by far to control or eliminate the fissile material at its sources. Mærli has worked at the Norwegian Radiation Protection Authority, with control and protection of nuclear materials as his prime responsibility. He has experience with the current situation and practices concerning the handling, storing and security of fissile materials in Northwest Russia. He has been a technical consultant to the Norwegian Ministry of Foreign Affairs.

Anatoli Diakov (Russia) is a Professor of Physics (Ph.D. in 1975) and, since 1991, Director of the Center for Arms Control, Energy and Environmental Studies of the Moscow Institute of Physics and Technology (Russia's MIT). Diakov has written papers on nuclear arms reductions, the history of Russia's plutonium production, disposition options for excess plutonium, and the feasibility of converting Russia's icebreaker reactors from highly enriched to low-enriched uranium as well as on many other topics relating to nuclear arms control and disarmament.

Jean du Preez (South Africa) is currently Director of the International Organizations and Non-proliferation Program of Monterey Institute for International Studies' Center for Non-proliferation Studies. Prior to Monterey, he served in the South African Ministry of Foreign Affairs for 17 years, including as Deputy-Director for nonproliferation and disarmament and as senior political counselor for disarmament affairs at South Africa's Permanent Mission to the United Nations. During this time, he represented his country at several international negotiating meetings, including the 1995 and 2000 NPT Review Conferences. du Preez has written extensively about the possible paths forward on the nuclear disarmament and nonproliferation agenda, including the Fissile Material Cutoff Treaty.

José Goldemberg (Co-chair, Brazil) has a Ph.D. in nuclear physics (1954). He was Rector of the University of São Paolo (1986-90), Federal Minister of Science and Technology (1990-91), and Federal Minister of Education (1991-92) and has been the Minister of Environment of São Paolo since 2002. While Brazil's Minister of Science and Technology, Goldemberg persuaded President Collor de Mello to end Brazil's nuclear-weapons program, which led Argentina to shut its program down as well under monitoring by a joint Argentine-Brazil inspectorate. Goldemberg is best known for his work on global energy (including the future of nuclear energy and its consequences) and environmental issues, which resulted in him being a co-recipient of Sweden's Volvo Environmental Prize in 2000.

Pervez Hoodbhoy (Pakistan) is professor of physics at Quaid-e-Azam University, Islamabad. He holds a Ph.D. in nuclear physics from the Massachusetts Institute of Technology and is the recipient of the Abdus Salam Prize for Mathematics, the Baker Award for Electronics, Faiz Ahmad Faiz Prize for contributions to education in Pakistan, and the UNESCO Kalinga Prize for the popularization of science. He has been a visiting professor at MIT, Carnegie Mellon University, the University of Maryland, and the Stanford Linear Accelerator. Dr. Hoodbhoy is a member of the Pugwash Council, and a sponsor of The Bulletin of the Atomic Scientists. He is frequently invited to comment on nuclear and political matters in Pakistani and international media.

Martin B. Kalinowski (Germany, shared membership with Schaper) holds a Ph.D. in nuclear physics (1997) dealing with international tritium control. For a decade, he was a scientific assistant in the Interdisciplinary Research Group on Science, Technology, and Security (IANUS) at Darmstadt University of Technology, Darmstadt, Germany. In October 1998, Dr. Kalinowski joined the International Data Center of the Provisional Technical Secretariat of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Vienna, Austria. His research focused on the development of analysis methods for atmospheric xenon gas samples. During the spring term 2005, he served as Assistant Professor in the Department for Nuclear, Plasma and Radiological Engineering (NPRE) and was on the faculty of the University of Illinois at Urbana-Champaign in the Program in Arms Control, Disarmament and International Security (ACDIS). March 2006, he became a full professor for Science and Peace Research and director of the newly established Carl-Friedrich von Weizsäcker Center for Science and Peace Research at the University of Hamburg, Germany. His research agenda deals with novel measurement technologies as well as nuclear and meteorological modeling of atmospheric radioactivity monitoring as a means to detect clandestine nuclear activities like plutonium separation and nuclear testing.

Jungmin Kang (South Korea) has a Ph.D. in Nuclear Engineering from Tokyo University (1999) and spent two years with Princeton's Program on Science and Global Security (1998-2000). He is currently the lead South Korean analyst in the MacArthur-Foundation-funded East-Asia Science-and-Security Initiative. Kang has co-authored articles on radioactive-waste management, spent-fuel storage, the proliferation-resistance of closed fuel cycles, plutonium disposition and the history of South Korea's explorations of a nuclear-weapon option. He has contributed many articles to South Korea's newspapers and magazines and is frequently interviewed about spent-fuel issues and the negotiations over North Korea's nuclear-weapon program. He served as an advisor to South Korea's National Security Council on North Korean nuclear issues during 2003 and currently serves on South Korea's Presidential Commission on Sustainable Development where he advises on nuclear energy policy.

Li Bin (China, shared membership with Shen), an arms-control physicist, is a professor of international studies and the director of the Arms Control Program at the Institute of International Studies, Tsinghua University. At Tsinghua University, he teaches arms control and international security, quantitative analysis in international studies, science and technology in international security. Since 1990, Dr. Li has been working on various arms control issues including space arms control, nuclear test ban, missile defenses, deep nuclear reductions and Chinese-U.S. nuclear relations. He has published papers on arms control issues in Chinese and international journals. His book, *Arms Control Theories and Analysis* will be published by Peking University Press. Professor Li is on the editorial boards of *Science and Global Security, Nonproliferation Review* and on the boards of China Arms Control and Disarmament Association and China-U.S. People's Friendship Association.

Miguel Marin Bosch (Mexico) currently a Professor considering offers from both Mexico's National University and its Foreign Service Diplomatic Academy, had a long career in Mexico's foreign service, ending up as Deputy Minister for Asia, Africa, Europe and Multilateral Affairs. During the early 1990s, he was Mexico's Ambassador to the Conference on Disarmament and chair of the Comprehensive Test Ban Negotiations during the first year of formal negotiations (1994).

Arend J. Meerburg (The Netherlands) has an MSc in nuclear reactor physics (1964). He worked some years in oceanography and meteorology (including in the Antarctic). He joined the Ministry of Foreign Affairs in 1970 and worked there until his retirement in 2004. During most of that period he was involved in multilateral arms control matters, including the final negotiations in Geneva of the Chemical Weapons Convention and the Comprehensive Nuclear-Test-Ban treaty. He was involved in many NPT-matters, the International Nuclear Fuel Cycle Evaluation (INFCE), discussions on an International Plutonium Storage regime (IPS), the Nuclear Suppliers Group etc. Recently he was a member of the IAEA expert-group on Multilateral Nuclear Approaches to sensitive parts of the fuel cycle. He also served as Ambassador to Yemen (1996-2000).

Abdul H. Nayyar (Pakistan) has a Ph.D. in physics (1973) from Imperial College, London. Nayyar retired from the faculty of Quaid-i-Azam University in 2005. He has been active in Pakistan's nuclear-weapon policy debate since 1997 and a regular summer visitor with Princeton's Program on Science and Global Security since 1998. Nayyar has co-authored articles on nuclear-reactor safety, fissile-material production in South Asia, the consequences of nuclear war in South Asia, and the feasibility of remote monitoring of a moratorium on plutonium separation in South Asia. He served as President of the Federation of Pakistani University Academic Staff Associations in 1989-90 and currently is President of Pakistan's Peace Coalition and the Co-convener of Pugwash Pakistan. Nayyar writes regularly on nuclear-policy issues in the South Asian press.

R. Rajaraman (India) has a Ph.D. in theoretical physics from Cornell University (with Hans Bethe, 1963). Rajaraman is one of India's leading theoretical physicists (Fellow of both the Indian Academy of Science and the Indian National Science Academy). He has been contributing articles to India's nuclear-weapons debate since 1970 and has been a regular summer visitor with Princeton's Program on Science and Global Security since 2000. Since he retired from the faculty of the Jawaharlal Nehru University in 2004, he has been devoting nearly full time to nuclear policy analysis and public education. He has written articles on the dangers of accidental nuclear war and the limitations of civil defense against nuclear attacks in South Asia. In recent years, his focus has been on capping South Asia's nuclear arsenals.

M. V. Ramana (India, shared membership with Rajaraman) a physicist by training, is currently a Fellow at the Centre for Interdisciplinary Studies in Environment and Development (CISED), Bangalore. He obtained his Ph.D. from Boston University, U.S. and has held research positions at the University of Toronto, the Massachusetts Institute of Technology, and Princeton University. He specializes in studying the Indian nuclear energy and weapons programs. Currently he is examining the economic viability and environmental impacts of the Indian nuclear power program. He is actively involved in the peace and anti-nuclear movements, and is associated with the Coalition for Nuclear Disarmament and Peace, as well as Abolition-2000, a global network to abolish nuclear weapons. He is co-editor of Prisoners of the Nuclear Dream (New Delhi: Orient Longman, 2003) and author of *Bombing Bombay? Effects of Nuclear Weapons and a Case Study of a Hypothetical Explosion,* (Cambridge, MA: International Physicians for the Prevention of Nuclear War, 1999).

Ole Reistad (Norway, shared membership with Maerli) is a research scientist with a joint appointment at the Institute of Physics in the Norwegian University of Science and Technology (NTNU) in Trondheim and at the Norwegian Radiation Protection Authority. Reistad's work thus far has focused primarily on the security and safety issues posed by the spent Russian naval nuclear fuel and retired Russian submarines on Russia's Kola Penninsula, in addition to more nuclear safety issues in Russia. Reistad is currently working on his Ph.D. on Russian naval reactor design and issues related to spent fuel material attractiveness and criticality.

Henrik Salander (Sweden) is an Ambassador currently on leave from Sweden's Foreign Ministry as the Secretary-General of the WMD Commission chaired by Hans Blix. He led Sweden's delegation to the 2000 NPT Review Conference where Sweden, along with the six other members of the New Agenda Coalition (Brazil, Egypt, Ireland, Mexico, New Zealand and South Africa), extracted from the weapon states, 13 specific commitments to steps toward ending the arms race, reducing their arsenals and the danger of nuclear use, and establishing a framework for irreversible disarmament. Salander was Sweden's Ambassador to the Geneva Conference on Disarmament (1999-2003) where he authored the 2002 "five ambassadors" compromise proposal that still is the basis for efforts there to start negotiations on an FMCT and other treaties. He also chaired the 2002 session of the Preparatory Committee for the 2005 NPT Review Conference.

Annette Schaper (Germany, shared membership with Kalinowski) is a senior research associate at the Peace Research Institute Frankfurt (PRIF) since 1992. Her research covers nuclear arms control and its technical aspects, including the test ban, a fissile material cutoff, verification of nuclear disarmament, fissile materials disposition, and nonproliferation problems arising from the civilian-military ambivalence of science and technology. She was a part-time member of the German CD delegation in Geneva in the CTBT negotiations and member of the German delegation at the NPT Review and Extension Conference. Her former position was at the Institute of Nuclear Physics at Technical University Darmstadt where she became a co-founder of the Interdisciplinary Research Group in Science, Technology, and Security Policy. Schaper holds a Ph.D. in experimental physics from Düsseldorf University. Currently, she directs a project on transparency of nuclear arms control related information owned by the nuclear weapon possessing states.

Dingli Shen (China, shared membership with Li), a physicist by training, is a professor of international relations at Fudan University. He is the Executive Dean of Fudan University's Institute of International Studies and Deputy Director of the Center for American Studies. He co-founded China's first non-government-based Program on Arms Control and Regional Security, at Fudan University. Dr. Shen teaches nonproliferation and international security, and China's foreign policy, in China and the United States. His research areas cover China-U.S. security and nuclear relationships, regional security and nonproliferation issues, and China's foreign and defense policies. Dr. Shen is a member of IISS, and a number of other international organizations and editorial boards of academic journals. In January 2002, he was invited by the Secretary General of the United Nations, Kofi Annan, to advise the SG of strategy panning for his second term, as the sole Chinese, out of 40 persons chosen worldwide. Dr. Shen received his Ph.D. in physics in 1989 from Fudan University and did his post-doc in arms control at Princeton University from 1989-1991. In 1997, he was awarded an Eisenhower Fellowship. From 1997-2000, he served as Fudan University's Director of the Office of International Programs and Deputy Director of Fudan's Committee on Research and Development.

Tatsujiro Suzuki (Japan) has a Ph.D. in nuclear engineering from Tokyo University (1988). He is a Senior Research Scientist in the Central Research Institute of [Japan's] Electric Power Industry in Japan as well as a Senior Research Fellow at the Institute of Energy Economics of Japan and Project Professor at the Graduate School of Law and Politics, University of Tokyo. He was Associate Director of MIT's International Program on Enhanced Nuclear Power Safety from 1988-1993 and a Research Associate at MIT's Center for International Studies (1993-95) where he co-authored a report on Japan's plutonium program. For the past 20 years, Suzuki has been deeply involved in providing technical and policy assessments of the international implications of Japan's plutonium fuel-cycle policies and in examining the feasibility of interim spent-fuel storage as an alternative. He was appointed as a member of the Working Group on International Affairs of the Japan Atomic Energy Commission's Long Term Planning Committee and now is a member of the of the Ministry of Economy, Trade and Industry's Advisory Committee on Energy (Nuclear Policy Subcommittee).

Frank von Hippel (Co-Chair, U.S.) has a Ph.D. in nuclear physics (1962). He is co-Director of Princeton's Program on Science and Global Security. In the 1980s, as chairman of the Federation of American Scientists, he partnered with Evgenyi Velikhov in advising Mikhail Gorbachev on the technical basis for steps to end the nuclear arms race. In 1994-5, he served as Assistant Director for National Security in the White House Office of Science and Technology Policy. von Hippel and his colleagues have worked on fissile material policy issues for the past 30 years, including contributions to: ending the U.S. program to foster the commercialization of plutonium breeder reactors, convincing President Gorbachev to embrace the idea of a Fissile Material Production Cutoff Treaty, launching the U.S.-Russian cooperative nuclear materials protection, control and accounting program, and broadening efforts to eliminate the use of high-enriched uranium in civilian reactors worldwide.

William Walker (U.K.) is Professor of International Relations at the University of St. Andrews. He is co-author of *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (SIPRI/Oxford University Press, 1997), author of *Weapons of Mass Destruction and International Order* (Adelphi Paper, 2004), and he has done much research on the domestic and international politics of reprocessing.

The Program on Science and Global Security

The Program on Science and Global Security (PS&GS) is located in Princeton University's Woodrow Wilson School for Public and International Affairs. For the past thirty years the Program's technical research and policy analyses have sought to foster cooperative international initiatives with a particular focus on controlling fissile materials. The Program also does research on the security-policy implications of the advance of biotechnology and on ways of improving public-health preparedness for infectious diseases.

PS&GS has helped educate and sustain an international community of technical experts in cooperative approaches to nuclear security and disarmament. It collaborates with a number of nuclear arms control and nonproliferation research centers and independent analysts in Russia, China, South Korea and South Asia.

Science & Global Security, which since 1989 has been the international journal of "arms control science" is based at the Program and edited by Dr. Harold Feiveson. It is now published in Russian and Chinese, as well as in English and is available on the web.

The Program's researchers are Professor Christopher Chyba, Dr. Harold Feiveson, Dr. Alexander Glaser, Dr. Laura Kahn M.D., Scott Kemp, Dr. Zia Mian, and Professor Frank von Hippel. The Program Manager is Dorothy Davis. Davis, Feiveson, Glaser, Mian and von Hippel provide research and administrative support for the International Panel on Fissile Materials.

Further information on the Program, its research activities, and publications can be found at www.princeton.edu/~globsec/.

PS&GS Research and Administrative Staff

Dorothy Davis, Program Manager, has been with the Program on Science and Global Security since the fall of 2002. However, she is a veteran employee of Princeton University, having served over 20 years. She manages all financial and administrative functions of the Program.

Harold Feiveson, Co-Director of PS&GS, Senior Research Scientist and Lecturer in Princeton University's Woodrow Wilson School, Feiveson's principal research interests are in the fields of nuclear weapons and nuclear energy policy. His recent work has focused on the ways in which the nuclear arsenals of the United States and the former Soviet Union can be dismantled and "de-alerted", the strengthening of the nuclear nonproliferation regime (including a universal ban on the production of weapon-usable material and on nuclear weapons testing), and the strengthening of the separation between nuclear weapons and civilian nuclear energy activities. Feiveson is the editor of the journal, *Science & Global Security*.

Alexander Glaser, Research Staff, joined the Program on Science & Global Security in February 2005. Previously, he was associated with the Interdisciplinary Research Group in Science, Technology, and Security (IANUS) of Darmstadt University of Technology, Germany, where he worked on his master's and Ph.D. thesis, both related to technical aspects of arms control and nuclear nonproliferation. Between 2001 and 2003, he was an SSRC/MacArthur pre-doctoral fellow affiliated with the Technical Group of the Security Studies Program and the Nuclear Engineering Department, both at MIT. Glaser has been an advisor to the German Federal Ministry of Environment and Reactor Safety in the years 2000 and 2001 and serves on the Council to the Executive Board of the German Physical Society.

Zia Mian, Research Scientist and Director of the Program on Science and Global Security's Project on Peace and Security in South Asia. His interests are in nuclear weapons and nuclear energy policy in South Asia. Recently, he has worked on issues of nuclear command and control, early warning and civil defense in South Asia, and on the challenges posed by non-compliance with international agreements and norms on nuclear arms control and nonproliferation, especially by nuclear weapon states. He is active with several social movements and civil society groups working for nuclear disarmament and more just and ecologically sustainable societies.

Frank von Hippel, Co-Chair of IPFM, Co-Director of PS&GS and Professor of Public and International Affairs.

Over the past six decades, our understanding of the nuclear danger has expanded from the threat posed by the vast nuclear arsenals created by the superpowers in the Cold War to encompass the proliferation of nuclear weapons to additional states and now also to terrorist groups. To reduce this danger, it is essential to secure and to sharply reduce all stocks of highly enriched uranium and separated plutonium, the key materials in nuclear weapons, and to limit any further production.

The mission of the IPFM is to advance the technical basis for cooperative international policy initiatives to achieve these goals.

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