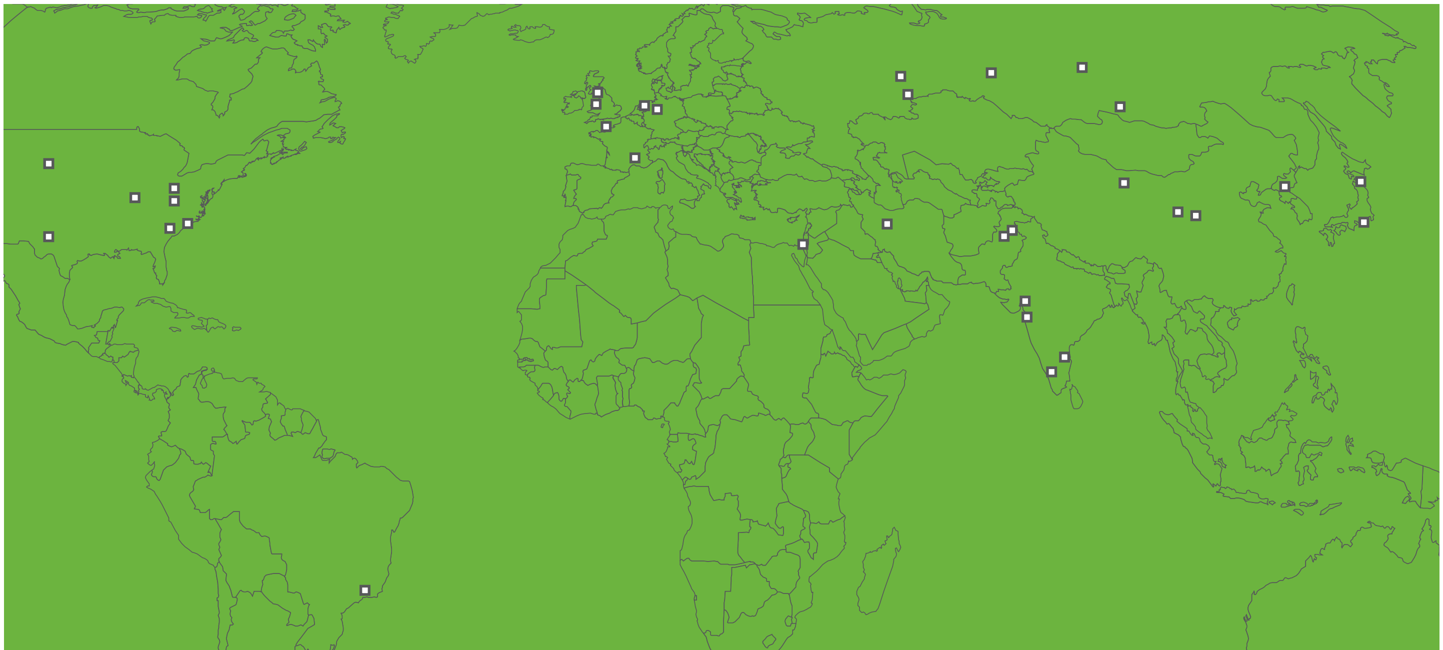

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

Global Fissile Material Report 2008

Scope and Verification of a Fissile Material (Cutoff) Treaty

Third annual report of the International Panel on Fissile Materials

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Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty

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On the cover: the map shows existing and planned uranium enrichment and plutonium separation (reprocessing) facilities around the world.
See pages 38–39 of this report for more details.

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About the IPFM

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

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

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

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

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

Princeton University's Program on Science and Global Security provides administrative and research support for the IPFM.

IPFM's initial support is provided by a five-year grant to Princeton University from the John D. and Catherine T. MacArthur Foundation of Chicago.

Overview: A Verified Fissile Material (Cutoff) Treaty

A treaty banning the production of fissile materials for nuclear weapons is an essential requirement for constraining nuclear arms races and, in the longer term, achieving nuclear disarmament. Fissile materials, in practice plutonium and highly enriched uranium, are the essential materials in nuclear weapons. Their production is the most difficult step in making nuclear weapons.

Negotiation of a Fissile Material Cutoff Treaty was endorsed without a dissenting vote in 1993 by the United Nations General Assembly.[1] In 1995, the Geneva based Conference on Disarmament (CD) agreed to begin negotiations on "a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile materials for nuclear weapons or other nuclear explosive devices." But talks did not begin. At the Review Conference of the Parties to the Non-Proliferation Treaty (NPT) in 2000, it was agreed that negotiations should commence immediately, "with a view to their conclusion within five years."[2] The CD has, for various reasons, again not formally launched negotiations on a treaty.

In the discussion of the proposed treaty, two issues have been especially contentious: pre-existing stocks and verification.

Pre-existing stocks. Proponents of a Treaty that would only ban production name it a Fissile Material Cut-Off Treaty (FMCT). There are, however, huge stocks of fissile material in weapons as well as outside the weapon complexes. The latter stocks are currently designated for civilian or naval reactor use or are being recovered from Cold War weapons that have been declared excess for military use. Those who would also like the Treaty to prevent possible future use of these materials for weapons prefer to call the Treaty a Fissile Material Treaty. To reflect this disagreement, this report uses the term Fissile Material (Cutoff) Treaty, or FM(C)T. It proposes, however, treaty articles addressing pre-existing civilian stocks, stocks declared excess to military purposes, and stocks of highly enriched uranium declared for use as fuel for naval-propulsion and other military reactors and verification of their non-weapon use.

Verification. On May 18, 2006, the Bush Administration submitted to the CD a draft FM(C)T that marked a break with previous U.S. policy, by omitting any provisions for international verification. The U.S. delegation asserted that "even with extensive verification mechanisms and provisions—so extensive that they could compromise the core national security interests of key signatories, and so costly that many countries would be hesitant to implement them—, we still would not have high confidence in our ability to monitor compliance with an FMCT."[3]

There are reasons, however, to prefer a verified treaty and to believe that it could be verified at reasonable cost:

- Agreed verification measures have been considered by the parties to be essential to creating confidence and trust for virtually all treaties pertaining to nuclear weapons.

- The non-nuclear-weapon state Parties to the Nonproliferation Treaty have accepted comprehensive international verification of their commitments under that treaty. Many of these states have repeatedly expressed concerns that, by not requiring parallel verification in the NPT nuclear weapon states, the treaty puts the non-weapon states at a competitive disadvantage in the development of civilian nuclear power. A verified FM(C)T would go far toward redressing this inequity.

- Interest in nuclear disarmament has recently revived. Much deeper cuts in the nuclear stockpiles will require intrusive inspections in the nuclear weapon states. International verification of a FM(C)T would be a step in the process of establishing a verification system for fissile materials in the nuclear weapon states.

In order to give the CD the option of a verified Treaty, we have therefore designed a treaty with verification arrangements.

We assume that the IAEA rather than a new verification agency would verify the FM(C)T. The IAEA has extensive experience in inspecting nuclear installations and nuclear materials, including a limited number of facilities in the NPT nuclear weapon states. To undertake the new responsibilities, the IAEA's Safeguards Division would have to grow substantially, and funding for such an expansion would have to be arranged. The costs would be negligible, however, in comparison, for example, with the production costs of nuclear energy.

In principle, verification of an FM(C)T in the civilian sectors of the nuclear weapon states could be based on the NPT verification procedures in the non-weapon states. It is possible, however, that some of these procedures may be difficult to implement quickly in the nuclear weapon states after the FM(C)T enters into force. The FM(C)T and NPT verification regimes should converge, however, as soon as possible.

There would also be special challenges in nuclear weapon states relating to excess fissile materials in classified forms, HEU-fueled military reactors and inspections in military nuclear facilities.

In the first chapter, we summarize the current publicly available information on global fissile-material stocks and production.

In the second chapter, we discuss why an FM(C)T is important.

In Chapter 3, we present and discuss draft articles of an FM(C)T, including obligations, definitions and verification. These articles, in addition to imposing a ban on all future production of fissile material for weapons, address also pre-existing stocks. They ban the use for weapons of fissile materials that are in the civilian sector at the time a state joins the Treaty, that states declare as excess to their weapon needs, and that have been declared for use in naval-propulsion or other military reactors.

The subsequent chapters discuss the challenges to the verification of such an FM(C)T, with regard to:

- Uranium enrichment facilities;
- Reprocessing facilities;
- Weapons materials declared excess for military use but still in classified form;
- HEU committed for naval reactor fuel;
- Challenge inspections at military nuclear sites; and
- Shutdown facilities that formerly produced fissile materials for nuclear weapons.

Uranium enrichment facilities

FM(C)T verification in enrichment facilities in the nuclear weapon states might initially be limited to verifying that no HEU is being produced. For enrichment facilities that have not made HEU in the past and have not become contaminated with HEU, such verification should be relatively easy. The detection of any HEU in, for example, the dust collected on a swipe of a surface—would reveal illicit production.

Large enrichment plants in which HEU particles from past production are present would pose a more difficult challenge. In such cases, it would be necessary to distinguish old from new HEU. Our analysis in Chapter 4 suggests such discrimination may be possible by characteristic isotopic signatures. A complementary approach that appears feasible for facilities that have not produced HEU for more than 20 years is age-dating of uranium particles.

Reprocessing facilities

For reprocessing plants that are already in operation at the time the treaty comes into force, there would be special verification challenges. It would not be possible for the IAEA to do complete design verification or install its own instrumentation as it can in new facilities before concrete is poured around pipes and before some areas became inaccessible because of high radiation levels. Compromises will have to be made in the verification at such facilities. In Chapter 5, we propose a safeguards approach and estimate the cost.

Weapons material declared excess for military use

Fissile material that was formerly in nuclear weapons and has been declared excess and converted to unclassified forms can be safeguarded by the IAEA in the same manner as fissile materials in non-weapon states. Materials that have been declared excess but are still in weapons components—for example the 14,000 U.S. nuclear-weapon "pits" that are stored at the U.S. Department of Energy's Pantex site—are a greater challenge.

From 1996 to 2002, IAEA, Russian and U.S. experts worked together to address this challenge. They developed techniques that would allow the IAEA to determine whether canisters declared to hold weapon components contain more than a threshold quantity of weapon-grade plutonium while blocking access to all other design information (Chapter 6).

This "Trilateral Initiative" did not address the monitoring of weapon components containing HEU. We believe that the verification approach described below for HEU-bearing naval-reactor fuel assemblies could be applied to such components.

HEU committed for use in naval-propulsion reactor fuel

The five NPT nuclear weapon states and India all use nuclear reactors for naval propulsion. Of these, four or five use HEU as fuel. An FM(C)T will have to verify that, at least, newly-produced HEU is not diverted from their naval fuel cycles to weapons. The challenge will be to devise a way to provide confidence to the international community in this regard while at the same time protecting the secrecy of design information.

The Nonproliferation Treaty also permits non-weapon states to remove enriched uranium from safeguards to fuel naval propulsion reactors. Although, to date, no non-weapon state has done this, Brazil, which is developing an LEU-fueled naval reactor, is expected to do so within the next several years. The IAEA and Brazil are working out procedures by which Brazil can reassure the IAEA that no nuclear material is being diverted without revealing classified design information. These procedures are not yet public.

We describe in Chapter 7 a partial approach to the problem of providing reassurance with regard to non-diversion of HEU from the naval-reactor fuel cycle. This same approach could be applied if countries were willing to place under IAEA monitoring pre-existing stocks of HEU committed for military-reactor use.

Challenge inspections at military nuclear sites

After the discovery of Iraq's clandestine enrichment program in 1991, the IAEA's Board of Governors authorized development of the Additional Protocol to the safeguards agreements between the IAEA and non-weapon states. Countries that ratify this protocol and bring it into force agree to provide the IAEA with information about all their nuclear-related activities, not just their nuclear materials. They also accept the possibility that the IAEA could undertake wide-area environmental monitoring and could request on-site inspections just about anywhere to confirm that the declarations are complete and correct. At sensitive facilities, this may involve "managed access" arrangements under which the IAEA and the inspected country agree on a procedure that will allow the IAEA to conduct its investigation without compromising national-security or proprietary information.

The NPT weapon states have also negotiated Additional Protocols with the IAEA. Most weapon-state Additional Protocols focus on reporting information on exports of nuclear technologies and materials to non-weapon states. The United States has gone further, however, and has agreed to the same Additional Protocol as the non-weapon states while adding a "national-security exclusion" that allows it to refuse access to sites or information relevant to its national security if, in its view, managed access is not feasible. For the types of sensitive facilities that are present in non-weapon states, managed access in weapon states could be conducted by the same procedures. We discuss how managed access under an FM(C)T could work at military nuclear facilities based on the Additional Protocol and the Chemical Weapons Convention in Chapter 8.

Shut-down production facilities

Many reprocessing and enrichment plants and plutonium-production reactors in the nuclear weapon states have been shut down. The cost of monitoring these sites to assure that they have not resumed operations would vary somewhat, depending on the complexity and accessibility of the plant and the presence or absence of any remaining fissile materials (Chapter 9).

Reprocessing plants would require the most attention. However, the use of tags and seals, radiation monitors, video cameras and photographic records, and periodic inspections, supplemented where appropriate by satellite observations, would be sufficient to provide assurance of a facility's non-operating status. Overall, the safeguards burden would be very low in comparison to that at operating facilities.

We conclude that the verification of an FM(C)T need not compromise core national-security interests nor be so costly that countries should hesitate to implement them. The technical challenges of verifying a FM(C)T are significant but manageable. The costs could be less than the current IAEA safeguards budget. Verifying an FM(C)T will become easier and less expensive as the remaining military fissile-material production facilities are shutdown and dismantled.

1 Nuclear Weapon and Fissile Material Stockpiles and Production

In mid-2008, the global stockpile of highly enriched uranium (HEU) was 1670 ± 300 tons.* Most of the uncertainty is due to Russia not having declared the quantities of HEU that it produced during the Cold War. More than 99% of the global HEU stockpile is held by the nuclear weapon states, with only about ten tons in non-weapon states—mostly in research reactor fuel. There is an international effort to convert civilian HEU-fueled research reactors to LEU and return the HEU to the United States or Russia, the countries that supplied the original fuel.

The global stockpile of separated plutonium, all of which is weapon-usable, is about 500 tons. About half of this stockpile is civilian and continues to grow. The growth of the global civilian plutonium inventory has slowed down to less than 5 tons a year temporarily because of shutdown by an accident at the Thorp reprocessing plant in the United Kingdom and continuing delays in the startup of Japan's large new Rokkasho reprocessing plant.

Only India, Pakistan and possibly Israel, continue to produce fissile materials for nuclear weapons. The United States, United Kingdom, Russia, France, and North Korea have officially announced an end to their production for weapons, while China has indicated this unofficially.

North Korea reportedly declared an inventory of separated plutonium of 37 kg as part of its 2007 agreement to end its nuclear program.

The United States and Russia have declared as excess to weapons requirements or for all military purposes a significant fraction of their stocks of both highly enriched uranium and plutonium produced for weapons. Much larger amounts could be taken out of the Russian and U.S. military stockpiles as they reduce their arsenals to 1700–2200 deployed strategic warheads by 2012 as agreed under the Strategic Offensive Reductions Treaty (SORT). Cuts in their arsenals to 1000 total warheads each, for example, would allow for their fissile-material stocks to be reduced by an order of magnitude to 5 tons of weapon-grade plutonium and 30 tons of HEU each, including material for nuclear weapon R&D and in working inventories.

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

The United States and Russia continue to blend down the 217 and 500 tons respectively of highly enriched uranium (HEU) that they have declared excess to military requirements to produce low-enriched uranium to fuel light-water reactors. Both countries retain large stocks of HEU for their naval-propulsion programs. The United States has assigned 128 tons of excess weapon-grade uranium as a reserve for naval fuel.

The United States and Russia have yet to put in place the infrastructure to eliminate the 34 tons of excess weapons plutonium each committed to dispose under the U.S.-Russian Plutonium Management and Disposition Agreement of 2000. In late 2007, the United States declared excess an additional 9 tons of weapons plutonium.

The United States and France have announced cuts in their nuclear warhead stockpiles. The most knowledgeable NGOs estimated that the U.S. cuts would take its warhead stockpile to fewer than 5,000 warheads. President Sarkozy announced a reduction in France's arsenal to fewer than 300 nuclear warheads, about half of its Cold War peak.

The year 2008 has seen the shutdown, dismantlement, and demolition of further production facilities. In April and June 2008, Russia finally shut down two plutonium reactors at Seversk (Tomsk-7), which had produced about ten tons of plutonium as a by-product of heat and electric power production since 1994. As part of the process of disabling and dismantling its nuclear-production facilities, North Korea demolished the cooling tower of its Yongbyon production reactor in June 2008. France, which closed its military enrichment and reprocessing facilities in 1996, invited international inspectors to confirm that they are being decommissioned.

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

Nuclear Weapon Stocks

Nine states have nuclear weapons. These are, in historical order: the United States, Russia, the United Kingdom, France, China, Israel, India, Pakistan and North Korea. Estimates of their current nuclear-weapon stockpiles are shown in Table 1.1. The U.S. and Russian stockpiles peaked at approximately 30,000 for the United States (around 1965) and 40,000 for Russia (around 1985).

Country	Nuclear Warheads
United States	about 10,000 5000 deployed + 5000 awaiting dismantlement
Russia	about 10,000 Large uncertainty as to the number of warheads awaiting dismantlement
France	fewer than 300
United Kingdom	185
China	about 240
Israel	100 – 200
Pakistan	about 60
India	60 – 70
North Korea	fewer than 5

Table 1.1. Estimated total nuclear-weapon stockpiles, 2008. [Source: NRDC/FAS]

Significant recent developments in the arsenals of the nuclear weapon states are summarized below.

United States. In December 2007, the Bush administration announced the early achievement of the 2004 decision to approximately halve the stockpile of nuclear warheads in possession of the military.[4] It stated that, with these cuts, by the end of 2007, "the U.S. nuclear stockpile will be less than one-quarter its size at the end of the Cold War."[5] No numbers were given, but R. S. Norris of the Natural Resources Defense Council (NRDC) and H. Kristensen of the Federation of American Scientists (FAS) estimated that this cut in forces meant that, as of January 2008, the U.S. military stockpile contained about 5400 nuclear warheads, with an additional 5150 warheads awaiting dismantlement.[6]

Along with the announcement, President Bush directed that the military stockpile be reduced by a further 15% by 2012, when the United States and Russia have agreed to reach a ceiling of 1700–2200 operationally deployed strategic nuclear warheads.[7] This would bring the above estimated U.S. military stockpile of nuclear warheads down to a total of about 4600.

Russia. As of early 2008, the NRDC/FAS estimate was that Russia had about 5200 nuclear warheads in its operational stockpile and a further 8800 in reserve or awaiting dismantlement, for a total of 14,000 nuclear warheads.[8] These estimates are much more uncertain than those for the U.S. stockpile.

China. As part of its modernization program, China is introducing new nuclear-weapons systems. The U.S. Defense Department's 2008 *Annual Report to Congress: Military Power of the People's Republic of China* suggests that China has increased its nuclear arsenal by 25 percent since 2006.[9] This increase is attributed to the deployment of 60–100 new solid-fueled ballistic and cruise missiles offset only in part by the retirement of older liquid-fueled ballistic missiles. Further additions and retirements are expected.[10] Currently, China is estimated by the NRDC/FAS team to have 176 deployed warheads, and a total stockpile of about 240 (Figure 1.1).[11]

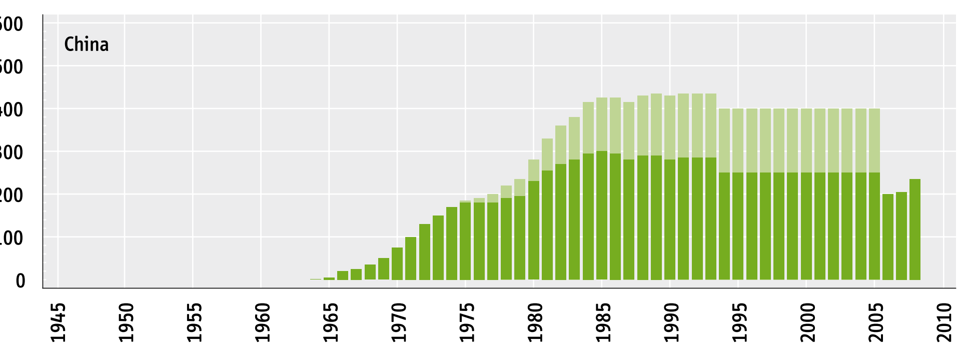

Figure 1.1. NRDC/FAS estimates of China's total stockpile of nuclear weapons. In 2006, the NRDC/FAS experts revised their estimates for China after the U.S. Department of Defense concluded that China may not have the tactical nuclear weapons previously ascribed to it (light green in graph).

France. In a March 2008 speech marking the launch of the new ballistic-missile submarine, *Le Terrible,* France's President Nicolas Sarkozy announced that the airborne component of France's nuclear forces would be reduced by one third "[w]ith respect to, the number of nuclear weapons, missiles and aircraft." He added that, "[a]fter this reduction, I can tell you that our arsenal will include fewer than 300 nuclear warheads. That is half of the maximum number of warheads we had during the Cold War."[12] Based on previous NRDC/FAS estimates, these cuts would be equivalent to a reduction of about 50 warheads compared to the 2007 stockpile. President Sarkozy also revealed that France "has no other weapons beside those in its operational stockpile." This would suggest France currently has about 290 warheads (Figure 1.2).[13]

The fissile material associated with the nearly 300 warheads that have been retired from the French arsenal since the end of the Cold War has not yet been declared excess. Assuming the usual average values per warhead,[14] these excess inventories should amount to about 1.2 tons of plutonium and 7.5 tons of highly enriched uranium.

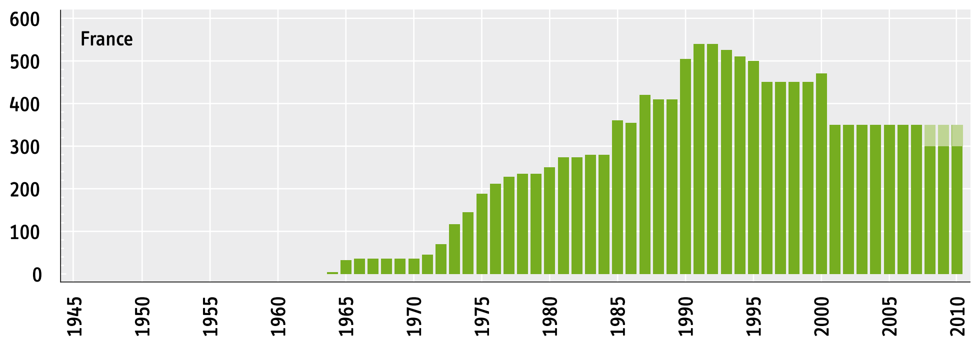

Figure 1.2. In March 2008, French President N. Sarkozy announced that, after the planned reductions, *"I can tell you that our arsenal will include fewer than 300 nuclear warheads. That is half of the maximum number of warheads we had during the Cold War."* NRDC/FAS estimates of the French nuclear arsenals (shown in the figure) peaked in the early 1990s at 540 warheads, which is roughly consistent with this official information.

Israel. There continues to be uncertainty about the size of Israel's nuclear arsenal, which is usually estimated at 100–200 warheads.[15]

Highly Enriched Uranium Stocks

Figure 1.3 shows the estimated national stocks of highly enriched uranium as of mid-2008. More than 99 percent of the global HEU stockpile is in the possession of the nuclear weapon states. Only the United Kingdom and the United States have made public the total sizes of their stocks of HEU.[16] Estimates of the remaining national holdings are generally quite uncertain. According to these estimates, despite the elimination of over 400 tons of Russian and U.S. HEU by down-blending to low-enriched uranium, the global inventory still totals 1670 ± 300 tons. The main uncertainty in estimating the global total is due to a lack of information on the Russian stockpile (see also Figure 1.4. below). *Global Fissile Material Report 2007* contains a detailed discussion of the elements of the U.S. stockpile.[17]

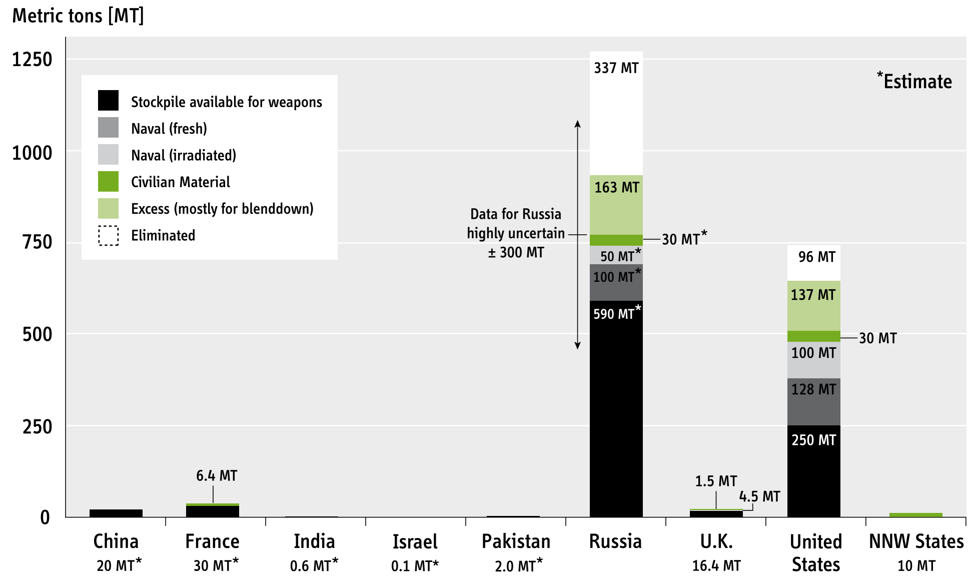

Figure 1.3. National stocks of highly enriched uranium as of mid-2008. The numbers for the United Kingdom and United States are based on official information. Numbers with asterisks are non-governmental estimates, often with large uncertainties.[18] Numbers for Russian and U.S. excess HEU are for June 2008. HEU in non-nuclear-weapon (NNW) states is under IAEA safeguards.

The most significant changes compared to the previous year are due to the ongoing blend-down activities in Russia and the United States, which together eliminated about 40 tons of HEU between mid-2007 and mid-2008. As of mid-2008, the United States had down-blended cumulatively about 96 tons of highly enriched uranium.[19] Little if any of this material was weapon-grade. As of June 2008, Russia had eliminated 337 out of 500 tons of weapon-grade HEU as part of its 1993 HEU deal with the United States,[20] which is to be completed in 2013.

The U.S. Department of Energy proposes to keep the H-Canyon at the Savannah River Site open until 2019 to reprocess spent HEU research reactor fuel and to recover HEU from composite (HEU and plutonium) pits. The recovered HEU is to be down-blended.[21]

Israel. For the first time, we add an entry of 100 kg of weapon-grade HEU for Israel, which may have acquired this material covertly in or before 1965 from the United States. There have been several classified investigations of this case. Recently two former government officials published articles to the effect that such a transfer did indeed occur. In October 2007, former Congressional staffer, Henry Myers wrote that "[s]enior officials in the U.S. government concluded in the late 1960s that weapon-size quantities of HEU had probably been diverted from NUMEC [Nuclear Materials and Equipment Corporation] to Israel."[22] Victor Gilinsky, a former U.S. Nuclear Regulatory Commissioner, has revealed that "the CIA believed that the nuclear explosives in Israel's first several bombs, about one hundred kilograms of bomb-grade uranium in all, came from material that was missing at a U.S. naval nuclear fuel plant."[23] Once Israel developed its plutonium-production capacity at Dimona, it may have used this HEU stockpile for other military-related purposes, such as to produce driver fuel for tritium production in the reactor.[24]

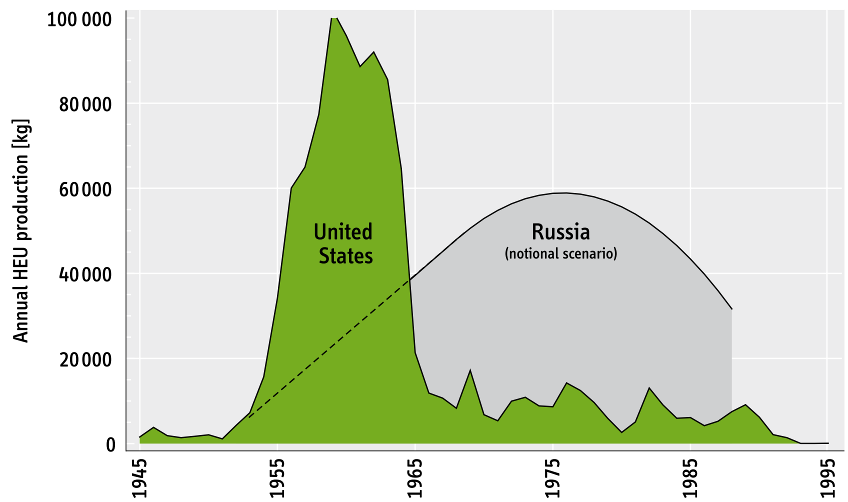

Figure 1.4. Historical production rates of HEU in the United States and Russia. The U.S. data is based on its 2001 declaration, which was released in 2006.[25] Annual U.S. production peaked in 1959 at 102,000 kg of HEU. The United States stopped production of HEU for weapons in 1964. However, it began producing even more highly enriched material (97 % vs. 93 %) for naval fuel. The scenario for Russia is based primarily on estimates of the growth of its installed enrichment capacity offset by the gradual rise in the use of this capacity to produce LEU for power-reactor fuel. Russia's estimated HEU production peaked at around 60,000 kg/yr in the mid-1970s. Total U.S. production was 1045 tons of HEU with an average enrichment of 82 %. Based on the notional scenario shown here, total Russian HEU production was on the order of 1400 – 1500 tons (90 % enriched).[26]

Pakistan.[27] Pakistan may be the only country producing HEU for weapons today. India is producing HEU for naval fuel—but probably less than weapon-grade. This is discussed further below.

Pakistan is believed to have first achieved the capacity to produce a significant quantity of HEU in the early 1980s and to have built up its enrichment capacity, using its P-2 centrifuges, until 1990.[28] Under pressure from the United States, Pakistan then limited its enrichment to LEU but continued to develop more powerful centrifuges, until the 1998 nuclear tests. It may then have resumed HEU production, starting by enriching its accumulated LEU stocks to weapon grade, and phasing in its more powerful P-3 and P-4 centrifuges. These machines have estimated separative capacities two and four times that of the P-2 respectively.[29]

Pakistan's annual HEU production capacity is constrained, however, by its limited domestic production of natural uranium (currently about 40 tons per year) and the need to also fuel its Khushab plutonium production reactor, which requires about 13 tons per year. This natural uranium constraint will become more significant when the second and third production reactors at Khushab come online. The three reactors will then require virtually all of the natural uranium that Pakistan produces. Figure 1.5 shows the cumulative HEU production for three possible enrichment capacities in the post-1998 period, taking into account the limits on natural uranium feed.

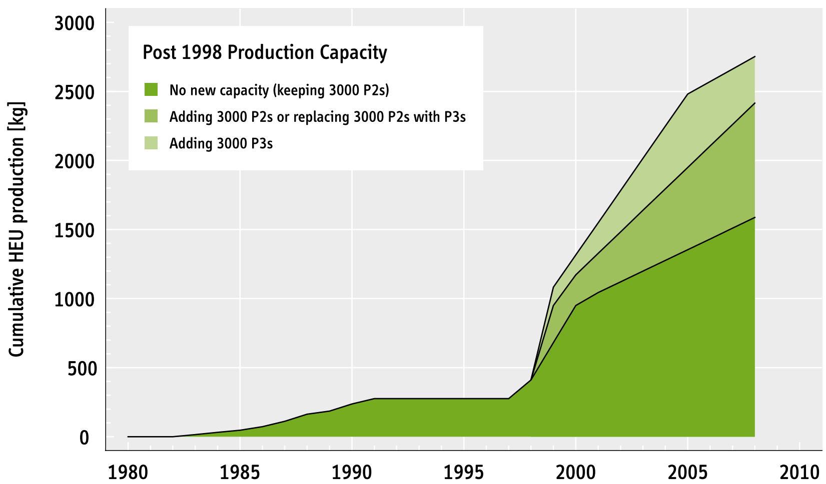

Figure 1.5. HEU production scenarios for Pakistan. Pakistan slowly increased its HEU production capacity through the 1980s, but is believed to have suspended HEU production from 1990–1998. After the 1998 nuclear tests, it may have enriched to HEU the low enriched uranium accumulated during this suspension before returning to natural uranium as feed material. By using more P-2 centrifuges or powerful P-3 machines, it could have significantly increased its HEU production rate over the past decade. As a result, Pakistan is estimated to have produced 1.6–2.8 tons of HEU by the beginning of 2008.[30] We use a value of 2 tons as a reasonable estimate for Pakistan's current stockpile of HEU.

Naval HEU Use

France, Russia, the United Kingdom, and the United States use HEU to fuel submarine and ship propulsion reactors, and India is preparing to do so. France has almost completed a switch to LEU fuel for its nuclear navy.

Towards the end of the Cold War, the Soviet Union and the United States each used annually about two tons of HEU for this purpose (Figure 1.6).[31] Today, Russia uses about one ton (not all weapon-grade) and the United States two tons of weapon-grade HEU per year. The Russian icebreaker fleet accounts for a significant fraction of Russia's HEU consumption. Russia also uses HEU for fueling plutonium- and tritium-production reactors.

The United States appears to be committed to maintaining its reliance on nuclear propulsion for its aircraft carriers and submarines, and possibly expanding it to include nuclear-powered cruisers. We estimate that the 128 tons of HEU that the United States has set aside for military naval nuclear propulsion would be sufficient to fuel its surface ships and submarines for 40–60 years. In 2008, the U.S. Senate required the navy to study the possibility of LEU fuel for future nuclear powered ships.[32] Further information on naval nuclear propulsion programs may be found in Chapter 7.

United Kingdom. In 1998, the United Kingdom declared an inventory of 21.9 tons of military HEU.[33] According to a 2002 U.K. government report, this inventory included 3.9 tons of HEU in 51 spent submarine reactor cores in pool storage in the U.K.'s Sellafield reprocessing complex.[34] We estimate that about 1000 kg of U-235 has been fissioned since 1998 and that, as of 2008, the amount of HEU in spent submarine reactors cores was about 4.5 tons.

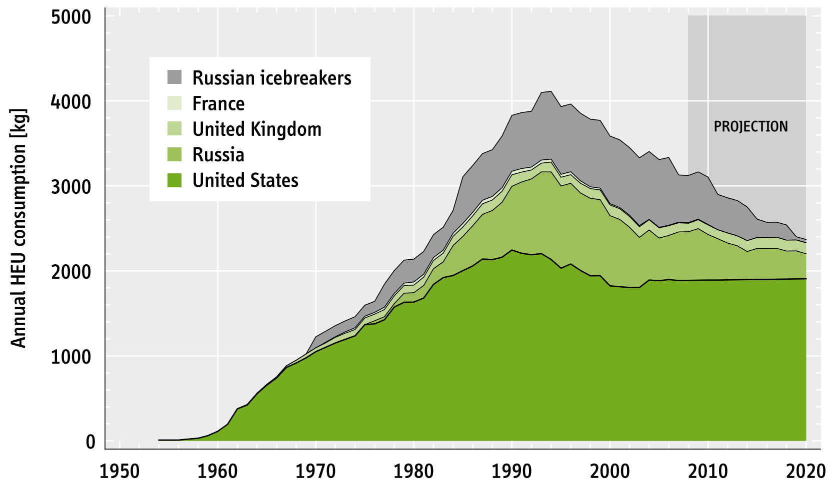

Figure 1.6. Estimated annual HEU consumption in naval vessels.[31] HEU consumption for nuclear propulsion increased steadily during the Cold War. With the possible exception of China, all NPT nuclear-weapon states equipped their nuclear navies with HEU cores. This assessment is based on the assumption that China uses low-enriched fuel for its nuclear navy. France has almost completed a switch to low-enriched fuel. Future levels of HEU use for naval propulsion purposes are highly uncertain. The United States is considering the use of nuclear propulsion reactors in additional types of surface vessels. Note that some Russian naval reactors use 40%-enriched HEU, and that the estimates shown in the figure are not weapon-grade equivalents. India is not shown.

India. India has been producing HEU to fuel its planned nuclear-powered ballistic missile submarine, the Advanced Technology Vessel. Construction on the vessel is near completion, with the reactor integrated into a submarine hull at the end of 2007, and plans are to begin sea trials in early 2009.[35]

As of the end of 2007, India would need to have produced an estimated 180 kg of uranium-235 (as 400 kg of HEU enriched to 45% uranium-235) to supply fuel for the land-based prototype reactor and the first submarine core.[36] Reports suggest India intends to deploy three nuclear submarines, each with 12 nuclear-armed ballistic missiles, by 2015.[37] This would require the production of an additional 800 kg of HEU fuel over the next five to six years. To reach this goal, India will need a larger uranium enrichment capacity.[38] India has been purchasing material for building additional centrifuges.[39]

Civilian Use and Management of HEU

Since 1978, an international effort has been directed at converting HEU-fueled civilian research 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.[40] By the end of 2007, the RERTR program had converted or partially converted 56 research reactors. The world's remaining research reactors consume about 800 kilograms of HEU per year—a significant reduction from more than 1400 kg that were needed annually in the early 1980s (see Figure 1.7).[41] Most of this reduction is due, however, to the shutdown of about 110 no-longer-required HEU-fueled research reactors rather than reactor conversions to low-enriched fuel.

In 2004, the U.S. Department of Energy responded to Congressional concern about how slowly the HEU-cleanout programs were moving by establishing a Global Threat Reduction Initiative (GTRI) into which its reactor-conversion and spent HEU-fuel take back efforts were merged. Figure 1.7 shows how the annual HEU demand could drop to very low levels by 2020 if this program achieves its ambitious objectives.[42] Recently, Russia has agreed to study conversion of six of its own research reactors.[43] Critical assemblies and pulsed reactors containing huge quantities of barely irradiated uranium are not yet formally being targeted by any of these cleanout efforts, however. 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 alternative accelerator-based 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.

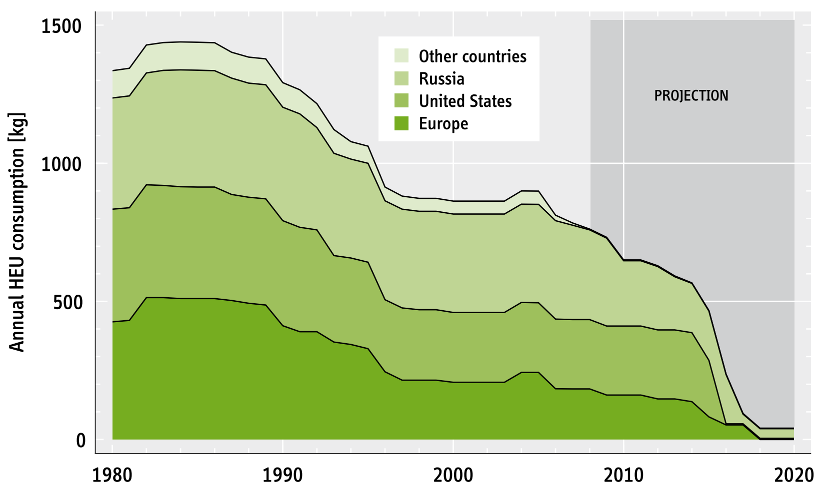

Figure 1.7. Estimated total annual HEU use in research reactors, 1980–2020.[41]

Separated Plutonium

The global stockpile of separated plutonium is about 500 tons. It is divided almost equally between civilian stocks and military stocks, including material declared excess but not yet disposed. Separated plutonium exists mostly in nuclear weapon states, but Japan and a few non-nuclear weapon states in Europe also have significant stocks. Figure 1.8 summarizes the data.

Russia and the United States possess by far the largest stocks of military plutonium: 120–170 and 92 tons, respectively. Russia has declared 34 tons, and potentially up to 50 tons, of its weapon-grade plutonium excess for weapon purposes.[44] The United States has declared excess 54 tons of separated government-owned plutonium, which includes 9 additional tons added to that category in September 2007.[45]

The Russian and U.S. plutonium disposition projects have suffered many changes of plans and delays since they were launched in the mid-1990s.[46]

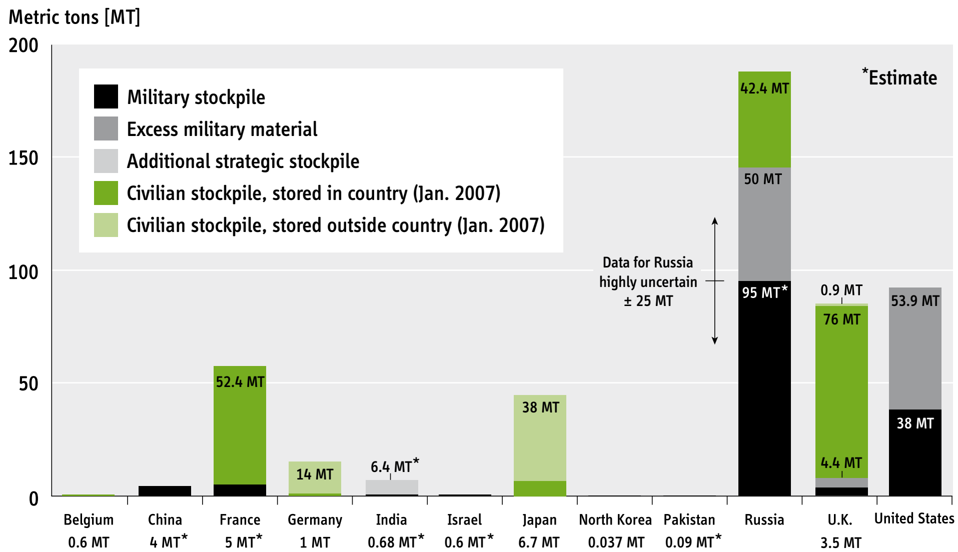

Figure 1.8. National stocks of separated plutonium. Civilian stocks are for January 2007 and based on the latest national INFCIRC/549 declarations to the IAEA (with the exception of Germany).[47] Civilian stocks are listed by ownership, not by current location. Weapon stocks are based on non-governmental estimates except for the United Kingdom and the United States, whose governments have made declarations. India's plutonium separated from unsafeguarded spent PHWR fuel is categorized as an additional strategic stockpile.

Weapons plutonium

United States. In May 2008, the U.S. Department of Energy signed a $2.7 billion contract for a mixed-oxide (uranium-plutonium, MOX) fuel fabrication plant to be built by the French company AREVA at its Savannah River Site. The plant is to produce mixed oxide fuel from 34 tons of U.S. weapons plutonium that have been declared excess and are to disposed of under the 2000 U.S.-Russia agreement.[48] The design of the facility is based on that of France's Melox plant at Marcoule.

There is a dispute over the safety of the MOX test assemblies provided by AREVA for irradiation in U.S. power reactors. According to Edwin Lyman of the Union of Concerned Scientists, testing was prematurely stopped because of a "potentially serious defect in the fuel design." He argued that this could require AREVA to "change the defective fuel design, manufacture new MOX fuel, and repeat the irradiation test," adding years of further delay to the plutonium-disposition program.[49] AREVA acknowledged that the length of the fuel assemblies had grown beyond the acceptance limits and that their reinsertion to complete the irradiation test was being reconsidered, but argued that there is no need for the test to be repeated.[50]

Israel. Assuming an average of 4 kilograms of plutonium per warhead, a mid-range stockpile of 150 weapons would imply that Israel has produced at least 600 kg of plutonium. Based on information from Mordechai Vanunu, Frank Barnaby estimated that Israel had produced 400–800 kg of plutonium in its Dimona reactor already by the mid-1980s.[51] But such a high estimate is based on the assumption that the thermal power of the reactor had been increased from its initial 26 megawatts (MWt) to 70 MWt, and later to 150–200 MWt.[52]

If the power level of Dimona never exceeded 70 MWt, which is equivalent to a plutonium production rate of about 14–17 kg/yr,[53] by the mid-1980s, Israel's inventory of separated plutonium would have been in the range of 280–340 kg. By today, the reactor could have produced 560–680 kg. If the Dimona reactor is operated only for tritium production today, Israel could be reprocessing its spent fuel and separating the plutonium, but not using it to make weapons.

Figure 1.9. The dome of the Dimona reactor in the Negev Desert, Israel, in a picture taken by M. Vanunu in or before 1985. The power level of the reactor is unknown, but probably is on the order of 70 MWt. At this power, the reactor would produce 14–17 kg of plutonium per year. Since it began operation in the mid-1960s, the reactor could have produced more than 600 kg of plutonium.

India. India continues to produce weapons plutonium in its two production reactors, *Cirus* and *Dhruva*, at a combined rate of about 30 kilograms per year. It separates much more reactor-grade, but still weapon-usable, plutonium from the spent fuel of its unsafeguarded pressurized heavy water power reactors (PHWRs). It may have separated about 6.4 tons of this power-reactor plutonium as of 2008.[54] This plutonium is intended to fuel the Prototype Fast Breeder Reactor (PFBR), expected to be completed in 2010. The PFBR would consume reactor-grade plutonium but, in doing so, could produce over 140 kg a year of weapon-grade plutonium in the "blanket" of natural uranium surrounding the core.[55]

India's annual domestic uranium production has been falling short of the combined demand from its growing nuclear power, naval-propulsion and plutonium production reactors. The average capacity factor for India's PHWRs fell from about 75 percent in 2003–04 to 44 percent in 2007–08.[56] Under U.S. pressure, the Nuclear Suppliers Group, in September 2008, exempted India from its requirement of full-scope safeguards as a condition of access to the international market for uranium and nuclear technology.[57] This will allow India to import uranium to make up the shortfall in supply and expand its nuclear energy program by purchasing reactors, while expanding its production of fissile material for nuclear weapons.[58]

Pakistan. Pakistan continues to produce almost 12 kg per year of plutonium for weapons at its Khushab production reactor.[59] Work appears to have started on two additional production reactors at this site in 2001 and 2005 respectively. A new reprocessing plant is reportedly being built near Chashma.[60] Pakistan's first plutonium-production reactor took about a decade to build. If the second and third reactors take as long, then they may be expected to begin operating around 2011–2014. As already noted, operating at full capacity, the three production reactors would require as fuel almost all the 40 tons/year of uranium that Pakistan currently produces.

North Korea. In June 2008, North Korea submitted a 60-page declaration of information on its plutonium production program backed up by 18,000 pages of documents. Reportedly, North Korea declared a plutonium inventory of 37 kg.[61] The U.S. government and independent analysts had previously estimated North Korea's plutonium stock as 30–50 kg.[62]

Civilian Plutonium

Japan. Japan's Rokkasho reprocessing plant, which began active testing in 2006, continues to experience problems and is unlikely to begin commercial operation in 2008. Active testing was to have been completed in February 2008, but this was extended to July 2008 and then again to November 2008.[63] As a result of the testing, however, as of May 2008, the facility had separated about 2.7 tons of plutonium, which is stored mixed with an equal amount of uranium.[64]

Figure 1.10. The Rokkasho Reprocessing Plant. [Source: Greenpeace/Gavin Newman]

United Kingdom. The history and legacy of the United Kingdom's reprocessing program is reviewed in a 2008 IPFM research report.[65] The United Kingdom began reprocessing in 1952 to separate plutonium for weapons. By the end of 2007, the United Kingdom also had separated a total of over 100 tons of civilian separated plutonium from domestic and foreign spent fuel. This amount will increase to 133 tons if existing contracts are fulfilled, with commercial operations expected to end by 2020. These activities have left a large environmental and cleanup problem at the Sellafield site, with estimated cleanup costs now running at about $92 billion.[66] The plutonium from foreign spent fuel, or equivalent U.K. plutonium, will be returned to foreign clients as mixed oxide (plutonium-uranium, MOX) fuel, but the United Kingdom has not yet determined a strategy for disposition of the approximately 100 tons of plutonium that will have been separated from domestic spent fuel.[67]

France. The experience of France's reprocessing program is summarized in another recent IPFM report.[68] Reprocessing for weapons started in 1958 and ended in 1993. Since then it has been a civilian program, with both domestic and foreign customers. It has accumulated over 80 tons of separated plutonium, 30 tons of which is foreign-owned. Almost all of the foreign spent fuel under contract has been reprocessed, and only minor new contracts have been signed. The economic burden of reprocessing is increasingly of concern to France's national electric utility (EDF). As in the United Kingdom, reprocessing has left a large environmental and cleanup legacy.

China. China is developing a civilian plutonium complex. Its long-delayed pilot reprocessing plant at the Yumenzhen site in Gansu Province, with a design capacity of 50 tons/yr, is reported to have been completed and to be undergoing testing prior to start up.[69] China's National Nuclear Corporation has also agreed with the French company AREVA on feasibility studies for the construction of a large commercial reprocessing and MOX fuel fabrication facility complex in China.[70]

National stockpiles of civilian plutonium declared annually to the IAEA under INFCIRC/549 are given in Appendix 1A.

Status of Production Facilities Worldwide

Aging and no-longer-operating fissile material production facilities in the nuclear weapon states continue to be closed down and in some cases dismantled. The status and verification of shut down and dismantled facilities is discussed in Chapter 9, which also lists currently shut-down production facilities in the United States and France.

Russia. In April and June 2008, Russia shut down its two remaining operating plutonium-production reactors at the Seversk/Tomsk-7 site.[71] The two reactors ADE-4 and ADE-5 had been operating since 1965 and 1968 respectively, each producing 0.4–0.5 tons of weapons plutonium per year, as well as electricity and steam for district heating.[72]

Russia's last remaining plutonium-production reactor (ADE-2), at the Zheleznogorsk/Krasnoyarsk-26 site, is expected to shut down 2010 when a replacement coal-fired plant is completed. The combined 1.2 tons of plutonium produced annually by the three reactors have been separated because the spent metal fuel could not be safely stored for more than a few months without serious corrosion. Since 1994, the plutonium separated from the fuel of the three production reactors has been stored and, under an agreement with the United States, committed not to be used for weapon purposes.

The three production reactors have produced a total of about 18 tons of weapon-grade plutonium since 1994, of which 10 tons are stored in Seversk and 8 tons in Zheleznogorsk. Rosatom plans to consolidate all this plutonium in underground storage in Zheleznogorsk.[73] Nine tons of the plutonium oxide is included in the 34 tons that Russia has committed to dispose of in MOX under the Russian-U.S. Plutonium Disposition Agreement.[74]

Figure 1.11. Seversk ADE-4 and ADE-5 reactors, when they were still operating. In this satellite image, note the clouds of water vapor visible above the cooling towers. [Satellite imagery courtesy of GeoEye; Image date: 18 Aug 2001]

United Kingdom. The eight dual-purpose British Calder Hall and Chapelcross reactors were used for both electric-power production and off and on for military plutonium production which ended in 1989.[75] The two groups of reactors shut down in 2003 and 2004 respectively and their cooling towers were demolished in 2007.[76]

North Korea. In October 2007, North Korea committed to end its nuclear-weapon program; declare all its nuclear activities; and disable its Yongbyon plutonium-production reactor and the associated fuel-fabrication and reprocessing plants by the end of 2007. The cooling tower of the Yongbyon reactor was demolished in June 2008 (Figure 1.12).

Figure 1.12. Demolition of the cooling tower of the North Korean Yongbyon reactor on 26 June 2008. This footage was distributed by China's official Xinhua News Agency, showing North Korea's commitment to the ongoing negotiations, a day after it submitted the declaration on its nuclear program. [Source: Reuters/Kyoto]

France. France shut down both the military reprocessing plant at Marcoule and its gaseous diffusion enrichment plant for production of HEU for weapons at Pierelatte in 1996. The two plants had been in operation since 1958 and 1967 respectively. Decontamination and decommissioning of these facilities is expected to take several decades. In 2008, as a transparency measure, the French President declared that "I have decided to invite international experts to observe the dismantlement of our Pierrelatte and Marcoule military fissile material production facilities."[77]

Appendix 1A. Civilian Plutonium Stockpile Declarations

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

Between 1996, the first year covered by the declarations, and the end of 2006 the global civilian plutonium stockpile rose from 160 tons to 254 tons, not including the plutonium declared excess for weapons use by Russia and the USA. Russia does not include in its declaration excess weapons plutonium, whereas the United States does.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Belgium (Addendum 3)	2.7	2.8	3.8	3.9	2.7	2.9	3.4	3.5	3.3	2.8	0.6
	not disclosed										
	?	0.8	1.0	0.9	0.6	1.0	0.4	0.4	0.4	0.0	0.0
France (Addendum 5)	65.4	72.3	75.9	81.2	82.7	80.5	79.9	78.6	78.5	81.2	82.1
	30.0	33.6	35.6	37.7	38.5	33.5	32.0	30.5	29.7	30.3	29.7
	0.2	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Germany (Addendum 2)	Germany's INFCIRC/549 declarations cannot be used to reconstruct the evolution of the German plutonium stockpile (see note below for details) The inventory is on the order of 15 tons today										
Japan (Addendum 1)	5.0	5.0	4.9	5.2	5.3	5.6	5.3	5.4	5.6	5.9	6.7
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	15.1	19.1	24.4	27.6	32.1	32.4	33.3	35.2	37.1	37.9	38.0
Russia (Addendum 9)	28.2	29.2	30.3	32.0	33.4	35.2	37.2	38.2	39.7	41.2	42.4
	0.0										
	0.0										
United Kingdom (Addendum 8)	54.8	60.1	69.1	72.5	78.1	82.4	90.8	96.2	102.6	104.9	106.9
	6.1	6.1	10.2	11.8	16.6	17.1	20.9	22.5	25.9	26.5	26.5
	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
United States (Addendum 6)	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	44.9	45.0	44.9
	0.0								0.0	0.0	0.0
	0.0								0.1	0.0	0.0

Table 1A.1. Annual inventories (as of December 31, 2006) of civilian separated plutonium in metric tons as declared through IAEA INFCIRC/549-communcations. White background: inventory held in country; light-green: foreign-owned; dark-green: stored outside the country (i.e., not included in local inventory). China and Switzerland also make INFCIRC/549 declarations, but China's have all been zero and Switzerland has only been declaring the amount of plutonium that is in fresh MOX fuel in the country and not yet loaded into its reactors as of the end of the year. Russia's declaration does not include its stockpile of weapon plutonium declared excess to military needs, whereas the U.S. declaration does include this material.

A Verified Fissile Material (Cutoff) Treaty

2 Why an FM(C)T is Important

The major challenge in creating the simple fission weapons that destroyed Hiroshima and Nagasaki was to make sufficient quantities of the fissile materials, highly enriched uranium and plutonium, respectively.[78] Producing fissile materials still remains the critical obstacle in any new nuclear-weapon program and for any country seeking a larger nuclear arsenal.[79] For over 50 years, this recognition has underpinned both the support for and opposition to the adoption of a binding international treaty banning the production of fissile materials for nuclear weapons.[80]

In December 1993, the UN General Assembly adopted by consensus a resolution calling for negotiation of a "non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."[81] The resolution declared that the General Assembly was "convinced" that a treaty meeting these criteria "would be a significant contribution to nuclear non-proliferation in all its aspects."

Since the NPT nuclear-weapon states have all stopped producing fissile material for weapons, the core concern for many states is how a treaty will deal with the stockpiles of weapons-usable material accumulated worldwide. The global stockpiles of HEU total between 1400 and 2000 metric tons, while the current global stockpile of separated plutonium is about 500 tons. Most of this material is in the possession of nuclear weapon states, predominantly the United States and Russia.

There is therefore disagreement today over whether a treaty on fissile materials should ban only the future production of such materials for weapons or if it should deal as well with fissile material in civilian use and even stocks of fissile material reserved for fuel for naval and other military reactors.

A fissile material cutoff treaty would strengthen the nonproliferation regime, reduce the risk of nuclear terrorism, and help lay a basis for nuclear disarmament by:

- Meeting international demands made by the United Nations General Assembly and commitments made by the NPT weapon states;

- Extending to the nine nuclear weapon states the legal ban on production of fissile material for weapons that currently applies only to non-nuclear weapon states;

- Further reducing the discriminatory aspects of the NPT by extending mandatory safeguards to nuclear facilities and materials in nuclear weapon states;

- Improving national monitoring and regulation of fissile material;

- Extending into the nuclear weapon states institutions and practices necessary for the eventual achievement of a nuclear weapons free world; and

- Helping to make nuclear weapons reductions irreversible.

Meeting International Demands and Commitments

An FM(C)T addresses the long-standing demands of the international community for a verifiable ban on the production of fissile materials for weapons. This was spelled out first by the U.N. General Assembly in November 1957 in Resolution 1148, which called for a treaty that would include:[82]

- "the cessation of the production of fissionable materials for weapons purposes,"

- "the complete devotion of future production of fissionable materials to non-weapons purposes under effective international control," and

- "the reduction of stocks of nuclear weapons through a program of transfer, on an equitable and reciprocal basis and under international supervision, of stocks of fissionable materials from weapons uses to non-weapons uses."

As already noted, in December 1993, the UN General Assembly adopted by consensus a resolution calling for negotiation of a "non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."[83] On 23 March 1995, the Geneva based Conference on Disarmament (CD) agreed to begin negotiations on a treaty.

At about the same time, the final document of the 1995 NPT Review Conference called for "[t]he immediate commencement and early conclusion of negotiations on a non-discriminatory and universally applicable convention banning the production of fissile material for nuclear weapons or other nuclear explosive devices, in accordance with the statement of the Special Coordinator of the Conference on Disarmament and the mandate contained therein."[84] This call for action was reiterated as one of the 13 steps agreed to at the 2000 NPT Review Conference, which commits at least the states party to the NPT, including the five nuclear weapon states, to negotiate an FM(C)T.

The continued delay and possible failure to achieve a treaty would heighten already significant concerns about the prospects of realizing other NPT commitments made by the weapon states.

Universalizing the Legal Ban on Production of Fissile Material for Weapons

All non-weapon states party to the NPT have accepted the obligation not to produce fissile material for weapons.

Although the NPT does not require the parties that joined as nuclear weapon states (United States, Russia, United Kingdom, France and China) to do so, four of the five have declared officially that they have ended production of fissile material for weapons, and the fifth, China, has indicated informally that it has suspended such production.[85] An FM(C)T would turn this production moratorium into a legally binding commitment for these states.

The other four nuclear weapon states—the Democratic People's Republic of Korea (North Korea), Israel, India, and Pakistan—are not parties to the NPT. North Korea, though, has also recently ended its production of plutonium and is committed to ending its nuclear-weapons program and returning to the NPT as a non-nuclear weapon state. India, Pakistan and perhaps Israel are believed to be still producing fissile materials in their weapon programs and have refused to join the moratorium.

Ending fissile material production for weapons is particularly important in South Asia, where Pakistan and India both appear to be increasing their rates of production of fissile materials for weapons (see Chapter 1).

An FM(C)T would create a requirement for Israel, India and Pakistan to end their production of fissile material for weapons and bring facilities under safeguards, and so join the nonproliferation and disarmament regime, without having to join the NPT as non-weapon states.[86]

Reducing Discrimination Between Nuclear Weapon and Non-weapon States

The NPT requires mandatory IAEA safeguards in non-nuclear weapon states, while requiring none in nuclear weapon states. This inequitable application of safeguards has raised concerns in non-weapon states about additional costs and vulnerability of proprietary commercial information.

The nuclear weapon states have sought to address this issue by making voluntary offers to open some of their facilities and materials for safeguarding.[87] The United States, followed by the United Kingdom, and later France, in the 1970s, and the Soviet Union and China in the 1980s, offered some facilities and materials for IAEA safeguarding. In practice, however, the IAEA has not been given enough resources to apply the safeguards.

An FM(C)T would impose for the first time compulsory safeguards in nuclear weapon states that would, at a minimum, cover all production facilities.

Improving National Accounting for Monitoring of Fissile-material Stocks

Since the end of the Cold War, it has been discovered that accounting for fissile materials has often been very loose in weapon states. An FM(C)T would require that, at least in their civilian nuclear sectors, nuclear weapon states meet internationally agreed standards for the control and accounting of fissile materials.

Making Nuclear-weapon Reductions Irreversible

The United States, Russia, United Kingdom and France have all announced reductions in the size of their nuclear arsenals from their cold war peaks. For the United States, the number of warheads peaked at about 30,000 in the mid-1960s, and the Soviet/Russian arsenal reached 40,000 in the 1980s. In the case of the United States and Russia, reductions have amounted to tens of thousands of weapons. The United Kingdom and France have reduced proportionately by hundreds of weapons each.

Some of the material from these weapon reductions has been declared as excess to military requirements by the United States, Russia and the United Kingdom. A total of about 700 tons of highly enriched uranium and almost 100 tons of plutonium (not all of which is from weapons) have been declared excess. This combined total is enough for over 30,000 weapons.

An FM(C)T that obliged states not to use for weapons fissile material either in civilian use or declared as excess for weapons would capture these materials and ensure that nuclear weapon reductions were irreversible. If future arms reductions were accompanied by declarations that the material in these weapons would be placed under international safeguards, the global stock of fissile materials would continue to be irreversibly reduced.

Creating Institutions for a Nuclear-Weapon-Free World

Any plausible enduring global prohibition on the production, possession and use of nuclear weapons would require that the nuclear weapon states eliminate their weapons and place all fissile material stocks and production facilities under strict international safeguards. The FM(C)T creates many of the norms, mechanisms and practices that would constitute the core of such regime, including the accounting for and safeguarding of stocks of fissile materials and the extension of mandatory international safeguards into the nuclear weapon states.

3 Design Choices: Scope and Verification

A treaty banning the production of fissile materials for nuclear weapons is an essential requirement for constraining nuclear arms races and for achieving the goal of nuclear disarmament.[88] Negotiation of such a treaty was endorsed without a dissenting vote in 1993 by the United Nations General Assembly.[89]

The Review Conference of the Parties to the Non-Proliferation Treaty (NPT) in 2000 agreed that negotiations "on a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile materials for nuclear weapons or other nuclear explosive devices" should commence immediately in the multilateral Conference on Disarmament (CD) in Geneva "with a view to their conclusion within five years."[90] Nevertheless, the CD has, for various reasons, not yet formally launched negotiations on such a treaty.

In the discussion of the proposed treaty at the CD, two issues have been especially contentious: verification and pre-existing stocks. The debate over whether the treaty should involve a ban on the use of some pre-existing stocks for weapon has even led to the use of two different names for the proposed treaty: Fissile Material Cutoff Treaty and Fissile Material Treaty. Here, we will use a name that makes this unresolved issue explicit: Fissile Material (Cutoff) Treaty, or FM(C)T.

This chapter gives the International Panel on Fissile Materials' (IPFM) perspective on the scope and verification of such a treaty. In early 2009, the Panel will provide a more complete draft treaty that will also address implementation and organizational issues, and the contents of the preamble. The Panel hopes that this draft may assist future negotiations of this long overdue Treaty.

Verification. On May 18, 2006, the Bush Administration submitted to the CD a draft FM(C)T that did not contain any provisions for international verification. The U.S. delegation asserted that

> "even with extensive verification mechanisms and provisions—so extensive that they could compromise the core national security interests of key signatories, and so costly that many countries would be hesitant to implement them—, we still would not have high confidence in our ability to monitor compliance with an FMCT."[91]

There are strong reasons, however, to prefer a verified treaty:

- Agreed verification measures are essential to creating confidence and trust in an FM(C)T;

- The non-nuclear-weapon states (NNWS) Parties to the Non-Proliferation Treaty (NPT) have accepted comprehensive safeguards, implemented by the International Atomic Energy Agency (IAEA), on their civilian nuclear programs to verify their commitments not to divert nuclear materials to weapon. Many of these states have repeatedly expressed concerns that, because the nuclear weapon states (NWS) are not required to have similar safeguards on their civilian nuclear activities, the NPT puts them at a competitive disadvantage in the development of civilian nuclear power. A verified FM(C)T would go far toward redressing this inequity; and

- Interest in nuclear disarmament has recently revived. Much deeper cuts in the nuclear stockpiles will require intrusive inspections of nuclear activities in the states possessing nuclear weapons. International verification of an FM(C)T would make an important contribution to establishing an effective verification system for future nuclear disarmament measures.

The IPFM draft treaty therefore has verification arrangements. We have chosen, however, to keep the verification articles as short as possible.[92] As with the NPT, the detailed verification arrangements are not spelled out in the treaty itself. The Panel has developed specific ideas on verification, however. Some of these are laid out in the following chapters.

Rather than proposing a new verification agency for the FM(C)T, we have assumed that the IAEA would take on this responsibility. The IAEA has extensive experience inspecting nuclear installations and nuclear materials, including in the NPT nuclear weapon states under their Voluntary-Offer Agreements. The obligations of states under the FM(C)T overlap strongly with the obligations of non-weapon states under the NPT and will become more and more similar as nuclear disarmament proceeds.

To undertake the new responsibilities, however, the IAEA's Safeguards Division would have to grow substantially. Funding would be required for such an expansion but it would be miniscule in comparison, for example, with the cost either of nuclear-weapon programs or of the production of nuclear energy.[93]

Pre-existing stocks. The FM(C)T could focus exclusively on a cut-off of future production of fissile materials for nuclear weapons or other nuclear explosive devices—or it could include also undertakings not to use for weapons pre-existing non-weapon stocks of fissile materials, including civilian stocks, stocks declared excess to military purposes, and stocks of highly enriched uranium declared for use as a fuel for naval-propulsion and other military reactors.

In a verified treaty, future production of fissile material for civilian purposes would in any case be under safeguards to prevent this material from being used in weapons. In our view, it would be unnecessarily complicated to keep separate unsafeguarded pre-existing civilian fissile material and safeguarded post-treaty civilian fissile material. It would be better to ask countries to decide at the beginning what pre-existing fissile material they wish to keep available for weapons and to put all other fissile materials under international safeguards. The IPFM's draft Treaty therefore requires states to separate weapons materials from their civilian nuclear sectors before the Treaty comes into force for them.

The draft Treaty also asks states to declare and submit to IAEA safeguards fissile materials from weapons that are excess to their military requirements, as well as future excess materials resulting from unilateral, bilateral, or multilateral nuclear disarmament measures.

A system could also be developed that would place under IAEA monitoring fissile material stored for future use as fuel for naval-propulsion or other military reactors.

Article-by-Article explanation of the main elements of the draft Treaty

The following provides an explanation of the main articles of the IPFM draft FM(C)T, including the basic undertakings and verification obligations. Other draft articles on legal and institutional issues, as well as a preamble, will be presented later by the IPFM.

Article I: Basic Undertakings

I.1. *Each State Party undertakes not to produce fissile material for nuclear weapons or other nuclear explosive devices.*

I.2. *Each State Party undertakes not to acquire from any source or to transfer to any state or non-state actor fissile material for nuclear weapons or other nuclear explosive devices;*

I.3. *Each State Party undertakes not to assist, induce or encourage in any way any state or non-state actor to engage in any activity prohibited under this Treaty;*

I.4. *Each State Party undertakes either to promptly disable and decommission its fissile-material production facilities and dismantle such facilities on an agreed schedule, or to use these facilities only for peaceful or military non-explosive purposes.*

I.5. *Each State Party undertakes not to use for nuclear weapons or other nuclear-explosive devices fissile materials:*

- ***i)*** *In its civilian nuclear sector*
- ***ii)*** *Declared as excess for all military purposes*
- ***iii)*** *Declared for use in military reactors.*

I.6. *Each State Party undertakes that any reduction in its stockpile of nuclear weapons will result in a declaration of the fissile material from those weapons as excess for weapon purposes.*

Paragraph I.1 lays out only the *cutoff* obligations of the Treaty. The ban on the production of fissile material only for weapons or other nuclear-explosive devices recognizes that some states currently choose to separate plutonium for recycle and/or produce highly enriched uranium for use in naval fuel. It also does not constrain military uses of stocks of fissile materials that are already in existence at the time that the Treaty comes into force.

Paragraph I.2 is a non-circumvention requirement, prohibiting the acquisition of fissile materials for weapons purposes in ways other than domestic production, as well as transfers for weapon use to other states or non-state actors. Transfers of fissile materials between states for weapons have reportedly occurred in the past.

Paragraph I.3 adds the requirement not to assist, induce or encourage other states or non-state actors to engage in activities that are prohibited by the Treaty.

Paragraph I.4 requires that reprocessing facilities and enrichment plants that have been used to produce fissile materials for weapons be converted to civilian or military non-explosive uses only, or be shutdown and decommissioned and ultimately dismantled. The purpose is to avoid having unnecessary production facilities kept in a standby mode.

Sub-paragraph I.5.i requires that fissile materials in the civilian sectors of the Parties at the time the Treaty comes into force for them may not be used in nuclear weapons. Without this obligation, fissile material in the civilian sector produced before the Treaty's entry into force for a country could still be used for nuclear weapons. This would make it necessary to undertake and maintain a complex segregation of fissile materials in the civilian sectors according to whether they were produced post- or pre-Treaty. It would be far simpler for a country, before joining the Treaty, to segregate from its civilian nuclear sector all pre-existing fissile material for which it wants to preserve the option of weapon use.

Sub-paragraph I.5.ii requires that all fissile materials declared excess to weapons or other military purposes remain so irreversibly. The Russian Federation, the United Kingdom, and the United States, to date the only countries that have made such declarations, have committed that these declarations are irreversible.

Sub-paragraph I.5.iii. The United States has declared a large stock of HEU excess for weapons use but has reserved much of it for future use as fuel for naval-propulsion reactors. Other states may do the same. They could also reserve HEU to fuel reactors for other military purposes that are not banned by the Treaty, such as producing tritium for nuclear weapons. The quantities involved are comparable to those in the weapon stockpiles and could become an obstacle to further reductions unless made unavailable for weapons purposes (see Chapter 7). This sub-paragraph requires that this material—although reserved for military purposes—will not be used in nuclear weapons or other nuclear-explosive devices.

Paragraph I.6 would require States Party to declare excess for weapon purposes fissile material recovered from reductions in their nuclear-warhead stockpiles through unilateral actions or bilateral or multilateral agreements and arrangements. After it has been converted to unclassified form, this material would be placed under the same IAEA safeguards that are used for civilian materials. It could also come under IAEA monitoring at an earlier stage with arrangements to protect classified information (see Chapter 6). It could subsequently be used for either civilian or military non-explosive purposes (see also the discussion of Paragraph III.3.ii.c below).

Article II: Definitions

II.1. *"Fissile material" means:*[94]

i) *Plutonium of any isotopic composition except plutonium whose isotopic composition includes 80 percent or more plutonium-238.*
ii) *Uranium containing uranium-235 and/or uranium-233 in a weighted concentration equivalent to or greater than 20 percent uranium-235.*[95]
iii) *Additional fissile materials suitable for the manufacture of nuclear weapons or other nuclear explosive devices, and changes in the above parametric values, may be decided upon by the Board of Governors of the IAEA.*

II.2. *"Producing fissile material" means:*

i) *Separating fissile materials mentioned in Paragraph 1 from fission products through reprocessing or any other process.*
ii) *Enriching any mixture of uranium isotopes to a weighted concentration of uranium-235 and uranium-233 equivalent to or greater than 20 percent uranium-235.*
iii) *Increasing the fraction of plutonium-239 in plutonium by any isotopic separation process.*

II.3. *A "production facility" means any facility in which any production of fissile material as defined in Paragraph II.2 is carried out or could be carried out.*

Sub-paragraph II.1.i. The definition of plutonium conforms to the IAEA definition of "direct-use material," i.e., "nuclear material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment."[96] Plutonium containing more than 80 percent Pu-238 is used in thermoelectric generators for space and other applications and generates so much radioactive decay heat that it is considered unusable as a weapons material.

Sub-paragraph II.1.ii. The IAEA defines a mixture of uranium-235 and uranium-238 enriched to 20 percent or more in U-235 to be "direct use material."[97] It does not have a corresponding definition of a mixture of uranium isotopes containing U-233, although U-233 has been used in at least one experimental nuclear weapon.[98] Since a mixture of 12-percent U-233 with U-238 has the same critical mass as a mixture of 20-percent U-235 with U-238, we have assumed that each atom of U-233 is equivalent to 20/12 = 5/3 atoms of U-235.[99]

Sub-paragraph II.1.iii. Although the most common fissile materials are HEU and plutonium, neptunium-237 and americium could be used be used for weapons manufacture and are therefore sometimes referred to as "alternative nuclear [weapon] materials."[100]

Paragraph II.2 defines the production of fissile material as either:

- Its separation from fission products; or

- The enrichment of uranium in the isotopes U-235 and/or U-233 to the equivalent of 20 or more percent of U-235; or

- The enrichment of plutonium in the isotope Pu-239.

The effect is to prohibit not only the production of highly enriched uranium or plutonium for nuclear weapons or nuclear explosive devices but also the further enrichment for these purposes of pre-existing highly enriched uranium or plutonium. Thus, for example, a State Party may not increase the enrichment of uranium-235 in unsafeguarded HEU from 21 to 90-percent U-235.

Paragraph II.3 defines facilities that can produce fissile materials, i.e., enrichment and reprocessing facilities, including hot-cells with reprocessing capabilities.

Article III: Verification

III.1. *Each State Party undertakes to accept IAEA safeguards to verify its obligations under Article I as described in this Article.*

III.2. *For those States Parties having a comprehensive safeguards agreement with the IAEA, incorporating IAEA-document INFCIRC/153 (corrected) as well as the Model Protocol Additional to the Safeguards Agreements (INFCIRC/540, corrected), no further agreements with the IAEA are necessary under this Treaty, unless that State Party intends to use fissile materials for military non-explosive purposes, in which case additional safeguards or arrangements are needed.*

III.3. *States Parties not having a comprehensive safeguards agreement [and possessing at least one significant quantity of unsafeguarded fissile material], undertake to accept safeguards in an appropriate safeguards agreement to be concluded with the IAEA to verify their obligations under Article I, including:*

i) *The non-production of fissile materials for nuclear weapons or other nuclear explosive devices and to that end:*
- ***a)*** *The disablement, decommissioning and dismantlement of production facilities or their use only for peaceful or military non-explosive purposes, and*
- ***b)*** *The absence of any production of fissile materials without safeguards.*

ii) *The non-diversion to nuclear weapons, other nuclear explosive devices or purposes unknown of:*
- ***a)*** *All civilian fissile materials, including in spent fuel,*
- ***b)*** *All fissile materials declared excess to any military purpose.*
- ***c)*** *All fissile materials declared for military non-explosive purposes*

III.4. *Negotiation of agreements and arrangements referred to in Paragraph III.2 and III.3 shall commence within [180] days from the entry into force of this Treaty. For States depositing their instruments of ratification or accession after the [180]-day period, negotiation of such agreements or arrangements shall commence not later than the date of such deposit. Negotiations of these agreements and arrangements shall be conducted in consultation with the Executive Secretary. Such agreements or arrangements shall enter into force not later than [18] months after the date of initiation of negotiations.*

Paragraph III.1 calls for the States Party to the treaty to accept the safeguards required to verify the main obligations of Article I of the Treaty. There are obligations in Article I, however, that cannot easily be verified by safeguards such as in Paragraph I.3. Paragraph III.3 therefore provides a description of those obligations under Article I that should be verified by the IAEA.

Paragraph III.2 recognizes that States Parties that have a comprehensive full scope safeguards agreement based on the NPT Model Agreement INFCIRC/153 (corrected) are already fully covered by safeguards on all their declared fissile materials and declared production facilities. These states include all the Non-Nuclear Weapon States (NNWS) party to the NPT having significant nuclear activities.[101]

Effective verification of a production cut-off, however, also requires measures to ensure that there are no undeclared prohibited activities. The Additional Protocol (AP) was specifically designed for this purpose and is thus crucial to any comprehensive and effective verification system.[102] Paragraph III.2 therefore requires that all States that have a comprehensive agreement also ratify the Additional Protocol. The states covered by Paragraph III.3 also will have to make declarations and accept inspections that would make it possible for the IAEA to look for undeclared production facilities. For the non-nuclear-weapon states which have not yet ratified the Additional Protocol, this would be their only new obligation under the FM(C)T.

For non-weapon states that decide to use fissile materials for military non-explosive purposes (such as naval propulsion), which is allowed under the NPT and thus the comprehensive agreement, special arrangements would have to be made to verify that such material is not used for weapons. This issue is discussed under Paragraph III.3.ii.c.

Paragraph III.3 describes the verification measures needed in those States Parties that do not fall under Paragraph III.2, i.e., countries that do not have a safeguards agreement covering all their fissile materials but have at least one significant quantity of such material.[103] Sub-paragraph III.3.i provides for the verification of the non-production of fissile materials for nuclear weapons or other nuclear explosive purposes while allowing the production of fissile material under safeguards. Sub-paragraph III.3.ii covers the non-diversion to use in nuclear weapons of different categories of fissile materials submitted to IAEA monitoring. These are fissile materials: in the civilian nuclear sector at the entry into force of the Treaty, produced later for civilian or military non-explosive purposes, or from the weapons sector that are declared excess and voluntarily placed under international monitoring or safeguards.

In the civilian sector, the safeguards needed for these States Parties could be patterned on the IAEA safeguards in non-weapon states. In other cases, such as excess weapon materials that are still in classified form or materials for non-explosive military uses, the IAEA, the governments of the states concerned and perhaps the governments of other interested states could develop model agreements. Requirements and challenges in applying these verification measures may vary considerably among countries, however, and some may have to be adapted to different situations.

Nuclear weapon states party to the NPT have already accepted some international safeguards on their civilian nuclear material and facilities. Some have offered all their civilian facilities for safeguards under their Voluntary Offer Agreements with the IAEA (through Euratom in the cases of France and the United Kingdom).[104]

States that do not have a Comprehensive Safeguards Agreement with the IAEA, namely the NPT nuclear-weapon states and the non-parties to the NPT, would also have to accept an Additional Protocol in order to provide the IAEA the access to detect clandestine production activities prohibited by the Treaty. Some NPT nuclear-weapon states have already concluded an Additional Protocol with the IAEA, but because of the limits they place on IAEA inspections, these agreements fall far short of those in INFCIRC/540. The not-yet-in-force U.S. Additional Protocol is the closest to the Additional Protocol for non-weapon states but allows the U.S. Government to prevent IAEA access "to activities with direct national security significance to the United States or to locations or information associated with such activities."[105] Under an FM(C)T, the relevant states and the IAEA would have to conclude "managed access" arrangements to protect sensitive national or commercial information while allowing IAEA inspectors to satisfy themselves that no clandestine production of fissile material is taking place. Chapter 8 discusses approaches to such managed access.

Sub-paragraph III.3.i refers to the obligations under Article I, Paragraphs I.1. and I.4. The IAEA should verify the disablement, decommissioning, and dismantlement in time of all enrichment and reprocessing facilities used for the production of fissile materials for nuclear-weapons purposes unless they are converted to the production of nuclear materials for civilian and/or non-explosive military purposes and placed under safeguards. The rationale is that an FM(C)T should not allow plants for which there is no foreseeable alternative use to remain in a state ready for production of fissile materials for weapons.

All enrichment and reprocessing plants should be brought under safeguards, and any fissile materials that they produce should remain under safeguards. Since it is unlikely that, for the foreseeable future, highly enriched uranium will be produced in more than a few states, the safeguards in most enrichment plants could be restricted to verifying that only low-enriched uranium is being produced. The IAEA already has extensive experience in this field. Chapter 4 examines the special issues that would arise at enrichment plants that have produced HEU in the past.

Sub-paragraph III.3.ii refers primarily to the obligations under Paragraph I.5, but also to those under Paragraphs I.2 and I.6. It mandates that all the fissile materials mentioned in Paragraph I.5 should come under some kind of safeguards regime. Since the status of each category is different and some can be in forms with classified designs, they are discussed separately below:

a) Civilian materials. The extension of IAEA safeguards to all civilian fissile material in all FM(C)T parties should not create major problems except increased cost. Safeguarding large already-operating reprocessing plants whose designs are not 'safeguards friendly' could be the biggest challenge and is examined in Chapter 5. During a transition period, the safeguards goals in the States Parties falling under Paragraph III.3 might be somewhat less strict than for those under III.2. Over time, however, the safeguards regimes for the different categories of states should converge, since it will be important to reduce the inequality in safeguards commitments on civilian nuclear power in different classes of states and because the ultimate goal is a world in which all states are non-weapon states.

We recommend placing plutonium and HEU in spent fuel under IAEA monitoring. With time, the radiation field around some of this fuel will decline to the point where it can no longer be considered "self-protecting" by the standards established by the IAEA.[106]

b) Excess weapon materials. Russia, the United Kingdom and the United States have already declared large quantities of weapons fissile materials excess for any military purpose. Russia and the United States have agreed to dispose of their excess weapon-grade plutonium irreversibly under international safeguards once the material is in unclassified form.[107]

Furthermore, the two governments and the IAEA also undertook a joint multi-year study (the Trilateral Initiative) to develop techniques to permit the IAEA to verify through an "information barrier" whether containers declared to hold plutonium in classified forms contain more than an agreed threshold amount of weapon-grade plutonium. This study, which identified and developed technical, legal, and financial approaches to accomplish the verification without compromising national security information, is discussed in Chapter 6 below.

During the 1990s, Russian and American weapons experts also developed, on a bilateral basis, ambitious verification procedures under which Russia and the Unites States could monitor the dismantlement of each other's excess warheads without revealing sensitive weapons design information.[108]

Sub-paragraph III.3.ii.b commits the Parties to develop with the IAEA appropriate safeguards arrangements on excess fissile material. Such arrangements could build on the Trilateral Initiative and the bilateral Russian-U.S. studies. If it proves impossible to agree on safeguards while the fissile material remains in classified form, however, standard IAEA safeguards should be applied as soon as the fissile material is converted into unclassified form.

c) Fissile material for military non-explosive purposes. The draft FM(C)T, like the Non-Proliferation Treaty, allows a Party to produce and use fissile material for military non-explosive purposes—notably fueling naval-propulsion or tritium-production reactors. In the model-agreement for NPT non-nuclear weapon states (INFCIRC/153, Paragraph 14) the possibility was created for safeguards on nuclear material to be temporarily suspended while the material is being used for a non-peaceful, non-explosive activity.

The state involved must provide information, however, that gives confidence that the material is not being used for nuclear weapons. It must also provide data on the "total quantity and composition" of the unsafeguarded material and bring it back under safeguards as soon as its permitted military use ends. Thus, a special agreement relating to this material must be negotiated with the IAEA. To date, no NNWS has asked for such an arrangement—although Brazil is pursuing a naval-reactor program that may soon require one—nor have the specifics of an arrangement been worked out. Under an FM(C)T, such an arrangement would be required for fissile material newly produced to fuel military reactors.[109] Some ideas for how to approach this challenge are presented in Chapter 7.

If HEU produced for military, non-explosive purposes after the treaty comes into force can be subject to arrangements that assure that it will not be diverted to explosive use, it should be possible to subject pre-existing HEU reserved for military reactor fuel to such arrangements as well.[110]

The use of HEU for naval reactor fuel would be a potential threat to the integrity of the FM(C)T, however. Given the sensitivity of the designs of both naval reactors and their fuels, it will be difficult to assure that some HEU withdrawn from safeguards for use in naval fuel has not been diverted to weapons. For this reason and because of the usability of HEU for terrorist nuclear weapons, the IPFM believes that states should make every effort to reduce and eliminate their use of HEU for military as well as civilian purposes. States with nuclear navies therefore should design their future naval reactors to use low enriched uranium (LEU) fuel. France is believed to have nearly completed a transition of its naval nuclear propulsion reactors to LEU fuel.

Article III.4. sets a timetable for conclusion of the safeguards agreements similar to that in the Non-Proliferation Treaty.

Verification Challenges

Enrichment and reprocessing facilities worldwide

◘ Enrichment Facility
● Reprocessing Facility

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

Operational
Under Construction
Planned
Future uncertain

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

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

IPFM graphics redrawn from Bulletin of the Atomic Scientists

Safeguards status of enrichment and reprocessing facilities that are operational, under construction, or planned. There are 22 enrichment and 18 reprocessing plants located in 13 countries, excluding R&D and pilot-scale facilities. Seven enrichment or reprocessing facilities in nuclear weapon states are under international safeguards. There are currently 15 facilities that have not been offered for safeguards.

FM(C)T verification at enrichment facilities in the nuclear weapon states might initially be limited to verifying that no HEU is being produced. For enrichment facilities that have not made HEU in the past, verification should be possible through analysis of HEU particles in swipe samples. For large enrichment plants contaminated with HEU particles, it would be necessary to distinguish old from new HEU. Such discrimination may be possible by characteristic isotopic signatures and age-dating of uranium particles.

For reprocessing plants in operation at the time the treaty comes into force, it would not be possible for the IAEA to do complete design verification or install its own instrumentation as it can in new facilities before concrete is poured around pipes and before some areas became inaccessible because of high radiation levels. But a modified safeguards approach is possible.


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

4 Uranium Enrichment Plants

One of the IAEA's tasks in verifying an FM(C)T will be to monitor that enrichment facilities are not producing highly enriched uranium for weapons purposes. This problem has been successfully tackled in all enrichment facilities in the NPT non-weapon states and in some civilian enrichment facilities in the nuclear weapon states.

The new problem for verification in enrichment plants in nuclear weapon states will be traces of HEU in enrichment facilities that were previously used to produce this material for weapons. In some cases, these facilities have already been converted to making low-enriched uranium for power reactor fuel. When an FM(C)T enters into force, others may also be converted. It is possible, however, that some facilities may continue to produce highly enriched uranium, for military reactor fuel.

These legacy facilities were not designed for safeguards and are likely to be hard to retrofit to the extent necessary to meet current safeguards standards. Given these difficulties, we propose a simplified approach for such facilities based on traditional inventory monitoring and environmental sampling inside the enrichment facility.

HEU Production: Status and Capabilities

The first uranium enrichment facilities were built for military purposes and primarily used for HEU production. Many of these facilities have been shut down, and, in some cases, even decommissioned. The United States, Russia, the United Kingdom, France, and China reportedly had all stopped production of highly enriched uranium (HEU) for weapons or other purposes by 1996 (Table 4.1).[111]

Only India and Pakistan are believed to be currently producing HEU. India is producing enriched uranium at least for naval fuel (less than 90%).[112] Pakistan is enriching for weapons. Israel may have produced enriched uranium in limited quantities, possibly as driver fuel to irradiate lithium targets for tritium production.[113] The existence of an enrichment program in the DPRK is disputed.

	HEU Production Start	HEU Production End
United States	1944	1992
Russia	1949	1987–88
United Kingdom	1953	1963
China	1964	1987–89
France	1967	1996
Israel	1979–1980	?
Pakistan	1983	Continuing
India	1992	Continuing
North Korea	?	?

Table 4.1. HEU production periods in nuclear weapon states. Production of highly enriched uranium has been pursued in nuclear weapon states for weapons purposes, and in some cases for naval and other military reactors, and for use as fuel in some civilian research reactors.[114]

It is likely that, by the time an FM(C)T comes into force, safeguarding of uranium enrichment will require monitoring only of centrifuge plants—and perhaps one laser-enrichment plant.[115] These facilities are listed in Table 4.2, which also includes centrifuge facilities operational, under construction, or planned in non-weapon states. The only two remaining large gaseous diffusion plants, one in the United States and one in France, will be shut down within the next few years.

In nuclear weapon states, there are currently plans for up to four very large new civilian enrichment plants in the United States, and one in France. Russia may build a new facility in Angarsk.[116] Pakistan too has announced plans for a commercial centrifuge plant.[117] The U.S. centrifuge plants will be offered for safeguards as part of its voluntary offer made to the IAEA.[118] Given the limited IAEA safeguards budget and the low priority assigned to such partial safeguards in weapon states, very few facilities on the Voluntary-Offer list are selected for safeguards. However, the IAEA could carry out at least design information verification, and take other preparatory steps, so that it can more easily implement full safeguards as a part of the FM(C)T.

Current Safeguards Approach for Centrifuge Enrichment Facilities

Until the mid-1970s, the supply of enrichment services for commercial purposes was monopolized by a few nuclear weapon states—notably, the United States. Then, it became apparent that non-nuclear weapon states with ambitious nuclear programs, namely Germany, Japan, the Netherlands and (it appeared at the time) Australia, would move forward with plans to build their own gas-centrifuge enrichment plants, which would have to be placed under safeguards. For this reason, when work on safeguards for enrichment plants started, it focused on centrifuge facilities. Studies carried out in the 1970s revealed no simple safeguards concept for centrifuge enrichment facilities.[119]

Technology holders seek to protect commercially sensitive design and operating information and have therefore been reluctant to grant visual access to the centrifuges. In fact, the question of whether or not inspectors would have access to the cascade halls at all was the subject of considerable debate during negotiations on safeguards concepts for centrifuge facilities. Design sensitivity continues to be an issue and was a critical element of the discussions between Brazil and the IAEA over safeguards at the Resende centrifuge facility.[120]

Country	Facility	Safeguards Status	Capacity [tSWU/yr]	HEU Status
Brazil	Resende	yes	120	none
Germany	Gronau	yes	4500*	none
Iran	Natanz	yes	250	none
Japan	Rokkasho	yes	1050	none
The Netherlands	Almelo	yes	3500	none
France	George Besse II	yes	7500	none
United Kingdom	Capenhurst	yes	4000	cc
United States	Piketon, Ohio	offered	3500	none
	Eunice, NM	offered	3000	none
	Areva Eagle Rock, Idaho	(offered)	3000	none
	GLE, Wilmington, NC		3500–6000	
China	Shaanxi	(yes)	1000*	potential cc
	Lanzhou II	offered	500	potential cc
Russia	Angarsk II	(offered)	5000	none
	4 others	no	~30000	ended 1988
India	Rattehalli	no	4–10	ongoing
Pakistan	Kahuta	no	15–20	ongoing
	Chak Jhumra, Faisalabad	(offered)	150	none

Table 4.2. World enrichment facilities and their safeguards status, expected situation for 2015. The facilities in Brazil, France, Iran, and the United States (Piketon and Eunice) are currently under construction. Additional facilities are in the early planning stages (Areva and GLE in the United States, Angarsk-II in Russia, and Chak Jhumra in Pakistan). Whether these projects will be realized as currently planned is less certain. In some cases, cross-contamination (cc) might result in the presence of HEU particles in facilities that never produced such material. Asterisks mark capacities after planned expansions are complete. Global Laser Enrichment (GLE) is a subsidiary of General Electric Hitachi (GEH) and Cameco using the Australian Silex process.

The first safeguards concept for centrifuge facilities under an INFCIRC/153-type agreement was developed in the 1980–83 Hexapartite Safeguards Project (HSP). This effort brought together Australia, Germany, the Netherlands, Japan, the United Kingdom, and the United States, as well as the IAEA and Euratom as observers. Russia chose not to participate.

The HSP approach, which became the de-facto standard for centrifuge facilities, envisions two different classes of activities:

- Activities outside the cascade halls primarily based on "conventional" safeguards practices and focused on material accountancy and containment/surveillance measures to detect diversion of declared material.

- Activities inside the cascade halls to verify that no material beyond the declared enrichment level, and in particular no HEU, is being produced.

Access to the cascade areas is governed by a Limited Frequency Unannounced Access (LFUA) approach, which regulates delays and maximum duration of the visits, as well as permitted activities of the inspectors.

The HSP approach is designed to detect:

- Diversion of low-enriched uranium produced from *declared* feed material and

- Covert production of HEU.

The possibility of *excess production* of low-enriched uranium using *undeclared* feed is not explicitly covered in the Hexapartite safeguards approach. Reportedly, some HSP participants at the time argued that undeclared nuclear material in non-nuclear weapon states does not exist and that this implausible scenario should be dropped. One result is that, even today, the actual enrichment work at a plant between two inspections, which has to be known to detect excess production of LEU using undeclared feed, is not being independently verified.

In 1995, IAEA safeguards techniques in centrifuge facilities were extended to include environmental sampling techniques, which have been used on a routine basis since then. Deposited UF_6 particles that have leaked from the cascade are collected with swipe samples, usually taken during inspections of the facility, including inside the cascade areas along agreed inspector access routes. These samples are analyzed off-site and provide accurate information on the composition of the feed, product and depleted materials.

Environmental sampling is a formidable tool for identifying traces of HEU. As a result, clandestine production of HEU in a safeguarded facility has become a risky undertaking. There is typically a several-week delay between release of a particle from the equipment and the result of the final analysis of a swipe sample, however. The IAEA one-month timeliness criterion for detecting undeclared HEU production is therefore difficult or impossible to meet with sampling techniques alone.[121]

In 1993, China offered its Russian-supplied centrifuge facility at Shaanxi for IAEA safeguards. Since the HSP approach was not fully applicable to this or other centrifuge facilities based on Russian centrifuge technology, in the late 1990s, China, the Russian Federation, and the IAEA initiated a Tripartite Enrichment Project to develop appropriate new safeguards options.[122] The goal was to design safeguards that would be applicable to any plant using centrifuges of Russian design. One problem was the flexible piping arrangements in such plants that apparently make it possible for the operator to route the gas around any instrument installed to monitor the enrichment level of the gas.[123] In addition, the remote location of the Shaanxi plant and unfavorable travel conditions make unannounced inspections difficult. Little has been published on the experience gained from this effort.

Other safeguards measures are being investigated and implemented to address some of the shortcomings of the HSP approach. This new "Model Safeguards Approach" seeks to deal with the challenge of large centrifuge plants and capture the excess LEU production scenario.[124] It includes short-notice-random inspections, enrichment and flow monitors, surveillance of UF_6 feed-and-withdrawal areas, and deposit of time-stamped operational data in an electronic mailbox for later IAEA inspector review.[125]

New Enrichment Facilities

New enrichment plants are being built or planned in the United States, France, China and Pakistan:

- *Facilities using Urenco technology.* The National Enrichment Facility (NEF) near Eunice, New Mexico, and the George Besse II (GBII) facility at the Tricastin site in France will use standard Urenco technology. In addition, Areva is pursuing plans to build a third centrifuge enrichment plant in the United States that also would use Urenco technology.

- *Facilities using American-Centrifuge technology:* The plant under construction in Piketon, Ohio, will use the so-called *American Centrifuge*, based on designs developed by the U.S. Department of Energy in the 1970s. The dimensions and the capacities of these machines are much larger than those of typical Urenco machines.[126] The number of machines per cascade (and plant) therefore is lower, and it can be expected that operational practices would be somewhat different from Urenco plants but the safeguards arrangements are likely to be similar.[127]

- *Facilities using Russian technology:* Russia has proposed turning its Angarsk enrichment complex into an international uranium enrichment center and significantly expanding its capacity by adding a new section to the plant (Angarsk II). Reportedly, no highly enriched uranium was ever produced in the original Angarsk Site, which could facilitate implementation of safeguards. The Tripartite Enrichment Project developed for Shaanxi offers a means for safeguarding this and other new enrichment plants using Russian centrifuge technology.

- *New facilities in other nuclear weapon states.* Pakistan has announced plans to build a new centrifuge facility for commercial fuel production that would be open for safeguards by the IAEA.[128] Pakistani centrifuge technology is based on and reported to be still similar to early Urenco technology,[129] and it appears likely that a safeguards approach could be developed based on the original HSP approach and on measures envisioned in the new model approach.

As part of the original Hexapartite negotiations, there was a common understanding among the participants that *all* facilities they would build would be safeguarded—even those in the participating nuclear weapon states, i.e., the United Kingdom and the United States. The IAEA is not, however, required to select these plants for safeguards.

The Capenhurst centrifuge facility in the United Kingdom is under IAEA safeguards, and has even been used to test and demonstrate new safeguards technologies.[130] The Hexapartite agreement would apply equally to the new U.S. facilities, but they may not be selected by the IAEA. In the case of the new French facility (GBII), the situation could be more complicated because it involves a party that was not originally a member of the Hexapartite agreements.

In summary, the safeguards approaches for new enrichment plants in weapon states, and the effectiveness of these safeguards, will be very similar to those currently employed in safeguarded plants in the non-nuclear weapon states and in China. The principle issue is the additional costs of safeguarding facilities. Some have already been offered to the IAEA for safeguards, but the IAEA has indicated that it may not have the required funding and personnel. This situation would have to rectified under an FM(C)T.

Incremental cost of safeguarding new enrichment facilities. Compared to other nuclear fuel cycle facilities that handle or can produce fissile materials, i.e., reprocessing and MOX fabrication facilities, however, safeguarding centrifuge enrichment facilities is relatively inexpensive. The main reasons are that uranium-enrichment plants process only weakly radioactive material, and that no directly weapon-usable material (HEU) is produced or present at these sites during routine operation.

Table 4.3 lists typical costs of safeguards on nuclear facilities expressed in annual person-days of inspection (PDI).[131] For a commercial-size centrifuge facility about 150 PDI are required per year, compared to up to 1,000 PDI/yr and 600 PDI/yr for a reprocessing and MOX fabrication facility, respectively.

Person-Days of Inspection (PDI's) for commercial-size facilities	
Reprocessing facility	up to 1000 PDI/yr
MOX fabrication facility	up to 600 PDI/yr
Centrifuge enrichment plant	up to 150 PDI/yr
Light-water power reactor (PWR or BWR)	10 PDI/yr
Breakdown of safeguards effort for typical centrifuge facility	
Annual physical inventory verification	about 40 PDI/yr
Routine inspections	about 100 PDI/yr
Additional LFUA inspections	about 10 PDI/yr
TOTAL	150 PDI/yr

Table 4.3. Costs of safeguarding nuclear fuel-cycle facilities and power reactors.[131]

The estimated 150 person-days of inspection per year is associated with several activities: about 40 PDI/yr are needed for the annual physical inventory verification (PIV), about 100 PDI/yr for the monthly inspections, and about 10 PDI/yr for limited-frequency unannounced inspections of the cascade areas that are *not* done in conjunction with routine inspections.[132] Depending on the approach taken to estimate total safeguards costs, one person-day of inspection costs between $2000 and $10,000.[133] Accordingly, safeguarding one commercial-size enrichment facility costs $0.3–1.5 million per year. For comparison, the American Centrifuge Plant, which is being built by USEC in Piketon, Ohio, with a capacity of 3.8 million SWU/yr, will cost on the order of $3.5 billion.[134]

The total inspection effort for the six new centrifuge plants (three in the United States, one in France, one in Russia, and one in China) would be on the order of 900 PDI/yr —about one tenth of the current IAEA safeguards effort.

Verification at Weapon-program Legacy Facilities

In unsafeguarded facilities that produce low-enriched uranium today, but produced HEU in the past, verification measures would have to be introduced in a potentially HEU-contaminated plant (Figure 4.1). Ideally, one would seek the same safeguards objectives here as are pursued in other enrichment plants. These are to detect: the diversion of LEU, excess LEU production, and covert HEU production. Implementing these safeguards objectives in such facilities would be challenging, however:

- Design information verification would be difficult in an old facility.

- These facilities were not designed for effective implementation of international safeguards. For example, as part of the Hexpartatite negotiations, it was agreed to not install valves or flanges in the cascade areas in order to preclude some possible undeclared activities.[135] "Flexible piping arrangements" in Russian-designed plants could make it possible, however, to bypass installed instruments.

- The concept of *Limited Frequency Unannounced Access*, which is a fundamental component of the HSP approach, may be difficult to implement in some regions or countries due to unfavorable travel conditions.[136]

Despite these difficulties, we believe that an adequate approach could be developed and implemented for these legacy facilities as part of a comprehensive FM(C)T verification regime. As a transitional measure, we propose a simplified approach that addresses the most fundamental safeguards objective at any enrichment plant, namely to detect covert HEU production.

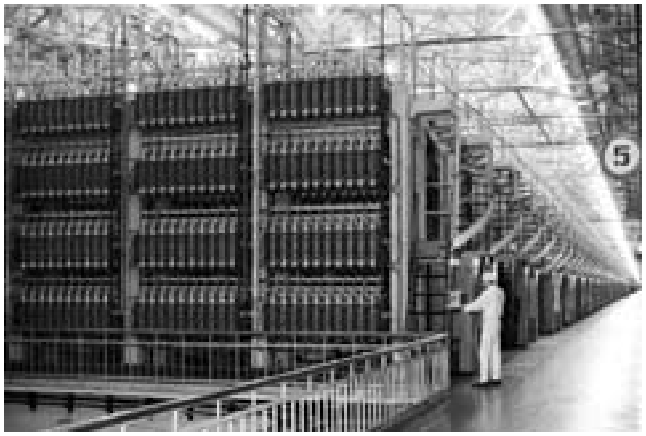

Figure 4.1. Cascade hall of the Novouralsk centrifuge enrichment plant, formerly known as Sverdlovsk-44. This facility has a capacity of almost 10 million SWU/yr, about 4–5 times more than a typical Urenco facility today. It is likely that, until the late 1980s, HEU production took place in the same building, using either centrifuge or gaseous diffusion technology.

The approach involves focusing the initial verification effort on the detection of undeclared HEU production only, with more comprehensive safeguards to detect excess production or diversion of LEU being added as soon as practical.[137]

Whenever possible, environmental sampling techniques would be used as the primary method to assure that no HEU is produced in the facility. If particles from historic HEU production are detected, there would at least two strategies to distinguish them:

- *Isotopic Signature.* An environmental sampling "baseline" would be established.[138] During this process, the U-234 and U-236 fractions are determined as a function of U-235 enrichment. It has been reported that HEU particles from historic production found in a safeguarded plant can be clearly identified based on such isotope-ratio baselines.[139]

- *Age.* Compliance with the treaty could be most directly confirmed with a measurement of the particle age to determine whether or not the particle was produced after the FM(C)T came into force for that state. Dating is based on the fractional concentrations of certain decay products in the material. For micron-sized particles of uranium, however, this analysis is challenging due to the long half-lives of all relevant uranium isotopes.

Appendix 4A discusses the best techniques available for the required isotope-ratio analysis. We conclude that new HEU particles can be distinguished from historical particles with such measurements if a relatively large suspect particle (with a diameter of 3 micrometers or more) is available for analysis *and* the particle is at least 20–30 years old. Note that the latter condition would be satisfied for all large facilities that have produced HEU, specifically those in Russia, which stopped HEU production in 1988 (see Table 4.1).

These methods would not be effective for verification at facilities in Pakistan and India, which still produce HEU and may continue to do so until an FM(C)T enters into force. These facilities will probably be shut down at that point. If not, it would be easier to monitor these small plants using traditional safeguards approaches without relying on environmental swipe sampling techniques.

The timeliness criterion currently used by the IAEA, i.e., detection of HEU production within one month, cannot be achieved with environmental sampling alone.[140] Routine detection times of 1–3 months, however, are plausible, which would be adequate for an FM(C)T in countries where large stockpiles of nuclear weapons still exist.

The use of continuous and portable enrichment monitors should therefore be considered to improve the timeliness of detecting covert HEU production. These monitors are designed for use on the "header" pipes that carry the enriched UF_6 produced by the cascades to determine whether a specified enrichment limit has been exceeded, providing simple "yes/no" answers. Such instruments have been used in some Urenco centrifuge facilities for years.[141] The development of adequate instruments for centrifuge facilities of Russian design was first proposed as part of the Tripartite Enrichment Project for use in the Chinese facility. According to the IAEA, in 2006, "two flow and enrichment monitors were installed at the Shaanxi enrichment plant. They will provide continuous unattended monitoring of enrichment levels and the quantity of the product."[142]

In sum, verifying that no HEU is being produced in enrichment facilities that were converted to civilian use more than 20 years ago seems feasible with environmental sampling techniques, supported by additional safeguards tools such as enrichment monitors. Other standard safeguards measures, based on material accountancy and containment and surveillance, could be implemented in order to cover the remaining safeguards objectives.

Conclusion

Some enrichment facilities in nuclear weapon states are already safeguarded today. New centrifuge facilities are currently under construction or planned, and all of them will be *offered* for safeguards. It is unlikely, however, that the IAEA will select all these facilities for safeguards when they first become operational. At a minimum, the IAEA should carry out design information verification and take other preparatory steps for these facilities, so that it can more easily monitor them as part of the FM(C)T.

The most important challenge for enrichment facilities under an FM(C)T are those that produced HEU in the past (namely the Russian enrichment facilities) and have been converted to civilian use.

We propose a phased approach for these facilities. Detection of covert HEU production is the key safeguards objective and can be satisfied with high confidence using traditional safeguards measures, including environment sampling and enrichment monitoring. Assuring that no HEU is being produced in enrichment facilities that have been converted to civilian use more than 20 years ago seems feasible with isotope signature baseline and age-dating techniques.

These methods should be viewed as a temporary solution. From a safeguards perspective, legacy facilities should be shut down and decommissioned where possible. The verification challenge at legacy facilities also would be eased if any modernization or expansion were in separate, uncontaminated buildings. For such new capacity, "safeguards-by-design" features should be introduced and efforts made to minimize HEU contamination from legacy equipment.

The safeguarding of all enrichment facilities would impose an additional burden equivalent to the NPT safeguards on 1–2 large reprocessing plants such as Rokkasho.

Appendix 4A.

Age-Dating of Highly Enriched Uranium Particles[143]

The concentration of decay products in a sample of nuclear material can be used to determine the age of this material, i.e., the time that has elapsed since production or last purification.[144] The relevance of such measurements has been previously recognized for the potential verification of an FM(C)T.[145]

Dating of HEU particles is challenging due to the long half-lives or low concentrations of the uranium isotopes. Typical isotopic fractions and decay data are listed in Table 4A.1. The numbers show that only the accumulation of Th-230, the decay product of U-234, can potentially be used for age-dating of highly enriched uranium particles—the concentrations of the decay products in the other isotope pairs (U-235/Pa-231 and U-236/Th-232) being orders-of-magnitude weaker.

	U-232	U-234	U-235	U-236	U-238
Half-Life	68.9 years	245 500 years	0.7 billion years	23 million years	4.5 billion years
Long-lived Daughter	Th-228	Th-230	Pa-231	Th-232	U-234
Decayed Fraction in 100 years	63 %	0.03 %	0.0000098 %	0.0003 %	0.0000016 %
HEU Isotopics (clean)	–	1 %	93 %	–	6 %
Potential Chronometer	–	1	0.03	–	0.0003
HEU Isotopics (from RepU)	4×10^{-8} %	1.15 %	93 %	1.35 %	4.50 %
Potential Chronometer	0.00008	1	0.03	0.01	0.0002

Table 4A.1. Buildup of decay products in an HEU particle. The usefulness of a potential chronometer (normalized to U-234/Th-230) is characterized by the relative abundance of the parent nuclide multiplied by its decayed fraction, which is determined by the age of the material. Even for HEU produced from reprocessed uranium, which contains both U-232 and U-236 in addition to the naturally occurring uranium isotopes, the U-234/Th-230 chronometer is the best candidate for age-dating.

Age-dating of HEU is straightforward and accurate if samples in the microgram or milligram range are available for analysis. It becomes more challenging for small particles, such as are picked up with swipe sampling techniques. The following discussion clarifies the capabilities and limits of this method.

Typical uranium particles found by the IAEA on swipes taken in safeguarded enrichment plants have a diameter of one to three micrometers (microns). Suspect (HEU) particles are identified with particle-analysis techniques and then selected and prepared for ultra-trace level analysis.[146]

For the following estimates, we assume that the effective uranium density in the original particle is about 10 grams per cubic centimeter. Table 4A.2 shows the number of thorium-230 atoms in particles of highly enriched uranium as a function of particle-size, particle-age, and year of analysis.

Year of Analysis	Age of Particle	Particle diameter		
		1 micron	2 micron	3 micron
2010	Minimum	9,600	76,700	258,800
	Average	15,200	122,000	411,700
2015	Minimum	11,800	94,100	317,600
	Average	17,400	139,400	470,500
2020	Minimum	13,900	111,500	376,400
	Average	19,600	156,800	529,300

Table 4A.2. Number of Thorium-230 atoms in a particle of highly enriched uranium as a function of particle-size, particle-age and year of analysis. Assumed production year for the minimum age is 1988, and for the average year 1975 (see Chapter 1, Figure 1.4). Under favorable conditions, current state-of-the-art measurement and analysis techniques are approaching the capability to certify that an HEU particle that may be found on a swipe sample was, in fact, produced prior to entry-into-force of an FM(C)T.

There are several advanced measurement techniques for ultra-trace level isotope ratio analysis, and their sensitivities are being continuously improved. The most promising techniques available for age-dating of bulk samples are Resonance Ionization Mass Spectroscopy (RIMS),[147] Inductively Coupled plasma Mass Spectrometry (ICP-MS),[148] and High-Efficiency Multi-Collector Thermal Ionization Mass Spectroscopy (TIMS).[149] Their current detection limit for plutonium and uranium is less than 100 attograms,[150] which corresponds to 50,000–200,000 atoms.[151] The technology is improving. In addition, the "blank level" has to be sufficiently low for the analysis to be carried out successfully.

We conclude that it is critical to obtain at least one uranium particle with a diameter of 3 micrometers, and preferably larger, or five to ten smaller suspect particles that contain an equivalent amount of atoms. It would be extremely difficult or even impossible, however, to determine the age of small particles only a few years old. As the time-span between production and detection increases to two decades and more, age-dating becomes easier and more accurate.

5 Reprocessing Plants

Under a Fissile Material (Cutoff) Treaty, or FM(C)T, the most costly new verification challenge will be to apply safeguards to reprocessing plants in the eight states having nuclear weapons (the five NPT nuclear weapon states, Israel, India, and Pakistan).[152] Although there are only two operating reprocessing plants in the non-weapon states, Japan's Tokai and Rokkasho facilities, these two plants alone account for 20 percent of the total international safeguards inspection effort performed by the International Atomic Energy Agency (IAEA).[153]

A 1996 Brookhaven National Laboratory study estimated that two thirds of the routine inspection effort devoted by the IAEA to verifying an FM(C)T in the nuclear weapon states would be focused on reprocessing plants.[154] The Brookhaven study estimated that there were 52 reprocessing installations, large and small, civilian and military, existing in various operating or shutdown modes in states having nuclear weapons. Although the total number of installations is fewer today, it is clear that safeguarding reprocessing plants under an FM(C)T will be challenging. This paper explores how the safeguarding could be done cost-effectively. It is assumed that the safeguarding will be done by the IAEA. The comprehensive safeguards approach developed by the IAEA for the Rokkasho Reprocessing Plant is taken as the point of departure.

In non-weapon states, safeguards are applied according to IAEA Safeguards Criteria[155] that specify the activities considered necessary by the IAEA to provide a reasonable probability of detecting the diversion of a significant quantity of nuclear material. The safeguards are designed to detect a diversion of one significant quantity (SQ) of nuclear material removed either abruptly or in a protracted manner. The IAEA defines an SQ as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. For plutonium, one SQ is defined to be 8 kg.[156] The time requirement for detection of an abrupt diversion of one SQ of plutonium is within one month and, for protracted diversion, it is one year.[157]

The definition of a reprocessing facility will need to be clarified in the relevant FM(C)T safeguards agreement. Currently, the IAEA defines a reprocessing facility to be any installation that has the capability to separate nuclear material from fission products, regardless of the throughput, inventory or operational status. This includes hot-cell facilities with separation capabilities. A more practical criterion for including facilities as reprocessing facilities under the FM(C)T could be that an installation must have the capability to separate and purify at least one significant quantity of fissile material per year.

The 15 largest operating reprocessing plants in the nuclear weapon states are shown in Table 5.1. Under an FM(C)T, many of the plants built to produce plutonium for weapons would be decommissioned. Some could continue in operation, however, for civilian purposes and some could be used for military purposes that would not be banned by an FM(C)T, for example, reprocessing fuel from naval-propulsion and tritium-production reactors.

Facility	Type	Operational Status	Operating Capacity (tHM/yr)
France			
UP2	Civilian	Operating	1000
UP3	Civilian	Operating	1000
India			
Trombay	Military	Operating	50
Tarapur	Dual	Operating	100
Kalpakkam	Dual	Operating	100
Israel			
Dimona	Military	Operating	40-100
Pakistan			
Nilore	Military	Operating	10-20
Russia			
RT-1	Dual	Operating	400
RT-2	Civilian	Construction suspended, 1989	800
Seversk	Dual	Operating	6000
Zheleznogorsk	Dual	Operating	3500
United Kingdom			
B205	Civilian	Operating	1000
THORP	Civilian	Operating	1200
United States			
PUREX	Military	Shut-down	7400
SRP	Converted	Special Operations	15

Table 5.1. Major reprocessing plants outside the NPT non-weapon states, their status and their operating capacities. Capacities are defined in terms of the operating or licensed maximum annual throughput of metric tons of "heavy metal" (uranium and plutonium) in the material being reprocessed (tHM/yr). Design capacity is sometimes much larger than the typical operational throughput.[158]

The reprocessing plants to be safeguarded under an FM(C)T may be grouped into the following categories:

- Operating civilian plants,
- Operating plants reprocessing fuel from military reactors, sometimes exclusively and sometimes in combination with civilian-reactor fuel,
- Shutdown or closed-down plants, and
- New civilian plants, not yet operating.

The large plants that have been operating without international safeguards prior to the FM(C)T will pose the greatest challenge. Unlike Rokkasho, provisions for safeguards will not have been designed into the plants nor verified by the IAEA during construction and before the plants went into operation. It would be extremely expensive for the IAEA to attempt to retrofit an operating plant with safeguards measurement and monitoring systems similar to those installed in the Rokkasho Plant. Where independent measurement and monitoring systems cannot be installed at reasonable cost for verification of operator measurements, the IAEA may have to accept a lower probability of detection of a diversion.

The following section of this paper describes the general approach to reprocessing-plant safeguards that has been developed by the IAEA and a modified approach that could be adapted to already-operating plants in weapon states. We include a brief discussion of safeguards at mixed-oxide (uranium-plutonium, MOX) plants. Subsequent sections describe more briefly safeguards approaches for military plants, and new operating plants constructed after an FM(C)T comes into force.

The discussion of safeguards at shutdown or closed-facilities may found in Chapter 9. Overall, the safeguards burden would be low in comparison to that at operating reprocessing plants.

FM(C)T Safeguards at an Operating Reprocessing Plant

A safeguards approach for reprocessing plants must address primarily two types of attempted diversion scenarios under which the operator either:

1. Reprocesses undeclared nuclear material, bypassing the accountancy measurement points; or

2. Removes plutonium at a low rate that cannot be detected with confidence, due to measurement uncertainties.[159]

Although almost all reprocessing plants use the PUREX process, their design and operating modes vary considerably. These plant characteristics and the operator's nuclear material accountancy systems must be considered when designing a safeguards approach for a specific facility. The arrangements necessary to implement the IAEA safeguards approach at a specific facility are described in the Facility Attachment to the national safeguards agreement.[160]

The next section provides a technical description of the activities and accountancy measurements within a reprocessing plant. This is followed by a discussion of the proposed FM(C)T Safeguards Approach.

Material Balance Areas and accountancy measurements. Using the Rokkasho Reprocessing Plant as an example, Figure 5.1 shows an accountancy structure having five Material Balance Areas (MBAs).[161]

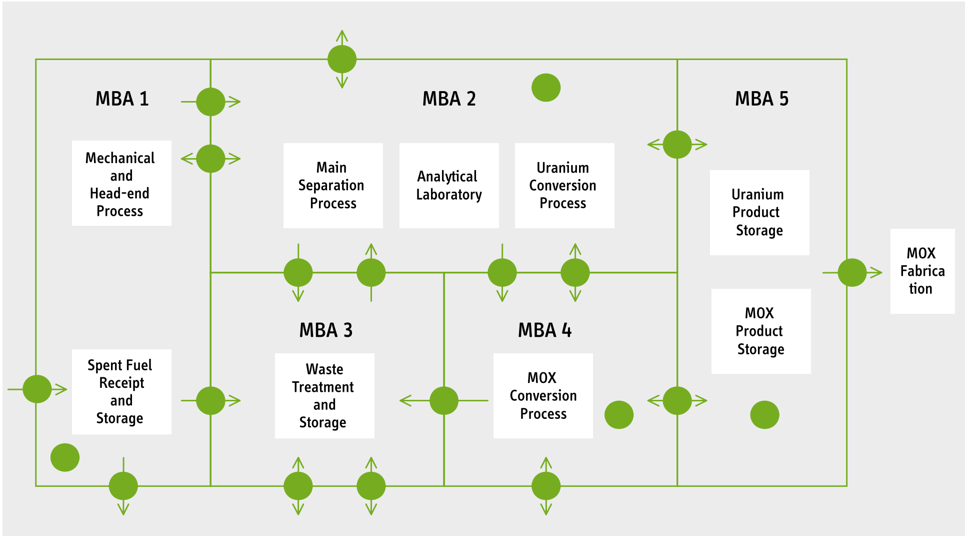

Figure 5.1. Accountancy structure for the Rokkasho Reprocessing Plant. The circles indicate Flow Key Measurement Points for verification of Inventory Changes. Circles with arrows indicate FKMPs across MBA boundaries and circles without arrows for those calculated within an MBA, such as nuclear material loss and gain. The boxes represent Inventory Key Measurement Points within the MBAs, which are established for the verification of inventory declarations and timeliness.

MBA 1: Cask Receipt and Storage, Spent Fuel Unloading and Storage, and Head- End Process. Irradiated fuel assemblies are received in casks from a reactor or away-from-reactor storage facility and stored in one or more ponds at the reprocessing facility (see, for example, Figure 5.2).

There are currently no accurate measurement methods available to verify the plutonium content in spent fuel. The uncertainties of reactor-operator calculations of plutonium content can be 3 to 10 percent, and sometimes even larger.

The fuel assemblies are later transferred from the storage pool(s) into the head-end process of the plant where they are chopped or sheared into small pieces for dissolution in boiling nitric acid. Most plants use a batch process for dissolution, but some modern plants, such as those in France, use a continuous-feed dissolver.

Accountancy measurements are made in a well-calibrated Input Accountability Tank. Measurements of the volume of the clarified dissolver solution and its concentration of plutonium provide the first good measurements (0.3 to 1.0 percent uncertainty) of the plutonium content in the spent fuel entering the reprocessing plant. The solution is then transferred in measured batches to the main separation process in MBA2.

Undissolved structural parts of the spent fuel assemblies, including fuel-rod-cladding "hulls" and assembly end pieces, are collected into drums. This highly radioactive solid waste and additional liquid wastes are transferred to a waste treatment and storage area (MBA3).

It is critical to assure that the dissolver solution being measured comes from the declared spent fuel and that none of the dissolver solution bypasses the Input Accountability Tank. Surveillance and radiation monitoring systems are used to track the spent fuel into the dissolver vessel, and solution-monitoring systems track the dissolver solution to the Input Accountability Tank.[162]

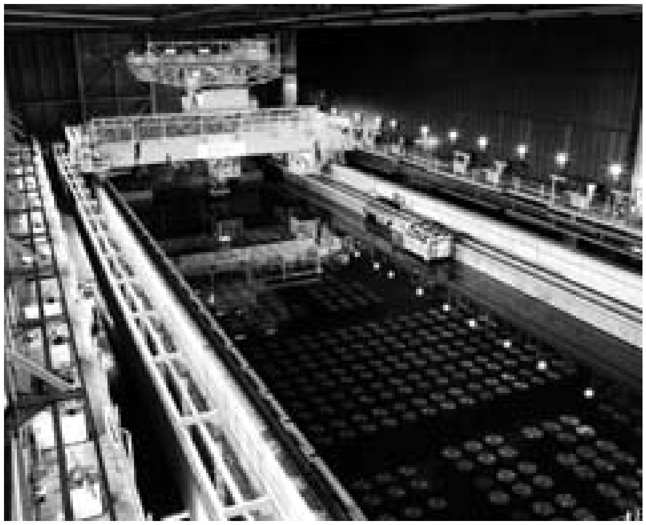

Figure 5.2. Spent-fuel storage pool at the U.K. Thermal Oxide Reprocessing Plant (THORP). [Source: World Nuclear Association.][163]

MBA 2: Main Separation Process. The measured batches of dissolver solution received from MBA1 are processed in a first extraction cycle. There the plutonium and uranium are separated from the fission products in an organic solvent mixed into the acid. Uranium and plutonium are then separated from each other and their solutions transferred to their purification cycles. Depending on the methods used, measurements of the purified plutonium in solution have an expected uncertainty of between 0.2 and 0.8 percent.

In the Rokkasho Reprocessing Plant, the separated uranium is purified, concentrated and approximately 99% of the uranyl nitrate is then transferred to a conversion process —all within MBA2. After conversion to UO_3, it is transferred to a product-storage area in MBA5. The remaining uranly nitrate is routed directly to the uranium-plutonium mixed-oxide (MOX) powder-production process in MBA4.

Although the uncertainties of the main flow measurements into and out of MBA2 are relatively small, if the process hold-up inventory is large, it could provide an opportunity to divert material that would not be detected until after the yearly clean-out and Physical Inventory Verification is conducted. Continuous monitoring of selected process flows within MBA2, using installed solution monitoring systems, provide continuity of knowledge and confirmation of the declared operational status.

MBA 3: Waste Treatment and Storage. Highly radioactive liquid waste, containing undissolved particles from the head-end process, concentrated fission products, and medium activity liquid waste are received in the waste-treatment area. They are further concentrated by evaporation and may be mixed together prior to being introduced to a "vitrification" process in which they are mixed into molten glass. After accountancy measurements have been completed for consideration of termination of safeguards, canisters of solidified vitrified waste are transferred to a long-term storage area.

At the Rokkasho Reprocessing Plant, the uranium and plutonium present in drums containing leached hulls and end pieces received from the Head-End (MBA1) are measured or estimated for accountancy purposes. Only when waste has been treated to make the nuclear material "practically irretrievable"—for example by vitrification or mixing with cement—can it be considered for termination of safeguards. Following accountancy measurements, wastes that have not been made practically irretrievable are stored at the MBA as "retained waste."

The total quantity of plutonium going into waste in a reprocessing plant is typically less that 0.5 percent of the total throughput, with concentrations in the milligram per liter (parts per million) range. Due to the low concentrations and inhomogeneities, the measurement uncertainty, using current technology, is 5 to 25 percent.

MBA 4: Mixed-oxide (MOX) Conversion Process. The process of producing uranium-plutonium mixed-oxide powder at the Rokkasho Reprocessing Plant starts with the mixing of uranyl and plutonium-nitrate solutions. The resulting mixture is dried and calcined to produce oxide powder, which is then milled to a uniform particle size. Processes used in other countries convert the uranium and plutonium solutions to oxide powders separately prior to mixing (see Figure 5.3).

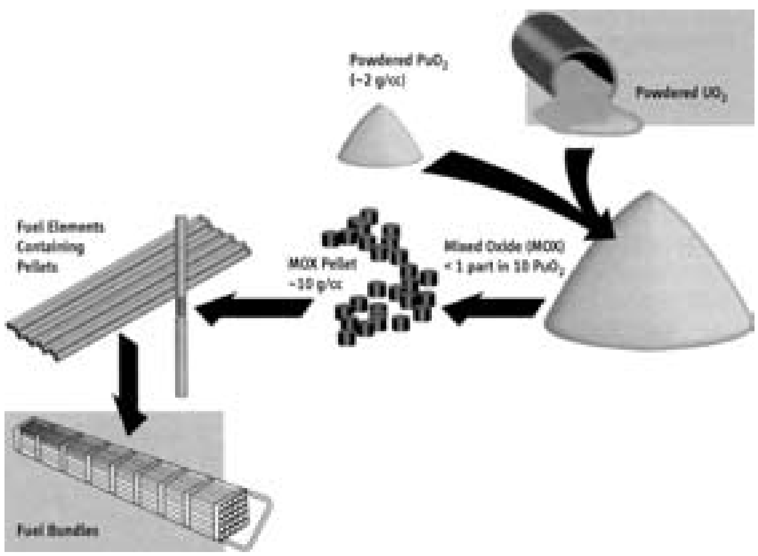

Figure 5.3. Generic stages of MOX fuel fabrication.[164] At a MOX-fuel fabrication plant, plutonium-oxide powder is blended with uranium oxide to the desired Pu/U ratio and turned into fuel pellets. The pellets are then loaded into fuel rods that are combined into fuel assemblies for use in a nuclear reactor. The process shown here is different from that used at the Rokkasho Plant, where the initial powder containing the plutonium oxide already contains an equal amount of uranium oxide.

Prior to canning, the powder lots are sampled, and the filled cans are weighed for nuclear-material-accountancy purposes. The cans are then packed into storage canisters and transferred to the product-storage area in MBA5.

Although the samples of the oxide product can be measured in a laboratory with uncertainties of about 0.2 percent, non-destructive analysis (NDA) using neutron and gamma radiation counters is more likely to be used on the storage containers for safeguards verification. The enhanced NDA system developed for the Rokkasho Reprocessing Plant has reduced these measurement uncertainties to less than 0.8%. Such measurements can be performed using an unattended measurement system.

The in-process inventory in the plutonium conversion line can be quite large. As a result, a significant diversion might not be detected until the annual clean-out and the physical inventory verification. Some form of continuous solution monitoring in the feed vessels and radiation monitoring[165] along the conversion lines is therefore needed to assure that the process is operating as declared.

MBA 5: MOX and Uranium Product Storage. In the Rokkasho Reprocessing Plant, canisters of uranium-oxide product are received for storage from the Conversion Process in MBA2 and canisters of MOX product are received from the MOX conversion process in MBA4.

Since this MBA is a storage area containing previously verified containers of product material, there need be no new measurements. The integrity of the measurements performed in MBA4 is maintained by surveillance and radiation monitoring systems to detect movements of containers and materials within and out of the facility. In other plants, containers used for long-term storage could be sealed with tamper-indicating seals.

MBA X: MOX-Fuel Fabrication. At Rokkasho, the JMOX fuel fabrication facility will be physically connected to the MOX conversion building. Although it could be considered as an additional MBA, at Rokkasho it will be a separate facility. If located on another site, as in France, it would normally be considered a separate facility. In the latter situation, continuity of knowledge would need to be maintained on the MOX powder during shipping—usually by sealing the containers—in order to avoid the requirement of re-measurement upon receipt in the fabrication plant.

At a MOX-fuel fabrication plant, MOX powder is blended with uranium oxide to the desired Pu/U ratio and introduced to the pelletizing process. The pellets are then loaded into fuel rods that are combined into fuel assemblies (see Figure 5.3). Storage areas are required between the various processes and for the final MOX fuel assemblies prior to shipment to the receiving reactors. Storage areas are also provided for MOX-containing scrap material from the process.

Because there can be large inventories stored in a MOX plant, they can contribute significantly to the over-all material-balance evaluation during the yearly physical inventory verification.

The uncertainty associated with the measurement of plutonium in the fabricated MOX fuel assemblies is quite high—approximately 10 percent.[166] Because of this high uncertainty, it is important to monitor the flow of material through the process with containment and surveillance devices and radiation monitoring systems.[167]

Safeguards Approach. At already-operating reprocessing plants in the weapon states, meeting the current IAEA Safeguards Criteria would be very costly and perhaps impossible. With some reduced confidence in meeting the IAEA timeliness requirements, however, newer verification and monitoring tools and methods could be used to drastically reduce the verification costs relative to those for Rokkasho with only a relatively modest increase in measurement uncertainties. Specifically, the proposed Safeguards Approach for FM(C)T verification at already operating reprocessing plants includes the following changes:[168]

- *Short-Notice Random Inspections (SNRI) would replace continuous inspector presence at reprocessing plants.*[169] SNRIs at a frequency of six to eight per year would replace the current NPT monthly inventory verification inspections to meet timeliness requirements. Although some intervals between inspections would be longer than one month, a delay in the detection of a diversion would be much less serious in a weapon state than in a non-weapon state. As will be shown below, eliminating the need for continuous inspector presence would greatly reduce costs.

  The operators of a reprocessing plant would be required to provide advance declarations of operational schedules and continuous, timely declarations of materials flows and inventories. These declarations would offset the reduced presence of IAEA inspectors and provide the basis for inspection activities during an SNRI.[170] This would also result in more transparent facility operations. Of course, while inspection efforts and costs would be reduced for the IAEA, more of a burden would be placed on the operators and their State authorities.

  The installation of continuous solution and radiation monitoring systems and Containment/Surveillance (C/S) measures would give additional confidence by providing continuity of knowledge of material flows and movements and of the operational status of the reprocessing plant between the SNRIs.

  Inspection activities at other strategic points during the SNRIs could provide added assurance that the facility is being operated as declared. These could include random, very short notice checks of expected or declared operating parameters in control rooms and a low level of random sampling of material in process.[171]

- *Use a random number of measurements during the SNRIs to replace the 100 % verification of major inventory changes in the MBAs.* The use of unattended measurement systems and continuous automated monitoring would compensate for the reduced verification level.

- *Focus primarily on establishing materials balances for plutonium and highly enriched uranium.*[172] Less effort than under NPT safeguards in non-weapon states would be devoted to verifying inventories of low-enriched, natural, and depleted uranium.[173] This would be compatible with most other proposals for verification of an FM(C)T in that they do not include monitoring of these materials at other facilities.

- *Verify waste transfers only in cases of large discrepancies between operator declarations and declared and verified design and operational production values.* If the design values are on the order of 0.5 percent of the plant throughput—i.e., the same order as the measurement uncertainties—this would not greatly increase overall uncertainties.

The following procedures and equipment would be the same as the current approach for NPT verification at the Rokkasho Reprocessing Plant:

- *Physical Inventory Verification once a year after the facility has been cleaned out and the operator has provided an inventory declaration.* Statistical evaluations of the operator's declaration and verification results would indicate whether significant quantities of nuclear material were ”unaccounted for.” Simultaneous inspections would be carried out at any other facilities in the state having the same type of nuclear material to assure that no “borrowing” between facilities was taking place.

- *Periodic verification of selected design information to confirm that no safeguards relevant changes have been made and that the facility design remains as declared by the operator.*

- *A large and dedicated Data Collection and Evaluation System to manage the volume of data and information resulting from operator declarations, surveillance and monitoring systems, and inspector on-site measurements*.[174] This system would collect data from inspector-controlled unattended measurement and monitoring systems and automatically perform preliminary evaluations based on the operator declarations or on expected or design values. The results, including alerts of possible discrepancies, could then be transmitted remotely to the IAEA.

This proposed simplified FM(C)T Safeguards Approach for operating reprocessing plants would yield an overall uncertainty for the annual material balance for the entire facility of about one percent—only marginally larger than the corresponding uncertainties for the NPT safeguards.[175] This excludes the larger uncertainties in both the NPT and FM(C)T safeguards approaches associated with the estimates of the amount of plutonium originally in the spent fuel and in measurements of the plutonium in fresh MOX fuel. These are dealt with by containment and surveillance to assure that no significant amount of plutonium is diverted between the dissolver and Input Accountability Tank or in the MOX fuel fabrication process. For a large facility such as the Rokkasho Reprocessing Plant, which has an annual throughput of 800 tons of spent fuel containing about one percent plutonium (about 8000 kg), a one-percent uncertainty translates into an overall measurement uncertainty of 80 kilograms plutonium—ten significant quantities. For this reason, the IAEA requires added assurance by additional measures. Many of these could be carried out during short-notice random inspections.

The following measures, for example, might be undertaken:

- *Random sampling of the process and waste streams,* including ratios of plutonium and uranium with the minor transuranics, curium, americium and neptunium, helps provide assurance that there has not been any change in operating parameters declared by the operator. Random measurements of the amount of plutonium in the newly filled plutonium-oxide containers can be carried out non-destructively through analysis of the emitted gamma and neutron radiation. Finally, the declared in-process inventory of the conversion and any MOX fuel-fabrication lines can be verified.

- *Use of containment and surveillance to detect attempts to send undeclared batches of spent fuel through the plant.* Measurements of plutonium in dissolver solutions in MBA1, in plutonium nitrate in MBA2, and in oxide in MBA4 could also be used to detect any abrupt large-scale diversion. Measurements at a few key points would make it more difficult to hide slow but sustained diversions of plutonium.

For any operating facility, the in-process hold-up of plutonium would be significant. The various verification measures taken during the short-notice inspections therefore would have to be confirmed by the annual Physical Inventory Verification, when the facility is completely cleaned out.

Equipment and inspection costs. The cost of the proposed FM(C)T Safeguards Approach for a large operating reprocessing plant would be significantly less than estimated in the 1996 Brookhaven Report and far less than cost of NPT safeguards at the Rokkasho Reprocessing Plant.

Equipment and software costs. Purchase of initial hardware and software would cost about $15 million (to be paid by the IAEA)—about one fifth the cost incurred for the Rokkasho Reprocessing Plant. Installation and maintenance (to be paid by the host state) would cost perhaps $5 million.[176] Maintenance and replacement over the first ten years would average about $1 million per year (to be shared by the IAEA and the state).

These estimates are based on experience at Rokkasho and other facilities. Costs for the proposed FM(C)T safeguards system are reduced by the elimination of a number of very expensive waste-measurement systems. Some savings also have been assumed for the measurement/monitoring and data handling systems because much of the R&D and design work carried out for the Rokkasho plant could be adapted for other reprocessing plants.[177] A final cost saving, compared to Rokkasho, would be that a full-capability on-site laboratory[178] would not be included. Unattended measurement systems and inspector operated equipment would be implemented to the extent possible. A few samples would be sent to the IAEA.

Inspection costs. Table 5.2 summarizes the projected routine inspection effort required to implement the proposed FM(C)T Safeguards Approach for an operating reprocessing plant. Although larger teams are required for Short Notice Random Inspections, the elimination of the requirement of continuous inspector presence reduces the Person Days of Inspection (PDI) to about one fifth or less that of the NPT safeguards at the Rokkasho Reprocessing Plant.[179]

Inspection or Visit	Visits per Year	Inspection Days	Number of Inspectors	Person Days
Short Notice Random Inspection	8	5	3	120 PDI
Physical Inventory Inspection	1	10	5	50 PDI
Other Activities				30 PDI
TOTAL	**9**	**15**	**8**	**200 PDI**
COST	**200 PDI x $2000/PDI/year = $400,000/year**			

Table 5.2. Annual inspection effort in Person-Days of Inspection (PDI) and cost.

Plants Reprocessing Fuel from Military Reactors

Of the 13 reprocessing plants currently operating in nuclear weapon states listed in Table 5.1, seven are labeled as military or dual purpose. Of these:

- The reprocessing plants at Seversk and Zheleznogorsk in Russia are to be shut down.[180]
- India's three reprocessing plants will either revert to civilian status when that country joins the FM(C)T or shut down; and

- Israel's and Pakistan's reprocessing plants would be expected to shut down when that country joins the FM(C)T.

This leaves Russia's RT-1 reprocessing plant at the Mayak complex in the Urals. It treats spent LEU fuel from first-generation VVER-440 light-water power reactors, and spent HEU fuels from the BN-600 demonstration breeder reactor, research reactors, naval reactors and the isotope-production reactors that produce tritium for Russia's nuclear weapons.[181] No other weapon state currently reprocesses its naval or tritium-production reactor fuel.[182] There may therefore be sensitivities at the RT-1 plant about foreign inspectors becoming aware of naval-reactor fuel design or perhaps about the power levels at which the tritium-production reactors are operating.[183]

Russia might want to conceal from IAEA inspectors the design and perhaps enrichment of the spent naval fuel. The quantities and isotopics of the fuel coming from different types of reactors could be concealed, however, by not revealing exactly which fuel is being reprocessed at a particular time and mixing fuel from different types of reactors in the same dissolution batch.[184]

Future reprocessing facilities

Under an FM(C)T, any new reprocessing plants built in nuclear weapon states should be subject to the same safeguards criteria as new plants in non-nuclear weapon states. Lessons learned from the Rokkasho plant have shown the importance of designing safeguards features into new facilities that will reduce the inspection effort and improve the quality of safeguards. Modernizing the safeguards approach for future reprocessing facilities could yield a great reduction of inspection effort and costs along with enhanced operational transparency. This would involve:

- Design features to make the plants more safeguards friendly;[185]

- An integrated state-level approach including all fuel-cycle facilities;

- Short-notice random inspections as an alternative to permanently-stationed inspectors;

- Remote monitoring capabilities for timely review at IAEA headquarters;

- Some on-site analytical capabilities for timely results;

- Continuous monitoring of major material flows and frequent (possibly daily), random sampling and measurement of in-process material. This could possibly be achieved using unattended, on-line measurement systems;

- Short-notice access to operating records to provide higher assurance of no tampering;

- Establishing expected ratios of selected isotopes and elements in wastes in order to better identify their source and confirm process operating parameters;

- Implementation of Flow Sheet Verification to confirm that neptunium, curium, and possibly americium follow their expected routes through the reprocessing plant, as declared by the operator; and

- Specialized inspectors.

Conclusion

Modern safeguards approaches would make possible verification of the FM(C)T at operating reprocessing plants. This could be done at a confidence level comparable to what is achieved by the IAEA today at Japan's Rokkasho facility with only a modest increase in the expected time for detecting a significant diversion of plutonium. By replacing the permanent on-site inspectors and laboratory with short-notice random inspections and other measures, the costs could be greatly reduced relative to the Rokkasho NPT safeguards system.

Plants (currently only one) that reprocess naval and other military-reactor fuel may require certain special arrangements to allow effective safeguarding while allowing the owning states to protect fuel quantity and design information that they may consider sensitive national-security information.

For any new reprocessing plant constructed after an FM(C)T comes into force, the safeguards approach should be the same as that used in the non-nuclear states under the NPT, but modernized to reduce inspection effort.

Verification of shutdown and closed-down plants could be done largely through a combination of remote monitoring, seals and short-notice random inspections. The safeguards burden would not be high (Chapter 9).

6 Weapon-origin Fissile Material: The Trilateral Initiative

International Monitoring of Weapon-Origin Fissile Material
Released from Defense Requirements in the Russian Federation and the United States

In 1996, the United States, Russia and the International Atomic Energy Agency (IAEA) launched a "Trilateral Initiative" with the aim of developing the means for the IAEA to monitor classified forms of weapon-origin fissile materials declared as excess to either country's defense needs.[186] The fissile materials are ordinarily plutonium or highly enriched uranium. A new scheme would be required for this monitoring task because the normal safeguards system applied for non-proliferation purposes in non-nuclear weapon state parties of the Non-Proliferation Treaty is not designed to cope with fissile materials with classified properties or inspections at locations where nuclear-weapon activities have taken place. The key challenge therefore was to come up with a scheme that would allow international monitoring while protecting classified information on nuclear weapons design or manufacturing.

Independent of the Trilateral Initiative, the United States and the Russian Federation concluded an agreement referred to as the Plutonium Management and Disposition Agreement (PMDA), signed in the summer of 2000. The PMDA made no arrangements for securing classified forms of fissile material and hence the two arrangements were never connected. The immediate goal of the Trilateral Initiative was to allow IAEA monitoring of the disposition of the weapon-grade plutonium that Russia and the United States had each declared excess to their weapon needs, much of which was still in the form of nuclear weapons components. Under the PMDA, the two countries had agreed to dispose of most of this excess material in mixed-oxide (plutonium-uranium, MOX) fuel.

Between 1996 and 2002, experts from the Russian Federation, United States and the IAEA worked together successfully to develop and demonstrate a system with which the IAEA could verify certain unclassified attributes of plutonium within a container while it was still in classified form without learning classified information relating to weapon design or the exact isotopic makeup of the plutonium. The attributes to be verified were that the container held plutonium, that the plutonium isotopic composition was consistent with that used in nuclear weapons, and that the container held more than an agreed mass of weapon-grade plutonium. An information barrier would screen out more revealing information obtained by the neutron and gamma-ray measurement system. (Note that, while the Trilateral Initiative encompassed HEU within its scope, no similar work was carried out on verifying the HEU in weapon components.)

In 2000, the final document of the Nonproliferation Review Conference, endorsed by all state parties, called for the implementation of the Trilateral Initiative as one of the "13 steps" by which the NPT nuclear-weapon states had agreed to demonstrate their commitment to progress toward nuclear disarmament. In 2002, with new Russian and U.S. Administrations in place, the two countries agreed that the Initiative had been successful and that either America or Russia could proceed when it wished. However, neither state has taken any steps towards implementing IAEA monitoring under the agreement developed under the Initiative.

This reflected in part a decision by the Bush Administration not to support the 13 steps toward disarmament that the Clinton Administration had committed the United States to. Partly also it reflected U.S. disappointment that Russia had decided not to submit weapon plutonium pits for IAEA monitoring but rather 2-kg plutonium-metal balls derived from its pits, thereby ruling out a symmetric undertaking such as had been traditionally preferred in Soviet-U.S. arms control agreements.

The 2002 report to the Trilateral Initiative Principals (the Director General of the IAEA, the Russian Minister of Atomic Energy and the U.S. Secretary of Energy) provides a comprehensive record of all work carried out. The work was performed under a confidentiality arrangement agreed by the parties and, unfortunately, the report is not publicly available. However, the Table of Contents may be found in Appendix 6A and a partial list of related technical reports is given in Appendix 6B.

This chapter describes the origins of the Trilateral Initiative, how it operated, its objectives and accomplishments, and why it was not completed and implemented.

Origins

The NPT includes the Article VI commitment by the weapon states to the ultimate elimination of nuclear weapons. With the end of the Cold War, Russia and the United States each reduced its nuclear arsenal by thousands of nuclear weapons and declared excess hundreds of tons of the highly enriched uranium and tens of tons of the plutonium that they contained.[187] In the early 1990s, the United States and the Russian Federation began to consider how they could involve the IAEA in providing international verification of some of the reductions that they were undertaking.

In 1993, under the Voluntary Offer Safeguards Agreement between the United States and the IAEA, the United States placed under IAEA safeguards 2 metric tons of plutonium and 10 tons of highly enriched uranium declared excess to weapons requirements. This fissile material was in unclassified forms. The United States paid for the costs of the inspections.

In 1996, senior Russian officials approached IAEA Director General Hans Blix and indicated that the Russian Federation might be interested in joint activities related to Article VI. Blix suggested that Russia, the United States and the IAEA enter into a combined exercise to develop a framework for such an activity.

The initial meeting was held at the time of the IAEA's 1996 General Conference. Russia's Minister of Atomic Energy Viktor Mikhailov and U.S. Secretary Energy Hazel O'Leary agreed with Blix to proceed.

The methods and the overall framework had to be designed to take into account the obligations of both countries under Article I of the NPT not to transfer weapon-design information, and their national laws and regulations governing the classification of nuclear-weapon-related information and access to classified information. The IAEA understood that its inspection rights and privileges would have to be limited so as to prevent the Trilateral Initiative from exposing its inspectors to weapon-design information.

Reflecting the positive attitude that the principals had at that time, efforts were made to inform the IAEA and the international community. Press releases were issued following the annual meetings between the Director General, the Russian Minister of Atomic Energy and the U.S. Secretary of Energy. Also, the Director General briefed the IAEA Board on progress at frequent intervals and the Board discussed the Trilateral Initiative at length in 1999. The purpose was to determine how the Board would react to the IAEA having a nuclear disarmament verification role and how IAEA verification activities would be financed. While a range of views were represented, the majority of the Board members were eager for the IAEA to begin substantive activities related to Article VI of the NPT. Several financing arrangements were presented, but no conclusion was reached. A demonstration of some of the specialized monitoring equipment had been developed was held at the 1999 IAEA General Conference.

Operations

The Trilateral Initiative operated at three levels. At the top, the Russian Minister of Atomic Energy, the U.S. Secretary of Energy and the IAEA Director General met at least annually on the margins of the IAEA General Conference.[188]

At the next level, the IAEA's Deputy Director General for Safeguards met with the U.S. and Russian Governors (i.e., their country representatives to the IAEA) on the margins of meetings of the IAEA's Board of Governors to review progress and provide working guidance.

The bulk of the work was carried out at the third level, in the Trilateral Initiative Working Group, by different experts depending on the tasks. The Working Group was given the responsibility to:

- Establish a legal framework, and develop a model verification agreement intended to enable the Russian Federation and the United States (and other nuclear-weapon states later on) to conclude separate verification agreements with the IAEA;

- Establish a security environment within the IAEA to hold design and other sensitive information on facilities in Russia and the United States that would be subject to IAEA monitoring once the agreements entered into force;

- Develop subsidiary arrangements and facility attachments defining how the IAEA would carry out its verification activities at specific facilities under agreements concluded pursuant to the Trilateral Initiative;

- Develop verification criteria and approaches relevant to this monitoring mission;[189]

- Develop verification measurement systems that could meet the criteria without divulging classified information and specialized containment/surveillance systems that could operate in facilities storing classified forms of fissile material; and

- Establish verification approaches for monitoring the activities required to process the fissile materials into unclassified, forms while maintaining continuity of verification from storage through transport through conversion and blending until the materials emerged for unrestricted IAEA verification and subsequent safeguards.

The principal work of the technical working group took place at workshops held in the United States, the Russian Federation, at the Joint Research Centre of the European Commission at Ispra, Italy, and at the Plutonium Fuel Production Facility at Tokaimura in Japan. Most of the participants did not change over the full period of the Trilateral Initiative.

At the IAEA, a Trilateral Initiative Office was established with U.S. financial support and experts provided by Russia and the United States.

Objectives

Early consideration was given to the relationship of the Trilateral Initiative to nuclear-weapon disarmament, including the dismantlement of warheads from delivery systems. Four levels of verification objectives were considered. Ranked from least to most ambitious, they were:

1. Limit the Initiative to accepting only unclassified materials, to assure that those materials cannot be re-used in weapons;

2. Monitor items containing fissile materials, without attempting to establish whether they are nuclear warheads or components;

3. Verify the fact that the fissile materials are, in fact, in nuclear warheads or specified components, including specific model identifications; or

4. Start with the dismantlement of weapon systems or an early subsequent stage so that the monitoring could attest to the origin of the fissile materials in warheads removed from delivery systems.

For practical purposes, it was decided that the Trilateral Initiative should aim for Level 2, which posed significant challenges but was considered to be achievable. Level 1 would not require a new framework. Going to Level 3 would have presented far greater security concerns and challenges related to authenticating warhead templates that could be used by the IAEA. Level 4 would be a simple extension of Level 3.[190]

Accomplishments

The Trilateral Initiative established the first structure for a nuclear disarmament activity that would involve international verification. The following excerpts from the final (2002) report of the Joint Working Group to the Trilateral Initiative Principals summarize the work completed and recommended future steps:

> ***Excerpt 1:*** *"Over the course of six years, the Joint Working Group addressed the technical, legal and financial issues associated with implementing IAEA verification of weapon-origin and other fissile material released from defence programmes and can now recommend the successful completion of the original task. The enabling technologies developed under the Initiative could be employed by the IAEA on any form of plutonium in nuclear facilities, without revealing nuclear weapons information. The Working Group found no technical problem that would prevent the IAEA from undertaking a verification mission*

in relation to such fissile materials released from defence programmes, and believes that many of the technical approaches could have broader applicability to other forms of fissile materials encountered in conjunction with nuclear arms reductions."

Excerpt 2: *"On the basis of the technical, legal and financial work completed, the Joint Working Group believes that each State may now proceed to negotiate a verification agreement with the IAEA in accordance with its national programmes for managing weapon-origin and other fissile material released from its defence programmes. Further work remains to prepare for such inspections, and the Joint Working Group recommends that technical work continue in relation to inspection procedures and authentication and certification methods applicable to possible future IAEA verification of weapon-origin fissile material with classified properties."*

It would have been possible in 2002 for the Russian Federation and/or the United States to conclude separate verification agreements based upon the Model Verification Agreement of November 2001. The details of implementation would still require further work to resolve but, from a legal perspective, the Model Verification Agreement was essentially finished and the Trilateral Initiative has been ready for implementation since September of 2002. As indicated in Excerpt 1, all the technical work focused on verifying plutonium in classified components.

Figure 6.1. Russian and U.S. storage facilities. Left: Inside Russia's Fissile Material Storage Facility at the Mayak Complex, near Ozersk. Cylindrical canisters, containing plutonium metal recovered from excess warheads, are stacked in vertical tubes in the thick concrete floor. The tops of these tubes are indicated by the covered circular openings. Right: Inside the U.S. K-Area Material Storage Facility at Savannah River, constructed in the reactor hall of a decommissioned production reactor. Pallets with plutonium containers are to be stacked inside the room shown.

Verification arrangements were essentially agreed for initial implementation at the Fissile Material Storage Facility at Mayak in the Russian Federation and at the K-Area Material Storage (KAMS) Facility at the Savannah River Site in the United States, both shown in Figure 6.1. In placing the KAMS Facility under voluntary-offer safeguards, the United States stated its intention to transfer its safeguards obligations to an agreement pursuant to the Trilateral Initiative.

Alternative verification technologies were examined for their suitability, looking first at whether a limited-ability technology might be found that could be used to make unrestricted measurements that would not be capable of extracting any classified information from the objects being measured. Not finding any suitable methods, the Joint Working Group agreed to base IAEA verification measurements on checks of unclassified attributes, using sensitive measurements operating behind "information barriers." The selected attributes were:

- The presence of plutonium;

- A "weapon-grade" plutonium isotopic composition with a ratio of ^{240}Pu to ^{239}Pu of 0.1 or less; and

- A mass of plutonium above an agreed minimum defined in relation to each facility.

Verification Methods

Attribute verification involves comparing measurements of an object to a set of reference characteristics. While the information to be obtained under the Trilateral Initiative would be far less than the IAEA obtains under routine plutonium safeguards, it was deemed to be sufficient to serve as the basis for accepting items for IAEA monitoring. Attribute verification therefore was formally adopted as the basis for verification under the Trilateral Initiative.

The method chosen to verify the selected attributes relies first upon high-resolution gamma-ray spectroscopy to establish the presence of plutonium and to measure the isotopic ratio of ^{240}Pu to ^{239}Pu and thereby to establish that it is weapon-grade (see Figure 6.2). Plutonium-239 is the dominant isotope (typically more than 93-percent) in weapon-grade plutonium. Plutonium-240 accounts for most of the remainder of weapon-grade plutonium.

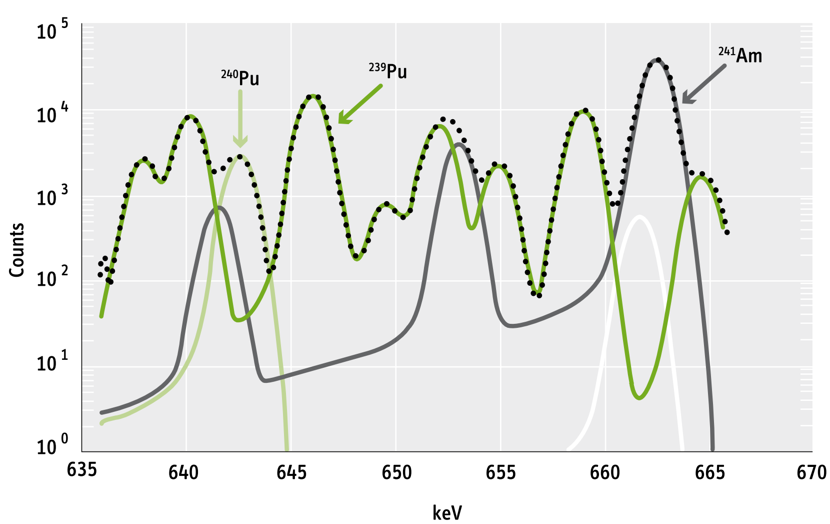

Figure 6.2. The 635 to 670-kilovolt region of the gamma-ray spectrum from plutonium contains emissions from both ^{239}Pu and ^{240}Pu. Precise measurements of the number of counts in each peak make it possible to establish the ratio ^{239}Pu/^{240}Pu and thereby the fact that the plutonium is weapon grade. There is also a gamma-ray peak from the decay of Americium-241, a decay product of 14.4-year half-life ^{241}Pu. The ^{241}Am/^{241}Pu ratio provides a measure of the length of time since the plutonium was last chemically purified.[191]

Secondly, neutron-multiplicity counting would be used to measure the rate of spontaneous fission in the plutonium and thereby the mass of ^{240}Pu, which accounts for about 98 percent of the spontaneous fissions in weapon-grade plutonium.[192]

The combination of good measurements of the mass of ^{240}Pu and of the ^{239}Pu/^{240}Pu ratio would allow the determination of the total mass of the plutonium. Each of the separate measurements and the inferred mass would be classified. The comparison of the measurement to the corresponding unclassified thresholds would therefore be behind an information barrier. The IAEA inspectors would witness containers entering the measurement system, identify tag information, confirm seal data and observe the attribute measurement results on a "pass/fail" panel.[193]

Figure 6.3 shows the Attribute Verification System with Information Barrier for Plutonium with Classified Characteristics Utilizing Neutron Multiplicity Counting and High-Resolution Gamma-ray Spectrometry (AVNG) measurement system. A canister holding a classified plutonium-containing component is placed in the counting chamber (beneath the yellow cover in the drawing) for simultaneous measurements of the emitted neutrons and gamma-rays. All analyses and comparisons are carried out by a computer and inspectors see only "pass-fail" signals (for example, a green or red light) indicating whether or not plutonium is present, the plutonium is weapon-grade and the container holds more than the agreed quantity.

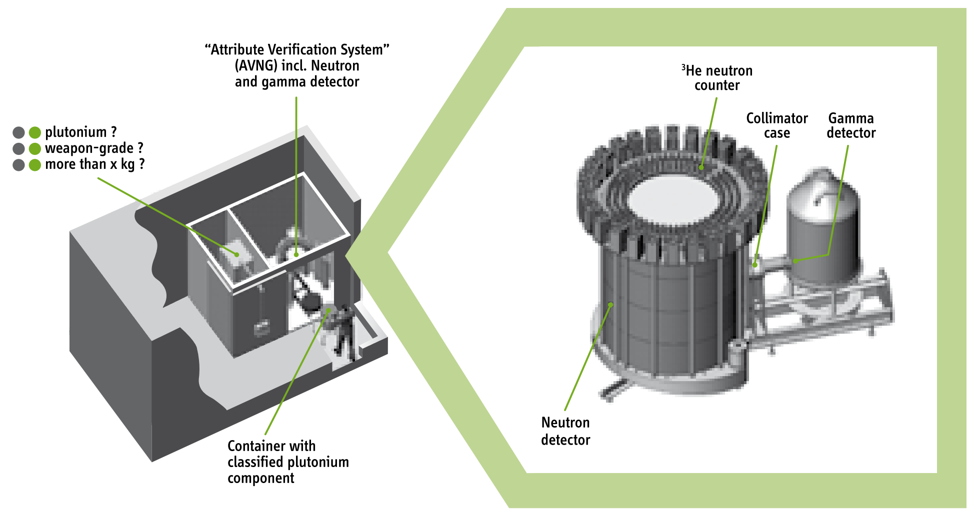

Figure 6.3. Attribute verification system for classified components containing plutonium developed by the Trilateral Initiative. Left: Artist's conception of attribute-verification system in a security enclosure with the computer inside lighting green or red lights outside to indicate whether or not the component has the required attributes. Right: Attribute-verification neutron-multiplicity detector on left, gamma detector on right.

Specialized containment/surveillance systems were also examined under the Trilateral Initiative, including novel seal concepts proposed by the participating Russian weapon-design laboratories at Sarov and Snezhinsk. As with IAEA safeguards, such seals would be used to maintain continuity of knowledge of items pending verification, or to assure that there had been no changes that would bring into question the validity of verification data. Such systems would limit the need for re-verification over time.

A radio-frequency transmitting sensor platform was introduced by the U.S. Sandia National Laboratory that would allow real-time remote monitoring of sensors on thousands of individual containers holding classified components of fissile material in a monitored storage facility.

The project also explored how items accepted under agreements pursuant to the Trilateral Initiative could be monitored through conversion to unclassified forms and thereafter. For instance, as part of the process of disposition, blend-stock of civilian plutonium amounting to up to 12 percent of the weapons plutonium would be mixed with it to conceal its exact isotopic makeup. The isotopics of the blend stock would not be verified in order to prevent the inspectors from back-calculating the isotopics of the original weapons material (see Appendix 6C).[194]

The resulting proposed scheme was straightforward: sealed containers would be transported to the facility used to convert plutonium from classified to unclassified form. The agreed attributes would be checked (a minimum mass of weapon-grade plutonium) at the entry point. A perimeter monitoring system would assure that no fissile material other than that in the containers plus blend stock would be allowed in. The containers exiting the conversion facility containing the unclassified fissile material would be measured using normal IAEA safeguards methods and then seals would be applied to the containers for storage or transport for further processing. Managed access would be allowed in the conversion facility annually to assure that there were no accumulations of fissile materials or undeclared penetrations that would allow for clandestine additions or removals of fissile material.

For such a scheme to be practical, the conversion facilities would have to be constructed following agreed architectural plans. The general concept was explored in the Joint Working Group; however, no discussions took place on the specific arrangements.

Why the Trilateral Initiative Has Not Been Implemented

Six years and some 98 trilateral meetings after the Trilateral Initiative was launched, President Putin had replaced President Yeltsin and President Bush had succeeded President Clinton. When President Bush took office, his Administration announced that it did not support the 13 disarmament steps agreed at the 2000 NPT Review Conference, which included the Trilateral Initiative. The Putin Administration also was not as supportive as its predecessor. At one point, Russian IAEA Governor Mikhail Ryzhov attempted—but did not succeed—to gain the approvals necessary for the Government of the Russian Federation to enter into a negotiation of a Trilateral Initiative agreement with the IAEA.

By the time of the 2002 IAEA General Conference, the IAEA Director General ElBaradei, Russian Minatom Minister Rumyantsev and U.S. Secretary of Energy Abraham had agreed that the Trilateral Initiative should be brought to a close. They concluded that it had been a success and that that it was now up to Russia and the United States to enter into implementation agreements with the IAEA. The September 16, 2002 Press Release stated that "the three Principals directed the technical experts to begin without delay discussions on future possible cooperation within the trilateral format." But such discussions were never held. It also stated that "Minister Rumyantsev, Secretary of Energy Abraham and Director General ElBaradei agreed that the Principals would meet again in September 2003 to review progress within the trilateral format." But neither they nor their successors have met since then on this topic.

Among the issues that dampened the two governments' enthusiasm for implementing the Initiative were an asymmetry in the classified forms that each side was willing to submit to monitoring and inadequate international funding for Russia's plutonium-disposition program.

Asymmetry in the sensitivity of the classified items to be monitored. The United States was willing to put forward the bulk of its weapon-origin material for monitoring in the form of plutonium pits. But the Russian Federation decided that it would melt its pits into 2-kilogram balls and pack two plutonium balls into each specialized AT-400R container (the standard container designed for Russia's Mayak Fissile Material Storage Facility and provided by the United States and Japan for storing plutonium pits and other items) before submitting the material for U.S. or IAEA verification. The Russians maintained that the isotopic composition of its weapon plutonium in the 2-kg balls was classified and hence that the attribute verification scheme was still essential.

Unlike Russia, the United States had no plans to transform the plutonium in its pits into an intermediate storage form. The United States also felt that allowing pits to be monitored by the IAEA was much more significant than having balls of weapon-grade plutonium monitored. Thus there was no symmetric agreement in which the United States and the Russian Federation could proceed in lock step.

Inadequate international funding for Russia's plutonium-disposition program. While the Trilateral Initiative was underway, the Russian Federation and the United States concluded an executive agreement referred to as the Plutonium Management and Disposition Agreement (PMDA).[195] Russian Prime Minister Chernomyrdin and U.S. Vice President Gore signed the PMDA in the summer of 2000. The agreement was to convert most of the 34 tons of excess weapon-grade plutonium that each country committed to dispose of into mixed oxide fuel and irradiate it in specified reactors at a rate of about two tons per year. The PMDA called for extensive financial support from international donors to cover Russia's costs. Russia initially requested two billion U.S. dollars: one billion to build the necessary facilities and another billion to cover operating costs. Pledges for the full amount were never secured.[196]

The PMDA focused on the implementation of the steps for disposition. Verification is one objective but not its primary focus. The PMDA provides for the possibility of IAEA verification and calls for "early consultations" with the IAEA to work out the verification arrangements but those consultations have yet to be held.

Could the Trilateral Initiative Be Reactivated?

If either the Russian Federation or the United States—or, for that matter, any other State possessing nuclear weapons—were interested, the "Trilateral Initiative" could be re-activated as a study effort to continue work aimed at fleshing out a verification system in relation to nuclear disarmament. With no obligations to commit, that would be the low-risk option but also would run the risk of being a perpetual research project.

Alternatively, the Russian Federation or the United States, or both acting together, could negotiate agreements in a few months that could allow them to begin to submit weapon-origin plutonium to IAEA verification. While the preparatory work carried out was extensive, significant practical issues remain. Phasing in the agreements over time could therefore allow progress to be made while gaining confidence in the security measures implemented.

Under such an arrangement, the United States or the Russian Federation would retain the right to determine which fissile materials to submit, when to submit them and the necessary conditions. Through such provisions, the United States and the Russian Federation, and any other State possessing nuclear weapons that entered into such an arrangement, could gain the assurances needed to protect their security interests. The agreements could have a specified duration to provide an out if the parties could not reach agreement.

Concluding a verification agreement based on the Trilateral Agreement would energize the international community, bolster support for the NPT and provide the foundation for engaging other States possessing nuclear weapons. Such a step could be carried out in time for the 2010 NPT Review Conference.

Other weapon states also could undertake to enter into agreements for monitoring their disarmament-related activities based on the work completed under the Trilateral Initiative—or propose further work with additional participants. The United Kingdom and France, for example, have announced plans to reduce their existing stocks of warheads.[197] With appropriate confidentiality arrangements, they could examine the results of the work carried out under the Trilateral Initiative.

Appendix 6A.

Report to the Principals on the Trilateral Initiative: IAEA Verification of Weapon-Origin Fissile Material

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Appendix 6B.

Some Technical Publications Related to the Trilateral Initiative

D.A. Close, D.W. MacArthur and N.J. Nicholas, *Information Barriers—A Historical Perspective*, Los Alamos National Laboratory Report, LA-UR-01-2180, 2001.

E. Haas and D.L. Mangan, "Information Security and Authentication—A Trilateral Initiative Challenge," *Proceedings of the 42nd Annual Meeting of the Institute of Nuclear Materials Management*, Indian Wells, California, 15–19 July 2001.

R.T. Kouzes et al., *Authentication of Radiation Measurement Systems for Non-proliferation*, Pacific Northwest National Laboratory Report, PNNL-SA-34871, 2001.

I.I. Kuleshov et al., "General Technical Requirements for an Inventory Monitoring System for the Trilateral Initiative," *42nd Annual Meeting of INMM, op. cit.*

D.W. MacArthur et al., *The Effects of Information Barrier Requirements on the Trilateral Initiative Attribute Measurement System*, Los Alamos National Laboratory Report, LA-UR-01-3333, 2001.

D.W. MacArthur and J.K. Wolford, Jr., *Information Barriers and Authentication*, Los Alamos National Laboratory Report, LA-UR-01-3334, 2001.

J.M. Puckett et al., "General Technical Requirements and Function Specifications for an Attribute Measurement System for the Trilateral Initiative," *42nd Annual Meeting of INMM, op. cit.*

T.E. Shea et al., "The Trilateral Initiative: IAEA Verification of Weapon-origin and Other Fissile Material Released from Defense Programs," *42nd Annual Meeting of INMM, op. cit.*

Appendix 6C.

Excerpts from the 2000 Russia-U.S. Disposition Agreement

The disposition agreement lays out how the exact isotopics of the weapon-grade plutonium are to be kept secret through the blend-down process as follows:

Article I.1: "Weapon-grade plutonium" means plutonium with an isotopic ratio of plutonium 240 to plutonium 239 of no more than 0.10.

Article II.6: Each Party shall have the right to mix blend stock with disposition plutonium provided that for nuclear reactor fuel containing disposition plutonium the mass of blend stock shall:

a) be kept to a minimum, taking into account the protection of classified information, safety and economic considerations, and obligations of this Agreement, and

b) in no case exceed twelve percent of the mass of disposition plutonium with which it is mixed.

The resulting mixture of disposition plutonium and blend stock shall be weapon-grade plutonium.

Article II.7: […] Blend stock shall not count toward meeting that thirty-four (34) metric ton obligation.

Annex on Monitoring and Inspection, Section II.11: Blend Stock Measurements: The monitoring Party shall have the right to confirm that the mass of any blend stock does not exceed what is allowed pursuant to Paragraphs 6 and 7 or Article II of the Agreement, upon receipt of such blend stock at a disposition facility, using agreed procedures developed pursuant to Section V of this Annex. Information concerning the composition of the blend stock shall not be provided to, or obtained by, the monitoring Party.

Section V.1: The Parties shall seek to complete by December 2002 an agreed set of detailed measures, procedures, and administrative arrangements, consistent with the terms of the Agreement (including this Annex), for monitoring and inspections of disposition plutonium, blend stock …

Source: *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.

7 HEU in the Naval-reactor Fuel Cycle

All five NPT nuclear weapon states operate submarines and, in some cases, surface ships propelled by nuclear reactors. By far the largest fleets are those of the United States and Russia. In addition, at least one non-NPT nuclear weapon state and one non-weapon state are pursuing naval nuclear propulsion. Table 7.1 lists those countries that currently are operating or developing nuclear-powered naval ships and/or submarines.[198]

	United States	Russia	United Kingdom	France	China	India	Brazil
Nuclear ships and submarines	86	60	15	10	6–10	under development	under development
Fuel-Type	HEU	HEU	HEU	LEU	?	HEU	LEU
Annual HEU demand	2000 kg	1000 kg	200 kg	–	–	not yet operational	–

Table 7.1. World naval nuclear propulsion programs. Annual HEU demands are estimates. Reportedly, China uses low-enriched uranium (LEU) or near-LEU fuel in its submarines, and France's new Barracuda-class attack submarine will use fuel with the same enrichment as France's pressurized-water reactors, which is less than five-percent enriched.[199]

India and Brazil are the most recent countries to have launched naval nuclear-propulsion programs. Little is known about India's submarine program, but the nuclear reactor for its indigenously designed nuclear submarine will most likely be fueled with highly enriched uranium produced in India's existing centrifuge enrichment plant.[200] The case of Brazil, an NPT non-weapon state is relevant, because it may involve enriched uranium being withdrawn from safeguards and therefore could require novel approaches to give the IAEA confidence that this material is not being diverted. Other non-weapon states have operated nuclear-powered civilian vessels in the past or seriously considered acquiring nuclear-powered submarines.[201]

As Table 7.1 indicates, at least four nuclear weapon states fuel their naval reactors with HEU. Indeed, the United States and the United Kingdom fuel their naval reactors with weapon-grade uranium (enriched to over 90 percent in U-235). Russia and India are believed to use mostly HEU enriched to about 40 percent.

The use of HEU fuel by naval nuclear propulsion programs may make future nuclear disarmament agreements more difficult. As reductions in the nuclear-weapon arsenals proceed, the relative size of naval stockpiles of HEU could increase, and concerns could develop about their potential conversion to nuclear weapons.

It would therefore be desirable that the weapons use of naval stocks of fissile material be banned under an FM(C)T treaty and that the stocks be subjected to international monitoring. Technically, this should not be a problem while the HEU is in unclassified form. It would become challenging, however, once the fuel is fabricated and also when it is loaded into a naval reactor, because the design of naval reactors and their fuel are considered militarily sensitive. The intrusiveness of the verification regime therefore would have to be limited so as to prevent the IAEA inspectors from acquiring classified information. This problem has been solved in the context of the Trilateral Initiative (see Chapter 6), where the participants devised a way in which the IAEA could monitor plutonium in classified weapons components without revealing classified information.

In this chapter, we consider a similar approach to determining the amount of HEU in nuclear fuel inside a container. The technology involved has to be somewhat different from that developed in the Trilateral Initiative, however, because the spontaneous neutron emissions from HEU are too low to allow useful measurements. It is therefore necessary to "interrogate" the material with neutrons from an external source to induce fissions and the emission of neutrons and gamma rays that make measurements feasible.

Naval-reactor Technology and Uranium Consumption

Nuclear-powered submarines typically use pressurized light-water reactors (PWRs). In fact, this reactor-type, which dominates the civilian nuclear power industry today, was originally developed for naval propulsion purposes and only later adapted for commercial use. The first U.S. land-based prototype PWR, designated STR (Submarine Thermal Reactor) Mk I, went critical in March 1953, and the USS *Nautilus* (SSN-571) put to sea in January 1955 using a virtually identical reactor (STR Mk II, later designated S2W).[202] The first commercial PWR, the 60 MWe Shippingport Atomic Power Station, went critical in December 1958, almost three years later.

One design objective for U.S. naval reactors has been to minimize the frequency of refueling because this has involved cutting a hole in the submarine or ship. The newest U.S. attack submarines (*Virginia* Class, shown in Figure 7.1) have lifetime cores.[203] Their U-235 core inventories therefore can be expected to be larger than that of other naval reactors of comparable power.

Figure 7.1. The new U.S. attack submarine (SSN-774, Virginia Class). The vessel uses highly enriched uranium in a lifetime core, i.e., does not require refueling. The total inventory of U-235 in the core is estimated to be on the order of 400 kg. [Source of graphics: U.S. Navy.]

Estimate of reactor power and uranium consumption. Typically, only about 20% of the reactor power is delivered to the propeller shaft. For a given shaft horsepower P_s, the maximum forward velocity v of a submarine is determined by the drag of the hull, which depends on its length l and diameter d. It can be approximated with the following expression:[204]

$$v \sim \sqrt[3]{\frac{P_s}{l\,d}}$$

The maximum velocity only increases with the cube root of the shaft horsepower, i.e., an eight-fold increase of reactor power is required to double the velocity of the boat. In practice, 30–40 knots are achievable forward velocities.[205]

For a typical attack submarine, a velocity of 30–40 knots corresponds to about 40,000 shaft horsepower or, equivalently, to a maximum reactor power level of 150 MW thermal (MWt).[206] If we assume an average power level of 30 MWt, i.e., 20% of the peak value, and a typical patrol rate of 180 days per year, then the annual U-235 consumption can be estimated as 7 kilograms per year.[207] Over 30 years, the submarine would consume about 200 kg of U-235 and, assuming a U-235 consumption of about 50% by the end-of-life, perhaps 400 kg of U-235 could be required initially in the core. If the core inventories varied with shaft horsepower and core life, the corresponding inventories for a U.S. ballistic-missile submarine and aircraft carrier lifetime cores would be 900 kg and 2,000 kg respectively.[208] On this basis, annual U-235 requirements for the approximately one hundred U.S. naval reactors[209] would be about two tons per year. Submarine reactors such as Russia's, which are refueled every ten years or so, would have lower core inventories.

Naval HEU in the Context of Global Stockpiles

As of early 2008, the global stockpiles of HEU totaled 1670 ± 300 metric tons (see Chapter 1). This estimate includes up to 100 tons of HEU in the civilian sector and about 300 tons of HEU that has been declared excess for weapon requirements and is to be blended down to low-enriched uranium (LEU) or is in spent fuel that is to be disposed of directly as waste. We also know that at least 100 tons of *irradiated* naval HEU exist in the U.S. military stockpile—material that has not been included in declarations of excess material.[210]

In late 2005, the United States declared an additional 200 tons of HEU excess for weapons purposes and set aside 128 tons of this material for future use in U.S. and possibly U.K. naval vessels. Given the size of the Russia's nuclear navy, we assume that it has reserved a similar stockpile of HEU for naval fuel (100 tons).

The significance of naval stockpiles becomes apparent when compared to the number of nuclear weapons in the arsenals under various arms-reduction scenarios (Figure 7.2). Even after the 2012 SORT reductions, Russia and the United States might each still have about 5000 nuclear weapons.[211] In that case, assuming 25 kilograms of HEU per weapon and a working stock of 20%, 230 tons reserved for naval fuel would constitute almost 40% of the global military HEU inventory, assuming that the combined inventories of the other weapon states remains 75 tons. If there are deeper cuts in the weapon stockpiles, the naval stocks already reserved today would clearly dominate the military HEU holdings. This dominance would increase if those nuclear weapon states using HEU to fuel naval reactors moved future excess material to their naval stockpiles.[212]

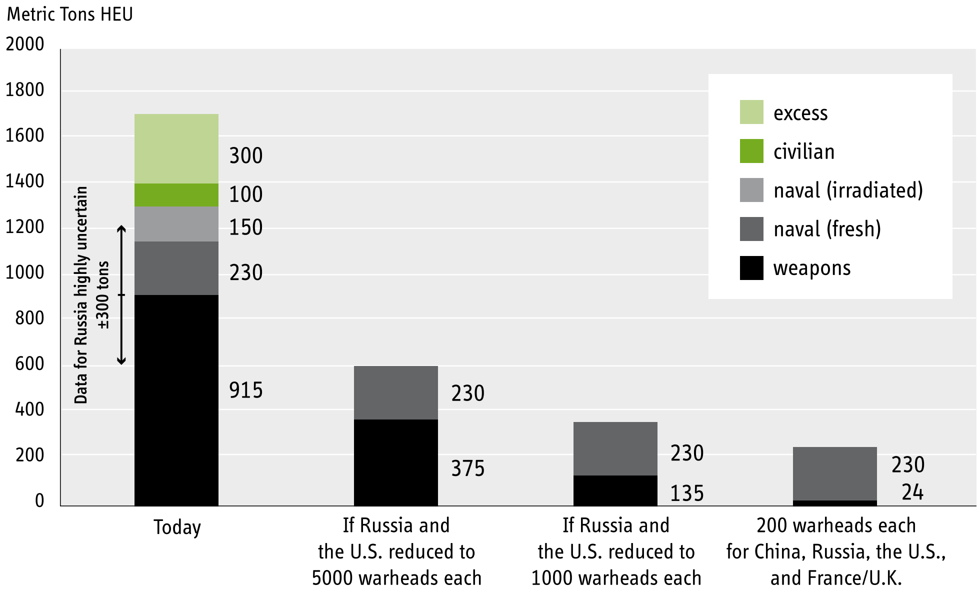

Figure 7.2. Potential for HEU reductions. Global stockpiles of HEU could shrink dramatically in the future if the United States and Russia continue to reduce their nuclear-weapon arsenals and continue to blend-down HEU recovered from dismantled warheads. Yet, the U.S. and Russian stockpiles of HEU already reserved for naval fuel begin to dominate the global stockpiles beyond SORT levels. The equivalent weapons stockpile numbers, assuming 25 kg of HEU per warhead, are 4,000 warheads per 100 tons. We assume 75 tons for weapon states other than Russia and the United States for the 5000 and 1000 scenarios and 20 % working stocks.

Design Classification Issues

Several performance characteristics of submarines and ships are considered militarily sensitive information. The peak power may not be so sensitive because the peak speed of the submarine increases so slowly with peak shaft horsepower. A 50-percent increase in power only yields a 15-percent increase in speed. The fuel design may be more sensitive. It determines the "ruggedness" of the reactor core, i.e., its ability to withstand shocks from nearby explosions and how rapidly its power output can increase.[213] Any verification procedure that could reveal such information would be unacceptable to countries with nuclear navies.

For an FM(C)T, however, only the initial uranium inventory in the core and its enrichment level are of interest. These are characteristics that determine the expected core-life of the reactor but are not directly related to its military performance. We therefore consider whether a verification system could be designed that would reveal only the quantity of U-235 in naval fuel, while shielding sensitive design information.

Total U-235 inventory in the core. The U.S. Navy, at least, apparently does not consider the enrichment of its fuel to be sensitive. The U.S. Department of Energy has officially made public that the nominal enrichment level of HEU produced for the U.S. Navy from 1964–92 was 97.65 percent.[214] Since U.S. HEU production was stopped in 1992, excess HEU originally produced for the weapons stockpile will be used for future naval fuel production.[215] The enrichment of this material averages about 93 percent.[216] Information on the enrichment level of naval fuel used by some other countries is less well known—and usually based on independent estimates, not official statements. But the example of the U.S. program shows that the enrichment level need not be considered militarily sensitive information.

Similarly, knowledge of the total uranium inventory in a fresh naval core does not reveal militarily sensitive information. Combined with the enrichment level of the fuel, the number can be used to estimate refueling frequencies but this information is published, for example, by the U.S. Navy.[217]

Fuel design. Both rod-type and plate-type fuels have apparently been used in naval reactors.[218] Beyond that, little is known publicly about the design of modern naval fuels—and we don't need to make particular assumptions about it for this analysis. Procedures for verifying the total quantity and enrichment of uranium in a core need not reveal features of the fuel design. If necessary, "information barriers," which have been successfully developed for other purposes, could be used to conceal such information (see discussion of the Trilateral Initiative in Chapter 6).

Non-diversion from the Naval Fuel Cycle in NPT Non-weapon States

The NPT allows non-weapon states to use nuclear material for non-explosive military applications, such as naval-nuclear propulsion, and to remove it from safeguards for these purposes. The challenge of verifying that naval enriched uranium is not diverted to weapons therefore will have to be worked out independently from an FM(C)T under the NPT, as soon as a non-nuclear weapon state decides to pursue a naval propulsion program. Unlike the FM(C)T, verification will be required for *any* type of nuclear fuel, i.e., based on highly enriched *or* low-enriched uranium.

The model safeguards agreement between the IAEA and non-weapon states requires only that, if a state decides to take nuclear materials out from under IAEA safeguards for a permitted military purpose,

> *"the state shall inform the agency of the activity, making it clear … [t]hat during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices."*

The country must also make an arrangement to keep the agency

> *"informed of the total quantity and composition of such unsafeguarded nuclear material in the State and of any exports of such material. […] The agreement … shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein."*[219]

At the moment, it appears that the IAEA will first be challenged to develop such verification procedures by Brazil's plan to build a nuclear submarine. We discuss the Brazilian case here to illustrate some of the procedures envisioned or required to carry out such a project in accordance with an INFCIRC/153c agreement.

The case of Brazil. Brazil has been pursuing a nuclear-submarine program since the late 1970s, but has recently re-emphasized and accelerated this effort.[220] Brazil is planning to acquire the design of a French diesel-submarine and build it in Brazil with a nuclear-propulsion system. If this plan is carried out, Brazil will be the first non-nuclear weapon state to build a nuclear submarine. Figure 7.3 shows a model of the submarine, which Brazil plans to have ready in 2020.[221]

Figure 7.3. Mockup of the Brazilian nuclear submarine, envisioned for deployment by 2020. Shown at a public event in São Paolo in February 2008, [Photo: Fernando Cavalcanti.][222]

Brazil is currently building a land-based prototype reactor and is planning to fabricate the fuel for this reactor within the next few years. Uranium conversion and enrichment, as well as fuel fabrication, will be carried out under IAEA safeguards. Brazil is apparently confident that fuel fabrication can be safeguarded by the IAEA without revealing design information that it considers sensitive. Fuel assemblies could be tagged before being loaded into the prototype reactor, and verification of the spent fuel is envisioned once the material is discharged from the reactor.[223] The Brazilian case could set a precedent of a successful application of IAEA monitoring measures to a naval nuclear fuel cycle.

General Approach to Verification

Our general approach to verification of HEU use in naval-reactor fuel cycles assumes that production of new HEU, if permitted at all, would be carried out under IAEA safeguards. Such material would remain under safeguards until needed. Countries also could place under IAEA safeguards pre-existing HEU that has been declared excess for weapons use and set aside for future naval use (Figure 7.4).[224]

The monitored stockpile could either contain HEU in an unclassified form, e.g., as metal disks or as an oxide powder, or in classified weapon components. If the HEU were in classified forms, verification approaches would be required that protect the classified information. Such an approach was developed in the context of the IAEA-Russia-U.S. Trilateral Initiative to verify that nuclear-weapon "pits" contain at least a threshold amount of weapon-grade plutonium without revealing additional design information. Since a major fraction of all excess weapons HEU is stored as weapon components today—primarily the secondaries from dismantled nuclear weapons—the advantages and disadvantages of both approaches would have to be balanced when HEU storage is devised. Reduced cost and rapid implementation of monitoring would favor the direct storage of weapon components, while classification concerns might favor additional processing of the material before it is moved into monitored storage.

We assume that when HEU is needed for naval fuel, a country would inform the IAEA that it intends to withdraw a certain amount of HEU from the stockpile to fabricate cores for specific new ships or submarines or to refuel existing vessels. The IAEA could, on the basis of public information about the shaft horsepower and refueling frequency of the ship (for example, from *Jane's Fighting Ships*) and estimates such as those made above, decide whether the request is plausible. The IAEA would not be able to refuse the release of the requested amount of HEU from safeguards, but it could alert the Parties to the FM(C)T if it believes that the request is implausible.

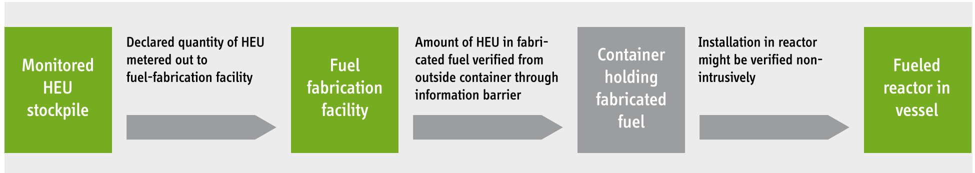

Figure 7.4. Flow diagram illustrating the potential verification of naval stocks under an FM(C)T. A declared quantity of HEU is metered out from the monitored HEU stockpile and delivered to the fuel fabrication facility. If the fuel design is considered sensitive information, the total quantity and the enrichment level of the material leaving the fabrication plant might be verified with special measurement systems (discussed further below). The fuel could be followed until it was installed in the vessel.

After the fuel is fabricated, it could be placed into an unshielded canister and, through radiation measurements described below, the IAEA could verify that the quantity of HEU in the fabricated fuel matches the amount (and the enrichment level) of the material that was released from the stockpile. Regular managed-access inspections in the fuel fabrication plant could provide additional assurance that no fissile material is accumulating inside the plant.[225]

It might also be possible for the IAEA to confirm that the fuel was installed in the reactor pressure vessel. Although it would be impossible to devise such a procedure without cooperation from the operators of the ships and submarines, we note that, under the START Treaty, Russia and the United States devised procedures by which each could check the number of warheads carried on the other's strategic missiles without compromising classified information. If such a procedure can be devised, it should also be possible for the IAEA later to monitor the spent fuel being unloaded from the reactors and placed in canisters that would be subject to IAEA inspection until the fuel was either reprocessed or emplaced in a deep underground repository.

Even after spent fuel is discharged from naval vessels, sensitivities would remain about its design and access to the material for safeguards purposes could still be restricted. The United States and the United Kingdom, and possibly others, store their spent naval fuel rather than reprocessing it, so these restrictions could last indefinitely.[226]

Non-intrusive Verification

A fundamental aspect of naval fuel verification would be the ability to confirm the quantity and enrichment level of a declared amount of nuclear material in a container, i.e., without being able to see the fuel.

This problem is not unprecedented. In their Trilateral Initiative (see Chapter 6), Russia, the United States, and the IAEA devised a way in which the IAEA could monitor plutonium in classified weapons components without revealing classified information. This was done by storing the components in containers and taking measurements outside the containers of the neutron and gamma radiation emitted spontaneously by plutonium. These measurements make possible precise measurements of the quantity and isotopic makeup of plutonium in the containers. Since this information is considered classified, it is passed through an "information barrier" that communicates—for example, through red and green lights—only that the amount of plutonium exceeds a certain agreed threshold and that the plutonium is weapon-grade.

Our approach would be similar in many respects. Since uranium is much less radioactive than plutonium, there would not be enough spontaneously emitted neutrons and gamma rays to make useful measurements. However, high-energy neutrons from a radioactive source or a neutron generator could be used to irradiate the canister and trigger fissions in the uranium. A detector system could then measure the number and timing of the photons and neutrons emitted by the nuclear reactions caused by each incoming neutron. This data could then be used to estimate the mass and enrichment of the uranium inside the canister.

For simplicity, we assume that an entire reactor core would be placed within the detector system. High-energy neutrons from a radioactive source or a neutron generator could be used to irradiate the canister and trigger fissions in the uranium. A detector system could then measure the number and timing of the photons and neutrons emitted by the nuclear reactions caused by each incoming neutron. This data might be used to help estimate the mass and enrichment of the uranium inside the canister. High-energy neutron sources, such as a 14 MeV deuterium-tritium source, could be used to interrogate the reactor core.[227] The simulations demonstrate that only a few percent of the neutrons are transmitted through the core (Figure 7.5). For a high flux source this is expected to be sufficient.

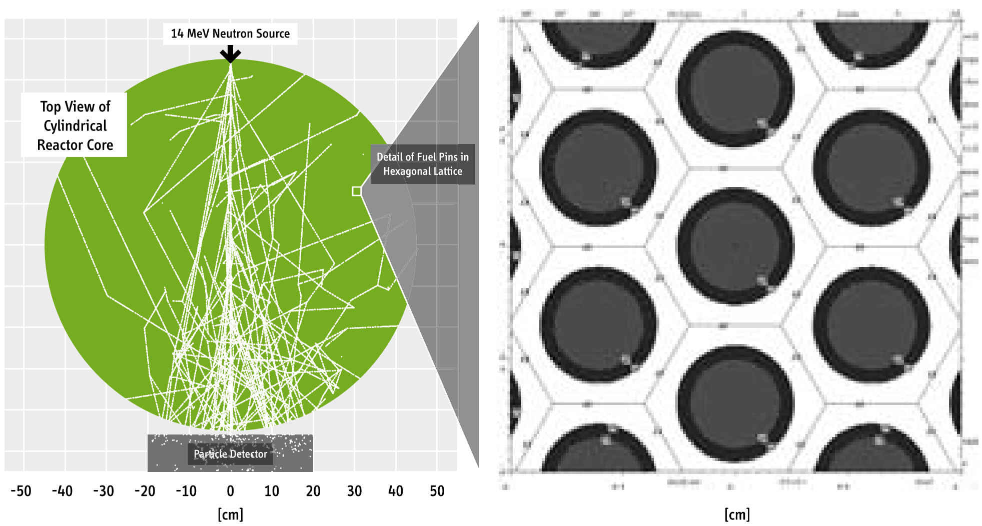

Figure 7.5. Notional submarine core and detector system. For simplicity, we assume that an entire reactor core would be placed within the detector system. The figure shows neutron tracks incident on the notional submarine reactor core. The neutron energy is assumed to be 14 MeV, and the detectors arranged around the core provide a trigger (top detector, not shown) and stop signal (bottom detector) for time-correlated measurements. Simulations demonstrate that approximately 3 % of the neutrons are transmitted through the reactor. A blowup of the cross-section of an array of cylindrical fuel rods is shown on the right with hexagons drawn in to show the core volume associated with each rod. In this example, we assume a core inventory of 375 kg of uranium with an enrichment of 40 % (150 kg U-235). For a typical fuel volume fraction of 30 % and an effective uranium density in the fuel of 2.2 grams per cubic centimeter, the core diameter and height are on the order of 0.9 m.

Similar active (interrogation) measurement systems have been developed since the 1990s for arms control and other purposes, but usually for smaller objects with lower uranium inventories.[228] Most notably, the Oak Ridge National Laboratory is still developing and enhancing the capabilities of its Nuclear Materials Identification System (NMIS).[229]

Figure 7.6 illustrates a specific experimental setup of NMIS. A monoenergetic (14 MeV) neutron source is used to interrogate a container of uranium powder of unknown distribution and density.[230] The detector system arranged on the opposite side of the target detects gamma radiation, transmitted neutrons, and secondary neutrons from induced fission and inelastic scattering. Because neutrons travel more slowly than gamma rays, they are detected in different time intervals after the incoming neutron enters the container. Multiple neutrons detected simultaneously provide a characteristic signal for fissions. Assuming prior knowledge of the uranium enrichment, it was possible to estimate the total amount in the container with an accuracy of one percent.[231]

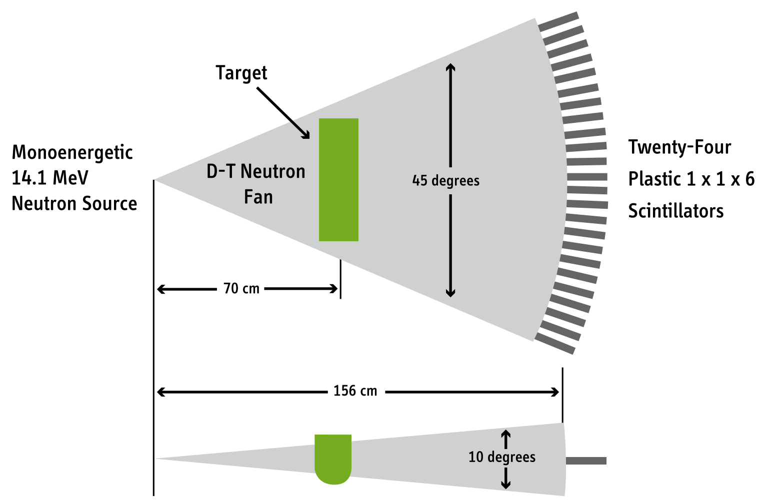

Figure 7.6. Diagram showing the NMIS setup for the non-intrusive interrogation of an object containing special nuclear material. In this case the particular experimental configuration is for determining the mass of uranium powder of given enrichment but unknown distribution and density in a container of known shape. Shown are a top and a side view. [Source: B. Grogan and J. Mihalczo]

Information about the enrichment could be obtained by various means.[232] One method would be to count the number of neutrons detected within a certain time interval after the arrival of the incident neutron in the object being interrogated.[233] Since secondary neutrons are produced principally by fission, the number of neutrons detected is sensitive to the U-235 content of the material. This method is currently under investigation as a possible technique for non-intrusive verification of naval reactor cores.[234]

Appendix 7A. Paragraph 14 of INFCIRC/153 (corrected)

NON-APPLICATION OF SAFEGUARDS TO NUCLEAR MATERIAL TO BE USED IN NON-PEACEFUL ACTIVITIES

14. The Agreement should provide that if the State intends to exercise its discretion to use *nuclear material* which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement, the following procedures will apply:

(a) The State shall inform the Agency of the activity, making it clear:

(i) That the use of the *nuclear material* in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and

(ii) That during the period of non-application of safeguards the *nuclear material* will not be used for the production of nuclear weapons or other nuclear explosive devices;

(b) The Agency and the State shall make an arrangement so that, only while the *nuclear material* is in such an activity, the safeguards provided for in the Agreement will not be applied. The arrangement shall identify, to the extent possible, the period or circumstances during which safeguards will not be applied. In any event, the safeguards provided for in the Agreement shall again apply as soon as the *nuclear material* is reintroduced into a peaceful nuclear activity. The Agency shall be kept informed of the total quantity and composition of such unsafeguarded *nuclear material* in the State and of any exports of such material; and

(c) Each arrangement shall be made in agreement with the Agency. The Agency's agreement shall be given as promptly as possible; it shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the *nuclear material* therein.

8 Challenge Inspections at Military Nuclear Sites

Managing the degree of access granted to international inspectors has emerged as a way for states to meet the verification demands of arms control agreements while ensuring that national and commercial secrets and proliferation-sensitive information are appropriately protected. This approach will be required in verification of an FM(C)T at some sites in both non-weapon and nuclear weapon states.

Nuclear weapon states obviously differ from non-weapon states in having sites with nuclear-weapon-related activities.[235] Today, most of them also differ from non-weapon states in having submarines and, in some cases, surface ships equipped with nuclear propulsion reactors. The NPT allows non-weapon states to use fissile material for such non-explosive purposes, however, and Brazil is in the process of developing a nuclear-powered submarine (see Chapter 7).

Under a verified FM(C)T any State Party, if challenged, would have to satisfy the IAEA that it was not conducting undeclared enrichment or reprocessing operations at a suspect site. Non-weapon States Parties to the NPT are already under such an obligation.[236] In weapon states, the procedures at facilities that have analogues in the non-weapon states could be adapted from the corresponding procedures used to implement the Additional Protocol in non-weapon states.

In nuclear weapon states that are parties to the Chemical Weapons Convention (all but Israel), *all* sites, including nuclear facilities, are subject to challenge inspections by the Organization for the Prohibition of Chemical Weapons (OPCW). The OPCW has developed detailed procedures for such inspections. Many of these approaches too could be adapted to manage access at the same facilities under an FM(C)T.

The principal work that remains to be done, therefore, is to develop procedures and instrumentation that could detect, without revealing sensitive nuclear-weapon or naval-fuel design information, the specific activities that would be banned by the FM(C)T: clandestine reprocessing or uranium enrichment.

China, France, Russia and the United Kingdom have all ratified Additional Protocols that focus on providing the IAEA with information about their nuclear exports to non-weapon states.[237] The United States has negotiated an Additional Protocol that also includes the possibility of "complementary access" inspections.[238] The Senate ratified the U.S.-IAEA Additional Protocol in 2004.[239] It has not yet been brought into force but it appears quite possible that the necessary U.S. regulations, including those regulating challenge inspections, will be completed by the end of the Bush Administration in

January 2009.[240] The territory explored in this paper is thus also being explored by the U.S. government.

This chapter reviews the relevant information on managed access in the Additional Protocols of the non-weapon states and United States, and in the Chemical Weapons Convention. It then examines in a preliminary way the instrumentation that could be used to detect unique indicators of reprocessing and uranium enrichment without revealing sensitive nuclear-weapon or fuel design information.

Managed Access Under the Additional Protocol in Non-weapon States

Checking for the presence of undeclared fissile-material production activities outside military nuclear facilities in the weapon states could be patterned on the investigations that the IAEA is authorized to conduct in non-weapon states that have ratified the Additional Protocol.

The Additional Protocol was developed following the IAEA's discovery of Iraq's undeclared enrichment-related activities. Iran voluntarily complied with the Additional Protocol from mid-July 2003 until February 2006 and the IAEA used this access to detect previously undeclared activities such as the enrichment experiments at the Kalaye Electric Company.[241]

Since the Additional Protocol represents such an important reference point for this chapter, it is useful to summarize the access it allows:

- Article 5 allows the IAEA access to any place in a non-weapon state where: 1) the state has declared that it is conducting or has in the past conducted fuel-cycle-related activities, 2) there are nuclear materials that are not of a quality or quantity to be subject to safeguards, or 3) "[A]ny [other] location specified by the Agency … to carry out location-specific environmental sampling, provided that if [the country] is unable to provide such access [it] shall make every reasonable effort to satisfy agency requirements through other means."

- Article 6 specifies permitted inspection methods including: "visual observation; collection of environmental samples; utilization of radiation detection and measurement devices; application of seals and other identifying and tamper indicating devices …"

- Article 7 provides the option of "managed access … in order to prevent dissemination of proliferation sensitive information, to meet safety or physical protection requirements, or to protect proprietary or commercially sensitive information." It requires, however, that "[s]uch arrangements shall not preclude the Agency from conducting activities necessary to provide credible assurance of the absence of undeclared nuclear material and activities at the location in question …"

Managed Access in the U.S. Additional Protocol

Virtually all the provisions of the U.S. Additional Protocol are identical to those in the Additional Protocol for non-weapon states. It contains, however, an added exemption (Article 1b), which allows the U.S. government to exclude the IAEA in instances "where [application of the Protocol] would result in access by the Agency to activities of direct national security significance to the United States or in connection with locations or information associated with such activities." Article 1c states, however, that the "United States shall have the right to use managed access in connection with activities with direct national security significance to the United States or in connection with locations or information associated with such activities."[242]

Thus, while the United States reserves the right to block the IAEA from access to activities that it deems of national security significance, it also commits to try to resolve the IAEA's questions at sites with such activities.

To prepare for the application of the Additional Protocol, the U.S. Nuclear Regulatory Commission has instructed approximately 60 licensees about activities that they must report to the IAEA under the Additional Protocol.[243] It is also working with the licensees to plan for the possibility that the IAEA may request access to their sites because of questions about the accuracy or completeness of their declarations. These preparations include plans for managed access to enable the IAEA to verify the declaration of civilian nuclear activities without revealing sensitive national-security information. Only if it is concluded that an "activity or information of direct national security significance cannot be effectively protected by such managed access [at a] location [will] no reporting or IAEA access to it be permitted."[244]

The U.S. Department of Energy is spending about ten million dollars making similar preparations for the nuclear-science, energy and weapon sites that it controls.[245]

By contrast, the U.S. Department of Defense has invoked the national security exclusion to exempt all its sites from reporting or inspection under the Additional Protocol.[246] This may reflect the fact that its nuclear activities are all associated with nuclear warheads and nuclear-powered naval vessels.

Managed Access in the Chemical Weapons Convention

Elaborate procedures for managed access have been developed in connection with the challenge inspections that are allowed under the Chemical Weapons Convention (CWC). Such procedures are available if a country brings to the attention of the Organization for the Prohibition of Chemical Weapons information that raises legitimate questions as to whether another country is carrying out clandestine activities that violate the CWC.

There is no restriction under the CWC on what facilities can be subject to challenge inspection. Parties to the CWC therefore have had to prepare themselves for the possibility of inspections at their most sensitive facilities, including military nuclear facilities in nuclear-weapon states.

The activities that CWC inspections are designed to detect are undeclared production or storage of chemical weapons or chemical-weapon agents or their precursors. If the instrumentation were adapted to the detection of clandestine fissile-material production, many of these procedures could be taken over directly into an FM(C)T. It is therefore useful to review these CWC managed-access procedures and instrumentation. They are outlined in the Convention itself and in its Annex on Implementation and Verification.[247]

Initiating a CWC Inspection. The CWC permits a member state that suspects a violation by another state to request an inspection by a team of experts organized by the Technical Secretariat of the Organization for the Prohibition of Chemical Weapons. The procedures laid out for the inspections achieve a delicate balance between, on the one hand, asserting the rights of the inspection team to use sensitive instrumentation that can detect chemical agents, and, on the other, allowing the inspected country to protect sensitive information not related to chemical-weapon agents.

Article IX of the Convention outlines the process for setting up the inspection, along with the need to balance prompt access with protection of unrelated information:

> "Each State Party has the right to request an on-site challenge inspection of any facility or location in the territory or in any other place under the jurisdiction or control of any other State Party for the sole purpose of clarifying and resolving any questions concerning possible non-compliance with the provisions of this Convention…
>
> "[E]ach State Party shall permit the Technical Secretariat to conduct the on-site challenge inspection…
>
> "[T]he inspected State Party shall have… [t]he obligation to provide access within the requested site for the sole purpose of establishing facts relevant to the concern regarding possible non-compliance; and… [t]he right to take measures to protect sensitive installations, and to prevent disclosure of confidential information and data, not related to this Convention…
>
> "The inspection team shall be guided by the principle of conducting the challenge inspection in the least intrusive manner possible, consistent with the effective and timely accomplishment of its mission.
>
> "If the inspected State Party proposes … arrangements to demonstrate compliance with this Convention, alternative to full and comprehensive access, it shall make every reasonable effort, through consultations with the inspection team, to reach agreement on the modalities for establishing the facts with the aim of demonstrating its compliance."

Part X of the Verification Annex details the conduct of the inspection.[248] It begins by specifying the contents of an inspection request:

> "[t]he concern regarding possible non-compliance … the nature and circumstances … as well as all appropriate information on the basis of which the concern has arisen…
>
> "The inspection site shall be designated … as specifically as possible [including] a diagram specifying as precisely as possible the requested perimeter of the site to be inspected … The requested perimeter shall run at least a 10 meter distance outside any buildings or other structures [and] [n]ot cut through existing security enclosures … [or] it shall be redrawn by the inspection team so as to conform with that provision … if the inspected State Party cannot accept the requested perimeter, it shall propose an alternative … In cases of differences of opinion [they] should engage in negotiations…"

Actions upon arrival at a site. So as to assure that evidence of non-compliance is not being removed, the inspection team has a right to

> “inspect on a managed access basis vehicular traffic exiting the site.”

In order to make clear its concerns about protecting sensitive information,

> “the inspected State Party may indicate to the inspection team the equipment, documentation or areas it considers sensitive and not related to the purpose of the challenge inspection.

Outside the perimeter of the inspected area,

> “the inspection shall have the right to … [u]se monitoring instruments [and] take wipes, air, soil or effluent samples”

Managed Access. Inside the perimeter,

> “48. … the inspected Party shall have the right to take measures to protect sensitive installations and prevent disclosure of confidential information and data not related to chemical weapons. Such measures may include *inter alia* … Removal of sensitive papers from office spaces … shrouding of sensitive displays, stores, and equipment … Shrouding of sensitive pieces of equipment, such as computer or electronic systems … logging off of computer systems and turning off data indicating devices …
>
> “49. The inspected State Party shall make every reasonable effort to demonstrate to the inspection team that any object, building, structure, container or vehicle to which the inspection team has not had full access, or which has been protected in accordance with paragraph 48, is not used for purposes related to the possible non-compliance concerns raised in the inspection request.
>
> “50. This may be accomplished by means of, *inter alia*, the partial removal of a shroud or environmental protection cover [or] by means of a visual inspection of the interior of an enclosed space from its entrance or by other methods …

Instrumentation. The inspection team has a right to bring with it

> “equipment which is specifically designed for the specific kind of inspection required … The inspected State Party shall have the right to … inspect the equipment in the presence of the inspection team at the point of entry” when the team arrives and departs.

The permitted equipment includes a gas-chromatograph mass spectrometer (GCMS).[249] This sensitive instrument is capable of identifying millions of chemical species and could be used for industrial espionage at chemical companies. When used in CWC inspections, however, it is limited by its database to identifying about 3000 chemical-weapon-related species and their degradation products.[250] This limitation serves as a barrier to the gathering of unrelated information in conformity with the verification annex, which allows the host country to

> "[restrict] sample analysis to presence or absence of chemicals listed in Schedules 1, 2 and 3 or appropriate degradation products …"

To assure that other information is not carried away, the hard drive storage of the computer in the GCMS and packing material from its chromatograph column are removed and left with the inspected country when the inspectors leave the site.[251]

The Parties to the CWC have also agreed on other portable equipment that can be used in inspections:

- Infrared spectrometers with databases similarly restricted to those of the GCMS; test-paper packages for CW agents; neutron-induced prompt X-ray spectrometers that allow the determination of element ratios inside a container; and ultrasonic pulse echo devices and acoustic resonance spectroscopes to determine whether containers are empty or full of liquid;

- Global Positioning System receivers to enable the inspectors to confirm that they are at the desired location within an accuracy of one second longitude or latitude (30 meters or less);

- Film and video cameras. These cameras can only be used, however, by representatives of the inspected country, who take pictures at the request of the inspectors and thereby can assure that sensitive information is not included in the camera's view;[252]

- Seals to secure structures and containers and prevent undetected removal of their contents during an inspection; and

- Short-range radios to allow communications within the team and satellite-link telephones to allow communication with OPCW headquarters.

Indicators of Reprocessing or Enrichment

In a CWC inspection, the inspectors are looking for the signatures of specific listed chemicals. In an FM(C)T inspection, the inspectors would be looking for signatures of clandestine reprocessing or enrichment.

Reprocessing. Off-site detection of clandestine reprocessing could be through the detection of volatile radionuclides released when spent fuel is dissolved. The fission product that has been detected furthest downwind from reprocessing plants is 11-year half-life krypton-85, which is produced in 0.3 percent of fissions of U-235.[253] Krypton-85 stays in the atmosphere because it is non-reactive, like helium. Unless the Kr-85 is removed from the effluent, it should therefore be possible to detect an *operating* reprocessing plant from outside the site fence.[254]

But, if the operators of a reprocessing plant had advance notice that inspectors would be outside their fence, they could stop dissolving fuel and releasing Kr-85. It is of interest, therefore, to determine whether there might be evidence of a reprocessing plant in the form of other distinctive isotopes released to the environment by reprocessing activity, which would then settle on local surfaces, in the soil or in local waters. In fact, elevated levels of carbon-14 (5600-year half-life), cesium-137 (30 years), cobalt-60 (5 years), iodine-129 (17 million years) and ruthenium-106 (1 year) have all been found in the environment around France's La Hague reprocessing plant, despite its advanced filtration systems.[255]

On-site managed access. A reprocessing plant has a number of characteristic features by which it might be identified during a managed-access inspection visually and/or with appropriate instruments without revealing non-germane information:[256]

- Heavy walls for gamma radiation shielding (typically 1–2 meters thick heavy metal-aggregate-containing concrete).[257] Commercially available ultrasonic gauges are calibrated for wall thicknesses up to 1.3 meters, but presumably could be calibrated for even thicker walls.[258]

- Very high gamma radiation levels inside the spaces where spent fuel has been dissolved and fission products separated from the plutonium. If an unusually thick wall were discovered, therefore, a request could be made for a gross gamma-ray radiation-level reading on the other side. This could be done with a simple Geiger counter, which measures only gamma dose rate and not the energy spectrum of the gamma rays.[259] It therefore would not reveal the presence of traces of plutonium from weapons work.[260]

Hot cells also have thick walls and high radiation levels. They should therefore be declared along with any reprocessing plants in the initial declaration of facilities to the IAEA. Most hot cells are equipped with thick lead-glass windows to allow the operators of the equipment within them to see what they are doing. Figure 8.1 shows a borderline case of a set of hot cells at the Korean Atomic Energy Research Institute that has been used to examine spent fuel and could be equipped to be a laboratory-scale reprocessing facility.

One feature of a reprocessing facility is equipment to handle the irradiated uranium. For production of weapon-grade plutonium in a reactor fueled with natural uranium, the concentration of plutonium would be about 1 kg per ton of uranium.[261] To produce 6 kg of plutonium, therefore, would require the processing of about 6 tons of irradiated uranium.

This irradiated uranium might be transported to the reprocessing plant in shipments of a ton or less, but because of the intense radioactivity of the irradiated uranium, a heavy cask with thick radiation-absorbing walls weighing on the order of ten tons or more would be required to hold it during transport.[262] A heavy-duty overhead crane rated for at least such a load would therefore ordinarily be present to move the casks into the reprocessing facility.

After reprocessing, the heat and radiation generation associated with spent fuel would be mostly in the high-level radioactive waste. Such material is usually stored in tanks.[263] IAEA efforts to follow up indications in satellite images of North Korean efforts to conceal the presence of such tanks intensified the 1992 crisis over North Korea's nuclear program.[264] If not discovered by satellite surveillance while under construction, underground radioactive waste tanks could be revealed by associated warm spots on the ground's surface visible in night-time thermal infrared images.

Other equipment that distinguishes a reprocessing plant includes dissolution tanks for digesting the irradiated uranium in acid and storage tanks for holding the extracted uranium and plutonium solutions. These tanks for holding concentrated plutonium solutions are often characteristically long and narrow or have flat or annular shapes to keep their contents sub-critical and thereby prevent an unwanted fission chain reaction.[265]

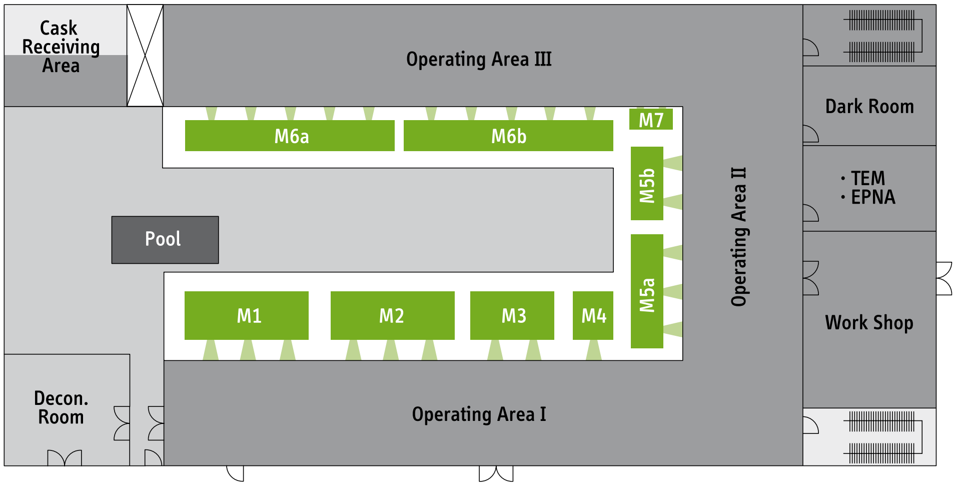

Figure 8.1. The hot cells in the Irradiated Materials Examination Facility at the Korean Atomic Energy Research Institute are labeled by M1, M2, etc. All the cells have walls of 0.8–1.2 meter thick of dense concrete loaded with iron aggregate except for the smallest (M7), which is shielded with 20 centimeters of lead. The cone-shaped penetrations in the walls between the hot cells and the operating area are thick windows of leaded glass. Spent-fuel casks are unloaded in the pool. Fuel rods are then introduced through a water-filled channel into the M1 fuel cell. The fuel can be passed from cell to cell for different types of measurements and processing.[266]

Enrichment. A number of different types of enrichment plants have been developed to the point of large-scale tests or production, including electromagnetic, gaseous diffusion, gas centrifuge and laser. Signatures would have to be identified for each. The most likely clandestine enrichment plant today, however, would be based on gas-centrifuges. We discuss possible approaches to their detection here.

Off-site detection. The off-site signatures of a clandestine gas-centrifuge enrichment plant would include UF_6 degradation products. The leakage of UF_6 from a centrifuge plant is quite small, however, because the gas in the centrifuges and their connecting piping is below atmospheric pressure.[267] In the absence of an accident, most of the leakage occurs during the connection and disconnection of the canisters used to introduce UF_6 into the cascade and extract it. Most likely, it would not be detectable off-site but it might be possible to detect clandestine UF_6 production in this way.[268]

On-site managed access. Centrifuge enrichment plants are visually quite distinctive, with a forest of identical cylinders connected with tubing (see Figure 8.2). Operating plants sometimes can be detected by the characteristic frequency of the weak electromagnetic emissions produced by their synchronized electrical motors.[269] Operating laser enrichment plants might similarly be detected by the electromagnetic and acoustic signals associated with their repetitively pulsed lasers.

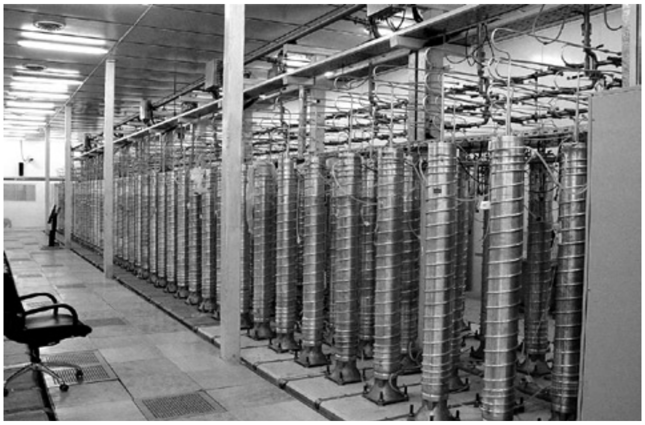

Figure 8.2. Iran's pilot plant with P1 centrifuges, 2005.[270] With 1000 centrifuges, this plant would be capable of producing about 15 kg of weapon-grade uranium per year.

A gas-centrifuge enrichment plant would contain UF_6 cylinders and autoclaves to heat them and turn their solid contents to gas. It would be expected also that evidence of UF_6 leakage could be detected in surface deposits.

UF_6 quickly reacts with water vapor in the air to become UO_2F_2, which is a solid and settles out. If it has not already been done, an attempt should be made to devise instruments that could identify UO_2F_2 on surfaces.

One possibility for such evaluation would be laser induced breakdown spectroscopy.[271] In this approach an intense laser beam vaporize a particle and heats it up to temperatures at which the material breaks down into excited ionized atoms. The atoms then release their internal energy in the form of light at wavelengths that are characteristic of each atomic type (see Figure 8.3).

To prevent it from picking up other information, the computer in the spectrometer could be limited to giving a yes-no indication of whether both uranium and fluorine had been detected in such a plasma at comparable concentrations.

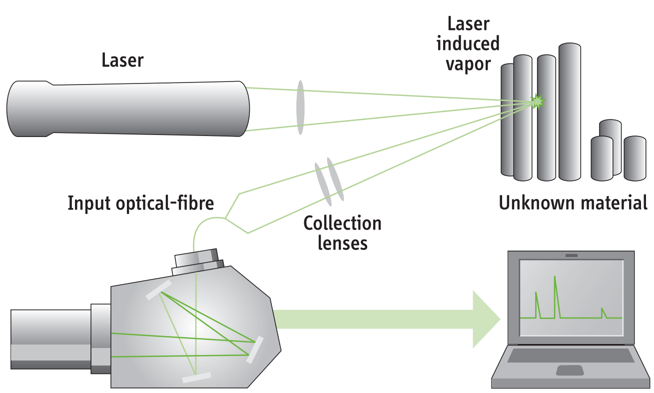

Figure 8.3. Laser-induced Breakdown Spectroscopy (LIBS). A laser is used to vaporize a microscopic amount of material on the surface of the object of interest. The light emitted by the resulting incandescent vapor is analyzed by a spectrometer and compared to a library of known spectra to determine material composition. [Graphics adapted from: IAEA, Canadian Safeguards Support Program]

Conclusion

Managed-access procedures are available under the Additional Protocol and the Chemical Weapons Convention and could be developed into tools for FM(C)T challenge inspections at military nuclear sites in the nuclear weapon states.

The use of managed access to check suspect sites for clandestine chemical-weapon-related activities is well developed. The same general approach toward balancing the need for access of the inspectorate with the need of the operators of the suspect facility to protect sensitive information could be applied to the detection of clandestine reprocessing and enrichment activities.

Managed access is also a part of the IAEA's repertoire under the NPT Additional Protocol for non-weapon states and has been used effectively in Iran to detect undeclared enrichment activities.

Some of the tools used by IAEA inspectors in non-weapon states, such as swipe samples, would not be allowed in weapon-state nuclear-weapon production facilities, however, since they could be too revealing about the isotopics and chemical forms of the nuclear materials used there. There might be similar concerns at the facilities at which naval-reactor fuel is fabricated.

We have therefore explored in a preliminary way some of the signatures of clandestine reprocessing and enrichment facilities that could be detected without revealing such sensitive design information.

9 Shutdown Production Facilities

In both nuclear weapon and non-weapon states, many fissile-material production facilities have been shut down and, in some cases, decommissioned. In weapon states, they are generally not under international safeguards. Many of these facilities would have to be placed under safeguards under an FM(C)T. It is likely that, before an FM(C)T comes into force, many more facilities, including notably reprocessing and uranium enrichment installations that could not be economically converted to civilian use, would be shutdown and these too would have to be put under safeguards. In non-weapon states, facilities that have been shut down or closed down continue to be categorized as nuclear facilities, irrespective of inventory, and remain under IAEA safeguards until they have been decommissioned.

Under IAEA definitions, a shutdown facility is one that contains nuclear materials and could be restarted. A closed-down facility is one in which operations have stopped and the nuclear material removed, but where the facility has not yet been decommissioned for safeguards purposes. A facility is considered as decommissioned for safeguards purposes when structures and equipment essential to the facility have been removed or rendered inoperable, and where the facility can no longer be used to store, handle, process, or utilize nuclear material.[272]

Verification activities are conducted for the purpose of assuring that no new nuclear material has been introduced, that the current inventory (if any) remains as declared and that operations of the facility have not been restarted. This approach would also apply under the FM(C)T.

The IAEA has developed an Essential Equipment List (EEL) for any given type of nuclear facility—a list of equipment, systems, and structures essential for the operation of the facility.[273] For the IAEA to stop inspecting a facility altogether, the Agency would have to verify that critical items on the EEL had been removed or destroyed and that all hold-up material (residual nuclear-material deposits) had been accounted for and removed. The removal of the critical items and any hold-up material would constitute the full decommissioning for safeguards purposes of the facility.

Table 9.1 shows a partial list of shutdown and closed-down sensitive fuel cycle facilities in non-nuclear weapon states still under IAEA safeguards. Several of the plants listed are in the process of being decommissioned (such as the WAK facility in Germany) and remain under safeguards because there is still some liquid waste containing nuclear material present. The reprocessing plant, Eurochemic, which is in the process of being decommissioned for radiological purposes (although already decommissioned for safeguards purposes), is not on the Agency list of safeguarded facilities though evidently the Agency does continue to visit (complementary access under the Additional Protocol).[274]

MOX fuel-fabrication facilities
BN-MOX, Dessel, Belgium
FBFC, Dessel, Belgium
FBFCMOX, Dessel, Belgium
Reprocessing plants
WAK, Eggenstein-Leopoldshafen, Germany
EURE, Saluggia, Italy
ITREC, Trisaia, Italy
Enrichment plants, including pilot plants
Pilcaniyeu enrichment plant, Pilcaniyeu, Argentina
Uranium enrichment plant, São Paolo, Brazil
Laser spectroscopy laboratory, San Jose dos Campos, Brazil
R&D facilities and locations associated with enrichment technology
Silex, Lucas Heights, Australia
UF_6 laboratory, Belo Horizonte, Brazil

Table 9.1. Shutdown/closed-down fuel-cycle facilities in non-nuclear-weapon states under IAEA safeguards at the end of 2006.[275]

In the United States and Russia, several plutonium production reactors have been shut down and are now being monitored, as discussed further below. Both countries also have several shutdown fuel cycle facilities. In the United States, for example, shut down reprocessing facilities include a PUREX reprocessing plant at Hanford, which was shut down in 1989, the Idaho Chemical Processing Plant used to reprocess naval fuel, which was shut down in 1992, and the F canyon at Savannah River, which is reported to be in a "safe state," but which has not yet been decommissioned.[276]

A Safeguards Approach for Shutdown and Closed-down Facilities

The Safeguards Approach for shutdown and closed-down facilities would be similar in non-nuclear and nuclear-weapon states. It would be based on a combination of remote surveillance (satellite or aerial monitoring); containment and surveillance measures (C/S), including radiation monitoring, video surveillance and photographic records; and periodic inspector visits. This monitoring could include operator declarations of schedules and activities in advance or in near-real-time, through for example transmission to locations off-site or through the standard electronic IAEA Mailbox System, which time-stamps and encrypts information so that it cannot be altered. The inspector visits could include both regular visits and short-notice random inspections (SNRI). The inspections would be performed to collect and review monitoring data and to check C/S systems.[277]

- *Containment and surveillance measures* include tamper-indicating cameras and seals. Surveillance cameras could pick up unusual activity in a facility, including the movement of people in and out of critical areas of the facility. Increasingly, the IAEA is moving toward systems where the cameras can transmit information in real time to Agency observers off-site. Not all countries are now permitting this. For the older systems, Agency inspectors would collect records upon on-site visits.

- *Radiation monitoring* through use of gamma and neutron detectors can detect movement of nuclear material.

- *Photographic records,* supplemented by the periodic visits of inspectors, would provide additional assurances that no new, undeclared activities were taking place at a shutdown facility.

- *Satellite monitoring* could assist in detecting unusual open-air activity at a site. Such monitoring could possibly detect arrival at a production facility of shipments of material or large equipment, such as cranes.

- *Periodic visits* by inspectors would be used to verify that the C/S systems had not been tampered with and that no new process equipment had been introduced.

Overall, the IAEA could implement some subset of these measures effectively and relatively inexpensively.[278] Incapacitating key equipment and placement of tamper-indicating seals, supplemented by Agency inspections every 1–3 years, would in most cases be sufficient to verify the shutdown status of a facility. If there is more than a significant quantity of hold-up material, the inspections might have to be somewhat more frequent.[279]

The most recent experience with these measures in states which have had nuclear weapon programs is the IAEA monitoring of shutdown facilities at the Yongbyon and Taechon sites in the DPRK and of South African enrichment facilities. These monitoring efforts are described briefly below.

Verifying the Shutdown of the DPRK's Plutonium-production Facilities

The recent decision of the DPRK to shut down its key nuclear facilities and to allow the IAEA to monitor and verify this shutdown provides an illustration of a safeguards approach that could be applied under an FM(C)T.

On 17 July 2007, following initial verification, the IAEA announced that the DPRK had shut down the following installations at the Yongbyon nuclear site and at Taechon:

- The nuclear fuel fabrication plant at Yongbyon

- The radiochemical laboratory (reprocessing plant) at Yongbyon

- The 5 megawatt-electric (MWe) nuclear power plant at Yongbyon

- The incomplete 50 MWe nuclear power plant at Yongbyon

- The incomplete 200 MWe nuclear power plant at Taechon

Since 17 July 2007, the Agency has continued to monitor and verify the shutdown status of these installations. The details of the IAEA measures have not been made public, but the agency has published an overview of how the shutdown is being monitored.[280] Photographic records have been made of the status of the facilities at shutdown and containment and surveillance (C/S) measures installed. At the reprocessing plant and 5-MWe reactor, the Agency also has installed radiation-monitoring devices covering key processes and equipment.

The shutdown status is being confirmed through periodic visits. The DPRK has agreed to provide the Agency inspectors with access to any location at the plants during their visits.

Verification of the Shutdown of South Africa's HEU-production Facilities

South Africa joined the Non-Proliferation Treaty in July 1991 and, signed a comprehensive safeguards agreement with the IAEA in September 1991. The task of the IAEA was to verify the correctness and completeness of South Africa's declared inventory of nuclear materials and to monitor the status of current nuclear activities and facilities, including the status of two shutdown enrichment plants.

One of these plants, the Y plant at Valindaba, employed an aerodynamic enrichment process, and produced the HEU for South Africa's nuclear weapon program. The facility was shut down in 1990. In September 1992, the IAEA reported that the high-enrichment separation units of the plant had been dismantled and removed, and the remainder of the plant had been decommissioned and partially dismantled.[281]

South Africa's second enrichment plant, the Z plant at Pelindaba, had a capacity of 300,000 SWU per year and produced low-enriched uranium. It also used the aerodynamic process. This plant was shut down in 1995.

Bilateral Verification of Shutdown Russian and U.S. Production Reactors

In September 1997, Russia and the United States concluded an agreement that specified in part that all plutonium-production reactors listed in Annex I to the agreement had ceased operations and would not resume operation.[282] The reactors listed include 14 U.S. reactors (9 at the Department of Energy's Hanford Site and 5 at the Savannah River Site); and 10 Russian reactors (5 at Ozersk, 3 at Seversk and 2 at Zheleznogorsk). Three additional Russian production reactors, one at Zheleznogorsk and two at Seversk (shut down in 2008), continued operation for a period to provide heat and electricity for civilian use, but are also covered by the Agreement.

The Agreement calls for monitoring of the shutdown reactors to assure that their operations have not resumed. It specifies that the other country's monitors shall have the right to conduct a monitoring visit to each shutdown reactor once a year. "In the first year of monitoring at each reactor, time spent by monitors at that reactor shall be no longer than 5 days, and the total monitoring effort at the reactor shall not be more than 30 person-days. Thereafter, time spent by monitors shall be no longer than 4 days per year at each monitored reactor site … and the total monitoring effort at each site shall not be more than 16 person days."[283]

The Agreement permits the monitoring party to install seals or other agreed monitoring equipment at access areas that would be necessary for the operation of the reactor "in a manner that will assure the infeasibility of putting the reactor into operation without breaking seals or being detected by the other monitoring equipment." Once the parties determine that the dismantling of the reactors is irreversible, they would no longer be subject to any monitoring. It is striking how little a monitoring effort was projected—after the first year, a maximum of 16 person-days per site in each country.

The mutual inspections have gone on in the manner expected. The U.S. and Russian inspectors chose initially not to exercise their right to place tags and seals on the shutdown reactors, but visually monitored the reactors, including taking photos to facilitate future monitoring. The areas subject to the visual monitoring included the reactor control rooms, reactor cooling inlet water supply piping, the fuel discharge rooms, pumps and water lines. Later, seals were placed at a few key points, with the annual inspections then allowing examination of the seals, along with the continued visual monitoring. Most of the reactors have now been decommissioned.

The monitoring of the three Russian production reactors still operating after 1997 has been more complicated. Here, during the annual visits, a few of the coffee-can size containers that hold the plutonium separated from the discharged reactor fuel during the past year (each containing roughly 4 kilograms of plutonium oxide) are randomly selected by the inspectors and brought out from the storage vaults for inspection. The inspectors have been allowed to determine by gross radiation counting that the containers contain some radioactive material. They have not done any non-destructive assays with instruments capable of measuring neutrons or the energies of the gamma rays to assure that the containers really hold plutonium. The containers are all tagged and sealed, however, so that when the non-destructive assays are done, any deception would be discovered.

Shutdown Reprocessing and Enrichment Plants

Reprocessing Plants. The Safeguards Approach in this case would be based on a combination of monitoring selected facility operations and short-notice random inspections (SNRI). This would require that the operator provide to the IAEA schedules for the specific operations being monitored in advance or in near-real time.[284] This could be done using the standard electronic IAEA Mailbox System, which time-stamps and encrypts information so that it cannot be altered.[285]

Short-notice, random, but infrequent inspections would be performed to collect and review monitoring data and to check containment/surveillance (C/S) systems. Declarations of planned operations received by the IAEA would be used as reference data and for planning inspections.[286] Depending on the specific facility situation and design, some combination of the following monitoring and inspection activities could be implemented:

- *Cameras and radiation sensors* could monitor movement of the spent fuel unloading and storage areas to detect the receipt of fuel.

- *Monitoring and/or sealing the spent fuel transfer channel to the head-end cells where the fuel is chopped up and fed to the dissolvers.* A combination of gamma and neutron sensors, along with video surveillance, would detect any movement of spent fuel to the mechanical cells. In some cases the channel could be blocked with tamper-indicating seals.

- *Sealing or monitoring the controls of the fuel-shearing mechanism.* In some facilities the control system can be immobilized with tamper-indicating seals. Surveillance of the control area along with acoustical monitoring could provide added assurance that shearing is not taking place.

- *Monitoring of solution flows through selected tanks* could confirm that there are no undeclared process operations. Declared operations such as cleanout or system testing would be monitored.

- *Monitoring of the plutonium conversion and/or fuel fabrication lines* could confirm that there are no undeclared operations. The installation of neutron detectors, at selected locations on the process lines could detect increases in the presence of neutron emitting plutonium and the direction of its movement.

- *Monitoring the use and/or storage of essential reagents, notably the organic solvent, tributyl phosphate,* could provide an indication of operational status. Feed valves could possibly be immobilized with tamper-indicating seals or ultra-sonic flow sensors could be attached externally to the feed lines.

- *Monitoring for the gaseous fission product Kr-85* could reveal undeclared fuel dissolution activities. During inspections, the operator's Kr-85 gas monitors could be checked, particularly on the safety panels. External environmental monitoring for Kr-85 gaseous effluents could be undertaken if there are no other operating reprocessing plants in the region.[287]

The use of only two or three of the above options would normally be sufficient to provide assurance of a facility's non-operating status.

Enrichment plants. Operation of the old gaseous diffusion plants could probably be detected by visible and infrared satellite images because of their energy intensity.[288] At centrifuge enrichment plants, power supplies and frequency converters for the centrifuges could be disconnected and sealed. Also, UF_6 feed and withdrawal points could be sealed and monitored with cameras. In addition, periodic visits could be used by inspectors to take swipe samples, For plants that had been shutdown for 20 years or longer, swipe samples could identify whether any LEU or HEU was produced more recently than that (see Chapter 4).

Conclusion

The cost of implementing safeguards at a shutdown or closed-down facility would vary somewhat, depending on the complexity and accessibility of the plant and the presence or absence of any remaining in-process or hold-up nuclear materials. Bulk-handling facilities such as reprocessing plants would require the most attention. However, in all cases, the use of tags and seals, radiation monitors, video monitors, photographic records, and periodic inspections would be sufficient to provide assurance of a facility's non-operating status. Overall, the safeguards burden would be very low in comparison to the safeguards that would have to be applied at operating facilities.

Appendix

Fissile Materials and Nuclear Weapons

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

Explosive Fission Chain Reaction

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

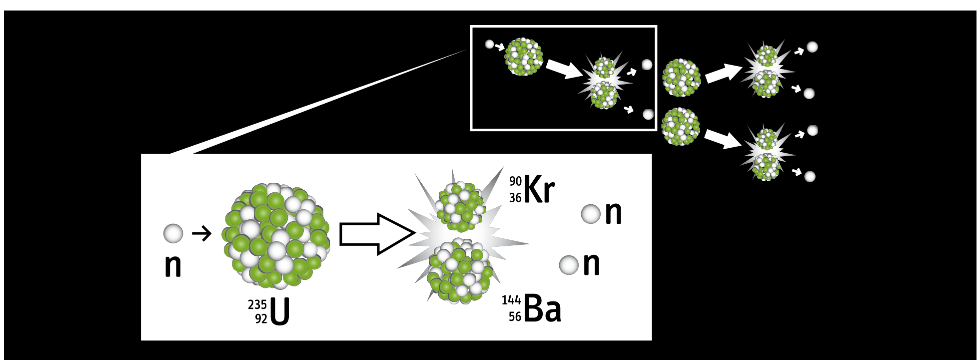

Figure A.1. An explosive fission chain-reaction releases enormous amounts of energy in one-millionth of a second. In this example, a neutron is absorbed by the nucleus of uranium-235 (U-235), which splits into two fission products (barium and krypton). The energy set free is carried mainly by the fission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

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

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

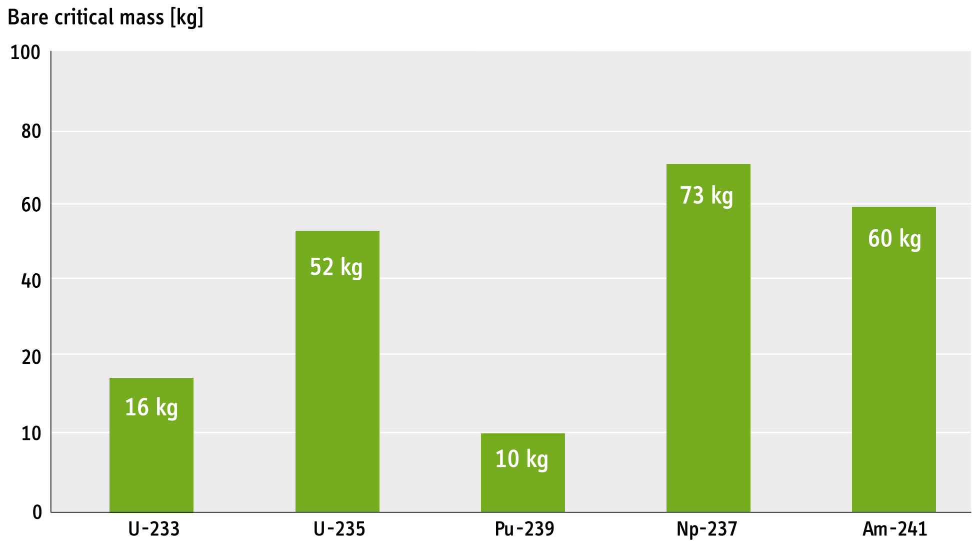

Figure A.2. Bare critical masses for some key fissile isotopes. A bare critical mass is the spherical mass of fissile metal barely large enough to sustain a fission chain reaction in the absence of any material around it. Uranium-235 and plutonium-239 are the key chain-reacting isotopes in highly enriched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

Nuclear Weapons

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

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

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

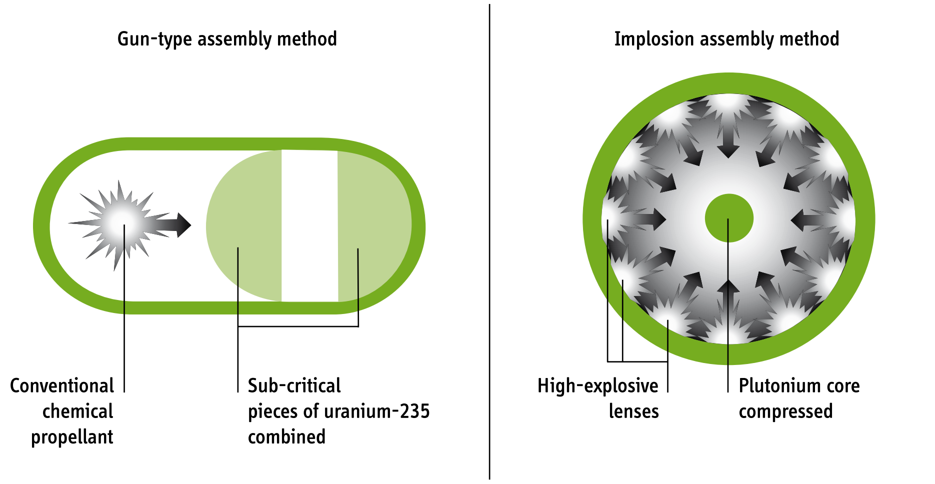

Figure A.3. Alternative methods for creating a supercritical mass in a nuclear weapon. In the technically less sophisticated "gun-type" method used in the Hiroshima bomb (left), a subcritical projectile of HEU is propelled towards a subcritical target of HEU. This assembly process is relatively slow.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

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

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

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

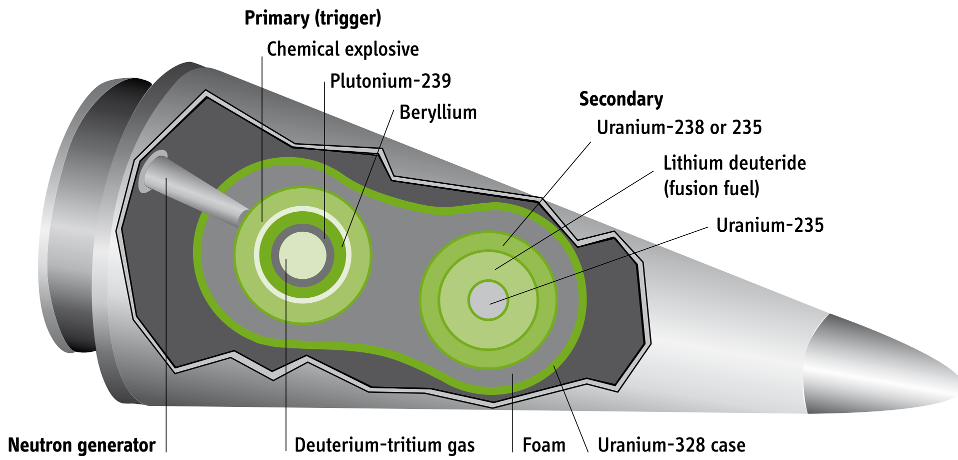

Figure A.4. A modern thermonuclear weapon usually contains both plutonium and highly enriched uranium. Typically, these warheads have a mass of about 200-300 kg and a yield of hundreds of kilotons, which corresponds to about one kilogram per kiloton of explosive yield. For comparison, the nuclear weapons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

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

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

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

Production of Fissile Materials

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

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

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

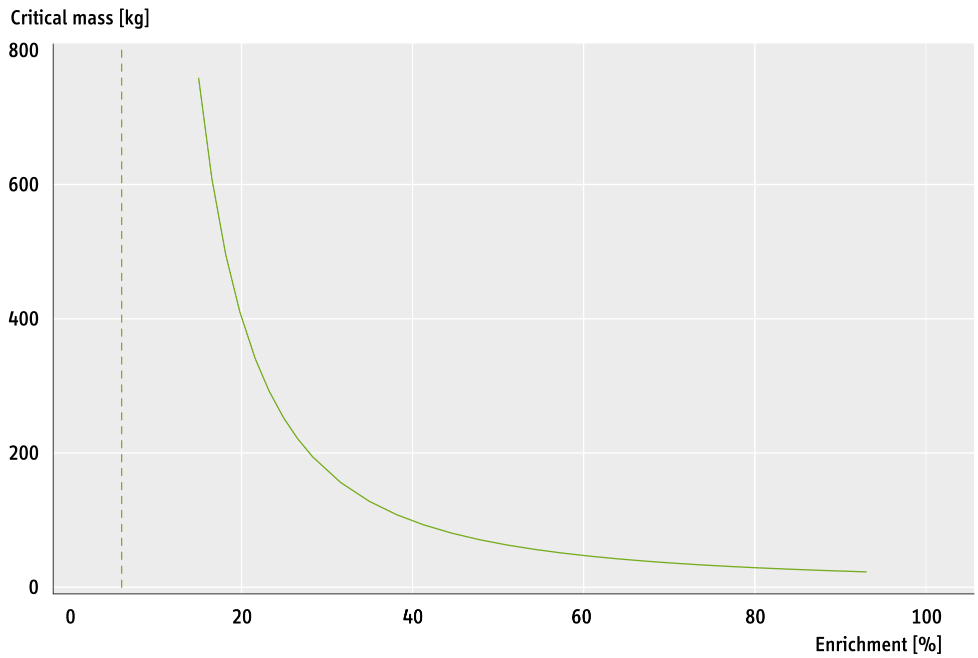

Figure A.5. The fast-neutron critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data in the figure is for a uranium metal sphere enclosed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

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

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

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

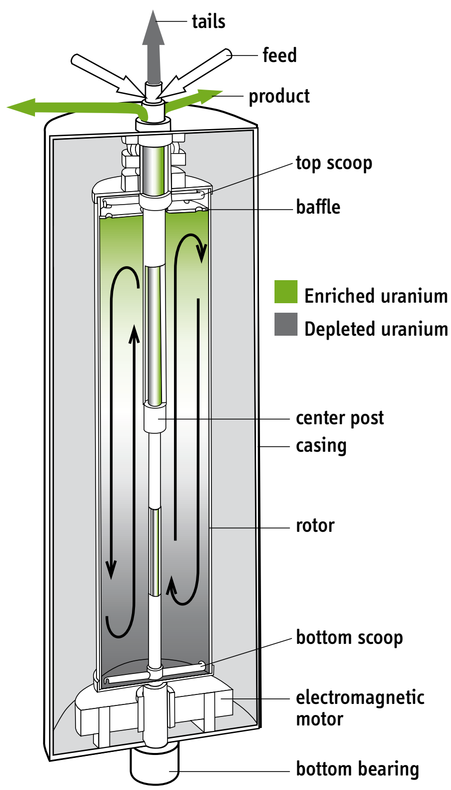

Figure A.6. The gas centrifuge for uranium enrichment. The possibility of using centrifuges to separate isotopes was raised shortly after isotopes were discovered in 1919. The first experiments using centrifuges to separate isotopes of uranium (and other elements) were successfully carried out on a small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

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

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

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

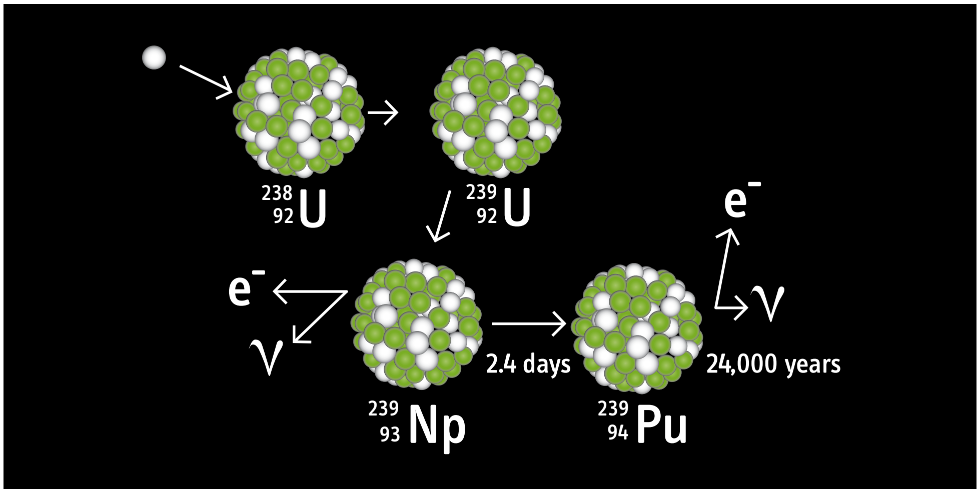

Figure A.7. Making plutonium in a nuclear reactor. A neutron released by the fissioning of a chain-reacting U-235 nucleus is absorbed by the nucleus of a U-238 atom. The resulting U-239 nucleus decays with a half-life of 24 minutes into neptunium, which in turn decays into Pu-239. Each decay is accompanied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

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

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

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

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

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

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

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

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

Endnotes

[1] UN General Assembly Resolution 48/75L, 1993, www.ipfmlibrary.org/unga4875.pdf.

[2] *2000 NPT Review Conference Final Document,* "Article VI and Preambular, Paragraphs 8 to 12," 15.3, see e.g. www.armscontrol.org/act/2000_06/docjun.asp.

[3] "United States of America: White Paper on a Fissile Material Cutoff Treaty," U.S. Mission to the United Nations in Geneva, Press Release, 18 May 2006.

Chapter 1. Nuclear Weapon and Fissile Material Stockpiles and Production

[4] Custody of these warheads was transferred from the Department of Defense to the Department of Energy. Dismantlement of these warheads is not expected to be completed until 2023.

[5] "President Bush Approves Significant Reduction in Nuclear Weapons Stockpile," 18 December 2007, www.whitehouse.gov, mirrored at www.ipfmlibrary.org/whi07.pdf.

[6] R.S. Norris and H. Kristensen, "U.S. Nuclear Forces, 2008," *Bulletin of the Atomic Scientists*, March/April 2008, pp. 50–53, 58.

[7] "Weapons," NNSA, U.S. DOE, nnsa.energy.gov/defense_programs/weapons.htm, mirrored at www.ipfmlibrary.org/doe08a.pdf.

[8] R.S. Norris and H. M. Kristensen, "Nuclear Notebook: Russian Nuclear Forces, 2008," *Bulletin of Atomic Scientists*, May/June 2008, pp. 54–57, 62.

[9] *Annual Report to Congress: Military Power of the People's Republic of China for 2008*, U.S. Department of Defense, www.defenselink.mil. The report asserts that China may have deployed up to 10 DF-31 missiles, up to 10 longer-range DF-31A missiles, and 60–80 DF-21 missiles.

[10] Hans Kristensen, "Chinese Nuclear Arsenal Increased by 25 Percent Since 2006, Pentagon Report Indicates," 8 April 2008, www.fas.org/blog/ssp.

[11] R.S. Norris and H. M. Kristensen, "Nuclear Notebook: Chinese Nuclear Forces, 2008," *Bulletin of Atomic Scientists*, July/August 2008, pp. 42–44.

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

[13] R.S. Norris and H. M. Kristensen, "French Nuclear Forces, 2008," *Bulletin of Atomic Scientists*, September/October 2008, pp. 56–58.

[14] Here, and throughout this report, we assume that an average modern (thermonuclear) warhead contains 4 kg of plutonium in the primary and 25 kg of HEU in the secondary.

[15] In May 2008, former President Jimmy Carter said that Israel has 150 nuclear weapons or more, "Israel 'has 150 nuclear weapons'," BBC News, 26 May 2008, www.ipfmlibrary.org/bbc08.pdf.

16 *Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, Draft, Rev. 1., U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf; and U.K. Ministry of Defence, *Historical Accounting for U.K. Defence Highly Enriched Uranium*, March 2006, www.ipfmlibrary.org/mod06.pdf.

17 *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf, Appendix 1A.

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

19 These 96 tons include: 14 tons (originally in the form of UF_6) and 47 tons for USEC; 31.7 tons for TVA as part of the BLEU (Blended LEU) Program; 1 ton for the Reliable Fuel Supply (RFS) Project, and 2.5 tons for research reactor LEU fuel. Data from: R. George, "U.S. HEU Disposition Program," *Proceedings of the 49th INMM Annual Meeting*, Nashville, TN, July 13–17, 2008.

20 As of 30 June 2008, according to www.usec.com/megatonstomegawatts.htm.

21 Daniel Horner, "DOE set to add HEU for downblending at Savannah River plant," *Nuclear Fuel*, 12 March 2007.

22 H. Myers, "The Real Source of Israel's First Fissile Material," *Arms Control Today*, October 2007, p. 56. Myers was on the staff of the House of Representatives Interior Committee, which had the responsibility for overseeing the Nuclear Regulatory Commission, when it investigated the NUMEC matter in the late 1970s.

23 V. Gilinsky, "Israel's Bomb," *New York Review of Books*, Vol. 51, No. 8, 13 May 2004, www.nybooks.com/articles/17104. From the same author, see also "Time For More NUMEC Information," *Arms Control Today*, June 2008.

24 In addition, Israel may have produced enriched uranium in limited quantities, but information on this program is very limited. Frank Barnaby, *The Invisible Bomb: The Nuclear Arms Race in the Middle East*, I. B. Tauris, London, 1989, p. 40; and M. Vanunu, Interviews with Barnaby, September 1986. According to Vanunu's statements to Barnaby, the enrichment plant started production in 1979–1980.

25 S*triking a Balance, op. cit.*, Table 5-1.

26 Note that stocks were reduced by nuclear-weapon tests, fuel consumption, or other processes. The Russian SWU capacity used for this estimate has been adapted from David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996*, SIPRI, Oxford University Press, 1997, pp. 94–116. A more detailed analysis of the Russian HEU stockpile estimated the cumulative HEU production in Russia to 1430 tons, Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security*, Vol. 6, 1996, pp. 59–77.

27 For a detailed analysis, see Z. Mian, A. H. Nayyar, R. Rajaraman, and M. V. Ramana, "Fissile Materials in South Asia and the Implications of the U.S.-India Nuclear Deal," IPFM Research Report No. 1, September 2006, www.ipfmlibrary.org/rr01.pdf.

28 Pakistan is estimated to have had an enrichment capacity of up to 15,000 kg SWU per year as of 1990 or, equivalently, 3000 P-2 centrifuges each with an enrichment capacity of 5 SWU/yr, *Plutonium and Highly Enriched Uranium 1996, op.cit.*, pp. 217–281.

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

30 Pakistan may not be able to take full advantage of its more powerful P-4 machines because of the limited supply of uranium that it has available, which must be shared with its Khushab production reactor and its Karachi power reactor. If Pakistan has an enrichment capacity much larger than 30,000 SWU, the uranium constraint means Pakistan might have to resort to enrichment of its accumulated uranium tails or of reprocessed uranium from its production reactor even before the two

new production reactors are completed around 2011–2014. Zia Mian, A. H. Nayyar and R. Rajaraman, *forthcoming.*

31 O. Reistad and S. Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *Nonproliferation Review*, Vol. 15, No. 2, July 2008.

32 "The committee directs the Office of Naval Reactors to review carefully options for using low enriched uranium fuel in new or modified reactor plants for surface ships and submarines," Senate Committee on Armed Services Report, *National Defense Authorization Act for Fiscal Year 2009*, 12 May 2008, p. 515.

33 *The Strategic Defence Review*, U.K. Ministry of Defence, Cm 3999, July 1998, www.ipfmlibrary.org/mod98.pdf.

34 *Implications of Declaring UK Uranium Stocks as Waste*, NIREX Technical Note, Document 375301, 26 March 2002, www.nda.gov.uk, mirrored at www.ipfmlibrary.org/nir02.pdf. We would like to thank Martin Forwood for bringing this report to our attention.

35 Sandeep Unithan, "The Secret Undersea Weapon," *India Today*, 28 January 2008, pp. 52–55.

36 The core is reported to be 80 MW fueled with nearly 45% enriched HEU, *Ibid*. It is estimated that such a core could contain about 90 kg of uranium-235. M. V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security*, Vol. 12, 2004, pp. 115–124.

37 "The Secret Undersea Weapon," *op. cit.*

38 India could not produce this much HEU by 2014 if it had simply maintained or even linearly increased its enrichment capacity from the estimated value of 3000 kg SWU/yr that it would have needed by 1999 to have produced the HEU for the land-based prototype core.

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

40 The most prominent and controversial exception is the research reactor FRM-II near Munich, Germany, which went into operation in 2004 and requires 35–40 kg of weapon-grade HEU per year. Enrichment reduction to 50% or less is planned, and should be completed by 31 December 2010 according to an agreement between the German Federal Government and Bavarian State Government.

41 Reistad and Hustveit, 2008, *op. cit.*

42 Only Germany's FRM-II would use HEU at that point.

43 Parish Staples, "An Overview of the Global Threat Reduction Initiative Program for Research Reactor Conversions," *49th INMM Annual Meeting*, 13–17 July 2008, Nashville, TN.

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

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

46 *Global Fissile Material Report 2007, op. cit.*, Chapter 3.

47 Germany's INFCIRC/549 declarations are only partially useful because "[d]ata on material outside Germany […] are not available." It is reasonable to assume that the bulk of material that Germany declared for January 2007 (10.4 tons) is located at the French MOX fuel fabrication site. Apparently, the declaration does not include material stored at the La Hague reprocessing facility. Our estimate is therefore based on a different source, which specified 9.15 tons Pu-fis (Pu-239 and Pu-241), or about 16 tons of total plutonium, remained to fabricated into MOX fuel in January 2007. At that

time, not all of this plutonium may yet have been separated from spent fuel. Scheduled plutonium draw-downs are about 3 tons per year for the next few years, before slowing down in 2012 and 2013. According to this reference, the German stockpile of separated plutonium will have been irradiated by 2014; M. Weis, M. Flakowski, R. Haid, F. Plaputta, and F. Völker, "Plutonium-Verwertung: 40 Jahre MOX-Einsatz in Deutschen Kernkraftwerken" [Plutonium-Recycling: 40 Years of MOX-Use in German Nuclear Power Reactors], *atw*, Vol. 51, No. 12, 2006, pp. 793–796. We assume that, as of January 2007, the German plutonium stockpile was on the order of 15 tons (i.e., one ton had not yet been separated), of which 1 ton may be located in Germany at any given time as fresh MOX fuel for reactor reloads and the rest was in France.

48 www.world-nuclear-news.org/C_Final_contract_for_US_MOX_2705082.html.

49 *AREVA Fuel Assembly Test Failure Dooms Plutonium Fuel Test*, Union of Concerned Scientists, Press Release, 4 August 2008, www.ucsusa.org.

50 www.world-nuclear-news.org/RS_Areva_no_need_to_repeat_MOX_trials_0608082.html.

51 *The Invisible Bomb, op. cit.*, p. 25.

52 According to Vanunu, Dimona produced 1.2 kg of plutonium per week for 34 weeks a year, *The Invisible Bomb, op. cit.*, p. 31. This corresponds to a power level of 214 MWt, if we assume a plutonium production rate of 0.8 g/MWt-day, which is typical for heavy-water-moderated natural-uranium-fueled reactors.

53 This production rate assumes 0.8 grams of plutonium produced per MWt-day, a reactor power of 70 MWt, and 250–300 effective full power days per year.

54 The plutonium content in all of the spent fuel generated in India's unsafeguarded PHWRs since they first came on-line in 1984, assuming 3.75 kg of plutonium per ton of spent fuel (equivalent to a burnup of 7000 MWd/t), is 13.8 tons. Not all of this would have been separated owing both to the need for cooling and because of inadequate reprocessing capacity, especially in recent years. Therefore, as of 2008, we estimate that about 6.4 tons of plutonium may have actually been separated, assuming losses of 3% during reprocessing.

55 A. Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science & Global Security*, Vol. 15, No. 2, 2007, pp. 85–105.

56 M. V. Ramana, personal communication, August 2008, based on data from Nuclear Power Corporation of India, Ltd., www.npcil.nic.in/plantsoperation.asp.

57 Somini Sengupta and Mark Mazzetti, "Atomic Club Votes to End Restrictions on India," *New York Times*, 7 September 2008. The text of the Nuclear Suppliers Group waiver is available at www.ipfmlibrary.org/nsg08.pdf.

58 For an analysis of the U.S.-India deal, see "Fissile Materials in South Asia and the Implications of the U.S.-India Nuclear Deal," *op.cit.*

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

60 For details see Chapter 1, *Global Fissile Material Report 2007, op. cit.*

61 Glenn Kessler, "Message to U.S. Preceded Nuclear Declaration by North Korea," *Washington Post*, 2 July 2008.

62 The U.S. estimate was that North Korea produced 40–50 kg of plutonium, including the amount used in its test, Helene Cooper, "In Disclosure, North Korea Contradicts U.S. Intelligence on Its Plutonium Program," *New York Times*, 31 May 2008. See also David Albright, Paul Brannan, and Jacqueline Shire, *North Korea's Plutonium Declaration: A Starting Point For An Initial Verification Process*, ISIS, 10 January 2008, www.isis-online.org.

63 CNIC, *Rokkasho active tests*, cnic.jp/english/topics/cycle/rokkasho/activetests.html.

64 Masa Takubo, personal communication, 10 August 2008, citing a report in the Japanese newspaper *Too Nippo*, 30 June 2008.

65 Martin Forwood, *The Legacy of Reprocessing in the United Kingdom*, IPFM Research Report No. 5, July 2008, www.ipfmlibrary.org/rr05.pdf.

66 *Ibid*.

67 *NDA Plutonium Options*, Nuclear Decommissioning Authority, August 2008, www.nda.gov.uk, mirrored at www.ipfmlibrary.org/nda08.pdf.

68 Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France*, IPFM Research Report No. 4, April 2008, www.ipfmlibrary.org/rr04.pdf.

69 Mark Hibbs, "CNNC favors remote site for future reprocessing plant," *Nuclear Fuel*, 7 April 2008.

70 Ann MacLachlan, "Areva, China seal long-term mining, fuel cycle pact," *Nuclear Fuel*, 3 December 2007.

71 C. J. Chivers, "Russians to Shut Reactor That Produces Bomb Fuel," New York Times, 20 April 2008, and "Russia ends plutonium production in Seversk," 5 June 2008; Russian Strategic Forces Blog, www.russianforces.org/blog/2008/06/russia_ends_plutonium_producti.shtml.

72 T. B. Cochran, R. S. Norris, and O. A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, 1995, p. 138.

73 Pavel Podvig, "Plutonium from last Russian production reactors," 16 July 2008, www.russianforces.org/nuclear/2008/07/plutonium_from_last_russian_pr.shtml.

74 *Agreement between [the U.S. and Russia] concerning the management and disposition of plutonium designated as no longer required for defense purposes and related cooperation*, "Annex on Quantities, Forms, Locations and Methods of Disposition," 2000, www.ipfmlibrary.org/doe00.pdf.

75 *Plutonium and Highly Enriched Uranium 1996, op. cit.*, p. 63.

76 "Chapelcross Cooling Towers," UK Nuclear Decommissioning Authority, 21 May 2007, www.nda.gov.uk; "Sellafield towers are demolished," *BBC*, 29 September 2007, www.ipfmlibrary.org/bbc07.pdf.

77 Speech by President Nicolas Sarkozy, 21 March 2008, *op. cit.*

Chapter 2. Why an FM(C)T is Important

78 While plutonium-239 and uranium-235 are the only fissile materials known to be used in currently deployed nuclear weapons, the United States has tested weapons designs containing uranium-233 and France may have experimented with neptunium-237 in nuclear tests. Also, U.S. weapons designers have concluded that "designs using americium as a nuclear weapon fuel could be made to work." See "Fissile Materials and Nuclear Weapons," *Global Fissile Material Report 2006*, International Panel on Fissile Materials, Princeton, NJ, September 2006, www.ipfmlibrary.org/gfmr06.pdf, Chapter 1.

79 See "Production and Disposition of Fissile Materials," *GFMR 2006, op. cit.*, Chapter 3.

80 This discussion draws on previous analysis of the importance of an FM(C)T in Frans Berkhout, Oleg Bukharin, Harold Feiveson, and Marvin Miller, "A Cutoff in the Production of Fissile Material," *International Security*, Vol. 19, No. 3, Winter, 1994–1995, pp. 167–202; David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, especially Chapter 15; and William Walker, "The Cutoff Treaty and Excess Stocks," in David Albright, and Kevin O'Neill, eds., *The Challenges of Fissile Material Control*, ISIS, 1999, and comments by Fred McGoldrick.

81 UN General Assembly resolution 48/75L, 1993, www.ipfmlibrary.org/unga4875.pdf.

82 UN General Assembly Resolution 1148, November 1957, www.ipfmlibrary.org/unga1148.pdf.

[83] UN General Assembly resolution 48/75L, *op. cit.* Since the CD operates by consensus, this was taken as a signal for it to begin to organize the negotiation of an FM(C)T.

[84] NPT Review and Conference Final Report 1995.

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

[86] Israel, India, and Pakistan cannot join the NPT as weapons states, since it recognizes as weapons states only those that tested a nuclear explosive device before 1 January 1967.

[87] For details on safeguards in nuclear weapon states, *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf, Chapter 6.

Chapter 3. Design Choices: Scope and Verification

[88] Fissile materials are materials that can sustain a fission chain reaction, in practice, primarily plutonium and highly enriched uranium.

[89] UN General Assembly Resolution 48/75L, 1993, www.ipfmlibrary.org/unga4875.pdf.

[90] *2000 NPT Review Conference Final Document*, "Article VI and Preambular, Paragraphs 8 to 12," 15.3, see e.g. www.armscontrol.org/act/2000_06/docjun.asp.

[91] "United States of America: White Paper on a Fissile Material Cutoff Treaty," U.S. Mission to the United Nations in Geneva, Press Release, 18 May 2006.

[92] In contrast, both the Chemical Weapons Convention and the Comprehensive Nuclear-Test-Ban Treaty have extensive verification provisions in the treaty texts.

[93] For example, one hundred million dollars per year corresponds to 0.004 cents per nuclear kilowatt-hour for the 2,625 billion kilowatt-hours of nuclear electricity produced in 2005 (U.S. Energy Information Administration, www.eia.doe.gov/emeu/international/electricitygeneration.html). That is about one thousandth the generation cost of nuclear electricity. Under the NPT safeguards regime for the non-nuclear weapon states, the nuclear weapon states share the bill. One could argue conversely that the non-weapon states should share in the costs of safeguards in the nuclear weapon states under the FM(C)T because the security of all countries benefits.

[94] See the corresponding definition of "direct use" material in: *IAEA Safeguards Glossary, 2001 Edition,* International Nuclear Verification Series, No. 3, International Atomic Energy Agency, Vienna, 2002, §4.25, www.ipfmlibrary.org/iaeaglossary.pdf.

[95] The weighting is as follows: $F_{235} + (5/3)\ F_{233}$, where F_{235} is the fraction of U-235 atoms in the mix and F_{233} the fraction of U-233 atoms.

[96] *IAEA Safeguards Glossary, op. cit.*

[97] *Ibid.*

[98] The United States carried out a nuclear weapon test on 15 April 1955 (the MET test in the "Teapot" series) using a composite plutonium and uranium-233 core, with a yield of 22 kilotons, see www.nuclearweaponarchive.org. There may have been other tests using uranium-233; T. B. Cochran, W. Arkin, and M. M. Hoenig, *U.S. Nuclear Forces and Capabilities*, Nuclear Weapons Databook, Vol. 1, Ballinger, Cambridge, 1984, p. 23. See also, 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.

[99] See e.g. the curves showing critical masses of U-235/U-238 and U-233/U-238 mixtures as a function of enrichment in Jungmin Kang and Frank von Hippel, "U-232 and the Proliferation-resistance of U-233 in Spent Fuel," *Science & Global Security*, Vol. 9, 2001, Figure 7.

[100] *IAEA Safeguards Glossary, op. cit.*, §4.18 and §4.19.

[101] Although the NPT requires that all NNWS should have a comprehensive Safeguards Agreement, some states with no significant nuclear activities have yet to conclude such an agreement with the IAEA.

[102] After the discovery of Iraq's clandestine nuclear program in 1991, the Additional Protocol (INFCIRC/540) was devised to provide the IAEA more information about nuclear-related activities in non-weapon states and to allow it to verify the correctness and completeness of such information including by the use of environmental sampling at undeclared locations such as swipes of surfaces to detect micron-sized particles of enriched uranium and plutonium. As of 30 May 2008, eighty-four non-nuclear-weapon states (as well as four nuclear-weapon states and Euratom) had an Additional Protocol in force, www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html.

[103] This group consists today of China, India, Israel, France, North Korea, Pakistan, Russia, the United Kingdom, and the United States. North Korea may rejoin the NPT as a NNWS, which would reactivate its Comprehensive Safeguards agreement.

[104] Under a Voluntary-Offer Agreement, a nuclear-weapon state gives the IAEA the opportunity to inspect specified civilian facilities and nuclear materials. These offers are meant to reduce the differences in the safeguards burdens on nuclear and non-nuclear weapon states but, in practice, the IAEA does not have sufficient funds to safeguard more than a few nuclear facilities in the weapon states. For an overview of these agreements, see *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, 2007, pp. 61–81.

[105] Protocol Additional to the Agreement Between the United States of America and the International Atomic Energy Agency for the Application of Safeguards in the United States of America, Article I.c, ratified in 1998 but not yet in force, www.ipfmlibrary.org/gov98.pdf.

[106] 1 Gray or 100 rads per hour at a distance of one meter, see IAEA-document INFCIRC/225, Rev.4, Section 5.2, Footnote b.

[107] "Each Party shall begin consultation with the International Atomic Energy Agency (IAEA) at an early date and undertake all other necessary steps to conclude appropriate agreements with the IAEA to allow it to implement verification measures beginning not later in the disposition process than: (a) when disposition plutonium or disposition plutonium mixed with blend stock is placed into the post-processing storage location of a conversion or conversion/blending facility; or (b) when disposition plutonium is received at a fuel fabrication or an immobilization facility, whichever (a) or (b) occurs first for any given disposition plutonium, *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, Article VII.3.

[108] Most of this work is recorded only in "official-use only" reports. Some of the ideas are reported, however, in Nicholas Zarimpas, ed., *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, SIPRI, Oxford University Press, 2003; and *Monitoring Nuclear Weapons and Nuclear-explosive Materials: An Assessment of Methods and Capabilities*, National Academy Press, Washington, D.C., 2005.

[109] Russia, the United Kingdom and the United States all have large stockpiles of pre-existing HEU that could be used to fuel their naval reactors for decades. India probably does not have such a stockpile for its nuclear-submarine program. Whether China uses LEU or HEU for its naval-reactor fuel is not known.

[110] To date, the United States is the only country that has declared a reserve of excess weapon HEU for future use in naval-reactor fuel.

Chapter 4. Uranium Enrichment Plants

[111] *Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf, Chapter 1. In the United States, production of HEU for weapons ended in 1964, but HEU was also produced for naval reactors to enrichment levels exceeding those used in nuclear weapons (97% versus 93%).

[112] Enrichment levels between 30% and 45% are reported. M. V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security*, Vol. 12, 2004, pp. 115–124.

[113] Information on the Israeli enrichment program is very limited. F. Barnaby, *The Invisible Bomb: The Nuclear Arms Race in the Middle East*, I.B. Tauris, London, 1989, p. 40; and M. Vanunu, Interviews with the author, F. Barnaby, September 1986. According to Vanunu, the enrichment plant started production in 1979–1980. See also, Leonard Spector and Jacqueline Smith, *Nuclear Ambitions*, Westview Press, 1990, p. 161, and Footnote 72, p. 361.

[114] D. Albright, F. Berkhout, and W. Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies*, SIPRI, Oxford University Press, 1997.

[115] "GEH Selects Site for Potential Silex Enrichment Plant," *World Nuclear News*, 1 May 2008, www.world-nuclear-news.org.

[116] *Communication received from the Resident Representative of the Russian Federation to the IAEA on the Establishment, Structure and Operation of the International Uranium Enrichment Centre*, INFCIRC/708, International Atomic Energy Agency, 8 June 2007. According to *World Nuclear News*, the capacity of this new facility could eventually be on the order of 5,000 tSWU/yr, "Enrichment Capacity at Angarsk to be Boosted," www.world-nuclear-news.org, 25 June 2007.

[117] M. Hibbs and Shahid-ur-Rehman, "Pakistan Civilian Fuel Cycle Plan Linked to NSG Trade Exception," *Nuclear Fuel*, 27 August 2007.

[118] For details on Voluntary-Offer Agreements, see *Global Fissile Material Report 2007, op. cit.*, Chapter 6.

[119] J.H. Menzel, ed., "Safeguards Approach for Gas Centrifuge Type Enrichment Plants," *Nuclear Materials Management*, Vol. 12, No. 4, Winter 1983, pp. 30–37; and A. von Baeckmann, Implementation of IAEA Safeguards in Centrifuge Enrichment Plants, Proceedings of the Fourth International Conference on Facility Operations-Safeguards Interface, September 29–October 4, 1991, Albuquerque, New Mexico, pp. 185–190.

[120] Brazil sought to limit the visual access of IAEA inspectors inside the cascade hall because of concerns about what it considers to be a unique centrifuge design, apparently because of its innovative bearings. Eventually, it was agreed that Brazil could conceal parts of the centrifuge under a shroud. For a discussion, see Sharon Squassoni and David Fite, "Brazil as Litmus Test: Resende and Restrictions on Uranium Enrichment," *Arms Control Today*, October 2005.

[121] W. Bush, G. af Ekenstam, J. Janov, E. Kuhn, and M. Ryjinski, "IAEA Experience with Environmental Sampling at Gas Centrifuge Enrichment Plants in the European Union," IAEA-SM-367/10/04, *Proceedings of the Symposium on International Safeguards, Verification and Nuclear Material Security*, 29 October–2 November 2001, Vienna, Austria.

[122] A. Panasyuk et al., *Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges*, IAEA-SM-367/8/02, 2001, www.ipfmlibrary.org/pan01.pdf.

[123] Panasyuk et al., *op. cit.*, 2001.

[124] The production capacity of commercial-scale centrifuge plants envisioned at the time of the Hexapartite Agreement ranged up to about one million SWU/year. The capacities of some existing and proposed new centrifuge facilities are several-fold larger.

[125] This brief discussion of new safeguards approaches and technologies is based on: J.M. Whitaker, *Safeguarding Uranium Enrichment: The Challenge of Large Gas-Centrifuge Facilities*, Presentation at Princeton University, Program on Science and Global Security, 18 October 2007; and J. Cooley, *Model Safeguards Approach for Gas Centrifuge Enrichment Plants*, Presentation at the 3rd IPFM Plenary Meeting in Vienna, Austria, 29 March 2007.

[126] The American Centrifuge is more than 10 meters tall and has a diameter of about 60 cm (compared to 3 meters and 20 cm for typical Urenco machines). The SWU capacity of one machine is on the order of 300 SWU/yr. Construction of the facility began in May 2007, and commercial plant operations are currently scheduled to begin in late 2009. For information and updates, see www.americancentrifuge.com.

[127] For instance, failed Urenco machines are reportedly not replaced or repaired, but are safely deactivated and remain in place. The larger—and per unit more expensive—American Centrifuge instead would undergo maintenance and repair in a dedicated workshop on-site. Associated practices and procedures may or may not require consideration in the safeguards approach to be implemented in the facility.

[128] M. Hibbs and Shahid-ur-Rehman, *op. cit.*

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

[130] For example, a continuous enrichment monitor (CEMO) has been tested and used at the U.K. Capenhurst facility. T.W. Packer, "Continuous Monitoring of Variations in the 235U Enrichment of Uranium in the Header Pipework of Centrifuge Enrichment Plant," *Proceedings of the 13th Annual Symposium on Safeguards and Nuclear Materials Management*, European Safeguards Research and Development Association (ESARDA), 14–16 May 1991, Avignon, France, pp. 371–376; M. R. Wormald, T. W. Packer, and C. Charlier, "Review of the Current Status of CEMO," IAEA-SM-351/169, *Symposium on International Safeguards*, 13–17 October 1997, Vienna, Austria.

[131] These numbers are partially based on: 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.

[132] Personal communication, IAEA official, August 2007. Similar, but somewhat lower numbers are also given in Dougherty et al., *op. cit.*

[133] An estimated $2000 are usually quoted for the costs of one person-day of inspection (PDI). This number does, however, not include the administrative "overhead" or other costs associated with safeguards, including equipment, training, etc. The higher value of $10,000 is obtained by dividing the total annual IAEA safeguards budget (about $100 million per year) by the number of PDI (about 10,000 per year).

[134] D. Horner, "USEC now says American Centrifuge Plant will cost about $3.5 billion," *Nuclear Fuel*, 10 March 2008.

[135] Such activities could include reconnecting cascades or undeclared feed or withdrawal of UF_6 inside the cascade hall.

[136] This includes remote locations, infrequent flights, delays at borders, etc.

[137] For example, annual physical inventory verification and routine inspections to verify the flows and inventories declared by the operator are designed to detect or deter the diversion of declared (low-enriched) material from the plant. Surveillance of feed-and-withdrawal areas, plus measures giving confidence in the absence of undeclared feed-and-withdrawal stations, can be used to address the scenario of excess LEU production using undeclared feed.

[138] In fact, this is done in any enrichment plant to be covered by safeguards; see Bush et al., *op. cit.*, 2001.

[139] J. Cooley et al., "Experience with Environmental Swipe Sampling in a Newly Built Gas Centrifuge Plant," *Proceedings of the 40th INMM Annual Meeting*, July 25–29, Phoenix, Arizona, 1999.

[140] Bush et al., *op. cit.*

[141] For example, a continuous enrichment monitor (CEMO) has been tested and used at the U.K. Capenhurst and the Dutch Almelo facilities since the 1990s; M. R. Wormald, T. W. Packer, and C. Charlier, *op. cit.*

[142] *IAEA Annual Report 2006*, GC(51)/5, International Atomic Energy Agency, Vienna, 2007, p. 68.

[143] This Appendix is based on A. Glaser and S. Bürger, *forthcoming*.

[144] For a general discussion of the principles and methods, see "Chronometry" and "Techniques for Small Signatures," Chapters 5 and 6 in K. J. Moody, I. D. Hutcheon, and P. M. Grant, *Nuclear Forensic Analysis*, Taylor & Francis, Boca Raton, 2005.

[145] M. Wallenius, A. Morgenstern, A. Nicholl, R. Fiedler, C. Apostolidis, and K. Mayer, *Age Determination of Highly Enriched Uranium*, IAEA-SM-367/5/07, 2001.

[146] The most important particle analysis techniques are *Fission Track* (FT) analysis and *Secondary Ion Mass Spectroscopy* (SIMS).

[147] C. Grüning et al., "Resonance Ionization Mass Spectrometry for Ultratrace Analysis of Plutonium With a New Solid State Laser System," *International Journal of Mass Spectrometry*, 235, 2004, pp. 171–178.

[148] J.B. Truscott et al., "Determination of Actinide Elements at Femtogram per Gram Levels in Environmental Samples by On-line Solid Phase Extraction and Sector-Field-Inductively Coupled Plasma-Mass Spectrometry," *Analytica Chimica Acta*, 433, 2001, pp. 245–253.

[149] S. Bürger et al., "A High Efficiency Cavity Ion Source Using TIMS for Nuclear Forensic Analysis," *Journal of Alloys and Compounds*, 444–445, 2007, pp. 660–662.

[150] One attogram is one billionth of a billionth gram (10^{-18} g).

[151] S. Bürger et al., "Isotope Ratio Analysis of Actinides, Fission Products, and Geolocators by High-Efficiency Multi-Collector Thermal Ionization Mass Spectroscopy," *forthcoming*.

Chapter 5. Reprocessing Plants

[152] It is assumed that the Yongbyon reprocessing plant in the Democratic People's Republic of Korea will have been fully decommissioned before an FM(C)T comes into force.

[153] The IAEA spent $92 million directly on safeguards in 2006. Including a 35-percent overhead for its share of Information and Support Services and Policy and General Management would bring the total to $124 million; *IAEA Annual Report 2006*, International Atomic Energy Agency, Vienna, 2007, Table A1.

[154] 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.

[155] *IAEA Safeguards Criteria*, Issued 1 January 2004.

[156] *IAEA Safeguards Glossary, 2001 Edition*, International Nuclear Verification Series, No. 3, International Atomic Energy Agency, Vienna, 2002, Table II, p. 23, www.ipfmlibrary.org/iaeaglossary.pdf.

[157] *IAEA Safeguards Criteria, op. cit.*

[158] *Global Fissile Materials Report 2006*, International Panel on Fissile Materials, Princeton, NJ, September 2006, www.ipfmlibrary.org/gfmr06.pdf, Table 3.3, corrected.

[159] Ralph G. Gutmacher, *Measurement Uncertainty Estimates for Reprocessing Facilities*, Los Alamos National Laboratory, LA-11839-MS (ISPO-315), October 1990; and *International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials*, IAEA STR-327, 2001.

[160] Tariq Rauf, "A Cutoff of Production of Weapons Usable Fissionable Material: Considerations, Requirements and IAEA Capabilities," Conference on Disarmament, Geneva, 24 August 2006, www.ipfmlibrary.org/rau06.pdf.

[161] S. Johnson and A. Islam, "Current IAEA Approach to Implementation of Safeguards in Reprocessing Plants", *Proceedings of the Fourth International Conference on Facility Operations—Safeguards Interface*, October 1991; S. J. Johnson, R. Abedin-Zadeh, C. Pearsall, et al., "Development of the Safeguards Approach for the Rokkasho Reprocessing Plant," *IAEA Symposium on International Safeguards*, Vienna, Austria, 1997.

[162] M. Ehinger, B. Chesnay, C. Creusot, J. Damico, et al., "Solution Monitoring Applications for the Rokkasho Reprocessing Plant", *7th International Conference on Facility Operations-Safeguards Interface*, Charleston, SC, 2004.

[163] www.world-nuclear.org/education/graphics/storpondthorp.gif, 5 June 2008.

[164] Figure adapted from *Management and Disposition of Excess Weapons Plutonium*, National Academy of Sciences, Washington, D.C., 1994, p. 155. This figure was redrawn for the National Academy report from a 1993 U.S. DOE study.

[165] K. Whitehouse, E. Carr, D. Sim, G. Morris, and K. Tolk, "PIMS for Safeguards Measurements at Rokkasho Reprocessing Plant", *7th International Conference on Facility Operations-Safeguards Interface*, Charleston, SC, 2004.

[166] Development work is currently underway to improve on this measurement in support of the construction of the JMOX Fabrication Plant in Japan.

[167] Y. Abushady, "Short Notice Random Inspection (SNRI) Regime at a Uranium Fuel Fabrication Plant in Spain," and T. Ishikawa, "Implementation of SNRI and Borrowing Inspection in Japan", *IAEA Symposium on International Safeguards*, Vienna, 16–19 October 2006.

[168] Thomas Shea et al., "Safeguarding Reprocessing Plants: Principles, Past Experience, Current Practice and Future Trends," *Journal of the Institute of Nuclear Materials Management*, Vol. 21, Issue 4, 1993; Fred Franssen, Shirley Johnson, and Thomas Shea, "Planning for Design Information Verification at the Rokkasho Reprocessing Plant", *Proceedings of the 35th Annual INMM Meeting*, July 1994; J. G. M. Goncalves, V. Sequeira, B. Chesnay, C. Creusot, et al., "Verification of Plant Design: Instruments and Methods", *Proceedings of the 44th Annual INMM Meeting*, Phoenix, AZ, 2003; and B. Chesnay, C. Creusot, S. Johnson, et al., "Innovative Approaches to DIE/DIV Activities at the RRP", *7th International Conference on Facility Operations-Safeguards Interface*, Charleston, SC, 2004.

[169] Y. Abushady, 2006, *op. cit.*, and T. Ishikawa, 2006, *op. cit.*

[170] J. Wuester, B. Chesnay, G. Gerrein, et al., "Automating the Operator Interface—Operator Declarations at RRP," *7th International Conference on Facility Operations-Safeguards Interface*, Charleston, SC, 2004.

[171] The samples could be subject to on-site measurements using non-destructive techniques for nuclear material content, ratios of selected isotopes or characteristics of process chemicals. A very small number of samples could be periodically sent for destructive analyses at the IAEA Safeguards Analytical Laboratory in Austria.

[172] Although most civilian reprocessing plants recover plutonium from low-enriched-uranium spent fuel, some military reprocessing plants recover HEU as well from naval, production and research-reactor fuel.

[173] Some verification of uranium would be required, however, because verification of the Pu/U ratios at selected points within the process is essential to understanding the operations of the facility.

[174] J. Wuester et al., 2004, *op. cit.*

[175] Ralph G. Gutmacher, "Measurement Uncertainty Estimates for Reprocessing Facilities," Los Alamos National Laboratory, LA-11839-MS (ISPO-315), October 1990.

[176] Installation costs are very dependent on the state.

[177] The data collection and evaluation system would still remain a major expense, however—more than half the initial investment by the IAEA.

[178] G. Duhamel, E. Kuhn, P. Zahradnik-Gueizelar, Y. Kuno, et al., "Establishing the Joint IAEA/JSGO/NMCC Safeguards On Site Laboratory for the Rokkasho Reprocessing Plant: a major challenge for managing the interfaces," *7th International Conference on Facility Operations-Safeguards Interface, Charleston*, SC, 2004.

[179] Our estimates do not take into account the effort required for the initial setting up and testing of safeguards equipment and procedures. Also, the travel time required to implement short-notice random inspections (SNRIs) in some States may affect the number of required PDIs per inspection. The $2000/PDI used in Table 5.2 is an incremental number. Dividing the total IAEA Safeguards budget by the number of PDIs per year would yield a number closer to $10,000/PDI.

[180] Two plutonium-production reactors in Seversk shut down in the summer of 2008, and Russia's remaining plutonium production reactor at Zheleznogorsk is to shut down in 2011, U.S. Department of Energy, *Fiscal Year 2009 Budget Request*, Vol. 1, National Nuclear Security Administration, February 2008, p. 509.

[181] Reportedly, the RT-1 plant has three separate spent-fuel dissolution lines for: 1) Low-enriched (3–4% enriched) uranium from Russia's first-generation VVER-440 light-water reactors; 2) Medium (17–26 percent) enriched uranium fuel from Russia's BN-600 demonstration breeder reactor; and 3) Ninety-percent-enriched uranium fuel from two isotope-production reactors at Mayak and HEU fuel from naval and research reactor fuels with a variety enrichments. For RT-1 reprocessing lines, T. B. Cochran, R. S. Norris and O. A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview, 1995, p. 84; and Anatoli Diakov, personal communication, 15 April 2008. For BN-600 fuel enrichment, O.M. Saraev, "Operating experience with Beloyarsk fast reactor BN600 [Nuclear Power Plant], *Technical committee meeting on unusual occurrences during LMFR operation*, IAEA-TECDOC-1180, 1998, p. 103. For enrichment of Russian isotope-reactor fuel, Oleg Bukharin, "The Size and Quality of Uranium Inventories in Russia," *Science & Global Security 6*, 1996, p. 59. For enrichment of Russian naval-reactor fuel, Chunyan Ma and Frank von Hippel, "Ending the production of highly enriched uranium for naval reactors," *Nonproliferation Review*, Vol. 8, 2001, p. 86. Russia's research reactors are fueled primarily by 90-percent or 36-percent enriched uranium, *Nuclear Research Reactors of the World*, International Atomic Energy Agency, Vienna, 2000.

[182] France, the United Kingdom and the United States all store their spent naval-reactor fuel, Ashot Sarkisov and Alain Tournyol du Clos, eds., *Scientific and Technical Issues in the Management of Spent Fuel of Decommissioned Nuclear Submarines*, NATO Science Series, Vol. 215, Springer, 2006. The United States produces its tritium in power reactors. France has been producing its tritium in its *Celestin* production reactors whose spent fuel is currently stored but may eventually be reprocessed at La Hague, Mycle Schneider, personal communication of information obtained from AREVA, 21 May 2008. Israel may be producing tritium at Dimona. The United Kingdom shut down its Chapel Cross power reactors, which also produced its tritium, in 2004. It is not known what arrangements the United Kingdom has made for its future tritium supply. One possible source is the United States.

[183] The production for use in nuclear weapons of tritium, an isotope with a half-life of 12.3 years, would not be banned by the FM(C)T because tritium is not a fissile material.

[184] There might be limits on the flexibility for mixing different types of fuel, depending on their dissolution characteristics.

[185] Permanently installed vessel calibration systems for convenience and reproducibility; remote viewing capabilities into strategic cells for design verification; improved mixing, sampling and calibration capabilities in accountancy vessels; improved transparency and authentication for sampling systems; installation of accountancy systems that allow operators to declare inventories for any location in the facility at any time in order to accommodate short-notice or no-notice inspections; minimization of recycling of plutonium solutions and powders and improved transparency of the recycling that does occur (such recycling can create uncertainty for the interpretation of plutonium flow measurements and provides an opportunity for the same material to be declared more than once); well-defined waste handling and treatment areas to simplify accountancy and tracing of waste sources; independent measurement and monitoring systems for the inspectors, whenever possible and reasonable; and easier access to safeguards-relevant operating information.

Chapter 6. Weapon-origin Fissile Material: The Trilateral Initiative

[186] The nuclear weapon states consider secret or "classified" the quantities, composition and form, of fissile material contained in nuclear warheads and their components, such as pits and secondaries. A pit is the fissile material core (usually plutonium) in the first fission stage of a nuclear weapon. A secondary can contain highly enriched uranium and thermonuclear fuel and accounts for most of the energy release from a modern two-stage nuclear weapon.

[187] For details, see *Global Fissile Material Report 2006*, International Panel on Fissile Materials, Princeton, NJ, September 2006, Chapter 2, and *Global Fissile Material Report 2007*, October 2007, Chapters 1–3.

[188] An annual General Conference of all 139 IAEA Member States meets in September of each year. Political direction of the IAEA is by a Board of Governors representing 35 Member States, which meets five times each year.

[189] For example, the Working Group proceeded on the basis that a removal on the order of 1% of the monitored inventory at any time could portend a strategic change. While never formally adopted, the one-percent figure served as the *de facto* reference for determining sample plan sizes for verification and re-verification.

[190] Thomas E. Shea, "Potential Roles for the IAEA in a nuclear weapons dismantlement and fissile materials transparency regime", in Nicholas Zarimpas, ed., *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, SIPRI, Oxford University Press, 2003, pp. 229–249.

[191] *Arms Control and Nonproliferation Technologies: Technology R&D for Arms Control*, U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Spring 2001, www.ipfmlibrary.org/doe01b.pdf, p. 34.

[192] Frank von Hippel and Roald Z. Sagdeev, eds., *Reversing the Arms Race*, Gordon and Breach Science Publishers, 1990, pp. 266, 269.

[193] The IAEA uses unique tags to identify safeguarded items. Seals are tamper-indicating devices used to assure that container cannot be opened or tag removed without detection.

[194] Plutonium from low-burnup (33-megawatt-day/kgU) light-water-reactor plutonium contains 60% ^{239}Pu and 24% ^{240}Pu, J. Carson Mark, "Explosive Properties of Reactor-grade Plutonium," *Science & Global Security*, Vol. 4, 1993, p. 111.

[195] *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.

[196] For subsequent developments, see *Global Fissile Material Report 2007, op. cit.*, Chapter 3.

[197] UK Prime Minister Tony Blair, Parliamentary Statement on Trident, 4 December 2006: "We have decided, on expert advice, that we can reduce our stockpile of operationally available warheads to no more than 160, which represents a further 20 percent reduction. Compared with previous plans, we will have reduced the number of such weapons by nearly half." French President, Nicolas Sarkozy, speech at launch of ballistic-missile submarine, *Le Terrible*, at Cherbourg, 21 March 2008: "With respect to the airborne component, the number of nuclear weapons, missiles and aircraft will be reduced by one-third. After this reduction, I can tell you that our arsenal will include fewer than 300 nuclear warheads. That is half of the maximum number of warheads we had during the Cold War." The full text is available at: www.ipfmlibrary.org/sar08.pdf.

Chapter 7. HEU in the Naval-reactor Fuel Cycle

[198] Data adapted and updated from C. Ma and F. von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Vol. 8, 2001, pp. 86–101.

[199] On the French transition to LEU, see C. Fribourg, "La Propulsion Nucléaire Navale," *Revue Générale Nucléaire*, March/April 1999, pp. 32–52. The 86 U.S. nuclear ships and submarines accommodate a total of 103 reactors, U.S. data from "2008 Owner's & Operator's Manual," *All Hands Magazine*, No. 1089, U.S. Department of Defense, Department of the Navy, Naval Media Center, 2008.

[200] India leased a nuclear submarine from Russia during 1988–91 and this is presumed to be the model for the Indian submarine. India's submarine is believed to have an 80MWt reactor, fueled with 30–40% enriched HEU. For details on the submarine project and the uranium enrichment program's capacity to provide the required HEU fuel, see M. V. Ramana, "An Estimate of India's Uranium Enrichment Capacity," *Science & Global Security*, Vol. 12, 1–2, 2004, pp. 115–124. The recent expansion of the enrichment program is discussed in David Albright and Susan Basu, *India's Gas Centrifuge*

Enrichment Program: Growing Capacity for Military Purposes, Institute for Science and International Security, 18 January 2007. The status of India's first nuclear submarine program and its plans to deploy a fleet of three nuclear powered ballistic missile submarines by 2015 are described in Sandeep Unithan, "The Secret Undersea Weapon," *India Today*, 28 January 2008, pp. 52–55.

201 Germany and Japan operated civilian nuclear-powered ships, the *Otto Hahn* and the *Mutsu*. These programs would not have qualified for an exemption from safeguards as envisioned in Paragraph 14 of INFCIRC/153c. In any case, they were abandoned due to economic non-viability or technical problems. Canada considered the acquisition of nuclear-powered submarines in the late 1980s.

202 N. Polmar and K. J. Moore, "U.S. Nuclear-Propelled Submarines," Chapter 4 in *Cold War Submarines*, Brassey's, Inc., Washington D.C, 2004.

203 "Fourth Generation Nuclear Submarines," Chapter 19 in Polmar and Moore, *op. cit.* The length is 115 m and the diameter is about 10 meters and the displacement 7800 tons.

204 T. Stefanick, "The Design of Submarines," Appendix 1 in *Strategic Antisubmarine Warfare and Naval Strategy*, Lexington Books, Lexington, MA, 1987.

205 30–40 knots correspond to roughly 55–75 kilometers (or 35–45 miles) per hour.

206 One shaft horsepower corresponds to 746 watts; as mentioned, even at peak reactor output, only a fraction of about 20% of the total reactor power is delivered to the shaft. The remainder is either lost to thermal-to-electric energy conversion or used for other purposes. See Stefanick, *op. cit.,* p. 143, for coefficient.

207 About 1.25 grams of U-235 in HEU are consumed daily per thermal megawatt.

208 Assuming 45-year lives for the ballistic-missile submarine and aircraft carrier cores and 40,000, 60,000 and 2 x 140,000 shaft horsepower for the attack submarine, ballistic-missile submarine and aircraft carrier, respectively, Director, Naval Nuclear Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion*, June 1995, www.ipfmlibrary.org/onnp95.pdf. All but one of the U.S. nuclear-powered aircraft carriers have two nuclear propulsion reactors. See also the estimates in Ole Reistad and Styrkaar Hustveit, "HEU Fuel Cycle Inventories and Progress in Global Minimization, *Nonproliferation Review*, Vol. 15, No. 2, July 2008, Figure B. Reistad and Hustveit used actual core lives. The first refueling of the *Nimitz*, which was launched in 1967, occurred in 1998, www.fas.org/man/dod-101/sys/ship/cvn-68.htm. The U.S. *Trident* ballistic-missile submarines are refueled at 20 years.

209 Ten *Nimitz*-class aircraft carriers with two reactors each and the *Enterprise*, with eight reactors; 18 *Ohio*-class ballistic-missile (12) and cruise-missile (4) submarines with one reactor each; 4 *Virginia*-class, 3 *Seawolf*-class and 46 *Los Angeles*-class submarines, all with one reactor each, www.navy.mil/navydata/fact.asp.

210 The 2001 *Striking a Balance* report noted that, as of 1996, the "majority of HEU assigned to the Naval Nuclear Propulsion Program is already in or has been used in naval reactor cores. The remainder will be fabricated into fuel in the near future," *Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996*, Draft, Rev. 1., U.S. Department of Energy, January 2001 (publicly released in 2006), www.ipfmlibrary.org/doe01.pdf, p. 39.

211 The Moscow (SORT) Treaty requires a limits the number of *operationally deployed* strategic nuclear warheads to 1700–2200. The SORT Treaty does not limit the number of non-deployed warheads in active reserve (responsive force) or inactive reserve.

212 The United States might well do so. Aside from 20 tons reserved for research and space reactors and 32 tons rejected by the U.S. Navy as not up to its specifications, the Unites States has so far moved all its excess weapon-grade uranium into a naval reserve.

213 *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion, op. cit.*, pp. 2 and 3.

214 *Striking a Balance, op. cit.*, Figure 2-2 (p. 27) and pp. 51 and 53.

[215] In fact, the U.S. Navy is developing a Next Generation Core (NGR-93) that will use 93-percent enriched HEU. See *FY 2008 Congressional Budget Request*, U.S. DOE, DOE/CF-014, Vol. 1, February 2007, p. 540, www.ipfmlibrary.org/doe07.pdf.

[216] *Highly Enriched Uranium: Striking a Balance*, p. 51.

[217] For example, the *Los Angeles* attack submarine (SSN 688) was launched in 1974 and refueled during 1992–95; the *Nimitz* aircraft carrier was commissioned in 1975 and was refueled during 1997–2001; the *Michigan*, the second *Ohio*-class ballistic-missile submarine was commissioned in 1982 and went in for refueling in 2004. This information is compiled on U.S. Navy websites, e.g. www.csp.navy.mil.

[218] Reportedly, U.S. fuel designs are—or were—based on UO_2-particles dispersed in a zircaloy matrix (Cermet fuel), see G.L. Hofman and J. L. Snelgrove, "Dispersion Fuels." Chapter 2 of Volume 10 A (Nuclear Materials, Part 1, edited by B.R.T. Frost) in R.W. Cahn, P. Haasen, and E.J. Kramer, eds.: *Materials Science and Technology,* VCH Verlagsgesellschaft mbH, Weinheim, Germany, 1994. France has used plate-type fuels, in which a large number of uranium-dioxide pastilles are arranged in a arranged in a rectangular pattern, separated by a spacer grid (Caramel fuel), see: J.P. Schwartz, "Uranium Dioxide Caramel Fuel—An Alternative Fuel Cycle for Research and Test Reactors." Communication presented at the International Conference on Nuclear Non-Proliferation and Safeguards. Atomic Industrial Forum, New York, 22–25 October 1978. Russian fuel designers apparently preferred pin-type fuels with twisted cruciform-shaped rods, which maximize both stability and surface-to-volume ratio, see: A.C. Diakov et al., *Science & Global Security*, Vol. 14, 2006, pp. 33–48.

[219] See Appendix for the full text of Paragraph 14 of INFCIRC/153c.

[220] For an overview and discussion, see S. Diehl and E. Fujii, "Brazil's Pursuit of a Nuclear Submarine Raises Proliferation Concerns," *WMD Insights*, March 2008, www.wmdinsights.com.

[221] Diehl and Fujii, *op. cit.*

[222] Online at www.flickr.com/photos/campuspartybr/2269565979/

[223] Professor José Goldemberg, University of São Paolo, Brazil, personal communication, January 2008.

[224] The excess HEU in the monitored stockpile could also include material to be blended down to LEU.

[225] Alternatively, or in addition to that, a perimeter control system at the fuel fabrication facility could guarantee that only the material released from monitored storage enters the plant. Manning a permanent perimeter-control system would be costly, however, and could be seen as unacceptably intrusive.

[226] A. Sarkisov and A. Tournyol du Clos, eds., *Scientific and Technical Issues in the Management of Spent Fuel of Decommissioned Nuclear Submarines*, NATO Science Series, Springer, Netherlands, 2006.

[227] In a deuterium-tritium source, a deuterium (D) or tritium (T) nucleus is accelerated into a tritium or deuterium target producing helium-4 and a neutron. The neutron carries off most of the energy (14 million electron Volts, MeV). The recoil of the helium nucleus in the direction opposite to the neutron can be detected and used to determine the time the neutron was created and its direction.

[228] For an excellent overview, see *Arms Control and Nonproliferation Technologies: Technology R&D for Arms Control*, U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Spring 2001, www.ipfmlibrary.org/doe01b.pdf.

[229] Besides nuclear materials, NMIS is designed to detect high explosives, chemical agents, and drugs. More recently, tomographic imaging capabilities have been added to the system. J.A. Mullens, P.A. Hausladen, D.E. Archer, M.C. Wright, and J.T. Mihalczo, *NMIS with Imaging and Gamma Ray Spectroscopy for Pu, HEU, HE, Chemical Agents, and Drugs*, ORNL/TM-2006/76R1, Oak Ridge National Laboratory, July 2007.

[230] B.R. Grogan, J.T. Mihalczo, and J.A. Mullens, "MCNP-PoliMi Simulation of Neutron Radiography Measurements for Mass Determination for a Trough of UO_3," *Journal of Nuclear Materials Management*, Volume XXXVI, No. 1, 2007, pp. 26–32.

[231] *Ibid*.

[232] J.T. Mihalczo, "Radiation Detection for Active Interrogation of HEU", ORNL report: ORNL/TM-2004/302, 2004.

[233] J.A. Mullens *et al*, "Fast coincidence counting with active inspection systems", *Nuclear Instrumentation and Methods*, B 241, 2005, pp. 804–809.

[234] At the time that this chapter went to press, the authors had not completed their computer simulations of the performance of such setups for determining the total amount and enrichment of uranium in simulated naval-reactor cores. The results will therefore be reported separately.

Chapter 8. Challenge Inspections at Military Nuclear Sites

[235] A few non-weapon states that are members of NATO (Belgium, Germany, Italy, the Netherlands, Turkey) have U.S. nuclear bombs located at one or two (Italy) of their air bases, Hans Kristensen, "United States Removes Nuclear Weapons From German Base, Documents Indicate," 9 July 2007, www.fas.org/blog/ssp/2007/07/united_states_removes_nuclear.php.

[236] See the discussion of special inspections in *The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, IAEA, INFCIRC/153 (corrected), June 1972, §73 and §77. See also the discussion of Complementary Access, *Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application of Safeguards* INFCIRC/540 (corrected) September 1997, Articles 4–9.

[237] *See Global Fissile Material Report 2007*, International Panel on Fissile Materials, Princeton, NJ, October 2007, Chapter 6.

[238] *Protocol Additional to the Agreement Between the United States of America and the International Atomic Energy Agency for the Application of Safeguards in the United States of America*, www.ipfmlibrary.org/gov98.pdf. The Article-by-Article analysis submitted with the Protocol to the Senate on 9 May 2002 may be found on the U.S. State Department website at www.state.gov/t/isn/trty/11757.htm.

[239] Senate ratification occurred on 31 March 2004 as Title II of the Hyde Act (H.R. 5682).

[240] Executive Order on "Implementation of the Protocol Additional Between the United States and the International Atomic Energy Agency for the Application of Safeguards in the United States of America," 4 February 2008, www.whitehouse.gov/news/releases/2008/02/20080205.html.

[241] *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, Reports of the Director General to the IAEA Board of Governors, 26 August 2003, §6 and §7; and 28 April 2006, §23; and 10 November 2003, Annex 1, §21.

[242] Protocol Additional to the Agreement Between the United States of America and the International Atomic Energy Agency for the Application of Safeguards in the United States of America. Senate ratification occurred on 31 March 2004 as Title II of the Hyde Act (H.R. 5682). The U.S. Government has not deposited the ratified protocol with the IAEA and therefore not yet brought it into force because it is still working on the implementing regulations.

[243] The United States has already volunteered 245 civilian nuclear-related sites for traditional IAEA inspections: 210 Nuclear Regulatory Commission licensed and 35 Department of Energy sites, Congressional Budget Office, *The Cost of Implementing the Additional Protocol to the Treaty on the Non-Proliferation of Nuclear Weapons*, 5 March 2004, www.cbo.gov/ftpdoc.cfm?index=5160&type=0.

[244] Bruce W. Moran, "The U.S. Nuclear Regulatory Commission's Preparations for Implementing the Additional Protocol," *Proceedings of the 48th INMM Annual Meeting*, 8–12 July 2007, Tucson, Arizona.

[245] "Written Testimony of Linton Brooks, Administrator for National Nuclear Security Administration, before the Senate Foreign Relations Committee, 29 January 2004, www.ipfmlibrary.org/bro04.pdf; Department of Energy, FY 2008 Congressional Budget Request, Vol. 1, p. 464; and interview with DOE official, 31 January 2008.

246 Congressional Budget Office *Cost of Implementing the Additional Protocol*, Table 1.

247 *Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction*, available at www.opcw.org.

248 An OPCW *Handbook of Inspection Operations* goes into still further detail.

249 The full list of equipment originally authorized may be found in Decision 71 of the First Session of States Parties, 23 May 1997, C-I/DEC.71 on the OPCW website. A supplementary list was issued by the Director General on 12 June 2007, www.opcw.org/docs/snotes/2007/s-644-2007(e).pdf. A GCMS involves two stages of separation of chemical species. In the first stage, a volatilized material is injected into a heated packed tube in which the different components of the gas travel at different speeds, depending upon their affinity to the packing material. The separated bunches of molecules that exit the tube are then broken down into ions by electron bombardment. The ions are then separated out in the mass spectrometer according to their mass/charge ratio. The combination of transit time in the gas chromatograph and mass spectrum of ionization products can usually be used to identify a chemical.

250 Personal communication, Rick D'Andrea, Deputy Office Director, Chemical and Biological Weapons Threat Reduction Office, 14 December 2007. Information about the Automated Mass Spectral Deconvolution & Identification System developed by the U.S. Government and examples of GCMS data can be found at chemdata.nist.gov/mass-spc/amdis/explain.html.

251 Personal communication, Rick D'Andrea, 14 December 2007.

252 Personal communication, Rick D'Andrea, 14 December 2007.

253 T.R. England and B.F. Rider, *Fission Product Yields per 100 Fissions for* ^{235}*U Thermal Neutron Induced Fission Decay*, LA-UR-94-3106, 1994, available at ie.lbl.gov/fission/235ut.txt.

254 A rate of separation of 6 kg of plutonium (the amount in the Nagasaki bomb) per year would release 10^{15} atoms of Kr-85 per second. About one kilogram of U-235 is fissioned for each kg of plutonium produced in a production reactor. The background level of krypton-85 in the atmosphere—mostly due to past reprocessing—is about $7x10^7$ atoms/m^3 (1.5 Bq/m^3). If the krypton-85 were released into a wind of 5 meters/second (18 km/hr), the average plume concentration would still be ten times background when the plume cross-section had grown to 500 meters high by 800 meters wide. This typically does not happen until about ten kilometers downwind. D. Bruce Turner, *Atmospheric Dispersion Estimates, 2nd edition*, CRC Press, 1994, Figures 2.3 and 2.4. For additional data, analysis and references, see *Global Fissile Material Report 2007, op. cit.*, Chapter 9 ("Detection of Clandestine Fissile Material Production").

255 Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France*, International Panel on Fissile Materials Research Report No. 4, May 2008, www.ipfmlibrary.org/rr04.pdf, Appendix C.

256 This description is drawn in part from the Model Additional Protocol INFCIRC/540.

257 See e.g. *Handbook for Notification of Exports to Iraq: Annex 3*, Chapter 9 ("Plants and Equipment for the Reprocessing of Irradiated Fuel Elements"), U.S. Department of Energy, Washington, D.C., 1998, www.iraqwatch.org/government/US/DOE/DOE-Annex3.htm, p. 5. The walls of the hot cells of the Korean Atomic Energy Research Institute Irradiated Materials Examination Facility range from 0.8 to 1.2 m of heavy concrete. One cell has walls of 0.2 m of lead. See ehome.kaeri.re.kr/nfcf/imef/english/default.asp.

258 See e.g. www.ndtsystems.com/Thickness_Gauges/thickness_gauges.html.

259 See e.g. members.cox.net/ylosk/private/Radex/index.htm.

260 Plutonium emits little gamma radiation.

261 To produce weapon-grade plutonium containing 94 percent Pu-239, the amount of fission, measured in megawatt-days per metric ton of uranium (MWd/tU) and the amount of plutonium produced in kilograms plutonium per ton of uranium (kgPu/tonU) is: natural-uranium fueled graphite moderated reactors (700 MWd/tU, 0.75 kgPu/tonU), natural-uranium fueled, heavy-water moderated reac-

tors (1200 MWd/tU, 1.1 kgPu/tonU), low-enriched-uranium fueled, boiling water reactors (4,000 MWd/tU, 2.6 kgPu/tonU), and pressurized water reactors (2800 MWd/tU, 1.6 kgPu/tonU), *Heavy-element Concentrations in Power Reactors*, NUS Corp, SND-120-2, 1977.

262 For each gram of plutonium produced in a production reactor about one gram of U-235 will have fissioned, releasing about one Megawatt-day of heat. For a reactor that has operated a length of time T_0 at a thermal power level of P_0, the decay heat generation rate from fission products a time t after shutdown (in seconds) is about $P(t) \approx 0.0065\ P_0\ [(t - T_0)^{-0.2} - t^{-0.2}]$, M. Ragheb, "Decay Heat Generation in Fission," University of Illinois, Urbana-Champaign. For a graphite-moderated reactor with a power of 3 Megawatts/ton and $T_0 = 1$ year, the irradiated fuel will contain about 1 kilogram of plutonium per ton of uranium and the decay heat power level at one year would be about 0.6 Watts/kg. About two thirds of the decay energy of fission products is from gamma rays with an average energy of 0.7 MeV (M. Ragheb, *op. cit.*). Neglecting "self-absorption" in the uranium, the average flux of gamma energy at a distance of a meter from a kilogram of the uranium would be about 0.017 joules/cm^2 per hour. Gamma rays with an energy of 0.7 MeV have a mean penetration distance of 10 cm in tissue. The deposition of gamma energy will therefore be about 1 joule/hour per kilogram of tissue or one Sievert/hour. This is about a ten million times gamma background, *Sources and Effects of Ionizing Radiation*, UN Scientific Committee on the Effects of Atomic Radiation, United Nations, Vol. 1, 2000, p. 91. About 30 cm thickness of iron would be required to reduce this dose rate to one hundred times background. Massive casks therefore are needed to transport irradiated fuel to a reprocessing plant and equipment is needed to move these casks around and unload them.

263 In modern reprocessing plants, after a period of months to years, it is mixed with molten glass, which then cools and becomes a storable solid.

264 "Evidence of Camouflaging Suspect Sites," Chapter 5 in David Albright and Kevin O'Neill, eds., *Solving the North Korean Nuclear Puzzle*, ISIS Press, 2000.

265 Such characteristics for vessels holding plutonium-nitrate solutions are described in the Additional Protocol, INFCIRC/540, Section 3.4.

266 This facility was used in South Korea's research on the DUPIC fuel treatment process in which irradiated light-water reactor ceramic fuel pellets were removed from their cladding, converted into a powder and then re-fabricated into fuel for heavy-water reactors in hot cells M6a and M6b, see ehome.kaeri.re.kr/nfcf/rwfef/english/default.asp.

267 *Global Fissile Material Report 2007, op. cit.*, Chapter 9.

268 R. Scott Kemp, "Initial Analysis of the Detectability of UO_2F_2 Aerosols Produced by UF_6 Released from Uranium Conversion Plants," *Science & Global Security*, Vol. 16, No. 3, 2008, to be published.

269 B. Habib, "Estimation of the Electromagnetic Radiation Emitted from a Small Centrifuge Plant," *Science & Global Security*, Vol. 15, 2007, p. 15.

270 Used in a presentation by Mohammad Saeidi at the 2005 Annual Symposium of the World Nuclear Association, www.world-nuclear.org/sym/2005/sym05prg.htm.

271 See further: *Laser-induced Breakdown Spectroscopy: Optical Sensing Technology for Rapid On-site Chemical Analysis*, Industrialized Materials Institute, National Research Council of Canada, 13 March 2002. One application to soil showed reasonable quantitative measurements of trace elements such as nickel at 10 ppm, R. Barbini et al., "Laser induced breakdown spectroscopy for semi-quantitative elemental analysis in soils and marine sediments," *Proceedings of EARSeL-SIG Workshop LIDAR*, Dresden, Germany, June 16–17, 2000. We would like to thank David Donohue and Julian Whichello of the IAEA for bringing this technique to our attention.

Chapter 9. Shutdown Production Facilities

272 *IAEA Safeguards Glossary 2001 Edition*, International Nuclear Verification Series, No. 3, International Atomic Energy Agency, Vienna, 2002. Decommissioning for safeguards purposes does not necessarily imply that a facility is fully decommissioned in regard to environmental matters, such as any residual radioactivity at the site.

[273] *IAEA Safeguards Glossary, op. cit.*

[274] The Eurochemic plant at Dessel, Belgium, operated from 1966–1974, and reprocessed 180 tons of natural and low-enriched uranium fuel and 30 tons of HEU fuel. It was shutdown in 1974. In 1986, it was decided not to resume reprocessing. Belgoprocess commenced decommissioning operations, which primarily consisted of dismantlement of the large cell-block containing the chemical process equipment. The dismantling of metal components is carried out by plasma-arc cutting, the cutting of pipes with radio-controlled hydraulic shears, and cutting of cast iron shielding blocks with hydraulically controlled saw blades. By 2002, much of the dismantling had taken place, www.belgoprocess.be.

[275] *Facilities under Agency Safeguards or Containing Safeguarded Material on 31 December 2006*, International Atomic Energy Agency, Vienna, 2007.

[276] The F-canyon's production mission was completed in March 2002, when solvent extraction processing was concluded. The facility has now been deactivated and awaits its final end state, to be determined by the DOE. It is being maintained in a safe state until those decisions are made. While awaiting the decision, portions of the facility has been utilized to repackage transuranic waste for shipment to the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, www.srs.gov/general/news/factsheets/fc.pdf.

[277] J. Wuester, B. Chesnay, G. Gerrein, et al., "Automating the Operator Interface—Operator Declarations at RRP," *7th International Conference on Facility-Operator Interface*, 2004, Charleston, SC; and Y. Abushady, "Short Notice Random Inspection (SNRI) Regime at a Uranium Fuel Fabrication Plant in Spain" and T. Ishikawa, "Implementation of SNRI and Borrowing Inspection in Japan," *IAEA Symposium on International Safeguards*, Vienna, 16–19 October 2006.

[278] Tariq Rauf, "A Cut-off of Production of Weapon-Usable Fissionable Material: Considerations, Requirements, and IAEA Capabilities," *Statement at Conference on Disarmament*, Geneva, 24 August 2006, www.ipfmlibrary.org/rau06.pdf, p. 21: "If the plants used in the past to produce fissile material for actual or potential use in nuclear weapons are shut down, verification could be based primarily on remote sensing and the use of seals and their periodic inspection, which would be a straightforward, inexpensive, and non-intrusive method. However, the provisions for assuring that such facilities remain shut down would also depend on their readiness to resume operations. If steps have been taken to decommission the plant or to dismantle key components, monitoring can be carried out infrequently, after initial on-site verification to confirm that the plant is decommissioned or that key components have been dismantled."

[279] Shirley Johnson, personal communication, 20 August 2008. The IAEA has worked out general "Design Information Verification (DIV)" procedures to be used in the Agency visits to verify the design and operational status of a facility, though these plans would have to be supplemented by facility-specific details.

[280] *Application of Safeguards in the Democratic People's Republic of Korea (DPRK), Report by the Director General*, GOV/2007/45-GC (51)/19, 17 August 2007.

[281] Jean Du Preez, personal communication, 5 August 2008. See also, Adolph von Baeckmann, Gary Dillon, and Demetrius Perricos, "Nuclear Verification in South Africa," IAEA Bulletin, Volume 37, Number 1; Waldo Stumpf, "Birth and Death of the South African Nuclear Weapons Programme," presentation at the conference, *50 Years After Hiroshima*, Castiglioncello, Italy, 28 September–2 October 1995.

[282] *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/gov97.pdf.

[283] Guidelines on the monitoring are specified in Subsidiary Arrangements A-1 and A-2 to Annex III.

[284] J. Wuester et al., *op cit.*

[285] Y. Abushady, *op. cit.*, and T. Ishikawa, *op. cit.*

[286] For such inspections, multiple-entry visas should be issued to IAEA inspectors for a period of one year so as to make them truly short notice. Actual notice available to the operators would be determined by the in-country travel requirements to the site and any non-visa-related restrictions imposed by the state.

[287] See e.g. Chapter 9 in *Global Fissile Material Report 2007,* International Panel on Fissile Materials, Princeton, NJ, October 2007, www.ipfmlibrary.org/gfmr07.pdf.

[288] Hui Zhang and Frank von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *Science & Global Security*, Vol. 8, 2000, pp. 261–313.

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