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MANAGING MILITARY URANIUM AND PLUTONIUM IN THE UNITED STATES AND THE FORMER SOVIET UNION

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ABSTRACT

Effective approaches to the management of plutonium and highly enriched uranium (HEU)—the essential ingredients of nuclear weapons—are fundamental to controlling nuclear proliferation and providing the basis for deep, transparent, and irreversible reductions in nuclear weapons stockpiles. The collapse of the Soviet Union and the ongoing dismantlement of tens of thousands of nuclear weapons are creating unprecedented stresses on the systems for managing these materials, as well as unprecedented opportunities for cooperation to improve these systems. In this article, we summarize the technical background to this situation, and the current and prospective security challenges posed by military stockpiles of these materials in the United States and Russia. We then review the programs in place to address these challenges, the progress of these programs to date, and the work remaining to be done, in five areas: (*a*) preventing theft and smuggling of nuclear warheads and fissile materials; (*b*) building a regime of monitored reductions in nuclear warhead and fissile material stockpiles; (*c*) ending further production of excess fissile materials; (*d*) reducing stockpiles of excess fissile materials; and (*e*) avoiding economic collapse in the nuclear cities where substantial fractions of these materials and their guardians reside.

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INTRODUCTION

Effective approaches to the management of plutonium and highly enriched uranium (HEU)—the essential ingredients of nuclear weapons—are fundamental to controlling nuclear proliferation and providing the basis for deep, transparent, and irreversible reductions in nuclear weapons stockpiles. These are global issues: All states bear a share of the risks, and all states using nuclear energy for military purposes or civilian power production share the responsibilities. This article, however, focuses primarily on the United States and the former Soviet Union, which have by far the largest stockpiles of nuclear weapons and weapon-usable nuclear materials and therefore have the greatest responsibility for effective management. Within these two states, the focus is on management of materials originating in the military sector, with only a brief discussion of the related issues of production, protection, use, and control of weapon-usable materials in the civilian sector.

Efforts to manage weapon-usable nuclear materials in these countries are now under unprecedented stress, as a result of two interrelated factors: the collapse of the Soviet Union (and the economic, political, and social transformations underway in the newly independent states), and the ongoing post–Cold War dismantlement of tens of thousands of nuclear weapons containing hundreds of tons of weapon-usable nuclear material.

In response to these new challenges, the United States and the nations of the former Soviet Union have, in recent years, begun a broad program of cooperation designed to (*a*) reduce the urgent risk that nuclear weapons or the materials needed to make them could fall into the hands of radical states or terrorist groups, and (*b*) lay the basis for further nuclear arms reductions that would reduce not only the numbers of strategic launchers and delivery vehicles but also the stockpiles of nuclear warheads and fissile materials.[1] The presidents of the United States and Russia have committed themselves to placing "high priority" on reducing the risks of theft of nuclear material, to achieving the goal of "transparency and irreversibility" of nuclear arms reductions (including exchanges of data on nuclear stockpiles and mutual inspections of fissile material from dismantled weapons), and, most recently, to negotiating measures to build transparency in the elimination of nuclear warheads (4–7).

We begin by summarizing the technical background, as well as the current and prospective security challenges, relating to management of plutonium and HEU. We then summarize the programs in place to address the "clear and present danger to national and international security" that inadequate management of these stockpiles could pose (8, p. 1),[2] the progress to date, and the work

[1]This article focuses primarily on management of fissile materials and does not address in detail recent progress in the extremely important related area of negotiating and implementing reductions in nuclear forces. For a useful summary of Clinton Administration efforts in that area through 1995 see (1); for recommendations concerning the course of future reductions see e.g. (2). A particularly remarkable and hard-won success in this regard was the removal, completed in November 1996, of all nuclear weapons from all of the non-Russian states of the former Soviet Union, and the accession of these states to the nuclear Nonproliferation Treaty (NPT) as non–nuclear weapon states (3). Efforts under the US "Nunn-Lugar" program of disarmament assistance played a major role in this success.

[2]This article draws heavily from several studies in which both of the authors have been involved (Holdren as chairman or participant, Bunn as study director or executive secretary), including a two-volume study of management and disposition of excess plutonium conducted by the National Academy of Sciences' Committee on International Security and Arms Control and its Panel on Reactor-Related Options for Disposition of Excess Weapons Plutonium, published in 1994 and 1995 (8, 9), hereinafter the NAS reports; a secret 1995 study of cooperation to improve security and accounting for weapon-usable nuclear materials in the former Soviet Union, prepared by a panel of the President's Committee of Advisers on Science and Technology (PCAST) (the PCAST report, summarized in 10); and the ongoing US-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium, which provided its Interim Report to President Clinton and Russian President Yeltsin in September of 1996 and its more detailed Final Report in June of 1997 (11, 12) (the Bilateral Commission reports). These reports and the present article drew heavily from the burgeoning literature in this field. For particularly useful summaries of the range of issues covered in this article see (13–17). For discussions of the threat of nuclear material theft and programs to prevent it see (18–27). For means to monitor reductions in stockpiles of warheads and fissile materials see (28–30; 67). For disposition of excess material see (31–37).

remaining to be done in the following areas: (*a*) preventing theft and smuggling of nuclear warheads and fissile materials, (*b*) building a regime of monitored reductions in nuclear warhead and fissile material stockpiles, (*c*) ending further production of excess fissile materials, (*d*) reducing stockpiles of excess fissile materials, and (*e*) avoiding economic collapse in the nuclear cities.[3]

TECHNICAL BACKGROUND

The materials that make nuclear bombs possible are those few isotopes,[4] among the hundreds found in nature or producible by technology, capable of sustaining an explosively growing chain reaction. Two isotopes of uranium fit this description (U-233 and U-235), as do all isotopes of plutonium (most importantly Pu-239, Pu-240, Pu-241, and Pu-242).

Uranium-235 is the only potential nuclear-explosive isotope that occurs naturally in significant quantities; it constitutes 0.7% of natural uranium, but its nuclear-explosive properties emerge only if the proportion of U-235 atoms in the uranium is much higher than in the natural element. Nuclear explosives can in principle be made with material containing somewhat less than 20% U-235, but the amount of material required at that level of enrichment is very large; in international practice, all uranium with a U-235 concentration of 20% or more is referred to as highly enriched uranium (HEU) and is subject to increased safeguard measures. For fission explosives, nuclear-weapon designers prefer a U-235 fraction of more than 90%, and HEU in this concentration range is called "weapon-grade."[5] Increasing the U-235 concentration above its level in natural uranium—uranium enrichment—is a technologically demanding and costly enterprise.

Plutonium is virtually nonexistent in nature but can be produced by bombarding uranium-238 with neutrons in a nuclear reactor or an accelerator. (U-238 is the most abundant uranium isotope, constituting 99.3% of natural uranium.)

[3]Parts (*a–d*) of this agenda were first presented in this framework in (38); see also (39).

[4]An element is uniquely characterized by the number of protons in its nucleus; an isotope is uniquely characterized by the combined number of protons and neutrons. For example, each uranium nucleus contains 92 protons; uranium-235 is the isotope of uranium in which each nucleus contains 92 protons and 143 neutrons (the 235 designation being the sum of these two numbers).

[5]In the most basic nuclear weapon designs, the entire nuclear-energy release comes from fission. In the more complicated thermonuclear weapons that predominate in the arsenals of the declared nuclear-weapon states, a "primary" nuclear-explosive component, in which the nuclear-energy release comes mainly from the fission of plutonium or highly enriched uranium, ignites a "secondary" nuclear-explosive component that derives its energy from a combination of fusion and additional fission. Such weapons generally contain both plutonium and HEU (see e.g. 8, 9). Uranium used in such secondaries covers a range of enrichments, some not within the range typically referred to as "weapon-grade."

Reactors have proven to be more practical than accelerators for producing plutonium in large quantities. In order to use the plutonium produced in a nuclear reactor in a nuclear weapon, it must be chemically separated from the fission products produced along with it, and from the residual U-238, by reprocessing the nuclear fuel. Reprocessing is also a technically demanding and costly operation; because of the intense gamma-radioactivity of the fission products, and the health risks posed by the alpha-activity of plutonium if inhaled or otherwise taken into the body, reprocessing also requires more stringent measures to mitigate its health and safety hazards than does enrichment.[6]

Although virtually all combinations of plutonium isotopes can be used to manufacture nuclear explosives,[7] nuclear-weapon designers prefer to work with plutonium containing more than 90% Pu-239 (called "weapon-grade" plutonium). This high Pu-239 concentration is commonly achieved by removing the plutonium from the reactor before the higher isotopes (which result from successive neutron absorptions) have a chance to build up. The longer refueling intervals typical of civilian nuclear electricity generation result in plutonium that contains only 60–70% Pu-239, which is called "reactor-grade" plutonium.

This term notwithstanding, reactor-grade plutonium can also be used to produce nuclear weapons at all levels of technical sophistication. This point is crucial to how a regime for protecting and safeguarding plutonium should be structured, and since it has been the source of considerable confusion over the years, we want to be as clear about it as classification boundaries permit.

Three aspects of reactor-grade plutonium pose additional difficulties for weapons design and manufacture: (*a*) the increased neutron background (which increases the chance of "pre-initiation" of the nuclear chain reaction at a moment before the weapon reaches the optimum configuration for maximum yield); (*b*) the increased heat (which may affect the stability and performance of the weapon's components); and (*c*) the increased radiation (which results in greater dangers to those fabricating and handling weapons produced from reactor-grade plutonium). The more sophisticated the designer, the greater the degree to which these difficulties can be overcome. Unsophisticated weaponeers could make crude but highly destructive nuclear bombs from reactor-grade plutonium, using technology no more sophisticated than that required for making similar bombs from weapon-grade plutonium, and sophisticated weaponeers

[6]Other potential nuclear-explosive isotopes, such as U-233, are also produced by neutron absorption (in thorium, in the case of U-233) and separated by chemical reprocessing but have not played any significant role in nuclear arsenals to date.

[7]The exception is plutonium containing substantial quantities of Pu-238, which generates such intense heat that it is not practical to make nuclear explosives from it; plutonium containing 80% or more Pu-238 is hence exempted from international safeguards.

could use reactor-grade plutonium to make very effective nuclear bombs quite suitable for the arsenals of major nation-states (8, 9, 33, 40).

A significant nuclear-explosive yield results even if the weapon goes off prematurely at the worst possible moment; in a design identical to the Nagasaki design, for example, this "fizzle yield" would be in the range of a kiloton—that is, the equivalent of 1000 tons of conventional high explosive—which would still have a destructive radius between a third and a half that of the Hiroshima bomb (40). Regardless of how high the concentration of troublesome isotopes was in the reactor-grade plutonium used, the yield would not be less than this figure.

The US government recently declassified a particularly explicit statement on the weapon-usability of reactor-grade plutonium (36, pp. 38–39):

> The degree to which these obstacles [to using reactor-grade plutonium in weapons] can be overcome depends on the sophistication of the state or group attempting to produce a nuclear weapon. At the lowest level of sophistication, a potential proliferating state or subnational 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....Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton range possible with a simple, first-generation nuclear device.

Obfuscation on this point, which continues in some debates concerning recycle of plutonium for civilian nuclear energy generation, is irresponsible and dangerous. Thus, in this article, we refer to separated plutonium of any grade, and all uranium enriched to 20% or more U-235, as weapon-usable material, as distinct from weapon-grade material.

Limited access to the principal weapon-usable materials has been for many years the primary technical barrier against the spread of nuclear-weapons capabilities to additional nations and to subnational groups,[8] for the following reasons. 1. As already noted, the technologies for producing separated plutonium and HEU are demanding and costly. 2. Plutonium and highly enriched uranium that have been produced have mostly been well guarded or have resided in forms awkward to steal and difficult to use in weapons (such as plutonium

[8]There are, of course, important political barriers to such proliferation, above all the international norm against proliferation embodied in the Non-Proliferation Treaty—extended indefinitely in 1995 with overwhelming support from its now 185 parties—and the International Atomic Energy Agency safeguards that monitor compliance with this and related agreements. For a useful examination of why states forgo nuclear weapons programs see (41).

in spent fuel, not separated from accompanying uranium and fission products). 3. In contrast to the relative difficulty of acquiring weapon-usable materials, the knowledge and expertise needed to use these materials to make (at least) crude nuclear weapons is very widely available, that is, available to virtually any country and potentially to some subnational groups. The ability to buy such materials on a nuclear black market could shorten a third-world bomb program from a decade to months or less.

The quantities of weapon-usable material needed to make a nuclear weapon are not large. Although the amounts used in specific nuclear-weapon designs are classified, numbers in the range of 4–6 kg of plutonium metal are widely cited in the unclassified literature as typical (and the figure would not be very different if reactor-grade rather than weapon-grade plutonium were used); a comparison of critical masses suggests that obtaining a comparable explosive yield from weapon-grade HEU would require a mass of uranium metal approximately three times greater.[9] The necessary amounts of material are easily carried by one person and easily concealed. These materials themselves are not radioactive enough to deter theft and handling of them; because of the very long half-lives of Pu-239 (24,000 years) and U-235 (0.7 billion years), the radiological dose rates from these materials are orders of magnitude lower than those that arise, for example, from spent fuel when it is unloaded from a nuclear reactor, which contains intensely radioactive fission products such as Cs-137 and Sr-90.[10] Unless proper security and accounting systems are in place, therefore, a worker at a nuclear facility could simply put enough material for a bomb in his briefcase or under his overcoat and walk out.

For comparison to the 4–6 kg figure mentioned above, a large civilian nuclear-power reactor of the most widely used type produces, in the course of a year of operation, about 250 kg of reactor-grade plutonium embedded, along with roughly a ton of intensely radioactive fission products, in the reactor's low-enriched uranium fuel. (In the prevalent "once-through" fuel cycle, the spent fuel is not reprocessed, and the plutonium therefore remains intimately mixed with fission products and the residual uranium and thus is not directly usable in nuclear explosives.)

[9]These figures apply to relatively simple pure-fission weapons or to the primary and not the secondary components of thermonuclear weapons. For an interesting discussion, based on unclassified sources, of the minimum amount of material from which bombs might be made, see (42).

[10]An intact sphere containing 4 kg of weapon-grade plutonium, for example, would have a gamma dose rate at 1 m of 0.005 roentgen-equivalent-man per hour (rem/h), whereas a 6-kg sphere of reactor-grade plutonium would have a dose rate of 0.03 rem/h at the same distance. By contrast, the equivalent dose rate for a spent fuel assembly irradiated to a typical burnup, 10 years after leaving the reactor, would be 2200 rem/h (see 9, p. 270).

THE CURRENT SECURITY CHALLENGES

As noted above, the collapse of the Soviet Union and ongoing weapons dismantlement are creating new security challenges for the management of weapon-usable materials. The essential facts relating to these current challenges can be divided into two categories: the size of the current stockpiles of nuclear weapons, plutonium, and HEU, and how these are changing under the influence of current nuclear arms reductions; and the vulnerability of these stockpiles to potential theft.

Stockpiles, Rates of Change, and Arms Reductions

In connection with arms-control agreements and unilateral commitments entered into by the United States, the Soviet Union, and the successor states to the Soviet Union at the end of the Cold War and thereafter, substantial fractions of the US and Russian nuclear arsenals became surplus to perceived military needs and were slated for dismantlement. Tens of thousands of these weapons, containing hundreds of tons of fissile material, are being dismantled. Ensuring that nuclear arms reductions could not be readily reversed would require that both the United States and Russia declare a very large fraction of this material to be excess and make it available for civilian use or disposal, as opposed to holding it in reserve for possible reincorporation into weapons.

HEU does not occur in nature, and plutonium occurs in only microscopic quantities, but the stockpiles of these materials produced technologically over the last five decades now amount to many hundreds of tons[11] (see Figure 1). One unclassified estimate suggests that as of the end of 1994 the global stockpile of plutonium (including military and civilian stockpiles and both separated plutonium and plutonium embedded in spent power-reactor fuel) was just short of 1200 tons, while the global stockpile of HEU was nearly 1800 tons (17).[12]

By this estimate, the global stockpiles of military plutonium (incorporated in intact weapons, weapon components, inventories of metal and oxides, and in solutions, scrap, and residues) accounted for 250 tons of the total world plutonium stockpile, while military stockpiles of HEU (including all the categories just mentioned plus naval fuel) amounted to 1750 tons (leaving only 20

[11]Tons used in this chapter are metric, hence 1 ton = 1000 kg.

[12]Because of the continued operation of nuclear power reactors and the blending down of a small portion of Russia's excess HEU stockpiles, these figures are estimated to have changed, by the end of 1996, to roughly 1300 tons of plutonium worldwide and 1750 tons of HEU. Throughout this discussion, the estimated number of tons of HEU is in fact tons of weapon-grade (90%) HEU equivalent; these estimates were produced by estimating the amount of enrichment effort [measured in "separative work units" (SWUs)] devoted to production of HEU, but there are no reliable unclassified estimates of the specific enrichment level of this HEU. If the enrichment level of a substantial fraction of this material is much lower than 90%, then the total quantity of material would be larger, though the amount of U-235 in that quantity would be similar.

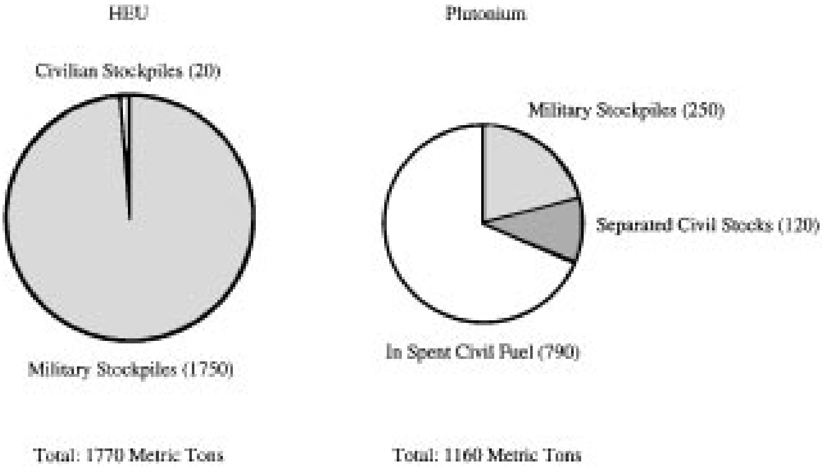

Figure 1 World inventories of plutonium and HEU (central estimates for end 1994, in metric tons). Figures are rounded to nearest 10 tons; HEU figures represent tons of 90% enriched HEU equivalent. (Source: Reference 17.)

tons of HEU in civilian stockpiles). These estimates are acknowledged to be uncertain to $\pm$25–30%, and different sources differ in their central estimates: Unclassified US government estimates, for example, suggest that the United States and Russia alone account for some 255 tons of military plutonium (85 for the United States and 170 for Russia).[13] The other nuclear weapon states and the threshold states have far smaller quantities of military plutonium and HEU, with combined totals estimated at just under 13 tons and just under 53 tons, respectively.

Civilian inventories of separated and unseparated plutonium are estimated to have stood at over 900 tons as of the end of 1994, of which 122 tons was separated plutonium in storage. Nearly 40 tons of the remaining civilian plutonium was in the midst of various fuel-cycle processes (fabrication, irradiation, and reprocessing), while more than 750 tons of civilian plutonium remained in unreprocessed spent fuel, mostly in spent-fuel cooling pools or dry storage casks at reactor sites.

By the 1990s, production of HEU had almost ceased and production of plutonium for military purposes had slowed to less than two tons per year, but

[13]The United States has formally declared that it has 99.5 tons of plutonium in the Department of Energy and Department of Defense stockpiles (43), of which 85 tons is weapon-grade (the only portion counted in the estimates for military plutonium cited in the text), and one US government source (44) estimates that Russia has approximately 170 tons of military plutonium (200 tons of total separated plutonium, including some 30 tons of civilian plutonium).

Table 1 U.S. warhead dismantlements 1990–1999[a]

Year	Warheads eliminated
1990	1154
1991	1595
1992	1856
1993	1556
1994	1369
1995	1393
1996[b]	1166
1997[b]	1221
1998[b]	1084
1999[b]	415

[a]Source: (46).
[b]Projected as of time of data.

the rate of growth of the stocks of civilian plutonium embedded in spent fuel, produced as a byproduct of continuing nuclear power generation, was about 70 tons per year. In recent years, roughly 20 tons of this material has been separated from spent fuel by reprocessing each year, and to date, fabrication of this separated material into fresh reactor fuel has not kept pace (resulting in the large and growing stockpile of separated civilian plutonium in storage, mentioned above).

Stockpiles of nuclear weapons, by contrast, are declining. For roughly a decade, for the first time in the nuclear age, dismantlement of nuclear warheads worldwide has far out-paced new production. Publicly available estimates suggest that the US stockpile of intact nuclear weapons (including both strategic and tactical weapons and both active weapons and reserves) stood at approximately 23,500 by the late 1980s (45) and had declined by 1996 to approximately 14,000–15,000 weapons,[14] as a result of nearly a decade of dismantlement proceeding as fast as the available facilities would safely allow. Dismantlement of US nuclear weapons has taken place at the Pantex facility in Texas, where these operations continue; a limited number of additional weapons were dismantled at Oak Ridge. (The year-by-year figures for US warhead dismantlement are shown in Table 1.) Unless further arms reduction agreements are reached, dismantlement in the United States is reportedly planned to essentially end in 1999, leaving an estimated 10,000 warheads remaining in the stockpile. Under current plans, if START II is ratified, the warheads retired as a result reportedly will simply be shifted from active to reserve status, without being eliminated (46).

[14]This figure combines the figure for 1993 reported in (45) and the figures for dismantlement since then in (46).

A similar pattern appears to be prevailing in Russia, though the United States has no transparency or verification measures in place to confirm this. Unclassified estimates suggest that the Soviet nuclear arsenal, now entirely inherited by Russia, has declined from a peak that may have been as high as 45,000 weapons in 1986 to perhaps 25,000 weapons as of 1996.[15] US intelligence estimates of the Soviet nuclear stockpile are publicly described as being uncertain by $\pm$5,000 warheads. Russian officials have indicated that, during the last decade, the Soviet Union and then Russia were dismantling weapons at a rate roughly comparable to the US rate, but these officials have not provided specific and consistent figures (47, pp. 31–32, 49–51). Nor have they indicated to what level they plan to reduce their stockpile.

What might these ongoing dismantlements mean in terms of the quantity of fissile material that may ultimately be surplus? One estimate based on unclassified sources suggests that the future US stockpile of 10,000 warheads will contain roughly 35 tons of plutonium and 225 tons of HEU (17). If this estimate is correct, nearly 50 tons of plutonium and over 290 tons of HEU will have been removed from nuclear weapons by the time currently planned dismantlement is complete, and the total stockpiles of US plutonium and HEU outside of weapons will be 65 tons and 420 tons, respectively. To date, the United States has declared that, of these amounts that will be outside of weapons, over 50 tons of plutonium and some 175 tons of HEU are excess to its military needs and has formally committed that this material will never again be used in nuclear weapons. (For a detailed and authoritative account of these figures, see 48). The remainder, under current plans, will stay in military reserves for possible reincorporation in the weapons stockpile or use as fuel for naval reactors.

Russia's stockpiles of plutonium, HEU, and nuclear weapons are all larger than those of the United States. If Russia also reduces its stockpile to 10,000 weapons, unclassified estimates suggest that Russia would then have 125–165 tons of plutonium outside of weapons (including 30 tons of civilian plutonium) and 825 tons of HEU outside of weapons.[16] Russia has made no formal declaration of how much of this material it considers excess to its military needs, but it has (*a*) agreed to blend down 500 tons of HEU for sale to the United States (discussed in more detail below); (*b*) agreed in principle that none of the tens of tons of plutonium to be stored in a facility being built with US assistance (described below) will ever again be returned to weapons; and (*c*) made a formal statement that none of the material produced in its plutonium production reactors since October 1994 will ever be used in weapons.

[15]This again combines estimates as of 1993 (45) with estimates of dismantlement since then (47).

[16]The HEU figure and the lower plutonium figure are based on (17); the higher plutonium figure is based on the larger total amount of plutonium estimated in (44).

Further progress in arms reduction could substantially increase the amount of excess fissile material. If further reductions were agreed on that required the United States and Russia to reduce their total stockpiles of nuclear warheads to, for example, 2000 warheads, and to reduce their stockpiles of military plutonium to the minimum required to support an arsenal of that size (perhaps with a 20% allowance for purposes of stockpile support and maintenance), then well over 90% of their existing plutonium stockpiles would be excess to their military needs. Using the unclassified estimates of material per warhead cited above, the United States would then be expected to have over 90 tons of excess plutonium, and Russia over 150 tons. Under that circumstance, if the two countries agreed that each would also maintain, for example, an additional 50 tons of HEU for naval fuel, the United States would be expected to have over 500 tons of excess HEU, and Russia roughly 1000 tons (17) (see Table 2).

None of these dismantlements and declarations of excess material is actually required by current arms control agreements. The agreements reached to date limit mainly strategic launchers (such as missile silos and submarines) and delivery vehicles (such as missiles and bombers). There is no requirement to dismantle, or even to account for, the nuclear warheads retired when a missile is

Table 2 Estimated US and Russian separated plutonium and HEU stockpiles, end 1994[a]

	United States	Russia
Total		
Plutonium	100	160
HEU	645	1050
Outside of warheads at stockpile of 10,000		
Plutonium	65	125
HEU	420	825
Declared excess to date		
Plutonium	50	0
HEU	175	0
Excess if stockpiles limited to 2,000 warheads		
Plutonium	90	150
HEU	540	950

[a]Figures rounded to nearest 5 tons; US and Russian stockpiles include both military and civilian separated plutonium, unlike the "military stockpiles" category of Figure 1. Source for estimates of total stockpiles and material per warhead: (17).

dismantled, and no transparency or verification measures are in place to confirm the ongoing weapons dismantlement.[17]

While the START II Treaty (not yet ratified) calls for the United States and Russia to reduce their deployed, strategic forces to 3,000–3,500 warheads on each side, as already noted the United States is reportedly planning to retain a total nuclear warhead stockpile (counting tactical warheads and reserves) of some 10,000 warheads, as well as large stockpiles of reserve fissile material (46).[18] Indeed, a 1997 General Accounting Office (GAO) report declassified the fact that the United States is planning to retain reserves sufficient to replace 100% of the warheads in the active arsenal—i.e. enough to rapidly double the deployed forces (50). As far as is known, Russia currently plans to maintain similar or even larger stockpiles of both warheads and fissile materials. These large reserve stockpiles of nuclear warheads and fissile materials would allow a rapid return to Cold War levels of nuclear armament should political circumstances change. If the United States and Russia are ever to achieve the goal of ensuring the "irreversibility of nuclear arms reductions" agreed to by Presidents Clinton and Yeltsin, these reserves and non-strategic warheads will have to be addressed, with new measures to verifiably reduce the stockpiles of nuclear warheads themselves and the fissile materials needed to make them.

Stockpile Vulnerability

The security challenges posed by the growing stockpiles of nuclear materials are related not only to the sizes of these stockpiles but also to the characteristics that govern their vulnerability to theft and diversion. [Following the NAS study (8) and International Atomic Energy Agency (IAEA) practice, we use the term "diversion" to refer to actions by the legitimate owners of the material to reincorporate it into nuclear weapons in violation of pledges not to do so, and the term "theft" to refer to acquisition of the material by parties other than its legitimate owners.]

Measures for securing and accounting for nuclear materials can be divided into two basic types. Programs for "domestic safeguards" are applied by individual states to the nuclear materials on their territories; they are designed

[17]The one exception is that Ukraine has reached agreement with Russia on procedures to satisfy Ukrainian officials that the warheads returned to Russia from Ukraine are in fact being dismantled. Neither Ukraine nor Russia, however, has provided a detailed account of what these procedures are.

[18]Indeed, as part of the Nuclear Posture Review early in the first Clinton term, the United States explicitly adopted a policy of "lead but hedge," meaning that while the United States would reduce its nuclear forces in line with its commitments, it would reserve the capacity to return rapidly to relatively high levels of nuclear armament (49). It is this requirement for a hedge that has led the United States to plan to retain such a large stockpile of intact nuclear weapons.

to prevent theft of nuclear materials by non-state actors (possibly working in conjunction with foreign states) and use for this purpose a range of technologies and procedures known collectively as material protection, control, and accounting (MPC&A). Programs for "international safeguards" are implemented by international organizations [such as the International Atomic Energy Agency (IAEA) and EURATOM]; they are designed to allow international monitors to detect diversion of nuclear materials from peaceful activities to military purposes, and they use primarily accounting and control technologies (and, more recently, an array of additional technologies and approaches to detect covert military activities at undeclared sites).

In the United States, the stringency and effectiveness of the system for securing and accounting for weapon-usable nuclear materials have increased markedly over the past several decades. During the 1970s and 1980s, rapid and large-scale efforts were undertaken to correct identified weaknesses in security and accounting systems (for critiques of these early weaknesses see 51, 52), with the result that, today, US MPC&A programs are widely regarded as some of the most stringent and effective in the world.

MPC&A for materials used in the US Department of Energy (DOE) complex is implemented by DOE's Office of Safeguards and Security, in compliance with a series of DOE orders, with oversight by DOE's separate Office of Security Evaluation. Private firms implement their own MPC&A, in compliance with national laws and regulations, with oversight and licensing by the Nuclear Regulatory Commission (NRC). The NRC has no authority over materials within the DOE or Department of Defense complexes (although an eventual transition to NRC regulation of DOE activities is now being contemplated). Both DOE orders and NRC regulations (which are intended to be generally consistent) rely on a "graded safeguards" system that divides nuclear materials into various categories of attractiveness requiring varying levels of protection. Facilities with significant quantities of weapon-usable materials are required to employ armed guards, fences, alarms, locked vaults, and a variety of other measures to detect any theft. Overall, the system places heavy reliance on security technology to provide effective protection. Both DOE and non-government stockpiles are included in a computerized national plutonium and HEU inventory known as the Nuclear Materials Management and Safeguards System (NMMSS). Despite the availability of NMMSS information, however, recent initiatives to declassify past production and current holdings of plutonium and HEU have required substantial effort to compile the relevant data (43).

Approaches to MPC&A in other countries vary widely and have evolved considerably over time. For example, countries such as France and Britain place reliance on both security technology and armed guard forces (as the United States does), whereas in Japan, no armed guards are in place at civilian nuclear facilities (even where many bombs' worth of separated plutonium is present). Instead, Japan relies on security technologies and the availability of armed police forces some distance away.

Unfortunately, there is no international mechanism in place to ensure that all countries using weapon-usable materials provide an effective and consistent level of security and accounting. The 1980 Convention on the Physical Protection of Nuclear Material was an important step in this direction, but this convention is "quite vague in its requirements, applies primarily to international transport of nuclear materials, and has no provisions for verification or enforcement" (8, p. 56; for the convention text see 53). The IAEA has published somewhat more specific guidelines, but these are purely advisory (54).

Through bilateral agreements, the United States seeks to ensure that other countries using nuclear materials of US origin provide effective security for those materials: US law requires visits to foreign facilities to examine physical protection arrangements and executive branch certification that these arrangements are adequate. Following the US lead, the Nuclear Suppliers Group has adopted guidelines for physical protection of material originating within its member states (55). Nevertheless, no organization monitors or compiles information on physical protection practices worldwide. Similarly, no international convention or agreement regulates the quality of material control and accounting programs that are part of domestic safeguards systems.

By contrast to the US approach, which relies heavily on technology, the Soviet system for securing nuclear weapons and materials was based on loyal, carefully screened, and well-paid personnel; armed guards; closed facilities; closed cities; closed borders; a closed society; and pervasive surveillance by the KGB (for a useful description see 19). As far as is known, this system worked well for decades.

Today, however, the collapse of the Soviet Union and the ensuing transformations in the former Soviet states have greatly weakened nearly all the pillars of the old system, while forcing it to meet challenges it was never designed to face. With little funding forthcoming from the central government, facilities have been unable to maintain existing security systems or to pay for needed upgrades. At the same time, the vast reduction in living standards among nuclear workers, combined with the marketization and criminalization of the economy, is creating new incentives for corruption and theft. Like the United States, moreover, Russia must cope with the unprecedented challenge of safely and securely managing hundreds of tons of weapon-usable material that, with the end of the Cold War, is no longer needed for military purposes. Furthermore, the non-Russian states have had essentially no previous experience with the MPC&A systems necessary to manage the weapon-usable materials left on their soil when the Soviet Union collapsed.

Despite the weakening of many ingredients of the former Soviet Union's security system, US intelligence agencies have judged that protection of intact nuclear weapons in Russia continues to be effective.[19] (As noted above, as of November 1996, all of the former Soviet Union's nuclear weapons had been removed from the non-Russian states and transferred to Russia.) Nuclear weapons are easily counted and are typically stored in secure vaults under heavy guard.

Nuclear materials are another matter. As of 1994 (when current cooperative programs first got underway on a substantial scale), essentially no former Soviet nuclear facilities had effective detection equipment (known as portal monitors) at the gates to sound an alarm if a worker were carrying out plutonium or HEU. Fences at many facilities had holes or were overgrown with vegetation. The principal devices used to indicate whether materials had been tampered with were easily-faked wax seals (most workers with access to the material had the stamp needed to create a new seal). Most sites had no accurate, measured inventories of their material, and no accurate national accounting systems or regulatory frameworks were in place. Although work is underway to correct these deficiencies, it will take years to complete.

For these reasons, the US Director of Central Intelligence has testified that weapon-usable nuclear materials "are more accessible now than at any other time in history—due primarily to the dissolution of the former Soviet Union and the region's worsening economic conditions," and that none of the facilities handling plutonium or HEU in the former Soviet states has "adequate safeguards or security measures" in place (18, pp. 304, 312).

Already, authorities have made multiple seizures of kilogram-quantities of stolen weapon-usable nuclear materials, including 1.5 kg of weapon-grade HEU from the "Luch" production association in Podolsk, Russia in 1992; 1.8 kg of 36% enriched HEU from the Andreeva Guba naval base near Russia's Norwegian border in July 1993; 4.5 kg of material enriched to over 19% U-235 from the Sevmorput naval shipyard near Murmansk in November 1993; over 360 g of plutonium on a plane from Moscow as a result of a German "sting" operation in Munich in August 1994; and 2.73 kg of essentially weapon-grade (87.7% U-235) HEU in Prague in December 1994 (23). While there is no evidence that enough material for a bomb has yet fallen into the hands of states such as Iran, Iraq, Libya, or North Korea, it is impossible to know what has not been detected. The fact that many reports of nuclear smuggling are scams or relate to materials with no relevance to nuclear weapons should not obscure the seriousness of the cases that have occurred.

In short, while the dismantlement of many thousands of nuclear weapons and the removal of hundreds of tons of fissile material from military stockpiles reflect

[19]The Director of Central Intelligence has indicated, however, that "the threat from within the Russian military and the deteriorating economy mean that this judgment could change rapidly" (18).

a most welcome reduction in the danger of global nuclear war that loomed over civilization for more than 40 years—and a major turning point in the history of attempts to bring the nuclear arms competition under control—deactivating and dismantling the weapons and properly managing the plutonium and HEU they contain pose an immense new set of challenges for international security and arms control, particularly when combined with the risks of nuclear theft arising from the collapse of the Soviet Union. We now turn to the various cooperative programs designed to meet these challenges.

DIRECT MEASURES TO PREVENT THEFT AND SMUGGLING

Because it is far easier to prevent theft of fissile material than to find and recover stolen material, the most efficient approach to reducing the risk of nuclear theft is to control the fissile material at its source. Therefore, the first priority is to ensure that all nuclear weapons and weapon-usable materials are secure and accounted for, i.e. to establish effective MPC&A. This involves facility-level security and accounting systems for both weapon-usable materials and nuclear weapons themselves; new, secure storage facilities; consolidation of weapons and materials at fewer locations; high security for transport of weapons and materials (often the most vulnerable point in their life cycles); national-level systems of accounting, control, and regulation; and ultimately, more stringent international standards. Should material nonetheless be stolen, programs to prevent nuclear smuggling provide a second line of defense.

Upgrading Security and Accounting at Nuclear Material Sites

In the United States, the number of facilities with kilogram-quantities of plutonium or HEU is declining as the nuclear weapons complex consolidates and fewer civilian facilities choose to make use of weapon-usable nuclear materials. As noted above, US MPC&A programs for these materials have been upgraded substantially in recent years and are now among the most stringent in the world. Nevertheless, debate continues as to whether the shrinking resources being applied to security for these materials are sufficient, given what some argue is a substantially increased terrorist threat in recent years (for a sample of this discussion see 56).

More than 50 locations in the former Soviet Union handle kilogram-quantities of weapon-usable nuclear materials.[20] Approximately a dozen of these—all

[20]There has been some confusion over this figure. This figure refers to separate sites with HEU or plutonium, each of which may contain a large number of individual buildings and fenced areas. The larger figure of 80–100 that is sometimes used refers to the number of individually fenced areas; a single site may contain several such areas. If every building where plutonium or HEU is located were counted, the figure would be in the many hundreds.

research or training reactors using relatively modest amounts of highly enriched uranium (HEU)—are outside Russia (including facilities in Kazakhstan, Ukraine, Belarus, Latvia, Georgia, and Uzbekistan). The facilities within Russia include the nuclear weapons complex of the Ministry of Atomic Energy (MINATOM), with its 10 "closed cities"; the civilian facilities of MINATOM; independent civilian research centers; and the facilities handling HEU for propulsion of naval ships and submarines and civilian icebreakers.

Russia has undertaken significant domestic efforts to upgrade security and accounting at nuclear sites but has been limited by severe economic constraints; the other former Soviet states have much less indigenous capability to implement effective safeguards (19). Accordingly, DOE has established a major program to cooperate with the states of the former Soviet Union in upgrading security and accounting systems at these sites. The program includes formal government-to-government efforts (originally funded by the Defense Department's Nunn-Lugar program but now funded from the DOE budget), a complementary lab-to-lab program, and work with nuclear regulatory agencies in the former Soviet states (pursued in cooperation with the US Nuclear Regulatory Commission).

This cooperative program has grown with remarkable speed as success was demonstrated and trust built. In early 1994, the Russian government was refusing to allow access to any of the facilities where separated plutonium or HEU were stored (arguing that these facilities, even the civilian ones, were too sensitive for such visits), and the United States had spent less than $3 million cooperating with Russia on MPC&A. Today, despite continuing sensitivities surrounding some sites and activities, cooperative work is underway at 44 of the locations in the former Soviet Union where weapon-usable materials are held (over 80% of the total), and the budget for the US side of this cooperative program has mushroomed by almost two orders of magnitude to $113 million in the current fiscal year, with a request of $137 million for Fiscal Year (FY) 1998 (DOE, unpublished data).[21] New fences, alarms, and personnel access systems are being installed, computerized accounting systems are being established, portal monitors are being deployed, operators and regulators are being trained, and new regulations are being written. Many tons of weapon-usable nuclear material are now demonstrably better protected and accounted for.

DOE has developed a classified, comprehensive program plan under which modern safeguards and security systems are expected to be in place at all of

[21] Although some form of cooperative work is underway at over 80% of the locations, at many of them the initial projects focus on only one or two of the many buildings at that site holding weapon-usable material. For a map of the sites where cooperation is underway and brief descriptions of the status of work at each site as of January 1997 see (25); for a collection of technical papers on activities at individual sites see (26).

the facilities handling weapon-usable materials in the former Soviet Union by 2002, if Congressional funding at projected levels and cooperation with the former Soviet states both continue (57). Installation of such modern systems at all of the former Soviet facilities with weapon-usable material outside of Russia is expected to be completed during 1997 (although that schedule may slip in the case of Kazakhstan owing to funding delays on the US side that were only recently resolved). The total remaining cost of the US contribution to the program is expected to be somewhat more than half a billion dollars, but that estimate will surely be modified as the program proceeds.

Currently, however, the vast majority of the fissile material in the former Soviet Union remains dangerously insecure; for a very large fraction of the material, all of the conditions described above still apply—and with the continuing budget crisis facing the Russian government, the prospect for financing such basic measures as regular payment of wages and maintenance of security systems does not appear bright. DOE's projected schedule is likely to be optimistic, given the vast scale and complexity of the nuclear complex in Russia—and even if the schedule were met, it would mean that for five more years, substantial quantities of nuclear material will not have effective modern safeguards systems in place, and the risk of theft will remain high. Even when the new systems are in place, it is not obvious that systems designed to meet US and international standards will be sufficient to reduce to low levels the threat of theft, as the severe economic crisis in Russia is creating potential motivations for "insider" conspiracies larger and more determined than standard safeguards systems could handle.

Unfortunately, modernization of MPC&A in the former Soviet Union could not be accomplished overnight even if budgets far larger than those now contemplated were available. New technologies and approaches take time to introduce in such a massive nuclear complex, and a new "safeguards culture" of scrupulous implementation of these new security and accounting procedures can only be developed over time. To help build the needed safeguards culture, a continued focus on genuine participation and engagement by users at facilities in states receiving US assistance is critical—as a recent National Research Council report emphasized (27). The participants in the DOE program currently believe that the program's pace is now constrained not as much by US funding as by "absorptive capacity"—the limited size of the cadre of people at the individual sites who can effectively be employed in designing and implementing security system upgrades (M Mullen & S Mladineo, personal communication).

To have any hope of meeting the projected schedule for upgrades would require full funding for the $137 million request for FY 1998, and the similar or larger requests expected in subsequent years. Some continued funding after 2002 is also likely to be necessary in order to continue the cooperation, maintain US-supplied equipment, and help ensure the rooting and maintenance of a far-reaching safeguards culture. It remains possible that the timetable for success could be modestly accelerated if efforts are made to identify creative means for further speeding progress and overcoming the "absorptive capacity" constraints—including additional emphasis on training of personnel and on providing resources and incentives for redirecting more personnel from other areas to the safeguards mission.

As the PCAST report concludes, these programs can only succeed if they are based on genuine cooperation and mutual trust and respect. Maximum success requires maximum flexibility; hence, the PCAST report recommends that Congress resist the temptation to impose burdensome restrictions on how business can be conducted, such as "buy American" requirements, and specified audit and examination procedures (10). During 1996–1997, progress on several projects was greatly slowed by another example of inflexibility: Application of export control restraints intended to control proliferation has prevented the delivery of equipment urgently needed to control proliferation. As of mid-1997, however, it was expected that a general license permitting the delivery of all needed MPC&A equipment would soon be approved (DOE and Russian institute officials, personal communications).

Building New Storage Facilities

New storage facilities can be important supplements to MPC&A upgrades at existing sites. The United States, however, has announced its decision not to build major new storage facilities for its plutonium and HEU but rather to upgrade facilities at Pantex, Savannah River, and Oak Ridge for this purpose (58).

Russia, by contrast, has concluded that its current storage facilities are inadequate, and the United States and Russia are cooperating to build a secure storage facility for plutonium and HEU from dismantled weapons at the site once known as Chelyabinsk-65 (now renamed Ozersk and also frequently known as Mayak, the name of the nuclear production association located there). The Japanese government has also agreed to contribute to this facility, primarily by providing additional fissile material storage containers above and beyond those being provided by the United States. The new facility would offer greatly improved security and accounting compared to the current storage locations, and the United States would be offered transparency measures in return for its assistance. An initial design has been completed, allowing construction to proceed; the foundation for the facility has been laid; and construction is actively underway, with a projected opening of the first phase of the storage facility (offering half of its eventual 50,000 container capacity) in mid-1999. The specific transparency measures to be applied at this facility have not yet been agreed to, however, and there have been some suggestions that modifications to the thermal design would be useful to allow more of the container spaces to be devoted to plutonium rather than HEU.[22]

Additional new storage facilities may be needed for the material from dismantled weapons beyond what can be accommodated in the first Mayak facility, for the 30 tons of civilian plutonium now stored in an inadequate facility at Mayak, and for other stocks. One approach to increasing secure storage space would be to use existing unused concrete-lined rooms (estimated at 500 m $\times$ 16 m) in the underground nuclear production facility at Krasnoyarsk-26, now known as Zheleznogorsk (59). Large-scale fissile material–storage facilities could potentially be installed in these highly secure facilities at relatively modest cost.

Upgrading Security for Nuclear Weapons Storage Facilities

Nuclear weapons in both the United States and Russia are held in secure vaults under heavy guard. No major changes or upgrades in security measures for nuclear weapons storage within the United States are planned.

In Russia although nuclear weapons are believed to be substantially more secure than some of that country's stockpiles of weapon-usable materials, the grave consequences that could result if a nuclear weapon were actually stolen are motivating cooperative efforts under the Nunn-Lugar program to further improve security. Efforts to upgrade security for nuclear warhead storage are slated to receive $15 million in the FY 1997 Nunn-Lugar budget, and the request for FY 1998 includes $36 million for this purpose (Department of Defense Cooperative Threat Reduction Program, unpublished data).

Because neither the United States nor Russia has permitted visits by the other country's representatives to nuclear warhead storage sites, in this program Russian experts will determine what upgrades are needed, the United States will provide equipment (as well as a physical-protection training facility), and Russian personnel will do the necessary installations. Flexible procedures, acceptable to both parties, will be needed to ensure that US-provided material is used appropriately, without unduly compromising sensitive information (Department of Defense officials, personal communications). Because security at these facilities is already substantial and no complex accounting of difficult-to-measure materials is required, upgrades in the security of warhead storage are expected to cost less than MPC&A upgrades, even if they are implemented at

[22]Because much of the excess Russian HEU is expected to be sold to the United States over the next 20 years, it may be desirable to build in some flexibility to deviate from the initial Russian design specifications calling for two thirds of the container spaces to hold HEU and only one third to hold plutonium, in order to avoid the possibility that two thirds of the facility would be empty for much of its design life. Allowing more plutonium would require changes to the thermal design (particularly if reactor-grade plutonium were also to be included) because plutonium gives off more heat than HEU.

all of the roughly 100 remaining storage sites with nuclear weapons [this figure has been reduced from roughly 600 in 1989 (60)].

Consolidating Storage and Converting Research Reactors

In the United States, the nuclear-weapons complex is undergoing a substantial consolidation, and with this contraction the number of sites with plutonium and HEU is being steadily reduced. In addition, most US research reactors (and most US-designed research reactors in other countries) have converted from HEU fuel to low-enriched uranium (LEU) fuel, greatly reducing the proliferation hazard from these civilian facilities. Indeed, in recent years the United States has revitalized its program to convert research reactors to LEU fuel, including its offer to take back spent fuel containing US-enriched uranium from foreign research reactors that have either converted to LEU fuel, agreed to do so in the future, or agreed to shut down (61).

In Russia, as just noted, a drastic reduction in the number of sites where nuclear weapons are stored has already been accomplished. But MINATOM is struggling to keep the major sites of the nuclear weapons complex open, despite the drastic decline in state funding; consolidation has yet to take hold in a serious way. The PCAST report recommends that DOE take every opportunity to emphasize to the former Soviet states, especially Russia, the need for a substantial consolidation in the number of sites with weapon-usable nuclear materials and in the number of separate areas containing such materials within each of those sites, and the recent National Research Council report on MPC&A emphasizes the same point (10, 27). Such consolidation has the potential to greatly reduce the costs of ensuring adequate safeguards and security.

With severe cutbacks in the funding of science in Russia, a considerable contraction in the number of civilian research centers using HEU—sites where security is particularly lax—is also inevitable. Encouraging research centers to eliminate their HEU stocks (perhaps by offering to purchase those stocks) and to convert whatever research reactors continue running to low-enriched fuels would help reduce current security risks. Cooperative US-Russian efforts are currently underway to develop and implement proliferation-resistant low-enriched fuels for Soviet-designed research reactors, and the recent National Research Council report recommends that additional efforts be made to convert these reactors and to purchase small insecure stocks of HEU in the former Soviet Union (27).

Upgrading Transport Security

During transport, nuclear weapons and weapon-usable nuclear materials must be heavily protected against overt theft by armed groups. DOE has long used a system of heavily guarded "Safe, Secure Transports" (SSTs) equipped with special security technologies to transport nuclear weapons, and the Department plans to use the same approach for shipments of fissile material required as part of the disposition program.

In Russia too, new attention is being paid to upgrading transport security. The US Department of Defense has been providing warhead-transportation equipment (including railcar security upgrade kits and "supercontainers" for warhead transport), and the Russian Ministry of Defense has indicated that this equipment has already substantially improved the security of Russian warhead transport (62). Delivery of this equipment is expected to be completed during 1997. Lab-to-lab cooperation on improving security of fissile-material transport is now also underway.

Improving National-Level Regulatory and Accounting Systems

Efforts at individual sites require coordination so that they fit together into national systems providing a generally consistent level of MPC&A for all weapon-usable materials. Improving national-level tracking and accounting systems is an essential element of any comprehensive MPC&A program, as is improvement of national regulatory functions. While regulations are often thought to be less urgent than securing materials on the ground, the fact is that only a sound set of regulations requiring effective MPC&A, backed up by realistic enforcement, will provide facility managers the necessary incentives to invest in, operate, and maintain MPC&A systems.

As noted above, regulation in the United States has long been split between commercial activities regulated independently by the NRC and self-regulated government activities, but a single computerized data base, the NMMSS, is kept for accounting of nuclear materials nationwide.

In most states of the former Soviet Union, the few nuclear regulatory agencies that do exist are new and suffering the growing pains of fledgling organizations with large mandates and small staffs. In the case of Russia, the balance of power between the nuclear regulatory agency—GOSATOMNADZOR (GAN)—and the ministries it is supposed to be regulating (including MINATOM) is still evolving, and MINATOM is far from enthusiastic about independent regulation. President Yeltsin, after initially giving GAN authority to regulate safety and security of both military and civilian nuclear activities, signed a decree in mid-1995 removing GAN's authority to regulate the activities of the Ministry of Defense (63). Ultimately, MINATOM and the Ministry of Defense themselves must have effective internal regulatory programs, in addition to independent regulation.

The US Nuclear Regulatory Commission (NRC) and DOE have established promising programs of regulatory support for the countries of the former Soviet Union, including work with GAN in Russia. Nevertheless, GAN has been making only slow progress toward establishing an effective set of regulations and an effective cadre of regulators and inspectors to implement them—and the effort to establish a national inventory system in Russia similar to the US NMMSS is proceeding slowly. Development of a strong regulatory system in this area will take many years and tens of millions of dollars in support from the international community.

Equally fundamental to any comprehensive MPC&A program is training of the operators and regulators who must carry out the program. The United States has several major training programs for domestic safeguards. Russia, the United States, and the European Union have cooperated in establishing a national MPC&A training center at Obninsk, near Moscow.

Creating Tougher International Standards

The need to modernize MPC&A systems is a global issue, not limited to the states of the former Soviet Union. Visits to sites handling weapon-usable materials indicate that materials in many countries do not have MPC&A systems that would be proof against theft by knowledgeable insiders or against attack by determined and well-trained terrorist groups. For these reasons, the NAS report recommends that the United States pursue new international arrangements to improve safeguards and physical security for all forms of plutonium and HEU worldwide, coming as close as possible to the stringent standards of security and accounting applied to nuclear weapons themselves (the "stored weapons standard"). An international panel of experts convened by the American Nuclear Society, including US, Russian, French, British, German, and Japanese representatives, made similar recommendations in 1995 (8, 9, 33). The NAS study also recommends increasing the international role in this area, including giving an international organization authority to carry out inspections to ensure that agreed standards of protection are being met. Negotiation of modified or new agreements will be necessary to meet these objectives.

Stopping Nuclear Smuggling

Although keeping fissile materials secure and accounted for at their source is the most critical part of the effort to reduce the global threat of nuclear smuggling, anti-smuggling efforts form an important second line of defense. Efforts are being pursued to exchange intelligence, coordinate responses, and train and equip police, investigators, customs officials, and border guards in the relevant states; these efforts could be substantially expanded. This is a global problem requiring intensive international cooperation.

At the 1996 Moscow Nuclear Safety and Security Summit, the assembled leaders of the P-8 countries (the "Political Eight," consisting of the traditional Group of Seven countries and Russia) announced an "action plan" on nuclear smuggling. So far, however, implementation of that plan has lagged, with most of the work focused on developing mechanisms for improved exchange of information among the participating countries (still a very difficult problem whenever sensitive sources and activities are involved) and on bringing additional countries into the plan. A variety of US agencies have programs in this area, but progress has been slow.

The US Customs Service, for example, has provided limited training and equipment to selected customs and border patrol officials in a few key states (focusing on Eastern Europe) and, in cooperation with DOE, has worked to develop equipment that is simple and cheap enough for customs agents to use (such as a "radiation pager," worn on the belt, capable of detecting unshielded plutonium and HEU in passing baggage). This effort was substantially limited by lack of funds until late 1996 (15), when Congress provided $9 million to the Department of Defense for cooperation with Customs in nuclear smuggling programs. Under current plans, this money will be spent over several years, initially focusing on completing previous Customs efforts in Eastern Europe.

Previously, in FY 1995, Congress authorized the Department of Defense to reprogram $10 million for a joint Defense–Federal Bureau of Investigation (FBI) program to address nuclear smuggling—but the joint Defense-FBI report on what would be done with the money (required before the funds could be spent) was not completed until nearly two years later, and the envisioned program of training and provision of equipment is only slowly getting underway. Visits to key states near Russia's borders (through which nuclear material might transit) to assess their needs are being conducted, several major international conferences on this subject have been held, and the first courses on nuclear smuggling under this program have been scheduled for mid-1997 at the FBI's International Law Enforcement Academy in Budapest. This Defense-FBI program also plans to spend the limited funds available over several years, with its initial focus on the states to Russia's south. Overall, efforts to date have been piecemeal and have not yet gelled into a comprehensive plan. As in the MPC&A case, such a plan would specify all the states and organizations that would receive assistance, the specific capabilities they would be encouraged and assisted to acquire, and the target dates for making these improvements.

Elements of a Comprehensive Nuclear Smuggling Prevention Program

INTELLIGENCE COOPERATION AND INFORMATION SHARING All of the major seizures of nuclear materials so far have been the result of having good information—from tips, stings, and intelligence work. One of the highest-leverage areas for improvement, therefore, is to increase cooperation between US intelligence and law-enforcement agencies and their counterparts in Russia and other relevant states, including creating mechanisms for exchanging sensitive law-enforcement and intelligence information on ongoing cases. This is an extremely difficult approach to pursue, given the deeply ingrained reluctance of these organizations to exchange information that could compromise sources and methods or ongoing investigations, but there is nonetheless the potential, particularly through building personal relationships and habits of exchanging routine information, to significantly improve information flows when compared to the current state of affairs. Hence, a comprehensive approach would include, among other efforts in this area, stationing nuclear smuggling experts permanently with the FBI or intelligence contingents at the US embassy in Moscow, to cooperate with their Russian counterparts.

LAW ENFORCEMENT UNITS Another key element of a comprehensive approach would be ensuring that each of the relevant states has at least a small police unit trained and equipped to investigate and respond to nuclear smuggling cases, with other law enforcement agencies trained to call them in when appropriate. The cost of providing limited training and equipment to such small units would be extremely modest for each country.

BORDER CONTROLS A comprehensive effort would include providing training and simple nuclear detection equipment to border guards and customs agents at key entry and exit points throughout the former Soviet Union (including particularly the southern tier states) and Central Europe. The immense volume of traffic that crosses international borders every day, and the vast and sparsely populated length of the borders between some of the key countries, makes the task of interdicting nuclear materials extremely difficult—as evidenced by the massive flows of drugs and other contraband that governments around the world have so far been unable to stop. But a carefully targeted training and equipment program could have a significant deterrent effect and greatly increase the chance of catching the "amateur" smugglers who account for nearly all of the nuclear smuggling detected to date. In close cooperation with DOE, US Customs has developed a training program and basic equipment suited to customs officers who typically have little technical training. Such equipment is surprisingly inexpensive: Customs agents and border guards at all the largest crossing points in Central Europe and the former Soviet Union (including the critical states to Russia's south) could probably be provided with basic training and equipment for a cost of less than $50 million.

ANALYSIS CENTERS There is a need for a small number of regional analysis centers in Eurasia, capable of both nuclear and traditional forensic analysis, to which material seized in nearby countries could be sent. These centers could provide isotopic analyses detailed enough that the countries where the material originated might be able to recognize their material (if they had sufficiently well-organized records of their material to attempt to make a match). The United States could assist other countries in establishing such centers or, where centers already exist, provide additional training and equipment as needed and help establish mechanisms for sending seized material to these centers.

Of course, ongoing efforts to improve export licensing and enforcement in the former Soviet states are also critical. Trained and equipped customs officers are of little use if they have no legal authority to seize nuclear materials or other materials and technologies whose export should be strictly controlled. A recent National Research Council review concludes that such export-control support programs, after initial delays, have been effective in stimulating new interest and action on the part of the recipient states; the review recommends continued and potentially increased financing for these programs (27).

In general, increasing the incentives for states to devote resources to this problem will be a critical part of the answer. For example, the European Union, after stepping up its own efforts to ensure that its member states have at least a minimal ability to monitor key transit points into its economic area, could consider making establishment of such a capability a condition of membership (while providing assistance to states to help them meet this condition)—a potentially significant incentive for states eager to join the union (JR Weeks, personal communication).

A possibility for the longer term is an international treaty on nuclear smuggling. Such a treaty could (*a*) mandate and otherwise encourage a variety of forms of cooperation in dealing with this threat, (*b*) require states to meet minimum standards for control of their borders, (*c*) require states that have not yet done so to pass domestic legislation imposing stiff penalties on unauthorized possession and transfer of weapon-usable nuclear materials, (*d*) perhaps include more stringent security requirements for nuclear material than the Physical Protection Convention, along with new requirements for control and accounting of nuclear materials, and (*e*) give the IAEA a mandate to establish a global data base of domestic safeguards practices and to begin a program of voluntary visits to provide advice on security for nuclear-material facilities, as has been done in the case of nuclear safety.

MONITORED REDUCTIONS IN NUCLEAR-WEAPON AND FISSILE-MATERIAL STOCKPILES

While past arms-control agreements have focused primarily on limiting missiles and launchers, the objectives of both irreversible nuclear arms reductions and reduced risk of nuclear theft call for the next generation of agreements to focus in addition on controlling nuclear weapons themselves and the fissile materials needed to make them. President Clinton and Russian President Boris Yeltsin have repeatedly agreed to pursue the goal of "transparency and irreversibility" of nuclear arms reductions, and at their summit in Helsinki, Finland, on March 21, 1997, the two Presidents agreed on a framework for a future START III agreement that included a call for transparency measures relating to "strategic nuclear warhead inventories and the destruction of strategic nuclear warheads," along with other measures to help ensure irreversibility and prevent "a rapid increase in the number of warheads." Transparency measures for tactical nuclear warheads and fissile material stockpiles are to be considered as separate issues (7). The United States has indicated, however, that it will not begin negotiations of a START III agreement until Russia's parliament ratifies the START II treaty; hence, the two governments have not yet begun to flesh out what the broad language of the Helsinki framework might mean in practice. To fully achieve the objectives of transparency and irreversibility of nuclear arms reductions and to lay the foundation for deep nuclear arms reductions in the future will ultimately require a comprehensive transparency and monitoring regime—but such a regime can be built step by step over time.

Outline of a Comprehensive Regime

The NAS report recommends that the United States work to reach agreement with Russia on a broad, reciprocal regime to include (8) (*a*) declarations of stockpiles of nuclear weapons and all fissile materials, (*b*) cooperative measures to clarify and confirm those declarations (including physical access to production facilities and production records for fissile materials), (*c*) an agreed, monitored halt to additions to these stockpiles of warheads and fissile materials for weapons, and (*d*) agreed, monitored net reductions in these stockpiles.

Monitoring of warhead dismantlement and commitment of excess fissile materials to non-weapons use or disposal, initially under bilateral and later under international safeguards, would be integral parts of this regime, as would some form of monitoring of whatever warhead assembly continues. Both the NAS study and the Bilateral Commission reports recommend that the United States and Russia agree to reduce to small, roughly equal remaining numbers of nuclear warheads and small, roughly equal remaining levels of plutonium and HEU in military stockpiles. All other plutonium and HEU, in this approach, would be placed under bilateral and ultimately international monitoring to ensure that it was used only for non-explosive purposes.

Such a regime would do a great deal to build confidence in the size and management of each side's nuclear stockpiles and the progress of nuclear arms reductions—and the information exchanged and the site visits conducted would provide useful additional information to support cooperative MPC&A efforts (though bilateral or international monitoring itself could only detect, not prevent, thefts of material). Creation of this broad regime could be approached step by step, with each step adding to security while posing little risk. While such a regime could never be rigorously verified, in the sense of absolutely confirming that a few dozen nuclear weapons or a few tons of fissile material had not been hidden away somewhere, these measures would be mutually reinforcing, building increasing confidence over time that the information exchanged was accurate and that the goals of the regime were being met. With a sufficiently inclusive approach, the difficulty of falsifying the broad range of information exchanged in a consistent way, so as to hide a stockpile large enough to be strategically significant, could be made reasonably high. The NAS report recommends that this regime ultimately be internationalized, so that all states would declare their holdings of fissile material and all the declared weapon states would declare their holdings of nuclear weapons.

While such a regime could ultimately provide a very high degree of transparency in the management of nuclear weapons and materials, nuclear arms reductions can never be truly irreversible; both the United States and Russia will retain the knowledge and the industrial strength required to rebuild large nuclear arsenals should a national decision be taken that it is a high priority to do so. Nevertheless, a series of steps is possible that could each add to the cost, delay, and observability involved in rebuilding a large arsenal, and thereby greatly reduce the probability of such a decision being made.

Removing warheads from missiles (the primary measure required for the United States under START II) would take only weeks or months to reverse. Dismantling the missiles required to launch those warheads, and the launchers for those missiles (required for certain types of missiles under the START agreements) greatly increases the cost and time required to rebuild. Dismantling the warheads themselves, not yet required under START I or START II, also provides a significant increment of increased cost and delay in rebuilding (particularly useful if the missiles and launchers that might carry those warheads have not been dismantled). The United States, for example, has been dismantling warheads at maximum capacity for roughly a decade, and the time required to reassemble them would be comparable (unless the existing facility for this purpose began working multiple shifts, which might cut the time required by 50% or more); substantially expanding the available capacity for warhead assembly would take nearly as long. If the plutonium and HEU warhead components are dismantled, then refabrication of these components would be necessary before the warheads could be reassembled, and this too would take time and cost money; today, the only operational US facility for fabricating plutonium weapons components is Technical Area 55 at the Los Alamos National Laboratory, which can only fabricate a few hundred components a year.

Ultimately, however, warheads and components that are disassembled can be reassembled—as long as the fissile material needed to do so remains available. While a degree of political and legal "irreversibility," as well as transparency, can be achieved through committing these materials to civilian use or disposal and placing them under bilateral or international monitoring (as well as through monitored commitments not to reverse other steps of this process), if circumstances changed, materials could always be removed from such arrangements. Thus, a fundamental long-term step toward "physical irreversibility" is to transform the excess stockpiles of plutonium and HEU into forms that would require re-enrichment or reprocessing to return them to weapons; recovering, for example, 50 tons of plutonium that had been transformed into spent reactor fuel or immobilized with highly radioactive fission products would require years of operation of large reprocessing facilities, at a cost likely to total billions of dollars (for a discussion of making these distinctions among political, legal, and physical irreversibility in more detail see 36). Moving forward as quickly as practicable in accomplishing such a transformation would also send the world an important signal of the United States' and Russia's intentions not to reverse their ongoing reductions. Even after such transformation, however, either the United States or Russia could reverse the process should they choose to devote enough time and resources to the task; indeed, even if the fissile material were eliminated completely (for example by shooting it into outer space), either nation could eventually produce new fissile material from which to rebuild a large nuclear arsenal. Of course, if sufficient warheads or fissile materials are retained in reserve to rebuild a Cold War strategic arsenal, then programs to eliminate other warheads and fissile materials will not truly achieve the irreversibility objective.

The remainder of this section focuses primarily on US and Russian efforts to build transparency in the management of fissile materials and the dismantlement of nuclear warheads; the question of transforming excess fissile material stockpiles into forms less readily usable in weapons is addressed in detail in a subsequent section.

For years before the Helsinki framework was agreed upon, the United States and Russia had been discussing a variety of elements of a transparency regime. During 1994–1995, the two countries reached several important agreements in principle, but none has been implemented—in large part because of concerns on the Russian side about revealing sensitive nuclear information. Unfortunately, little attention has been paid to date to examining how financial and other incentives could be structured to convince Russian officials that it is in their nation's interest to reverse five decades of Cold War nuclear secrecy and participate in a broad program to monitor and reduce stockpiles of warheads and fissile materials.[23]

[23]If, for example, financial assistance were offered for actual dismantlement of nuclear weapons in return for some means of confirming that dismantlement (as envisioned in the original Nunn-Lugar legislation but never implemented), and reciprocal confirmation of US dismantlement were permitted, this could provide an attractive package.

A broad range of efforts is underway in this area, including formal bilateral US-Russian transparency negotiations; negotiations concerning international, rather than bilateral, monitoring; and alternative, less formal transparency approaches. We now discuss the status of each of these areas in turn.

Bilateral Transparency Negotiations

INSPECTING PLUTONIUM AND HEU FROM DISMANTLED WEAPONS In March 1994, in the first major US-Russian agreement in this area, Secretary of Energy Hazel O'Leary and Russian Minister of Atomic Energy Victor Mikhailov agreed to establish a regime of mutual inspections to confirm the inventories of plutonium and HEU removed from dismantled nuclear weapons. This initiative eventually came to be called Mutual Reciprocal Inspections (MRI).[24] Since 1994, US and Russian experts have carried out a number of joint experiments and come close to agreeing on the specific types of measurements that would be used to confirm that an inspected canister contained a plutonium weapon component; a less intrusive regime is proposed for inspections of HEU components. Such inspections have not yet been implemented, however, because doing so would require an agreement providing the legal basis for exchanging limited types of classified nuclear information (see below).

EXCHANGING NUCLEAR STOCKPILE DATA At their September 1994 summit, President Clinton and President Yeltsin agreed that for the first time ever, the two sides would exchange "detailed information" on "aggregate stockpiles of nuclear warheads, on stocks of fissile materials and on their safety and security" (5). This data exchange has never been implemented either, for the same reason. (Both the United States and Russia still consider the size of their nuclear weapon stockpiles to be classified information.)

German Foreign Minister Klaus Kinkel and others have recommended the establishment of an international nuclear weapons register containing declarations from each nuclear weapon state concerning its stockpiles of nuclear weapons (and in some formulations, stockpiles of plutonium and HEU as well). The weapon states, however, have not been willing to seriously consider this proposal (17, 64, 65; for a similar 1992 proposal from Andrei Kozyrev, then Russia's Foreign Minister, see 66).

CONFIRMING WARHEAD DISMANTLEMENT AND FISSILE MATERIAL DATA In their May 1995 summit statement, Presidents Clinton and Yeltsin reaffirmed that their two governments would negotiate agreements on MRI and the stockpile data exchange and also called for a third agreement on "other cooperative

[24]This name suffers from two drawbacks: the apparent redundancy of "mutual" and "reciprocal" and the fact that the initiative actually covers only a few of the many areas where mutual inspections might occur in the future.

measures, as necessary to enhance confidence in the reciprocal declarations on fissile material stockpiles." More vaguely, the two Presidents agreed to "examine and seek to define" possibilities for "intergovernmental arrangements to extend cooperation to further phases of the process of eliminating nuclear weapons." These modest additional steps forward were based on measures included in a comprehensive US transparency proposal tabled in December 1994, which called for detailed data exchanges on all warhead and fissile material stockpiles and a range of measures (including on-site inspections) to confirm the data exchanged and help confirm the dismantlement of nuclear weapons.[25] The latter objective came to be referred to in the US government as tracing the "chain of custody" of nuclear weapons, from storage sites to dismantlement sites to the fissile components resulting from dismantlement. With neither the MRI concept nor the data exchanges moving forward, no negotiations on these additional subjects were pursued after the May 1995 summit statement, and as of mid-1997, no official US-Russian discussions of how to implement either these past commitments or the broader measures called for in the Helsinki framework had yet begun. Various approaches to confirming the dismantlement of warheads have been proposed. They range from simply monitoring the buildup of plutonium warhead components, or "pits", in storage and assuming that these did in fact come from warhead dismantlement to establishing monitoring systems surrounding the warhead disassembly facilities that would count the warheads and pits going in and out of the facilities (identifying them as such by a variety of possible means, particularly checking of certain radioactive "signatures") (for discussions see 8, 28–30, 67).

LAYING THE LEGAL BASIS FOR CLASSIFIED NUCLEAR EXCHANGES Both the US and Russian legal systems impose stringent requirements for protecting classified information related to nuclear weapons. In 1994, Congress amended the Atomic Energy Act to provide legal authority to negotiate an "Agreement for Cooperation" with Russia that would provide the legal basis for exchanging classified nuclear information (known under the Act as "restricted data") for nonproliferation and arms control purposes. The two sides began negotiating such an agreement in 1995 and had it nearly completed by late 1995, but at that

[25]The most detailed unclassified description of this proposal is in (39). The proposal was quite sweeping, offering to open all fissile material sites to reciprocal visits except those containing intact warheads and naval fuel. It was not as sweeping as the regime recommended in the NAS report, however, as it did not include perimeter-portal monitoring of dismantlement facilities to verify the dismantlement of nuclear weapons and it did not include "nuclear archaeology" measures designed to compare the physical state of fissile material production facilities to the data exchanged in order to build confidence in the accuracy of that data and increase the difficulty of providing false data without detection on a scale large enough to be strategically significant (8).

time the Russian government called off further talks pending a "policy review," and the talks have never resumed.

This should perhaps have been expected. Breaking down the barriers of five decades of Cold War secrecy continues to be a very difficult task in the United States, with its established democracy, and could be expected to be even more difficult in a system emerging from communism. The broad Agreement for Cooperation that was being negotiated in 1995 would have allowed (though not required) the exchange of a broad range of nuclear information related to both warheads and fissile materials and therefore brought into play the interests of a wide range of competing agencies in Russia, including the Ministry of Defense, the Federal Security Service (successor to the KGB), the Ministry of Foreign Affairs, and others, in addition to MINATOM itself. Fundamentally, it appears that in late 1995–1996, with Yeltsin's future uncertain (first with elections upcoming and then with his health in doubt), Russian officials concluded that there would be considerable risk and little benefit in signing a document making it possible to open Russia's nuclear secrets to the United States. Whether this will now change remains to be seen.

As Russian officials have frequently suggested, a step-by-step approach may be needed, narrowing the range of issues initially tackled. One idea suggested privately by some Russian officials is to reach an Agreement for Cooperation limited to only one very specific initiative—such as inspections of plutonium from dismantled weapons—which would not raise the whole range of concerns brought up by the broader proposed agreement. As further steps were agreed to, the language of such an initial agreement could be adapted for new specific agreements on those subjects as well.

NUNN-LUGAR STORAGE SITE TRANSPARENCY As noted above, the United States and Russia have agreed in principle that transparency measures will be applied at the storage facility being built with US assistance. No significant progress has been made, however, in determining what those measures will be—a process complicated by the question of how, if at all, they would differ from the bilateral transparency measures for storage facilities contemplated under the MRI approach or from the international measures contemplated in discussions of placing excess material under IAEA verification (described below). The overlap of three different proposed transparency regimes at this one facility—unilateral Nunn-Lugar transparency, bilateral MRI measures, and international IAEA verification—has complicated negotiations considerably, and the US government's inability, through mid-1997, to provide a clear answer to Russian concerns about how these measures would interrelate and what reciprocal measures would be imposed on US excess weapons components in storage has provoked significant suspicion on the Russian side.

HEU PURCHASE AGREEMENT TRANSPARENCY The one area where the United States and Russia have actually agreed on and are implementing specific transparency measures is the one area where large sums of money are involved—the US purchase of HEU from Russian weapons, blended down to LEU. Transparency measures have been established to provide the United States high confidence that the LEU it is purchasing in fact came from HEU, and at least modest assurance that the HEU came from weapons. These measures are also designed to give Russia confidence that the LEU, once in the United States, is used only for peaceful purposes.[26]

International Monitoring of Excess Material

Some progress is being made toward placing excess material under international monitoring to verify that it is never again returned to weapons—a step recommended in both the NAS and Bilateral Commission reports—but as with bilateral transparency efforts, the process has been painfully slow.

In September 1993, President Clinton announced that the United States would make its excess fissile material eligible for IAEA safeguards, to assure the world that these materials would never again be used for nuclear weapons. To date, the United States has placed only 12 tons out of more than 225 tons of excess material (10 tons of HEU and 2 tons of plutonium) under IAEA safeguards; classification issues, budget constraints, and safety concerns related to monitoring material in radioactive facilities have slowed progress. Several tens of tons of additional material, however, are now being made available for IAEA verification.

At the Moscow Nuclear Safety and Security Summit, the assembled P-8 leaders agreed that excess fissile material should be placed under international safeguards as soon as it is practicable to do so (68). On that occasion, Russian President Yeltsin made a commitment to place the storage facility being built at Mayak, which will hold an estimated 40 tons of plutonium and a much larger amount of HEU, under IAEA safeguards.

[26]At the facility where the material is blended, the United States will have regular access to the three pipes in the "Y" joint where the blending occurs: One carries 90% enriched uranium hexafluoride, one carries 1.5% enriched uranium hexafluoride used to blend down the HEU, and the third carries the merged blend, at approximately 4.4% enrichment. (Slightly enriched material rather than natural or depleted uranium is being used for the blending to further dilute undesirable isotopes in the HEU, such as U-234.) The United States will also make several visits each year to the facilities where HEU metal weapon components are cut into metal shavings and converted to oxide; during these visits, the United States has the opportunity to take rough measurements of the U-235 enrichment of the weapons components in containers and of the resulting metal shavings and oxide in containers, to tag and seal containers being readied for shipment to the blending facility, and to review records of these activities that take place when US inspectors are not present. Russian inspectors have a similar permanent presence at the US enrichment facility where the LEU is received and processed and similar frequent visits to the US fabrication facilities where the material is fabricated into reactor fuel (DOE officials, personal communications).

Traditional safeguards, however, cannot be applied to material in the form of weapons components—a category that includes the material to be stored at Mayak and much of the US excess fissile material—without revealing classified information that could contribute to nuclear proliferation. Neither the United States nor Russia currently has operational industrial-scale facilities for converting metallic plutonium pits to unclassified forms such as plutonium oxide. Thus, if these materials are to be placed under international monitoring in the near term, a modified verification approach that provides confidence without revealing sensitive weapon design information will be required.[27]

A consensus is developing among the IAEA, the United States, and Russia that this effort represents a fundamentally new mission—verifying disarmament in heavily-armed nuclear-weapon states rather than verifying nonproliferation in non-nuclear-weapon states—and that therefore new terminology ("verification" rather than "safeguards") and new approaches should be used. In September 1996, the United States, Russia, and the IAEA established a trilateral forum to discuss the broad range of issues related to placing excess materials under IAEA verification—including not only the technical issues related to classified materials but also questions such as who will pay for the substantial costs incurred by the IAEA in implementing such monitoring; how the commitment to keep these materials under safeguards can be made irreversible when both the US and Russian "voluntary offer" safeguards agreements with the IAEA allow them to remove material from safeguards at any time; and how much effort should be placed on monitoring different types of material (weapons components, metals, oxides, and difficult-to-measure impure forms and residues). Little progress has been made in this forum to date, however. Indeed, as of mid-1997, disputes continued over even the basic purpose of this trilateral initiative (should the monitoring be intended to ensure that the material is never returned to weapons, and if so, should it not continue after the material leaves the storage facility?) and its scope (should the effort cover only the weapons components in storage at Mayak, similar US excess weapons components as well, or broader categories of material excess to military needs?).

Such safeguards on excess fissile material could ultimately cost millions of dollars a year to implement, a cost small by security standards but large

[27]The NAS report concluded that adequate safeguards could be provided without compromising sensitive weapon-design information; it proposed permitting inspectors to confirm the total amount of plutonium in a large number of containers (thus revealing the average amount of plutonium per pit, which it proposed be declassified). A variety of other technical approaches to this task have also been considered. One potentially promising idea under active consideration is to develop "templates" of the radiation signatures of given types of weapon components. A detection machine could then be built that would tell international inspectors only whether the object inspected matched the template. The validity of the templates might be certified to the IAEA bilaterally by the United States and Russia (if an agreement to exchange necessary classified information between these two states can be reached).

in the context of the IAEA budget. The NAS report recommends that the United States and Russia (possibly with some contributions from other members of the international community interested in verified disarmament) pay the IAEA's costs for this mission. More broadly, to carry out its expanded, post–Gulf War missions, along with the new missions of monitoring excess nuclear material and monitoring a global fissile material production cutoff, the IAEA's safeguards budget will need to be substantially increased and other steps taken to strengthen the IAEA's ability to carry out its expanding responsibilities. The IAEA Board of Governors' approval, in May 1997, of a Model Protocol to states' safeguards agreements, which would vastly expand IAEA access to a broad range of sites and information, is a welcome and important step in the long-term effort to strengthen the global safeguards system—but the proof of the effectiveness of the new approaches will be in their implementation (69).

Informal Approaches to Transparency Objectives

Given the slow pace of formal negotiations, a variety of more informal efforts are being made to pursue transparency objectives, including unilateral openness measures and lab-to-lab transparency technology development initiatives.

UNILATERAL OPENNESS INITIATIVES The United States in particular has taken major unilateral initiatives to increase the openness of its nuclear activities, including those related to fissile materials. The objective of these measures was not only to help provide the basis for monitored reductions in warhead and fissile material stockpiles but more broadly to provide the US and world publics with the information needed for democratic decision-making on the future of these nuclear activities. The declassified information ranges from details of past radiation experiments on humans to the number of US nuclear tests. For present purposes, the most crucial information concerns the size, characteristics, and locations of the stockpiles of nuclear weapons, plutonium, and HEU. Although information about the size and locations of US nuclear weapon stockpiles remains classified, detailed data on US warhead dismantlement rates and plutonium stockpiles have been released. Data on the US HEU stockpile are being prepared for release (43). In addition, visits to many nuclear facilities by the public and by Russian representatives have been permitted for the first time. The NAS report recommends that additional information be declassified, including the number of nuclear weapons and the average amount of plutonium in each weapon pit—both important to building an overall reductions regime (8).

While Russia has not yet matched all of these initiatives, a significant increase in openness is apparent. Russia has allowed unprecedented visits to many formerly secret nuclear sites (while keeping the most sensitive areas off-limits) and has declassified full information on past Russian nuclear testing, paralleling the information the United States released earlier on its own nuclear testing program. Information on the size, locations, and characteristics of Russia's stockpiles of warheads and fissile materials remains classified, however.

Several other countries are also increasing transparency with respect to their nuclear stockpiles. In particular, most major states engaged in separating and recycling civilian plutonium are now annually publishing figures on their stockpiles, and discussions among nine of these states, including the United States and Russia and all the states most extensively involved in civilian plutonium recycling, recently led to general agreement—now being considered by the central governments of those states—on a set of guidelines intended to provide a generally consistent level of transparency in civilian plutonium management (for a brief discussion see 17).

LAB-TO-LAB TRANSPARENCY TECHNOLOGY DEVELOPMENT Building on the successful model of the MPC&A program—in which laboratory experts working directly together succeeded in demonstrating technology, building trust, and establishing a constituency to expand similar programs, eventually leading to new government-to-government agreements—US and Russian laboratories have begun a modest program to jointly develop and demonstrate transparency technologies. The first initiative in this effort was a demonstration of technology for remote monitoring—using video cameras and similar technologies to monitor material in storage without on-site inspectors. Equipment was hooked up to monitor HEU in storage at the Kurchatov Institute in Moscow and at Argonne National Laboratory–West in Idaho, and the images and data were uplinked via satellite. Additional remote monitoring efforts, including other facilities, are now being planned. This approach, based on technology developed to improve the cost effectiveness of IAEA safeguards, offers a potentially promising method of confirming that material is secure and not being tampered with or removed, without revealing classified information and without the substantial cost of permanent inspector presence.

A newer initiative involves US and Russian laboratories cooperating to identify and demonstrate technologies for verifying the actual dismantlement of nuclear warheads while minimizing any compromise of sensitive information. This is a modest-scale effort so far (slated to receive approximately $1 million in the current fiscal year) but holds enormous potential for the future.

The Bilateral Commission's reports review the status of these various projects and recommend a reinvigorated transparency effort (11, 12). Specifically, the reports suggest that the United States and Russia

1. resume negotiations with the objective of completing agreements during 1997 providing the legal basis for exchanges of classified nuclear information

and the framework for implementing the agreed stockpile data exchanges;

2. accelerate work on developing measures to verify warhead dismantlement and to inspect plutonium and HEU components arising from dismantlement, with the goal of conducting initial demonstration experiments during 1997 and having a full bilateral regime in place during 1998;

3. develop a credible approach for international verification of material in classified forms by the end of 1997 and begin implementing it in 1998; and

4. make tens of tons of additional material eligible for international verification during 1997.

Unfortunately, however, despite the Presidential-level agreement on the Helsinki framework, as of mid-1997 few experts in either the US or Russian governments were optimistic about achieving rapid progress in these transparency initiatives.

ENDING PRODUCTION OF EXCESS FISSILE MATERIALS

Ending the relentless growth in the stockpiles of weapon-usable nuclear materials worldwide is a critical aspect of any comprehensive plan for effective management of these materials.

The United States and Russia have both ceased producing HEU for weapons, and the United States has ceased producing weapons plutonium as well—although no verification of these facts is in place at present.[28] In Russia, three military plutonium-production reactors continue to operate, not because the plutonium is needed for new weapons, but because the reactors provide essential heat and power for hundreds of thousands of residents of nearby communities. Ending this production has been the first priority of the effort to limit further accumulation of excess materials. These reactors, located at Krasnoyarsk-26 (Zheleznogorsk) and Tomsk-7 (Seversk), are graphite-moderated thermal plants similar to the Chernobyl type, with significant safety weaknesses and no containment vessels (though the Krasnoyarsk-26 facility is underground).

[28]The United States has, however, recently restarted one of its reprocessing plants at the Savannah River Site to clean out solutions held within the reprocessing canyons and reprocess certain types of fuel at the site that are judged to be unsuitable for direct disposal. (An additional reprocessing operation, using a molten salt "pyroprocessing" technology, has also been started in Idaho to demonstrate the technology and to process some sodium-contaminated fuel also considered unsuitable for disposal without processing.) The United States has announced that the Pu-239 separated in these operations will be declared excess to military needs.

In June 1994, the United States and Russia signed an agreement under which these reactors would be shut down by the year 2000 (with verification that the plutonium produced in the interim would not be used in weapons), and the United States was to help Russia identify alternative sources of heat and power. Russia never allowed this agreement to enter into force, as doing so would have created a legal commitment to shut the reactors down at a time when Russia was not yet confident that alternative energy would be available—and when Russia was unsatisfied with what it saw as minimal US assistance in that regard. The United States funded feasibility studies of both conventional and nuclear replacement power sources that analyzed the costs, schedules, and potential financing arrangements for different approaches to providing the necessary power. But neither the United States nor Russia was prepared to provide the financing required to build major new power plants, and MINATOM insisted (over the objections of some of the local authorities) that nuclear plants must be replaced by nuclear plants, not conventional ones.

Ultimately, the two sides agreed in principle to convert the three remaining production reactors to a new fuel cycle whose spent fuel will contain dramatically lower quantities of plutonium (of far lower isotopic quality) and which will not require near-term reprocessing. The conversion will also significantly increase the plants' safety. This conversion will cost tens of millions of dollars rather than the hundreds of millions or billions of dollars required for new plants, but it also means that plants that will never be as safe as modern reactors will continue to operate for a longer period, and the existing plants will eventually have to be replaced anyway when their operational life runs out (estimated to occur in approximately 2010).

After substantial delays caused primarily by turf and funding disputes on the US side, this conversion effort is now moving forward, with the conversions expected to be accomplished during the summers of 1999 and 2000. The US contribution to the project is expected to be somewhat less than $100 million. The United States and Russia are still negotiating a modified agreement changing the 1994 reactor-shutdown agreement into a reactor-conversion agreement (for a useful account of the history of this project see 70).

The second step in this path is a worldwide fissile cutoff convention, banning production of plutonium or HEU for nuclear explosives or outside of international safeguards. Such an agreement would be a major nonproliferation achievement and would mean placing enrichment and reprocessing plants worldwide under international safeguards, including those in the former Soviet Union, which will require a major improvement in MPC&A at some facilities. The IAEA secretariat has estimated that the most likely approaches to monitoring such an agreement might increase the IAEA's annual safeguards costs by $40–$90 million, depending on the types of inspections included (71); the costs of initially preparing older reprocessing plants for safeguards would also be significant.

Unfortunately, since 1993, when President Clinton called for such an agreement and the UN General Assembly unanimously supported its negotiation, virtually no progress has been made. Several countries have objected that an agreement limited only to new production would effectively "grandfather" existing stockpiles, and they have blocked progress until the major nuclear-weapon states and threshold states agree to include negotiations on their existing stockpiles, which those countries have refused to do. No break in this deadlock is expected in the near term. In the interim, a number of analysts have suggested steps toward a "fissile moratorium" in which states would make political commitments not to produce plutonium or HEU for nuclear explosives during the period before an agreement is reached, paralleling the nuclear test moratorium that contributed to the recent negotiation of a comprehensive nuclear test ban (72). The United States, Russia, Britain, and France have already formally declared, in different contexts, that they have permanently ceased production of fissile materials for weapons, but no verification of these commitments is in place. China has indicated publicly that it has not produced fissile material for weapons in recent years, but has not committed not to do so in the future in the absence of a negotiated agreement; the same is true for Pakistan. India and Israel have not made similar statements (72).

It is also important to limit the ever-increasing buildup of weapon-usable civilian separated plutonium around the world. Regardless of countries' views of the best approach to the nuclear fuel cycle, it makes little sense to pay the cost of reprocessing long before the separated plutonium is actually needed for use in reactors, leaving the plutonium stored in weapon-usable form for years or decades at a time. Nevertheless, in discussions of plutonium management among several of the major countries involved, the participating states have rejected US suggestions that they make commitments to cap and reduce these growing stockpiles on specified timetables. Arrangements that would allow utilities to postpone implementation of their reprocessing contracts until they could make use of the resulting separated plutonium (or cancel such contracts with less financial penalty) would be a significant step toward ending this continued buildup.

For example, despite having no commercial-scale plutonium fuel fabrication capability—and therefore no near-term need for civilian plutonium—Russia continues to reprocess at the Mayak plant, adding another ton or more annually to the roughly 30 tons of plutonium in storage there. The Mayak plant's economic survival depends on a relatively small amount of hard-currency income from foreign reprocessing contracts. Providing alternative jobs at Mayak that would offer the same or more income (and providing assistance in dry-cask storage for the countries sending their spent fuel there for reprocessing) could offer the possibility of achieving at least a temporary moratorium on reprocessing in Russia.[29]

More broadly, many utilities' decisions to contract with reprocessors to separate plutonium from their spent fuel are driven not by a desire for the resulting separated plutonium but by the lack of available alternatives for storage and management of their spent fuel. In a number of countries, political or licensing restrictions have limited the expansion of spent fuel storage capacity, giving some utilities no alternative but to find someone who will take their spent fuel (only the reprocessing companies, to date) or to shut their reactors down. Increased efforts to provide interim dry-cask storage of spent fuel—including reexamination, over the longer term, of the possibility of some form of international site for long-term spent-fuel storage[30]—would allow utilities greater flexibility in choosing whether or not to commit their spent fuel to reprocessing.

REDUCING STOCKPILES OF EXCESS FISSILE MATERIALS

No matter what security and monitoring measures are imposed on the huge stockpiles of excess plutonium and HEU now arising, these materials will continue to pose significant security risks as long as they remain in combinations of forms and locations from which they could be rapidly returned to use in weapons if political circumstances change or security arrangements collapse. Hence, there is a growing international consensus [reflected, for example, in the statement of the 1996 Moscow Nuclear Safety and Security Summit (68)] that, as rapidly as practicable, physical barriers should be erected that would make it substantially more costly, difficult, and time-consuming ever to reuse these materials in weapons—either by transforming the materials physically or

[29] Russia is also planning construction of a massive new reprocessing plant at Krasnoyarsk-26 (Zheleznogorsk). MINATOM would like to be able to change Russian law to permit it to offer reprocessing contracts to foreign utilities under which Russia would keep the waste and plutonium separated during reprocessing, meaning that utilities could send their spent fuel to Russia and never have to worry about it again. This increased incentive for utilities could result in a major increase in global reprocessing. For the moment, however, prospects for financing this plant and for such a change in the atomic law appear slim.

[30] While such an international site may not be politically realistic in the near term, it is likely to be essential in the longer term, as many smaller countries are unlikely to be able to find appropriately remote domestic sites for long-term storage or disposal of their nuclear wastes. International attention to the possibility of such a site has increased in recent years, and the possible commercial benefits of such an operation—which could compete commercially with reprocessors in managing utilities' spent fuel—may someday be enough to overcome the obvious political difficulties.

by removing them to locations from which their recovery would be physically impractical.

This situation has motivated considerable attention, which began even before the Cold War ended, to the technical options for accomplishing this objective (for early studies see e.g. 73–78). It has become customary to use the term "disposition" for this phase of nuclear weapon–material management, which goes beyond engineered and guarded interim storage and entails physical transformation and/or relocation of the materials with the aim of increasing the difficulty and cost of their recovery and reuse for weaponry.

A great many approaches to disposition have been conceived and, in varying degrees, analyzed in recent years. As described in the 1994 NAS report (8), these include the following classes of options:

1. *Burning the material as fuel in nuclear reactors.* Either currently operating or more advanced types of reactors could be used.[31] The fuel cycle could be "once-through" (whereby part of the weapon material is fissioned and part remains embedded in the spent fuel together with highly radioactive fission products), or it could entail fuel reprocessing with recycle of the recovered fissile materials (which, depending on the reactor/fuel combination, the number of cycles, and how the fuel cycle is operated, may be able to fission a higher fraction of these materials than a once-through cycle). The residual (unfissioned) nuclear-weapon materials from these approaches would become part of the radioactive wastes that will be produced in any case from nuclear energy generation and would accompany these wastes to whatever final resting place society chooses for them (which, for the United States, now seems likely to be a mined geologic repository).

2. *Mixing the material with pre-existing high-level radioactive wastes in an immobilized waste-form for eventual geologic disposal.* Large quantities of high-level radioactive wastes have been generated in the course of both nuclear-weapons production and nuclear-energy generation. Surplus fissile materials could be mixed with these—preferably intimately mixed to maximize the difficulty of reseparation, and preferably in a stable matrix that would minimize leakage of radioactive isotopes from the waste package after eventual geologic disposal. The resulting immobilized mixtures of fissile materials and radioactive wastes would then be disposed of in the same final resting places chosen for the rest of the high-level military and civilian wastes.

[31] These could include, in the future, irradiation with neutrons from fusion reactors, accelerator spallation systems, or accelerator-driven subcritical reactors.

3. *Disposing of the material, without mixing it with radioactive wastes, in locations selected to make recovery difficult or impossible.* Options that have been mentioned in this category include burying the material in sediments on the deep ocean floor, burying it beneath the Antarctic ice sheet, placing it at the bottom of deep (several kilometers) boreholes in solid rock, diluting it to low concentrations in the open ocean, and launching it into the sun or out of the solar system on rockets.

It would also be possible to combine the third category with the first or second, that is, to dispose of spent fuel or mixtures of fissile materials and high-level radioactive waste in some of the ways mentioned under heading 3, most of which entail a higher level of difficulty of access—and probably higher costs of emplacement—than the mined geologic repositories currently contemplated for disposal of the bulk of military and civilian high-level radioactive wastes. Finally, an approach that resembles category 2 but combines a small amount of new-fission-product creation, mixing with the surplus fissile materials, and geologic emplacement all in one step is to detonate a nuclear bomb in the midst of suitably arranged surplus weapon material underground, resulting in an underground cavity lined with glassified rock formed by the explosion and containing its fission products along with the surplus material.

What criteria should be used to choose among this array of possibilities for fissile-materials disposition? Probably most people would agree that the criteria should include at least the following:

1. timing, meaning how quickly the option could be brought into operation and how quickly it could complete processing of the quantities of surplus weapon-usable material that need to be dealt with, which is critical to reducing, as rapidly as practicable, the security risks posed by continued storage of the material;

2. the dangers of diversion of the material to weapons use (by the country that initially owned it) or its overt or covert theft for weapons use (by anyone else), which are affected by the magnitudes of the flows and stocks of weapon-usable material and the combination of intrinsic, locational, engineered, and institutional barriers surrounding it, at each step of the disposition process (including the material's final state);

3. compatibility with wider arms-control and nonproliferation goals;

4. environment, safety, and health (ES&H) considerations at each step in the disposition process, including, for example, occupational and public

exposures to radioactivity and radiation in the course of routine disposition operations, safety of disposition operations against accidents (including criticality accidents in material processing and storage, and reactor accidents), and effects on the character and magnitude of the radioactive-waste–management burden faced by society;

5. net monetary costs of the disposition operations (after allowing for any saleable products), not only up to the time of emplacement of the material in its final location but also, if applicable, thereafter; and
6. the magnitude of the uncertainties attached to all of the foregoing characteristics, including not only technical uncertainties but also uncertainties (especially of timing) arising from institutional complexities and potential difficulties of securing public acceptance.

Much harder than listing the relevant factors, however, is addressing what relative weight should be assigned to them and how to deal with trade-offs among them (and among different aspects of a given characteristic, such as security or environment).[32]

One of the more important contributions of the NAS study (8) to the disposition discussion, in our view, was in sorting out some of the weighting and trade-off issues by (*a*) defining standards of sufficiency (answering the question, "How good is good enough?") for some of the factors and (*b*) specifying which of the other factors should dominate choices among those options that meet these sufficiency standards. More specifically, the NAS report argued that sufficiency in a disposition option entails the following.

1. With respect to the final condition of the fissile material, plutonium should end up not significantly easier to recover and reuse in nuclear weapons than is the plutonium in typical spent fuel from civilian nuclear reactors (the "spent-fuel standard").[33]
2. With respect to ES&H aspects, the disposition processes should (*a*) comply with existing national regulations (and subsequent modifications of these) governing allowable emissions of radioactivity to the environment, allowable risks of accident, and allowable radiation doses to workers and the public from civilian nuclear-energy activities in the country where the disposition

[32]For example, disposition option A may offer greater security than option B against theft but smaller security than option B against diversion; or one option may be better than another in minimizing routine emissions but worse in effects on radioactive-waste–management burdens.

[33]An analogous standard for HEU, not addressed in the NAS report, is that the HEU should end up not significantly easier to recover and reuse in nuclear weapons than is the U-235 in ordinary low-enriched uranium used in civilian nuclear reactors.

operations take place; (*b*) comply with existing international agreements and standards (and subsequent modifications of these) governing nuclear safety and radioactive materials in the environment; and (*c*) not add significantly to the ES&H burdens that would be expected to arise, in the absence of weapon-materials disposition activities, from responsible management of the environmental legacy of past nuclear-weapons production and from responsible management of the ES&H aspects of past and future civilian nuclear energy generation.

The NAS report argued further that, among the disposition options meeting the foregoing sufficiency criteria, the choice should be most heavily influenced by considerations of most advantageous timing (soonest start, earliest completion), closest approach to the stored weapons standard (described above) in relation to the quality of materials protection and accounting achievable throughout the disposition process, and smallest uncertainties (technical, institutional, and public-acceptance). Monetary costs, while not unimportant (especially in the cash-short former Soviet Union), should be less important than timing and other security considerations unless the costs differ by margins substantial enough to affect more important criteria, such as the timing and uncertainty of carrying out the undertaking at all.

Since the appearance of the NAS study, the essentials of this approach to the disposition issue, and particularly the spent-fuel standard, have been endorsed by a number of other studies (see e.g. 33) and by the US government (see e.g. 34, 36, 37, 39). Its key ingredients have been endorsed, as well, by Russia and the other major industrialized nations, as reflected in the Moscow summit statement just referred to, which in particular endorsed the spent-fuel standard by calling for surplus weapon materials to be "transformed into spent fuel or other forms equally unusable for nuclear explosives." The statement also called for the application of international safeguards and stringent standards of security and accounting for the nuclear materials, and for heavy emphasis on nonproliferation and environment, safety, and health objectives (68).

Highly Enriched Uranium Disposition

In the case of HEU, it has turned out to be relatively easy to find a disposition method that meets the "sufficiency" conditions for end-point security and ES&H characteristics, could be started with little delay and completed rather quickly, allows for a high standard of materials protection and accounting at all intermediate steps (including its entailing a minimum of transport of weapon-usable material in vulnerable forms), and actually makes rather than costs money. This attractive situation results from the fact that highly enriched uranium can be blended in a technically straightforward way with natural or depleted uranium to produce proliferation-resistant LEU, which is a valuable fuel for reactors of currently operating civilian types.

The 3–5% concentration of U-235 in these LEU fuels is well below the minimum required for making a nuclear explosive and far below the 90% or higher figure preferred by weapon designers. LEU can only be re-enriched to weapon-usable U-235 concentrations, moreover, by prolonged use of technologically demanding and costly uranium-enrichment facilities. Only a dozen or so nations, and no subnational groups, have such facilities; they are not easy for a nation to acquire or conceal, and they would not be easy for a subnational group to take over for long enough to use them for enriching LEU to weapon-usability.

The approach of "blending down" HEU to make LEU is the one that both the United States and Russia have decided to use for their excess HEU stockpiles. The US DOE issued a Record of Decision in July 1996 recording its decision to blend the roughly 175 tons of excess US HEU to LEU (79). In September 1996, DOE published a plan for HEU disposition, under which as much as 85% of the blended LEU would be sold for commercial fuel over 20 years (the remainder being extensively contaminated material that will be disposed of as waste after blending) (80).

The United States has also agreed to purchase LEU blended from 500 tons of Russian excess HEU over a period of 20 years (for the article widely credited with suggesting this idea, see 81). If current prices persist, the value of the deal over that period will be roughly $12 billion. A series of difficult negotiations took place over the period 1992–1996 to reach this agreement, work out the implementation details, settle on prices and delivery schedules, and arrange this material's entry onto the commercial market in a way that would not unduly depress uranium and enrichment prices or provide a basis for successful legal action by producers of uranium and enrichment services (for a critical discussion of US handling of these negotiations, see 82). Most of these issues have been resolved (at least for now), and the deal is moving forward—material has been blended from some 18 tons of HEU already delivered, and a contract was recently signed that resolves disputes over pricing and delivery rates for the next five years. Unfortunately, however, in the spring of 1997 another obstacle arose, involving US legal constraints on the re-export to Russia of natural uranium blendstock provided in payment for the natural uranium component of the delivered material, which led to a Russian decision to halt shipments; as of mid-1997, US officials expected this obstacle to be overcome and deliveries to resume shortly thereafter.

Currently, the HEU deal is for 500 tons of material to be purchased over 20 years. There are strong security arguments for increasing both its size and speed. Russia has indicated informally that it has substantially more than 500 tons of

HEU it would be willing to sell. As with the initial deal, additional purchases would help reduce the stockpiles of weapon-usable material in Russia, create an additional incentive for weapons dismantlement, and provide much-needed hard currency—all at zero or modest net cost to the US taxpayer. Arrangements might be reached, moreover, under which the profits from additional purchases might be used to fund high-priority nuclear security objectives, such as upgrading MPC&A or undertaking plutonium disposition (see below). Speeding up the deal would reduce the time during which this material remained in weapon-usable form and bring the other benefits just described more rapidly. Even if the commercial market cannot absorb the material more rapidly, it would make sense to attempt to expand available blending capacity to blend the material as rapidly as practicable. If blending capacity cannot be expanded dramatically, the practicality of other options should be closely examined, including blending the material rapidly to an intermediate level below 20% enrichment, so that it is no longer usable in weapons, or shipping it to the United States as HEU, for blending at a later time (82). The full impact of these options should be considered, however, including the costs of blending before the material can be released on the market and the impact on needed jobs in Russian nuclear cities of shipping the material to the United States as HEU.

Plutonium Disposition: Narrowing the Options

Plutonium raises more difficult issues, and hence our treatment of plutonium disposition in this article will be substantially more detailed. Because virtually all mixtures of plutonium isotopes can readily be used for nuclear weapons, plutonium cannot simply be diluted isotopically, as HEU can, into a form that would require technically demanding isotopic re-enrichment before becoming usable in weapons again.[34] Uranium ore and enrichment services are so cheap, moreover, that even "free" plutonium is not economic to use in water-reactor fuel in competition with low-enriched–uranium fuel in a once-through fuel cycle. [An important contributor to this surprising result is the very high cost of fabricating plutonium-based fuel, arising from the special security safeguards

[34]As noted in the introduction, plutonium mixtures containing large fractions of Pu-238 cannot practically be used to make nuclear weapons because of the intense heat output of Pu-238. There is currently not enough Pu-238 in the world to isotopically "denature" substantial quantities of weapons plutonium to the point that it would clearly be unusable in weapons; the United States, for example, recently paid Russia millions of dollars for 5 kg of this material for use in spacecraft power supplies. Some fuel cycles, however, produce more Pu-238 than others; in the long-term context of reducing security risks from residual plutonium in forms meeting the spent-fuel standard, possibilities for maximizing Pu-238 fractions deserve additional consideration. As production of Pu-238 requires a series of three successive neutron captures beginning with U-235, however, it appears unlikely that practical and economic fuel cycles can be designed that would result in plutonium containing very large fractions of Pu-238.

and worker-health precautions it requires. See (9).] As a consequence, disposition of surplus weapons plutonium will cost money, not make money, no matter which option is chosen.

The NAS study reviewed the full array of options outlined above for disposition of surplus nuclear-weapon plutonium, applying the indicated sufficiency criteria and examining the options appearing to meet these criteria in terms of the further desiderata of timing; other security characteristics; detailed ES&H properties; costs; and technical, institutional, and public-acceptance uncertainties. The study concluded that, while all plutonium disposition options suffer from drawbacks and significant uncertainties, the two least problematic disposition options are

1. fabrication of the plutonium into mixed-oxide fuel (a mixture of plutonium dioxide and uranium dioxide, termed MOX) for use on a once-through basis in a limited number of civilian power reactors of currently operating types (albeit possibly with some modifications to increase the allowable plutonium loading per reactor, thus speeding up the process or reducing the number of reactors needed); or

2. vitrification of the plutonium together with high-level radioactive wastes, achieved by mixing the plutonium and fission products from previous military or civilian nuclear energy activities into molten glass to produce glass "logs" of mass, bulk, radioactivity, and resistance to chemical separation of the plutonium comparable to these properties for spent-fuel bundles from civilian reactors.

The NAS study found that both of these approaches would meet the spent-fuel standard; that both could be accomplished within the ES&H sufficiency criteria described above; that they would be comparable to one another in timing, other aspects of security, overall level of uncertainties, and cost; and that both of them would be superior in timing, cost, and uncertainties to all of the other options investigated that could meet the spent-fuel standard and the ES&H sufficiency criteria.

The conclusion that suitable versions of the immobilization-with-wastes option meet the spent-fuel standard deserves some elaboration. That standard refers not to matching any single characteristic of spent fuel but to making it roughly as hard to acquire the material, recover the plutonium, and make a bomb from it as it would be to do the same with the plutonium in commercial spent fuel. This overall difficulty in returning the plutonium to weapons results from the various barriers that characterize typical spent fuel from currently operating commercial reactors—the mass and bulk of the fuel elements, their radiation field, the low concentration of the contained plutonium and the difficulty of separating it chemically from the materials with which it is intermixed, and the deviation of the plutonium's isotopic composition from the ideal for weapons use. Achieving the spent-fuel standard means that the material's characteristics pose difficulties for theft and weapons use of the plutonium that are generally comparable to those associated with typical spent fuel, which itself varies with reactor type and the specific fuel's history inside and outside the reactor; it does not mean that the material needs to be identical, in each category of barrier, to a particular type of spent fuel.

The immobilization option, unlike the MOX/current-reactor option, does not change the isotopic composition of weapon-grade plutonium at all. But because the NAS committee judged that isotopic variations from the weaponeer's ideal are a much smaller barrier to bomb-making than is intimate mixing of the plutonium with fission products (and no barrier at all to actual theft, compared to mass, bulk, and fission-product radioactivity), the committee held that the standard would be met by plutonium- and waste-bearing glass logs whose mass, radioactivity, and difficulty of chemical processing were expected to be generally comparable to those of typical spent fuel.[35]

In terms of the risk of theft and proliferation, the difference between reactor-grade and weapon-grade plutonium is very modest. For the United States or Russia, weapon-grade plutonium would be somewhat more attractive for reincorporation in their arsenals in the event of a reversal of current arms reductions (since it could be used with high confidence in existing designs without nuclear testing), but the cost and difficulty of recovering the material would be substantial, and both the NAS and subsequent DOE studies concluded that overall, the level of "irreversibility" offered by the reactor and immobilization approaches would be roughly comparable. Perceptions that leaving the material in weapon-grade form offers an option for rapid reversal could be important, however, as discussed below.

[35]In the case examined in the NAS study, plutonium would be mixed into glass logs scheduled for production at Savannah River for the immobilization of defense high-level wastes, at a loading of 1.3% plutonium by weight. This would yield logs with a mass of 2200 kg (versus 660 kg with roughly 1% plutonium for an LEU spent-fuel assembly from a pressurized-water reactor, or roughly 2.7% for a nominal MOX spent-fuel assembly) and an initial surface gamma dose rate of 5200 rem per h, compared to 7900 rem per h for 30-year-old spent fuel (9, p. 270). There are debates about the degree of chemical processing difficulty: Some argue that glass is a simpler matrix to dissolve and process than spent fuel; others argue that the large quantities of silica present in the glass would present removal complications, and it might be more difficult for small nations or subnational groups to separate plutonium from waste-bearing glass logs than to separate it from spent fuel, because technology, experience, and open literature concerning reprocessing of spent fuel is so widespread (see e.g. 36, 56). The NAS report and subsequent DOE studies explicitly rejected the option of immobilizing plutonium without fission products, because chemical separation without the need for heavy shielding would not pose a barrier comparable to the difficulty of recovering plutonium from spent fuel.

Under current US policy, the ultimate fate of the plutonium-bearing waste form from either of these options—spent MOX fuel or plutonium and high-level wastes in glass logs—would be in a geologic repository. Spent fuel and glass logs containing high-level wastes will exist in large quantities and will need to be safely managed and eventually disposed of regardless of what happens to the excess weapon plutonium. The NAS study's conclusion that these two options are the most attractive ones available does not depend on emplacement of the waste forms in a particular repository or by a particular time, or even on emplacement in a repository at all. The key point is that once the weapons plutonium is embedded in spent fuel or waste-bearing glass logs of suitable specifications, it will be approximately as resistant to theft or diversion as the larger quantities of reactor-grade plutonium in commercial spent fuel—and will then represent neither a unique security hazard nor a large addition to the radioactive-waste–management burdens that the spent fuel and immobilized defense wastes would pose in any case.

Nevertheless, both approaches require further study to determine what modifications may be needed to the nuclear-energy and nuclear-waste–management facilities and procedures to ensure that the addition of weapon plutonium would not pose significant problems in relation to accidental chain reactions, worker hazards, and other ES&H issues. For both approaches, it is important to ensure that the characteristics of the plutonium-bearing waste forms and their repositories preclude the residual fissile material's ever reaching criticality in the ground and that addition of weapon plutonium to these wastes does not add significantly to the environmental hazards expected to result from disposal of these wastes (one of the sufficiency criteria).

Subsequent to the publication of these NAS findings, very detailed reexaminations of the full array of plutonium disposition options by the US DOE (34–36, 58, 83) concluded, similarly, that once-through MOX and immobilization with radioactive wastes are the two least problematic plutonium-disposition possibilities and that both would meet the spent-fuel standard. A detailed US-Russian joint study also concluded that these two options are feasible and could meet the spent-fuel standard, though it made no choices of recommended options (37). The reactor-MOX option and the immobilization approach were also identified as the two leading options in the Moscow summit statement and at the subsequent International Experts Meeting on Disposition of Excess Weapons Plutonium. The only significant difference between the more recent official studies and the NAS study in these respects is that "vitrification" has now been replaced with "immobilization" in the description of the mixing-with-wastes option to leave open the possibility that the embedding matrix might not be glass but rather a ceramic or other type of material.

The NAS study's preference for glass—more specifically, for borosilicate glass—is based on this material's having already been relatively well studied in relation to its capacity to contain radioactive wastes and plutonium in a geologic-repository environment and having been the material of choice in most countries for HLW disposal, where there has been substantial industrial experience with its production and handling. This, in the NAS committee's view, means that choosing another glass type or a non-glass embedding material might require substantially more time for testing and licensing before disposition using the immobilization approach could begin. There are, however, some arguments in favor of using a ceramic rather than a glass matrix for immobilizing radioactive wastes, and the question of which is the most appropriate embedding material for such wastes—whether or not they contain plutonium[36] —has become a more active area of investigation over the past few years (84–89).

All of the other options considered in the NAS study or subsequently either (*a*) failed to meet one or more of the sufficiency criteria proposed by the NAS study or (*b*) met or exceeded these criteria, but with longer delays, greater uncertainties, and/or higher costs than the leading candidate options. We now summarize the reasons why specific other disposition options were deemed less attractive, by the NAS study and the subsequent DOE studies mentioned above, than the once-through-MOX and immobilization-with-wastes options (for more detail see 8, 9, 83).

DEEP BOREHOLES Deep boreholes were identified in the 1994 NAS volume as the third option for near-term plutonium disposition most deserving of further study. They also survived DOE's process of screening out unreasonable options, and hence were analyzed in some detail in DOE's studies of the reasonable disposition approaches (34–36). Placing plutonium in very deep boreholes would provide excellent protection against its theft by subnational groups; the protection offered against recovery by the country that emplaced it would be somewhat less, though how it compared to the difficulty of recovering plutonium from spent fuel would depend on the details of the emplacement scheme. Unlike the once-through-MOX and immobilization-with-wastes options, however, the borehole option would achieve its security benefits only once a borehole repository had been approved and licensed and the geologic emplacement accomplished. Given the history of nuclear waste management in the United States, substantial implementation delays, which would prolong the risks of

[36]Particularly relevant to the wastes-with-plutonium case is that dissolution of some of the ceramic forms would be significantly more difficult than dissolution of glass, thereby posing a greater obstacle to recovery of weapon-usable plutonium by means of chemical reprocessing (see e.g. 36, 56).

continued storage in directly weapon-usable form for an unpredictable period, seem likely with this approach. Ultimately, it was judged impossible to have sufficient confidence that the borehole option could be accomplished on a reasonable timescale for reliance to be placed on this option, and DOE eliminated it in the final choice of preferred approaches.

ADVANCED REACTORS AND FUELS During the initial flurry of analysis and thinking about plutonium disposition that followed the end of the Cold War, there was considerable enthusiasm in the nuclear-reactor community about the possibility that the plutonium-disposition mission might serve as the rationale for government support for the development and demonstration of new nuclear-reactor types that would combine high burnup capabilities for weapon plutonium with improved efficiency, economics, safety, and/or waste-management characteristics in the nuclear-energy–generation role. In the early 1990s, Congress directed DOE to sponsor a variety of studies of these possibilities by reactor manufacturers (see e.g. 90). The approaches that were studied included advanced light-water reactors using both conventional MOX fuels and advanced fuel types lacking fertile material (91–94), high-temperature gas-cooled reactors (95, 96), and liquid metal reactors (97). Some of them involved the use of plutonium recycle to achieve, ultimately, the fission of a large fraction of the weapon plutonium, and others showed the possibility of achieving burnups in once-through operation that would be considerably higher than those possible in once-through operation in currently operating reactor types with conventional fuels. Studies conducted in DOE national laboratories also explored the use of accelerator-driven subcritical reactors for plutonium disposition and power generation. Versions of this approach using both molten salt and particle-bed cores were examined in some detail, along with fully critical variants lacking the accelerator. (For somewhat critical summaries of such approaches, see 98, 99).

The NAS study, after examining these findings and conducting its own further analyses of many of the advanced-reactor options, concluded that the MOX/current-reactor and immobilization-with-wastes options can achieve the spent-fuel standard more quickly, more cheaply, and with smaller uncertainties than any of the advanced reactor or advanced fuel options and that the advanced options offered no advantages in other aspects of security or in ES&H aspects that would be large enough to justify delaying weapon-plutonium disposition until such options could be developed and deployed.[37] An important contributor

[37]This was not an argument against advanced reactors per se—which the NAS study noted might well be desirable to develop for their energy applications—but only against the proposition that there was a need to develop them for weapon-plutonium disposition and/or that disposition should wait until they become available. The issue of delinking current disposition decisions from choices about the long-term future of nuclear energy is discussed further elsewhere in this article.

to this conclusion, in relation to advanced options that could burn up a higher fraction of the plutonium than the 25–40% achieved by once-through MOX use in currently operating reactors, is that there is no great security benefit in pushing beyond the spent-fuel standard for weapon plutonium unless and until one is in a position to similarly reduce the security risks posed by the much larger and still growing quantities of civilian plutonium in spent fuel worldwide. In other words, it makes most sense to move quickly to bring the surplus weapon plutonium to the spent-fuel standard and then ask what further measures society might wish to take to reduce the residual security risks from spent fuel.

SUBSEABED DISPOSAL AND OCEAN DILUTION Burial in the mud layer on the deep-ocean floor, known as subseabed disposal, has long been considered by some to be a leading alternative to mined geologic repositories for the disposal of high-level radioactive wastes (100–102); it could also be considered for the disposal of wastes incorporating excess weapon plutonium. Large areas of the abyssal muds have been geologically stable for millions of years and are thousands of miles from human population centers, and the properties of the mud itself would contain most radionuclides for hundreds of thousands if not millions of years. Emplacement could be accomplished by various methods, including the dropping of appropriately designed canisters from ships on the surface. The canisters in that case would embed themselves tens of meters down in the mud.

Most of the parties to the London Dumping Convention, however, agree that it bans dumping of radioactive wastes not only in the oceans but also in the subocean mud; in late 1996, the parties adopted modifications that made this prohibition explicit. Hence, this approach fails to meet one of the sufficiency criteria in the NAS report: compliance with national and international regulations and agreements. Such an approach would also be likely to generate overwhelming national and international political opposition, creating large uncertainties about whether and when it could be implemented. For these reasons, the NAS report recommends this approach not be pursued unless it is reconsidered for the broader purpose of radioactive waste disposal (8).

Similar arguments apply to proposals for diluting the plutonium in large volumes of the ocean. The basis of this rather counterintuitive idea is a simple calculation showing that mixing, say, 250 tons of weapon plutonium into the combined volume of the world's oceans would yield an average plutonium concentration low enough that current standards would deem it entirely acceptable for drinking water. This approach would considerably exceed the spent-fuel standard, making the plutonium practically irrecoverable. But it would be prohibited by the London Dumping Convention, would evoke substantial political opposition, and would entail the possibility that localized "hot spots" and bioaccumulation in food species could lead to significant human doses (8). The idea of placing the plutonium in the subduction zones at the edges of continental plates, so that it would be carried downward as one plate slips under another, makes even less sense: The motion of the plates is so slow that most of the plutonium would have decayed by the time it moved more than a few meters, and the subduction zones are far less stable than many other parts of the ocean.

LAUNCHING THE PLUTONIUM INTO SPACE At various points in the past, the possibility of launching radioactive wastes into space—into the sun, out of the solar system, or into some other orbit that would have little chance of ever intersecting that of the earth—has also been considered (see e.g. 103). For the weapons plutonium, the costs of such a program would be high, the possibility of failure of one or more of the rockets significant, and the likely public opposition overwhelming; these obstacles would be even greater for the much larger program that would be required to deal with radioactive wastes (8).

VAPORIZING THE PLUTONIUM IN UNDERGROUND NUCLEAR EXPLOSIONS Another proposal is to use underground nuclear blasts for disposition of excess weapons plutonium (104). In one concept, some 5,000 plutonium pits would be arranged around a 50-kiloton nuclear explosive, which, when detonated, would vaporize the pits and 50,000 tons of surrounding rock, all of which would then resolidify underground in a glassified mixture containing rock, plutonium, and a tiny amount of fission products from the detonation. (If safety issues could be resolved, such an approach might even be used with 5,000 assembled nuclear weapons rather than 5,000 pits, avoiding the weapon-dismantlement step, but throwing away the valuable highly enriched uranium also contained in the weapons.) The obvious safety and environmental issues raised by disposing of large quantities of plutonium in an explosively created waste form in a non-engineered repository were never analyzed in detail, as the proposal was easily rejected on other grounds. Since a treaty has now been reached banning underground nuclear explosions, this approach fails to meet the sufficiency criterion of compliance with international regulations and agreements. As the reaction to recent French nuclear testing has shown, moreover, public opposition to such a program would probably be intense, and the plutonium in the rock would remain an extremely rich “plutonium mine” for the country where it was located, failing to meet the spent-fuel standard at least in respect to recovery by the host state (8).

Requirements of the Two Preferred Approaches

To implement plutonium disposition using the preferred approaches will require a number of large-scale facilities, including the following.

1. Both options require facilities for converting plutonium weapon-component "pits" to oxides and for processing other types of plutonium to prepare it for disposition.

2. The once-through-MOX option requires (*a*) facilities for fabricating plutonium oxide into MOX fuel and (*b*) sufficient numbers of reactors capable of safely handling MOX fuel and licensed to do so.

3. The immobilization-with-wastes option requires facilities for immobilizing plutonium with high-level wastes (either together in the same immobilized matrix or in separate matrices that would then be intermingled).

Neither the United States nor Russia has large-scale operational facilities for converting pits to oxide, fabricating plutonium fuel, or immobilizing plutonium with radioactive wastes. New facilities will have to be built, or existing facilities modified, for these purposes. In addition, neither country has operating commercial reactors licensed to use MOX fuel. Analysis, testing, and in some cases reactor modifications will be needed to acquire the necessary licenses or license amendments for the use of MOX fuel.

PIT CONVERSION AND PLUTONIUM PROCESSING Both of the preferred approaches require a facility to prepare plutonium for disposition. A prototype facility capable of handling approximately 200 pits per year will be operational at the Los Alamos National Laboratory in early 1998, but a larger facility will eventually have to be built or an existing facility modified for this purpose. New or modified facilities will have to be provided for this purpose in Russia as well. A significant fraction of the US excess plutonium is in forms other than plutonium pits (including various types of impure or contaminated forms, scrap, and the like), which also require processing to prepare them for disposition. Thus, either more than one facility will be required or the processing facility will require the flexibility to handle different types of input materials. This preprocessing step is expected to account for a significant fraction of the total cost of the disposition mission, and it is an important factor in determining when plutonium disposition on a substantial scale could begin (34).

THE ONCE-THROUGH-MOX APPROACH Nearly two dozen light-water reactors (LWRs) around the world are already using MOX fuel made from plutonium reprocessed from civilian spent fuel (105). While some modest differences are associated with using weapons plutonium in such fuel (resulting from both isotopic and chemical factors), the MOX option can be considered essentially a demonstrated technology. Typically, the mix of uranium and plutonium oxides in MOX fuel for LWRs contains 3–5% plutonium.[38] Most of the LWRs now using MOX use this fuel in only one third of their reactor cores (with the remaining two thirds containing traditional LEU fuel); this minimizes the change in core neutronic characteristics (and the resulting increase in requirements on reactor control systems) resulting from the different properties of plutonium and uranium (9, 105).

Using MOX in a larger fraction of the reactor core would allow a faster disposition campaign (if sufficient MOX fuel fabrication capability were available) or the use of fewer reactors. Three operating reactors in the United States (the System-80 reactors at Palo Verde) were specifically designed to be capable of handling MOX in 100% of their reactor cores, and recent studies by reactor vendors and DOE have concluded that many other US reactors would be capable of handling MOX in 100% of their reactor cores with only modest modifications while remaining within their existing licensed safety margins (34, 106–109). License amendments would be required for use of either one-third or full-core MOX, and the complications would be greater in the case of full-core MOX. An approach under active consideration, therefore, is to begin with one-third MOX cores and move to full-core MOX later, as the relevant issues are resolved (34).

A typical 1000-MWe LWR using MOX fuel with 4% plutonium in one third of its core, operating at a capacity factor of 75% and irradiating the fuel to 42,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) would absorb 275 kg of weapon plutonium per year;[39] thus, under these circumstances, some 180 reactor-years of operation would be required to absorb and irradiate a nominal 50 tons of weapons plutonium. The same reactor using MOX in 100% of its core would absorb about 830 kg of weapon plutonium per year. Consuming 50 tons of excess plutonium in 20 years of operation would require 9 reactors of this type using one-third–MOX cores or three such reactors using full-MOX

[38]Plutonium percentages refer to the weight percent of plutonium as a fraction of the "heavy metal" content of the fuel, meaning the sum of uranium plus plutonium and other transuranics.

[39]Such a reactor would actually discharge in its spent fuel about 320 kg of plutonium per year, more plutonium than it took in, because of production of new plutonium by absorption of neutrons in uranium-238 in the MOX and LEU fuel. If, however, the reactor operated with an all-LEU core (that is, with no MOX), it would discharge about 210 kg of plutonium in spent fuel per year. Thus the net effect of operating, for a year with one-third MOX fuel, a 1000-MWe reactor that would have operated otherwise with all-LEU fuel is a reduction of the amount of separated plutonium by 275 kg and a reduction of the total amount of plutonium in the world (weapon plutonium plus reactor plutonium, separated and in spent fuel) from $275 + 210 = 485$ kg to 320 kg, that is, a net reduction of $485 - 320 = 165$ kg. If the same reactor operated with a full-MOX core, it would absorb 830 kg/yr of weapon plutonium and discharge 530 kg/yr of plutonium in spent fuel. In this case, then, the reduction in the amount of separated plutonium is 830 kg/yr, and the annual reduction of the total amount of plutonium in the world is $830 + 210 - 530 = 510$ kg.

cores. In either case, supporting the mission with these time parameters would require a pit-conversion facility capable of handling 2.5 tons of plutonium per year and a MOX plant capable of fabricating about 63 MTHM of MOX each year.

Canadian deuterium-uranium (CANDU) reactors could also be used for plutonium disposition; this approach was analyzed in the NAS report and subsequent DOE-sponsored studies and has since been endorsed by the Canadian government (34, 110, 111). CANDU reactors are believed to be capable of handling 100% MOX cores without significant changes to their control systems. Using MOX based on the existing fuel design, with an average loading of 2.2% plutonium, a single 825-MWe CANDU reactor (such as those at the Bruce A station, being considered for this mission) could irradiate over 1.4 tons of plutonium per year to a burnup of 9700 MWd/MTHM. Using the more advanced fuel design now undergoing testing would allow higher average plutonium concentrations of 3.4%; if the burnup were left the same, this would increase the throughput to over 2.2 tons per year, but if the burnup were increased to take advantage of the energy potential of the fissile material in the fuel, throughput would actually decline slightly, to 1.25 tons of plutonium per year (34). Thus, between 23 and 40 reactor-years of operation would be required to irradiate 50 tons of weapons plutonium. Accomplishing this in 25 years would require a pit conversion plant capable of processing 2 tons of plutonium per year and a MOX plant capable of producing 60–90 MTHM of MOX per year (depending on the plutonium loading in the MOX).

In the United States, several dozen reactors, far more than required, have sufficient licensed reactor lifetimes remaining to participate in the plutonium disposition mission. Although some US reactors may shut down as utility deregulation takes hold if their utility owners do not succeed in operating them in a way that is cost-competitive with other sources of power, the number of reactors likely to remain operational will still be far more than sufficient. The number of CANDU reactors in Canada is also more than sufficient for the mission. In Russia, by contrast, only seven modern VVER-1000 LWRs are operational, and there is some doubt as to whether the older units of this type could practically be converted for MOX use; if all seven could be used, but they were limited to one-third cores, it would take more than their remaining licensed lifetimes to carry out disposition of 50 tons of excess plutonium. An additional 11 VVER-1000 reactors, supplied with fuel by Russia, are operational in Ukraine, however; Russia apparently already intends to supply these reactors with MOX fuel made from civilian plutonium originating from reprocessing of Ukrainian fuel, if Russia eventually builds a MOX fuel fabrication plant that could be used for this purpose (37). With one-third cores, these 18 reactors combined could carry out disposition of even as much as 100 tons of excess plutonium in less than 25 years. If the Russian VVER-1000s could be modified to handle full MOX cores at reasonable cost, five of these plants could carry out disposition of 100 tons of excess weapons plutonium in 25 years, without requiring the Ukrainian plants.[40]

Neither the United States nor Russia has an operational industrial-scale MOX fuel fabrication plant, though such plants are operational in several other countries. The time required to provide such a capability is a key limiting factor on when the once-through-MOX option could begin; DOE estimates that a domestic facility will not begin producing MOX assemblies until 2007. An earlier start could be made on disposition in both the United States and Russia by contracting with existing European facilities for fabrication of initial lead test assemblies and possibly even the first reactor cores, as recommended in the Bilateral Commission reports. Careful attention would have to be paid to the safety and security issues involved in international plutonium transport, however, and the associated political difficulties (11, 12, 34).

The NAS study estimated that disposition of 50 tons of weapons plutonium in existing US LWRs, using modified existing facilities for pit conversion and fuel fabrication, would have a net discounted present cost (at a 7% discount rate) of about $0.5 billion in 1992 dollars, not counting the cost of fees utilities are likely to charge the government for "irradiation services." The equivalent cost for the CANDU approach was estimated at just under $1.0 billion (primarily because the unenriched CANDU fuel the MOX would replace is very cheap, making the gap between the usual cost and the cost for MOX fuel very large).[41] More recent DOE studies, using 1996 dollars and a 5% discount rate, estimated the costs for similar approaches at just over $1 billion for existing LWRs and nearly $1.7 billion for the CANDU alternative. Costs in Russia are much more difficult to estimate: Capital costs of the required facilities are likely to be in the range of several hundred million dollars. DOE currently estimates that either the LWR or CANDU approaches could begin in 2007–2008, and irradiation of 50 tons of excess weapons plutonium could be completed in 2021–2022 (34).

Since the MOX option is largely technically demonstrated, the principal uncertainties facing its implementation in the United States are political and institutional; it may ultimately prove to be very difficult to acquire the necessary

[40] Russia also has a currently operating BN-600 fast-neutron reactor that could potentially be modified to use a partial core of MOX fuel; in the lifetime it would have remaining after suitable MOX fabrication capacity could be provided, it could perhaps irradiate 4–5 tons of plutonium (see 37).

[41] Both Canada and the United States have indicated that this approach is only likely to be used for US plutonium if it is also going to be used for Russian plutonium. In that case, substantial additional costs would likely arise, as Russia would presumably wish to be compensated for shipping its plutonium abroad. Substantial safety, security, and political issues would also be posed by the very large-scale international transportation of plutonium required in this case.

political approvals and licenses to implement the MOX option in the United States. The controversy that has already begun over the possible use of plutonium in US commercial reactors is described below.

THE IMMOBILIZATION-WITH-WASTES OPTION Both the United States and Russia are currently immobilizing high-level wastes in glass, but neither of these operations is designed to handle substantial quantities of plutonium safely. (Compared to immobilizing high-level wastes without plutonium, plutonium immobilization requires dramatically different security and safeguards approaches, new measures to prevent accidental nuclear chain reactions as the waste form is being produced, and careful design of the waste form to ensure appropriate performance after eventual disposal in a geologic repository.) Two approaches are being considered to provide the necessary capability: (*a*) building new immobilization facilities designed to handle both plutonium and fission products or (*b*) immobilizing the plutonium and fission products separately using existing facilities and intermingling the immobilized products to create similar barriers to theft and recovery of the material.

A particular version of the second approach, known as "can in canister," is now judged to be the leading contender in DOE's immobilization program. In one recent variant of this concept, the plutonium would be immobilized without fission products, in small glass melters or ceramic production facilities installed in existing plutonium-handling glove-box facilities (such as those at the Savannah River Site, where DOE's principal HLW immobilization operation is underway). The resulting "pebbles" of immobilized plutonium would be placed into aluminum cans, which would be arrayed in the large glass canisters used to contain immobilized HLW. These canisters would then be filled with molten glass containing HLW (as they normally would be); the aluminum cans would melt, allowing the molten glass to flow in amongst the plutonium pebbles, intimately mixing the plutonium and the radiation barrier. (Concerns about the impact of the aluminum from the cans on the chemical properties of the surrounding glass are motivating consideration of other approaches to achieve similar results.) In the end, the plutonium would be contained within a 3-m, 2-ton glass log that would generate a radiation dose rate of 400–1000 rads per hour at one meter (decreasing to 200–500 rads/hour after 30 years), comparable to the dose rate from a spent fuel assembly. (For a comparison of current estimates of the physical characteristics of different disposition waste forms, see 36). The advantage of this approach is that existing facilities can be used, reducing costs and delays, and the glass or ceramic to contain the HLW, or to contain the plutonium, can each be optimized for its particular purpose.

DOE estimates that immobilization using such a can-in-canister approach would have a net discounted present cost of just under $1 billion (1996 dollars, 5% discount rate), roughly the same as the costs of using existing LWRs (though utility fees will eventually increase the latter costs somewhat). Immobilization using new facilities designed to safely mix plutonium and HLW in a single immobilized product, with the new facilities built as adjuncts to existing operations, is estimated to have a net discounted present cost of over $1.8 billion, because of the high cost of building new facilities designed to handle intensely radioactive HLW. (If the capability to handle plutonium were built into new HLW handling facilities that have to be built in any case, such as the planned HLW melters to be built at Hanford, the net additional cost would presumably be reduced significantly.) DOE estimates that immobilization using the can-in-canister approach in modified existing facilities could begin in 2006 (or a few years earlier if already available plutonium oxides are used to begin), and immobilization of 50 tons of excess weapons plutonium could be completed after 9–10 years of operation, while immobilization using the new adjunct melter approach could begin in roughly 2009 and be completed after a similar period of operation (34).[42]

Like the United States, Russia is already vitrifying high-level wastes. While Russia could probably undertake plutonium immobilization on a schedule similar to that of the US if it decided to do so (and Russian experts are carrying out technical analyses of this approach with US funding), Russia is unlikely to dispose of any large fraction of its excess weapons plutonium, which Russian officials generally view as a national asset to be used for energy production.

Because plutonium has never been immobilized for disposal on a large scale before, this option presents significantly greater technical uncertainties than the demonstrated MOX option. Political and institutional difficulties, however, are likely to be somewhat less for the immobilization approach. The NAS report judged that the overall uncertainties facing the two approaches were roughly comparable.

The second volume of the NAS study, after reviewing the issues and uncertainties in the two preferred approaches in detail, recommends that implementation of both options be pursued in parallel, as quickly as possible, "because it is crucial that at least one of these options succeed, because time is of the essence, and because the costs of pursuing both in parallel are modest in relation to the security stakes" (9, p. 14). The Bilateral Commission reports make the same recommendation (11, 12).

After several years of intensive studies and analysis, in early December, 1996, the US government announced that it had chosen this "dual track" approach as

[42]These costs are a small fraction of the overall projected costs of managing plutonium and plutonium-bearing material in the DOE complex, including storage, stabilization, waste management and the like; this total cost is estimated at nearly $19 billion during fiscal years 1995–2002 (50).

its preferred alternative for disposition of US excess weapons plutonium. This decision has provoked considerable controversy, described below. Nevertheless, on January 14, 1997, with the personal approval of the President, DOE confirmed the dual-track approach in its Record of Decision on plutonium disposition (58). DOE expects the net discounted life-cycle cost of implementing the dual-track approach to be roughly $1.3 billion, only modestly more than implementing either the reactor or the immobilization tracks by themselves (34). DOE is now moving to carry out the necessary preparations for implementing both tracks as rapidly as practicable; the Record of Decision specifies, however, that the extent to which "either or both" of these technologies will actually be implemented will be decided in the future (58).

Russian Plutonium Disposition and International Cooperation

US government deliberations concerning plutonium disposition have devoted considerable attention to trying to ensure that disposition of Russian excess plutonium goes forward in parallel. Disposition of US excess plutonium is closely linked to disposition of Russian excess plutonium. It is highly unlikely that the US Congress will agree to finance the significant costs of disposition of US excess plutonium unless Russia has committed to carry out disposition of its excess plutonium; and Russia has already formally indicated that it will not carry out disposition of its plutonium unless the United States is doing so as well.

The situations in the United States and Russia, however, are very different. While the United States has decided not to pursue a civilian fuel cycle based on plutonium reprocessing and recycling and sees its excess weapons plutonium primarily as a security hazard, Russia continues to plan to implement a plutonium-recycling fuel cycle and sees both weapons plutonium and civilian plutonium as essential parts of that plan. Indeed, alone among the major nuclear powers, Russia still hopes to build commercial-scale fast-neutron breeder reactors in the near term (using a design designated the BN-800, similar to the currently operating BN-600 reactor), and Russian nuclear officials have advocated using the excess weapons plutonium as fuel for these reactors once they are built—though funding to complete these reactors is unlikely to become available for many years.

Perhaps the most fundamental problem with disposition of plutonium in Russia is money. As noted above, capital investments of hundreds of millions of dollars would be needed to provide industrial-scale pit conversion, MOX fabrication, and/or vitrification facilities in Russia—a figure that would grow into the billions if new reactors such as the BN-800s had to be built as well. Given Russia's current economic circumstances, it appears very likely that if these investments are to be made in the relatively near term, the international community will have to help finance them. For better or for worse, it appears unlikely that the United States will agree to pay all the costs of its own disposition and Russia's, so other countries may have to participate as well.

One obvious approach to this issue would be for the United States to simply purchase the Russian plutonium, as it is doing in the case of HEU. The material could be purchased and either brought to the United States or some other country for disposition, or disposition could be carried out in Russia. Russian officials have sometimes argued that since plutonium has the same energy value as HEU, it should have the same market value (a notion that is contradicted by the far higher cost of extracting the energy from the plutonium, as described above); by that standard, using the estimated prices that pertain in the HEU purchase agreement, the purchase of, for example, 100 tons of plutonium would cost approximately $2.4 billion. Presumably after purchasing the material, the United States would then be responsible for its disposition, at a substantial additional cost. While we regard these figures as small by comparison to the security stakes, the difficulty of gaining appropriations for such sums in the current environment of budget stringency has been considered so daunting that the US government has never seriously contemplated this approach. Moreover, the political difficulties of importing 100 tons of Russian plutonium into the United States would be severe, and the argument for spending a large sum to buy the material only to leave it in Russia for disposition would be difficult to make. Ashton Carter and others have proposed an approach that is similar to a purchase in some respects, in which an international fund would be established that would pay Russia (and the United States) to place their plutonium in internationally guarded and monitored storage facilities. While this approach would have the novel and useful feature of establishing international, rather than solely national, guarding of the facilities where this particular plutonium was stored, it has never been seriously considered within the US government—perhaps because Russia has already agreed to place its excess plutonium in a storage facility being built with US help and has agreed in principle to international monitoring (though not guarding) of this facility without being paid to do so (see 8, 82).

Thus, the focus of discussion of disposition of Russian excess plutonium has primarily been on options in which the plutonium would remain Russia's and disposition would occur either completely within Russia or at most making use of reactors in other countries after the plutonium was already fabricated into fuel (as in the Canadian and Ukrainian cases mentioned above). The United States, Russia, and other countries have been working slowly to attempt to find a mutually agreeable approach. In their January 1994 summit statement, President Yeltsin and President Clinton directed their experts to conduct a joint study of the options for disposition of excess weapons plutonium. This government-level study, completed and published in September 1996, covers a range of different options, providing assessments of technical feasibility, cost, schedule, nonproliferation impact, and other matters. While the study did not make specific recommendations, the forum it provided for ongoing discussion of plutonium disposition issues has proved to be an important channel of communication (4, 37). Following up on the joint study, US and Russian experts are now conducting joint analyses and tests of key technologies related to MOX, immobilization, and conversion of plutonium "pits" to oxide. To date, however, this channel has been limited almost exclusively to discussions of technical issues related to plutonium disposition and has not focused on the larger political and financing issues. France, Germany, Canada, and other countries are also working with Russia on related studies and technical programs.

Early in 1996, at President Yeltsin's suggestion, the United States and Russia also established an independent group of senior US and Russian scientists (of which Holdren is the US cochairman and Bunn the US Executive Secretary) charged with making recommendations to the two Presidents on how best to accomplish plutonium disposition. This group, the US-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium, made its Interim Report to the Presidents in September 1996, and a more detailed Final Report in June 1997 (11, 12). These reports recommend that both the United States and Russia implement the dual-track approach as rapidly as practicable and that both countries start the reactor part of the approach using currently operating reactors—rather than waiting for MINATOM's hoped-for BN-800 breeder reactors or high-temperature gas reactors (HTGRs) to be built. The reports outline a series of technical steps that have to be accomplished to prepare each of these tracks for implementation in each country and suggest that the funding obstacle be addressed either through contributions from governments or by the use of proceeds from additional sales of blended-down Russian HEU, which the Western countries would agree to allow into their restricted fuel markets. As noted above, the reports also recommend a series of near-term steps to ensure security and international monitoring for nuclear stockpiles (11, 12).

The April 1996 Moscow Nuclear Safety and Security Summit was a major milestone in focusing high-level international attention on the need to move forward with plutonium disposition. The assembled leaders of the P-8 countries agreed that these excess stockpiles should be reduced as quickly as practicable (contradicting the view that simply storing this material indefinitely is sufficient) and, as noted above, agreed on the spent-fuel standard recommended by the NAS. They agreed that disposition should be done under international safeguards (applied as early in the process as practicable) and with stringent security and accounting measures providing effective nonproliferation controls. In addition, they agreed that both converting plutonium to MOX fuel with subsequent irradiation in reactors, or vitrifying it with high-level wastes, are reasonable options for achieving these objectives. Finally, they endorsed plans for small-scale demonstrations and pilot projects related to these technologies and called for an international experts meeting, which was held in Paris in October 1996, to lay out next steps in international cooperation in this area.

The Paris meeting confirmed the conclusions of the summit and concluded that both MOX and vitrification were important complementary options for plutonium disposition. France, Germany, and Russia put forward a trilateral proposal to build pilot-scale pit-conversion and MOX plants in Russia. As proposed, these plants would be capable of handling approximately 1.3 tons of weapons plutonium per year—enough to provide one-third MOX cores for the four VVER-1000 reactors at the Balakovo site, and a partial MOX core for the BN-600 fast reactor, modified to consume more fissile material than it produces (serving as a "burner" rather than a "breeder"). The three parties are now engaged in design and cost studies of these facilities, though Germany is involved only in fuel fabrication, not in converting weapons components to oxide (112). The United States has indicated that it is prepared to support this approach, if four nonproliferation conditions are met: (*a*) international safeguards on the entire process; (*b*) stringent standards of MPC&A, to ensure effective nonproliferation controls; (*c*) use of the facility only for excess weapons plutonium as long as stockpiles of excess weapons plutonium remain, to ensure that stockpiles of this material are reduced as quickly as practicable; and (*d*) no reprocessing and recycling of the resulting spent fuel, at least as long as stockpiles of excess weapons plutonium remain. The last two of these ideas were controversial at the Paris meeting—both the Russian and some G-7 delegations raised concerns—but more recent discussions suggest greater flexibility; in particular, the US and Russian participants in the Bilateral Commission agreed on all four of these points (12). A number of experts at the Paris meeting also made the case for designing the pilot plants for expandability: Given that the pilot plants themselves are expected to cost hundreds of millions, that money would be better spent as a down payment on a facility with the full capacity needed to accomplish the mission.

As of mid-1997, all of these issues, as well as prospects for financing the substantial costs of such facilities, were being discussed in further bilateral meetings and multilateral meetings of the P-8 Nonproliferation Experts Group, which prepares decisions on nonproliferation issues for P-8 summits. Substantial additional discussion and work will be needed to reach agreement on an international cooperative approach to disposition of excess weapons plutonium.

Ultimately, disposition of US plutonium will not be accomplished unless disposition of Russian plutonium is accomplished, and disposition of Russian plutonium will not be accomplished without success in a very difficult diplomatic juggling act—harnessing skills and financing from several countries with mutual interests in reducing the security risks posed by excess weapons plutonium but with profoundly conflicting views of plutonium's role in the civilian nuclear fuel cycle, for a long-term project that must last for decades. Moreover, as noted above, the irreversibility goal of plutonium disposition will not be achieved unless both the United States and Russia eliminate much more of their plutonium stockpiles than they have to date. To succeed in the difficult negotiation required, and to shift policy as needed to achieve the irreversibility objective, substantially greater high-level leadership will be needed than has so far been exerted.

US Controversy Over the "Dual-Track" Decision

The difficulty of this juggling act is well illustrated by the substantial controversy the dual-track decision has engendered in the United States. A number of nonproliferation and environmental groups have opposed using any of the US excess weapons plutonium in reactors, arguing that doing so would reverse long-standing US fuel cycle policy and increase proliferation and safety risks. These critics have also argued that the MOX approach might require expensive and unjustified subsidies to the nuclear industry and may face sufficient public opposition (in both the United States and Russia) to make its implementation implausible (113). Some have counseled delay for still further study.

Others, including the authors, have argued that these concerns are misplaced, that delay is against the security interests of the United States and the world, and that the nonproliferation arguments favor the dual-track approach (114). The plain fact is that delay on the US side would mean delay on the Russian side as well. That would mean, in turn, prolonging the exposure of an immense quantity of Russian weapons plutonium to significant dangers of diversion (for reuse in Russian weapons) or theft (for use in somebody else's). It also would mean that both the United States and Russia would postpone signaling to each other and to the rest of the world their intention to "lock in" their progress in disarmament by transforming this material in ways that would make it far more difficult to use again in nuclear weapons.

In a December 1996 letter to President Clinton, along with our US colleagues on the Bilateral Commission, we offered the following four arguments for pursuing both the MOX and immobilization tracks in both the United States and Russia.

1. Two tracks minimize uncertainties and delay. Both options face technical and institutional obstacles that will need to be overcome, and it cannot be predicted a priori which set of obstacles will prove more time consuming. Moving ahead on both tracks increases the chance of having at least one implementable option without excessive delay.

2. Two tracks send the message to Russia and others that US disposition is irreversible. While weapon-grade plutonium mixed with wastes in glass is about as difficult for third countries or terrorists to use for weapons as is plutonium in spent reactor fuel, as noted above the weapon-grade plutonium in glass would be somewhat easier for the United States or Russia to reincorporate into their own arsenals if they chose. Thus vitrification alone sends a less reassuring signal about US and Russian intentions to pursue irreversible reductions than does a dual-track approach.[43] Moreover, there is some reason to think that Russia will not eliminate its plutonium stockpile at all if the United States implements only immobilization, leaving all US plutonium weapon-grade. Russia might then merely store its stockpile of weapons plutonium indefinitely, which is what the United States should most wish to avoid. (Both Russian Minister of Atomic Energy Victor Mikhailov and Deputy Minister Nikolai Yegorov strongly expressed the view in late 1996 that it was unacceptable for Russia and the United States to pursue disposition options that would convert Russia's excess plutonium to reactor-grade while leaving US plutonium weapon-grade.)

3. Two tracks have the best chance of garnering needed long-term support. While including the once-through MOX option has proven controversial, excluding it might well have led nuclear power advocates in Congress to force some reactor approach on the executive branch—as they have done several times before. Given that Congress, the Executive Branch, and the interested public include strong proponents of both the MOX and the immobilization options, and that many of the G-7 countries favor primarily a MOX option, only the dual-track approach is likely to be able to muster the bipartisan domestic support needed to fund US plutonium disposition over the long term and the international support needed to help fund plutonium disposition in Russia.

4. Two tracks make it possible for the United States to credibly take part in Russian disposition. A US decision to opt out of the reactor option would make it much more difficult for the United States to credibly participate in

[43]Some analysts have suggested that this objection could be overcome by adding reactor-grade plutonium to the weapon-grade plutonium. The United States, however, does not have substantial stockpiles of separated reactor-grade plutonium available for such mixing; shipping reactor-grade plutonium to the United States from other countries for this purpose would pose difficult political obstacles similar to the obstacles, described above, to purchasing Russian plutonium. In principle, spent fuel could be reprocessed to provide the necessary reactor-grade plutonium, but separating additional plutonium would be contrary to the entire point of the enterprise; new techniques might be developed to combine the weapons plutonium with reactor plutonium in spent fuel without fully separating the reactor plutonium, but these would involve additional cost and delay for further development. None of these approaches has been examined in detail.

implementing the same option in Russia. It would be quite difficult, for example, to make the case to a skeptical Congress that using plutonium in US reactors would pose unacceptable political risks and therefore should not be pursued, while at the same time making the case that Congress should provide financing to help implement the same option in Russia, where the proliferation risks are clearly higher. Yet if the United States did not take part in plutonium disposition in Russia, the effort would either not succeed or would go forward without a US voice in setting the nonproliferation conditions, neither of which would serve US nonproliferation interests.

These arguments and others proved compelling to the government, which ultimately chose a dual-track approach. But the serious criticisms raised about the dual-track approach must be considered and addressed. The main critical assertions are that the MOX component of the dual-track approach would lead to greater direct proliferation risks through possible theft of the material; that it would indirectly lead to increased proliferation risk by encouraging additional reprocessing, in the United States or other countries; that it would indirectly lead to increased proliferation risk by contradicting US fuel-cycle policy and thereby undermining the US ability to convince other countries not to pursue reprocessing and recycle of plutonium; and that it would require costly subsidies to the nuclear industry and might not be technically or politically feasible to implement safely in any case. We address each of these criticisms below.

RISKS OF NUCLEAR THEFT COMPARABLE TO THE IMMOBILIZATION APPROACH Some nonproliferation advocates have warned that the bulk processing of plutonium required for MOX fabrication cannot be adequately safeguarded and that the transportation of plutonium required to ship MOX fuel from the fabrication plant to the reactors raises risks of theft by armed attack on the transports. As the NAS report and subsequent DOE studies concluded, however, bulk processing will be required for both the MOX and immobilization options, and there is little reason to conclude that the immobilization options will be greatly easier to safeguard (8, 36);[44] the risk of theft during transport can be reduced to very low levels by applying levels of security meeting the stored weapons standard, as the NAS recommended and DOE has indicated it will do. Over the long term, disposition of excess plutonium will greatly reduce the risk of nuclear

[44]While the processing may in some cases be somewhat simpler for the immobilization options, the technology for safeguarding such operations has not yet been developed or demonstrated, and the learning involved in implementing safeguards for new processes—under way for decades in the case of MOX—has not yet taken place. Experts on US domestic safeguards identify developing technology for safeguarding plutonium immobilization as the most substantial technical challenge facing US domestic safeguards programs (D Rutherford, personal communication).

theft by transforming vast stockpiles of material now at risk of theft into forms dramatically less attractive to potential proliferators.

MINIMAL IMPACT ON CIVILIAN REPROCESSING PROGRAMS It is unlikely that a US decision to use some of its excess weapons plutonium as MOX would lead to significant increases in the separation and use of civilian plutonium, either in the United States or in other countries. US nuclear utilities are potentially interested in burning MOX made from weapons plutonium because they expect to be paid to do so; they have no interest in pursuing a plutonium recycling fuel cycle that would force them to pay more than they would for continuing to rely on uranium fuel. Even if current policy changed in the future and a MOX plant built for plutonium disposition eventually became available to the utilities for civilian recycling, this would not change this economic calculus significantly, as the capital cost of the MOX plant is only a small part of the overall cost of the reprocessing and recycling fuel cycle (far smaller, for example, than the capital cost of the necessary reprocessing plant). Similarly, such an approach would offer foreign utilities no new financial or technical incentives to reprocess and recycle plutonium. Even in Russia, where a new MOX plant might be provided with international support, reprocessing is proceeding in the absence of a MOX plant, and there is little reason to believe that the presence of a MOX plant would increase the scale of plutonium separation; in any case, current US policy is to insist that a commitment be made to use such a MOX plant only for excess weapons plutonium, at least until disposition of all excess weapons plutonium is complete.

CONSISTENCY WITH US FUEL CYCLE POLICY A strong argument can be made that using some excess weapons plutonium in US reactors is not in fact a reversal of the long-standing US policy of not encouraging the civilian separation and use of plutonium, but is fully consistent with that policy. The dual-track approach is about getting rid of an existing dangerous stockpile of separated plutonium, not about separating more. From President Clinton on down, the US government has emphasized that the United States is "not changing our fundamental policy toward nonproliferation and the nuclear fuel cycle" (115). Consistent with that policy, DOE has pledged that any excess weapons plutonium used in US reactors will be used once-through with no reprocessing and that the MOX plant built for this purpose will be licensed and used only for this purpose and dismantled when that mission is completed (58).[45] Using both of the best technologies

[45]Some have argued that it would have been better to use DOE-owned reactors, rather than commercial facilities. But the available DOE-owned reactors do not have sufficient capacity to accomplish the mission within a reasonable time (though the Fast Flux Test Facility has been considered for part of the mission), and hence this approach would have required building new DOE-owned reactors, or DOE purchasing existing commercial plants. Both of these approaches would carry a heavy burden of additional institutional complexity; the option of building new reactors, as noted above, would also involve substantial additional cost and delay.

available—reactors and immobilization with wastes—to get rid of this material as quickly and reliably as possible should reinforce, rather than undercut, the US message to the rest of the world on the dangers of separated plutonium.

TECHNICAL AND POLITICAL PLAUSIBILITY OF SAFE IMPLEMENTATION Critics of the MOX component of the dual-track approach argue that it will significantly increase risks of reactor accidents or increase generation of radioactive waste. DOE environmental impact studies, however, did not find substantial environmental or safety differences between the MOX and immobilization approaches (35). If the relevant reactors cannot operate with MOX fuel within the same safety envelopes within which they are currently licensed, they will not receive licenses to burn such fuel—and if they do not, the beauty of the dual track is that immobilization will be available to fall back on. There clearly will be strong political opposition in some quarters—as well as strong support from other quarters—to the use of MOX fuel in US or Russian reactors; again, if such opposition proves insurmountable, the dual-track approach offers the possibility of falling back on immobilization. Similarly, if the payments demanded by utilities to carry out MOX irradiation are large enough to make the cost of the MOX option dramatically higher than that of the immobilization approach, the government has the option of relying on immobilization and can use that fact in negotiations with the utilities. But by the same token, should immobilization encounter major technical or political obstacles—for example, objections by South Carolina officials to bringing the nation's plutonium to their state to be stored there in immobilized form until the uncertain day when a repository becomes available—the dual track offers the option of the MOX approach. The fundamental advantage of the dual-track approach is that it avoids making disposition dependent on the success of any one approach.

A decision now to back away from the dual-track approach and instead designate immobilization as the primary approach, with MOX as a backup (as some have advocated), would likely severely undermine US utility interest in participating in the program, thus effectively eliminating MOX as a viable alternative and resulting in all the liabilities of reliance on a single option. To maintain the interest of utilities with well-operated and maintained nuclear plants will require convincing these utilities that (*a*) the government will stand firmly behind them with their local publics and make the case for the national security importance of the program and (*b*) the utilities will have a reliable source of fuel—not a program that will be constantly shifting with the political winds. If MOX were suddenly relegated to the role of an unlikely backup, few if any utilities would see the near-term public relations costs of being associated with the program as being worth the increasingly doubtful long-term benefits. And to make such a change in the US approach now would be seen in Russia and in the G-7 as a sign of US inconstancy, calling into question the US ability to undertake a long-term and irreversible program of excess plutonium disposition. Whatever the validity of these arguments, it is clear that each step toward the potential use of excess weapons plutonium in US reactors will be immensely controversial; this discussion will continue for years or decades to come.

To sum up: Technologies are readily available that can accomplish the job of plutonium disposition. Each has its advantages and drawbacks. The principal task now is mustering the political will to implement the choice that has been made in the United States and similarly in Russia, and to provide the substantial funds needed to get the job done.

Civil-Military Linkages

The links between managing military nuclear materials and managing civilian nuclear fuel cycles arise, at the most fundamental level, from the facts that (*a*) military plutonium and HEU are potential civilian nuclear fuels and (*b*) plutonium and HEU from civilian nuclear-energy activities are potential nuclear-bomb materials. As discussed at length above, this qualitative interchangeability gives rise to the potential application of civilian nuclear reactors for disposition of military HEU and plutonium by using these materials as fuel; in addition, given that most of the world's plutonium resides in relatively theft- and proliferation-resistant civilian spent fuel, it gives rise to the idea of the spent-fuel standard as the appropriate goal for near-term disposition of excess weapons plutonium.

A closer look at the implications of the weapons/fuel interchangeability of plutonium and HEU in light of the quantities of these materials that exist in different forms suggests two further conclusions about the links between the civil side and the military side of these matters.

First, the energy-generating potential of surplus military plutonium and HEU, while not completely insignificant, is small compared to the requirements of the world's nuclear energy system. Specifically, one ton of plutonium or HEU represents about one reactor-year of electricity from a large (1200-MWe) LWR, the type of reactor that dominates world nuclear electricity generation today (9). Inasmuch as world nuclear generating capacity is equivalent currently to about 300 such reactors, 100 tons of excess military plutonium represents about a four-month fuel supply for the world's nuclear-energy system, and 500 tons of excess military HEU represents a 20-month supply. These facts have two important implications: (*a*) Although the excess military nuclear materials are a very big security issue, they are only a small energy issue, which means that security considerations, not energy considerations, should dominate decisions about how to deal with the material. (*b*) Disposition of excess weapons plutonium by using it in MOX fuel in power reactors over a period of decades would not entail converting a significant fraction of the world's civilian power reactors to use of MOX: Disposition of 100 tons of plutonium in 20 years would entail use of less than 2% of the world's nuclear generating capacity if full-MOX cores were used, and 5% if one-third MOX cores were used.

Second, although much more civilian plutonium remains in spent fuel than has been separated from it, the quantity of separated civilian plutonium—about 150 tons at this writing—is more than half as large as the world military plutonium stockpile and considerably larger than the quantity of weapon plutonium declared surplus to military needs to date. Since, as noted above, this separated civilian plutonium is not much more difficult to use in nuclear explosives than is separated military plutonium, its existence should be regarded as posing international-security challenges comparable to those associated with the excess military plutonium. While the national and international efforts being devoted to protecting and accounting for this separated civilian plutonium are by no means negligible, we believe it is far from clear that these efforts are fully commensurate with the risks this material poses (for a variety of perspectives on this issue over time, see e.g. 51, 116–118). As noted above, the NAS study recommends the negotiation of more stringent international standards for protection of this material, approaching the stored nuclear weapon standard.

Another dimension of civil-military linkage with respect to the management of weapon-usable nuclear materials is the question of whether, in the long run, the military and civilian plutonium embedded in spent fuel will be considered "safe enough." As noted above, the principal barriers against weapon reuse of plutonium embedded in spent fuel are the mass, bulk, and intense radioactivity of this material (making it difficult and dangerous to steal) and the demanding nuclear-chemical–engineering technology required to separate the plutonium from the fission products and the uranium while avoiding lethal radiation doses to the people doing it. These barriers, constituting the core of the spent-fuel standard, are very much worth striving to impose on as much as possible of the world's separated plutonium over the decades immediately ahead. Unfortunately, however, these barriers will shrink over time, as sophisticated technological capabilities spread and as the radioactivity in the spent fuel decays.[46] Society might ultimately decide that this material—including spent fuel from ordinary nuclear power generation as well as spent MOX fuel or immobilization forms resulting from disposition of military plutonium—ought to be better guarded than has been thought necessary until now, that its emplacement in geologic repositories ought to be accelerated, or that advanced reactors or accelerator-driven systems should be used to reduce the residual amounts of

[46]For the first few hundred years, the radiological hazard posed by spent fuel to those approaching or working with it is dominated by the fission-product cesium-137, so for this period the hazard falls at a rate corresponding to this isotope's half-life of 30 years.

plutonium disposed of as waste.[47] The NAS study recommends that research on fission options that might reduce the long-term security risks of plutonium in spent fuel "should continue at the conceptual level" (8, p. 17).

If nuclear energy ends up playing a significantly expanded role in the world energy future, the burden of managing spent fuel and the burden of protecting separated plutonium are both likely to increase. Once-through use of low-enriched uranium fuels might end up being greatly expanded and extended through the use of low-grade uranium ores, including even the dilute (3 parts per billion) but vast (4 billion tons) quantities of uranium in seawater. Alternatively, a greatly expanded nuclear-energy system might rely on reprocessing and recycling large quantities of weapon-usable plutonium bred from uranium-238 or, equivalently, weapon-usable uranium-233 bred from thorium.[48] Recycling plutonium or uranium-233 on such a large scale without creating intolerable security risks is likely to require MPC&A measures even more challenging to implement than those currently contemplated for military plutonium, or to require the use of proliferation-resistant advanced-reactor and fuel-cycle technologies that are not yet fully developed (122, 123).

In concluding, as they did, that advanced nuclear reactors are not needed for the purpose of bringing currently surplus military plutonium to the spent-fuel standard, the NAS plutonium study (8, 9), DOE's subsequent reviews (83), and the Bilateral Commission report (12) were all careful to say also that advanced reactors and fuel cycles deserve continuing investigation based on the prospects of such technologies for improving the economic, environmental, safety, and proliferation-resistance characteristics of nuclear power as a major potential contributor to meeting civilization's long-term energy needs. These studies also noted that, if and when advanced reactor or fuel-cycle technologies are developed and deployed based on their merits in this energy role, it could prove

[47]There has been increasing discussion in recent years of the potential security risks posed by the possibility that geologic repositories may become "plutonium mines." Within the IAEA, the safeguards division has determined that a minimal level of continuing safeguards will be necessary even after spent fuel repositories are closed, possibly extending indefinitely, to ensure that plutonium is not being recovered from them (119); discussions of the shape of a safeguards regime for repositories are continuing. One provocative recent study has suggested that tunneling to retrieve plutonium from aged spent fuel may become relatively easy and cheap, raising a serious long-term proliferation concern (120); some others argue that the potential long-term proliferation risk posed by plutonium mines has been exaggerated (see e.g. 121).

[48]Breeding and recycling can extract perhaps 50–100 times as much useful energy from each kilogram of uranium mined than is extracted by the once-through fuel cycle that dominates world electricity generation today; and resources of thorium, which can support a breeding/recycling fuel cycle but not a once-through one, are even larger than uranium resources. Because the breeding/recycling technology is currently costly and uranium currently cheap, however, breeding/recycling is not economically competitive (and is not likely to become so for decades, if then) despite its large advantage in fuel-utilization efficiency (see e.g. 9, 98).

desirable to employ them in the disposition of any surplus military plutonium that remains at the time or in further reducing the risks from spent fuel or other plutonium-bearing waste forms (whether from civilian energy generation or disposition of military plutonium).

But these studies were emphatic that disposition, to the spent-fuel standard, of the surplus military plutonium that exists today should proceed in the meantime, using the existing reactor technologies and immobilization technologies that can most quickly, safely, and inexpensively be adapted to this task. It is worth quoting the Bilateral Commission report on precisely this point (12):

> Notwithstanding these linkages, it is not appropriate to entangle the short-term decisions needed to minimize the immediate security hazards of surplus military plutonium with longer-term decisions about the optimum technologies for meeting future nuclear energy needs. There is much uncertainty and controversy about how much energy will be required from nuclear sources in the future and about which nuclear-energy technologies will prove most attractive for meeting the nuclear-energy needs that materialize. These uncertainties and controversies may take decades to resolve. To delay decisions about the disposition of surplus military plutonium until the shape of the nuclear-energy future is clarified is to countenance unacceptable prolongation of the higher security risks of interim storage of this material (as compared with the improved protection against theft and diversion, and the positive "signal" for arms-control and nonproliferation, that would result from processing it as quickly as practicable into spent fuel or waste-bearing glass logs).

AVOIDING ECONOMIC COLLAPSE IN THE NUCLEAR CITIES

All the measures described above are essential parts of a long-term program to manage and control weapon-usable plutonium and HEU. None of these efforts will be successful in the long run, however, absent a still broader agenda of reform, including improving the economic conditions of those responsible for nuclear weapons and materials. Desperate people are ingenious in overcoming obstacles; whatever security technologies are deployed, significant proliferation risks will continue to exist if the personnel who must guard and manage nuclear weapons and fissile materials are underemployed, ill paid, embedded in a culture of growing crime and corruption, and confronted with an uncertain future offering no assurance that they will be able to provide the necessities of life for themselves and their families. These issues can only be addressed as part of a broad effort devoted to economic renewal in the former Soviet Union and the establishment of a strengthened legal system able to cope with crime and corruption.

A critical step in that broader effort will be developing new businesses to diversify the economic base of the nuclear cities in the former Soviet Union. Economic collapse in these cities would pose a serious threat to the security of the United States, given the large quantities of nuclear weapons and nuclear materials stored there. The recent suicide of the director of Chelyabinsk-70, one of Russia's two premier nuclear weapons design laboratories—apparently in significant part provoked by anguish over inability to pay his people's salaries—highlights the desperation felt by some in Russia's nuclear cities.

Diversifying the economies of these cities will not be easy. They were created for only one purpose: the production of nuclear weapons and their essential ingredients. By design, they are remote and isolated, limiting the opportunities for trade. They remain "closed cities," meaning that no one can enter or leave without special permission. While these cities once received the best of everything the Soviet Union had to offer, including deep respect from the society at large for their scientific contributions and national defense mission, their economies have virtually collapsed with the drastic decline in central government funding for nuclear weapons activities. (In the United States, the contraction of the nuclear weapons complex has been accompanied by a vast increase in spending on cleanup (so that some sites now employ more people than they did in the days of maximum production), and hundreds of millions of dollars have been spent on easing worker and community "transition" from government dependence; but in a Russian society short on cash for even the most basic needs, a similar approach has not been possible.) In general, these cities have seen less of the benefits of reform than virtually any other part of Russia. Thus, efforts to develop new businesses in these cities are certain to be difficult and are likely to require enormous creativity, perseverance, and substantial government subsidies.

Some programs designed in part to foster such diversification are already underway. The International Science and Technology Center (ISTC) in Moscow, a similar center in Kiev, and a variety of lab-to-lab programs are already employing thousands of former Soviet weapons scientists in useful civilian work. (Thousands more, however, are either still focusing their efforts on weapons of mass destruction or remain underemployed.) A recent review by the National Research Council strongly supports the science centers program, pointing out the critical role it has played in providing peaceful work as an alternative to work that might be offered by potential proliferating states and recommending that core funding be continued at least until 2003 (124). Similarly, DOE's Initiatives for Proliferation Prevention program (IPP, formerly the Industrial Partnering Program), which seeks to provide initial funds to link Russian and US laboratory technical experts with businesses willing to invest in commercializing their technologies, is examining scores of potentially promising technologies (125)—but only a small number have graduated to the commercialization stage, and few if any have yet demonstrated that they will be ongoing, commercially self-sustaining ventures. Both of these programs are making important progress and adapting to new opportunities. The ISTC, for example, has launched a "partners" program to facilitate funding from other government agencies and private entities who want to accomplish research programs through the ISTC mechanism. Neither of these programs, however, is specifically targeted on the nuclear cities, and as of today, there are no mechanisms to support establishment of new businesses in these cities in which US labs and businesses do not play a central role. Similarly, existing defense conversion programs have begun contributing to the shift of some facilities from commercial to civilian production, but none of these programs has been targeted specifically at the nuclear cities and only a tiny amount of funding from them is going to the nuclear cities.

Nevertheless, the prospects are not entirely bleak. The nuclear cities have a variety of diversification efforts underway, with varying degrees of success; in some cases, thousands of people are employed in non-nuclear work, and in others (such as Tomsk-7), employment has actually increased in recent years because of the volume of foreign commercial uranium processing contracts. As a result of an IPP-organized conference in late 1996, a major US-funded feasibility study is under way that is intended to provide an investment-quality plan for the construction of a large silicon plant at Krasnoyarsk-26; IPP and the US Defense Enterprise Fund are involved in financing the initial studies, but the project is intended to be commercially self-sustaining and to employ many of the workers who will lose their jobs at the reprocessing plant there when conversion of the plutonium production reactors is complete (126; M Bunn, unpublished data; Russian institute officials, personal communications).

A large international effort is needed to identify and support new business prospects for these cities. While some successful diversification is already underway, in other cases diversification has had few successes and will require major cultural changes and substantial government financial support. A useful first step might be to organize business development conferences in each of the major nuclear cities, bringing together local interests with ideas for new businesses, Russian and foreign investors, and international banks and financial institutions. The emphasis should be on partnership with private industry, in order to target funds to projects that business identifies as having a substantial chance of success. There are also opportunities for increased US funding for work in these cities on projects that directly benefit the United States. For example, some of the substantial research and development of nuclear cleanup technology now underway could be contracted to Russian experts, potentially improving the cost effectiveness of the development effort while providing new jobs in the nuclear cities.

LEADERSHIP AND SYNERGIES

This article outlines a wide array of major projects, each with its own complexities and issues, whose completion will stretch for years into the future and require the expenditure of hundreds of millions of dollars. (Table 3 outlines the currently allocated and requested US funding for the programs described in this article.) In implementing any such program, it is essential to prioritize the key objectives, coordinate the efforts closely, and seize opportunities for synergies between different parts of the program.

A consistent theme of many of the studies of these subjects has been that implementing this complex array of projects will require stronger support and more active leadership from both the executive and legislative branches in both the United States and Russia than has been available to date (see e.g. 8, 10). Currently, there is no high-level official in the US government whose mandate is principally focused on securing nuclear warheads and materials and achieving monitored reductions in nuclear warhead and fissile material stockpiles, and high-level attention to these issues has been intermittent at best.

In 1996, in legislation originated by Senators Sam Nunn (D-GA), Richard Lugar (R-IN), and Pete Domenici (R-NM), Congress mandated the establishment of a national coordinator covering a broad portfolio including all aspects of nonproliferation, as well as related terrorism and organized crime issues. (That mandate was almost certainly too broad for such a coordinator to be effective in the absence of a substantial staff.) Ultimately the original language was modified so that a reorganization of the government's management of these issues was no longer required and it became legally possible to simply designate the existing Deputy National Security Advisor as the mandated coordinator, which is the approach the Clinton Administration has chosen to take (for the text of the final version, see 127). It remains to be seen whether this approach will be sufficient to carry out the monumental tasks involved in carrying this agenda to fruition. Energetic and high-level leadership will be required to keep these issues at the front of the agenda with Russia and other relevant countries, to defend the budgets of these growing programs in Congress (where many legislators continue to see these programs as "foreign aid" rather than as investments in US security), and to coordinate and integrate the broad range of efforts now under way.

All of the efforts described in this article can and should reinforce each other. Technologies and institutional relationships developed in the course of upgrading MPC&A will also contribute to building transparency. Data exchanges and reciprocal visits carried out under the transparency program will provide useful information for the effort to upgrade MPC&A. Storage and disposition of excess plutonium and HEU will inevitably be integrally linked. New businesses

Table 3 US funding related to control of plutonium and HEU in the former Soviet Union (in millions)[a]

	FY 1997 Allocation	FY 1998 Request
Direct measures to prevent theft and smuggling		
MPC&A (DOE)	113	137
Fissile material storage facility (DOD)	105	65
Nuclear warhead security (DOD)	15	36
Nuclear smuggling: border security (DOD/Customs)	9	0
Nuclear smuggling: law enforcement (DOD/FBI)	10[b]	0
Nuclear smuggling: R&D and support (DOE)	9	21
Monitored reductions in nuclear stockpiles		
Mutual reciprocal inspections (DOE)	—	—
Stockpile data exchange (DOE, DOD)	—	—
Verified warhead dismantlement (DOE)	3	?
Nunn-Lugar, HEU transparency (DOD, DOE)	13	?
IAEA verification of excess material (DOE)	1	?
Unilateral openness measures (mainly DOE)	—	—
Ending production of excess material		
Plutonium reactor conversion (DOD)	13[c]	41
Worldwide fissile cutoff (State/ACDA[d]/DOE)	—	—
Reducing stockpiles of excess material		
HEU purchase (DOE)	—	—
Russian plutonium disposition (DOE)	10	10
Avoiding economic collapse in the nuclear cities		
ISTC (State)	14	?
IPP (DOE)	30	30

[a]Source: Budget figures provided by DOD, DOE, and State Department officials (rounded to nearest million). Figures include only US government funding for programs in the former Soviet Union, not funding from other countries, private funding, or US government funding for programs primarily within the United States. In many cases, funding figures for former Soviet programs represent a fraction of a larger overall program (for example, the overall US budget for fissile material storage and disposition is over $100 million for both years, of which $10 million is devoted to Russian cooperation). Question marks represent FY 1998 allocations not yet determined by agencies; dashes represent initiatives not yet involving significant funding.

[b]These funds were authorized in FY 1995, but are still available and are now being spent.

[c]This includes $10 million in the DOD budget and $3.5 million in the DOE budget.

[d]Arms Control and Disarmament Agency.

for the nuclear cities will inevitably include efforts in all these areas, including fissile material disposition, production of MPC&A equipment, and the like.

In particular, the large sums of money involved in the HEU purchase can provide substantial leverage for accomplishing other nuclear security objectives, and this needs to be carefully considered. Looked at in isolation, raising the billion dollars or more that might be required to finance plutonium disposition in Russia might seem extremely difficult. But, as one example, the Western countries could agree to purchase another 100 tons of HEU—a 20% addition to the 500-ton deal already underway—linked to an approach for using the proceeds to finance disposition of Russia's excess weapons plutonium (for a detailed proposal for setting up a Russian–Western joint venture financed by such an arrangement, see 128). The idea of offering to purchase HEU more quickly or in larger quantities if Russia agrees to take certain steps that are in US interests has not yet been pursued (14).

CONCLUSIONS

The control of plutonium and HEU—the essential ingredients of nuclear weapons—is perhaps the most serious and urgent security challenge facing the United States in the coming decade. Successful acquisition of enough material for one or a few bombs by a rogue state or terrorist group could cause a severe threat to international security with little or no warning. And controlling nuclear warheads and fissile materials will be an essential part of any long-term effort to drastically reduce or ultimately eliminate nuclear arsenals.

Meeting this challenge will require a comprehensive program of action on many fronts. To succeed, this program will require more energetic leadership and substantially higher levels of funding than it has had to date, along with strong Congressional and international support. All told, the programs outlined above will cost several billion dollars over the next decade or more.[49] Although these sums are substantial, particularly in the current atmosphere of budget constraints, they are tiny by comparison to the hundreds of billions a year the United States is accustomed to spending to ensure its security.

The costs to the United States of improving the protection of nuclear materials in the former Soviet Union should be seen as an investment in national and international security—just as the cost of producing the US stockpile of nuclear weapons and weapons materials was once viewed. The costs of failure to

[49] Plutonium disposition alone will cost more than a billion dollars in the United States, and a similar amount in Russia, in discounted terms; MPC&A will cost another roughly half-billion dollars; and the costs for comprehensive approaches to nuclear smuggling, transparency, and economic diversification of the nuclear cities, while not yet fully calculated, are likely to be significant.

act—in higher defense budgets and lower security in the future—would be far higher than the cost of timely action now.

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